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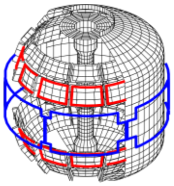

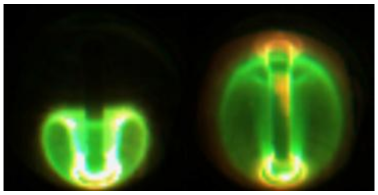

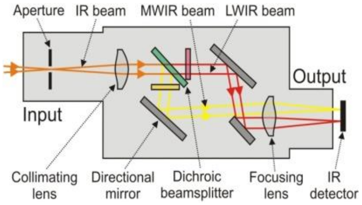

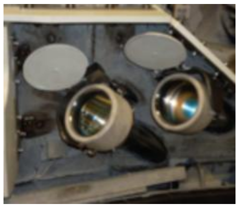

NSTX-U Collaborator Research Plans

11.1 Introduction

Research on NSTX-U is carried out by a National Team of research groups from 24 universities, national laboratories (including PPPL), and private industry, many of which participated in the team building effort since FY1998, obtaining direct collaboration funding from DOE. Approximately 68% of the NSTX-U scientific staff is from these collaborating institutions. The contributions of all collaborating institutions, including foreign cooperation not funded by DOE, have been extensive, as is evident from the overview and plan sections of this 5-year plan. The collaboration plans by U.S. institutions other than PPPL are briefly described in this chapter to provide supporting information to the overall NSTX-U 5-year plan. These plans include activities already funded by DOE for durations up to 4 years, and contain new ideas that extend to FY2018. The out-year collaborative research plans will require timely discussions within the NSTX-U research team before formal proposals are submitted to DOE for peer review and approval. It is expected that during the FY2014-2018 period the research efforts by collaborating institutions will increase at a rate proportional to the rate of NSTX-U research efforts by PPPL. Among the 156 research users of NSTX-U funded by DOE including graduate students and post-doctoral researchers, 106 are from collaborating institutions and 50 are from PPPL. An additional 89 national and 61 international scientists not funded by DOE also collaborate on NSTX via analysis, simulation, and experiments. PPPL engineers and technicians carry out the operation, maintenance, and upgrades of the NSTX facility, and the interface, installation, and maintenance of diagnostics including those provided by the collaborating researchers at an effort level of 107 FTEs. The research and facility operations teams have worked together effectively to enable rapid progress toward the mission of NSTX-U since the beginning of NSTX operation.

11.2 NSTX-U National Collaborator Research Plans

Detailed descriptions of proposed/planned research are provided below organized by institution, research topic, principal investigator, and contributing scientists and students. Multiple listings for the same institution imply research is being carried out on more than one grant and/or topic.

11.2.1 University of Colorado at Boulder

Research Topic: Assessment of Edge Turbulence and Convective Transport through Velocity Field Analysis

Principal Investigator: Tobin Munsat
Participating Graduate Students: Yancey Sechrest
Funded under DOE Grant: DE-FG02-08ER54995

Introduction

This collaboration involves both analysis of data from the NSTX Gas Puff Imaging (GPI) diagnostic and hardware modifications to this diagnostic instrument. The goal of the data-analysis portion of the project is to bring the unique GPI data to bear on the diverse topics of scrape-off layer turbulence and transport, identification of zonal flows and geodesic acoustic modes (GAMs) in the NSTX edge, the relationship between edge poloidal flow and turbulence, relationships between flows and transport bifurcations (including L-H transitions), ELM physics and ELM-related transport including Lithium effects, and divertor and x-point fluctuation studies. Analysis of this type and advanced understanding of the quantities uniquely accessible to GPI are critical to the evaluation the plasma-boundary interface in fusion plasmas, and can have significant impact on next-step devices.

The hardware portion of the project involves a continual evolution of the GPI instrument (as space and budget allow) to address several of the scientific goals of NSTX-U through a suite of edge turbulence studies. Potential modifications include the implementation of multiple cameras and multiple simultaneous views (increased from 1 view currently). The hardware plans are kept as simple as possible, taking advantage of re-entrant windows and external coherent fiber bundles (i.e. avoiding in-vacuum optical hardware), while making use of fast cameras that are already in-hand. The enhanced capability will enable extended measurements of 3-D turbulent structures along common B-field lines, as well as detailed information on the interplay between 3-D resonant magnetic perturbations (RMPs) and turbulence dynamics.

Current research contributions to NSTX Upgrade

Recent studies include the development of the HOP-V velocimetry code, written by the Principal Investigator specifically for use with the NSTX GPI data [1], as well as a series of edge-turbulence studies which have characterized the behavior of coherent structures in the NSTX edge [2-5]. We have collaborated closely with Dr. Stewart Zweben on this work.

Summary of proposed research plan for 2014-18

To address several of the scientific goals of the forthcoming NSTX upgrade, we propose to continue our experiments with the curent Gas-Puff Imaging (GPI) diagnostic for a suite of edge turbulence studies, as well as implement a series of upgrades, as access and budget allow. Critical topics addressed by this diagnostic (in its current and modified form) include scrape-off layer turbulence and transport, identification of zonal flows and geodesic acoustic modes (GAMs) in the NSTX edge, study of the underlying relationship between edge poloidal flow and turbulence, relationships between flows and transport bifurcations (including L-H transitions), ELM physics and ELM-related transport including Lithium effects, and divertor and x-point fluctuation studies. Many of the topics studied for general understanding of edge turbulence and flow will have additional importance when studied in the context of resonant magnetic perturbations (RMPs) in the upgraded NSTX.

While there is not currently budget for an extensive modification of the diagnostic or the NSTX interface, there are several diagnostic enhancements that are possible using existing hardware. Specifically, the current single GPI view can be extended to include a second view from Bay B with only a minor modification of the existing GPI re-entrant port and will enable simultaneous sightlines in opposite directions along the same flux tube. In addition to the second Bay B view, we may have an opportunity to make use of a top-view (Bay E) onto a divertor-region gas manifold, all of which exists or is already under development.

Furthermore, we may be able to implement two additional Phantom v710 cameras, which were purchased by PPPL and are currently in use at C-Mod, if they become available (the additional cameras are perhaps the most costly component of an enhanced GPI system). These relatively minor modifications will enable extended measurements of 3-D turbulent structures (along common B-field lines), as well as detailed information on the interplay between 3-D resonant magnetic perturbations (RMPs) and turbulence dynamics.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Continue analysis of single-view GPI data, emphasizing "blob" transport and interplay with edge turbulence, transport bifurcations, and ELM studies.

FY2015:

- Continue analysis of single-view GPI data, emphasizing "blob" transport and interplay with edge turbulence, transport bifurcations, and ELM studies.

FY2016:

- Implement second Phantom v710 camera at Bay B for dual-view studies.
- Analysis of extended 3-D structures in NSTX edge.

FY2017:

- Implement top-view camera of divertor gas-manifold.
- Analysis of divertor behavior and linkage between divertor and edge structures.

FY2018:

- Continue analysis of combined GPI dataset for boundary turbulence studies.

Contributions to the NSTX-U 2014-18 Five Year Plan:

The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes to the Boundary Physics chapter of the NSTX-U Five Year Plan and was defined in consultation with Dr. Ahmed Diallo who is deputy leader of the Boundary Physics topical science group.

References

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[2] Y. Sechrest, T. Munsat, D.J. Battaglia, and S.J. Zweben, "Two-Dimensional Characterizaton of ELM Precursors in NSTX," Nucl. Fusion **52** 123009 (2012).

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11.2.2 Columbia University

Research Topic: Study of MHD Stability, Active Mode Control, and Disruption Avoidance in NSTX-U

Principal Investigator: Dr. Steven A. Sabbagh
Participating Scientists: Dr. John Berkery, Dr. James Bialek, Dr. Young-Seok Park
Funded under DOE Grant: DE-FG02-99ER54524

Introduction

The overall goal of macroscopic stability research in NSTX-U is to establish the physics understanding and control capabilities needed to produce sustained stability of high performance ST plasmas in a yet unexplored hotter operational regime at the highest level of current self-sustainment ever routinely produced in such a device. Dating back to before the construction of the NSTX device, Columbia University group research has historically aimed toward advancing the goal of sustained high beta, high performance operation in the ST. The presently proposed research plans to logically extend this successful work in the areas of passive global mode stabilization and the prediction of marginal kinetic stability boundaries, active RWM detection, real-time modeling and control, rotation control and related physics of non-resonant neoclassical toroidal viscosity, and to expand our understanding of 3D fields for MHD mode stabilization. Past work had the implicit goal of disruption avoidance. An emphasis for the coming 5 year plan is the application of the physics understanding of the global mode passive and active stabilization physics, and non-resonant rotation alteration for direct prediction of disruptions, and avoidance of disruptions through rotation and q profile control. This research will provide the predictive physics understanding needed to confidently extrapolate toward the goal of a steady-state Fusion Nuclear Science Facility (ST-FNSF) / Component Test Facility (ST-CTF) [1-3], a pilot plant [4], or DEMO based on the ST [5]. As was exploited in NSTX, the unique ST operational space and device geometry of NSTX-U will be leveraged to extend and test physics theories and technological solutions for next-step spherical torus (ST) and tokamak operation, including ITER. To further support ITER, and expand explicit connection between NSTX-U and ITER, Columbia U. group leadership in the ITPA will evolve to improve connection and communication of global mode stabilization and control with the disruption avoidance goals of both devices. Also, in the last five years, the Columbia U. group has expanded international collaboration activities with the South Korean long-pulse superconducting tokamak program and the KSTAR device. This work has been, and continues to be a complementary connection to our primary research on NSTX/NSTX-U. Along with the unique long-pulse, advanced tokamak device capability of KSTAR, the device also offers the largest difference in aspect ratio of large-scale tokamaks in the world, providing the best platform to compare experimental results and test theoretically expected differences due to aspect ratio with NSTX/NSTX-U. A summary of our research plan elements is given below:

Physics Research Elements

- Understand and advance the passive stabilization physics of global modes for disruption prediction and avoidance, focusing on plasmas with reduced collisionality.
- Create and study improved techniques of global mode active feedback control to sustain macroscopic stability, including ITER-relevant low rotation regimes.
- Understand unverified theoretical aspects of neoclassical toroidal viscosity physics (NTV), with direct and unique application of non-resonant NTV for open and closed-loop rotation control.
- Expand the understanding of the application of 3D fields for MHD mode stabilization.

Current research contributions to NSTX-Upgrade and vision for the next five years

The Columbia University group research has contributed to NSTX since the conceptual design of the device. As this research has a long history, we restrict this brief summary to start with the significant milestone reached by the group on NSTX - the first active stabilization of the resistive wall mode (RWM) at low aspect ratio, and at reduced plasma rotation applicable to ITER [6]. This initial work evolved into expanded long-pulse control capability [7], and the most recent successful application of dual-field component (poloidal and radial field) proportional gain feedback of $n = 1$ RWM instability [8]. The Columbia University group was also responsible for the design and implementation of the first model-based real-time RWM state-space controller, first run on long-pulse plasmas with among the highest $\beta_N = 6.4$ and $\beta_N/\ell_i > 13$ operated in the device [8-10]. The group will continue this research in the coming 5 years of NSTX-U, expanding the present system for independent control capability of the actuator coils, addition of new coils, and advancing the physics models used in control, for both off-line and real-time research. This will include an initial study of the control or avoidance of large internal instabilities. During the last 5 years, the group established a new physics paradigm to explain the complex behavior of the observed RWM stability boundary as a function of plasma rotation. A theoretical model of kinetic RWM stabilization physics [11] was tested against specific NSTX experiments [7,12]. The model and coding (the MISK code) continues to be developed, with attention now placed on the effects of fast particles and plasma collisionality [13]. Recent analysis of specific experiments directly measuring the RWM stability of plasmas approaching the marginal stability boundary by low frequency MHD spectroscopy is helping to explain striking experimental results by the group of improvement to RWM stability at the highest values of $\beta_N/\ell_i > 10$ [8,14]. The results appear generally consistent with the present kinetic RWM stabilization physics hypothesis. Critical research in the coming NSTX-U operation will be the testing of this hypothesis at further reduced plasma collisionality. This will include the testing of highly-simplified stability models that will be used in real-time instability avoidance via rotation profile control. The Columbia U. group began the investigation of plasma rotation alteration via the application of non-resonant 3D fields in the early 2000s, and a multi-year research program of experiments and quantitative theoretical understanding led to the published observation of neoclassical toroidal viscosity [15] (NTV) in NSTX [16]. In 2013, the group plans to continue analysis on data taken in several dedicated experiments run on NSTX, including further analysis of the superbanana plateau regime in NSTX [9]. The Columbia U. group will continue this research in the coming five years of NSTX-U, aiming at quantitative comparison between theory and experiment. Some examples include the comparison of results from several codes including NTVTOK which the Columbia U. group is now testing, and the IPEC (J.K. Park) and POCA (K. Kim) codes, understanding of NTV physics at reduced collisionality, and long-pulse aspects such as the NTV offset rotation, which appears to be quite small in NSTX, and therefore is different from results published on DIII-D. This research will additionally be directly applied toward creating a reduced model of NTV suitable for use in the planned real-time rotation control system for NSTX-U. The Columbia U. group was also responsible for the physics design of the present RWM control coils system on NSTX [17], and continues this effort in the present calculations of RWM control performance (see Chapter 2) of the proposed off-midplane NCC coils, which are included in the base research budget of NSTX-U. These coils will bring significant new capability that will greatly enhance research on NSTX-U for the entire team, as well as for the Columbia U. group. Intriguing results of ELM mitigation attempts in NSTX by a team experiment led by the Columbia U. group are of increased importance when compared to recent ELM mitigation results on KSTAR by the Columbia U. group using n = 2 non-resonant applied fields. The comparison of these results may reveal key physics aspects of ELM mitigation due to the significant aspect ratio difference between the devices. A present urgent need for ITER, as well as for future ST fusion devices planned to operate continuously, is the reliable prediction, avoidance, and mitigation (PAM) of plasma disruptions. Macroscopic stability research by the Columbia U. group on NSTX from its inception has targeted the stabilization of beta-limiting, disruptive instabilities that stop the plasma, or otherwise prevent it from operating at high fusion performance. The research described above will directly and substantially contribute to the advanced disruption prediction and avoidance studies and control described in detail in Sections 2.2.1, 2.2.3, and 9.2.3. This research will be addressed in close conjunction between the Macrostability and Advanced Scenario and Control topical science groups. An essential component of all research mentioned above has been the ready availability of accurate, between-shots experimental kinetic equilibrium reconstructions with the NSTX EFIT code [18,19]. The Columbia U. group has provided this capability for NSTX since its inception, and will continue this effort on NSTX-U with upgrades suitable for the new device capabilities.

Summary of proposed research plan for 2014-18

Progress accomplished to date in the study of MHD stability, active mode control, and configuration optimization in NSTX sets the stage for the Columbia U. group to propose a 5 year program of study, leading research in several key areas to support the long-pulse sustainment of high beta plasmas created in the device. The research applies to NSTX-U and the future development path of the ST, and will provide key physics understanding for advanced tokamak operation and future burning plasma devices, including ITER. This plan is well-aligned with the detailed plan presented in the Macroscopic Stability research chapter (Chapter 2) of this document. A summary of specific tasks in our plan displayed in a timeline are:

Timeline

FY2014:

- Expand RWMSC real-time control software to allow independent actuation of six RWM control coils, and a more general sensor input scheme, for Day 0 plasma operations.
- Complete analysis of existing NSTX data from specific experiments investigating NTV. This existing data includes an investigation of NTV vs. plasma collisionality over a broad range attainable in NSTX, past operation in the superbanana plateau regime, and magnetic braking by dominant n = 2 and n = 3 field configurations.
- Update all NTV experimental analysis tools to allow processing suitable for NSTX-U capabilities (e.g. independent control of the midplane RWM coils).
- Evaluate simple physics criteria (suitable for real-time use) for the approach to global mode marginal stability based on ideal (e.g. pressure peaking, β_N/l_i) and kinetic stability physics using initial high performance NSTX-U plasmas, emphasizing rotation profile and speed.
- Compare n = 2 ELM mitigation results on KSTAR using the midplane in-vessel coil configuration with past NSTX results showing a lack of mitigation with a similar applied field scenario, targeting field pitch and aspect ratio effects as key differences.

FY2015:

- Conduct initial assessment of stability limits on normalized β and plasma rotation, V_ϕ, at the increased aspect ratio of NSTX-U, with new shaping control and off-axis NBI. Compare to ideal and kinetic stability limits using DCON and MISK codes.
- Begin assessment of theoretically favorable stability conditions, through a combination of dedicated experiments utilizing low frequency MHD spectroscopy to directly measure stability and by probing unstable plasmas, for enhanced kinetic stabilization of global MHD modes (including rotation profile proximity to stabilizing, energetic particle profile and distribution, q_{min}, and β_N). Test stability physics expectations of increased global

mode stability at the highest β_N/l_i in NSTX-U plasmas, and compare to positive results found in NSTX, examining potential differences due to aspect ratio.

- Establish dual field component n = 1 active control capability in new NSTX-U operational regime. Compare theoretically expected changes in feedback phase/gain to experiment. Examine expanded capabilities allowed by six independent power supplies for the RWM control coils.
- Examine effectiveness of n =1 RWM model-based state space control with independent actuation of six control coils for initial high β_N plasmas. Compare RWMSC modeled sensor signals (controller observer model) with experiment for a single n = 1 eigenfunction versus adding n = 2 eigenfunctions. Initially compare the degree of mismatch between the RWMSC observer model and sensor measurements, and the occurrence of plasma disruptions for future input to the disruption warning system.
- Determine optimizations of RWMSC control by varying the amount of plasma rotation-induced stabilization in the controller guided by MISK kinetic stabilization calculations.
- Examine the real-time difference between the n = 1 RWMSC observer and measured RWM poloidal field sensors to evaluate the observer physics model and determine thresholds for disruption detection appropriate for use in the NSTX-U disruption warning system.
- Utilize initial NSTX-U ME-SXR and poloidal USXR diagnostics to characterize the RWM eigenfunction by non-magnetic means.
- Make initial assessment of the dependence of NTV profile and strength as a function of plasma collisionality. Conduct initial experiments using combined n = 2 and 3 field configurations versus the separate application of n = 2 and n = 3 fields.
- Prepare an initial simplified real-time model of NTV profile as a function of applied field and available plasma parameters for use in initial plasma rotation control system.
- Evaluate the neoclassical offset rotation as a function of plasma parameters in long-pulse, steady-state plasmas. Examine the NTV offset rotation utilizing HHFW heated plasmas.
- Perform initial experiments using open-loop plasma rotation, current profile, and energetic particle control to demonstrate the ability to avoid encountering disruptive global mode stability boundaries based on kinetic RWM stabilization models.

FY2016:

- Begin investigation of the dependence of global mode stability on reduced collisionality through a combination of dedicated experiments utilizing low frequency MHD spectroscopy to directly measure stability, creating unstable plasmas, and investigating mode-induced disruptions in the general database. Compare experimental results to kinetic stabilization theory. Open-loop rotation control will be the default for these studies, with initial closed-loop control used if available.

- Adjust present simplified physics models of RWM marginal stability based on initial high beta operation of NSTX-U in the first year of operation, and operation at reduced collisionality reached in the second year, appropriate for real-time calculations.
- Theoretically determine improvements to global mode stability expected by adding the partial NCC based on improved understanding gained in the first 2 years of operation.
- Examine effectiveness of $n = 1$ active mode control as a function of plasma rotation. Compare theoretically expected changes in optimal $n = 1$ feedback phase and gain including stabilization effects due to plasma rotation to experimental results. Examine the effect of partial RWM control coil use during $n = 1$ feedback, examining the impact on the higher-n perturbation spectrum (also supports ITER, JT-60SA).
- Assess global mode stability and control modifications during the more standard use of the snowflake divertor configuration.
- Examine RWMSC multi-mode control with n up to 3 and determine improvements of theory / measurement comparison shown by the controller observer. Test optimizations of RWMSC control by varying the plasma rotation-induced stabilization in the controller; compare to experiment and MISK calculations. Examine improvements to disruption detection via the RWMSC based on multi-mode capability of the observer.
- Conduct initial tests on the observer physics model by adding dual-component sensors in RWM feedback, comparing experiment to theory.
- Theoretically assess the importance of real-time variation of plasma response parameters in the RWMSC based on experimental studies conducted in the second year of operation.
- Theoretically determine improvements to the RWMSC by adding the partial NCC (planned for addition to NSTX-U in FY2017) and an extended RWM sensor set (planned for addition to NSTX-U in FY2018).
- Examine changes to ME-SXR/poloidal USXR measured RWM eigenfunction as a function of plasma rotation. Determine the degree of global mode internalization by comparing magnetic and SXR diagnosis as a function of proximity to marginal stability.
- Determine improvements to kinetic RWM stability possible by utilizing expanded capability for non-resonant rotation control by the enhanced 3D field spectrum afforded by the planned partial NCC, based on theory and the first 2 years of NSTX-U operation.
- Determine improvements to active feedback of $n > 0$ modes via PID and RWMSC control allowed by the partial NCC, and implement control system changes to test theory in Year 4 device operation.
- Determine the experimental dependence of the superbanana plateau NTV on plasma collisionality and compare to theory.
- Utilize real-time model of NTV profile as a function of applied field configuration, strength, and plasma rotation in the plasma rotation control system and evaluate model performance in closed-loop feedback.

- Improve simple physics criteria used to determine global mode marginal stability adding energetic particle stabilization and expanding the kinetic stabilization model.
- Determine the applicability of single mode RFA phase information in low frequency MHD spectroscopy measurements to supplement amplification in determining proximity to global mode stability boundaries.
- Improve disruption prediction using the RWMSC observer model and sensor measurements by improving the model and/or sensor mismatch criteria used.
- Implement and test initial disruption avoidance using the real-time RWMSC observer model. Test open-loop disruption avoidance criteria at low rotation (most ITER relevant).
- Implement results from a real-time evaluation of the simple global mode marginal stability model into plasma rotation and q profile control systems that will be available in real-time during FY17-18.
- Implement single mode RFA amplitude and phase as input to profile control systems and disruption warning system.
- Determine physics implications of scenarios that overload 3D field and NBI actuators for simultaneous use in meeting open-loop requests for plasma profile targets for rotation, q, energetic particle population, β_N, and other key parameters for disruption avoidance.
- Combine physics criteria for disruption avoidance systems (profile control and disruption warning systems) allowing variable prioritization of control to avoid physics request conflicts and to avoid actuator overloading.

FY2017:

- Utilize V_ϕ control to improve RWM stability by: (i) performing closed-loop rotation control studies, and (ii) changing proximity to stabilizing kinetic resonances for stability control
- Validate kinetic RWM stabilization physics at reduced ν* and varied fast ion populations with closed-loop q_{min} control in plasmas with non-inductive current fraction approaching, or at 100%; determine changes to the effectiveness of n = 1 PID and RWMSC active mode control during closed-loop feedback of plasma rotation profile and q_{min} control in these plasmas.
- Generalize n = 1 control software for n = 2 control use and to allow the use of a poloidally extended RWM sensor set (available in Year 5) and the partial NCC coils.
- Compare n = 2 active feedback control using proportional gain to the NSTX-U model-based RWM state space controller.
- Examine the effect of varying kinetic RWM stabilization in the RWMSC by varying RWMSC control inputs via multi-phase PCS operation based on real-time β_N calculation.
- Implement real-time RWMSC observer into disruption warning system. Use RWMSC observer in disruption warning system during closed-loop feedback of plasma rotation profile, and q_{min} control with non-inductive current fraction approaching or at 100%.

- Examine time-evolution of global mode internalization using newly-installed, toroidally-displaced ME-SXR diagnostic; prepare for real-time input to disruption warning system.
- Experimentally determine the dependence of NTV profile and strength as a function of plasma collisionality at the highest ion temperatures, and evaluate the expected stronger role of electron NTV in this condition.
- Determine/implement a real-time evaluation of a simple global mode marginal stability model including key parameters (e.g. plasma rotation speed and profile, q_{min}, T_e, n_e) that will be available in real-time during Years 4-5.
- Add/use real-time rotation and q_{min} measurements and evaluations for determining global mode marginal stability boundaries, enabling improved evaluation of physics model.
- Examine real-time low frequency MHD spectroscopy in determining global mode stability boundaries for input to stability profile control systems (e.g. rotation, q). Determine single mode RFA amplitude and phase criteria that predict disruptions, and evaluate possible improvements afforded by multi-mode RFA.
- Evaluate and study the stability physics response of real-time rotation and q profile control using the simple kinetic stabilization physics criteria and real-time low frequency MHD spectroscopy for avoiding global mode marginal stability boundaries, including initial use of the partial NCC as an actuator for rotation control.
- Test coupling of real-time RFA, simple physics model, and RWMSC observer systems in providing simultaneous actuation of stability profile for global mode stability avoidance.
- Perform initial studies of mode stabilization utilizing improved open-loop plasma rotation profile control afforded by the partial NCC added to the present RWM coil set.
- Perform initial investigation of dual field component $n = 1$ active control using the newly-installed partial NCC, including variations of feedback phase vs. poloidal angle.
- Perform initial investigation RWMSC active control using the newly-installed partial NCC, including applied control field helicity with respect to mode helicity.
- Utilize the newly-installed partial NCC to expand plasma rotation profile variation and control, with the goal of improving RWM stability, with comparison to theory.
- Conduct active $n > 0$ feedback research using the partial NCC to uniquely address physics for ITER and future STs and tokamaks (e.g. JT-60SA), including (i) mode control with partial toroidal / poloidal coverage of the control coils, (ii) robustness of model based RWM state space control with reduced sensor / control coil availability, (iii) relative importance of midplane vs. off-midplane control coil arrays.
- Utilize closed-loop rotation control, including initial use of the partial NCC, to produce the broadest and most peaked rotation profiles possible, and high, intermediate, and low rotation levels, comparing offline and real-time rotation models to theory.
- Make initial use of the partial NCC to test theoretical expectations of applied 3D fields as their helicity is varied compared to the equilibrium plasma field helicity.

FY2018:

- Test kinetic RWM stabilization models in the lowest ν^* regimes.
- Characterize the poloidal variation of $n = 1 - 3$ global mode activity using a newly-installed expanded RWM sensor set, including a comparison to the theoretically computed NSTX-U multi-mode spectrum.
- Evaluate experimental improvements to real-time kinetic stabilization models through the addition of real-time Thomson scattering results.
- Determine physics improvements to RWMSC observer for disruption detection and implement to demonstrate reduced disruptivity to internal modes in 100% non-inductive, high β_N plasmas. Improve disruption prediction using the RWMSC observer by the addition of the newly-installed expanded RWM sensor set.
- Combine disruption avoidance control with simultaneous use of $n > 0$ active feedback and the partial NCC, determining physics implications and potential control conflicts.
- Experimentally determine optimal 3D field spectra, including use of the partial NCC, for minimizing or maximizing NTV vs. applied current and compare to theory.
- Examine NTV at the lowest plasma collisionality possible in the device to determine if a saturation of NTV at low collisionality can be found, as expected by theory.
- Demonstrate low rotation profile operation using NTV in steady-state with closed-loop rotation control, producing plasma rotation most applicable to ITER and utilizing the partial NCC, with comparison to theory.
- Combine plasma rotation, q-profile, and, β control to demonstrate improved RWM and internal MHD mode stability using ITER-relevant (low rotation), high rotation inductive scenarios, and 100% non-inductive ST-FNSF scenarios, demonstrating very low plasma disruptivity in dedicated experiments.
- Determine the physics and controllability implications of using/omitting upgrades to the combined control systems, including the partial NCC, expanded RWM sensor set, real-time Thomson scattering, and real-time ME-SXR data.
- Test the RWMSC observer physics model by adding a newly-installed expanded RWM sensor set providing improved diagnosis of the mode spectrum in the poloidal direction.
- Examine superior RWMSC settings and multi-mode active control with n up to 3 and the partial NCC to demonstrate improved global MHD mode stability in 100% non-inductive plasmas, demonstrating very low plasma disruptivity in dedicated experiments.
- Utilize the added profile control capabilities allowed by the partial NCC with closed-loop plasma rotation profile control to demonstrate, based on kinetic stabilization theory, reduced disruptivity by actively avoiding global instabilities.

Contributions to the NSTX-U 2014-18 Five Year Plan:

S.A. Sabbagh is responsible for defining the Columbia University group contributions to the NSTX Five Year Plan. J.W. Berkery is the present deputy leader of the Macroscopic Stability topical science group and is responsible for overseeing the Macroscopic Stability chapter (Chapter 2) of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes significantly to the Macroscopic Stability research plan, and interfaces with other topical science group research, especially the Advanced Scenarios and Control group.

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11.2.3 CompX

Research Topic: Collaboration with NSTX in Calculations of Radiofrequency and Neutral Beam Heating and Current Drive Sources

Principal Investigator: R.W. (Bob) Harvey
Participating Scientists: R.W. Harvey, Yuri V. Petrov
Funded under DOE Grant: DE-SC0006614

Introduction

This grant supports development of finite-orbit-width (FOW) capabilities in the CQL3D Fokker-Planck code, and validation, interpretation and prediction of the NSTX-U experimental heating, current drive, and prompt fast ion losses. CQL3D is used in conjunction with the DC Lorentz equation FOW RF diffusion coefficient calculator, the GENRAY ray tracing code, and the ORNL AORSA full wave code. NSTX, and now NSTX-U, are ideal machine for exploration of finite-orbit-width effects on heating, current drive, transport, and NBI particle sources. CompX's code suite provides relatively fast estimates of FW, EC, EBW and NBI heating and current drive. The codes calculate time-dependent velocity distribution functions of ions and electrons throughout the tokamak cross-section, from which many synthetic diagnostic signals are (and others can be) obtained, for validation against experiment.

Current research contributions to NSTX Upgrade

Implementation and validation of finite ion orbit width effects in the bounce averaged Fokker Planck code CQL3D

A sequence of major modifications was made to the ion zero-orbit-width (ZOW) Fokker Planck code CQL3D [1] to include finite-orbit-width (FOW) corrections [2,3,4]. In addition, the effects of evolving the background plasma, and of time-dependent modulated neutral beams, were implemented [5]. Part of the motivation for these modifications came from 2010 comparisons between measured and simulated Fast Ion Diagnostic FIDA by Liu *et al.*[4] of signals resulting from neutral beam injection (NBI) and high harmonic fast wave (HHFW) RF power injected into the NSTX spherical tokamak. A significant radial inward shift of the simulated FIDA signal using the previous zero-orbit-width (ZOW) CQL3D was found compared to the NSTX experimental results [6,7]; however, the comparison between finite-orbit-width the PPPL (FOW) NUBEAM Monte Carlo Fokker-Planck code (NBI only) derived FIDA and experiment was excellent[7]. This [7,8] strongly motivated, and led to, a new program to include FOW effects in the CQL3D finite-difference FP code.

A first order (in banana width over minor radius) FOW correction was initially implemented in CQL3D which gave too large an outward shift [2], presumably due to very fat orbits.. This is shown by the green curves in Figures 1(a) and 1(b). On the other hand, the ZOW CQL3D predictions (blue curve) are clearly shifted inwards compared to the experimental FIDA data (black curves) . CQL3D was modified by including full guiding-center orbits in the neutral beam and HHFW quasilinear diffusion calculations [3]. This model gives accurate fast ion losses to the plasma edge, including an added gyro-radius shift from the guiding center orbits. Simulations based on this most recent model (red curves in Fig. 1) were found to produce quite good comparison with experiment.

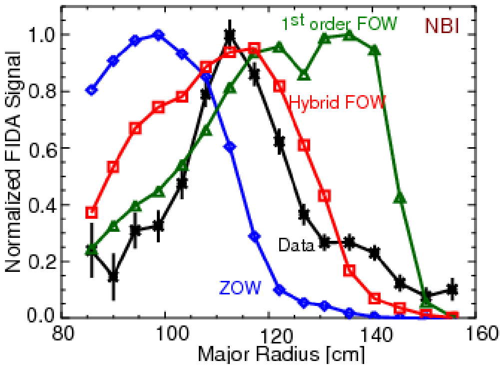

Figure 1(a): Measured and simulated FIDA signals for NBI heating only in NTSX. FIDA data is shown as black curve and symbols, simulated FIDA data for ZOW, 1st order FOW, and Hybrid FOW CQL3D are shown as the blue, green, and red curves and symbols respectively.

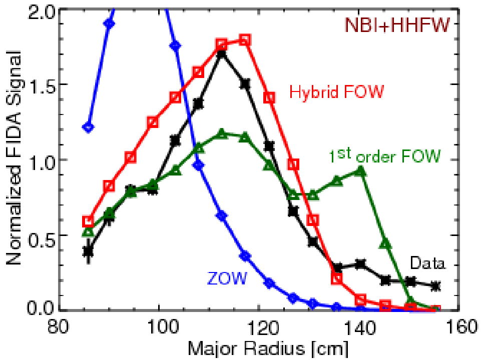

Figure 1(b): Measured and simulated FIDA signals for NBI+HHFW heating in NTSX. FIDA data is shown as black curve and symbols, simulated FIDA data for ZOW, 1st order FOW, and Hybrid FOW CQL3D are shown as the blue, green, and red curves and symbols respectively.

A new result from the CQL3D NBI+HHFW NSTX calculation is greatly enhanced FI power losses to the chamber wall compared to the NBI phase Losses are 7% of NBI power, and 28%, and increasing, of the HHFW power.

The Hybrid-FOW CQL3D does not currently include neoclassical radial diffusion, but rather calculates the distribution function separately on each flux surface. A full FOW upgrade of CQL3D that is now underway will provide neoclassical radial diffusion. It is a step beyond the usual theory in that there is no assumption of small orbits, and it includes nonthermal effects. The inclusion of the full radial neoclassical diffusion may account for the small calculated FIDA signal (in red curves) compared to the measured FIDA signals in Figure 1(a) and 1(b) at high plasma radius. This work is in progress.

CompX Recent Supporting Activities for GENRAY/CQL3D at PPPL

(1) Gary Taylor was assisted in modeling of ECH for NSTX-U, using updated GENRAY/CQL3D at PPPL[9].
(2) GENRAY ray tracing results were benchmarked against a new paraxial ray tracing code (LHBEAM), and the TORIC-LH code, in work led by Nicola Bertelli at PPPL[10].
(3) CompX assisted Nicola Bertelli at PPPL in using GENRAY, particularly in his addition of a density fluctuation scattering operator for modeling of LHCD in C-Mod. Further modeling in conjunction with CQL3D examined the effects on density fluctuation scattering on calculated C-Mod LH current drive profiles[11].
(4) Gary Taylor was supported in calculations of HHFW CD pertaining to NSTX, using GENRAY/CQL3D [12].

Summary of proposed research plan for 2014-18

CQL3D, DC, GENRAY and AORSA will be validated against NSTX-U and NSTX, and applied to interpretation and prediction of these experiments. The primary near term goals are upgrade and verification of NFREYA in CQL3D, verification against NUBEAM, completion of the finite-orbit-width neoclassical modification of CQL3D, application and comparison of the DC-AORSA RF diffusion coefficient calculation with GENRAY/CQL3D-FOW, and support of HHFW, MHFW, EBW, EC, and NBI code application activities of PPPL NSTX scientists.

Elements of our plan displayed in a timeline are:
(Throughout the period, NSTX scientists are supported in use of CompX codes.)

Timeline:

2014-2015:
- Complete Finite-Orbit-Width CQL3D Modification.
- Upgrade NFREYA cross-sections in CQL3D and verify against NUBEAM.
- Continue DC-AORSA Lorentz orbit RF diffusion calculations.

2015-2016:
- Comparisons/predictions of CQL3D-FOW with NSTX and NSTX-U.
- Continue DC-AORSA Lorentz orbit RF diffusion calculations.

2016-2017:
- Introduction of radial transport, per gyrokinetic codes, into CQL3D.
- Comparison of transport effects with experiment.

2017-2018:
- Comparison of transport effects with experiment.

Contributions to the NSTX-U 2014-18 Five Year Plan:

The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes to the Wave Heating and Current Drive chapter of the NSTX-U Five Year Plan and was defined in consultation with Dr. Gary Taylor who is leader of the Waves and Energetic Particles topical science group.

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11.2.4 Florida International University

Research Topic: Fast Fusion Proton Diagnostic
Principal, Co-Principal Investigators: Werner U. Boeglin (PI/PD)
Participating Scientists: Douglass S. Darrow
Participating Post-docs: none
Participating Graduate Students: Ramona Valenzuela Perez
Participating Undergraduates: 3
Funded under DOE Grant: DE-SC0001157

Introduction

The purpose of a charged fusion product detection system is to obtain time-dependent, precise information on the d(d,p)t fusion rate profile in NSTX-U with the goal of determining the neutral beam ion density profile as a function of R, z, and t and to provide new data for a global analysis of fast ion diagnostic data with the aim of extracting the fast ion distribution function.

Besides providing new data on the slowly varying neutral beam radial density profile, this measurement would provide new data on how MHD and other activity in the plasma transport neutral beam ions radially and would allow one to study modes such as toroidal Alfvén eigenmodes (TAEs), neoclassical tearing modes (NTMs), edge localized modes (ELMs), fish-bones/energetic particle modes, and internal reconnection events (IREs). This extensive new data set will be used to test models of neutral beam current drive and the effect of MHD instabilities on the profile of the driven current. In NSTX-U and future spherical tokamaks, neutral beam current drive is relied upon heavily to obtain the necessary current profiles. Designing these new machines therefore requires well-tested current drive models and a thorough understanding of the effects of MHD activities on current drive. The new diagnostic would consist of two arrays of collimated MeV ion detectors arranged in such a way that they measure MeV charged fusion products (CFPs) within well defined bundles of orbits (similar to sight lines) that cross the plasma. The detection system, based on solid state detectors and fast multi-channel digitizers, will be able to handle the expected high particle rates (up to a few MHz) allowing integration times as short as 1 ms, and leading to a time resolution of the same order of magnitude [1].

The same profile information could in principle also be measured with a neutron camera. However, the sheer physical size of a neutron camera together with a lack of space close to the NSTX-U vacuum vessel prevents its implementation without severely affecting the multiplicity of available diagnostics. Conversely the proton detector system is highly compact and hence can be installed with little effect on other diagnostics.

Current research contributions to NSTX Upgrade

Current funding has been used to build a first two-channel prototype system with adjustable detector orientations including the necessary hardware and software for the data acquisition system as well as a 4 channel system with fixed orientations. We are currently carrying out signal noise tests at MAST and plan to install and use the new 4-channel system in MAST in July 2013. A new version of the Lorentz orbit code as been tested and is currently being used for simulation calculations for the upcoming experimental campaign at MAST. Unfortunately due to the NSTX TF coil problem no data could be taken up to now but we are on track to obtain first physics data this July, 2013 at MAST using the 4 channel system. The upcoming MAST experiment offers a unique opportunity to observe simultaneously the same DD reaction rate profiles with both the proton detector array and a neutron camera, two very different methods employing different reaction products. Request for continued funding have not been successful up to now [2].

Summary of proposed research plan for 2014-18

Given the necessary funding and the experience gained by operating the prototype system at MAST we plan to upgrade the system to 16 channels, which would allow for a much more model independent analysis of the emissivity profile [2].

Timeline

2014-2015:
- Take data with prototype array at NSTX-U (contingent on available funding)
- Complete and publish analysis of MAST data
- Obtain funding for upgraded system
- Design full 16 channel system and Procure equipment for full system

2015-2016:
- Pass final design review
- Construction of fixed array completed
- Full data acquisition system ready
- System ready for installation

2016-2017:
- Construction of probe arm array completed
- Installation in the NSTX-U Vessel

2017-2018:

- Data taking with fully instrumented system
- Analysis and presentation of first data

Contributions to the NSTX-U 2014-18 Five Year Plan:

Mario Podesta is the present leader of the Energetic Particles topical science group and is responsible for overseeing the Energetic Particles chapter of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan.

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11.2.5 General Atomics

Research Topic: National Spherical Torus Experiment Research Participation
Principal Investigator: Robert J La Haye
Co-Principal Investigators: Todd E Evans, David A Humphreys and Thomas H Osborne
Participating Researchers: Philip B Snyder, Michael L Walker, Anders Welander and Wen Wu
Funded under DOE Grant: GRANT10701787 (March 1, 2011 – March 1, 2014)

Introduction

General Atomics is principally participating [1] in the NSTX research program in three topical areas: (1) plasma control, (2) H-mode edge pedestal characterization, and (3) boundary physics research focusing on applied resonant magnetic field perturbations.

We are continuing to support the existing plasma control software that has already been provided. In addition, we are implementing the advanced model-based shape control algorithm which has been under development during the previous grant period. These algorithms will be particularly useful for the precise control of the strike point location required by the liquid lithium divertor research program.

General Atomics has supplied data processing tools used for extracting pedestal characteristics from NSTX experimental data. In addition, we have provided edge stability analysis using the ELITE code and pedestal structure analysis under the EPED model. These efforts have contributed to improved understanding of pedestal physics in spherical tokamaks including contributing to an understanding of the effects of Lithum coatings on pedestal characteristics.

The use of magnetic perturbations primarily located in the H-mode edge pedestal region has shown great promise for the stabilization of ELMs. The General Atomics team has extensive experience in this type of research, including the design of the optimized coil set to produce the necessary magnetic fields. We are continuing analysis to understand the existing set of non-axisymmetric coils to study the effect of resonant magnetic perturbations on ELMs in NSTX.

Current research contributions to NSTX Upgrade

Control - Recent progress includes a study of the mid-plane gap controllability and steps toward more accurate predictions of vertical growth rates in NSTX. A key result of the recent model validation process is that the representation of experimental response appears accurate enough to enable reasonable calculation of high order matrix controllers produced using the decoupling approach or other model-based design method. Work on disruption halo current dynamics is also in the current grant.

H-mode edge physics - An ability to include the fast ion pressure computed with the TRANSP transport code into the MHD equilibrium pressure profile was added which significantly improved the accuracy of the equilibrium fits. A new model for the bootstrap current based on results from the XGC0 code was added to the equilibrium reconstruction tool. A number of improvements were made to the codes to simplify their application including simplification and consolidation of the code run control tables, improved auto-knotting for the spline fits, and improved documentation. Several improvements in the visualization tools for equilibrium reconstruction and profile analysis were made. The equilibrium and profile analysis has been applied to the study of ELM suppression in discharges with lithium conditioning. The XGC0 model predicts a pedestal bootstrap current in NSTX that is 40% larger than the standard Sauter model. ELITE peeling-ballooning stability calculations based on the XGC0 mode indicate a closer agreement between the critical current density for peeling instability and the pedestal conditions just before an ELM.

Resonant Magnetic Field Perturbations - The TRIP3D code has recently been modified to run on a 960 core Tesla GPU computer and is being used to study the open field line properties in NSTX due to 3D fields from an external non-axisymmetric RWM field-error correction coil. The Tesla computer is essential for carrying out these studies since reasonably good quality simulations of divertor footprint distributions require calculations of at least 800,000 field lines.
Stability - Work on the physics of neoclassical tearing modes and the effects of error fields on their stability was ongoing and a continuation of the previous 3 year grant; advantages at low aspect ratio were confirmed of both a relatively larger characteristic small island for NTM stabilization/seeding and the presence of a significant stabilizing curvature effect and published in [2].

Summary of proposed research plan for 2014-18

Control - A strong role will continue to be played in the development of the NSTX plasma control system that is providing capability for production of the quality discharges required for the experimental research program.

H-mode edge physics - General Atomics will continue participation in analysis to improve understanding of the H-mode edge pedestal and edge localized modes in NSTX. Plans include adding the MSE data to the equilibrium reconstruction. We would also like to add the ability to use density profiles from the reflectometer diagnostic as a standard in the profile reconstruction. We will also port IMFIT to NSTX. IMFIT provides a widget-based interface to several high-level analysis codes including EFIT (MHD equilibrium), ELITE (MHD stability), and TRANSP (transport). IMFIT handles construction of input files for these codes and translation of output from one code to input to another.

Resonant Magnetic Field Perturbations - We are collaborating with the NSTX team in the modeling and design optimization of a new resonant magnetic perturbation (RMP) coil set to be installed in NSTX. As the development of the TRIP3DGPU code continues over the next few years, simulations of the open field line properties from a proposed internal non-axisymmetric perturbation coil on NSTX-U will be carried out and field-error models will be tested. New algorithms have recently been added to the TRIP3DGPU code for modeling field-errors from misaligned poloidal field coils and non-axisymmetric toroidal field coil busbar field-errors. These will be used with NSTX-U equilibria to assess the symmetry of divertor footprints as the field-error spectrum from each source is varied. Once completed, predictions from these divertor footprint simulations will be compared to IR camera data in order to better understand potential sources of intrinsic field-errors in NSTX-U and to help refine the field-error models in the TRIP3DGPU code. In addition, it is anticipated that the conceptual design of a new RMP coil, to be done under the existing grant using the TRIP3D, SURFMN, PROBEG, and TRIP3DGPU codes, will assist in leading to an engineering design, fabrication, and installation with both experimental analysis and modeling participation by GA.

RF Physics, Stability and More - Contributions continuing from the current grant are anticipated that could also include rf physics (antennas), the physics of rotation and NTMs, error fields, resistive wall modes, and MHD stability in general, and extension of axisymmetric modeling to include analysis and design for NSTX-U control needs. This work could also include an NSTX-U simserver for testing of NSTX PCS algorithms in simulation.

A proposal for a further three-year grant renewal is expected on or around October 1, 2014.

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11.2.6 Johns Hopkins University

Research Topic: Soft X-ray measurements of transport and MHD activity in the core and edge NSTX plasma

Principal, Co-Principal Investigators: Dan Stutman (PI), Kevin Tritz (Co-PI)
Participating Scientists:
Participating Post-docs: Dan Clayton
Participating Graduate Students:
Participating Undergraduates:
Funded under DOE Grant: DE-FG02-99ER5452

Introduction

The Johns Hopkins Plasma Spectroscopy Group will continue to expand its collaborative NSTX research by implementing and operating on NSTX upgrade (NSTX-U) a suite of new and upgraded SXR to VUV diagnostics based on the multi-energy imaging technique developed in our previous research. The diagnostic suite will enable improved measurements of the impurity content and radial transport, of radial and toroidal MHD mode structure and of T_e profiles and perturbations in the core, edge and divertor, and in all NSTX-U operating scenarios, from non-inductive start-up and sustainment, to high power beam and RF driven regimes.

These diagnostics will contribute to multiple NSTX-U research priorities and will also constitute the basis for continuing and expanding the physics studies initiated by our group at NSTX. In addition, the proposed diagnostics will be useful also for the initial and routine operation of the upgraded NSTX (Sec. 10.6.1.3). The proposed implementation tasks include:

i) Set of edge and core tangential ME-SXR arrays
ii) Fast tangential Transmission Grating Imaging Spectrometer (TGIS)
iii) Repetitive laser blow-off system for multiple injections of non-recycling impurities during the shot

If further resources become available, the JHU group proposes the following additional measurements over the course of the NSTX five year plan:

iv) Divertor Imaging Radiometer for spectrally resolved measurements of the radiated power

v) Additional, toroidally displaced set of edge and core tangential ME-SXR arrays
vi) Set of SXR sensors for non-magnetic plasma boundary and position measurement with eventual application to real-time feedback control

Current research contributions to NSTX Upgrade

The ME-SXR diagnostic system is the primary tool for the planned JHU research on NSTX-U. Such a system has provided measurements of the temperature profiles on fast (>10kHz) time scales by using measurements of several filtered soft X-array emission radial profiles to interpolate between Thomson scattering profiles [1,2]. A AXUV diode-based system, which provides higher sensitivity, better dynamic range, and a more compact design, has been tested on NSTX and is the basis for the system planned for NSTX-U, which will have coverage both in the core, and in the edge with higher spatial resolution (Sec. 3.4.2.4). Additionally, a novel first stage A/D electronics design is under development to decrease system costs, increase modularity, and improve the capability for 'in-vessel' installation of the ME-SXR systems.

The main research goals of the fast T_e profile measurements include the investigation of low-f MHD activity and mode structures, ELM profile dynamics, the evolution of the thermal quench during disruptions, and perturbative electron thermal transport measurements. The transport measurements are especially important to probe the response of the typically flat core T_e profile. Given recent work that demonstrates a correlation between Alfven Eigenmode activity in NSTX and high core electron thermal transport (Sec. 3.3.2.2.3) [3,4,5], measurements of perturbative thermal transport using ELMs or LBO-induced cold pulses provide a method of directly comparing measured e^- thermal transport with predictions of AE structure from HYM simulations coupled with ORBIT transport modeling.

In support of this research, two additional tools are under development. The use of Neural Network algorithms to derive electron temperature profiles from ME-SXR measurements has already provide fast T_e profiles with error bars <~10% [6]. Further algorithm development can improve these results by using additional constraints, such as time and space resolved spectroscopy from the JHU Transmission Grating Imaging Spectrometer (TGIS), line integrated density measurements, and other diagnostics (e.g. BES) that may help constrain the neural network reconstructions. Potentially, with enough additional diagnostic constraints, fast measurements of density and impurity concentration profiles may also be extracted from the ME-SXR measurements.

The other important tool that will assist the perturbative thermal transport measurements is the Laser Blow-off (LBO) system. The flexibility in choosing the injected material and the ability to precisely control the timing and amount of injected impurity will provide an excellent tool for initiating a cold pulse at the plasma edge. The propagation of this cold pulse perturbation will probe the electron thermal transport in the NSTX-U core and provide validation comparisons with the predictions from the simulations mentioned previously. Additionally, the LBO will provide a precision tool for the investigation of impurity transport. The JHU group has previously measured impurity transport using the ME-SXR system and neon gas puffs (Sec. 3.3.1.3) [7], but the flexibility of the LBO system will dramatically improve this capability and provide access to a wide range of impurity transport studies including Z-scaling experiments, a comparison between recycling and non-recycling impurities, and a simultaneous measurement of transport in multiple channels.

The proposed diagnostics requiring additional resources also have significant contributions to research on NSTX-U. One region that could benefit greatly from increased diagnosis is the divertor. The increased power handling in NSTX-U along with the proposed advanced divertor regimes discussed in Sec. 4.2.4 indicate the importance of a thorough characterization of divertor parameters such as radiated power, electron temperature, and impurity concentration, distribution, and transport. The JHU Divertor Imaging Radiometer (DIR) is a variant of the TIGS optimized to provide spatially and spectrally resolved measurements of radiated power for the plasma divertor regime. These measurements are an essential tool that can be coupled with divertor codes and synthetic diagnostic outputs to provide a powerful constraint on the relevant divertor physics. Simulations have already demonstrated the utility of the DIR [8,9], and the JHU group considers this diagnostic to be high priority in the event that further resources become available.

The other proposed diagnostics, the additional toroidally displaced ME-SXR system and ME-SXR sensors, are aimed at improving non-axisymmetric measurements of low-f MHD activity. The two displaced ME-SXR profile systems will provide detailed measurements of asymmetries in the X-ray and T_e profiles, suitable for mode structure measurements of islands, RWMs, ELMs, disruptions, and similar events. The ME-SXR sensors will provide distributed measurements of plasma position and boundary which can be used for real-time feedback of plasma control as well as detection and potential real-time feedback of MHD as described in section 2.2.1.4.2.

Summary of proposed research plan for 2014-18

The JHU research plan will focus first on development and testing of the ME-SXR system, including the advanced electronics featuring onboard A/D and digital data streaming. The final, validated system will be ready for installation and operation by Day 0 operation. An upgraded TGIS with a faster frame rate along with the poloidal USXR system will also be ready for initial plasma ops. Along with the diagnostic development, code development and simulations will focus on improving the neural network T_e profile reconstructions as well as AE-induced core electron thermal transport using a coupling between the HYM and ORBIT numerical codes.

The JHU operational research plan includes using ME-SXR measurements of impurity transport, initially with gas puffing, to compare with previous NSTX results. Upon addition of the LBO system, our group plans more advanced impurity transport experiments along with cold pulse perturbative transport experiments utilizing the full flexibility of the injection system.

Both the divertor research and non-axisymmetric MHD research with the ME-SXR arrays and sensors depend on additional resource availability, and is planned for later in the NSTX-U 5 year run plan.

Timeline

FY14:

- Development and testing of ME-SXR advanced electronics and data acquisition
- Simulations and predictions of AE-induced core e^- transport on NSTX-U using HYM-ORBIT coupled modeling
- Development of advanced Neural Network algorithms for improved measurements of fast T_e, n_e, and impurity concentration profiles
- Use fast measurements of profile with NSTX data for study of ELM induced perturbative e^- transport measurements.

FY15:

- Installation/operation of ME-SXR edge/core systems
- Installation/operation of TG spectrometer
- Initial impurity transport experiments with comparisons to previous NSTX results
- Installation/operation of poloidal USXR system

FY16:

- Installation/operation of Laser Blow-off system
- Advanced impurity transport experiments using repetitive LBO
- Perturbative e^- thermal transport experiments and relationship to core AE activity

FY17:

- Installation of Divertor Imaging Radiometer
- Installation of toroidally displaced ME-SXR edge/core systems
- Measurements of spectrally/spatially resolved radiated divertor power in advanced divertor regimes

FY18:

- Installation of SXR edge sensors

- Measurements of non-axisymmetric MHD/disruptions using fast T_e profile diagnostics
- Development of position/boundary non-magnetic measurements, make available for integration with real-time feedback control system

Contributions to the NSTX-U 2014-18 Five Year Plan:

The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan and is represented throughout the chapters on Transport and Turbulence (Chap. 3, impurity transport and AE-induced e^- transport), Macrostability (Chap. 2, MHD measurements, non-magnetic RWM detection and feedback, disruption physics), Solenoid Free Startup (Chap 8, impurity measurements using the TGIS and SXR diagnostics), and Boundary Physics (Chap 4, divertor characterization using the DIR). The broad applicability of the JHU diagnostics and measurements across the range of important physics topics guarantees a tight integration of the JHU research plan and the broader mission of the NSTX-U program.

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11.2.7 Lawrence Livermore National Laboratory

Research Topic: CHI Modeling on NSTX-U
Principal Investigator: E. B. Hooper
Participating Scientists: R. Raman (U. Washington), C. R. Sovinec (U. Wisconsin), F. Ebrahimi U. New Hampshire
Funded under DOE Contract: DE-AC52-07NA27344

Introduction

This research contributes to the NSTX Relevant Area of Research V, *Start-up, Ramp-up and Sustainment without Solenoid*. It will continue resistive MHD simulations of plasma startup using Transient Coaxial Helicity Injection (TCHI) using the NIMROD code, with the focus on NSTX-U. Tasks include extending simulations from the present NSTX model to NSTX-U and participating in studies on the transition to using non-inductive current drive. Simulations addressing physics in NSTX will continue to be important for validation of the models used in the code.

Current research contributions to NSTX Upgrade

Current whole-device simulations have resulted in a model of NSTX in NIMROD, including the geometry, boundary conditions for the injection and absorption slots, time-varying boundary conditions for the bias magnetic field including wall eddy currents, and coupling to a power supply for the CHI injection. Simulations using this model produce injected flux bubbles that compare well with photographs and reconstructions from experiment, with the injected current concentrated in a layer at the boundary of the injected flux. Toroidal currents and plasma temperature magnitudes and distributions are similar to experiment. A toroidal n=1 mode has been found but shown to have little effect on the flux injection and plasma evolution. Flux-surface closure is observed in high-resolution axisymmetric simulations when the injection voltage and current drop at the end of injection. Closure for the experimental extractor width (4 cm) occurs when local currents driven by injected plasma flow near the forming X-point drop sufficiently to allow resistive reconnection. Ongoing research includes the optimization of injector parameters to maximize the closed volume and current, which are less than in the experiment.

Summary of proposed research plan for 2014-18

The research in this project will: (a) add additional physics to the simulations, including density evolution and impurity effects. Validation will be done by comparison with NSTX, including plasma behavior following flux-surface closure; (b) construct a model in NIMROD of NSTX-U; (c) run predictive simulations in NSTX-U to support preparations for TCHI experiments, including determining scaling with injection voltage and current, injection-slot dimensions, input density and other parameters; and (d) collaborate in simulations of non-inductive current drive, addressing the transition from the TCHI plasma to neutral-beam current drive. In addition, extension to possible future machines will be explored.

The elements of our plan displayed in a timeline are:

Timeline

2014-2015:

- Continue Ohmic-drive simulations in NSTX to optimize flux surface closure and other parameters. Improvement the modeling of plasma external to the injected flux.
- Develop and exercise a CHI model for NSTX-U. Determine optimization parameters in support of experimental planning.
- Assess neutral beam current drive in NSTX-U and conduct initial current drive simulations.

2015-2016:

- Undertake quantitative comparison with CHI experiments when available.
- Conduct current-drive simulations in NSTX-U.

2016-2017:

- Support experimental planning for NSTX-U.
- Extend simulations to possible future machines.

2017-2018:

- Continue and extend simulations as appropriate.

Contributions to the NSTX-U 2014-18 Five Year Plan:

The research defined above contributes strongly to the solenoid-free start-up and ramp-up chapter of the 5 year plan.

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11.2.8 Lawrence Livermore National Laboratory

Research Topic: The Plasma-Material Interface Development and Boundary Physics Program support on NSTX-U

Principal Investigator: Vsevolod A. Soukhanovskii
Participating Scientists: P. Beiersdorfer, one LLNL Theory and Modeling scientist
Participating Post-docs: 2
Participating Graduate Students: 1
Participating Undergraduates: none
Funded under DOE Contract DEAC5207NA27344
LLNL-PROP-62511

Introduction

The goal of the present LLNL research effort on NSTX-U is to contribute to the development of physics basis for an integrated boundary interface for ST-FNSF and ITER, by taking advantage of the unique edge and divertor plasma conditions expected in NSTX-U. Our approach is based on four main elements: 1) design and execution of experiments, 2) numerical multi-fluid transport and turbulence modeling, 3) diagnostic development, operation and calibration, 4) NSTX-U Boundary Physics program development. The present research effort is a continuation of a long-term collaboration of LLNL's Fusion Energy Sciences Program on NSTX that included a number of leading contributions, e.g., the first successful divertor heat flux mitigation studies with radiative divertor in a high-power spherical-tokamak [1-3], snowflake divertor configurations studies [4-9], and a major contribution to the lithium research program in the areas of impurity transport and plasma-surface interactions [10-29]. We plan to expand and continue these studies on NSTX-U as described below.

Current research contributions to NSTX Upgrade

The LLNL collaboration in currently contributing to NSTX-U program in data analysis, active experiments on other devices, and diagnostic development for future measurements, as follows:

- Diagnostic development and data analysis on boron and molybdenum erosion at Alcator C-Mod tokamak [30]
- Snowflake divertor configuration control and physics studies at DIII-D [31]
- Radiative divertor with feedback control at DIII-D, and development for NSTX-U [32]
- Modeling of NSTX snowflake divertor and lithium radiation with two-dimensional multi-fluid code UEDGE and projections to NSTX-U [4, 33-35]
- Diagnostic development in preparation for NSTX-U operations

Summary of proposed research plan for 2014-18

The LLNL research collaboration program takes a full advantage of the LLNL Boundary Physics experimental and modeling expertise. The goal of the proposed research is to advance an experiment-based understanding and a predictive modeling capability of the main plasma-material interface elements: the SOL and divertor heat and particle transport and control in innovative divertor configurations, plasma-surface interactions with lithium-coated graphite and molybdenum plasma-facing components, and their impact on core plasma. The planned research program directly addresses highest NSTX-U Research Program priorities and enable the FNSF-relevant boundary interface development. Substantial model development and validation are planned with NSTX and NSTX-U data. The elements of the planned research are:

- In the area of **SOL energy and particle transport and turbulence** studies, we plan edge theory development and turbulence simulations using the BOUT++ code to enable comparisons with NSTX data and first-principle projections of the SOL heat flux width for NSTX-U and ST-FNSF. We also plan to contribute to the NSTX-U cryogenic panel design using the multi-fluid edge transport code UEDGE, by simulating the cryo-pump particle removal effects in high-flux expansion (snowflake) divertor configuration and with impurity seeding.
- In the **snowflake divertor and radiative divertor** areas, we plan to continue our successful multi-year experimental divertor effort. In the snowflake divertor area we plan to study heat and impurity transport, SOL turbulence, as well as pedestal stability and ELM transients, compatibility with high-Z plasma-facing components, and the possible radiation enhancement with lithium. The radiative divertor experiments will study detachment properties and calibrate the detachment control diagnostics for active feedback control of divertor heat flux via impurity gas seeding. Deuterated methane, neon and argon are planned for radiative divertor with lithium-coated graphite plasma-facing components. The developed control solutions of divertor power and particle exhaust will be integrated with **advanced operating scenarios** to support high-performance H-mode plasmas with reduced collisionality.
- In the area of **lithium-based plasma facing components** we plan to continue our multi-year experiment, analysis, modeling and diagnostic efforts to study the multi-faceted effects of lithium-coated graphite plasma-facing components on hydrogenic fuel recycling and pumping, divertor impurity erosion and SOL transport. In this area, we plan to field additional diagnostics to support Li, C, and Mo impurity erosion studies: 1) an intensified camera diagnostics enabling two wavelength two dimensional imaging of impurity emission; and 2) a spectroscopic monitor of the Material Analysis Particle Probe head (a collaboration with Purdue University). The experiments will be supported by UEDGE simulations of SOL impurity transport, lithium radiation effects, and improved erosion models.
- In the area of **multi-scale transport physics**, we plan to extend the studies of low-Z impurity transport and accumulation in ELM-free H-mode plasmas with lithium conditioning to high-Z impurities - molybdenum and tungsten. The impurity density measurement capabilities in this area will be enhanced by three extreme ultraviolet spectrometers that can measure line radiation over a wide spectral band that covers K-shell, L-shell, and M-shell radiation impurity ions such as Li, B, C, O, Ne, Ar, Mo, W. Comparisons to neoclassical models implemented in numerical codes TRANSP, NCLASS and NEO will be made. The medium-Z and high-Z core impurity density measurements

would also be instrumental in divertor impurity compression and impurity penetration factor studies in snowflake and radiative divertor experiments.

- In the **diagnostic** area, we plan to continue supporting the existing edge spectroscopic diagnostics, namely: 1) 30 spectrally filtered detectors (EIES); 2) the LADA divertor radiometer array; 3) the divertor vacuum ultraviolet spectrometer SPRED; 4) Upgraded one-dimensional filtered camera arrays with divertor and midplane views; 5) the ultraviolet-visible-near-infrared spectrometers VIPS and DIMS. The DIMS spectrometer was designed to provide ion temperature measurements using Doppler line broadening, and this capability would be further pursued in NSTX-U.

Timeline

FY2014:

- Continue analysis of boron and molybdenum erosion data from Alcator C-Mod tokamak
- Develop multi-spectral imaging (charge-injection device camera and image splitter) for NSTX-U and prepare for installation
- Develop and install one-dimensional camera array modules on NSTX-U
- Install LLNL-operated diagnostics on NSTX-U (SPRED, LADA, VIPS, DIMS, EIES)
- Install supersonic gas injector
- Construct MonaLisa spectrometer at LLNL and complete photometric calibration
- Develop BOUT++ model and apply to NSTX and NSTX-U geometry. Start comparisons with NSTX heat flux width database.
- Modeling with UEDGE
    - Use the developed snowflake model for cryo-pump studies
    - Start developing impurity-seeded divertor model
    - Start modeling of lithium radiation effects
- Start setting up neoclassical and impurity transport codes for NSTX-U

FY2015:

- Finalize diagnostic and erosion analysis approach based on NSTX and Alcator C-Mod studies
- Develop and install optics for viewing the Material Analysis Particle Probe head
- Install of all three XUV spectrometers on NSTX-U
- Develop projections of heat flux width and impurity transport for NSTX-U using BOUT++
- Modeling with UEDGE
    - Continue modeling of cryo-pumping impact on snowflake and radiative divertors
    - Continue modeling lithium radiation effects
- Continue development of collisional-radiative and transport models in support of impurity transport modeling for NSTX-U geometry
- Snowflake and radiative divertor studies
    - Prepare and execute scoping studies of snowflake divertor configurations
    - Collaborate on snowflake magnetic control development
    - Prepare and execute scoping studies of radiative divertor with deuterium and argon seeding
    - Start comparing initial divertor data with UEDGE models

- Plasma-surface interaction studies and diagnostic development
    - Prepare and execute scoping studies of recycling and impurity influx with boron and lithium coatings on graphite plasma-facing components
    - Support experiments with UEDGE interpretive modeling
- Operate all three extreme ultraviolet spectrometers
- Develop improved K-shell emission models and determine absolute impurity concentrations of K-shell ions in the core of NSTX-U plasmas
- Initiate interpretive analysis of impurity transport with impurity transport codes

FY2016:

- Snowflake and radiative divertor studies
    - Continue experimental studies of snowflake divertor configurations with divertor cryo-pumping and magnetic control
    - Optimize radiative divertor with impurity seeding and start implementing radiative divertor control diagnostics
    - Continue comparing divertor data with UEDGE models
- Plasma-surface interaction studies
    - Prepare and execute scoping studies of recycling and impurity influx with lithium coatings on molybdenum PFCs, if installed
    - Support Material Analysis Particle Probe studies
    - Support experiments with UEDGE interpretive modeling

- Impurity transport
    - Operate all three extreme ultraviolet spectrometers
    - Perform experiments and interpretive analysis of high-Z impurity transport

FY2017-FY2018:

- Execute experiments with snowflake divertor configurations with cryo-pumping and combine with high-performance H-mode scenarios
- Radiative divertor feedback control experiments
- Continue molybdenum core, edge transport and erosion studies
- Characterize divertor lithium radiation in experiments
- Validate UEDGE models with measurements

Contributions to the NSTX-U 2014-18 Five Year Plan:

V. A. Soukhanovskii is the present leader of the Boundary Physics topical science group and is responsible for entire overseeing and parts of the Boundary Physics chapter of the NSTX-U Five Year Plan. He presented the Five Year Plan for pedestal, scrape-off layer and divertor research at the NSTX-U Physics Advisory Committee meeting in February 2013.

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11.2.9 Lehigh University

Research Topic: Model-Based Current Profile Control Development for NSTX-U
Principal, Co-Principal Investigators: Prof. Eugenio Schuster (PI).
Participating Scientists: N/A
Participating Post-docs: N/A
Participating Graduate Students: 1 PhD Student.
Participating Undergraduates: N/A
Funded under DOE Grant: N/A

Introduction

Setting up a suitable current profile, usually defined in terms of the safety factor q or the rotational transform ι profiles, plays a critical role in the achievement of advanced tokamak scenarios characterized by high confinement and the non-inductive sustainment of the plasma current necessary for steady-state operation. Therefore, while the control of scalar parameters associated with the safety factor q such as q_{min} has been proven critical to mitigate plasma instabilities and improve confinement, the shaping of the entire q profile (q at several points in space) will be necessary to stably maximize the fraction of bootstrap current in advanced scenarios. Therefore, techniques to actively control the evolution of the entire q profile during the discharge are of paramount importance to the success of ITER and their development has recently begun to receive a great deal of attention. The high dimensionality of this problem, along with the strong nonlinear coupling between magnetic and kinetic profiles motivates the use of model-based control synthesis that can accommodate this complexity through embedding the known physics within the design. By capturing the response of the system to the available actuators in a control-oriented model, such control designs can achieve improved performance without the need for extensive trial-and-error tuning. Motivated by this need, the Lehigh University (LU) Plasma Control Group has worked for several years now on the development of control-oriented models for current-profile response and the design of active current-profile controllers based on those models for L-mode and H-mode discharges.

A substantial theoretical and experimental physics effort has been going on for several years to develop predictive models for plasma evolution in toroidal plasmas. The work by the LU Plasma Control Group draws on the result of those efforts but does not supersede it, since the purpose is the conversion of these accepted physics models to a form useful for control synthesis and simulation. It is important to emphasize that these plasma response models are developed only for control design and not for physical understanding, and consequently, the developed model needs only to capture the physics that is relevant for control design. The objective of the control-oriented plasma-response models is two-fold: control synthesis and control simulation. To be tractable from the point of view of available control techniques, the complexity of models used for the synthesis of controllers usually needs to be lower than that of models used for the performance evaluation of controllers in closed-loop simulations. Therefore, the control-oriented models used for control simulation must be reduced further in complexity before being used for control synthesis. The control-oriented models used for control simulation need however to be much less sophisticated than those powering predictive codes such as PTRANSP, CORSICA or ONETWO, which are used for physics studies. This need is motivated by the fact that a control control-oriented predictive simulation code must be capable of running closed-loop simulations in a matter of minutes, at the most, to be an effective tool for iterative control design. Control-oriented models of the current profile dynamics can be divided into two groups: those created entirely from experimental data and those that are driven by first principles.

The data-driven modeling approach lacks unfortunately the ability of arbitrarily deciding on the level of simplicity, accuracy and validity of the model since it directly produces *linear models based on ordinary differential equations (ODEs)*. As the identified models are linear, they are only valid around the reference plasma state adopted during the system identification experiment. Therefore, the effectiveness of the controllers synthesized based on these models may be limited when the plasma state moves away from the reference state. Moreover, as these models are device-specific, dedicated system identification experiments are needed in each device, and potentially for each control scenario, to develop model-based controllers. A robust, model-based, MIMO, ι-profile and β_N controller has been recently designed and experimentally tested by the LU Plasma Control Group for the flat-top phase of DIII-D H-mode discharges. The design is based on a data-driven, two-timescale, linear, dynamic, plasma-response model that has been identified around a reference profile during the flattop phase. The feedback controller [1] is designed to regulate the system around a target profile, which is assumed to be close to the reference profile around which the model has been identified. The proposed controller represents one of the first profile controllers integrating magnetic and kinetic variables ever implemented and experimentally tested in DIII-D. More experiments are needed to assess the appropriateness of using data-driven linear models for current profile control. While data-driven, control-oriented, linear models may still be useful for the design of local regulators around a reference state in the flat-top phase, being able to control the current profile during the ramp-up and ramp-down phases, being able to regulate the current profile for different scenarios (around different reference states), or being able to drive the current profile from one target profile to another will most likely require adaptive or nonlinear control approaches based on richer dynamic models obtained by first-principles-driven modeling.

First-principles-driven modeling, and subsequent controller design, has the potential of overcoming some of the limitations exhibited by the data-driven approach. Unlike data-driven modeling, first-principles-driven modeling has the potential of producing *nonlinear models* *based on partial differential equations (PDEs).* The LU Plasma Control Group advocates for a first-principles-driven approach to model-based control and estimation. The availability of a first-principles-driven PDE model capturing the nonlinear dynamics of the system allows not only for: i- the design of feedback controllers with objectives beyond just regulation around a fixed reference state but also for: ii- the design of optimal feedforward controllers for a systematic model-based approach to scenario planning, iii- the design of state estimators for a reliable real-time reconstruction of the plasma internal profiles based on limited and noisy diagnostics, and iv- the development of fast (potentially real-time), control-oriented, predictive simulation codes for closed-loop performance evaluation of the controllers before experimental implementation. As dictated by the application (control simulation vs control synthesis (see above)) and the design objective, the complexity of the first-principles-driven model can be eventually reduced. It is interesting to note that a first-principles-driven nonlinear PDE model can be reduced all the way to a linear ODE model, similar to that produced by data-driven modeling, by linearization and spatial discretization. However, the first-principles-driven modeling approach provides the freedom of arbitrarily handling the trade-off between the simplicity of the model and both its physics accuracy and its validity range, i.e., provides the freedom of deciding on the level of simplification of the model as a function of the design goal. While first-principles-driven modeling may still need empirical correlations from experimental data to provide closure to the first-principles laws, unlike data-driven modeling, it does not need dedicated experiments to produce a model. Moreover, the empirical laws employed to close the first-principle model (e.g., the magnetic diffusion equation in the case of the current profile response model) are based on physical observations of the plasma response to the control actuators, which are not unique to any one machine. Robust/optimal/backstepping, model-based, MIMO, θ-profile ($\theta=\partial\psi/\partial\rho$) controllers have been recently synthesized and experimentally tested by the LU Plasma Control Group for the ramp-up and flat-top phases of DIII-D L-mode discharges. The first-principles-driven, two-timescale, non-linear, dynamic, plasma-response model proposed in [2] was used to synthesize combined feedforward [3, 4] + feedback [5-7] control schemes to drive the current profile to a desired target profile. The controllers were tested very successfully in both reference-tracking and disturbance-rejection experiments [8-11]. These experiments mark the first time ever a first-principles-driven, model-based, closed-loop, current-profile controller was successfully implemented and tested in a tokamak device. The quality of the experimental results demonstrates the applicability of a first-principles-driven control approach to active, closed-loop, current-profile control.

Current research contributions to NSTX Upgrade

New actuator capabilities planned for the NSTX-U will enable the manipulation and optimization of the current profile in a way that was not possible with the NSTX. In order to study and optimize the Spherical Tokamak (ST) concept for future fusion reactors and to make use of the new actuator capabilities to their fullest, new control algorithms are needed. These algorithms will synergistically combine diagnostics and actuators to manipulate not only the bulk plasma properties but also the plasma profile to achieve the scientific goals of the NSTX-U. The objective of the work currently carried out by the LU Plasma Control Group on NSTX-U is to study and understand the current profile dynamics for the NSTX-U, to develop current profile control algorithms that enable the efficient and optimal use of the actuators by using modern model-based control approaches, and in this way to further the scientific mission of the NSTX-U.

Summary of proposed research plan for 2014-18

Broadly, the work by the LU Plasma Control Group has five separate components:

1. Development of first-principles-driven, control-oriented, nonlinear, dynamic models of the NSTX-U plasma current profile evolution, the diagnostic measurements and the effect of the actuators on the plasma. The aim of this component of the work is to set the groundwork for the scientific understanding of the current profile response dynamics in the NSTX-U that is necessary for control design.
2. Development of real-time current-profile control algorithms based on the developed control-oriented dynamic models. Testing and tuning of the developed control algorithms in simulations based on PTRANSP.
3. Implementation and validation of the developed control algorithms on the NSTX-U PCS (Plasma Control System).
4. Testing and tuning of the developed control algorithms in experiments on the NSTX-U. The focus of this component of the work is on the development of control tools that will be used routinely by PPPL scientists.
5. Integration of current profile control with other control objectives in NSTX-U.

Scientific publications and presentations on current-profile control-oriented dynamic modeling and modern model-based control synthesis for the NSTX-U and ST in general are also part of the work carried out by the LU Plasma Control Group on NSTX-U.

Timeline

FY2014:

- Continue development of first-principles-driven control-oriented models for the NSTX-U current-profile dynamic response. The LU Plasma Control Group is currently working on determining the critical factors that need to be modeled to capture the relevant dynamics of the feedback system composed by the control logic, the actuators, the plasma current-profile dynamics, and the diagnostics. The PTRANSP simulation code is employed to tailor the first-principles-driven model to the NSTX-U geometry. These models provide the capability of understanding the effect of the control actuators on the NSTX-U current profile dynamics and will be exploited during control design (synthesis + simulations). First-principles-driven modeling has the potential of retaining the nonlinear dynamics of the plasma in the control-oriented model, which is critical for current profile control as dictated by the experience acquired by the LU Plasma Control Group in recent years.

- Development of real-time current-profile control algorithms for the NSTX-U. The response models that capture the relevant dynamics of the current profile in the NSTX-U will be embedded in the control synthesis. Model-based, feedforward+feedback, control algorithms that can be implemented in the real-time NSTX-U PCS will be developed. Preliminary closed-loop simulations will be carried out based on the developed current-profile nonlinear dynamic models. Promising control algorithms will be further tested in closed-loop simulations based on more sophisticated predictive codes such as PTRANSP.

FY2015:

- Continue development of real-time current-profile control algorithms for the NSTX-U.
- Implementation of the control algorithms on the NSTX-U PCS. The NSTX-U will use a modified version of the General Atomics PCS. The ability to evaluate the closed-loop behavior of the control algorithms based on a simplified response model is available in the PCS through a Simserver simulation. The proposed control algorithms will be implemented in the PCS and linked with a Simserver based on the developed control-oriented current-profile nonlinear dynamic model to debug the PCS implementation.

FY2016:

- Testing and validation of the proposed control algorithms in NSTX-U control experiments. It is anticipated that the experimental results will dictate the need for model refining and control redesign. The physics-based control-oriented model may need adjusting of parameters in order to achieve the required accuracy level. The adjustment of the model-based control algorithm will follow.

FY2017:

- Continue testing, validation and redesign of the current profile controller in the NSTX-U.

FY2018:

- Work towards integration of current profile control with other control objectives.

Contributions to the NSTX-U 2014-18 Five Year Plan:

Prof. Eugenio Schuster is one of the contributors to the Safety-Factor Profile Control task described in Chapter 9 of the NSTX-U Five Year Plan. The research plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team.

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11.2.10 Lodestar Research Corporation

Research Topic: Edge and Scrape-off-Layer Physics for NSTX-U

Principal, Co-Principal Investigators: James R. Myra (PI), Daniel A. D'Ippolito (Co-I), David A. Russell (Co-I)

Participating Scientists: (separately funded external collaborators) S.J. Zweben (NSTX research contact), J. Boedo, B. Davis, T. Gray, R. Maingi, R.J. Maqueda, D.P. Stotler

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Introduction

An improved understanding of edge and scrape-off-layer (SOL) physics is essential to the goals of NSTX-U, future spherical tokamaks, and to ITER. The work carried out under this project will address critical physics associated with boundary plasma turbulence: the origin and propagation of blob-filaments, their interaction with oscillating zonal flows and mean flows, and the resulting scaling of SOL characteristics (such as the heat flux width) with experimental parameters. Plasma exhaust in the form of heat flux impacting the divertor is still one of the most critical issues facing the magnetic fusion program in general, and the spherical torus concept in particular. Radial transport competes with classical parallel transport to determine the radial penetration of plasma into the tokamak SOL, and therefore the area “wetted” by the exhaust power. Furthermore, convective radial transport in the boundary plasma is believed to be mediated by intermittent coherent propagating structures, i.e. blob-filaments, produced by edge turbulence.[1,2] Thus, both the SOL heat flux width and the physics determining it are of primary importance.

Current research contributions to NSTX Upgrade

Ongoing work is focused on two major research areas: basic properties of the SOL plasma, especially the heat flux width, and fundamental physics of blob-filaments and their interaction with zonal and mean flows. In previous work[3,4] we successfully modeled (at factor-of-two or better level accuracy) the scaling of the heat-flux width for four discharges in NSTX. The experimentally observed strong inverse scaling with plasma current, I_p, and a much weaker scaling with exhaust power, P_{sol}, were obtained numerically. These studies provided an experimentally validated base from which further numerical exploration of the SOL width scaling are being carried out using the SOLT (Scrape-Off Layer Turbulence) code.[5] (See the Boundary chapter section on Theory and Simulation Capabilities for a brief description of SOLT.) The new studies have so far revealed an important phenomena: a transition from quasi-diffusive to convective transport in the SOL.[6] At the transition, the transport becomes intermittent, and the SOL heat flux width is broadened due to increased blob emission. At the resulting larger values of the SOL width, gradient driven diffusion is ineffective and gives way to convective transport. It is expected that this blob-filament-driven transport acts in addition to particle-driven transport described by drift-orbit theory[7], which could set a minimum density width. In a drift-orbit theory, turbulent transport of electron heat in the SOL is still required to obtain the heat flux width.

Closely related to the practical matter of determining scalings of the SOL heat flux width is the underlying fundamental physics that controls the formation and propagation of blob-filaments and their dynamical interactions with mean and zonal flows. In particular, in recent work[8-10] it was shown that strong sheared flows can either trap blobs preventing their ejection or enhance their ejection and radial velocity in the SOL. This work employed both SOLT code simulations and gas-puff-imaging (GPI) data analysis of NSTX discharges using a recently developed blob-tracking algorithm.[11] The simulations reproduced many qualitative and quantitative features of the data including size, scale-length and direction of perpendicular (approximately poloidal) flows, the inferred Reynolds acceleration and residual stress, and poloidal reversal of blob tracks. Mechanisms related to blob motion, SOL currents and radial inhomogeneity were shown to be sufficient to explain the presence or absence of mean and oscillating zonal sheared flows in selected shots.

Summary of proposed research plan for 2014-18

Ongoing and future work will continue in the two key areas of SOL properties (including the heat flux width, and associated scalings) and fundamental questions elucidating blob-filament dynamics. In particular, the behavior of blob-filaments in lithiated discharges is of special interest. Such discharges provide modified edge conditions which are potentially beneficial for plasma performance and of great scientific interest in their own right. Diagnostics of potential interest for this work include gas puff imaging, probes, infrared thermography, Thomson scattering and beam emission spectroscopy.

In addition to studying the effect of lithium, we are working on a version of SOLT that includes the physics of neutrals. It would be interesting to assess whether neutral friction and neutral recycling have a significant effect on SOL turbulence and blob propagation. This would also relate directly to the effect of Li on recycling in NSTX-U.

Depending on the results of these ongoing studies, several ideas for experimental tests may be interesting. These include controlled broadening of the SOL width by increasing blob radial velocities with SOL collisionality as a knob, and blob control using driven *axisymmetric* SOL flows which may provide an alternative to non-axisymmetric biasing [12].

The elements of our plan displayed in a timeline are:

Timeline

2014-2015:

- Carry out detailed comparison studies between the SOLT code and experimental data (GPI and other diagnostics) for discharges with varying degrees of lithium, including studies of blob structure and motion and the resulting SOL properties.

2015-2016:

- Extend previous studies using the SOLT turbulence code to examine the variation of SOL turbulence and the heat flux width with machine (plasma) parameters on NSTX-U.

2016-2017:

- Work with NSTX-U team to design possible critical experiments to further test and/or explore scalings and critical phenomena. Assess the role of neutrals in modifying SOL turbulence and edge confinement.

2017-2018:

- Analyze available additional experimental data from previous years and assess the implications of all the work for future STs and ITER.

Contributions to the NSTX-U 2014-18 Five Year Plan:

Lodestar has contributed to the development of the NSTX-U 2014-18 Five Year Plan through discussions with the NSTX-U team on blob-filament diagnostics, blob and SOL flow control and SOL modeling using the SOLT code. See the Boundary chapter section on Theory and Simulation Capabilities for a brief description of SOLT.

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11.2.11 Massachusetts Institute of Technology

Research Topic: Full-wave studies of high harmonic heating in NSTX with application to antenna coupling and parasitic fast ion interactions in advanced operating modes

Principal, Co-Principal Investigators: Paul T. Bonoli (PI/PD), John C. Wright (Co-I.)
Participating Scientists: Joel C. Hosea, Stan Kaye, Cynthia K. Phillips (PPPL), L. A. Berry, D. L. Green, and E. F. Jaeger (ORNL)
Participating Post-docs: Nicola Bertelli (PPPL)
Funded under DOE Grant: DE-FG02-99ER54525

Introduction

During the past several years radio-frequency power in the high harmonic fast wave (HHFW) regime was used with increasing success on the National Spherical Torus Experiment (NSTX). Experimental breakthroughs were achieved in understanding how to avoid surface wave excitation by moving the onset density for wave propagation farther into the plasma and away from the antenna array. This resulted in record central electron temperatures of 6.2 keV with core HHFW electron heating in L-mode plasmas and greater than 5 keV electron temperatures in H-mode plasmas with concomitant neutral beam injection (NBI) heating. These successes have underscored the importance of having an accurate predictive capability for HHFW wave propagation, absorption, coupling and current drive in order to optimize the use of HHFW power in the NSTX-U device for plasma heating and bootstrap current generation in plasma startup and ramp-up scenarios and for H-mode sustainment.

Current research contributions to NSTX Upgrade

During FY2012 the MIT effort contributed to the NSTX-U program in three important areas: (a) completed the testing and demonstrated the efficacy of a new parallel TORIC solver that can be invoked directly from TRANSP [1], thus enabling time dependent transport simulations of proposed discharges in NSTX-U with adequate numerical resolution and multiple toroidal modes; (b) assisted in the theoretical and numerical analysis of slow wave mode conversion in NSTX and NSTX-U in the HHFW regime; (c) assisted in the assessment of HHFW damping on thermal and non-thermal ion populations in NSTX-U, which is expected to be important because of the higher toroidal field ($B_T \sim 1T$). Much of this work was done in close collaboration with C. K. Phillips, E. Valeo, and N. Bertelli at PPPL and E.F. Jaeger and L.A. Berry at ORNL.

Summary of proposed research plan for 2014-18

1. Verification studies of ion cyclotron damping in the HHFW TORIC solver

Recently Dr. C. K. Phillips initiated an effort to simulate HHFW heating in the NSTX-U device using the TORIC and AORSA solvers. Particular emphasis was given in these studies to the predicted damping of the HH fast wave on the background deuterium and energetic deuterium neutral beam. Initial results from these studies [2] indicate more power absorption by the thermal D ions is seen in NSTX-U than was seen previously in NSTX simulations at similar values of incident parallel wavenumber. This result is not surprising owing to the lower cyclotron harmonics in NSTX-U. However significant differences between TORIC and AORSA on the power absorbed by thermal D and nonthermal beam ions was also found, with TORIC predicting 3-4 times as much absorption on thermal D ions than AORSA, and about 1/3 as much power absorption on energetic deuterium beam ions than AORSA. The working hypothesis thus far is that the AORSA simulations are correct because that code retains all-orders in the ion cyclotron harmonic sum of the conductivity operator. During 2014-2015 we will determine the reasons for this discrepancy and make the required modifications in TORIC if necessary so that its predictions are valid in this regime. This will enable the TORIC in TRANSP code to continue to be used as a useful tool for NSTX-U discharge analysis.

By 2015-2016, work will have been completed on the implementation in TORIC of a non-Maxwellian dielectric tensor valid in the HHFW regime. This work is being led by Dr. N. Bertelli, in collaboration with the SciDAC Center for Wave-Plasma Interactions (CSWPI). This will then make it possible to more accurately assess the interaction of HHFW power in NSTX-U with fast ions from NBI heating.

2. HHFW coupling studies in NSTX-U plasmas

During 2016-2017 we plan to investigate linear HHFW coupling and surface excitation using the standalone TORIC solver. Recently the TORIC code was modified to allow specification of density and temperature profiles for the SOL in an improved manner. Using an exponential step function, the normal generalized parabolic profiles inside the last closed flux surface (LCFS) were modified to include a scrape-off layer of a specified width by multiplying the exponential shape function with the original profile. This is an improvement over the original scrape-off layer model that deformed the profile to make room for the addition of a scrape-off layer within the LCFS. We plan to use this improved SOL model for these coupling studies.

As with the previous SOL model, the new model still extends out to a Faraday screen and beyond that is a current strap in vacuum. A conducting wall is placed in back of the current strap. The locations of the current strap, Faraday screen, and conducting wall correspond to conforming flux surfaces and their locations can be specified arbitrarily. Similarly, the density profile and width of the SOL are also arbitrary. We will perform simulations with the Faraday screen removed and the current strap placed right at the edge of the plasma SOL, with a vacuum region extending from the outside edge of the current strap to the conducting wall. In order to better study the possibility of surface wave excitation it will be necessary to perform 3-D field reconstructions. This will be accomplished by calculating the 2-D (ψ, θ) electric field solution with TORIC for each toroidal mode of the antenna and then superposing these solutions. Additionally each toroidal mode will be weighted by the vacuum power spectrum of the antenna and the partial loading resistance computed by TORIC for each toroidal mode.

These studies will be aimed at understanding qualitatively the experimentally observed dependence of HHFW electron heating in NSTX with toroidal magnetic field, antenna phasing, and SOL density profiles

[3, 4]. These dependencies were successfully simulated [5] using the all-orders full-wave spectral code AORSA with the inclusion of a realistic scrape off-layer in that code and thus the comparison with AORSA and experiment will serve as an important validation of the adequacy of the coupling model in the HHFW TORIC solver. Recall that the density for onset of fast wave propagation scales as $n_{onset} \approx B_\phi \times (k_{//})^2 / \omega$. Plasma parameters, in particular the SOL density profiles from discharges reported in Ref. [2] will be used in the full-wave simulations. The antenna phasing will be fixed at $k_\phi = -8\ m^{-1}$ (current drive phasing) and 3-D field reconstructions will be performed, one at $B_\phi = 4.5$ kG and one at $B_\phi = 5.5$ kG. In each case the radial, poloidal, and toroidal extent of the fields will be investigated with the expectation that at 4.5 kG the wave fields will be confined to the periphery. Because these studies are considered qualitative and scoping in nature we plan to scan the toroidal field beyond 5.5 kG if a clear effect on wave penetration is not seen initially. The next simulation comparison will be a 3-D field reconstruction at 4.5 kG using heating phasing ($k_\phi = 14\ m^{-1}$), where good wave penetration was also seen experimentally. The final simulation study will be to fix (B_ϕ, $k_{//}$, ω) and change the density profile of the SOL from what is expected typically without lithium wall conditioning [3] to what was reported with lithium conditioning [4]. Qualitatively it would be expected that the 3-D field reconstructions using the lower SOL densities characteristic of lithium wall conditioning will exhibit better wave penetration. Again, because of the scoping nature of these simulations we plan to vary the shape and magnitude of the SOL density profile in order to investigate the sensitivity of surface wave excitation to this plasma parameter.

If it is found that the 3-D field reconstructions qualitatively reproduce the conditions for surface wave excitation and its avoidance found in NSTX then this approach would be used in 2017-2018 for assessing the viability of applying HHFW power under a variety of distinctly different edge plasma conditions in NSTX-U; for example L-mode, H-mode, and start-up plasmas. These simulations would be both standalone and time dependent, using 3-D wavefields reproduced from the multi-toroidal mode capability of the parallel TORIC in TRANSP. This work will be carried out in collaboration with Dr. J. Hosea, Dr. C. K. Phillips, and Dr. G. Taylor at PPPL.

Timeline

2014-2015:

- Benchmark ion cyclotron damping at intermediate harmonic number (2-4) against AORSA solver for thermal (Maxwellian) and non-thermal (bi-Maxwellian) ion distributions.
- Resolve differences between TORIC and AORSA solvers.

2015-2016:

- Compare ion cyclotron damping in TORIC solver with new non-Maxwellian dielectric tensor against AORSA solver, using bi-Maxwellian distribution functions.
- Carry out time dependent simulations with TORIC in TRANSP, using effective temperature Maxwellian from NUBEAM to evaluate the non-Maxwellian dielectric tensor in TORIC.

2016-2017:

- Test adequacy of modified TORIC SOL model for reproducing dependency of NSTX coupling results on B_ϕ, k_ϕ, and n_{SOL}.
- Implement modifications to SOL model as needed based on tests.

2017-2018:

- Perform standalone simulations of antenna coupling for NSTX-U configuration using TORIC with benchmarked SOL model.
- Study time dependent coupling of HHFW heating power in start-up and ramping plasmas in NSTX-U discharges using parallel TORIC in TRANSP.

Contributions to the NSTX-U 2014-18 Five Year Plan:

The plan above was defined in a process carried during CY2012, in coordination with the NSTX-U Research Team as they developed their 2014-2018 Five Year Plan document. Specifically this plan contributes to Thrust RF-1: "Develop RF/EC Heating for Non-Inductive Plasma Current Start-Up and Ramp-Up" and to Thrust RF-2: "Validate Advanced RF Codes for NSTX-U and Predict RF Performance in Future Devices", as articulated in Chapter Seven of the NSTX-U Research Plan on Wave Heating and Current Drive.

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11.2.12 Nova Photonics

Research Topic: The Motional Stark Effect Diagnostic for NSTX
Principal, Co-Principal Investigators: Dr. Fred M. Levinton
Participating Scientists: Dr. Howard Yuh
Participating Post-docs: N/A
Participating Graduate Students: 0
Participating Undergraduates: 0
Funded under DOE Grant: DE-FG02-99ER54520 & DE-FG02-01ER54616

Introduction

The MSE diagnostic addresses several needs of the project as outlined in the "NSTX Program Letter for Research Collaboration Employing Innovative Diagnostics for FY 2012-2015" and "NSTX Research Program Five Year Plan for 2009-2013". The NSTX project goals for FY 2012-2015 are grouped into six scientific topics; Macroscopic Stability, Multi-Scale Transport Physics, Plasma Boundary Interfaces, Energetic Particles, Start-up, Ramp-up, and Sustainment without a Solenoid, and Advanced Operating Scenarios. The need for MSE measurements is listed in all six scientific areas because of its fundamental importance for equilibrium, stability, and transport. As part of our collaboration on NSTX we have designed, fabricated, and installed the MSE-CIF diagnostic system. This includes the collection optics, polarimeter, fiber optic bundles, detectors, and development of a new, high throughput, high resolution, birefringent interference filter (BIF) that has made MSE-CIF measurements at low magnetic fields possible. The development of the birefringent filter for the MSE-CIF diagnostic was key to its success. This filter allows very high throughput with high resolution (FWHM~0.06 nm). We have also completed the data acquisition and control system using LabVIEW and integrated it into the NSTX data system that uses MDS+. Software development is now complete, and analysis of the MSE-CIF data is completed between shots and made available for equilibrium reconstruction for between shot analysis. This has proven extremely valuable in many experimental campaigns where development of the appropriate q-profile was essential to guide the session leader toward the experimental goals. At present the diagnostic is providing calibrated magnetic field pitch angle data from 18 channels with sightlines covering from inboard of the magnetic axis to the plasma edge. The MSE-CIF system has been operating routinely, supporting many experimental proposals (XP's) on NSTX at toroidal fields between 3.0-5.5 kG. During the 2011 run period we installed the new MSE-LIF diagnostic, including the diagnostic neutral beam, laser, and collection optics for 5 sightlines. We completed some initial testing of the system and will resume shakedown when NSTX-U starts up in FY15. The new Motional Stark Effect with Laser-Induced Fluorescence (MSE-LIF) diagnostic will allow radially resolved, high-precision measurements of magnetic field magnitude as well as pitch angle. The installation and use of the

MSE-LIF diagnostic on NSTX will enable new physics studies in several topical areas, including fast ion instabilities from a unique measurement of the non-thermal ion population, rf heating and current drive as well as non-inductive startup and current drive in the absence of heating beams, effects of radial electric fields with the combination of the existing MSE-CIF system and the new MSE-LIF, and a contribution to ITER via a unique opportunity to directly compare the utility of two proposed types of MSE measurement that have been proposed for ITER equilibrium reconstruction. Because the MSE-LIF is based on the use of a diagnostic neutral beam, MSE measurements can be made in the absence of heating beams, which will contribute to studies of HHFW heating and current drive, as well as CHI methods of non-inductive startup and current drive.

Current research contributions to NSTX Upgrade

Working with NSTX-U on rtMSE plans and best way to deliver signals to the NSTX-U PCS.

Summary of proposed research plan for 2014-18

The proposed goals of the collaboration for FY14-18 are;

1. Provide calibrated magnetic field pitch angle profiles for the NSTX project. This involves operation of the diagnostic and routine calibration. We will work closely with the NSTX team on several related diagnostic issues such as equilibrium reconstruction. Install MSE-LIF system with 20 channels.

2. Upgrade the data acquisition and computer system to provide real-time MSE-CIF (rtMSE) data for current profile control utilizing the new neutral beam injectors being installed on NSTX as part of the upgrade.

3. Provide measurements of radially resolved internal magnetic fluctuations.

4. Hardware modifications for NSTX-U compatibility. With a doubling of the magnetic field as part of the NSTX upgrade the MSE-CIF collection optics will be optimized to increase the throughput.

5. Participate in physics planning and the experimental program on NSTX. In addition to supporting experiments by providing MSE data, we have proposed and run experiments on NSTX in the past and plan to continue to do so in the future. We expect to continue studies of the effect of magnetic shear on electron transport, and investigate neutral beam current drive from the new current drive beam that will be installed during the NSTX

upgrade. With the combination of the MSE-CIF and the new MSE-LIF, that is supported under a separate Diagnostic Development Grant from DOE/OFES, we will be able to provide radial electric field (E_r) and pressure profiles.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:
- Development of rtMSE hardware and software.
- Installation of MSE-CIF and MSE-LIF components removed for upgrade.
- Installation of additional fiber, filters, and detectors for the MSE-LIF system.
- Modify optics of the MSE-CIF for higher throughput.

FY2015:
- Operation of MSE-CIF to measure pitch angle and magnetic fluctuations.
- Shakedown of rtMSE.
- Shakedown of MSE-LIF.

FY2016:
- Operation of MSE-CIF to measure pitch angle and magnetic fluctuations.
- Equilibrium reconstruction from MSE-LIF using magnitude of the magnetic field, |B|.

FY2017:
- No Operation for extended outage.
- Additional MSE-LIF channels installed to bring the total to 38.

FY2018:
- MSE-CIF/MSE-LIF operation.
- MSE-CIF/MSE-LIF combination to measure radial E_r profiles.
- rtMSE operation.

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11.2.13 Oak Ridge National Laboratory

Research Topic: Boundary Physics, Heating, and Current Drive Program

Principal, Co-Principal Investigators: J.M. Canik, P.M. Ryan

Participating Scientists: J.-W. Ahn, T. S. Bigelow, J. B. O. Caughman, S. J. Diem, T.K. Gray, D. L. Green, D.L. Hillis, J.D. Lore, A.C. Sontag, J. B. Wilgen

Participating Post-docs: 1

Participating Graduate Students: 0

Participating Undergraduates: 0

Funded under DOE Grant: DE-AC05-00OR22725

Introduction

The ORNL research program is divided into two main thrusts: Boundary Physics and RF Heating. The focus of the Boundary Physics program is on improving the physics basis for projecting and optimizing the edge plasma in fusion devices, including the scrape-off layer and divertor. The particle and power exhaust challenge in STs is enhanced by their compact nature, which results in high fluxes and constraints on the space available for highly shaped PFCs. This motivates the search for novel solutions such as the use of liquid metal PFCs and the application of 3D fields for edge control, both of which are areas of emphasis for the ORNL collaboration. The focus of the RF Heating and Current Drive program is to progress toward fully non-inductive operation and solenoid-free plasma current ramp-up to steady-state high-beta operation. RF power will be used to initiate plasma pre-ionization, ramp up low current coaxial helicity injection (CHI) plasmas to the currents and densities needed for neutral beam application, and to further reduce volt-second consumption for long pulse operation at high beta. The ORNL research program includes the installation and operation of several boundary diagnostics, the design, execution, and analysis of experiments, and modeling and simulation in support of these experiments.

Current research contributions to NSTX Upgrade

ORNL staff leads research in the areas of H-mode pedestal and ELM physics [1-9]. We also contribute to the experimental test of lithium as a divertor PFC [10-15]. Our divertor physics program includes leading research on divertor heat flux scaling and the impact of 3D fields [16-23]. ORNL researchers conduct 2D modeling of ST plasmas, including both of present-day experiments and for projection to future STs such as ST-FNSF, and have also led the physics design of the cryo-pumping system for NSTX Upgrade.

ORNL staff operates several IR cameras, including both fast and slow systems, with the capability of dual-band measurements for extracting the divertor heat flux when lithium coatings are present. We also operate a fast filterscope array, visible spectrometers, and thermocouples for PFC temperature measurements.

ORNL historically provides manpower and support for HHFW system design, equipment operation, and experimental implementation and analysis, as well as theory assistance through rf/plasma modeling. The ORNL reflectometer and other edge diagnostics provide crucial information for the optimization of the power coupling and performance of the HHFW systems. The edge profile data is also used to benchmark the modeling codes in order to better understand and interpret the experimental results.

Summary of proposed research plan for 2014-18

The ORNL Boundary Physics program involves research in three main areas: 1) power and particle exhaust, 2) H-mode pedestal research including the effects of lithium, and 3) the effects of 3D magnetic fields on the edge plasma.

In the area of power and particle exhaust, ORNL researchers will conduct experiments measuring the divertor heat flux, characterizing its width, and documenting its scaling with various machine parameters including plasma current and divertor flux expansion. We will also test the effects of lithium on the heat flux profile, including possible novel scenarios such as a highly radiating regime induced by strong lithium evaporation from the PFC surface. The use of lithium for particle control will be studied, including combining lithium PFC coatings for deuterium control with ELM-triggering for impurity control, and extending these scenarios to the longer pulse durations planned for NSTX-U. In addition, ORNL researchers have led the physics design of a cryo-pumping system to be installed on NSTX-U, and will conduct experiments to test the effectiveness of this more conventional pumping technique.

H-mode pedestal research will also be conducted by ORNL researchers. This includes conducting experiments to document the pedestal characteristics (e.g., height and width) over the widened operating space available in NSTX-U in terms of plasma current, magnetic field, heating power, and collisionality. A further emphasis will be on researching the impact that lithium has on the pedestal structure, including both experiments and simulations using gyrokinetic codes such as GS2 and GENE.

The final ORNL boundary physics research area is on the impact of 3D fields on the edge plasma. This thrust includes characterizing how 3D field application alters the pedestal structure and stability, and scenario development using these effects to improve NSTX-U plasma performance, for example by expelling impurities and reducing losses due to core radiation. The effect of 3D fields on the divertor plasma is also an area of ORNL research. This includes both the geometric changes to the heat and particle strike patterns on the divertor (so-called strike point splitting), as well as the impact these fields have on detachment onset conditions. This research will be performed through a combination of experiments on NSTX-U and modeling using state-of-the-art tools such a EMC3-EIRENE.

These proposed research elements reflect a continuation of the ORNL contribution to the NSTX boundary physics program. To carry out this research, the following ORNL diagnostics, which were operated on NSTX, are proposed for implementation on NSTX-U:

- Fast framing dual-band infrared camera viewing the lower divertor,
- 32 channel filterscope system for visible light emission,
- 3-4 compact Ocean Optics high throughput visible spectrometers,
- A wide-angle IR camera with dual-band adapter, and
- Fast time response eroding thermocouples for PFC surface temperature.

To this suite of diagnostics, we are proposing to add:

- An upper-viewing fast dual-band IR camera,
- An additional 8-10 fast time response ‘eroding’ thermocouples,
- Neutral pressure gauges in the cryopump plenum region and main chamber, and
- A densely packed diagnostic tile near the plenum entrance for detailed measurement of local divertor plasma properties.

The ORNL RF research program will concentrate on the following areas of activity over the FY 2014-2018 time period:

- Assess HHFW heating and current drive efficiency for the upgraded plasma conditions of NSTX-U. Analyze and perform experiments to optimize HHFW heating and current drive in low-current, low-density, low-temperature, start-up target plasmas.

- Perform experiments, measure RF/edge plasma interactions, and provide data to theoretical models to understand, predict, and control the RF power flow from the antenna to the core plasma, including wave interactions with NBI fast ions and edge plasma losses (parametric decay instabilities, sheath losses, wave scattering, edge ion heating, and power propagation in the scrape off layer).

- Improve the high power capability and reliability of the HHFW system by designing and testing antenna modifications.

- Design and evaluate the overall operation of a HHFW launcher employing a reduced number of array elements, including control, tuning and matching, and protection.

- Provide and operate antenna/edge diagnostics (microwave reflectometer, antenna IR camera) to measure edge conditions and RF/plasma/antenna interactions.

- Model and evaluate ECH/EBW start-up/ramp-up scenarios. Design the power transmission and delivery system for a 1 MW, long pulse system operating at 28 GHz.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Continue analysis of edge microstability without and with lithium coated PFCs in NSTX experiments
- Complete preliminary physics design of cryo-pumping system consistent with engineering design
- Install and commission a slow wide-angle dual-band IR camera for the lower divertor, obtain full (r, ϕ) 2D heat flux profiles
- Install and commission a high-speed dual-band IR camera for the upper divertor along with the implementation of the existing high-speed dual band IR camera for the lower divertor, obtain 2D heat flux profiles with ELM resolution
- Initiate EMC3-Eirene modeling for 2D divertor heat and particle profiles, preliminary comparison with IR measurements with and without 3D fields
- Install and commission eroding thermocouples embedded in divertor tiles for power and magnetic balance control
- The electronics, data acquisition hardware, and waveguide needed to bench-top test the upgraded NSTX-U reflectometer will be purchased in 2013. In 2014 the replacement vacuum flange and launch/receive antennas will be fabricated and the microwave reflectometer system will be tested and installed on NSTX-U.
- Install and test the IR camera for dedicated antenna structure temperature monitoring.
- Begin modeling the fast wave interaction with fast ions at high cyclotron harmonics, using DIII-D/NSTX experimental data and offset Maxwellian ion distributions in AORSA.
- Initiate EC/EBW modeling using GENRAY/CQL3D and perform code comparisons between GENRAY/CQL3D and ARM.

FY2015:

- Document plasma profiles near candidate plenum entrance, and use this data to confirm and finalize cryo design
- Improve IR analysis software to deal with heat flux onto metallic PFC and long pulse
- Effect of 3D fields on divertor heat and particle profiles; parameter dependence on the asymmetry in heat flux and mean heat flux width (stationary and transient)
- Initiate study of 3D effects on divertor detachment, both for heat and particle flux profiles. Begin EMC3-Eirene modeling for 3D effects on detachment
- Continue analysis of how heat flux and the SOL width vary at the higher Ip, Bt and PSOL available in NSTX-U. Scale for a potential ST-FNSF divertor design.
- Perform initial pedestal scaling studies in NSTX-U
- Assess performance of HHFW array with/without lithium.
- Quantify expected improvement of center-grounded vs end-grounded strap configuration.
- Apply operating techniques for power coupling into ELMing H-modes being developed on DIII-D to NSTX-U.

FY2016:

- Continue data taking, analysis of 3-D effects from ELM control experiments
- Conduct study on relationship between pedestal and divertor/SOL plasmas in the presence of 3D field
- Begin to study 3D effects on divertor flux profiles and EMC3-Eirene modeling in the lithium environment
- Assess the effect of increasing lithium deposition on NSTX-U divertor plasmas and SOL thermal transport
- Verify the microwave reflectometer edge profile measurements and test the full quadrature detection of PDI and edge density fluctuations will be tested, under the supervision of a postdoc.
- Complete design and evaluation of a reduced-element antenna array and power transmission system (tuning/matching/decoupling/phase control).
- Compare the HHFW power flow in the edge plasma with AORSA-3D calculations.
- Heating of low current plasmas for full non-inductive H-modes will be investigated and non-inductive current ramp-up will be initiated.

FY2017:

- Conduct experiments testing performance of cryo system and compare to models
- Extended parameter scan (ν^*, q_{95}, β_N) for 3D divertor physics study with lithium, establish relationship with pedestal parameters

- Extend EMC3-Eirene modeling to deal with 3D + detachment + lithium, and comparison with measurement
- Install and commission divertor “smart tile” with eroding thermocouples, ASDEX style pressure gauge and Langmuir probes to help assess the performance of the newly installed cryo-pump
- Provide routine diagnostic operation of the microwave reflectometer and antenna IR camera.
- Simulate reduced-element HHFW array operation with portions of existing array and compare with design code predictions.
- Test low frequency wave excitation with modified HHFW system.
- Make fully self-consistent iterative calculations of wave-particle interactions with AORSA-2D and NUBEAM. Plasma edge wave fields will be investigated with test particle tracing.
- Design an optimized wave launcher for AE or EHO studies.
- Design low loss, high power EC/EBW transmission system and launcher.
- Optimize plasma start-up, ramp-up, and sustainment during NBI H-mode using HHFW.

FY2018:

- Fully implement measurement and modeling capabilities for the full plasma performance for lithiated PFCs
- Comparison with simultaneous modeling of upper and lower divertors with EMC3-Eirene
- Comparison of particle pumping ability of cryo-pumped and lithiated discharges
- Implement reduced-element HHFW array to drive central current in H-mode plasmas.
- ECH will be used with CHI for plasma startup scenarios. Test EBW heating with fixed horn system; use results to finalize optimized launcher design.

Contributions to the NSTX-U 2014-18 Five Year Plan:

Major contributions were made to the Boundary Physics chapter of the NSTX-U Five Year Plan, including sections 4.2.1, 4.2.2, 4.2.4, and 4.2.6, and to the Wave Heating and Current Drive chapter, including sections 7.2.1, 7.2.2, 7.2.3, and 7.3.2. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan.

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11.2.14 Princeton University

Research Topic: Extended MHD Studies of Flow-Driven and Reconnecting Instabilities in Toroidal Plasmas

Principal, Co-Principal Investigators: Fatima Ebrahimi (PI) and A. Bhattacharjee (co-PI)
Participating Post-docs: 1/2 Post-doc
Funded under DOE Grant: DE-SC0007868

Introduction

Reconnecting and flow-driven instabilities are believed to play an important role in fusion plasmas as well as in the nonlinear dynamics of astrophysical settings. Our work aims to study these instabilities and their role in the nonlinear dynamics of the NSTX fusion toroidal device in the framework of MHD. NSTX has achieved high beta regimes (both toroidal and normalized beta) with large toroidal plasma flows (near Alfvenic). As NSTX-U plans to operate in high-beta regimes using non-inductive current-drive techniques and neutral beam injection, plasma flows can be expected to have increasing impact on MHD instabilities, mircoinstabilties and ultimately on plasma transport. Doubling of the toroidal field, plasma current and NBI heating in the NTXS-U would introduce new physics challenges. Numerical modeling of both reconnecting and flow driven instabilities in these new regimes would therefore be essential. Our work aims to study two major physics aspects of NSTX and NSTX-U, 1) physics of coaxial helicity injection as a non-inductive startup current drive technique, 2) the role of rotation and magnetic shear on ideal and non-ideal current-driven instabilities in the linear and nonlinear regimes. The simulations will be performed using the extended MHD codes NIMROD (nimrodteam.org) and M3D-C1.

For steady-state reactor scenarios, inductive ohmic current drive alone is not sufficient. If helicity is created and injected into a plasma configuration, the additional linkage of the magnetic fluxes can sustain the configuration indefinitely against resistive decay. Various techniques of helicity injection can be used for steady-state current drive, edge current drive and non-inductive startup current drive.

Advancing toward non-inductive current drive, a solenoid-free plasma start-up method called transient coaxial helicity injection (CHI) first developed on the small HIT-II device, has been extended to the large NSTX device. [1] Recent CHI experiments in NSTX have demonstrated a closed-flux equilibrium with a peaked CHI-driven current of about 300 kA. In addition, it was shown that the CHI-produced toroidal current well couples to the induction, resulting in an additional total plasma current of 200kA.[1]. CHI experiments will be extended to NSTX-U and will be coupled to NBI for non-inductive startup current drive. We perform nonlinear CHI simulations in NSTX, which will provide further insight into the viability of CHI as a startup current drive technique and its role in ultimate steady-state operation of fusion reactors.

Slowly evolving reconnecting instabilities may limit the confinement and long time operation of fusion plasmas. They have been demonstrated to be critical in the nonlinear dynamics of many processes in toroidal laboratory plasmas, such as sawtooth oscillations, saturation of internal kink modes and plasma disruption. Toroidal fusion plasmas also rotate in the toroidal and poloidal directions. Experimental observations have demonstrated that rotation and rotation shear can strongly affect reconnecting instabilities as well as plasma transport. Recent experiments in the NSTX have shown correlation between the rotation/magnetic shear and the onset and dynamics of reconnecting events. [2,3] In slab and cylindrical geometries it has been shown that the tearing mode growth rate is increased for small shear flow and the tearing mode becomes stable at larger shear flow. In fact, the ratio of shear flow to magnetic shear determines the stability of the tearing mode.[4] At higher shear, the tearing mode can transition to a Kelvin-Helmholtz instability. The numerical study of these effects in experimentally relevant *toroidal* configurations, and in the nonlinear regimes, is very limited.

Current research contributions to NSTX Upgrade

NSTX geometry and experimentally relevant boundary conditions for CHI operations, including external magnetic fields and coil currents, have been incorporated in NIMROD (by Hooper and Sovinec). NIMROD simulations of CHI with time-dependent boundary fields from an experimental discharge have been performed and reported. [5,6] We have also performed NIMROD simulations of CHI for NSTX with *fixed boundary flux*. The purpose of our simulations is first to explore the possibility of flux closure with constant boundary fields and second to understand the physics of flux closure by isolating different physics models. Our resistive MHD simulations started with fixed boundary fields (including NSTX poloidal coil currents) for a narrow slot of 4 cm, with an injector voltage of 1.77 kV as in the experiment. A large injector current (I_{inj} ~ 12 kA during the flat injected phase) and total toroidal current (I_{tor} ~ 0.28 MA) are generated in this simulation. To understand the physics of flux closure as was observed during the CHI experiments in NSTX, we have isolated different physics models. The finding of our simulations at constant flux are 1) We find that as in the experiment, an X point followed by a fairly large volume of closed-flux surfaces are rapidly formed when the injector voltage (between the two divertor plates) ramps down to zero in the simulations, 2) We also find that unlike the HIT-II simulations at zero beta [7], in the constant flux NSTX simulations, flux closure is only obtained when plasma temperature is evolved by including anisotropic thermal diffusivity, ohmic heating and temperature dependent resistivity. We have started using M3D-C1 to perform simulations of double tearing modes in toroidal geometry.

Summary of proposed research plan for 2014-18

The goals of our simulations are to understand the physics of current relaxation by CHI in relation to transport and mode dynamics, and to perform long term simulations when CHI is coupled to the induction. The nonlinear 3-D simulations are also planned to provide guidance and possible improvement for the present CHI experiments in NSTX-U. We propose to continue the ongoing computational efforts for understanding and reproducing the CHI experiments in NSTX as was explained above. To further investigate and obtain the exact volume size of the closed flux surfaces, which is observed experimentally, we also propose to port the time-dependent boundary conditions from an experimental discharge into the simulations and to compare with the constant flux simulations. Using higher injector voltage and new divertor poloidal coils, CHI experiments in NSTX-U are planned to produce larger CHI-generated current (0.4-0.6MA). It is therefore expected that the CHI-generated current and the volume of the closed flux in NSTX-U is very different from NSTX. To study the stability of CHI-driven current, we therefore propose to perform simulations in NSTX-U geometry and its parameter regimes. We propose to perform long timescale simulations in which the CHI simulations are coupled with induction. This is of great importance since the coupling of CHI with the induction will determine the global and long term behavior of the plasma. Global MHD dynamics and possible reconnecting events such as double tearing observed in the experiment will be investigated. In each step in addition to axisymmteric simulations, we will also study the role of non-axisymmteric modes by including more toroidal modes.

We also propose to perform numerical simulations to study the role of rotation/magnetic shear on reconnecting instabilities in both linear and nonlinear regimes. The proposed simulations will be carried out in the NSTX configuration with experimentally relevant equilibria. In NSTX with high power neutral beam injection, mean flows can play critical roles on the plasma stability. Shear flows can affect ballooning modes and resistive tearing modes. Other important questions are whether large mean flows can cause instability of the continuum spectrum or whether plasma flows by themselves can be the source of free energy or instability. Flow-driven instabilities and local pressure-driven instabilities, Suydam modes, in the presence of shear flows have been studied in cylindrical geometry. [8] It was found that Suydam criterion was significantly modified by the mean flows. It was also found that in the absence of pressure gradient, purely flow-driven modes are unstable at speeds slightly below the critical speed.

As the Alfven Mach number may reach up to 0.5 in the NSTX-U, flows and flow-driven instabilities can have an increasing role on the plasma stability. Preliminary simulations with the MARS-K code predict instability at ½ the rotation of the experimental value in the absence of dissipation.[2] To study flow-driven instabilities in NSTX-U, we propose to preform similar linear stability with M3D-C1 code and compare with the eigenvalue code MARS.

Timeline

2013-2014:

- Continue the ongoing computational efforts for understanding and reproducing experimental closed-flux currents in NSTX. Perform simulations with experimental time-dependent boundary conditions, by using the boundary flux generated by LRDFIT to compare with constant flux simulations. Also include n=1 and higher order modes (in collaboration with B. Hooper and C. Sovinec) with evolving temperature and density. Perform parameter scan to maximize closed flux generation.
- Perform linear simulations of current-driven and flow-driven instabilities using M3D-C1 code with NSTX relevant equilibria. Perform linear simulations of NSTX cases with high rotation (in collaboration with S. Jardin).

FY2015:

- Continue parameter scan for NSTX-U and implement the NSTX-U geometry in NIMROD. Perform nonlinear simulations of CHI coupled to the induction. The physics of this coupling will be investigated and compared with experiment.

- Perform simulations of reconnecting instabilities in NSTX, such as double tearing mode with different equilibria (with magnetic shear) in the presence of shear rotation in the linear regime.

FY2016:

- Continue nonlinear simulations of CHI for NSTX-U with and without coupling to induction.
- Study self-consistent nonlinear generation of shear flows using extended-MHD simulations by including two-fluid physics at different equilibria (with magnetic shear).

2017 -2018 :

- Simulations of CHI coupled to NBI to find parameter regimes to improve NBI current drive.
- Start to couple MHD codes to gyrokinetic codes to investigate transport properties of self-generated MHD flows.

Contributions to the NSTX-U 2014-18 Five Year Plan:

Contributed to Chapter 8 Plasma Current Start-up and Ramp-up Research Thrusts.

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11.2.15 Princeton University

Research Topic: Rotation control in NSTX
Principal, Co-Principal Investigators: Clarence W. Rowley (PI), David A. Gates (PI)
Participating Scientists: Stefan Gerhardt
Participating Post-docs: (none)
Participating Graduate Students: Imène Goumiri
Participating Undergraduates: (none)
Funded under DOE Grant: PPPL NSTX grant number

Introduction

The main motivation of our work is model-based control of plasmas in tokamaks. Previous successes include strike point control [2] and shape control [3] in NSTX. These controllers were designed using models tuned to match experimental data; our present plans are to build on these results, and develop control-oriented models directly from simulations. This capability would have a large impact: fewer experiments would be needed to calibrate the models/controllers, and more importantly, one could predict actuator requirements (e.g., amplitude, bandwidth, latency), and any inherent performance limitations for planned/future machines such as ITER.

Ultimately, we wish to develop these control-oriented models from high-fidelity simulations, such as those being developed in P-TRANSP. This is a complex task, however, so for now we are working with simpler model problems.

Current research contributions to NSTX Upgrade

Over the past year, this collaboration supported a graduate student (Imène Goumiri), who studied a two-dimensional model problem, in order to test model-based control strategies. In particular, she worked with the modified Hasegawa-Wakatani model, a PDE in two variables that models edge turbulence in a cold plasma. This model describes the interaction of drift waves and zonal flows: zonal flows are known to inhibit the growth of drift waves, and hence quench plasma turbulence. Our aim was to tap into this interaction, and attempt to stabilize the overall system using feedback.

We successfully obtained a low-dimensional model, and used it to stabilize the drift waves in numerical simulations of the full PDE model. In particular, we considered parameter values for which only one or two modes were unstable, and used a technique called balanced Proper Orthogonal Decomposition to determine a linear model of just a few ODEs (about 10) that closely represents the full dynamics. Actuation was introduced using a modification to the potential, and we designed a feedback controller using standard tools from optimal control (Linear Quadratic Regulator) to stabilize the linearized model. We then tested this controller on the full nonlinear PDE, and indeed the controller was able to stabilize the drift waves. This work was recently accepted to *Physics of Plasmas*.

Summary of proposed research plan for 2014-18

Building on this success with a model problem, we plan to apply these techniques to rotation control in NSTX. Specifically, we plan to control plasma rotation using neutral beam injection, together with manipulation of neoclassical toroidal viscosity (NTV) using RWM coils. Our starting point is simplified physics (including only diffusive terms in the momentum diffusion equation, for instance neglecting pinch terms), and our aim is to identify diffusion coefficients and other parameters in the model, in order to obtain a highly simplified model that only crudely represents the actual physics, but captures the essential effects of the control parameters (neutral beam injection and NTV) on the rotation and shape. These models can then be used for model-based control design as in our previous work described above.

Our longer-term plans are to continue with model-based control design, applying these techniques to more complex problems, with more realistic physics and boundary conditions. In particular, we plan to leverage recently-developed predictive capabilities in PTRANSP, integrating them with our data-driven model-reduction techniques to develop reduced-order models suitable for control design.

Longer-term plans are to develop integrated controllers, which can address multiple objectives (e.g., vertical mode stabilization, strike point control, shape control, current profile control, and rotation control) within a single control design. Such an integrated controller would have significant advantages over the current piecemeal design, because when controllers are designed separately, they often ``fight" each other, resulting in decreased performance, or even loss of stability. An integrated, model-based control design would allow us to understand the interactions between the different control objectives, and design better controllers to meet these objectives.

Timeline

2014-2015:

- Develop reduced momentum diffusion models based on NSTX data/TRANSP analysis
- Design basic rotation controller based on reduced NSTX model
- Verify reduced model and PTRANSP predictive model against NSTX data

2015-2016:

- Demonstrate control PTRANSP predictive model using basic controllers
- Develop predictive PTRANSP model for NSTX-U
- Develop reduced model of NSTX-U

2016-2017:

- Develop advanced rotation profile controllers for NSTX-U
- Begin implementation of advanced controllers in the NSTX-U PCS

2017-2018:

- Demonstrate control of the rotation profile within the PTRANSP predictive model
- Complete implementation of NSTX-U rotation control
- Begin rotation control experiments

Contributions to the NSTX-U 2014-18 Five Year Plan:

Stefan Gerhardt is the present leader of the Advanced Scenarios and Control (ASC) topical science group and is responsible for overseeing the ASC chapter of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan.

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11.2.16 Purdue University, West Lafayette IN

Research Topic: Impact of Disruptions and ELMs on Liquid Lithium Surfaces in NSTX and Mitigation and Extrapolation to ITER Relevant Conditions

Principal, Co-Principal Investigators: Ahmed Hassanein (PI), Tatyana Sizyuk (Co-PI)
Participating Scientists: Valeryi Sizyuk, Jeff Brooks
Participating Post-docs:
Participating Graduate Students: A. Al-Ajlony
Funded under DOE Grant: DE-FG02-08ER54991

Introduction

Edge plasma evolution plays major role in tokamak plasma confinement and determines/control the High-confinement mode (H-mode) operation. Experiments show the complex character of the edge plasma interaction with tokamak components and as a result the complex self-consistent behavior of plasma in the entire SOL. The edge plasma drift and contact with plasma facing components (PFCs) results in changing of D-T plasma and components material impurities, affects toroidal plasma motion, and redistributes energy load. The integrated models should combine micro- and macro-scale physical processes within the divertor nearby areas and the SOL edge plasma. The energy load emitted from core plasma particles into divertor/wall surface and the resulting heat conduction, melting (solid components), and vaporization of plasma facing materials should be considered in detail in which the MHD vapor expansion and evolution is controlled by the heating of the escaped core particles. Magnetic diffusion, heat conduction, and photon radiation transport should be calculated in fine details in the developed vapor edge plasma. Most recent experimental and theoretical studies of PFCs erosion were performed considering only local areas of tokamak PFCs [1-3]. Composite/mixed materials as plasma facing components (PFCs) in NSTX device add significant challenge to understanding the effects of core plasma particles impact on LLD surface, lifetime, core plasma contamination, hydrogen recycling, and surface material dynamic properties. For example, deuterium recycling from chamber walls in NSTX is determined by recycling conditions at inner divertor with Mo tiles, characterized as high recycling region, and at outer divertor with liquid Li coating on porous Mo substrate (LLD). Theoretical predictions of low deuterium recycling from LLD are based on the low reflection of hydrogen isotopes from Li surface and high diffusion and uptake of deuterium in liquid lithium. However, realistic picture of the reactor environment can significantly change the value of deuterium recycling, obtained theoretically or in the laboratory experiments.

Current research contributions to NSTX Upgrade

In our recent study [4] we simulated the evolution of edge plasma during the normal and disruptive operation of tokamak devices in localized areas of the SOL using our HEIGHTS (High Energy Interaction with General Heterogeneous Target Systems) computer simulation package containing various integrated models [5-7]. We included in our models five main parts: Monte Carlo block of disrupting plasma particles interaction with solid and plasma matter; MHD block of plasma evolution taking into account magnetic field diffusion; heat conduction and vaporization block for plasma facing components; heat conduction block for vapor and plasma; and Monte Carlo radiation transport block. The radiation transport block is based on the optical data calculated by HEIGHTS atomic physics package [8]. Direct expansion of the computational domain to include the entire SOL leads to significant calculations overload and to the problem of multiscale description of the complex various design components. The size of the fusion device is measured in meters, accurate MHD calculations require cell sizes of 100–200 μm, and detail surface erosion simulation requires mesh discretization level of cell size less than 0.5 μm. To avoid the described limitations in edge plasma modeling and to adopt the multiscale approach of the integrated physical and mathematical models, we developed unstructured adaptive mesh approach in computational domain and reconstructed all integrated physical processes in the upgraded numerical methods and computational algorithms of HEIGHTS package. A five-layer quadtree refinement scheme [9] is used for simulation of the entire SOL plasma evolution and the extra refinement (~ 0.5 μm) allowed calculations of subsurface particle implantation, heat deposition, and erosion processes. Using actual NSTX geometry and magnetic field structure we simulated in full 3D the evolution of escaped core plasma particles: starting at core border, gyration and scatterings in SOL, and penetration and deposition into PFCs [10]. The escaped core particles determined the initial energy source and boundary conditions for the edge plasma MHD evolution. The plasma magnetic diffusion, heat conduction, and radiation transport are also considered in the quadtree grid hierarchy (Fig.1). The lithium divertor heat load, divertor surface erosion profile, and potential lithium impurities drift were calculated for the coupled system of the inner and outer divertors interconnected through the SOL. We implemented, verified, and benchmarked our new Monte Carlo kinetic model in our HEIGHTS simulation package to study the spatial profile of ions and electrons energy deposition of the escaped core particles of both inner and outer divertor plate for NSTX and ITER device parameters, magnetic field complex structure, and components geometry [11]. The detailed simulation results of the inner-outer divertor system are currently under preparation now for the comprehensive publications.

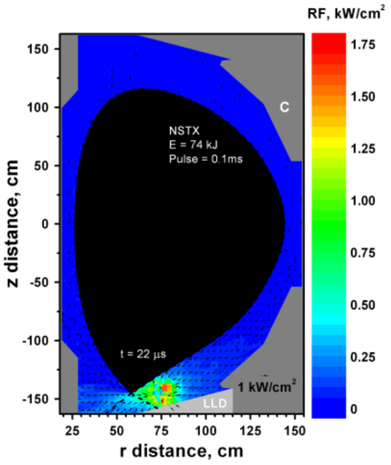

Fig.1. HEIGHTS calculated radiation fluxes for a disrupted energy of 74 kJ

We also enhanced our dynamic Monte Carlo ITMC-DYN package [12,13], combining integrated models for studying the time-dependent dynamic surface evolution at nano/micro layers under impact of plasma particles to address self-consistently all phenomena, specific for NSTX design and conditions. These phenomena include the effect of compounds formation and impurities, the influence of Mo substrate porosity on Li erosion, mixing, deuterium diffusion and desorption, and overall fuel recycling. Using ITMC-DYN we simulated deuterium release from the surface due to reflection, surface molecular recombination, and desorption for various lithium compounds, layers thicknesses, temperatures, and impurities concentrations. Simulation results showed that formed lithium compounds filling porous Mo, such as layers of lithium oxide or hydroxide, will result in deuterium accumulation near the surface due to the reduced diffusion to the bulk, that can slightly increase desorption rate (Fig.2). On the other hand, increase of carbon impurities in edge plasma will lead to carbon accumulation on LLD that will act as barrier to deuterium release from the surface [14].

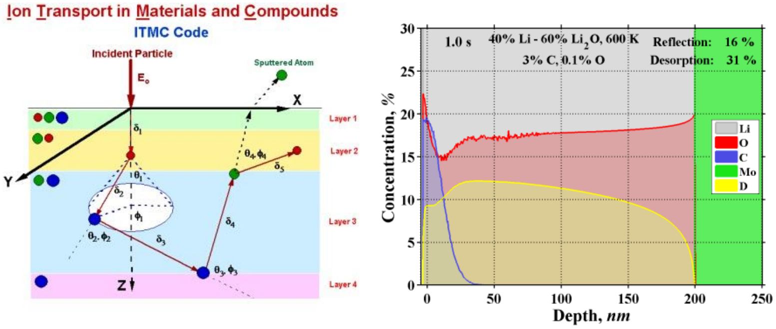

Fig.2. Schematic of ITMC-DYN base model and simulation results: deuterium diffusion and desorption in Li/Li_2O compound at 600 K temperature

Summary of proposed research plan for 2014-18

We developed and benchmarked the initial version of the integrated HEIGHTS package for simulation of the edge plasma evolution in entire SOL area of the actual NSTX device geometry. Our next activity should be focused on three main directions: 1) continue enhancement and improvement of physical and mathematical models, significantly enhance parallel calculation scalability, upgrade of computer package/routines for acceleration of tokamak device simulations; 2) application of package to current NSTX experimental studies of the edge plasma phenomena as interaction with the device components, energy and mass redistribution in SOL including detail radiation losses, study of escaped core particles drift, prediction and optimization of the heat load scenarios of the new NSTX divertor design; 3) investigate different transient mitigation methods and extrapolate to help ITER conditions.

We will further enhance our ITMC-DYN package to simulate plasma facing surfaces evolution in NSTX environment and analyze parameters and conditions, which can determine and optimize deuterium recycling. In such complicated PFC system, as NSTX, with lithium and molybdenum surfaces, with presence of carbon and oxygen, several factors and the interplay of various processes will influence particles diffusion and surface molecular recombination, surface modification and erosion, impurities distribution, sputtering, and overall plasma performance.

The timetable for our plans is given below:

Timeline

FY2014:

- Continue development/enhancement of new scalable methods and numerical algorithms for simulation of plasma dissipative processes: heat conduction and magnetic diffusion.
- Increasing the multi-scale efficiency of HEIGHTS package simulations, optimization of computational time balance and accuracy of the physical processes involved.
- Integrated simulation of NSTX transient events in current geometry. Investigation of the escaped core particles drift, edge plasma evolution, components heat load, and shielding effects. Calculation of radiation loses. Comparison with available experimental data.
- Models development and simulation of LLD surface evolution during NSTX operation. Development and integration into ITMC-DYN package models for chemical compounds formation to predict surface chemistry and surface composition of LLD as function of surface temperature and chamber plasma edge conditions before, during, and after discharge.

FY2015:

- Continue upgrade the parallel version of HEIGHTS package for the calculation acceleration of multi-scale physical processes during edge plasma evolution in SOL. Development of effective merge procedure of the MHD and under-surface subdomains in multiprocessor calculations.
- Integrated simulation of the NSTX-U device transient events in novel "snowflake" divertor (SFD) configuration. Investigation of the escaped core particles drift, edge plasma initiation, components heat load and shielding effects. Calculation of accurate radiation losses in whole 3D domain. Comparison with available NSTX data.
- Modeling deuterium trapping in lithium and compounds and analyze mechanisms of hydrogen isotopes exchange in PFMs (e.g., initial presence of hydrogen in lithium hydroxide on the surface of LLD) to predict H/H+D ratio in desorption rate from the surface.

FY2016:

- Comparison of simulation results for both divertor configurations: heat load, erosion, contamination drift, and radiation losses. Integrated simulation and optimization of the tokamak overall components geometry.
- Investigation of edge plasma drift during NSTX-U normal operation and contamination of core plasma. Comparison of the calculated plasma parameters with NSTX-U data.
- Benchmarking of modeling results for deuterium retention and desorption with data from NSTX-U device and particle beam experiments. Theoretical prediction of deuterium recombination and diffusion coefficients for pure and contaminated lithium and comparison with experimental results.

FY2017:

- Development of physical and mathematical models for neutral gas injection into the SOL. Enhancement of the MHD, heat conduction, and radiation transport models.
- Upgrade of HEIGHTS package for modeling neutral gas injection optimization and capability.
- Initiate studies of various transient mitigation methods in full NSTX-U geometry.
- Based on predicted surface chemistry and compounds evolution on LLD, benchmarked with experimental results, modeling deuterium interaction with materials in surface layers. Evaluate the effect of impurities and surface composition on hydrogen isotopes molecular recombination and desorption or penetration to the bulk.

FY2018:

- Integrated simulation of the NSTX-U transient events and the neutral gas injection. Investigation of the heat load parameters. Optimization of the neutral gas injection.
- Detail studies of transient mitigation methods and feedback to ITER design.
- Modeling ions / target interaction on the surface of inner divertor (high recycling region), taking into account impurities in edge plasma, dynamic changing of surface composition, diffusion and deuterium recombination from Mo surface and Mo with lithium coating.

Contributions to the NSTX-U 2014-18 Five-Year Plan:

The plan above contributes strong to the research goals established in the Materials and Plasma Facing Components chapter of the 2014-2018 NSTX-U five year plan plan and was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team.

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11.2.17 Purdue University, West Lafayette IN

Research Topic: Deciphering the PMI Surface Chemistry of Lithium-based PFCs
Principal Investigator: Jean Paul Allain
Participating Scientists: Charles Skinner (PPPL), Robert Kaita (PPPL), Predrag Krstic (UTK),
Participating Post-docs: Osman El-Atwani
Participating Graduate Students: Sean Gonderman, Anton Neff, Kara Luitjohan, Brandon Holybee
Participating Undergraduates: Tian Qiu, Dan Klenosky, Stephen Taller,
Funded under DOE Grant: DE-FG02-08ER54990

Introduction

This project leverages previous work by our group under Grant DE-FG02-08ER54990, which elucidated the role surface chemistry plays on D particle pumping in lithiated graphite. This project will *elucidate the role surface chemistry and topology has on the ability for liquid lithium surfaces and lithium-based surfaces on graphite and refractory metal (e.g. W, Mo) substrates to control particle pumping and plasma performance in NSTX-U plasmas*. In addition, this project will provide for controlled *in-situ* characterization of re-deposited mixed materials and the effect on deuterium pumping.

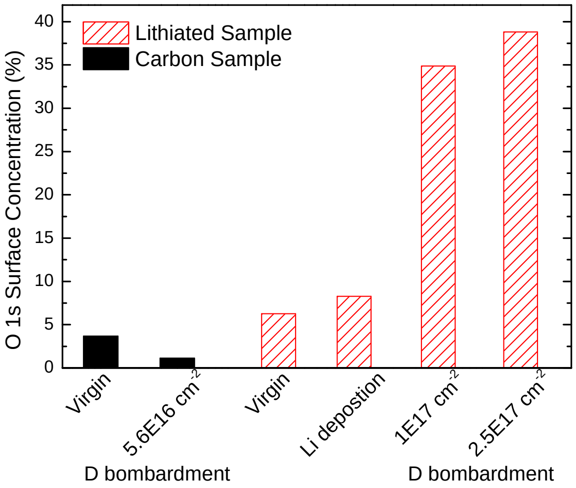
Mixed materials continue to be a dominant environment at the plasma-material interface given the transition in NSTX-U from carbon-based PFCs to full-metal PFCs beyond 2018. Questions addressing how the role of carbon can influence the performance of refractory substrates (e.g. W) in pumping hydrogen and influence performance of thin Li films will be assessed. The work pioneered by our group at Purdue University has already made great strides in understanding what will continue to be the baseline NSTX Upgrade PFCs, mainly: lithium conditioning resulting in thin-film coatings on a variety of substrate materials including graphite and tungsten.

The work proposed in this project effectively complements the surface science work being conducted at Princeton University and at PPPL. In the former case a newly funded project focuses on liquid-metal interface behavior. In the latter, lab experiments are addressing specific questions on lithium-based coatings on refractory metal substrates. Our work focuses on the *dynamic* measurement of an irradiated surface with candidate materials under simulated conditions of the NSTX-U private-flux region and outboard region. None of the groups in either PPPL or PU are addressing the lingering question of the effect surface morphology has on lithium conditioning and *dynamic* hydrogen particle control. Moreover the interplay between surface chemistry (as indicated by the role of oxygen) and nano and micro-scale morphology on particle pumping is still largely not understood. Our group and this project addresses those questions directly.

In this project, fluence exposures will be extended to those of shots of longer duration expected in NSTX-U. This strategy will address the fundamental question about the ability for lithium conditioning to provide effective particle control over longer time scales as previously studied in NSTX. Further studies will study liquid lithium and its ability to control particle recycling and power handling. These are two aspects critical to NSTX-U's PMI overall research strategy. One important aspect of the controlled *in-situ* work in this project is the development through a growing collaboration of surface response computational simulation codes. This is accomplished with a successful collaboration with Dr. Predrag Krstic and colleagues from the Oak Ridge National Laboratory (ORNL).

Current research contributions to NSTX Upgrade

Currently work under this project has mainly focused on understanding particle pumping in lithiated graphite systems. In particular, our work identified the role of oxygen in the retention of deuterium on lithium-conditions ATJ graphite surfaces by a detailed effort between controlled *in-situ* experiments and advanced atomistic simulations [1]. Simulation results demonstrated that oxygen contributes to the effective pumping of hydrogen but only in the presence of lithium in the ATJ graphite matrix. Moreover, the amount of oxygen is important and it was discovered that the magnitude needed to be comparable to the amount of lithium on the surface. However, the most striking result was that it wasn't until lithiated graphite was irradiated that led to a dramatic increase in surface oxygen content enabling enhanced hydrogen retention. This *dynamic* effect was discovered by running *in-situ* surface characterization of the lithiated graphite irradiated with low-energy deuterium ions as demonstrated in Fig. 1.



Additional work in this project also included the study of lithium thin-film coatings on porous Mo substrates (the same Plasma Processes, Inc. (PPI, Huntsville, AL) material for the liquid lithium divertor (LLD)). These studies identified surface chemistry behavior of the lithium coatings and on-going work currently is investigating the ability for these coatings to pump hydrogen. Critical questions remain on lithium coating viability and solid-liquid metal transitions influenced by the substrate morphology (e.g Mo porosity).

Summary of proposed research plan for 2014-18

This project proposes to continue addressing critical questions for PFC/PMI strategies in NSTX-U and in particular the planned transition from carbon-based PFCs to metal-based PFCs. There remain questions about how effectively will lithium conditioning influence NSTX-U long pulsed plasmas in the context of particle control (e.g. D uptake) and heat flux mitigation. Given the ability for thin lithium coatings (~ 100-500 nm or depositions of as little as 100 mg Li) to control plasma behavior, a fundamental question that remains unanswered is how long can lithium coatings maintain their hydrogen uptake property given that plasma shots will increase a factor of 5-10X in time. This is nearly an order of magnitude in fluence. Additional questions linger on the amount of lithium needed for effects on plasma behavior (e.g. heat flux mitigation) and whether erosion/redeposition processes could also be playing an important role in providing for “active” hydrogen pumping interfaces to the plasma. More importantly, questions remain on the exact mechanism responsible for such thin lithium coatings deposited on graphite to effect plasma behavior. Furthermore, the use of lithium coatings in a next step device has been questioned due to its feasibility and potential issues with tritium retention. Tritium retention must be assessed; however indications show that annealing up to 500-600 C could remove implanted deuterium and likely similar for tritium. Furthermore, although applying lithium evaporated coatings may not scale to a large-scale reactor alternative delivery methods of lithium to PFC surfaces could be explored by the use of nanostructured materials being developed in Prof. Allain’s labs.

One particular example of how *in-situ* experiments by our group using PRIHSM coupled to simulations will address these questions is by examining re-deposited layers on candidate material substrates (e.g. amorphous hydrogenous carbon and W) under He and D irradiation to dynamically measure surface chemistry (e.g. O, H) and deuterium uptake. These questions will address concerns about reliance on lithium coatings to provide particle control in NSTX-U and the need for cryo-pumping in future NSTX-U operations.

NSTX-U will also be addressing the issue of particle heat flux control. Power handling is an important issue for future burning plasma fusion reactors. P/S ratios between 0.5 and 1.0 are attractive experimental scenarios accessed by NSTX-U that can be exploited to study power handling PMI issues. In this context, the strategy to progressively convert from an all-carbon fusion device to an all-metal (e.g. with tungsten) fusion device, opens the door for questions regarding how PFCs will perform under a changing PFC platform. Although the current plan between 2014 and 2018 is to keep NSTX-U as a predominant all-carbon machine, mixed-material scenarios with the introduction of a liquid lithium divertor (LLD) and tungsten outboard upper and lower toroidal sections will certainly have an impact on particle pumping and power handling PMI strategies. Our proposed work here will examine the implications of these changes in PFCs by studying *dynamically* how candidate systems behave including: 1) lithium coatings with re-deposited hydrogenated carbon surfaces on ATJ-graphite and tungsten, 2) on boronized ATJ graphite and 3) hot lithium films on ATJ graphite, tungsten and Mo substrates. Our work will address particle pumping via measurement of *both* surface chemistry and hydrogen emission from these surfaces utilizing the suite of materials characterization tools in PRIHSM: XPS, TDS, DRS and LEISS. Furthermore, a newly designed technique using energetic hydrogen forward scattering (HFS) will also be utilized.

Two key collaborations will be central to the work proposed: 1) Sandia National Labs with Richard Nygren and Dennis Youchison on correlation of surface emissivity, surface temperature and surface chemistry for measurements of lithium coatings on candidate substrates, and 2) high heat flux exposures on advanced tungsten substrates with lithium coatings in the Pilot-PSI and Magnum-PSI facilities in DIFFER in collaboration with Greg DeTemmerman.

Collaboration with SNLA

PFC surface temperatures in NSTX are routinely measured based on IR thermography. Temperature is measured by converting intensity signals from infrared energy emitted from the PFC surfaces inside a tokamak, such as NSTX. One critical gap is how the emissivity changes with surface chemistry (e.g. impurities, re-deposited material, etc…) and surface roughness (e.g. morphology, phase variation, etc…). The goal of this project is to correlate the surface emissivity of candidate PFCs in NSTX including: ATJ graphite, TZM (molybdenum alloy), and tungsten with and without lithium surface coatings with: 1) surface chemistry and 2) surface roughness. The objective is to conduct systematic studies using IR thermography in the PRIHSM (Particle and Radiation Interaction of Hard and Soft Matter) experimental facility in RSSEL. The hypothesis is that surface chemistry and surface roughness will have an effect on surface emissivity measurements. To achieve this objective and test this hypothesis a number of systematic experiments are envisioned:

1. Determining and calibrating measurement of temperature on the sample surface
    a. Test with local thermocouples temperature gradients from PRIHSM sample e-beam heater to sample surface
    b. Design and integrate a movable temperature finger to map in 2D the temperature field on the sample surface
2. Measurement of surface chemistry of candidate fusion materials
    a. Measure with IR thermography temperatures in range between 25-400 C on candidate materials and correlate with XPS, TDS and LEISS
    b. Correlate IR thermography data with surface roughness

        i. For example controls with smooth samples (e.g. HOPG, polished Mo)
3. Measurement of IR thermography and impurities
    a. Expose candidate sample materials to controlled impurities via local doser of impurity source such as H_2O, methane, oxygen and monitor effect on emissivity and surface chemistry (e.g. XPS, TDS, LEISS)

Collaboration with DIFFER

Advanced nano and micro-structured tungsten materials are under development at Purdue University with various collaborators including UC Davis, Oklahoma State University, UCLA and a number of faculty at Purdue. The aim is to process a scalable tungsten material that is both tough and radiation resistant. Spark plasma sintering (SPS) has been the synthesis technique of choice yielding tungsten samples with greater than 98% theoretical density, averaging 500 kg/mm^2 Vickers hardness and stable surface and grain boundary chemistry. The samples nomially have a bimodal microstructure with large grains averaging about 1-2 um and small grains between 100-500 nm [O. El Atwani et al. Materials Science and Engr A, 528 (2011) 5670]. An alternative synthesis route is being also pursued in collaboration with Prof. K. Trumble and Prof. S. Chandrasekar of the School of Materials and Industrial Engineering, respectively. This work focuses on using a technique known as large strain extrusion machining (LSEM) can introduce plastic deformation to both surfaces and small chips of tungsten. This approach has led to novel tugnsten nanograin materials with average grain sizes between 50-100 nm.

Another aspect of the tungsten work at Purdue has focused on coupling low-Z coatings on refractory metals including tungsten and molybdenum. Our group has worked on high temperature examination of lithium on micro-porous Mo materials [see: B. Heim, NIMB 269 (2011) 1262]. We have also extensive work on lithiated graphite, which we'd like to extend this work mostly from the PhD effort of Chase Taylor. In our work with thin films and nanopatterning we have evidence that the films can dramatically change the nano-topography. This correlation between the surface composition/chemistry and nanomorphology is being conducted in our *in-situ* PRIHSM device and would be good to extend in our collaboration with FOM-DIFFER.

To date MMG-W and LSEM samples have been irradiated at nominal He and D fluences of order 10^{18} cm^{-2} and temperatures below and above (600 C) the thermal vacancy migration limit for tungsten. Incident particle energies between 50-200 eV have been used for He ions using nominally an RF broad-beam ion source at normal incidence.

One key question in PMI performance of tungsten materials in general is both their resistance to erosion and mechanical property behavior after irradiation. The irradiation-driven surface nanostructured morphology is also an important issue given the propensity for He to induce bubble formation even at energies below the damage and sputter thresholds (e.g. between 50-200 eV). To elucidate the underlying mechanisms of low-energy irradiation of refractory metal surfaces at Purdue University we have focused on two primary fronts: 1) study of defect dynamics of nano and micro-structured W using TEM techniques before and after irradiation, and 2) study *in-situ* correlation between erosion and morphology evolution from these surfaces and their impact on ion-surface interactions. At Purdue University in the PRIHSM facility we are limited to fluences of 10^{18} cm^{-2} and fluxes of less than 10^{14} $cm^{-2}s^{-1}$. Therefore complementary work is necessary at a high-flux facility such as the Magnum-PSI and Pilot-PSI plasma devices at DIFFER. In addition, lower flux plasmas are also desired to obtain a full spectrum of plasma-surface interactions on advanced tugnsten materials developed at Purdue University. More importantly the interest in the DIFFER facilities are plans for the use of a combined high flux of low-energy ions coupled to transient heat/particle pulse. This is by far the biggest motivator for the collaboration in the context of fusion materials science given no other linear plasma device has such capability as described in a recent paper [De Temmerman et al. Nucl. Fusion 51 (2011) 073008]. There are therefore the following three thrusts of fusion-related work in the Purdue-DIFFER collaboration:

- Irradiation of nanostructured tungsten and molybdenum with and without lithium coatings in ELM simulated experiments coupled to steady-state plasma (Magnum-PSI)
- Flux and fluence-dependent irradiations (across all plasma devices at FOM-DIFFER) of nanostructured W or Mo with/without Li to study damage and surface morphology
- Temperature-dependent effects on H and He sputtering of W and Mo surfaces

The elements of our plan displayed in a timeline are:

Timeline

2014-2015:

- *In-situ* surface characterization of dynamic lithium conditioned ATJ graphite surfaces as a function of deuterium fluence and surface temperature
- Studies with SNLA to correlate surface emissivity of lithium conditioned ATJ graphite and surface properties (chemistry, morphology) to assess effect on IR measurements of surface temperature in NSTX-U
- Studies on advanced nanostructured refractory metal substrates with and without lithium coatings in PRIHSM and Magnum-PSI (DIFFER)

2015-2016:

- Study of re-deposited lithium-treated hydrogenated amorphous graphite coatings under various irradiation conditions (effect on D uptake)
- Study of alternative nanostructured matrices containing lithium for dynamic delivery of lithium coatings to PFC surfaces (coordinated tests with MAPP can be included)

2016-2017:

- Conduct coordinated and support experiments with MAPP-U diagnostic and other surface analysis facilities on lithium coatings on high-Z metals and liquid Li surfaces
- Continue study of alternative nanostructured matrices containing lithium for dynamic delivery of lithium coatings to PFC surfaces

2017-2018:

- Conduct mixed-material studies of C, W and Li and their surface chemistry effect on D uptake properties
- Study of hot lithium coatings on candidate substrates and correlate with NSTX-U MAPP experiments and DIFFER exposures

Contributions to the NSTX-U 2014-18 Five Year Plan:

Dr. Michael Jaworski is the present leader of the Materials and Plasma-Facing Components (M and P) topical science group and is responsible for overseeing the M and P chapter of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan.

References

[1] P.S. Krstic, J.P. Allain, C.N. Taylor, et al. “Deuterium uptake in magnetic fusion devices with lithium conditioned carbon walls,” Phys. Rev. Letters, In Press 2013.

Research Topic: Upgrade of the Materials Analysis Particle Probe (MAPP)

Principal Investigator: Jean Paul Allain
Participating Scientists: Charles Skinner (PPPL), Robert Kaita (PPPL), Predrag Krstic (UTK),
Participating Post-docs: Osman El-Atwani
Participating Graduate Students: Felipe Bedoya, Sean Gonderman, Anton Neff, Eric Yang
Participating Undergraduates: Mitch Ketinley, Miguel Gonzalez, Mohammad El-Atwani
Funded under DOE Grant: DE-FG02-08ER54990

Introduction

The Materials Analysis Particle Probe (MAPP) is the first in-vacuo surface-sensitive inter-shot tokamak diagnostic capable of correlating surface chemistry evolution with plasma response to PMI (plasma-material interface) conditioning. MAPP utilizes multiple surface-science measurement techniques to characterize a sample material exposed to NSTX plasma conditions and assess plasma-surface interactions near the strike point. MAPP will help elucidate the complex surface physics and chemistry correlating PSI behavior at spatial scales of 10 to 100's nm (penetration depth of incident energetic D atoms) to the macro length scales of plasma behavior (e.g. ELMs, confinement, etc…). Due to the harsh conditions in the tokamak edge, surface-sensitive conditions on the order of 10 to 100 nm are rendered impossible. However, ion-induced modification mechanisms at fluxes above 10^{15} $cm^{-2}s^{-1}$ typically have time scales between a few seconds to 10's of minutes (nearly 50-60). Therefore correlations between surface chemistry and physics via surface conditioning are plausible by characterizing these plasma-facing surfaces within the order of a few minutes to 10's of minutes. MAPP includes a manipulator probe to insert a probe head with four samples expose to plasma and in between shots characterize these surfaces. Techniques currently include: Thermal Desorption Spectroscopy (TDS), X-ray Photoelectron Spectroscopy (XPS), Low energy Ion Secondary Scattering (LEISS), and Direct Recoil Spectroscopy (DRS).

Current research contributions to NSTX Upgrade

MAPP-U will allow time-resolved PMI data by tuning plasma shots that vary from 1 second and stepped up to longer pulses (up to 5 seconds for NSTX upgrade), the surface chemistry can be assessed under the context of "long-time" "high-power" operation with ramifications to materials design for future steady-state devices and for the progressive transition of NSTX-U from carbon to an all-metal PFC device. Both strategies would be in principle important to ST-FNSF and ITER. Currently much of the work on MAPP has been its engineering design, testing and integration to the NSTX environment. Due to NSTX shutdown for the upgrade, diagnostics are being improved in MAPP including an upgrade that integrates a QCM system for erosion measurements. Details of the preliminary engineering design and testing can be found in a recent publication by Taylor et al. [1]. Initial tests have successfully shown measurements of TDS and XPS measuring D uptake in lithiated graphite surfaces. Current development focuses on the use of ion-probe based spectroscopies.

Summary of proposed research plan for 2014-18

MAPP-U will enable the study of advanced materials and their controlled exposure to designed plasma shots to guide materials and component options. For example tests will include nanostructured lowZ/highZ hybrids, nanocomposites, liquid metals and alloys, and any new material configuration being considered. One particular knowledge gap that MAPP addresses is to correlate shot-to-shot PMI behavior to the surface physics and chemistry. Mixed materials and migration via erosion/redeposition processes will become more important as NSTX-U includes more metal-based PFCs (e.g. tungsten, liquid lithium, etc…). The upgrade to MAPP will consist of integrating a quartz crystal microbalance (QCM) system to assess erosion levels and correlate them to surface chemistry. The QCM system in MAPP-U will allow *in-situ* erosion diagnosis, critical to determine re-deposition vs erosion mechanisms and their effect on surface chemistry ultimately influencing hydrogen-recycling properties.

The MAPP-U system will be integrated to NSTX-U and plans for 2014-2018 are to enable deciphering the surface chemistry and materials mixing and migration effects on particle control in NSTX-U plasmas.

The elements of our plan displayed in a timeline are:

Timeline

2014-2015:

- Integrate MAPP-U remote systems with probe assembly linear and rotational actuation
- Verify all interlocks and systems are compliant and under proper procedures for running in new NSTX-U configuration
- Install MAPP-U chamber on TIV along with electronics rack housing all desired equipment

2015-2016:

- Integrate probe assembly and MAPP-U chamber, overlay all interlocks and proper procedures to verify MAPP-U operation does not interfere with NSTX operation and vise versa.

- Preliminary piggy-back experiments to test MAPP-U operations and verify all systems can work on shot to shot basis. Also to measure and assess particle fluxes for various NSTX-U plasma configurations at the outboard location of MAPP.

2016-2017:

- Investigate new novel material substrates for use with lithium coatings and as robust high-Z materials in NSTX-U.
- Elucidate the surface properties of lithiated graphite and the performance this baseline NSTX PFC in the context of NSTX-U advanced plasmas with 4-5 second discharges.
- Measure D pumping from various ATJ graphite morphologies under fluences equivalent to 4-5 second NSTX-U discharges
- Study liquid lithium surfaces in an upgraded MAPP-U holder for liquid-metals
- Initial boron vs lithium conditioning techniques

2017-2018:

- Comparison of local plasma parameters between Lithium and non-lithium wall conditions.
- Study of lithium deposition and passivation as a function of lithium deposition by LITERS and deuterium flux.
- Comparative data relating the chemical functionalities of lithiated graphite interaction with deuterium and lithium wall conditions influence on plasma performance.
- Mixed material studies using MAPP-U

Contributions to the NSTX-U 2014-18 Five Year Plan:

Dr. Michael Jaworski is the present leader of the Materials and Plasma-Facing Components (M and P) topical science group and is responsible for overseeing the M and P chapter of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan.

References

1. C.N. Taylor, B. Heim, S. Gonderman, J.P. Allain, Z. Yang, R. Kaita, A.L. Roquemore, C.H. Skinner, and R.A. Ellis, “Materials Analysis and Particle Probe: A compact diagnostic system for *in-situ* analysis of plasma-facing components (invited)”, Rev. Sci. Instrum. 83 (2012) 10D703.

11.2.18 Sandia National Laboratories

Research Topic: Sandia thermal analysis of NSTX-U Tiles and approaches for gas cooling and flowing lithium

Principal, Co-Principal Investigators: Richard E. Nygren (PI), Dennis Youchison (Co-I.)

Participating Graduate Students: To Be Determined

Funded under DOE Grant: LAB12-03

Introduction

One important parameter related to power handling is the thickness of the relatively thin layer (called the power scrape-off length or λ_q) that carries power out of the plasma and primarily onto the divertor. For a given configuration of a long pulse plasma, the width of this layer determines the peak heat load and therefor the maximum surface temperature of the divertor. Furthermore, λ_q is not easy to manipulate, nor are the processes that set this key parameter well enough understood to support confident predictions of λ_q in future devices such as an FNSF or DEMO. Extracting accurate estimates of λ_q is an important objective in research in all large confinement experiments. The main focus of our proposal relates to this area of power handing.

A second area of focus for this proposal is the initial development of approaches to gas-cooling for some structures in NSTX-U. The critical points are (1) Sandia has extensive expertise in this area, and (2) the goal of going to longer pulse lengths in NSTX-U as well as interest in a component exposure probe or CEP is likely to bring a requirement for active cooling of some structures in NSTX-U. Such gas-cooled structures have relevance to the path of development for an FNSF and DEMO. The necessary staging of the development and deployment of such structures means that, to be included in the next NSTX-U 5-Year Plan, some significant design development must be done during the period of this proposal.

Current research contributions to NSTX Upgrade

The deployment at PPPL of the liquid lithium divertor (LLD) in NSTX and trays of liquid lithium in CDX-U were the first deployments with large area of liquid lithium. Over the last six years with two previous NSTX-Lab Grants, Sandia has collaborated on the development of the LLD and experiments in NSTX. Sandia delivered the four heated plates for the LLD and the control network for the heaters. Figure 1 shows one of the plates after the HIP-brazing operation that joined a 0.3 mm thick stainless

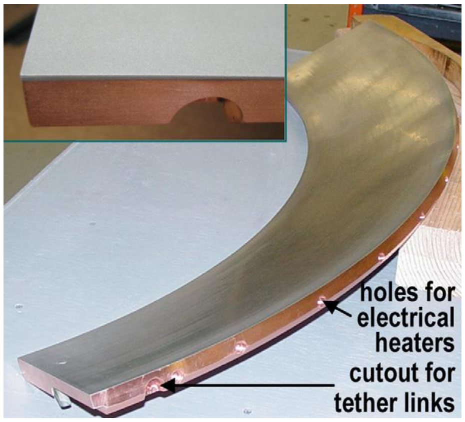


Fig. 1. Copper plate with brazed stainless steel skin for LLD

steel skin the underlying copper plate.[1] Sandia has also performed thermal analysis of the LLD in the interpretation of experiments.

Figures 2 and 3 respectively show the peaked heat load profile used for the thermal analysis and some results. These results were presented at the 2nd International Workshop on Lithium Applications in Fusion[2] and only a brief explanation is given here. The point is that a detailed 3-D thermal analysis is needed to explain the observed behavior. The results here are included in a paper being prepared for publication that compares the thermal performances of graphite and moly tiles and the LLD with a focus on the evolution of the thermal footprint of the strike point in the outer divertor.

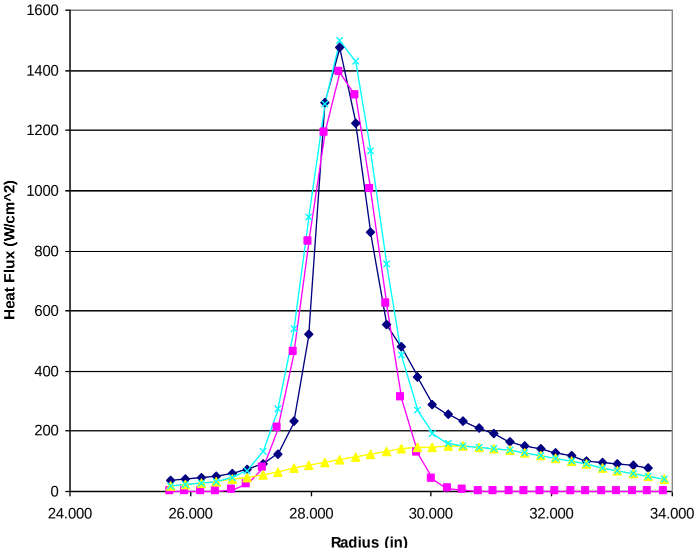


Fig. 2. Heat load profile at the strike point, from data provided by Maingi; broadest profile (crosses) is sum of peak and background (squares and triangles); diamonds shows fit of polynomial series.

The assumption of simple thermal diffusion in a semi-infinite solid with the rise in temperature proportional to the square root of time is inaccurate for the LLD. Copper's high conductivity permits heat to diffuse rapidly both into the heated surface and laterally away from the peak heating.

In the plot on the upper left of Figure 3, by 4800.5 s (0.5 s after the shot starts) heat has reached the back of the Cu plate (bottom of LLD) and the Li surface is over 140° higher than the underlying Cu (top surface). After this time the thermal gradient through the plate is established and the plate does not behave like a semi-infinite solid. The temperature rises more slowly and roughly linearly with time. At the end of the 5-s shot, the Li has risen to 875K from ~650K, the heat load ceases and the temperatures near the top surface drop and those at the bottom increase as the plate attains its average temperature.

Explanations involving broadening of the heat load due to evaporative cooling and lithium in the plasma edge have been proposed to explain the rollover of the temperature curve in the first second of the shot. But another explanation accounts for the observed temperature.

The rise in the temperature of the Li is proportional to the heat load, as can be verified by the plots at the bottom of Figure 3. After 4 s at10 MW/m^2, the rise is 465° and at 5.4 MW/m^2 it is 262°. In each case the rise in temperature divided by the heat load is 46.6 degrees per MW/m^2. So evaporative cooling is not a significant factor. And, lateral conduction of heat is important as the initial peaked heat load diffuses into the LLD. If the loading is changed from a peaked load to a uniform load of 5.4 MW/m^2, so there is no lateral heat conduction, the temperature rises to over 800º.

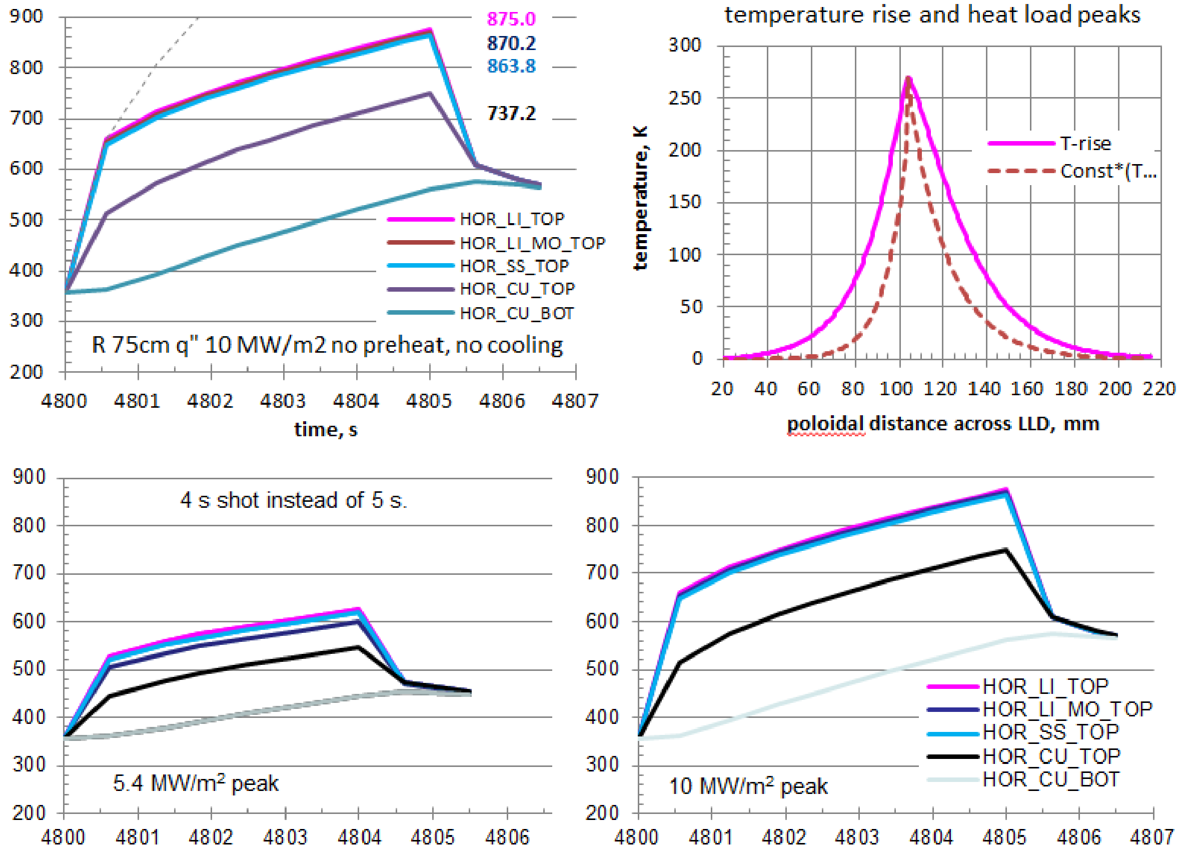


Fig. 3. Plots show temperature versus time on the LLD for the heat fluxes indicated and the following positions: Li plasma facing surface (red), top of porous Mo (black), top of SS skin 0.1 mm below Li surface (blue), top of Cu plate (black), back of Cu plate (gray).

Finally, the plot at the upper right shows the shape of the peak heat load superimposed with a normalized distribution of temperature from the end of the shot, when the peak has broadened by about a factor of two. The temperature rises during the shot, and the peak progressively broadens due to lateral heat conduction in the plate. This broadening is greatest at the end of the shot when the temperatures are highest. This is also the time when the IR data are the most likely to be selected for evaluation.

Continuing work in FY2012-13 includes further thermal analysis comparing the thermal performances of graphite and moly tiles and the LLD with a focus on the evolution of the thermal footprint of the strike point in the outer divertor. We are also completing a collaborative effort with Purdue University to measure the emissivity of liquid lithium surfaces with varying degrees of contamination by C and O.

Summary of proposed research plan for 2014-18

The primary focus of this proposal is (a) 3-D thermal analyses of NSTX-U divertor tiles as the primary deliverable and (b) an improved understanding by the NSTX-U Team working on the plasma edge of heat exhaust in NSTX-U under various conditions. The 3-D analysis is off-site work to be done at Sandia. The interaction to improve understanding includes off-site work to compile, digest and evaluate data from NSTX-U and on-site participation in experiments. The on-site participation includes such activities as monitoring data during shots, engaging in meetings and discussions with other investigators to discuss the conditions and diagnostics for shots, and discussing the implications of accumulated data and planning for various experiments. An example of the latter would be to estimate peak temperatures for hot spot conditions that present limitations on power and shot duration. This effort complements the work proposed by ORNL in their NSTX-U-Lab Grant proposal.

The cases will be of the types listed below. The sequence in this task will depend on results from NSTX-U.

1. Analyses of inboard and outboard tiles (3-4) with fast thermocouples (FTCs) – (a) initial cases to confirm the correlation between the FTC temperature and temperatures at nearby locations on the tile and (b) later cases for clarification of data taken during campaigns.
2. Analyses of misaligned tiles, e.g., hot leading edges – (a) initial cases with step height, angle of incidence of parallel heat flux, nominal power and shot duration as variables, and (b) later cases with iterations to try to match observed tile heating in NSTX-U campaigns.
3. Analyses of tiles with split strike points – (a) initial cases based on observations with 3-D fields and n=1 and n=3 modes and (b) later cases with iterations to try to match observed tile heating during applications of 3-D fields in NSTX-U campaigns.
4. Off-site work will also include effort to collect data, e.g., from IR cameras and FTCs, and to discuss the interpretations with NSTX-U Team members in calls and by e-mail. This element includes the use of NSTX-U data to develop the loads for 1a, b and c above. Typical data will be IR data, FTC data, D_α and probe data, and plots (magnetic reconstructions) that give the angle of incidence of parallel heat flux on the divertor. The heat loads will be developed from extracted data from past shots.

A second focus is participation in component design in two areas: 1) concepts for lithium surfaces in the NSTX-U divertor (e.g., a future upgrade of an LLD) that provide a lithium reservoir or other system for active regeneration of the lithium surfaces plus a scheme, e.g., gas cooling, for active heat removal; and 2) the development of active heat removal schemes for in-vessel components such as RF launchers and guard limiters and materials probe that receive high heat loads. The roles of Sandia will be (a) to work with PPPL staff and suggest how gas-cooling can be applied to some specific NSTX-U components of interest and how such structures can be fabricated with existing industrial capability and (b) to perform thermal-hydraulic analyses to show the effectiveness of the heat transfer in the applications of interest. The expectation is that some ideas will need to be developed to the point of confidence, perhaps even with plans for some limited testing, during the period of performance of this proposal in support of planning and decisions for the next NSTX-U 5-year Plan.

Collaboration Researcher Questions and Issues:

The primary task of thermal analysis requires access to NSTX-U data that is supported by ORNL, specifically IR cameras, probes and fast thermocouples as noted above. Sandia will work closely with ORNL in requesting and exchanging information. Sandia has spoken with ORNL staff in this regard. They indicated the ORNL proposal would acknowledge possible collaboration with Sandia. The collaboration is also likely to extend into activity related to approaches for future applications of flowing lithium.

PPPL also has several ongoing international collaborations and Sandia is interested in becoming a partner in these collaborations. One is with EAST that involves ORNL. Sandia has also spoken to PPPL about the ORNL connection in this regard as well as Purdue. Another is design work with Korea on a Korean DEMO under the leadership of PPPL for the US effort. The request for this effort is likely to grow and include R&D if Korea launches an intensive program to develop a Korean DEMO. Sandia has also spoken with PPPL about its involvement.

Timeline

The elements of our plan are summarized below by year.

2014-2015:

- Continue thermal analysis of divertor heat load profiles for NSTX shots. Anticipated cases for analysis are: a) strike point on inner divertor near location of FTCs, b) strike point on outer divertor near FTCs, c) preferred snowflake divertor configuration, d) strike point splitting for n=1 3-D ELM suppression fields and possibilities for plasma rotation to enhance view under down-looking IR camera, and e) strike point splitting for n=3 ELM suppression fields and possibilities for plasma rotation to enhance view under down-looking IR camera.
- Develop concepts for gas-cooling of NSTX-U components and study related issues

with machine interfaces, e.g., RF guard armor and machine interfaces for gas-cooling, e.g., N_2 and He systems, feed-through locations and services for RF antennae and MAPP-U, etc. Perform 3-D heat transfer model of preferred application, e.g., gas-cooled frame for BN RF protection tile. Consider development path for deployment of hardware, e.g. detailed design and fabrication of mockup(s) and deployable testing in NSTX-U.

2015-2016:

- Continue thermal analysis of divertor heat load profiles for NSTX shots. Revise work scope based on observations during experimental campaign, e.g., more/different analyses of leading edge problems, issues with MAPP-U, etc.
- Continue development of concepts for gas-cooling of NSTX-U components and study of related issues with machine interfaces.

2016-2017:

- Sandia looks forward to a continuing collaboration with PPPL and the NEXT Team in further thermal analysis of heat loads in the NSTX-U divertor and refinement of gas-cooling concepts, pending additional funding.

Contributions to the NSTX-U 2014-18 Five Year Plan:

Dr. Michael Jaworski is the present leader of the Materials and Plasma-Facing Components topical science group (MP-TSG) and is responsible for overseeing the MP chapter of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team and the MP-TSG.

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11.2.19 University of California, Davis

Research Topic: FIR Density Monitoring, Feedback Control and Fluctuation Diagnostics
Principal, Co-Principal Investigators: N.C. Luhmann, Jr.
Participating Scientists: C.W. Domier
Participating Post-docs: C.M. Muscatello
Participating Graduate Students: R. Barchfeld
Funded under DOE Grant: DE-FG02-99ER54518

Introduction

UC Davis is reconfiguring and upgrading the Far Infrared Tangential Interferometer/ Polarimeter (FIReTIP) and high scattering systems on NSTX for use after the completion of the center stack and 2nd neutral beam injector (NBI) source upgrade now underway. UC Davis will also operate and maintain these systems once they have been installed and commissioned.

The FIReTIP system was previously configured as a 6 chord system operating at 119 µm. The two central chords monitored the NSTX core density while the other chords provided core and edge density fluctuation data. All FIReTIP beams entered through Bay K, with retro reflectors positioned on Bays F, G, H, and I. The previous high-k_r scattering system employed a 280 GHz source to form a beam that was launched via a translatable/rotatable mirror on Bay H to different plasma radii with scattered signals collected over a 20° range. The scattered signals were coupled through a rotatable collection mirror to a set of 5 mixers located outside the Bay K exit window. Each mixer monitored density fluctuations at a different wave-number with a k_r wave-number range up to ±20 cm^{-1}.

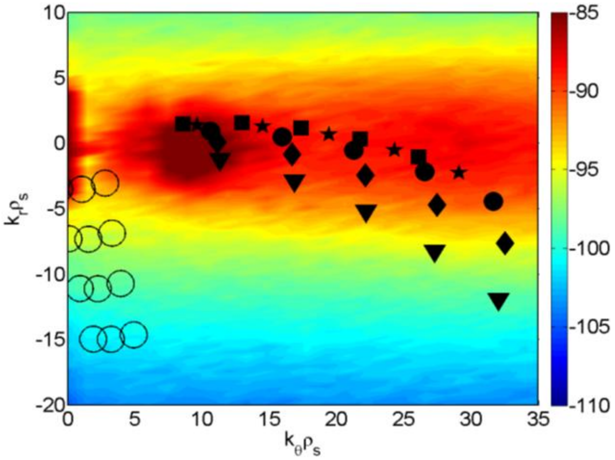

Fig. 1. A simulation by Dr. Y. Ren of PPPL, of ETG turbulence on NSTX overlaid with k-space coverage of the previous (o) and new (●,■,▼,◆,★) high-k scattering systems.

The use of Bay K for a second NBI source has forced the FIReTIP and high-k scattering systems to be dramatically reconfigured. The high-k_r scattering system [1,2] will be transformed into a high-k_θ scattering system employing a vertically extended window on Bay L, with significant changes proposed to both source and receiver hardware coupled with new optics. While the previous system provided primarily radial wavenumber ($k_r\rho_s$) coverage, the new system additionally provides poloidal wavenumber ($k_\theta\rho_s$) space with coverage very near the estimated spectral peak of the 2D ETG fluctuation k-space (see Fig. 1).

The reconfigured FIReTIP system will comprise 4 chords: two central channels to monitor the NSTX core and provide density feedback data for NSTX, and two to monitor core and edge density fluctuations. The central chords will be incorporated into a density feedback control system for NSTX and provide density calibration data for the Thomson scattering system. Polarimetry data collected on all FIReTIP channels will provide chord-integrated information on NSTX magnetic profile and fluctuations.

Current research contributions to NSTX Upgrade

As part of the NSTX upgrade activities, the FIReTIP lasers (CO_2 and FIR) were returned to UC Davis in Spring 2012 for overhaul and refurbishment. The FIReTIP system employs one high power CO_2 laser and three optically-pumped FIR lasers. The new high-k_θ scattering system will employ an ~600 GHz source (which is double the frequency of the previous high-k_r scattering system) will initially be generated by an optically pumped FIR laser. Thus, the need to refurbish not only the FIReTIP lasers, but also additional CO_2 and FIR lasers is a major effort currently being taken on by students and staff at UC Davis.

The CO_2 and FIR lasers for both FIReTIP and high-k_θ scattering will be placed outside the NSTX test cell, in an area that housed the previous high-k scattering source. Collimated FIR beams for both systems will be transported via low loss waveguides to the NSTX vacuum vessel. The high-k_θ beam will be launched from Bay G, as will the initial two chords of the reconfigured FIReTIP system. Design of the Bay G port cover is nearing completion, with installation planned for June 2013. The high-k_θ scattered beams will exit through a large window [5 inches (wide) by 13.4 inches (high)] on Bay L, whose port cover is already designed. The initial FIReTIP beams will reflect from internal retroreflectors to be mounted on the inside of a large flange on Bay B. The remaining two FIReTIP chords (to be added in future years as NSTX resources permit) will have sight lines stretching from Bay F to Bay K (to monitor core density and magnetic fluctuations) and Bay I to Bay L (to monitor edge density and magnetic fluctuations).

Design of the Bay L receiver optics is underway in collaboration with PPPL personnel under the leadership of Dr. Yang Ren. Both the FIReTIP and high-k_θ scattering systems will be installed and begin operating in FY2015.

Summary of proposed research plan for 2014-18

Hardware

The FIReTIP system will begin operation in FY2015 with two plasma chords. In subsequent years, two additional FIReTIP chords, for a total of 4, will become available. Albeit a reduced number of channels, the new FIReTIP system will nonetheless continue to play a key role for NSTX in providing density feedback stabilization for NSTX and provide density calibration for the Thomson scattering system. The high-k_θ poloidal scattering system will be installed in FY2015 with a 4×1 imaging receiver array, with commissioning to be completed in FY2016. The high-k_θ receiver system will be expanded in later years to 2-D as resources permit.

In the long term, UC Davis is investigating ways to replace the large cumbersome ~600 GHz optically-pumped FIR laser with a compact, higher-power source. UC Davis has entered into a collaboration with Prof. Claudio Paoloni of Lancaster University to investigate the fabrication of an ~600 GHz backward wave oscillator (BWO) capable of delivering > 100 mW. This leverages separately funded work at UC Davis on microfabricated THz vacuum electron beam sources.

Physics

There is no doubt that electron thermal transport will pose the ultimate limit to the confinement performance of future devices. For example, electron heating will be dominant in ITER discharges, and efficient heating of fuel ions by electrons requires good electron thermal confinement. It is shown that experimentally relevant electron thermal transport is driven almost exclusively through stochastic magnetic field. Further parametric scans demonstrate that the s/q, Zeff, β and collisionality dependences of microtearing modes are different to those of ETG modes [3], which provides a potential way for separating them experimentally. Large scale magnetic fluctuations (n~10) associated with microtearing modes make it possible to measure magnetic fluctuations directly through Faraday rotation effects. The FIReTIP system, with its high sensitivity to magnetic fluctuations, will be particularly useful here.

Electron-scale turbulence has long been considered as a potential candidate in driving electron thermal transport, i.e. ETG turbulence [4], and its correlation with electron thermal transport has been observed in NSTX. Electron-scale turbulence was first identified in NSTX with the previous high-k scattering system [5] with local electron temperature gradient varied by RF heating in NSTX L-mode plasmas. However, the relationship between the electron scale turbulence measured by the previous high-k system and electron transport is not fully established, with agreement in certain situations but not in others [6,7]. This is not surprising, since limitations of the previous scattering system (which consisted of five channels measuring five radial wavenumbers with k_θ scannable from 0–7 cm^{-1}) spanned a perpendicular wavenumber range of $k_\perp \approx 5$–$25\ \mathrm{cm}^{-1}$. The limited coverage of the previous high k_r scattering system failed to sample the spectral peak of the ETG fluctuations (at ~$10\ \mathrm{cm}^{-1}$, assuming ρ_s~1) as calculated by the nonlinear GYRO code [8]. The new configuration will span $k_\theta \approx 5$–$40\ \mathrm{cm}^{-1}$, centered at $k_r \sim 0$. Additional benefits include an enhanced signal-to-noise ratio arising from (a) increased incident beam power, (b) increased scattering cross-sections (due to low k_r), and (c) significantly increased radial coverage.

Furthermore, Alfvén eigenmodes are found to be potentially important for electron thermal transport in the core (r/a<0.4) of NSTX high-power neutral-beam injected H-mode plasmas. This electron thermal transport mechanism is potentially important for ITER since fusion α particles (which ITER relies on to heat electrons) may drive AE activities and thus could lead to degraded electron thermal confinement. The Alfvén eigenmodes are excited by fast particles from neutral beam injection due to their super-Alfvénic velocity. In a set of H-mode plasmas, flattening of central electron temperature profile is observed as NBI power is increased from 2 MW to 6 MW with increased AE activity indicated by Mirnov coil measurements [9]. Multi-chord density fluctuation measurements of spatially extended instabilities, such as Alfvén eigenmodes, would support ongoing research of a broad range of transport issues from electron thermal transport to fast-ion transport due to avalanches and other Alfvénic instabilities.

The reconfigured FIReTIP system, with its high sensitivity to edge density fluctuations and its demonstrated realtime capabilities, would help to address many physics demands of NSTX as well as providing density control in support of advanced operating scenarios. The prospect as a real-time density diagnostic for advanced plasma control would complement, for example, measurements of the safety factor profile, temperature and density profiles, divertor heat-flux, radiation, and/or surface temperature measurements.

Timeline

FY2014:

- Mock up the FIReTIP and high-k_θ scattering diagnostics at UC Davis, and characterize these systems using synthetic targets
- Install and operate the FIReTIP system on NSTX

FY2015:

- Commission the reconfigured FIReTIP system
- Work with NSTX personnel to implement a density feedback control system
- Install and operate the high-k_θ scattering system on NSTX, and employ initial plasma data to optimize system performance

- Physics studies will focus on assessing low-k turbulence (e.g. electron thermal transport in ITG/TEM regimes) appropriate for interferometric fluctuation measurements

FY2016:

- Install 3rd FIReTIP sight line
- Commission the (optimized) high-k_θ scattering system
- Physics studies continue to assess low-k turbulence, shifting focus toward high-k turbulence (e.g. ETG regimes) appropriate for newly commissioned scattering diagnostic

FY2017:

- Install 4th FIReTIP sight line
- Expand high-k_θ coverage from 1D to 2D with addition of a second 4-channel mixer array
- Conduct laboratory tests of a new high power (>100 mW) ~600 GHz BWO source
- Extensive testing of turbulence models; develop synthetic fluctuation diagnostics for rigorous testing of high-k/FIReTIP data against models

FY2018:

- Phase-out 600 GHz FIR laser for high-k_θ system in favor of a higher power BWO source for increased signal-to-noise ratios

Contributions to the NSTX-U 2014-18 Five Year Plan:

UC Davis contributed to Section 3.4.2.1 for Turbulence (and Transport) Diagnostics.

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11.2.20 University of California, Irvine (UCI)

Research Topic: Active Beam Diagnostics to Measure the Fast-ion Distribution Function in NSTX-U, Beam Ion Studies in NSTX

Principal Investigator: Bill Heidbrink
Participating Scientists: Deyong Liu
Participating Graduate Students: Luke Stagner. *Note: an additional postdoc or Ph.D. student will be recruited once operation commences.*
Participating Undergraduates: 1
Funded under DOE Grants: DE-FG02-06ER54867, DE-FG03-02ER54681

Introduction

UCI joined the NSTX team at the beginning of NSTX operation. A study of beam-ion confinement based on the "beam-blip" technique was published in 2003. Several studies of fast-ion driven instabilities followed. Meanwhile, UC Irvine assumed responsibility for the solid state neutral particle analyzer (SSNPA) diagnostic and Deyong Liu began a Ph.D. project at NSTX. Following the development of the fast-ion D-alpha (FIDA) technique on DIII-D, a FIDA diagnostic for NSTX was proposed and funded. Mario Podesta was the postdoc who developed the NSTX spectroscopic "s-FIDA" and bandpass-filter-based "f-FIDA" instruments, both of which worked very well. For his thesis, Deyong Liu analyzed FIDA measurements of fast ions accelerated by HHFW. More recently, a new postdoc named Alessandro Bortolon completed assembly of new tangentially-viewing FIDA instruments just prior to the shutdown. Bortolon also performed new studies of fast-ion instabilities.

Current research contributions to NSTX Upgrade

Current Irvine personnel on the NSTX-U project are Prof. Heidbrink, Dr. Deyong Liu, and Mr. Luke Stagner. In addition, although he no longer works for UCI, Dr. Alessandro Bortolon is completing papers on projects he performed while an Irvine postdoc.

Deyong Liu is stationed at PPPL and works full time on the NSTX-U project. Under the supervision of Guo-Yong Fu, he is presently spending ~50% of his time on simulations of NSTX data. In particular, he has developed a method to incorporate accurate modeling of the fast-ion distribution function into the M3D-K code. The other half of Liu's effort is devoted to NSTX-U diagnostics. He is presently designing the new SSNPA diagnostic. Our ASDEX-Upgrade collaborator Benedijt Geiger has improved our synthetic diagnostic code FIDASIM; Liu is responsible for porting and testing FIDASIM for NSTX-U use.

Heidbrink and Bortolon are concentrating on completion of Bortolon's physics papers. A draft submission for *Physical Review Letters* on "Mitigation of Alfven activity in a tokamak by externally applied static 3D fields" was recently completed. Another paper will be based on Bortolon's invited talk at the 2012 APS-DPP conference on the synergy between AEs and kink modes. Earlier work presented at the IAEA Technical Meeting on Energetic Particles will also be published.

For his Ph.D. thesis, Luke Stagner is developing Bayesian techniques to infer the fast-ion distribution function. This project is in collaboration with Mirko Salewski of the Danish Technical University. The project is jointly supported by DIII-D and NSTX-U, as it is anticipated that Stagner's algorithms will be employed on both devices.

Summary of proposed research plan for 2014-18

In hardware, UCI will concentrate on four active beam measurements: vertical FIDA, tangential FIDA, SSNPA, and E||B NPA. The vertical FIDA system [1] is a working diagnostic that has been producing valuable data for several years. The tangential FIDA system [2] is patterned after the vertical FIDA diagnostic. Although it has not collected data during plasma operations, the diagnostic is essentially complete. The SSNPA diagnostic [3] was displaced from its former location by the new beamline. A new SSNPA diagnostic is being designed that will measure trapped fast ions at several radial locations. In addition, we will collaborate with Princeton personnel on operation of the E||B NPA if and when it is reinstalled.

Software to interpret the fast-ion data is another area of responsibility. FIDASIM [4] is a forward-modeling synthetic-diagnostic code that models active FIDA and NPA signals. Improvements to this code that allow it to run an order of magnitude faster will be implemented. A new code that models passive FIDA signals [5] (i.e., signals produced by collisions with edge neutrals rather than injected neutrals) is under development. In addition to these forward-modeling efforts, direct reconstruction of the fast-ion distribution function F from the fast-ion data is desirable. This is the topic of Luke Stagner's Ph.D. thesis. Through our collaboration with Salewski, initial progress in this area has already been achieved [6]. We will also develop a reduced model for the expected signals produced by classical fast-ion populations. This rapid, reduced model will be used to guide experiments in the control room and also for mining extensive datasets.

In experiments, we expect to contribute to validation experiments for the second neutral beamline; these will likely be similar to experiments Heidbrink performed at DIII-D [7]. New FIDA measurements of the interaction of fast ions with fast waves [8] (at intermediate cyclotron harmonics) are also anticipated. In later years, we plan to concentrate on studies of fast-ion driven instabilities.

In analysis, Liu will continue to work closely with Princeton theorists to simulate NSTX-U experimental conditions. Once the machine is operating, a new postdoc or Ph.D student will be recruited who will assume some of Liu's diagnostic or analysis responsibilities.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- FIDA calibrations
- SSNPA electronics
- Complete NSTX fast-ion instability papers
- Test fast-ion inversion code on best available data from NSTX, DIII-D, and other devices

FY2015:

- Operate and maintain FIDA and SSNPA diagnostics
- Deploy reduced model during operations
- Validation experiments for 2nd neutral beamline
- First fast-wave measurements of beam-ion acceleration

FY2016:

- Operate and maintain FIDA and SSNPA diagnostics
- Publish paper on beam validation experiments
- Dedicated beam-ion acceleration by fast waves experiment
- New study of an interesting fast-ion instability

FY2017:

- Operate and maintain FIDA and SSNPA diagnostics
- Publish paper on FIDA fast-wave acceleration observations
- Fast-ion instability studies

FY2018:

- Operate and maintain FIDA and SSNPA diagnostics
- Fast-ion instability studies

Contributions to the NSTX-U 2014-18 Five Year Plan:

UCI contributed material to chapters 6 and 7 of the Five Year Plan, particularly these sections:

- "Develop reduced physics-based models for *AE-induced fast ion transport,"
- "Validate classical TRANSP predictions for 2nd NB line,"
- "F_{nb} inversion code for interpretation of fast ion data"

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11.2.21 University of California – Los Angeles

Research Topic: Cross-Cutting Research Studies on NSTX-U
Principal, Co-Principal Investigators: P.I. - Dr. Tony Peebles, Co-P.I.s - Prof. T Carter
Participating Scientists: Dr. Neal A. Crocker and Dr. Shige Kubota
Participating Graduate Students: Mr. Jie Zhang
Funded under DOE Grant: DE-FG02-99ER54527

Introduction

UCLA, as an active NSTX-U team member, is contributing to the research priorities of NSTX-U with innovative, cross-cutting measurement techniques applied across a broad range of research topics. In particular, UCLA has developed two diagnostic systems, a 16 channel array of reflectometers and a 288 GHz polarimeter that will be used to significant effect in NSTX-U. These diagnostics will enable advances in areas such the study of fast-ion modes, turbulence and transport, and edge pedestal control. Working with Culham Research Fellow and recent UCLA graduate Dr. Jon Hillesheim, UCLA is also collaborating with MAST to adapt the reflectometer array for use as a Doppler Backscattering diagnostic (DBS). This would provide MAST with a unique measurement capability for spherical tokamaks (ST), the capability to probe intermediate-scale $(k_\perp \rho_s \sim 1-5)$ density fluctuations, bridging the gap between BES $(k_\perp \rho_s \leq 1)$ and high-k collective scattering. This innovative development of DBS opens up the possibility of bringing a similar capability to NSTX-U.

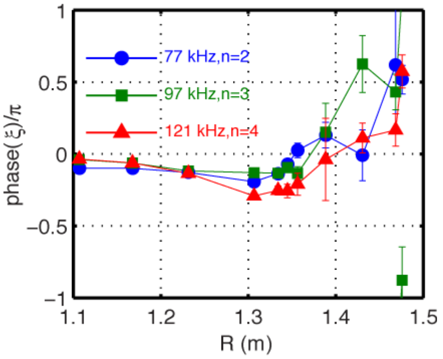

Figure 1: Phase of effective displacement of TAEs measured via reflectometer array [1].

Current research contributions to NSTX Upgrade

Fast-ion modes UCLA is contributing to the study of fast-ion modes in NSTX-U several ways. The reflectometer array consists of 16 fixed frequency reflectometers operating in the frequency range of 30 to 75 GHz. The system was operational in the 2010, permitting measurements of fast-ion mode structure in NSTX that contributed to several research priorities and guide the course of future research in NSTX-U. In particular, radial structure measurements were obtained for toroidicity-induced (TAE) [1], global (GAE) and compressional (CAE) Alfvén eigenmodes [1,2]. TAEs play a significant role in fast-ion transport and development of a predictive

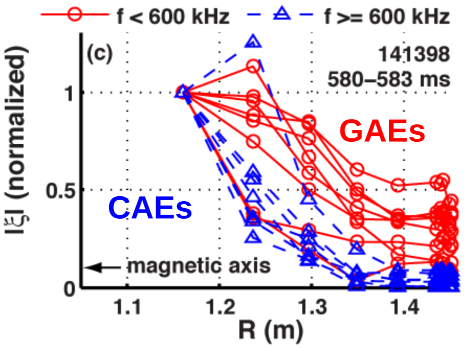

Figure 2: displacement (|ξ|) vs. R (normalized by |ξ| at R=1.16 m) for CAEs (blue) and GAEs (red). (Adapted from [2].)

capability is a high research priority for NSTX-U. GAEs and CAEs are of particular interest because they have also been implicated as possible cause of enhanced core electron thermal transport.

The measurements of TAE radial structure, which included both amplitude and phase contribute significantly to the ongoing development of a predictive capability for transport. The measurements show a radial phase variation (Fig. 1) that is not consistent with expectation from ideal MHD, a theory that has been notably successful in predicting TAE structure in other cases [3,4]. This brings into question the limits of ideal MHD theory in predicting TAE structure. These measurements are currently being compared with calculations using M3D-K, a code that models a kinetic fast-ion population coupled to an MHD plasma [4]. The initial results are promising.

The measurement of CAE and GAE structure has had a significant impact in the investigation of the enhanced core thermal electron transport that has been observed to correlate with high frequency Alfvén eigenmode activity [5]. The amplitude and structure of CAEs and GAEs were measured in a high power, beam heated H-mode plasma similar to those in which the correlation was observed (Fig. 2) [1,2]. The measurements facilitated identification of the modes, allowing the CAEs to be distinguished from the GAEs. The two types of modes affect electron orbits differently, which must taken into account when making a theoretical prediction of transport for comparison with the experiment. Such modeling, which has previously considered only GAEs [6], is currently being adapted to consider CAEs as well.

Plasma Turbulence and Transport UCLA is contributing to the study of plasma turbulence in NSTX-U in several ways. The reflectometer array has been used to investigate edge turbulence in NSTX, where it has helped to advance understanding of H-mode edge stability and pedestal structure. In particular, it was used to measure the evolution of turbulence correlation length in the plasma edge during the ELM cycle [7]. With these results in conjunction with other measurements, it was possible to show that spatial scales at the pedestal top are found consistent with ion-scale microturbulence propagating in the ion diamagnetic direction and to make comparisons with gyrokinetic simulations.

Pedestal control UCLA is also contributing in the area of pedestal control. The reflectometer array has provided measurements of edge harmonic oscillation (EHO) mode structure [8] that help to motivate a possible technique for ELM suppression. The EHO is thought to be capable of suppressing ELMs, but only at larger amplitude than the internally driven (i.e. unstable) EHO that is experimentally observed. Modeling shows that the HHFW antenna can be used at low frequency (~ 5 kHz) to externally drive a large amplitude perturbation with a structure similar to that measured with the reflectometers.

Polarimeter Development UCLA has made significant progress preparing a 288 GHz polarimeter for operation on NSTX-U [9]. The polarimeter can monitor magnetic fluctuations inside the plasma, with applications to wide ranging research priorities including the study of fast-ion driven modes and neoclassical tearing modes. Another promising area of application for the polarimeter is the investigation of microtearing modes, which potentially play a significant role in electron thermal transport. UCLA graduate student Jie Zhang recently submitted a manuscript to Plasma Physics and Controlled Fusion showing synthetic diagnostic modeling using gyrokinetic simulations performed by Dr. Walter Guttenfelder of PPPL that demonstrate the polarimeter is sufficiently sensitive to detect microtearing modes in NSTX-U [10]. Another possible application for the polarimeter is to provide feedback in plasma control scenarios involving 3D fields by gauging the plasma response to the externally applied fields. Mr. Zhang has begun initial efforts working with Dr. Michael Van Zeeland of DIII-D to assess the polarimeter response to externally applied fields using M3D simulations.

Originally constructed for installation in NSTX in 2011, early commencement of the upgrade to NSTX-U prevented operation of the polarimeter. In preparation for NSTX-U, the polarimeter was installed on DIII-D for testing over a wide range of conditions similar those planned for NSTX-U. The polarimeter phase was measured for a large range of toroidal magnetic field (0.5 – 2 T), plasma current (0.3 & 1.0 MA) and line average density (0.95 & 1.7 x 10^{19} cm^{-3}). Plasma height was also varied substantially (± 20 cm, or ~ 25 % of the plasma vertical extent) to test the polarimeter under conditions where the polarimeter chord is far from the plasma midplane. The polarimeter measurements were compared with predictions from a synthetic diagnostic that models millimeter-wave propagation in the plasma, using EFIT equilibrium reconstructions and density profiles determined via Thomson scattering and the CO_2 interferometer. Good agreement was found over this broad range of conditions, including conditions where Faraday Rotation (polarization rotation due to B parallel to propagation) was the dominant effect and conditions where polarization was strongly influenced by the Cotton-Mouton effect (elliptization due to B transverse to propagation).

Collaboration with MAST – DBS development UCLA is collaborating with MAST, working with Culham Fusion Research Fellow and recent UCLA graduate Dr. Jon Hillesheim to adapt the UCLA reflectometer array for use as a DBS diagnostic, as well as utilize it for conventional reflectometry. (The array will be returned to NSTX-U for installation in 2014.) Doppler backscattering uses millimeter waves launched oblique to the cutoff surfaces to probe intermediate-scale ($k_\perp \rho_s \sim 1 - 5$) density fluctuations and plasma flows. These scales include trapped electron modes (TEM) and possibly extend into the electron temperature gradient (ETG) mode regime. The launched radiation backscatters from intermediate-scale turbulence with a Doppler shifted imparted by the propagation of the turbulence. The velocity of the turbulence is typically dominated by ExB flow of the background plasma, allowing E to be inferred, while the backscattered power provides information about density fluctuation amplitude, both with good spatial (Δr < 1 cm) and temporal (Δt < 1μs) resolution. DBS has been deployed on numerous standard tokamaks, but, to date, has seen limited use in a spherical tokamak, and only in the extreme edge. The proposed collaboration would therefore provide MAST with a unique measurement capability for STs. There are currently no diagnostics for core turbulence at intermediate scales in MAST, or planned for NSTX-U. UCLA is currently exploring options to develop a DBS system for NSTX-U, so the lessons learned on MAST will be beneficial to future research efforts. The DBS measurements of plasma flows would also add powerful measurement capabilities to MAST, as well as NSTX-U if implemented there. Similar multichannel DBS systems have provided data for studies of geodesic acoustic modes [11] and zonal flows during the L-H transition [12]. The system will also be configured to operate as a conventional reflectometer while at MAST, enhancing MAST's capability to investigate fast-ion driven modes and fast-ion transport, allowing comparison with previous NSTX results in preparation for NSTX-U operation.

Summary of proposed research plan for 2014-18

The reflectometer array and polarimeter will be installed on NSTX-U for the start of plasma operations in late 2014. The polarimeter will be utilized in experimental investigation of microtearing modes and may also provide feedback for plasma control scenarios that involve the application 3D fields, such RWM control, ELM control, pedestal control through active EHO excitation. The reflectometer array will be exploited to further investigate edge fluctuations such as ELMs, EHOs and ion-scale turbulence in the pedestal with the goal of facilitating pedestal control. Both systems will be employed in the investigation of fast-ion driven modes. Integration of their measurements with density fluctuation and poloidal flow measurements obtained via BES will provide a powerful tool for validating the predictions of codes such as M3D-K.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Continue investigation of EHOs. Contribute reflectometry analysis to on-going investigation of ELMs and ion-scale pedestal turbulence.
- Continue integration (started FY2013) of CAE and GAE mode structure measurements with particle orbit code (ORBIT) to develop capability to predict electron thermal transport from mode structure measurements.
- Install polarimeter and reflectometers in anticipation of plasma operations in FY2015.

FY2015:

- Begin integrating mode structure diagnostics with fast-ion mode simulation (M3D-K, NOVA-K) and fast-ion orbit codes (ORBIT, SPIRAL) to predict transport based on measured mode structure. Begin comparisons with fast-ion population diagnostics (FIDA).
- Investigate fast-ion mode spectrum with new neutral beams.
- Exploit polarimeter to investigate coherent magnetic fluctuations (e.g. fast-ion modes) and microtearing modes. Assess potential for feedback in plasma control scenarios with 3D fields.
- Develop analysis techniques to integrate mode structure diagnostics (BES, reflectometers and polarimeter). Compare results with M3D-K and NOVA-K. Assess limits of ideal MHD theory.
- Investigate edge fluctuations (ELMs, pedestal turbulence, EHO) in new parameter regime. Contribute to development of pedestal and plasma control scenarios.
- Based on DBS development at MAST, aggressively pursue options to implement at NSTX-U

FY2016:

- Investigate changes in fast-ion mode spectrum at increasing I_P and B_T and in 3D fields.
- Investigate of CAEs and GAEs and their role in electron thermal transport at increasing I_P and B_T.
- Investigate edge fluctuations in new parameter regime.

FY2017-FY2018:

- Continue developing capability to predict of fast-ion transport from measured mode structure. Integration mode structure measurement and resulting fast-ion transport predictions with model of plasma and fast-ion population (TRANSP). Compare with fast-ion population diagnostics.
- Continue investigation of CAEs and GAEs and development of predictive capability for electron thermal transport from mode structure measurements.
- Continue investigate edge fluctuations and contribute to development of control scenarios.

Contributions to the NSTX-U 2014-18 Five Year Plan:

The cross-cutting research plan above contributes to multiple Topical Science Groups (TSG), including Waves and Energetic Particles (WEP), Turbulence and Transport (T&T), Boundary

Physics and Macroscopic Stability, whose contributions to the Five Year Plan are discussed in chapters 6, 3, 4 and 2, respectively. The plan above was defined in a process performed over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan, with the perhaps most significant focus in the areas of Waves and Energetic Particles and Turbulence and Transport. A central goal of the WEP is the development of a predictive capability is the construction of reduced models for prediction of fast-ion-mode-induced fast-ion transport. Several aspects of the plan presented here related to fast-ion mode structure and magnetic fluctuation measurements directly address this goal. Several aspects of the plan related to investigation of microtearing modes and the role of CAEs & GAEs in electron thermal transport also advance the mission of the T&T to investigate the cause of electron thermal transport.

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11.2.22 University of Illinois

Research Topic: Enhanced Lithium Pumping in the RLLD via LiMIT
Principal, Co-Principal Investigators: David Ruzic (PI/PD), Daniel Andruczyk (Co-I.)
Participating Scientists:
Participating Post-docs: 1
Participating Graduate Students: Wenyu Xu, Soonwook Jung, Peter Fiflis, Mike Christiansen
Participating Undergraduates: 10
Funded under DOE Grant: DE-SC0008587, DE-SC0008658, DE-ER54515

Introduction

There are many concerns that exist about the ability of divertor components to scale from the current limits of tungsten divertors (~5 MWm^{-2}) to much higher heat loads as may be expected in devices beyond ITER (>20 MWm^{-2}). Even current flowing liquid lithium divertor concepts, while alleviating many of the issues associated with solid divertors, may not be able to “take the heat” under conventional thinking. This thinking limits the operating temperature of the lithium to below 400 ^{o}C to avoid lithium evaporation. Once this restriction is relaxed, however, operation at much higher heat fluxes may be accessible. By taking advantage of liquid lithium in a radiative liquid lithium divertor (RLLD), large heat fluxes to the divertor may be distributed over a much wider area of the device [1]. As currently envisioned, the RLLD would utilize external pumps to move a small volume of liquid lithium through the device. In order to decrease the amount of power required for these pumps, it is proposed to propel the lithium through the RLLD via a LiMIT device [2], developed at the University of Illinois at Urbana-Champaign (UIUC), which would utilize TEMHD to pump lithium through the RLLD without the need for a mechanical pump. We have had direct experience working on NSTX in the past. The Langmuir probe array embedded in the LLD was an Illinois project staffed by an Illinois research engineer on site at PPPL.

Current research contributions to NSTX Upgrade

The Center for Plasma Material Interactions (CPMI) at UIUC are currently contributing to NSTX-U campaign in several ways:

1. Characterization of liquid lithium as a plasma facing component material. CPMI have provided data on both the material properties of liquid lithium and its compatibility with various materials.
    a. Thermoelectric properties of fusion relevant materials (stainless steel, tungsten, molybdenum, tantalum) have been performed as well as lithium and other potential liquid metal candidates such as tin [3].
    b. Wetting properties of lithium and tin with fusion relevant materials such as stainless steel, tungsten, molybdenum and tantalum have been characterized [4].

    c. With NSTX-U being mainly a carbon machine, understanding the plasma interactions with graphite and lithium covered graphite is of great importance. UIUC has been conducting studies in the IIAX device to better understand these interactions for NSTX-U [5].
2. Illinois is also providing support of the lithium dripper and granular injector systems. A theory for the formation of liquid metal droplets has been developed and initial experiments with a simple injector at UIUC and PPPL have been performed [6].
3. CPMI is embarking on the development of a new innovative liquid divertor PFC that can withstand high heat fluxes. This is based on the LiMIT concept. Thermoelectric-Driven Liquid-Metal Plasma-Facing Structures (TELS) [7] will extend the work that has been done at CPMI in four ways:
    a. Develop, refine and test new geometries for thermoelectrically driven structures that would be more relevant for fusion devices such as NSTX-U.
    b. Expansion of the Illinois pulsed and continuous systems so that pulsed plasma heat loads impinge on a surface that already has a continuous heat load.
    c. Increase the magnetic field to make it more relevant to fusion type environments that will be seen in NSTX-U.
    d. Study alternate PFC materials such as tin-lithium eutectics that may be relevant for fusion in the future.

    TELS will be built and tested at UIUC and is based on LiMIT, SLiDE and DEVeX and will investigate prototype designs for the RLLD that will be developed for NSTX-U.

Summary of proposed research plan for 2014-18

We propose to enhance the flow of liquid lithium through a RLLD for NSTX-U by utilizing TEMHD to actively pump the lithium. By combining experimental and modeling efforts, we propose to design and test a LiMIT style device to utilize TEMHD to achieve the aforementioned effect. Previous modeling efforts have made gains in determining the heat transfer within the device as well as the flow of the liquid lithium [8], and experiments both at the University of Illinois, and on HT-7 have demonstrated the viability of such a device [9]. Therefore, we propose to collaborate with the NSTX-U team on designing and implementing a LiMIT device for use in an RLLD system for NSTX-U.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Continue modeling efforts into the heat transfer and fluid flow of the LiMIT device.

- Continue experimental characterization of the LiMIT device under a variety of operating conditions.

FY2015:

- Using experimental and model data, design ideal LiMIT device for incorporation into the RLLD system
- Test viability of design with experimental capabilities at UIUC

FY2016:

- Continue testing of design viability, particularly under extreme (accident) conditions
- Begin construction of practical device for inclusion into the RLLD

FY2017:

- Installation and testing of the LIMIT-like RLLD and other flowing lithium test structures for NSTX-U
- Station a Research Engineer at PPPL to aid in operations and data analysis
- Work at Illinois on technological needs that arise.

FY2018:

- Station a Research Engineer at PPPL to aid in operations and data analysis
- Work at Illinois on technological needs that arise. Start design of next upgrade.

Contributions to the NSTX-U 2014-18 Five Year Plan:

The plan listed above is to install a LIMIT-like lithium delivery system to the RLLD. It has the advantages of being self-pumping and always presenting a clean fresh lithium surface to the heat flux. This is superior to other designs and much simpler. Illinois stands by to help with the design, engineering, assembly, testing and analysis of such a device.

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11.2.23 University of Tennessee, Knoxville (UTK)

Research Topic: Study of poloidal asymmetries of lithium coatings
Principal, Co-Principal Investigators: B. D. Wirth (PI/PD), R. Maingi (Co-I.)
Participating Scientists:
Participating Post-docs: A. Bortolon
Participating Graduate Students: 1
Participating Undergraduates: 0

Introduction

The development of stationary, high performance, long-pulse plasmas is stated as a high programmatic objective of the NSTX upgrade [1]. Previous experiments on NSTX demonstrated the beneficial effect of lithium coating in terms of energy confinement, profile peaking and ELM frequency. The use of lithium coating will remain a key element of the NSTX-U operation.

However, open questions remain as to which mechanisms govern the effectiveness of lithium coating and in particular the incremental improvements with amount of evaporated lithium [2]. The main objective of the UT-K program on NSTX-U is to evaluate the how the effectiveness of lithium evaporation is affected by poloidal and toroidal asymmetries of lithium coatings. To achieve this, the proposal entails installation of new diagnostics and leadership/participation in relevant experiments, as well as key modeling of the obtained data. The UT-K program grant was initiated in July 2012, with an annually renewable program through June 2016. Note that there is a strong synergy between the UT-K program and the ORNL boundary collaborative program on NSTX-U, with sharing of hardware and expertise.

To enable this study a new set of diagnostics are being be deployed, that will provide NSTX-U with spatially and spectroscopically resolved measurements of the previously un-sampled regions of the upper divertor and central stack wall. In addition, new infrared camera views of the same regions will ensure the heat flux measurements required as constraints for interpretative modeling. The improved diagnosis of the upper divertor will become increasingly important during the five-year plan as NSTX heating and pulse lengths are increased to full capability.

The novel measurements will permit to track the evolution of emission by different impurities (C, Li) from various regions of the wall. This will allow to study phenomena as lithium distribution, lithium migration and re-deposition, surface carbon-lithium chemistry and, ultimately, to assess the impact of each of these mechanisms on the effectiveness of lithium evaporation.

The added diagnostic capabilities will also support a range of other critical plasma boundary interface issues, including particle and heat sharing between the upper and lower divertors, as NSTX-U will employ more routinely the standard double null and “snowflake” configurations for power handling. The diagnostic will also be useful to study impurity migration when high-Z tiles will introduced as part of plasma facing components.

To accomplish the collaboration mission, interpretative 2-D modeling of the plasma boundary is envisioned, in particular using the SOLPS code as used in previous interpretive edge studies [3]. This will be coupled to an effort to model the dynamical evolution of the plasma facing material with first principle simulations.

Current research contributions to NSTX Upgrade

The near-term effort is predominantly devoted to the design and construction of the new diagnostics.

The spectroscopic emission from plasma facing surfaces away from the lower divertor will be collected into fiber optics by two different optic assemblies, providing 16 view-lines focused on the upper divertor region and 16 on central stack tiles. The spectral analysis is performed the acquisition room far from the experimental hall, by a multichannel, high-throughput, high dispersion spectrometer, equipped with a CCD detector. The use of broad band transmission components ensures the possibility to observe and track the evolution multiple impurity lines in the visible-UV range of wavelengths.

Two new infrared cameras will monitor the tile temperature and heat deposition in the upper divertor and central stack. The use of lithium in NSTX-Upgrade requires that dual-band adapters be implemented, as presently used on the lower divertor, fast IR camera [4]. The center stack camera will likely be a standard 30 Hz or 60 Hz camera. The upper divertor camera is intended to be a similar camera, but may be superseded by a fast, dual-band IR camera planned by ORNL. In this case, UT-K staff will share responsibility for operation and data analysis with ORNL staff.

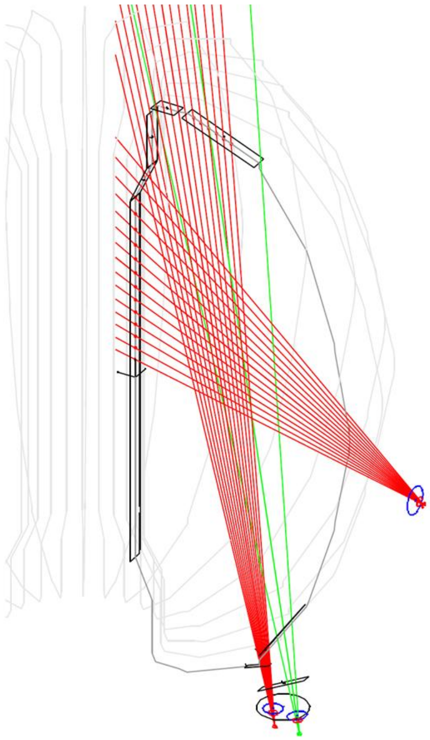

Figure 1 Schematic of view lines for the spectroscopic observation of upper divertor and central stack of NSTX-U (red). Field of view the fast IR camera (green).

Presently, the conceptual design of the diagnostics described above is complete, and the main equipment elements are being acquired (spectrometer, fibers, lenses). Dedicated port access has been allocated, including two bottom windows (bay G) and two mid-plane windows at (bay J). A schematic of the observation geometry is shown in Figure 1.

Summary of proposed research plan for 2014-18

The research plan requires a first phase with high priority to the diagnostic installation (2014-2015), commissioning and operation. Along with the availability of validated data from the new diagnostics and with the establishment of the NSTX-U operation, the emphasis will shift on designing and performing plasma experiments dedicated to the scope of the collaboration, i.e. the study of the effectiveness lithium evaporation (2015-2016). At the same time, with the support of one graduate student, the plasma and material modeling effort will begin and to allow a proper the interpretation of the experiments (2016-2018).

Timeline

2014-2015:

- Finalize construction installation of spectroscopy diagnostic (collection optics, fiber bundles, spectrometer) and IR cameras (1 fast, 1 slow).
- Diagnostic calibration and alignment.
- Diagnostic commissioning and integration into NSTX-U acquisition system.
- Document first data from upper divertor and central stack.

2015-2016:

- Support NSTX-U activity with installed diagnostics.
- Perform dedicated plasma experiments to study poloidal distribution of Li coating in different divertor magnetic configurations.
- Apply plasma boundary modeling (SOLPS) to newly acquired data.

2016-2018:

- Upgrade the slow IR camera (25 Hz frame rate) to a fast IR camera (1 kHz frame rate).
- Model dynamic response of materials, using SOLPS plasma solutions.
- Assess the effect of poloidal variation in lithium deposition on plasma performance.

Contributions to the NSTX-U 2014-18 Five Year Plan:

Vlad Soukhanovskii, Ahmed Diallo, and Rajesh Maingi are the present leaders of the Boundary Physics topical science group and are responsible for overseeing the Boundary Physics chapter of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Boundary Physics topical science group and contributes heavily to the 5 year plan.

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11.2.24 University of Washington, Seattle

Research Topic: Solenoid-free current start-up with CHI and current ramp-up using NBI and RF

Principal, Co-Principal Investigators: Thomas R. Jarboe, Roger Raman

Participating Scientists: B.A. Nelson, D. Mueller, S.C. Jardin, C. Kessel, F. Poli, E.B. Hooper, F. Ebrahimi from Univ. of Washington, PPPL, LLNL and Univ. of New Hampshire

Funded under DOE Grant: DE-FG02-99ER54519 [T.R. Jarboe, R. Raman]

Introduction

Our plans are to continue to develop solenoid-free plasma start-up and current ramp-up on the NSTX-U using Coaxial Helicity Injection (CHI), originally developed on the HIT-II device at the University of Washington, and then to ramp-up the current produced by CHI using neutral beams and HHFW.

Transient CHI first developed on the HIT-II ST at the University of Washington was, then tested and further improved on the much larger NSTX device at PPPL [1,2,3]. These results coupled with recent simulations with the TSC code [4] have revealed many important aspects of CHI physics and its application to future machines. The key results are briefly summarized below.

- NSTX and HIT-II, two machines of vastly different size (NSTX plasma volume is 30 times that of HIT-II), have both achieved significant levels of start-up current through CHI. 300 kA start-up current has been demonstrated on NSTX [5,6,7].
- On NSTX, the method is highly efficient, producing more than 10 Amps/Joule of initial stored capacitor bank energy.
- The scaling to larger machines with higher toroidal field is quite favorable: NSTX achieves 10 times the current multiplication factor of HIT-II. Current multiplication is defined as the ratio of the CHI produced plasma current to injected current, which is over 50 in NSTX.
- In addition, the CHI generated plasmas on NSTX have desirable properties including low normalized internal inductance of 0.35, low electron density and low impurity content, as needed for subsequent non-inductive current ramp-up using NBI and RF waves.
- Simulations with the TSC code show agreement with the theoretical prediction for CHI as it is scaled to larger machines.

Current research contributions to NSTX Upgrade

Enhanced system capabilities for CHI on NSTX-U and our plans are:

- NSTX-U is planned to have 1 MW ECH capability that would increase the electron temperature of the CHI target as needed for direct coupling to neutral beams.
- Factor of two increase in the toroidal field which further increases the current multiplication factor and allows more poloidal flux to be injected at a given injector current.
- The injected poloidal flux capability in NSTX-U is more than 2.5 times that in NSTX. Because the generated plasma current magnitude is proportional to the injected poloidal flux, this would allow NSTX-U to generate well in excess of 400 kA start-up current, enough so that, neutral beams can efficiently couple to the plasma discharges.
- The CHI system operating voltage on NSTX-U will be increased from 1.7 kV in NSTX to up to 3 kV on NSTX-U. This should greatly improve CHI start-up capability in NSTX-U, as this increased voltage will allow more poloidal flux to be injected.
- NSTX-U will have capability for a second (new) 6 MW tangential neutral beam system that is well suited for driving current in the plasma. TSC simulations show that current ramp-up to the steady-state sustainment levels should be possible starting from an initial current level of less than 400 kA. Thus CHI has an adequate margin for the initial seed current magnitude.
- NSTX-U will incorporate metallic divertor plates, which should further improve plasma start-up by CHI by reducing low-Z impurities.

Summary of proposed research plan for 2014-18

We will establish transient CHI discharges in NSTX-U. These discharges will then be coupled to induction to assess flux savings and to compare with results from NSTX. CHI-started discharges will be heated using 28 GHz ECH to increase its electron temperature. These discharges will be further heated using HHFW. The RF heated CHI discharges will be ramped up in current using neutral beams for a demonstration of full solenoid-free current start-up and non-inductive ramp-up. In other experiments we will drive edge current in pre-established lower single null discharges and assess current penetration to the interior with and without the presence of edge magnetic fluctuations imposed by the NSTX-U non axis-symmetric coils.

In support of these experiments we will continue to use the TSC/TRANSP codes for simulating plasma start-up and current ramp-up. Plasma start-up simulations conducted with TSC/TRANSP will be used for establishing the initial transient CHI start-up discharges in NSTX-U. We are also working with E.B. Hooper (LLNL) and F. Ebrahimi (Univ. of New Hampshire) in developing a NIMROD model of NSTX/NSTX-U CHI start-up discharges. Towards the later part of the 5YR plan, we plan to use simulations from these codes in a predictive mode initially to support

NSTX-U research and later for understanding the requirements for solenoid-free plasma start-up and current ramp-up using CHI in a FNSF.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Continue analysis of NSTX CHI data and conduct TSC/TRANSP simulations to develop CHI start-up and current ramp-up scenarios for NSTX-U.
- Design a CHI system for the Quest ST in Japan to obtain additional information of CHI scaling with machine size.

FY2015:

- *Plasma start-up:* Establish transient CHI discharges using graphite lower divertor tiles, up to 0.8 T capability of NSTX-U, and full Li coating of the lower divertor tiles. Using the 2 kV capability of the CHI capacitor bank, assess maximum toroidal currents that can be generated by increasing the amount of injector flux and the size of the capacitor bank. Use the upper divertor buffer coils to suppress arcs.
- *Coupling to induction:* Couple the CHI generated plasma to inductive drive to show compatibility with inductive operation. Use a solenoid with zero pre-charge.

FY2016:

- *Plasma start-up:* Improve the magnitude of the closed flux CHI produced current by using Li coating of the upper divertor to further reduce the influx of low-Z impurities. The objective is to improve on the results from YR1 and to obtain 400 kA of closed flux plasma current that is suitable for meeting the needs for satisfying Thrust 2 during YRs 3-5. Compare to and improve the NIMROD simulations.
- *Coupling to induction -1:* Extending on the work from YR1 establish the flux savings that can be realized using the above plasma start-up target and with zero pre-charge in the central solenoid.
- *Coupling to induction -2:* Conduct an initial test of coupling to induction using 10 – 20% solenoid pre-charge. The goal is to use some solenoid flux to increase the magnitude of the generated plasma current, but by ramping the current in the solenoid to zero, so that it can be maintained at zero during sustained non-inductive operation.
- *Assess coupling to NBI:* In CHI discharges that are weakly driven by induction, measure and increase the magnitude of the neutral beam driven toroidal current. Compare these results to simulations using the TSC code that uses TRANSP to calculate the neutral beam power deposition profile and neutral beam current drive.

- *Edge current drive:* To a pre-formed lower single null discharge, apply a current pulse using the CHI capacitor bank and measure the presence of any edge driven current and the resulting changes to the edge current profile.

FY2017:

- *ECH heating of CHI discharge:* Heat a CHI started plasma using ECH both to demonstrate heating and a longer current decay time to provide a better target for NBI.
- *Plasma start-up:* Maximize the levels of CHI produced plasma currents using the new capabilities that will be available during YR3. These are (1) metal divertor plates, (2) 1 MW ECH, and (3) 2.5-3 kV CHI capability. All these should allow more injector flux to be injected into the vessel at reduced levels of low-Z impurities. If results are available from Quest, compare with Quest results to understand any differences between the two machines.
- *Couple CHI to NBI:* Using the best available CHI targets, conduct an initial test of the effectiveness of NBI coupling to a CHI generated target.
- *Couple to induction:* Couple to induction using the maximum possible solenoid pre-charge CHI allows. Ramp the solenoid current to zero, maintain the solenoid at near zero current, and test establishment of a >600kA high temperature plasma target for use by other TSGs for sustained non-inductive operation.
- *Edge current drive:* Based on YR2 results, to a pre-formed lower single null target, apply a current pulse using the DC power supplies to extend the magnitude and duration of the edge current pulse, and measure changes to the edge current profile, edge current penetration to the interior and changes to the plasma MHD stability limits, with and without the presence of edge magnetic fluctuations imposed by the non axis-symmetric coils.

FY2018:

- *Plasma start-up:* Maximize the levels of CHI produced plasma currents now also using the new cryo pump and assess its effectiveness in suppressing absorber arcs. Validate NIMROD simulations on CHI plasma start-up using NSTX-U results and begin to develop a NIMROD model for FNSF.
- *Couple CHI to NBI:* Using the best available CHI targets, ramp a CHI started discharge to 1 MA using a combination of NBI and bootstrap current over drive. Use experimental results to improve the NBI current drive model in NIMROD simulations.

- *Plasma start-up:* Compare results obtained from NSTX with other recent results from Quest. Of the more than 300 mWb of injector flux that is available in NSTX-U determine the maximum levels that are usable and use these results for CHI design studies for a FNSF. Use these results to improve the TSC model for FNSF

Contributions to the NSTX-U 2014-18 Five Year Plan:

R. Raman is the present leader of the Solenoid-free Plasma Start-up and Current Ramp-up topical science group and is responsible for overseeing chapter 8 write-up of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan.

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11.2.25 University of Washington, Seattle

Research Topic: Disruption Mitigation Studies on NSTX-U
Principal, Co-Principal Investigators: Roger Raman, Thomas R. Jarboe
Participating Scientists: D. Stotler (PPPL)
Participating Graduate Students: T. Abrams (PPPL)
Funded under DOE Grant: DE- SC0006757 [R. Raman, T.R. Jarboe]

Introduction

At present, MGI (Massive Gas Injection) is the most promising method for safely terminating disruptions in ITER. On ITER, because of the large minor radius of the device, the long transit times for the slow moving neutral gas, and the large scrape-off-layer flows, it is not known if a simple MGI pulse would be adequate for securely terminating an ITER discharge. While MGI experiments are being conducted at a number of tokamak facilities, the impact of varying the poloidal injection location has not been adequately studied, and injection into the private flux region has not been studied.

Additional insight into ways for reducing the total amount of injected gas and appropriate injection locations would further help optimize the MGI system for ITER. NSTX-U can offer new data by injecting gas into the private flux region and into the lower X-point region to determine if this is a more desirable location for massive gas injection.

Current research contributions to NSTX Upgrade

Injection from the private flux location has two advantages. First, the gas does not need to penetrate the scrape-off-layer region. Second, because the injection location is located near the high-field side region, the injected gas should be more rapidly transported to the interior as known from high-field side pellet injection research and from high-field side gas injection on NSTX-U. By comparing gas injection from this new location to results obtained from injecting a similar amount of gas from the conventional outer mid-plane region and from other poloidal locations, NSTX-U results on massive gas injection can provide additional insight and a new set of database for improving computational simulations and add new knowledge to disruption mitigation physics using massive gas injection.

With the help of D. Stotler (PPPL) and T. Abrams (PPPL), we are also modeling the gas penetration physics using the DEGAS-2 code [1,2,3]. The present plans are the determine the optimum injection location for NSTX-U and eventually to have the system on stand-by so that it could be automatically triggered based on sensor information that predicts an impending disruption. Such capability is also needed for a future ST based FNSF.

We are also developing (for NSTX-U) a new system for safely terminating discharges in ITER. The system, referred to as an Electromagnetic Particle Injector (EPI) propels a coaxial projectile, containing particulate matter of various sizes and composition, in a coaxial electromagnetic rail gun, then shatters it prior to injecting a dust of particles into the tokamak.

At the recent US Disruption Mitigation Workshop (GA, March 12-13, 2012) it was concluded that although the Massive Gas Injection system is the best understood for safely terminating discharges in ITER, both the time response of this system and the controllability of the amount of gas and impurities injected by this system for variations in the initial plasma current at which a disruption initiates may be inadequate to fully rely on this system. It was decided that other faster acting systems should also be tested and developed. During this meeting, we presented the EPI concept. It was noted that this system was more complex as compared to a conventional gas gun, but no technical flaws were identified. It was also suggested that a proto-type should be built and tested before considering it for ITER. The system is described in more detail in Chapter 2 of the NSTX 5YR plan document.

Summary of proposed research plan for 2014-18

We will install Massive Gas injectors at four poloidal locations on NSTX-U and measure the gas penetration efficiency and the thermal and current quench time scales when the poloidal gas injection location is varied. Reduction to divertor heat loads during normal and MGI forced disruptions will be measured. Eventually, the plan is to trigger these valves using sensor provided data of an impending disruption. We will also build and test an Electromagnetic Particle injector on NSTX-U in support of ITER research.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Model gas penetration through the SOL using DEGAS-2
- Design, build, test and install new MGI valves for NSTX-U
- Design, build and test the EPI injector for NSTX-U

FY2015:

- Using a low triangularity discharge, we will compare massive gas injection (using a combination of deuterium and helium) of gas injected into the lower X-point and private flux region to that from the vessel mid-plane.
- The shape of the plasma will be varied to make it highly triangular so that the outer strike point rests on the inner divertor plate and at a radius less than the radius of the gas

injection port. Gas will then be injected into the scrape-off-layer region near the divertor, which is now located in a region of high toroidal field. This injection location will be compared to mid-plane injection to understand the effects of gas penetration through the scrape-off layer that is located in regions of high vs. low toroidal field. The same combination of deuterium and helium will be used for these experiments to compare these results to those for the low triangularity discharges.

- During the first year of NSTX-U operations, much of the MGI studies will use a combination of deuterium and helium primarily to gain experience in conducting these studies on NSTX-U for the first time and to commission the diagnostics that will support MGI studies. Towards the end of YR1 operations we will conduct some tests in which neon is introduced as an additional impurity gas in the deuterium/helium gas mix used above to gain experience with the use of high-Z gas and to develop experiments for YR2 that will begin to use high-Z gasses.

FY2016:

- Based on YR1 results, a desired fraction of neon (in a combination of deuterium/helium carrier gas) will be used for all subsequent comparison experiments to be conducted this year.
- We will compare: (1) the gas transit and system response times, (2) propagation time for the cold front to reach the q=2 surface, (3) the amount of gas required for initiating a rapid thermal quench and (4) symmetry of the radiated power profile.
- We will simultaneously inject gas from three locations (bottom, mid-plane and top) to see if a cold mantle could be continually maintained around the disrupting plasma, and assess the benefits of multiple injection location for reducing localized radiation thermal loading.
- Finally, towards the end of YR2 operation, for a chosen condition from the YR2 experiments, neon will be replaced with argon to assess the benefits of each of these gases and to select the gas combination for YR 3 experiments.
- The primary objective for the EPI system during Year 2 (but before the end of FY2016) is to assess the EPI injector system's capability to initiate a forced thermal quench in less than 10ms after the system is triggered. This is for assessing its potential to meet ITER needs.

FY2017:

- Quantify the gas assimilation fraction for variations in the gas injection location and compare to DEGAS-2 modeling results. Assess if a full DEGAS-2 model is required for future work.

- Assess reduction in divertor heat loads and reduction in divertor halo currents for variations in the gas injection location.
- Measure asymmetries in the radiated power profile for variations in the gas injection location and for simultaneous gas injection from multiple locations.
- Obtain additional measurements using the EPI system to assess its benefits over the MGI system.

FY2018:

- Inject MGI at different times into a discharge in which the q-profile is evolving to understand the importance of the location of the q=2 surface to the plasma edge.
- For a high-powered NSTX-U discharge compare the thermal quench rates and the current quench rates for forced disruptions using MGI and EPI.
- We will work with groups using NIMROD, KPRAD, and if possible the EIRENE-SOLPS codes to simulate NSTX-U experimental observations. This is work will have been initiated during Year 1 of NSTX-U operations.
- Continue to include the NSTX-U MGI and EPI data into the ITER database to contribute to the continued understanding of these systems for ITER, future tokamaks and STs.
- We will trigger the MGI system based on sensor provided data on an impending disruption. Additionally, we will determine if the DM control system is capable of triggering a specific MGI valve based on the plasma configuration (i.e., downward vs. upward moving disruption)

Contributions to the NSTX-U 2014-18 Five Year Plan:

J.K. Park is the present leader of the Macro Stability topical science group and is responsible for overseeing chapter 2 of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes heavily to the plan.

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11.2.26 University of Wisconsin-Madison

Research Topic: Investigations of Long-Wavelength Turbulence and Instabilities in the Spherical Torus

Principal, Co-Principal Investigators: G.R. McKee (PI), R.J. Fonck, (Co-PI)
Participating Scientists: D. Smith
Participating Graduate Students: D. Thompson
Funded under DOE Grant: DE-SC0001288

Introduction

The University of Wisconsin-Madison is collaborating with Princeton Plasma Physics Laboratory to develop an advanced, multi-channel Beam Emission Spectroscopy (BES) diagnostic system for measuring turbulence and other instabilities in NSTX plasmas [1]. The principle goals of this collaboration are continued expansion and operation of BES and future related diagnostics, performing focused transport experiments on NSTX-U, exploring the properties and dynamics of turbulence and related instabilities, and seeking to validate comprehensive simulations of core and edge spherical torus plasmas. Understanding the unique aspects of turbulence and other long-wavelength instabilities in high-pressure spherical torus plasmas is crucial to comparing with conventional tokamak plasmas, challenging models and simulations of the ST configuration, optimizing performance, and projecting to future experiment designs.

BES measures density fluctuations associated with long-wavelength turbulence, MHD modes, Alfvenic modes, and pedestal instabilities in the core, edge and scrape-off regions of NSTX plasmas. The NSTX BES system is an advanced, highly modernized diagnostic that employs customized viewing optics to match the steep pitch angles of spherical torus plasmas, high throughput fiber bundles, fast optics and custom interference filters, and a new generation of cooled low-noise preamplifiers and detectors that were developed at UW [2]. BES observes Doppler-shifted Balmer (D_α) emission (n=3-2, λ~658-660 nm) from collisionally-excited neutral beam fluorescence. Deuterium beams are injected into NSTX plasmas with an energy of E_b = 70-90 keV via three nearly collinear ~2MW tangentially-directed co-current neutral beam sources. The diagnostic is fully remotely operable and has demonstrated high reliability, functionality, and utility.

The scientific program is carried out primarily by a full-time UW scientist (Dr. D. Smith), who is located on-site at PPPL, and we anticipate that a graduate student will join the program in 2014 when NSTX-U begins operations. Other part time scientists and technicians at UW assist with diagnostic development and scientific analysis. This UW-PPPL collaboration aligns well with several major research elements of the NSTX program, DOE-FES goals, and supports a number of NSTX and JRT milestones.

Current research contributions to NSTX Upgrade

BES fluctuation measurements were acquired with an initial 16-channel and later 24-channel system for a wide range of experiments during the 2010-2011 NSTX operational campaigns [3]. 32 channels are currently deployed on NSTX, and 16 more are currently being developed at UW. The new channels will be deployed before the 2014 operations commence and will enable more comprehensive measurements of core, edge/pedestal and SOL fluctuation measurements.

Analysis to date has focused on the general characteristics of core and pedestal turbulence. Numerous valuable observations have been obtained that include: relatively long poloidal correlation lengths (~10-15 cm); strong suppression of turbulence in both the core and edge regions after an L-mode to H-mode transition; core-localized GAE modes that may drive electron thermal transport; TAE-mode bursts; pedestal-localized high-frequency coherent modes associated with ELM events in some H-mode conditions, long-wavelength pedestal turbulence [4], and edge fast-ion signals [5].

A comprehensive data base has been assembled that related pedestal turbulence properties, such as poloidal correlation lengths and wavenumber, decorrelation times, to pedestal parameters, including density, ion and electron temperatures, toroidal velocity, gradients therein, and radial electric field [6,7]. A model aggregation technique was used to determine the parametric dependencies between these turbulence and plasma parameters. General dependencies are found to be most consistent with trapped-electron mode, kinetic ballooning mode and microtearing modes [8], but not to ion temperature gradient modes. These dependencies are also consistent with turbulence regulation by flow shear. These results have been presented in major conferences and are submitted for publication. We will further develop and refine advanced analysis capabilities, including time-delay-estimation, velocimetry, and nonlinear techniques to more fully exploit the wealth of information available in these multipoint fluctuation data.

These results are being published in relevant plasma physics journals and are being presented at meetings and workshops, including: APS-DPP, Transport Task Force, High Temperature Plasma Diagnostics, IAEA-FEC, H-mode workshop, etc.; the new NSTX BES system is described in three publications by our group in Reviews of Scientific Instruments [1-3]. Of particular note, Dr. D. Smith presented an Invited Talk at the 2012 APS-DPP meeting, as well as an IAEA-FEC-2012 conference paper [7].

Summary of proposed research plan for 2014-18

We propose to develop and implement new diagnostic capability to enhance fluctuation diagnostic measurements at NSTX-U and exploit new experimental capabilities that will become available when NSTX-Upgrade is complete. The primary diagnostic goals are to:

- Increase the number of BES detection channels from 32 to 48
- Develop wide-field 2D turbulence imaging capability

A major component of this proposal is the expansion and enhancement of the BES system to allow for more comprehensive examination of turbulence and other instability properties in NSTX. The BES system will be expanded from 32 to 48 channels to allow for simultaneous core-to-edge sampling; this detector development is being be performed at UW.

A major diagnostic upgrade for this research program is to deploy 2D measurement capability for the outer region of the plasma to study turbulence and flow evolution during L-H transition, pedestal dynamics, instabilities across the ELM and in-between ELMs, as well as during ELM-suppressed or ELM-mitigated scenarios. Measurements to date have obtained radially and poloidally resolved density fluctuation measurements during this initial phase of operations to survey fluctuation characteristics. To exploit the radially and poloidally resolved measurement capability, and to explore the inherent 2D behavior of turbulence, we will deploy radially and poloidally resolved 2D measurement capability with BES. This will allow for several new scientific measurement capabilities that the present 1D configurations don't provide. These include:

- Modest spatial resolution, high-speed imaging of turbulent eddy structures.
- Radially resolved measurement of turbulence poloidal velocity, and velocity shear.
- Fully 2D correlation function, $\rho(r, \theta)$ and wavenumber spectrum: $S(k_r, k_\theta)$.
- Zonal flow structure
- Velocimetry (inferring 2D turbulence flow field)
- Nonlinear dynamics of turbulence-flow system

The pedestal region is unique for its high-pressure gradient, relatively narrow width, and high E_r shear. We will thus initially deploy a 2D viewing array in this edge region to probe the outer minor radius, separatrix and SOL region. We will explore with PPPL the feasibility of deploying a toroidally-displaced BES viewport on the new neutral beam to allow for toroidal mode number measurements of zonal flows and other low to medium-n instabilities.

We propose to perform a series of experiments to investigate the dependence and scaling properties of turbulence and transport. Parametric dependencies will be examined as a function of rotational shear, ρ^*, T_e/T_i, β_N (normalized plasma pressure), and, in combination with DIII-D, aspect-ratio. We will also investigate the effects of 3D radial fields on turbulence and the relationship between turbulence and pedestal modifications that drive or suppress ELMs, depending on stability properties of the pedestal. In addition to core turbulence and transport, we will investigate the eigenmode structure and behavior energetic-particle-driven instabilities such as Toroidal and Global Alfvén Eigenmodes, and examine edge instabilities that limit the height and width of the pedestal, and drive ELMs.

We will also run advanced simulations of core and edge plasmas (e.g., GYRO, GEM and BOUT++) to support testing and validation studies through comprehensive comparison of multiple measured turbulence properties with simulations. Performing BOUT++ simulations will bring new capabilities to the NSTX program at a time when there is significant focus on edge physics. This will advance the development of a validated predictive capability for transport in magnetically confined plasmas. In addition, we will seek to perform NSTX-relevant experiments on affiliated experiments, such as Pegasus, DIII-D and MAST that will support our future NSTX experiments.

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Implement 16 additional BES spatial channels (total to 48 channels)
- Deploy 2D channel configuration for edge viewing array (R140)
- Continue analysis of pedestal and core fluctuation characteristics
- Propose experiments to study core turbulence properties and dependencies as well as L-H transition dynamics

FY2015:

- Evaluate feasibility and design for a toroidally-displaced BES system
- Execute experiments on NSTX-U
- Continue analysis of L-H, pedestal and core fluctuation characteristics
- Bring a new graduate student to UW/NSTX-U collaboration

FY2016:

- Expand from 48 to 64 channels if resources become available
- Implement 2D core viewing array (R130)
- Continue analysis of L-H, pedestal and core fluctuation characteristics

FY2017:

- Deploy a high-resolution spectrometer for comprehensive beam emission spectral characterization

- Implement toroidally-displaced BES viewing optics, as feasible
- Continue analysis of L-H, pedestal and core fluctuation characteristics

FY2018:

- Continue analysis of L-H, pedestal and core fluctuation characteristics
- Consider deployment of UF-CHERS diagnostic for measuring ion temperature and toroidal velocity fluctuations for multifield turbulence studies
- Consider design and deployment of a low-coherence microwave backscattering diagnostic [9] for non-beam-based, high-resolution turbulence investigations

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11.2.27 University of Wisconsin - Madison

Research Topic: Test of Point-Source Helicity Injection for Non-Solenoidal Startup in NSTX

Principal, Co-Principal Investigators: R.J. Fonck (PI), A.J. Redd (Co-PI)
Participating Post-docs: M.W. Bongard
Participating Graduate Students: E.T. Hinson
Funded under DOE Grants: DE-FG02-96ER54375 and DE-SC0006928

Introduction

Local Helicity Injection (LHI) is a non-solenoidal plasma startup and current drive technique, similar in concept to Coaxial Helicity Injection (CHI), except that the injector is relatively compact, may be located anywhere at the plasma boundary, and can in principle be withdrawn after plasma startup. Current is driven on open field lines at the tokamak edge, injecting both power and magnetic helicity. Over relatively short timescales MHD activity incorporates this increased magnetic helicity as an increase in the toroidal plasma current. Experimental studies using the Pegasus Toroidal Experiment have demonstrated the formation and growth of more than 170 kA of plasma current, using only 4 kA of driven open-field-line current.

This technique appears to be scalable to a device of the scale of the NSTX Upgrade (NSTX-U) and beyond, and the conceptual design of a 1 MA startup system for NSTX-U is presently under development in an external collaboration with the Pegasus team. This collaborative activity encompasses the materials and technology in any deployed NSTX-U injector, a deeper understanding of the physical processes that guide the injector design, and development of realistic operating scenarios for LHI startup to the 1 MA level on NSTX-U. The goal of this collaboration is the conceptual design of a cost-effective MA-class LHI-based startup system for deployment on NSTX-U.

Magnetic helicity, as the name suggests, is a measure of the helicity of the magnetic field lines in a volume of interest, analogous to vorticity of flow in a standard fluid. In a toroidal magnetized plasma, the magnetic helicity measures the linkage between the toroidal and poloidal magnetic fluxes. In a tokamak, where the toroidal magnetic field is almost entirely generated by external coils, the magnetic helicity is approximately proportional to the toroidal plasma current I_p, and magnetic helicity injection is equivalent to toroidal current drive. Experimentally, magnetic helicity is “injected” by driving current along field lines, increasing the helicity of that magnetic field. The ultimate current that can be driven and sustained by this technique is governed by two physical limits: a magnetic helicity limit and a helicity injection balance.

The first is a magnetic geometry limit, as described in the theory by J.B. Taylor [1], which sets an upper limit on the allowed I_p in terms of externally driven currents, the geometry of the confinement region, and the width of the driven region in the plasma. For a tokamak with toroidal field coil current I_{TF}, injected current I_{inj}, and width w of the driven plasma edge, the maximum plasma current scales [2] as the square root of $I_{TF} I_{inj} / w$.

The helicity balance limit is simply a balance between the rate of magnetic helicity injection and the resistive helicity dissipation, very similar to the usual balance of applied power to the total power dissipation. The effective loop voltage due to helicity injection is proportional to the helicity injection rate, itself proportional to the product of the bias voltage with the active cross-sectional area of the compact injector. Just as with power balance, the exact helicity injection rate necessary to create and sustain a target plasma against resistive dissipation depends upon the target I_p and the nature of the dissipation (*i.e.*, stochastic confinement and/or standard closed-flux confinement). Technological limits may place an upper bound of 1 kV for the bias voltage of any injector at the edge of a tokamak discharge, implying that order-of-magnitude increases in the helicity injection rate must be achieved through increases in the injector cross-sectional area.

Taken together, these two current limits dictate that any high-capability injector system will involve an injector with cross-sectional area on the order of 100 cm^2, shaped so as to be narrow in the radial direction, with the exact injector size dictated by the nature of the dissipation.

For recent experiments, the injector assemblies in the Pegasus device are located near the outboard midplane. Pegasus discharges formed by LHI start out near the outboard injectors, are relatively small with an apparently near-circular cross-section, and grow inward as the plasma current increases. This outboard formation allows the I_p growth to be enhanced by a ramp in the outer Poloidal Field (PF) coil currents, by using this outer-PF induction drive to increase the effective loop voltage on the discharge [2]. The outer-PF induction is actually the dominant current drive during the late I_p rampup phase. Variations in the I_p ramp rate correspond to variations in the driven J_T distribution, with rapid I_p ramps producing very hollow current density distributions, and slower ramps allowing more uniform current distribution throughout the plasma cross-section. These current profiles are then “frozen into” the discharge after the LHI is shut off, as it is sustained by other current drive techniques (solenoidal induction in the case of Pegasus), enabling the formation of high-current MHD-stable tokamak equilibria [3].

LHI can be quite flexible with regards to the location of the injector, with any particular injector location offering its own advantages and disadvantages. Early Pegasus injection experiments used divertor-region plasma guns [4], which had a relatively high helicity injection rate (in the high-field divertor region) and simple plasma radial position control. Outboard injection offers easier maintenance, better diagnostic access, and scope for significant outer-PF induction, at the cost of a relatively lower helicity injection rate and more complicated radial position control requirements. That is, current buildup in outboard injection scenarios is much less demanding for the helicity injection system, but more demanding for the plasma control system. Designing the optimum injection system and corresponding operating scenario for NSTX-U or any other device will require understanding of these trade-offs, potentially with the limitations of the coil current supplies and plasma control system driving the conceptual design of the injector location, the helicity injector size, and the injection bias supply parameters.

Current research contributions to NSTX Upgrade

The ongoing collaboration with the Pegasus group encompasses the materials and technology of LHI, understanding of the relevant physics, and the conceptual design of a LHI-based MA-class startup system for NSTX-U. There are significant physics- and technology-based issues which impact the design, some of which have been described in the previous section, and all these issues must be resolved before proceeding:

- The electron emitter technology that will be used as a helicity injector in NSTX-U
- The minimum active area of the injector, related to the plasma confinement/dissipation
- Injection bias power supply requirements, related to injector bias impedance
- The location of the injector, related to the relative "weight" of PF induction in operations
- The radial width of the injected current channel
- Tokamak-like plasma formation in conditions relevant to NSTX-U operations
- NSTX-U machine access for deploying the helicity injection system
- Plasma-Material Interactions (PMI) at the injector structures

Each of these issues is the focus of specific research efforts, and each will be addressed and brought to some conclusion in the context of the planned research, as described in the next section. The following paragraphs outline recent results that advance some of these issues.

As described in Refs [5] and [6], there has been considerable evolution in the construction and understanding of the injection sources since the beginning of the formal collaboration in 2010. Early Pegasus helicity injection studies used relatively large active plasma sources (called "guns") to create a local discharge, which was then the source of free electrons for the injector bias current. These sources have intrinsic limitations on their cross-sectional area and discharge duration, which confound easy extrapolation to higher-I_p plasmas in Pegasus and NSTX-U. Subsequent experiments showed that a bare electrode, though conceptually and technologically simple, was inappropriate as a source of significant helicity injection. Experimental attention in the Pegasus program has thus shifted to gas-fed electrodes, to use the "hollow cathode" effect to give an extended uniform current source with sufficient area.

A parallel effort on Pegasus has greatly reduced the interactions between driven plasma and the material surfaces of the injectors, typically boron nitride sheathing of metallic injector components. A long-standing problem with these injectors is inadvertent arcing back from the injector face to structural components supporting the injector assembly, typically along boron nitride sheathing. This arcback heating of the boron nitride would cause material eruptions, which would fuel the plasma in an uncontrolled manner, introduce significant impurities, cause significant damage to injector components, and (by supplying large amounts of gas in an unexpected location) reduce voltage standoffs on the injector structure and make additional arcing easier. This arcback was prevented by the addition of a thin floating molybdenum plate behind the injector face, to shield the boron nitride without being charged to the injector potential. Additionally, each Pegasus injector assembly now incorporates a local scraper limiter to reduce PMI between the main discharge and boron nitride sheathing of the injector assembly.

Finally, the detailed shape of any deployed metallic electrode is now optimized to control the motion of inadvertently-created cathode hot spots, with any such spots kept away from boron nitride near the injector face. Together, these changes have led to a dramatic reduction in the uncontrolled fueling of LHI-driven Pegasus discharges, and a corresponding reduction in the impurity content of those plasmas. Each of these features will be used to improve the PMI aspects of any NSTX-U injector.

As described in Refs [7] and [8], scientific understanding of the impedance of the injector on the external bias circuit has also improved. The observed impedance for an active plasma source is consistent with a double layer sheath, with a low-current low-voltage operating regime that has bias current bounded by space charge limits (for a bias current that scales as the bias voltage to the three-halves power), and a high-voltage high-current regime constrained by the Alfven-Lawson magnetic current limit [9] (for bias current scaling as bias voltage to the one-half power). These models are also broadly consistent with the observed dependence on electron density, with the bias current increasing with increasing electron density at fixed bias voltage. However, these first-order models do not explain the mechanism for the observed dependence of the impedance upon the external fueling rates, and both theoretical development and detailed experiments are needed.

Summary of proposed research plan for FY2014-2018

The collaboration between the Pegasus and NSTX-U teams has the deliverable goal of producing a conceptual design for a MA-class LHI-based NSTX-U startup system. From this conceptual design, the detailed design for this startup system will take shape, in direct collaboration with PPPL science and engineering staff. Part of this detailed design activity should culminate in the installation of ports or port covers on the NSTX-U device that will enable machine access for the

LHI system. This installation activity should be targeted for the planned outage/upgrade in FY2016-2017, and would enable the LHI system to be installed without requiring a major interruption to NSTX-U operations, whether at the end of this five-year period or at the beginning of the next.

In the FY2014-2018 period, results from the separate Pegasus research program will naturally address physics and technology issues for LHI startup in NSTX-U. For example, studies of electron source technology for LHI on Pegasus will yield insights for extrapolation to NSTX-U parameters, and ultimately for choosing the optimum source technology for NSTX-U startup. Active plasma sources, as presently deployed on Pegasus, have one to three PFN-driven arc discharges of ~2 kA each, for durations of 8-10 milliseconds, compatible with inertial cooling of the plasma source structures. The size and current scales of these sources are consistent with a Pegasus startup dominated by outer-PF induction, with compact high current-density sources yielding a high Taylor I_p limit but relatively little helicity injection drive. In contrast, the timescales of NSTX-U startup (~100 milliseconds), along with a demand for higher-performance current drive, extrapolates to an LHI startup system that deploys tens of sources with lower arc currents, in order to meet the Taylor current limit for 1 MA startup. The longer timescales of NSTX-U startup would require active cooling of these plasma sources, with each source also having its own arc PFN, gas feed, and bias current connection. This complexity may be undesirable, especially if a passive large-area electron emitter can fulfill the requirements.

The Pegasus team is presently evaluating large-area gas-fed electrodes, using the hollow cathode effect to source electron current at each gas feed. Even if the hollow cathode effect leads to a viable injector technology for Pegasus parameters, the physics of this effect may not allow a simple extrapolation to the relatively high-field environment of NSTX-U. Pegasus experiments will be directed at demonstrations of viable large-area injectors, especially those that will extrapolate to relatively simple injector systems in NSTX-U.

LHI startup has been developed in Pegasus device, which has no large conducting structures near the confinement region and a relatively low base pressure. For presently unexplained reasons, LHI startup is somewhat sensitive to the initial conditions, and computational and experimental confirmation is needed to demonstrate that LHI startup can work in the presence of the NSTX-U passive plates and its relatively high base pressure.

Experiments will address the fundamental issues of the impedance of the injection source and the dissipation in LHI-driven plasmas, using a more capable Pegasus diagnostic set (including multi-point Thomson scattering, improved interferometry, and SXR). Both of these issues significantly impact the extrapolation to NSTX-U startup, via the minimum size of the injector and the requirements for the bias power supply.

Computational activities will also evolve from the present 0D/1D modeling developed for Pegasus and initial TSC validation activity to detailed modeling of LHI operating scenarios in both the Pegasus and NSTX-U devices. The 0D/1D modeling efforts will yield initial parameters for the helicity injector and bias power supply, as well as giving insight for the helicity dissipation and the optimum amount of PF induction to use in an LHI startup scenario. These results will be replicated and extended using detailed scenario modeling with the TSC code. Additionally, the formation of a poloidal null, a necessary condition for LHI startup, must also be modeled in the context of the NSTX-U coil set and the presence of the passive plates. As the conceptual design of the LHI startup system takes shape, the detailed modeling will shift in emphasis, to development of realistic operating scenarios relevant to LHI startup experiments in NSTX-U, from null formation to the initial relaxation, through the current rampup phase, up to reaching the 1 MA target plasma current.

Research Timeline during the FY2014-2018 Period

Items prefaced with “(P)” are Pegasus program activities that will inform this collaboration.
Items prefaced with “(N)” are specific activities related to this collaboration.

FY2014-2015:

- (P) Refine injector impedance model
- (P) Pursue the science and technology of large-area electron emitters that can be used for helicity injection in high-field NSTX-U parameters, including demonstration of injector technology relevant for NSTX-U
- (P) Evaluate the confinement and electron energy dissipation in LHI-driven discharges, both in terms of overall confinement properties and the corresponding MHD activity
- (N) Examine (computationally and experimentally) the conditions for initial relaxation in LHI discharges, under conditions relevant to NSTX-U
- (N) Detailed modeling of NSTX-U LHI startup scenarios, focusing especially on confirming and extending 0D/1D results regarding LHI-dominated current drive scenarios versus PF-induction contributions
- (N) Deepen dialogues with PPPL personnel, especially with regards to NSTX-U access and the use of PPPL-compliant materials and design parameters for the LHI startup system.

FY2016-2017:

- (N) Composition of conceptual design for MA-class LHI startup system
- (N) Installation of LHI port(s) on NSTX-U device during the FY2016-2017 outage/upgrade

FY2017-2018:

- (N) Projected start of incremental funding for startup system at the beginning of FY2017
- (N) Detailed design and design review activities, transitioning to fabrication when possible
- (N) Projected installation of the LHI system after the FY2018 run period
- (N) Composition of LHI startup experimental plans, in collaboration with PPPL staff

This timeline is illustrated with a Gantt chart, appended to the end of this section.

Contributions to the NSTX-U 2014-18 Five Year Plan:

Roger Raman is the present leader of the solenoid-free startup and rampup topical science group and is responsible for overseeing the “Plasma Formation and Rampup” chapter of the NSTX-U Five Year Plan. The plan above was defined in a process carried out over CY2011-12 in coordination with the NSTX-U Research Team. The research defined above contributes to the long-term goals of NSTX-U and the spherical torus, by demonstrating a non-solenoidal startup technique capable of generating a tokamak discharge that can be subsequently sustained using only the steady-state current drive systems. As planned, this research will not impact the NSTX-U 2014-2018 Five Year Plan in terms of operations, as the helicity injection system may not be installed and tested until the end of FY2018. However, the machine access required for the LHI system will be determined long before any installation, and whether this will require simply installing gate valve(s) on existing port(s) or creating new port(s), arranging this access will impact the upgrade activities during the FY2016-2017 outage.

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11.2.28 X Science LLC

Research Topic: Absolutely Calibrated Tangential Imaging of Divertor
Principal Investigator: Ricardo Maqueda
Participating Scientists (not funded by this grant): Vlad Soukhanovskii (LLNL)
Funded under DOE Grant: DE-SC0007979

Introduction

Researchers from X Science LLC are working on an upgrade to an existing diagnostic that can provide extremely useful information in divertor physics research. The lower divertor tangential imaging system of NSTX will be absolutely (i.e., photometrically) calibrated and this calibration will be maintained throughout the experimental campaign by measuring the transmission through the vacuum interface window and other optical components. The data obtained in NSTX-U will be used together with edge models to guide their development and implementation in NSTX-U and to indirectly obtain measurements of physics relevant quantities such as the densities in the divertor region of neutral deuterium and impurities like carbon and lithium.

Current research contributions to NSTX Upgrade

Work is currently underway to upgrade the lower divertor tangential imaging system of NSTX [1], adapting it to the NSTX-U device and being able to perform absolutely calibrated measurements. Figure 1 shows the planned field of view on the lower half of an equilibrium calculated for NSTX-U. This diagnostic system is usually operated with interference filters for deuterium (D_α, D_γ) or impurity line emission (LiI, LiII, CII, CIII, etc) which are located on a remote controlled filter. Fast-framing digital cameras are used to obtain highly resolved (1 kHz or better) measurements.

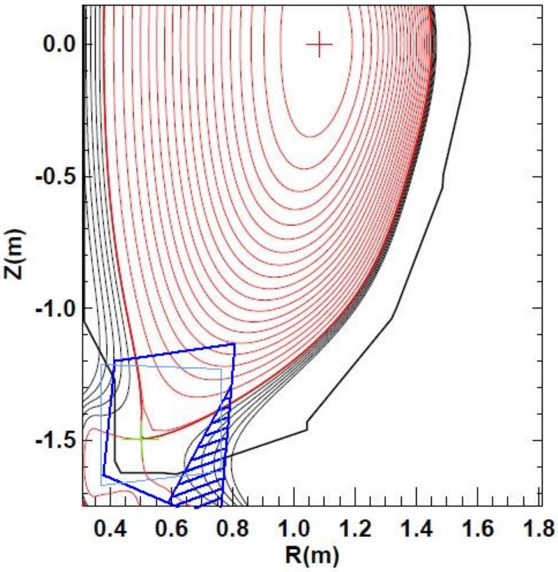

Figure 1: Planned view of lower divertor tangential camera system on NSTX-U (blue box). The dashed region is obstructed by near field tiles and other hardware.

The largest difficulty when performing the calibration for this imaging system resides not on the calibration itself but in maintaining this calibration throughout the several months-long experimental campaign. Coatings inevitably develop through the campaign on the vacuum interface window and other invessel optics such as mirrors. One of the main aspects of the planned work, in addition to performing the calibration and making use of the data, resides in the implementation and use of invessel illumination hardware that will permit the measurement of the optics transmission as the campaign progresses.

Summary of proposed research plan for 2014-18

At this time several research tasks are planned for NSTX-U in the area of divertor physics. These include the further development of the snowflake divertor, development and assessment of divertor detachment and performance, generation and transport of impurities (and recycling) at the divertor, and study of 3-D field effects on divertor physics. NSTX-U is also planning the development and implementation of cryo-pumping in the lower divertor region. The use of the absolutely calibrated lower divertor tangential imaging system will assist in these research tasks as well as in the physics research of high-Z materials used as plasma facing components in the divertor region.

An important component of the research plan for 2014-2018 is the integration of the measurements obtained with this diagnostic with the modeling efforts within the NSTX-U team. The UEDGE fluid code [2] has been previously been used in NSTX [3] in a limited way but it is expected to be further developed for use in NSTX-U with the research efforts from team members from LLNL. The UEDGE code can then be used to generate background plasma conditions, with which neutral Monte Carlo codes like DEGAS2 [4] can be run to study neutral transport and, coupled to collision rate tables, obtain emission rates that can be compared to the measurements obtained with the calibrated divertor tangential camera

Conversely, once the codes have been benchmarked against the available diagnostics it is the results from these codes what would allow the indirect measurements of many physics parameters relevant to divertor research in NSTX-U. Perhaps the most immediate indirect measurements associated with the calibrated 2-D emission profiles obtained with the tangential divertor camera would be the deuterium neutral density and the impurity densities at the different ionization levels being observed. Another indirect measurement would be the diffusion and flow of deuterium and impurities (carbon, lithium and, possibly, high-Z materials). This measurement would be made easier if one can use transient and/or localized events in the field of view of the camera, like the localized injection of methane in DIII-D [5].

The elements of our plan displayed in a timeline are:

Timeline

FY2014:

- Complete design, fabrication and installation of hardware in NSTX-U.

FY2015:

- Obtain (first) absolutely calibrated tangential images of plasmas in lower divertor region.
- Invert images into emission profiles in the R, Z plane.
- Initiate comparisons with UEDGE runs.
- Obtain (first) measurements of deuterium density and impurity densities.

FY2016:

- Continue with measurements and analysis through the FY2016 experimental campaign.
- Perform transient/localized measurements to obtain diffusion coefficients and flow speeds of deuterium and impurities.

FY2017:

- TBD, current grant period ends in June 2016.

FY2018:

- TBD, current grant period ends in June 2016.

Contributions to the NSTX-U 2014-18 Five Year Plan:

The plan above contributes heavily to the research goals established in the 2014-2018 NSTX-U plan in the areas of divertor performance (Sections 4.2.4, 4.2.5 and 4.2.6): assessment and control of heat and particle fluxes by means of (further) development of advanced divertor configurations, physics of the impurity transport from the divertor PFCs (carbon, lithium, high-Z), and particle control via cryo-pumping.

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