Appendix - NSTX Collaboration Research Plans

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The NSTX National Research Program is carried out by a broadly based research team which has greatly advanced the understanding and performance of spherical torus plasmas since the start of NSTX experimental operations in FY2000. NSTX research collaborations have made substantial contributions to the long term goals of the OFES program: Configuration Optimization and developing a Predictive Capability for Burning Plasmas. This collaboration will continue to grow in breadth and effectiveness.

A.1 - Introduction

Research on NSTX is carried out by a National Team of research groups from 19 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 40% of the NSTX scientific staff in full time equivalent (FTE) and 59% of the personnel are from these collaborating institutions. The contributions of all collaborating institutions, including foreign cooperation not funded by DOE, have been extensive, as can be seen in the overview and plan sections of this 5-year plan. The work plans of the collaborating research by the institutions other than PPPL are briefly described in this appendix to provide supporting information to the overall NSTX 5-year plan. These plans include those already funded by DOE for durations up to 3 years, and new ideas that extend the work to FY 2013. The extended collaborative research plans will require timely discussions within the NSTX research team, before formal proposals are submitted to DOE for peer review and approval. It is expected that, during FY 2009-2013 period the NSTX research efforts by the collaborating institutions will increase at a proportional rate equal to or faster than the NSTX research efforts by PPPL.

Among the 189 active research users of NSTX including graduate students and post doctoral researchers, 87 are from these collaborating institutions, 59 are from PPPL, and 43 are from fusion institutions of other countries. PPPL engineers and technicians carried out the operation, maintenance, upgrade of the NSTX facility, and the interface, installation, and maintenance of diagnostic systems including those provided by the collaborating researchers, at an effort level of 80 FTEs. The entire NSTX research and facility operations team have worked together effectively to enable rapid progress toward the proof-of-principle mission of NSTX, since the beginning of experimental research in FY2000.

A.2 - NSTX National Collaboration Research Capabilities and Plans

The success of the NSTX national research team is ensured by an effective integration of these broad and exceptional capabilities and expertise into a research force aimed toward achieving the NSTX research goals. NSTX collaborators play an essential role in leading the NSTX scientific program as indicated by Table 1.8.1 in Chapter 1 which indicates that nearly half (6 of 14) of the topical science group leadership, deputy leadership, and run coordination support is provided by non-PPPL researchers. Working together, the NSTX national research team is effectively meeting the challenge of producing an expanded scientific knowledge base for practical fusion energy based on the ST concept.

The capabilities and plans of the NSTX national collaboration research are organized by the list of collaborating institutions, principal investigators, and research topics are provided below:

A-1. Columbia University (S.A. Sabbagh)
Study of MHD Stability and Active Mode Control in NSTX
A-2. General Atomics (R.J. La Haye)
Plasma Control, H-mode pedestal stability, and ELM control with RMP
A-3. Johns Hopkins University (M. Finkenthal)
USXR Measurements of Core and Edge Transport and MHD
A-4. Lawrence Livermore National Laboratory (V. Soukhanovskii)
Integrated Measurements and Modeling of Edge Transport and Turbulence
A-5. Lodestar Research Corporation (J.R. Myra)
Edge and Scrape-off-Layer Physics for NSTX
A-6. Los Alamos National Laboratory (X. Tang)
Predictive Modeling of Helicity Injection Startup
A-7. Los Alamos National Laboratory (G. Wurden, J. Wang)
Hypervelocity Dust Injection/ Dust Studies
A-8. Massachusetts Institute of Technology (P.T. Bonoli)
Full-wave Studies of High Harmonic Fast Wave heating

A-9. Nova Photonics, Inc. (F.M. Levinton)

Radially resolved internal measurements of $\mathbf{B}$ *and* E_r *for reconstruction of* q *and* p

A-10. Oak Ridge National Laboratory (D.L. Hillis)

Boundary Physics, Heating, and Current Drive Program for NSTX

A-11. Purdue University (J.P. Allain)

Elemental & Chemical Characterization of D-Recycling on Lithiated Graphitic Surfaces

A-12. Purdue University (A. Hassanein)

Impact of Disruptions and ELMs on Liquid Lithium Surfaces in NSTX

A-13. Sandia National Laboratory (R.E. Nygren)

Liquid Lithium Divertor Experiments and Preparation for NHTX

A-14. University of California at Davis (N.C. Luhmann, Jr.)

Millimeter-Wave Fluctuation Diagnostics for NSTX and KSTAR

A-15. University of California at Irvine (W. Heidbrink)

Energetic Particle Physics

A-16. University of California at Los Angeles (T. Peebles)

The Study of Alfvén Mode Physics and Turbulent Transport in NSTX

A-17. University of California at San Diego (J. Boedo)

Heat and Particle Transport (radial and parallel) and divertor physics

A-18. University of California at San Diego (A. Pigarov)

Simulations of Synergy of Li-Coating, Non-diffusive Anomalous Transport and Drifts

A-19. University of Colorado at Boulder (T. Munsat)

Evaluation of Edge Turbulence & Convective Transport through Velocity Field Analysis

A-20. University of Illinois at Urbana-Champaign (D.N. Ruzic)

LLD and SOL Interactions on NSTX

A-21. University of Tulsa (D.P. Brennan)

Energetic Particle and Flow Shear Effects in Resistive MHD Instabilities

A-22. University of Washington at Seattle (T.R. Jarboe, R. Raman)

Solenoid-free Startup using CHI, Deep Fuelling and Momentum Injection using CT Fuelling

A-1. Columbia University Collaboration

Research Topic: **Study of MHD Stability and Active Mode Control in NSTX**

Principal, Co-Principal Investigators: Steven A. Sabbagh (PI/PD), G. A. Navratil (Co-I.)

Participating Researchers: S. A. Sabbagh, J.M. Bialek, J.W. Berkery, O. Katsuro-Hopkins (NSTX analysis in relation to KSTAR research).

Funded under DOE Grant: DE-FG02-99ER54524

Introduction

The spherical torus (ST) magnetic fusion concept uses strong geometric alteration of the magnetic field to produce stable plasmas at relatively low toroidal field, and hence high toroidal beta, β_t. Practical understanding of this magnetic confinement device has been significantly increased by the study of an expanded ST database of plasmas with high $\beta_t \equiv 2\mu_0<p>/B_0^2$ up to 39%, high $\beta_N \equiv 10^8<\beta_t>aB_0/I_p$ up to 7.2, high energy confinement (τ_E / $\tau_{E\ ITER\text{-}89P} > 2.5$), and β_N to internal inductance ratio, β_N/ℓ_i exceeding 11 in NSTX. With high toroidal and normalized beta, wall-stabilized operation established, the Columbia University group proposes to continue, as part of the NSTX Research Team, research on macroscopic stability aimed directly at the long-term goal of this topical area: demonstration of sustained plasma operation in the wall-stabilized high β state, with high reliability, at or near the highest β_N produced in the device. This research also aims to address the two long-term OFES goals of Configuration Optimization (development of the spherical torus toward a spherical torus component test facility, ST-CTF) and Predictive Capability for Burning Plasmas (development of stability physics understanding applicable to tokamaks in general including ITER, leveraged by the unique low aspect ratio, *A*, and high beta operational regime of NSTX). One of the critical questions that must be addressed in the development of the ST concept for fusion energy and for toroidal magnetic fusion devices in general: what is the level of β_N that can be reliably sustained at high bootstrap current fraction and high β_t. Addressing this question through a careful research plan has brought, and will continue to bring to fruition goals of passive and active stabilization research envisioned since the creation of first plasma in NSTX, as well as critical physics understanding applicable to advanced tokamak operation in general.

Current research contributions to NSTX

Columbia group research has contributed to NSTX since the conceptual design of the device. A long-term experimental research plan over the past several years spanned the creation of the original equilibrium in the device and their reconstructions [1] to the significant milestone of the first active stabilization of the resistive wall mode (RWM) at low aspect ratio, and at reduced plasma rotation applicable to ITER [2]. The characteristics of the unstable RWM at low A were documented in NSTX by the Columbia group. Early work determined that the RWM eigenfunction is ballooning in nature with the largest perturbation on the outboard side and that the mode effectively couples to the passive stabilizing plates. This investigation included a physics design of an active stabilization control system for the device [3] (which was constructed and implemented by PPPL engineering). The presence of large error fields in early device operation resulted in unstable RWM growth soon after β_N exceeded $\beta_N^{\text{no-wall}}$, indicating reduced passive stabilization in this condition [4]. Subsequent error field reduction resulted in a much larger stabilized operating space with $\beta_N/\beta_N^{\text{no-wall}}$ up to 1.5 at the highest β_N values reached in the device [5]. Here, $\beta_N^{\text{no-wall}} = \beta_{N(n=1)}^{\text{no-wall}}$ is the β_N value above which ideal $n = 1$ MHD kink-ballooning modes are computed without the stabilizing effect of nearby conducting structure. Here, n is the toroidal mode number. Maintaining high toroidal rotation across the entire profile leads to passive RWM stability [6]. Unstable RWMs with toroidal mode number up to three were observed in NSTX for the first time in a tokamak experiment [5]. Resonant field amplification (RFA) with $n = 1$ was also observed [5], and increases with increasing β_N as observed in DIII-D. These experiments also led to an important new branch of research addressed by the Columbia group on NSTX – the physics of plasma viscosity induced by non-axisymmetric fields. A multi-year experiment led to the observation of neoclassical toroidal viscosity [7] (NTV) in NSTX due primarily to non-resonant fields [8]. 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 [1,9], which now can include toroidal rotation, flux-isotherm constraint (using Te data), and internal magnetic constraints (utilizing motional Stark effect data)) that allows between-shots MHD stability analysis (using the DCON code [10]) as required. The Columbia group has provided this capability for NSTX for several years (since sufficient diagnostic data became available).

Summary of proposed research plan for 2009-13

Progress accomplished to date in the study of global MHD mode stability and active RWM control in NSTX sets the stage for the Columbia group to propose a 3 year program of study, leading research in several key areas to support the maintenance of high beta plasmas created in the device. The research applies to NSTX, the future development path of the ST, and will provide key physics understanding for advanced tokamak operation and future burning plasma devices.

The elements of our plan displayed in a timeline are:

Timeline

2009-2010:

- Continue experimentation and analysis of plasmas above the present NSTX ideal no-wall beta limit with the goal of firmly understanding the physics of the instabilities setting the beta limit under passive and active stabilization and maintaining the high beta state. (applies to all years).
- Continue experimentation to determine superior feedback control settings and sensor combinations for RWM active stabilization (continues into second year).
- Compare VALEN model of RWM active stabilization in NSTX with experimental RWM active stabilization results, including real geometry and positions of sensors

and the influence of plasma rotation. Use results to guide control system improvements (applies to all years).

- Continue the study of RWM mode rigidity and unstable n spectrum during $n = 1$ RWM active stabilization (applies to all years).
- Begin investigation of multi-mode model as a suitable hypothesis to explain RFA and RWM characteristics.
- Develop multi-mode VALEN code and begin initial tests.
- Begin assessment of advanced RWM control algorithms in conjunction with RWM control algorithm design studies for KSTAR.
- Begin analysis to support design of non-magnetic RWM sensors for NSTX in collaboration with JHU (continues into second year).
- Continue to investigate the role of ion collisionality, plasma rotation magnitude and profile in RWM active and passive stabilization; if approved, perform a second joint experiment with DIII-D to examine aspect ratio effects on RWM stabilization and differences based on different plasma rotation profile shapes and magnitude.
- Conduct MARS-F code stability analysis in collaboration with Y. Liu (including toroidal rotation, dissipation, kinetic effects) to evaluate the role of Alfven and sound wave continuum damping physics in support of the RWM passive stabilization physics study (applies to all years).
- Conduct analysis of trapped particle precession drift stabilization on NSTX plasmas at low plasma rotation in collaboration with B. Hu and R. Betti in support of the RWM passive stabilization physics study (applies to all years).
- Examine the role of increased applied non-axisymmetric field (resonant and non-resonant) on RWM stabilization.
- Continue to test the theory of neoclassical toroidal viscosity, especially the dependence of ion collisionality (ITER relevant); if approved, perform a joint experiment on DIII-D proposed for 2008 in this regard.

- * Begin experiments to determine the role of island-induced NTV during observed resonant magnetic braking or tearing mode activity.
- * Continue to distribute equilibrium reconstructions to the NSTX Research Team in a common public database format (applies to all years).
- * Continue to provide supporting work and analysis for the NSTX real-time EFIT plasma control system, implemented by Dr. David Gates and Dr. John Ferron. (applies to all years).
- * Initiate and lead a collaboration of NSTX physicists, engineers and design technicians on a practical and effective design of the new non-axisymmetric control coil (NCC) proposed for NSTX (applies to all years).

2010-2011:

- * Use present RWM coil to dynamically suppress resonant field amplification, addressing the present amplitude modulation of the RFA observed.
- * Make comparison between experimental observations of RWM amplitude modulation and multi-mode VALEN calculations using experimental equilibria.
- * Continue investigation of multi-mode model as a suitable hypothesis to explain poloidal deformation of RWM during stabilization by comparing to multi-mode VALEN calculations.
- * Determine the effect of varying latency in sensor feedback on RWM active stabilization (ITER application) as control system software upgrades allow.
- * Begin steps to implement advanced RWM control algorithms in conjunction with RWM control design studies for KSTAR.
- * Reach 2009 NSTX RWM milestone by drawing conclusions regarding physics models of RWM stabilization that support experimental results.
- * Investigate a combined model of torque on the plasma due to both resonant and non-resonant NTV by comparing theory to experiment.

* Support NSTX plasma rotation control design effort by performing NTV calculations as needed.

* Compute stability of resistive MHD modes using resistive DCON (when available) on NSTX equilibrium reconstructions. Compare theory to experiment to develop the capability for future predictive use (extends into year 3).

* Incorporate conclusions reached in Year 2 into the continued NCC design

* Examine NCC design implications of enabling the increase of plasma rotation by non-resonant rotating fields.

2011-2012:

* Support $n = 1$ RWM active stabilization system modifications and its use as a general tool for NSTX experiments.

* Determine needs for $n > 1$ RFA suppression and active stabilization and apply to the NCC design.

* Determine needs for suppression of poloidal deformation of RWM and apply to NCC design.

* Continue comparison of multi-mode RWM behavior between experiments and VALEN theory model to establish the latter as a design tool for future devices.

* Provide physics support for implementation of non-magnetic RWM sensors by JHU group and design for future use in RWM feedback loop.

* Implement advanced RWM control algorithms to establish the first experimental tests (supports KSTAR and ITER).

* Implement results from plasma viscosity model due to non-axisymmetric fields into NCC design for plasma rotation control.

2012-2013:

* Upgrade existing between-shots EFIT reconstruction to support operation with new center stack and associated machine alterations.

* Perform experiments and associated theoretical analysis to examine RWM control and to gain physics understanding of passive stabilization at significantly lower (order of magnitude) ion collisionality with new center stack upgrade than in present NSTX plasmas.

* Determine how well the high β_N state can be maintained against RWM instability through the combination of LLD operation, plasma rotation control, and n = 1 RWM control.

* Examine RWM measurement with non-magnetic sensors and compare to standard measurement with magnetic sensors. Determine the role of $n > 1$ RWM activity during $n = 1$ stabilization and expand study to higher power and increased q_0 when additional NBI power capability becomes available.

* Conduct RWM stabilization and NTV rotation damping experiments using the NCC (incremental). Compare stabilization performance with design expectations and viscous torque profile with theory.

* Determine a reliable physics model to confidently predict RWM stabilization as a function of rotation and ion collisionality. Test this model against equilibria created with the second neutral beam when available (further variation of V_ϕ and q profiles).

* Perform experiments and associated theoretical analysis to determine the scaling of neoclassical toroidal viscosity at significantly lower (order of magnitude) ion collisionality. This is especially important as the scaling of NTV between the present NSTX operating space and that predicted for operation with the new center stack upgrade is not well understood.

Contributions to the NSTX 2009-13 Five Year Plan:

S.A. Sabbagh is the present leader of the NSTX Macroscopic Stability Topical Science Group and is responsible for overseeing the NSTX Five Year Plan. The plan was defined in a process carried out over CY2007-08 in coordination with the NSTX Research Team. The research defined above contributes heavily to the plan.

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A-2. General Atomics

Research Topic: **5 year plans for NSTX**

Principal, Co-Principal Investigators: Robert J La Haye, Todd E Evans, Thomas H Osborne and David A Humphreys

Participating Researchers: John R Ferron, Lang L Lao, Anthony W Leonard, James A Leuer, Benjamin G Penaflor, Philip B Snyder, Alan D Turnbull, Michael L Walker, and Anders Welander

Funded under DOE Grant: GRANT00351261 (March 1, 2008 – March 1 2011)

Introduction

General Atomics is participating in the NSTX research program in three topical areas: (1) plasma control, (2) H-mode edge pedestal character and stability, and (3) ELM stabilization using resonant magnetic perturbations (RMP). General Atomics has played a strong role in development of the NSTX plasma control system that is providing capability for production of the quality discharges required for the experimental research program. 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 algorithms which have 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. We are continuing participation in experiments and analysis to improve understanding of the H-mode edge pedestal and edge localized modes in NSTX. As part of work in the previous grant period, a large set of General Atomics developed data analysis tools specially designed for this type of research was adapted for use at NSTX and applied to preliminary analysis of NSTX H-mode pedestal data. These tools will continue to be exploited for analysis of the extensive set of NSTX pedestal data that is becoming available. In addition, the ELITE stability code will be used for analysis of medium toroidal mode number instabilities in the edge region, and other codes such as NIMROD will be tested for pedestal simulations. 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 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. We are also continuing participation in experiments exploiting the existing set of non-axisymmetric coils to study the effect of resonant magnetic perturbations on ELMs in NSTX.

Current research contributions to NSTX

We provide support on control, H-mode edge pedestal physics, and design of a new resonant magnetic perturbation coil for edge control; details are given in the grant proposal [1]. Work on the physics of neoclassical tearing modes and the effects of error fields on their stability is ongoing and a continuation of the previous 3 year grant (March 1, 2005 – March 1, 2008).

Summary of proposed research plan for 2009-13

Details through March 2011 are given in (1); this will be coordinated with the NSTX staff on an ongoing basis. It is anticipated that the conceptual design of a new RMP coil to be done under the existing grant will lead to an engineering design, fabrication, and installation with participation by GA under a grant renewal for the years after March 1, 2011. Collaborations not in the grant are anticipated on the physics of NTMs, error fields, resistive wall modes, and MHD stability in general on a year-to-year basis through proposals at annual research opportunity forums.

References

1 GACP 20000318 National Spherical Torus Experiment Research Participation, October 11, 2007, General Atomics

A-3. Johns Hopkins University

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

Principal, Co-Principal Investigators: M. Finkenthal, D. Stutman

Participating Researchers: K. Tritz, L. Delgado-Aparicio, G. Caravelli (graduate student)

Funded under DOE Grant: DE-FG02-99ER5452

Introduction

The role of the ST in the US fusion program is to provide the basis for a volumetric neutron source for a Nuclear Testing Facility or, possibly, hybrid fusion-fission energy applications. Since the ST neutron source will be in good part a 'beam-plasma' device, it is essential that it maintains a high electron temperature, so that the fast beam ion population is not quickly degraded in energy. Understanding the highly anomalous electron transport observed in NSTX is thus of fundamental importance for the ST future. Neoclassical effects such as collisional impurity penetration through the edge H-mode barrier can also be important in a ST volumetric neutron source. In addition, non-magnetic identification of MHD instabilities during operation in an extreme radiation environment will be another critical issue. The current and proposed JHU research at NSTX addresses all these topics.

Current research contributions to NSTX

Our current research at NSTX has two main directions:

(i) The application of soft X-ray diagnostics and techniques for measurements of particle and electron thermal transport and of MHD activity

(ii) Identifying the physical mechanisms behind the highly anomalous electron transport in the region of low T_e gradient inside $r/a \leq 0.4$.

In the area of particle and electron thermal transport our contributions are based on a recently developed *multi-energy SXR* (ME-SXR) technique and diagnostic. The technique consists in simultaneously imaging the plasma in multiple energy bands and using the SXR profiles to constrain the evolution of the T_e and $n_e x n_z$ profiles. This enables to interpolate with high temporal and spatial resolution between the Thomson scattering T_e profiles, as well as to measure with accuracy the penetration of injected impurities. The diagnostic we built to implement this technique on NSTX is a tangential three-energy 'optical' array that measures the core plasma inside r/a <0.8 [1].

Our recent contributions can be summarized as follows:

- identification and study of electron transport barriers in beam L-mode plasmas [2]
- perturbative electron transport studies that established unusually rapid electron transport in the central plasma of high beam power H-modes [3]
- impurity transport measurements indicating that particle transport is around neoclassical levels in the core of high beam power NSTX H-modes [4]
- study of the correlation between large ELMs and the perturbed electron thermal transport, showing that the electron transport accompanying the ELM is consistent with critical gradient ETG activity in the peripheral plasma [5]
- proposal for a possible correlation between rapid electron transport in the central plasma of high beam power H-modes and the shear Alfven (GAE) activity [6]

In addition, several diagnostics of interest for the future ST and Burning Plasma research have or are being demonstrated at NSTX under the Advanced Diagnostic DoE Program:

- USXR BES Telescope for measurement of low-k core fluctuations [7]
- Imaging XUV spectrometer using free-standing Transmission Gratings (TG) [8]
- 'Hybrid' ME-SXR/ME-XUV array combining multi-energy SXR with multi-energy XUV imaging for line and continuum emission measurements

The JHU contributions to MHD diagnostic and measurement are based on a system of poloidal USXR arrays that image the internal MHD activity. A set of selectable filters allows for discrimination of the SXR emission from the edge, mid-radius, and central plasma, respectively. With a mode frequency capability from DC to > 100 kHz the arrays have been used to study a broad range of MHD phenomena:

- imaging of low-frequency RWM activity showed differences in internal mode structure between stabilized and un-stabilized modes [9]
- identification of double tearing mode activity provided first indication that electron transport barriers in NSTX are associated with reversed magnetic shear [2]
- imaging of tearing mode position and growth was applied to NTM beta threshold studies (ongoing DIII-D collaboration)

- SXR imaging of internal MHD contributed to the study of kink-mode dynamics and other internal MHD of high beta plasmas [10]
- measurement of ELM filaments in the USXR data led to the discovery of the small, Type V ELMs in high performance NSTX discharges [11]
- imaging of energetic particle modes has been used to localize and identify the eigenmode of bursting, 'fishbone-like' MHD activity and contributed to the identification and localization of the global BAAE, recently discovered at NSTX [12]

Summary of proposed research plan for 2009-13

For the period 2009-2013 we propose to *continue and expand* the above lines of research, as well as to begin exploring *a new direction*, the control of fusion plasmas using ME-SXR feedback.

In the diagnostic area, will continue to maintain and operate the poloidal USXR system. In addition, we propose to develop and implement several new diagnostic systems. In the 2009-2011 timeframe, we plan implementing:

(i) A *high spatial resolution ME-USXR/ME-XUV tangential array* for fast measurements of the edge plasma profiles

(ii) *Two toroidally displaced, high resolution ME-SXR tangential arrays* for non-magnetic identification and measurement of low-frequency core MHD (RWM, ELMs and disruptions)

The edge ME-USXR/ME-XUV tangential array will be a 'hybrid' device, incorporating together with multiple low-energy USXR filters also an XUV TG dispersive and imaging element. The array will cover the plasma at $0.8 \leq r/a \leq 1.1$ and will measure with high spatial ($\geq$ 1 cm) and temporal resolution ($\geq$ 1 ms) the edge line and continuum emission profiles, together with their MHD perturbations. Using normalization to the temporally and radially sparser Thomson profiles, we aim to obtain higher resolution T_e, n_e, and n_z profiles. These in turn will be instrumental for many of the edge studies planned at NSTX, such as pedestal stability, ELM physics and mitigation, as well as studies of Li effects on the plasma.

The two toroidally displaced ME-SXR tangential arrays will cover the plasma from $0 \leq r/a \leq 0.9$ and will serve to identify and discriminate between toroidally symmetric profile changes, such as those associated with the ELMs, and toroidally asymmetric perturbations, such as those arising from the RWM. The aim is to provide higher sensitivity in low frequency MHD detection than possible with magnetic sensors. In addition, the two arrays will provide unique information about the internal structure of low frequency MHD phenomena, such as the n=1 RWM or the modes leading to disruption. The edge ME-USXR array and one of the ME-SXR arrays will be integrated in a single tangential enclosure in order to save port space.

The above diagnostics also project into our NSTX research in the 2012-2013 timeframe. The hybrid edge array will pave the way towards the implementation of a 2-D ME-XUV tomographic diagnostics for the NSTX divertor. The system of n=1 toroidally displaced ME-SXR arrays can be upgraded in the same period for the identification and diagnostic of low frequency MHD with n>1. In addition, this system will be used to assess the possibility of active RWM and ELM control using non-magnetic ME-SXR sensing [13].

Lastly, pending verification of our hypothesis on a connection between shear Alfven activity and electron transport in NSTX, we will consider developing in the 2012-2013 timeframe a XUV BES system for the imaging of fast Alfven modes, such as the GAEs, in the central NSTX plasma ($r/a \leq 0.4$).

As in our previous work, the diagnostic implementation will be accompanied by physics studies. The main topics we plan to investigate are:

- the possible connection between electron transport and Alfven MHD activity
- SXR signatures of stochastic/μ-tearing electron transport in the core and edge plasma during heating/cooling transients
- study of the role of neoclassical impurity transport in the formation of the NSTX pedestal
- effects of active RWM stabilization and of ELM mitigation on the internal MHD activity

Timeline

2009-2010: Construction of edge ME-USXR/ME-XUV hybrid array

2010-2011: Implementation and operation of edge hybrid array and construction of n=1 toroidally displaced ME-SXR arrays

2011-2012: Implementation and operation of toroidally displaced arrays

2012-2013: XUV-BES GAE diagnostic

2013: 2-D ME-XUV divertor diagnostic, ME-SXR n>1 RWM, ELM detection

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A-4. Lawrence Livermore National Laboratory

Research Topic: **The Study of Edge Transport and Turbulence - An Integrated Measurements and Modeling approach**

Principal Investigator: Vsevolod Soukhanovskii

Participating Researchers: new postdoctoral staff

Funded under DOE Contract DE-AC52-07NA27344

Introduction

The goal of the present LLNL research effort on NSTX is to develop an experiment-based understanding and a predictive computational capability of the edge (pedestal and scrape-off layer) parallel and perpendicular heat and particle transport and plasma-wall interactions in the spherical torus (ST) magnetic geometry, to enable extrapolations to future high power density ST-based devices.

Current research contributions to NSTX

The present LLNL collaboration on NSTX includes both the experiment and modeling, and takes advantage of the PI located on site at PPPL. The PI is involved in all aspects of the NSTX Research Program. The PI served as a Boundary Physics Experimental Task Group Deputy Leader in 2006, a Leader in 2007, and is now serving as a Boundary Physics Topical Science Group Leader. The LLNL Collaboration has been responsible for maintaining and operating five edge spectrally filtered CCD arrays, one spectrometer, and about 30 edge spectrally filtered detectors (“filterscopes”), as well as the supersonic gas injector. The LLNL research program in the Boundary Physics area focused on the divertor physics studies and the development of novel fueling techniques, while providing experimental and modeling contributions to many NSTX research efforts. In the divertor area, we studied divertor transport regimes and access to detachment in a range of H-mode plasma configurations, with the emphasis on ST SOL geometry effects. We demonstrated experimentally for the first time in a high power density ST the possibility of significant divertor peak heat flux reduction in the high flux expansion radiative divertor with simultaneous good core H-mode confinement. In the fueling area, we have designed and built in collaboration with PPPL researchers the novel high-pressure supersonic gas injector (SGI). The SGI demonstrated high fueling efficiency, and was used in H-mode fueling optimization experiments, complemented by particle balance and ionization source studies. In the modeling area, LLNL supported radiative divertor experiments and LLD modeling efforts with the UEDGE code, and edge turbulence studies with the BOUT code.

Summary of proposed research plan for 2009-13

The proposed continuation of LLNL research collaboration is well aligned with the NSTX priorities and takes a full advantage of the LLNL Boundary Physics experimental and modeling expertise. We propose an expansion in the scope of collaboration toward a "full service" (experiment, diagnostics, and modeling) effort. A modest increase in funding (1+ FTE) would allow LLNL to implement unique ST divertor measurements and strengthen the corresponding edge transport and turbulence modeling.

The proposed effort will focus on

1) Further studies of divertor heat flux mitigation using novel high flux expansion divertors and radiative solutions at reduced plasma collisionality
2) Experimental characterization of NSTX divertor heat and particle transport and particle sources with active recycling control provided by the lithium coatings and liquid lithium divertor (LLD)
3) Further optimization of the supersonic gas jet fueling for density control in long pulse discharges with the complementary pumping by lithium coatings
4) Further development of the two-dimensional multi-fluid UEDGE and three-dimensional turbulence BOUT computational models in support of LLD and SOL width research

To support these experimental activities and modeling, we propose a staged diagnostic development effort: new Lyman-α diode arrays, a new multichannel divertor spectrometer, and a divertor Thomson scattering (DTS) system. In particular, the proposed DTS system would be implemented by a new staff member, and could possibly take advantage of the legacy Thomson scattering hardware from the completed Sustained Spheromak Physics Experiment at LLNL, providing significant cost and effort savings for NSTX. In combination with the planned midplane SOL Thomson scattering channels, the DTS system would provide unique two-dimensional SOL T_e and n_e measurements that would allow critical tests of SOL heat and particle transport models.

Timeline

2009-2010:

- Experiments aimed at initial characterization of SOL regimes in the presence of LLD: characterization of LLD pumping capability, fueling and impurity sources, and access to radiative and partially detached divertor regimes
- H-mode fueling optimization using SGI for fueling and LLD for pumping
- Laboratory studies of advanced supersonic nozzles and cryogenic SGI for enhanced deuterium jet penetration
- In support of the above, an implementation of Lyman-α AXUV diode arrays for recycling measurements in the presence of highly-reflective liquid lithium surfaces
- In support of the above, installation of the new imaging divertor spectrometer to study 1) divertor deuterium, lithium and carbon sources 2) role of molecular sources in the divertor 3) private flux region transport
- Modeling of the above experiments with UEDGE multi-fluid transport code
- Systematic analysis of NSTX turbulence data with BOUT code in support of SOL width studies
- Design and installation of the new divertor Thomson scattering system

2010-2012:

- Experiments aimed at optimization and control of partially detached divertor regime with impurity and deuterium injections at high power and reduced density (with new center stack and active pumping), and integration with long-pulse H-mode scenarios
- Development and characterization of novel divertor flux expansion configurations with existing or new magnetic coils
- SOL transport studies with DTS: general divertor heat transport studies, SOL kinetic effects, ELM divertor impact studies
- Modeling of the above experiments with UEDGE multi-fluid transport code

2012-2013:

- Continuation of SOL transport studies with DTS: general divertor heat transport studies, SOL kinetic effects, ELM divertor impact studies
- Contribute to the design of the upgraded divertor and diagnostics for its characterization

Contributions to the NSTX 2009-13 Five Year Plan:

PI wrote two sections (“ST divertor physics and heat flux control” and “Fueling”) for the Boundary Physics Chapter. This work also contributes to chapters on “Plasma start-up and sustainment” and “Advanced Scenarios and Control”.

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Invited Talks:

"Divertor Heat Flux Reduction and Detachment in NSTX", APS DPP, Orlando, Florida, 11/2007.

A-5. Lodestar Research Corporation

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

Principal, Co-Principal Investigators: James R. Myra, Daniel A. D'Ippolito and David A. Russell

Participating Researchers: Stewart Zweben (PPPL), Daren Stotler (PPPL), Ricky Maqueda (Nova Photonics), Vlad Soukhanovskii (LLNL), Jose Boedo (UCSD), Tobin Munsat (CU Boulder)

Funded under DOE Grant: DE-FG02-02ER54678

Introduction

An improved understanding of edge and scrape-off-layer (SOL) physics is essential to the goals of NSTX, future spherical tokamaks (STs), 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, the role of convective plasma transport in defining the SOL plasma, scaling of SOL characteristics with experimental control parameters, and the relation of experimental control parameters to the dimensionless control parameters in the latest theoretical models of edge turbulence and blob-filament propagation.

Current research contributions to NSTX

In ongoing work, we are exploring the dynamics of SOL blob-filaments and comparing observation, primarily from gas-puff-imaging (GPI) data, with theory. We carried out GPI analysis and interpretation, testing theoretical predictions for the magnitude and scaling of blob velocity. The work [1, 2] showed that the data obeyed bounds associated with theoretical predicted regimes, but did not obey a deterministic scaling. Statistical variations within a shot could mask expected differences between shots. We conducted a birth zone analysis, and showed that blobs are born in a zone associated with maximum linear instability. Blobs convect plasma with density and temperature characteristic of the birth zone. We introduced a dimensionless parameter space [2] in which to analyze blob velocities and showed that NSTX data lay within the expected region. The same parameter space was applied to understand inter-machine blob characterization (task ITPA-DSOL-15) [3].

Summary of proposed research plan for 2009-13

The proposed research for the next five years falls into three broad categories

1. Baseline topics addressing key SOL issues for NSTX, STs and ITER
2. Fundamental physics studies of blob-filaments
3. Novel topics

Our main project consists of several closely related studies under Category 1, which build on work discussed in the preceding. Here we seek to understand the origin of blobs (i.e. the turbulent creation zone, and the resulting level of blob activity) in terms of experimental and machine parameters. This important, but so far elusive, goal for the fusion community is key to eventually obtaining a predictive capability for heat and particle transport in the SOL. Lodestar will apply our 2D SOLT (Scrape-off-Layer Turbulence) simulation code in comparison with existing and/or new GPI experimental datasets to make progress in this area. The first step, already proceeding well, is to obtain quantitative agreement on SOL turbulence metrics (describing e.g. fluctuation levels, blob statistics, blob velocity distributions and dynamics) between the SOLT code and GPI data for a best case. This comparison invokes a simulated GPI diagnostic in SOLT that takes into account atomic radiation physics using models described in Refs. [2, 4]. In the next step, we will investigate the effect of parameter (code and machine) variations.

Research topics under Category 2 address the blob interaction with the magnetic geometry of the torus, and its influence on blob propagation and dynamical evolution, and on the heat and particle flux footprints on the divertor. We have proposed that increased blob speeds (and hence broader SOL widths) could be achieved if the more collisional ("disconnected") blob transport regime could be accessed. Experiments to test this in partially detached plasmas are being carried out. Our analytical and numerical models will assist in the interpretation of these ongoing and proposed experiments on NSTX. This work will also address the parallel structure of blob-filaments, relevant to their interaction with the divertor. Finally, as time permits, a novel area of exploration will be considered under Category 3, viz. the interaction of ion-cyclotron radio frequency waves (ICRF) in the edge plasma with edge turbulence and its possible use as a means of edge control.

There is significant synergy of the proposed work with other presently funded research: Lodestar's theory grant under which the blob and turbulence simulation models were developed, and an rf-SciDAC grant under which Lodestar is studying some related aspects of rf edge propagation and rf-sheath formation.

Timeline

2009-2010:

Carry out detailed comparison studies between the SOLT code and experimental data (GPI and other diagnostics such as probes) for a base case.

2010-2011:

Extend the base-case studies to examine the variation of SOL turbulence with the SOLT turbulence code and machine (plasma) parameters.

2011-2012:

Attempt to construct SOL turbulence scaling laws from 2010 studies. Begin work on one or more of: (i) blob speed in disconnected/detached plasmas, (ii) parallel blob-filament structure in the presence of X-points, (iii) ICRF interaction with edge turbulence.

2012-2013:

Continue work on previous year studies. As warranted, work with NSTX team to design possible critical experiments to further test and/or explore scalings.

2013:

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

Contributions to the NSTX 2009-13 Five Year Plan:

Contributed to the writing of Chapter 5 on boundary physics. This work also contributes to Chapter 6 on sustainment with regard to heat flux issues for long-pulse operation.

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A-6. Los Alamos National Laboratory

Research Topic: **Predictive Modeling of Non-inductive Startup by Helicity Injection on NSTX**
Principal Investigator: Xianzhu Tang
Participating Researcher: Allen Boozer (Columbia University)
Funded under DOE Grant: C52-06NA25396

Introduction

For the spherical tokamak (ST) to be a viable option for Component Test Facility (CTF) and DEMO, NSTX must demonstrate a way that enables mostly solenoid-free startup because of the intrinsic limitation on the physical size of the center stack. Furthermore, the solenoid-free startup scheme must scale up to an ST-based reactor and CTF. The leading candidate scheme that has been investigated experimentally on NSTX, which also has the highest performance to date, is the so-called transient co-axial helicity injection (CHI). This collaborative effort develops the theoretical basis and provides modeling support of current and future NSTX CHI experiments.

Current research contributions to NSTX

We have made substantial progress in understanding the equilibrium [1], stability [2], and nonlinear relaxation [3] of a co-axial helicity injection plasma. Our recent publications on flux amplification in an ST-CHI plasma [4] and its reactor scalability [5] have laid out the theoretical and quantitative bases for future CHI experiments and design optimization on NSTX and future ST devices. The fundamental advances in the theory of magnetic self-organization via linear [6, 7, 8] and nonlinear [9] resonant coupling between the driven plasma and the helicity injector, in addition to applications in ST-CHI for solenoid-free startup, also find important applications in spheromak reactor [10] and astrophysical radio lobes [11].

Summary of proposed research plan for 2009-13

We propose to continue our investigation of NSTX solenoid-free startup by helicity injection in support of the current experiments and to develop the physics bases for a new transient helicity injection startup scheme that can be scaled up to spherical tokamak-based (ST) Component Test Facility (CTF). These research objectives will be accomplished by combining (1) analytical theory; (2) numerical calculation of spherical tokamak co-axial helicity injection (ST-CHI) equilibria; and (3) full torus 3D nonlinear MHD simulation of full cycle ST-CHI discharges. The programmatic goal will be achieved by working closely with NSTX experimentalists in formulating an experimental strategy to carry out the proposed new operational mode on NSTX and the post-run data analysis and physics interpretation. We will also continue our support of the current fast transient CHI startup campaign on NSTX and explore the feasibility of non-inductive startup via plasma gun helicity injection. The specific research tasks that will be carried out include: (1) further improving our understanding of how spherical tokamak plasma under co-axial helicity injection relax under sustained external drive, and correlating it to flux amplification and current multiplication; (2) understanding the physics that governs the flux amplification and current multiplication in a spherical tokamak plasma under helicity injection; (3) specifying the requirements on co-axial helicity injection in terms of flux amplification and current multiplication for spherical tokamak reactor and CTF applications, and demonstrating that the relaxed transient co-axial helicity injection scheme has the scalability to enable solenoid-free startup of the ST-based CTF. The proposed research is built upon a number of recent theoretical breakthroughs and computational advances that were made possible by previous NSTX collaboration support. If the proposed research is carried out with the required support, it promises a solenoid-free startup scheme that would overcome a primary obstacle in the ST path toward controlled fusion energy.

Contributions to the NSTX 2009-13 Five Year Plan:

Contributed CHI theory for Chapter 6, Section 4.

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A-7. Los Alamos National Laboratory

Research Topic: **Hypervelocity Dust Injection/ Dust Studies**
Principal, Co-Principal Investigators: Glen Wurden, Jeff Wang
Participating Researchers: TBD
Funded under DOE Grant: Will propose to be restarted

Introduction

In FY07, our Marshall gun/ high-speed dust injector collaboration on NSTX was discontinued. We propose restarting our experimental collaboration for this 5 year NSTX plan. Dust in plasmas is an interesting and exciting area of research. Studying dust interactions has value for ITER (dust can be an unwanted problem), and yet also other possible benefits as a way to inject neutrals across the plasma separatrix. Depending on the dust speed, (for example if launched at 5-10 km/sec), it may penetrate deeply. Previously (1-3), we developed a high speed dust injector, which utilizes a high speed (but cold) deuterium plasma to accelerate dusts to high velocities, and more recently, LANL has published a PRL on dust acceleration [4] physics.

Current research contributions to NSTX

Presently, the piezoelectric dust dropper system (from our hypervelocity hardware), operated very successfully dropping lithium dust into NSTX for 2 days during the FY08 run. It was loaned to PPPL/NSTX (D. Mansfield) by Los Alamos in the fall of 2007.

Summary of proposed research plan for 2009-13

We propose to install our hypervelocity dust injector, which can also inject slow speed dust, onto NSTX. The previously planned port is occupied by other diagnostics, so interfacing has to be re-organized, taking into account sightlines from various imaging systems already on NSTX. We also know that helium used at PPPL to inject Lithium pellets was problematic for good NSTX plasma operations.

- Gas load measurements at LANL, selection of port at NSTX, reconfigure hardware
- Install equipment at NSTX, conduct initial tests with carbon, and lithium dusts.

- Compare to dust ablation codes, look for diagnostic uses of dust in high temperature plasma

Timeline

2009-2010:

Restart the project. Make gas load measurements at LANL. Prepare interfaces to NSTX.

2010-2011:

Install hypervelocity dust injector system at NSTX. Make initial measurements by piggybacking.

2011-2012:

Compare with dust ablation/penetration models. Vary the types/size/speed of dust

2012-2013:

With higher resolution imaging, study dust ablation cloud for possible B-field measurements

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A-8. Massachusetts Institute of Technology

Research Topic: **Full-wave studies of high harmonic heating in NSTX**

Principal Investigator: Paul T. Bonoli

Co-Principal Investigator: John C. Wright

Participating Researchers (at PPPL): Cynthia K. Phillips, Joel Hosea, Stanley Kaye, Douglas McCune

Funded under DOE Grant: DE-FG02-99ER54525

Introduction

In order to accurately assess the role of high harmonic fast wave (HHFW) heating in the NSTX device it is important to have a predictive calculation for the wave propagation, absorption, coupling and current drive. A full-wave electromagnetic field solver is generally the best approach to this type of calculation because effects due to toroidal geometry, focusing, diffraction, antenna geometry, nonthermal particles, and the edge scrape off layer (SOL) can all be included in such a calculation. These effects are all of great importance in NSTX as the device is low aspect ratio, employs a twelve strap antenna to couple ICRF power to the plasma, contains a population of fast ions due to neutral beam injection (NBI), and is characterized by a tenuous scrape-off-layer density that extends out to and beyond the antenna launching structures.

Current research contributions to NSTX

One of the primary research contributions of this collaborative proposal is application of the high harmonic fast wave (HHFW) version of the TORIC full-wave ICRF field solver [1] to transport analysis studies of HHFW experiments in the NSTX device. This work consists of implementation of a "standalone" version of the solver on the PPPL computing clusters (PETREL, VIZ, and MHD) as well as an identical implementation of the solver in TRANSP. This implementation was accomplished by setting up a CVS repository for TORIC at MIT, which allows upgrades and improvements in the code to be immediately available to collaborators at PPPL (Drs. Cynthia Phillips and Dr. Ernie Valeo). This CVS version of TORIC is kept consistent with an SVN version that resides at the IPP in Garching, Germany.

Although TRANSP simulations have yet been performed, the HHFW version of the TORIC solver was successfully installed in TRANSP and we are now ready to begin these studies.

Concurrent with code development activities we have worked with Dr. Cynthia Phillips (PPPL) on studies of the dependence of electron heating on antenna phase in NSTX [2] using the MARSHALL computing cluster at MIT. We also worked with Dr. Phillips on high resolution TORIC simulations aimed at trying to understand the improvement in HHFW electron heating in NSTX at higher parallel wavenumber ($k_{//} = 7\ m^{-1}$) and magnetic field ($B_0 = 0.55T$) [3]. These simulations show coupling of the HH fast wave to a short wavelength mode that has tentatively been identified as a slow wave with dispersion relation given by $n_{\perp}^2 \sim -K_{zz} (n_{//}^2 - S)/S$, where K_{zz} and S are elements of the dielectric tensor in the Stix notation. This mode is usually evanescent but can propagate under conditions where $\zeta_{oe} = (\omega / k_{//} v_{te}) < 1$, that is at higher $k_{//}$ and low frequency (ω), both of which occur in NSTX. Initial studies with TORIC indicate the coupling to this mode can be strong but the simulations we did were plagued by poor power balance, particularly at the highest poloidal mode resolution.

Summary of proposed research plan for 2009-13

The objective of this collaborative proposal is to use the TORIC full-wave field solver [1] for analysis of HHFW experiments in NSTX in the following four areas:

- Analysis of HHFW surface wave excitation, motivated by recent experimental observations of the edge density affecting the core heating efficiency in NSTX.

- Analysis of parasitic HHFW – fast NBI ion interaction and HHFW-background ion (hydrogen) interaction in NSTX experiments.

- Time dependent and stationary (in time) transport analysis and RF analysis of NSTX discharges with HHFW heating (and current drive), including the possible use of HHFW electron heating in NSTX start up scenarios.

- Computational and theoretical support for PPPL program studies of slow wave mode conversion in the HHFW regime and simulations of Compressional Alfven Eigenmodes (CAE's) and related RF-driven eigenmodes.

Timeline

2009-2010:

Finish standalone HHFW TORIC simulations to demonstrate surface wave excitation for relevant experimental parameters in NSTX, (that is, the measured density profile and parallel wave number).

Perform parametric scans to determine under which conditions (density, magnetic field, and parallel wave number) surface waves are excited and can be avoided.

2010-2011:

Use standalone HHFW TORIC solver to investigate parasitic HHFW interaction with fast NBI ions and with background hydrogen, using relevant NSTX parameters.

Execute and test the HHFW TORIC solver within TRANSP for an NSTX discharge with HHFW electron heating.

2011-2012:

Continue simulations of HHFW slow wave mode conversion in NSTX.

Perform TRANSP simulation of HHFW – fast ion interaction using an effective beam temperature from TRANSP.

2012-2013:

Execute and test the HHFW TORIC solver within TRANSP for an NSTX discharge with HHFW current drive.

> Perform time dependent TRANSP simulations of HHFW electron heating and current drive to demonstrate non-inductive plasma start-up for access to high performance

Contributions to the NSTX 2009-13 Five Year Plan:

The work described in each of these areas is closely aligned with the following two NSTX scientific priority areas:

> Exploit improved coupling efficiency of launched fast waves at high ion cyclotron harmonic frequencies (n=10-15), with emphasis on simulating and enhancing plasma performance in advanced operating scenarios.
>
> Develop scenarios for solenoid-free ramp-up to substantial plasma currents by neutral beam injection and high harmonic fast wave.

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A-9. Nova Photonics, Inc.

Research Topic: **Radially resolved internal measurements of magnetic field magnitude and direction, radial electric field, and use of these for reconstruction of q-profiles and total pressure profiles**

Principal, Co-Principal Investigators: Fred M. Levinton

Participating Researchers: Howard Yuh & Jill Foley

Funded under DOE Grant: DE-FG02-99ER54520 & DE-FG02-01ER54616

Introduction

The primary goal of our critically important research is to provide magnetic field pitch angle profiles. The MSE-CIF diagnostic system is currently operational with 16 sightlines. The data is routinely incorporated into LRDFIT to obtain q-profile and current profiles.

The new Motional Stark Effect with Laser-Induced Fluorescence (MSE-LIF) diagnostic[1] 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 through the ability to make MSE measurements in the absence of heating beams, effects of radial electric fields through the ability to measure them via the combination of the existing MSE-CIF system with 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.

All MSE systems are potentially sensitive to radial electric fields, and as such can be used to determine them given two independent measurements. In the NSTX case, the MSE-LIF system has a near-radial beam injection angle, and is minimally sensitive to radial electric fields, but the existing MSE-CIF system is sensitive to radial electric fields. Hence, the combination of MSE-CIF and MSE-LIF data can be used to subtract out the purely magnetic aspects of the measurement to give radial electric field measurements when both MSE systems are operated in conjunction.

Current research contributions to NSTX

The MSE-CIF diagnostic system is currently operational with 16 sightlines. The data is routinely incorporated into LRDFIT to obtain q-profile and current profiles. We have been actively engaged in transport analysis that has investigated the effects of magnetic shear on ion and electron transport. This has resulted in a publication and invited APS talk[2] and recently an invited talk to be presented at the APD-DPP 2008 conference, to be given by H. Yuh.

Summary of proposed research plan for 2009-13

Magnetic field magnitude measurements in the MSE-LIF approach are achieved through a spectroscopic measurement of the line spacing in the MSE spectrum, and the use of this measurement for equilibrium reconstruction we refer to as MSE-LS for MSE with line shifts. In contrast, the traditional MSE measurement which relies on line polarization is termed MSE-LP. The MSE-LIF system will be capable of providing both MSE-LS (magnetic field magnitude) and MSE-LP (magnetic field pitch angle) measurements. The MSE-LIF diagnostic is presently funded through 2010 under a diagnostic development grant. During this time period, installation of the diagnostic on NSTX and initial data collection are planned. Though MSE-LIF is capable of both MSE-LS and MSE-LP measurements, the unique capability of MSE-LIF on NSTX is the magnetic field magnitude measurement, as the existing system provides reliable pitch angle data. Thus, the magnetic field magnitude measurements will be emphasized earlier in the research program plan.

The MSE-CIF diagnostic will complete the optics upgrade to improve sensitivity for magnetic fluctuation measurements and, if funded, will provide real-time MSE q-profiles. Research activities will probably focus on electron transport in the reversed shear regime developed on NSTX. We also plan to investigate Er corrections based on using the new MSE-LIF system as well as poloidal CHERS.

Timeline

2009-2010:

MSE-LIF: Install diagnostic beam, laser, collection optics and fibers in NSTX test cell, detectors in mezzanine. Perform initial tests of alignment/operation of all components, plan to collect 'first light' from beam in NSTX plasma.

MSE-CIF: Complete upgrade of filter optics. Operate 16 channels.

2010-2011:

MSE-LIF: Operate four channels in MSE-LS configuration. Shakedown of system. Write new grant proposal.

MSE-CIF: Operate 16 channels.

2011-2012:

MSE-LIF: Upgrade system to include 12 channels. Use MSE-LIF data to perform reconstructions of q-profile and pressure. Demonstration of this ability relevant to ITER MSE system design. Use of system will contribute to NSTX research program in areas of non-inductive startup and current drive, fast ion instability studies, and radial electric fields.

MSE-CIF: Operate 16 channels. Add real-time MSE. Write new grant proposal. Design modifications of MSE-CIF for higher field operation.

2012-2013:

MSE-LIF: Installation of polarization rotation to achieve MSE-LP measurements with MSE-LIF system. Continued operation of MSE-LIF, further studies of phenomena related to non-inductive startup and current drive, fast ion instability studies, and radial electric fields.

MSE-CIF: Operate 16 channels. Install modification for higher toroidal field operation.

2013:

MSE-LIF/MSE-CIF: Operate 16 channels, further studies of phenomena related to non-inductive startup and current drive, fast ion instability studies, transport, and radial electric fields.

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A-10. Oak Ridge National Laboratory

Research Topic: **ORNL Boundary Physics, Heating, and Current Drive Program for NSTX**

Principal Investigators: D. L. Hillis, R. Maingi, D. A. Rasmussen, P. M. Ryan

Participating Researchers: T. Biewer, T. S. Bigelow, J. Canik, J. B. O. Caughman, S. Diem, E. F. Jaeger, A. Sontag, J. Wilgen and 1 post-doc(TBD)

Funded under DOE Grant: ORNL FWP (ERAT 308)

Introduction

This document details the participation of staff members from the Oak Ridge National Laboratory (ORNL) in the physics program of the National Spherical Torus Experiment (NSTX) for the period 2009 - 2013. The scope of work is divided into the areas of Boundary Physics and RF Heating and Current drive.

The boundary physics research has two primary components: (a) execution and analysis of experiments, including physics analysis support with detailed modeling, and (b) operation and installation/upgrading of diagnostics.

The topics discussed in this plan are:

1. H-mode pedestal, ELM, and power threshold physics,
2. Scrape-off layer and divertor optimization for long pulse plasmas, including modeling and analysis with the SOLPS 2-D fluid code package
3. Boundary studies to enable improved RF coupling efficiency, and
4. Support for density control experiments, as well as density profile control enabled via pellet fueling.

These elements largely reflect a continuation of the existing ORNL leadership of and contribution to the NSTX program. The three main goals of these research lines are: 1) to develop the scientific basis for extrapolation to larger spherical tori, including a low aspect ratio Component Test Facility, 2) to test theories used for higher aspect ratio designs, such as the International Thermonuclear Experimental Reactor (ITER), and 3) to optimize NSTX long pulse discharges. It is noted that ORNL staff presently serve as the Boundary Physics Experimental Task (ET) Group Deputy leader.

Progress toward research goals relies both on existing measurements and a few new diagnostics. Thus, ORNL's participation in the NSTX program relies on the conduct and analysis of experiments, as well as diagnostic operation of infrared cameras, reflectometry, and filterscopes. Looking forward, ORNL staff may support operation of the Edge Rotation Diagnostic and associated upgrades.

The proposed RF research is intended to advance the progress toward the IPPA-FESAC 5-10 year goals for the Spherical Torus concept of fully non-inductive operation and solenoid-free plasma current ramp-up to high beta operation. The combination of ECH/HHFW/EBW 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 RF research can be divided into High Harmonic Fast Wave (HHFW) and Electron Bernstein Wave (EBW) activities. The HHFW program is a natural continuation and extension of ongoing research:

1. Understanding and improving the HHFW power deposition, heating, and current drive efficiency.
2. Understanding and improving the power propagation through the edge plasma and its deposition in the core.
3. Increasing the HHFW power and reliability.
4. Providing heating power to transition from non-inductive startup plasmas to NBI target plasmas.

RF theory support will assist in the understanding of power flow, deposition, and loss channels by using the AORSA 1D and 2D codes to study wave propagation in the plasma edge, excitation of parametric decay instabilities and edge ion heating, and the damping of HHFW on the fast ion tails from neutral beam injection.

The EBW program is intended to provide off-axis electron heating and current drive for NSTX, as well as for ECH plasma startup and ramp up. We will continue EBW emission measurements to understand and optimize mode conversion mechanisms, and we will develop, install, and operate a high power (~200 kW) EBW/ECH system at 15.3/28 GHz. The system will use existing equipment to minimize hardware and installation cost. It will provide sufficient power for proof of principle experiments on a reasonable schedule yet be easily upgradeable to higher power in the future. During the first year of operation, the system is expected to deliver a 0.5 s pulse at 300 kW for 28 GHz and 150 kW at 15.3 GHz; the power will double in the next year with the addition of a second gyrotron.

Current research contributions to NSTX

ORNL staff leads research in the areas of H-mode pedestal and ELM physics and edge stability issues. We also contribute to the experimental test of Lithium as a divertor PFC. Finally we lead the effort on heat flux scaling, including peak heat fluxes and SOL widths. We also conduct 2-D modeling of ST plasmas for projection toward future STs, including NHTX and ST-CTF.

ORNL staff operates 2 slow IR cameras, a fast filterscope array on NSTX and the fast SOL microwave reflectometer for a variety of studies. In addition we are in the process of commissioning a fast IR camera for transient heat pulse studies, starting in 2009.

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 mentioned above and other edge diagnostics provide crucial information for the optimization of the power coupling and performance of the HHFW/EBW systems. The edge profile data is also needed to benchmark the modeling codes in order to better understand and interpret the experimental results.

Summary of proposed research plan for 2009-13

The boundary physics program will carry out research in the following areas:

- H-mode pedestal – analyze dependencies on external parameters and determine explicit role of aspect ratio in setting heights, widths, and gradients

- ELMs – assess role of ideal and resistive MHD stability as the trigger for large and small ELMs, and extrapolate toward next step STs
- L-H Power threshold – assess role of shape in setting the power threshold in STs
- SOL and divertor physics – investigate underlying physics of SOL power flux peaks and widths (steady and transient), e.g. role of gyro-radius, collisionality, and beta, and participate in design efforts of novel divertors for improved power flux control
- Assess role of neutrals in edge RF coupling, and develop small/no ELM scenarios for improved coupling
- Lithium program – contribute to assessment of Lithium as a particle control and power control tool, including design of LLD module upgrades, and commission a pellet injector to enable core fueling

The HHFW research program will concentrate on four areas of activity:

- Understanding and improving the HHFW core propagation and absorption, heating, and current drive efficiency.
- Understanding and improving the power propagation through the edge plasma and its deposition in the core.
- Increasing the HHFW power and reliability
- Providing heating power to transition from non-inductive startup plasmas to NBI target plasmas.

ORNL will also provide theory support to the HHFW effort:

- <u>HHFW coupling to fast ions</u>: develop full time-dependent energetic tail evolution including radial diffusion and finite orbit effects and incorporate a second non-Maxwellian ion species.
- <u>Excitation of parametric decay instability</u>: develop resonant 3-wave interaction package to study “extended pump”.
- Collisionally enhanced absorption (AORSA-1D).
- Employ the full wave 3D power progation capabilities of AORSA to study edge losses and far field sheaths.

The ECH/EBW program will provide off-axis electron heating and current drive for NSTX, as well as for ECH plasma startup and ramp up. ORNL will provide gyrotrons, each with a nominal 350 kW output power at 28 GHz, for installation on NSTX and will assist in the design of the launchers and operation of ECH/EBW experiments.

Timeline

2009:

Boundary Physics:

- Commission fast IR camera for steady and transient heat pulse studies
- Resolve common features of small ELM regimes between NSTX and other devices, i.e. MAST and Alcator C-Mod
- Assess role of aspect ratio in pedestal similarity experiments with MAST and DIII-D
- Measure dependence of L-H threshold on a few shape parameters (X-point height, connection length, elongation, triangularity)
- Assess impact of LLD on plasma parameters

HHFW:

- Complete the upgrade of the current straps to center-grounded operation for improved power delivery and reliability, including the re-tuning of the decouplers and the optimization of the power matching and distribution system.
- Optimize heating and CD operation with NBI; begin HHFW coupling optimization into plasma startup/ramp-up.

ECH/EBW:

- Optimize EBW emission coupling in H-mode with Li evaporation.

2010-2011:

Boundary Physics:

- Commission 2-color IR system for measuring heat flux in Lithium environment for FY2010 multi-machine Joule milestone
- Use enhanced edge diagnostics in NSTX 5 year plan to better assess ideal MHD stability of large ELMs and resistive MHD stability of small ELMs

- Commission pellet injector for core fueling experiments
- Develop small/no ELM scenarios for RF experiments using LLD
- Participate in design of upgraded LLD, cryopump for installation in 2012
- Participate in design of X-divertor or Super X-divertor for installation in FY 2012

HHFW:

- Divide the 12-strap array into three sections to test competing ELM-resilient matching technologies under consideration for ITER. Design a "Conjugate-T" matching system for four of the straps and an "ELM-dump" matching system for four other straps, leaving four straps as an unmodified reference standard.
- Further optimize H-mode heating and CD operation with this system.
- Compare the ELM-resilient techniques and subsequently convert the full array to employ the most successful approach.
- HHFW coupling into ramp-up combined with 28 GHz ECH-assisted non-inductive startup

EBW:

- Complete installation of 350 kW, 28 GHz gyrotron system, study ECH-assisted startup using fixed horn launcher.

2012-2013:

Boundary Physics:

- Commission and study impact of upgraded LLD or cryopump on plasma
- Commission and study impact of X-div/Super X-div on plasma
- Pellet upgrade if needed for core fueling

HHFW/EBW:

- Assess high power long pulse HHFW at high B-field, support very long pulse scenario.
- Install second 350 kW, 28 GHz gyrotron and locally-steered O-X-B launcher.
- Combine ECH/EBW to provide fully non-inductive plasma startup and ramp-up.
- Upgrade to remotely-steered O-X-B launcher; benchmark deposition codes with 700 kW core and off-axis heating studies.

Contributions to the NSTX 2009-13 Five Year Plan:

Lead authorship of Chapter 5 (Boundary Physics). Major contributor to the writing of Chapter 4 (Waves and Energetic Particles), sections 4.0, 4.1, and 4.2.

Appendix – list of ORNL first-author NSTX-related refereed journal articles (FY 2004-2008)

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A-11. Purdue University

Research Topic: **In-Situ Elemental and Chemical Characterization of D-Recycling on Lithiated Graphitic Surfaces With Applications to NSTX**

Principal, Co-Principal Investigators: J.P. Allain

Participating Researchers: Dmitry Zemlyanov, Chase Taylor (graduate student), Dimitris Tsarouhas (graduate student)

Funded under DOE Grant: DE-FG02-08ER54990

Introduction

This project consists of designing and conducting laboratory experiments that elucidate the effect of lithiated graphite and liquid lithium (Li) surfaces on deuterium recycling in NSTX Li evaporation and liquid Li experiments (e.g. liquid lithium divertor). In particular this work seeks to undertake systematic studies of energetic particle-surface interactions that can guide understanding of how lithium-based systems affect the plasma-material interface in NSTX. This understanding can further help to develop strategies to optimize particle density control and plasma performance in advanced NSTX plasma operation. This work is particularly important since lithium wall conditioning and proposed LLD will provide a unique approach to control hydrogen recycling and enhanced performance under high heat flux conditions. In addition, ELM suppression has been found to be associated with lithium wall conditioning in NSTX and thus laboratory experiments proposed here could help understand possible mechanisms behind this phenomenon.

Little is known about how long the Li layers remain on the substrate surface and how deuterium is pumped by a lithium-graphite mixed surface [1]. Questions that arise are for example: is it elemental lithium that is responsible for deuterium pumping or is it lithium in the presence of a compound (e.g. lithium carbide or lithium carbonate) that is responsible for D pumping? What is the effect of lithiated graphite plasma-wetted surface on the LLD in NSTX and are there conditioning scenarios that can be designed based on laboratory studies?

At Purdue University we conduct state-of-the art *in-situ* surface characterization techniques capable of monitoring lithium-based surfaces during particle irradiation. We can in principle, measure how the surface and near-surface is affected by energetic D particle irradiation during exposure ultimately elucidating on the D-pumping characteristics of lithium-treated surfaces. We can in addition measure the chemical evolution of the surface as a function of depth, which is important in determining the chemical state of the lithium atoms once deposited on a given matrix.

Our research supports the following key experimental areas in NSTX:

1) D pumping and particle density control
2) High-power particle handling
3) ELM suppression by lithium conditioning

Current research contributions to NSTX

At Purdue University the PRIHSM, IMPACT and Omicron Cluster experimental laboratory facilities are being used to measure surface performance properties of lithiated graphite and liquid lithium surfaces simulating scenarios in NSTX [2,3]. In this project we address several critical questions that challenge our understanding of the plasma-lithium surface interface in NSTX:

- How long does the Li layer remain on the substrate surface?
- How does the layer evolve at elevated temperatures and what is the impact on D recycling?
- What is the state of Li during this time? Is there a change in the surface chemical state over time?
- What is the amount of Li atoms available to pump D?
- How is D bound to the lithium-graphite system? Is elemental lithium responsible for pumping D or is it Li in the presence of a compound (e.g. lithium carbide), which is responsible for pumping?
- What is the impact of lithium-graphite surface chemistry on D recycling in NSTX?
- What is the impact of liquid Li on D recycling under NSTX-relevant conditions?

This project started just recently in May 2008 and work is currently investigating the hydrogen pumping capabilities of lithiated ATJ graphite. Advanced particle-beam facilities are designed to determine the response of mixed and multi-species surfaces under energetic particle irradiation. These facilities consist of three main experiments: PRIHSM, IMPACT and the Omicron Cluster system. Each system uses complementary surface-sensitive techniques including: direct recoil spectroscopy (to measure impurity levels in the film) and angle-resolved X-ray photoelectron spectroscopy during irradiation of the surface with low-energy deuterium. The facility is equipped with in-situ ultra-sensitive dual microbalance unit measuring total erosion yields and these are coupled to two separate mass spectrometry systems capable of measuring chemical sputtering of hydrocarbon species formed during irradiation.

In addition to laboratory experiments at Purdue University, an in-situ surface analysis facility will be designed by Purdue University and delivered to NSTX as a plasma-facing surface diagnostic. The facility will study erosion/redeposition properties of lithiated graphite in NSTX and its impact on the LLD system performance. This will be accomplished by coupling erosion/redeposition data from this probe with computational edge modeling by the PI and collaborators (J.N. Brooks, et al.).

Summary of proposed research plan for 2009-13

We propose to elucidate the hydrogen pumping mechanisms in lithium-based surfaces to optimize particle-density control strategies during lithium wall conditioning coupled to the LLD in NSTX. The primary elements of our plan are:

- Conduct laboratory experiments to understand the underlying mechanisms behind hydrogen pumping by lithium-based surfaces under simulated NSTX plasma conditions

- Design, proposed and execute experimental runs in NSTX plasmas that utilize recipes guided by laboratory experiments on optimized methods to pump hydrogen

- Design and install in-situ plasma-surface interaction probe to study erosion/redeposition mechanisms in NSTX plasmas dominated by lithiated graphite and LLD

Timeline

2009-2010:

- Develop strategies for laboratory experiments based on recent NSTX lithium wall conditioning runs
- Li exposure on ATJ graphite calibrated to NSTX 2007 run conditions (high vs low Li vapor flux) to study effects on Li-C chemical state as function of Li flux and temperature
- Li exposure on SS (as a control) calibrated to NSTX 2007 run conditions (high vs low Li vapor flux)
- Exposure of Li/graphite with exposure to low-energy D to measure effect on particle sputtering (C, D and C_xD_y). Impact energies and angles will be varied and validated with surface response codes and serve as input to subtask #5 below
- Design and construct plasma-surface interaction probe for erosion/redeposition measurements

2010-2011:

- Subsequent TDS (thermal desorption spectrometry) tests to assess D uptake and chemistry
- Install plasma-surface interaction probe in NSTX and conduct in-situ experiments to understand erosion/redeposition mechanisms with lithiated graphite and LLD
- Couple experimental laboratory data to erosion/redeposition modeling codes modeling the NSTX divertor floor in collaboration with J. Brooks
- He trapping in solid lithium and liquid lithium surfaces studies and He treatment of lithiated surfaces to study effect on D uptake

2011-2012:

- Experiments to measure the Li surface diffusivity on candidate substrates as a function of impact energy for species (D, He, Li) on: ATJ graphite, Mo, SS using LEISS, XPS and EUPS. Refer to appendix for details on techniques.
- Exposure to *both* D and He energetic beams to study their synergy and effect on surface Li coating properties (e.g. D pumping, erosion, etc…)

- Address the role of thin vs thick liquid Li coatings on D recycling.

2012-2013:

- Conduct experiments that measure D-retention from static free liquid Li surfaces on various substrates and couple to surface response modeling as function of temperature.
- Assess the role of impurities on liquid Li to D recycling properties as a function of temperature.
- Couple experimental laboratory data to erosion/redeposition modeling codes modeling the NSTX divertor floor in collaboration with J. Brooks (Argonne), R. Maingi (ORNL) and D. Stotler (PPPL)

Contributions to the NSTX 2009-13 Five Year Plan:

The primary contributions of the experimental work in this project address NSTX plans focused on "Operation at High Heat Flux in NSTX with applications to ITER and Beyond" by means of lithium conditioning strategies in NSTX.

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A-12. Purdue University

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

Principal, Co-Principal Investigators: Ahmed Hassanein

Participating Researchers: V. Sizyuk, G. Miloshevsky, and Graduate Students

Funded under DOE Grant: **DE-PS02-07ER07-29**

Introduction

The primary goal of our critically important research is to:

(1) Characterize the H-mode pedestal, scrape-off layer, and divertor plasma at low pedestal collisionality with ITER-level heat fluxes and relevance to CTF, and

(2) Model and assess experimentally the impact of off-normal events (disruptions, ELMs) on liquid lithium surfaces in the divertor.

Current research contributions to NSTX

1. Update physical and mathematical models in HEIGHTS of plasma particles motion (both ions and electrons) and interaction with the lithium divertor plate during plasma disruptions and ELMs using for NSTX conditions.

2. Upgrade HEIGHTS to NSTX divertor geometry for the full 3-D simulation. This will include calculation of plasma energy deposition in target material, heat conduction in bulk, debris vapor evolution, vapor-plasma heating, photon generation and transport, with taking into account detail local magnetic fields direction and magnitude. This will include performing full resistive 3-D MHD calculations for eroded materials.

3. Integrate HEIGHTS for ELMs modeling that include models from core plasma, SOL, and divertor response using two-fluid model. Unlike disruptions, the two-fluid model is important in this case where the evaporated Li material is comparable with incoming plasma particles.

Summary of proposed research plan for 2009-13

We propose to calculate:

A. Lithium evolution dynamics in NTSX during Disruptions and ELMs

1. Benchmark disruption and ELMs data for Li with NSTX conditions against numerical simulation of HEIGHTS.
2. Compare results of similar Li disruption experiments performed at TRINITI and Red Star facilities.

B. Study plasma contamination during ELMs

1. Help develop diagnostic methods for monitoring particle flux increase during ELMs in private flux region.

2. Benchmark data for Li back diffusion in NSTX private flux region against numerical simulation of HEIGHTS

Summary of proposed research plan for 2010

We continue to evaluate:

A. Lithium evolution dynamics in NTSX during Disruptions and ELMs

1. Benchmark and compare various ELMs data for Li with different NSTX scenarios against numerical simulation of HEIGHTS.
2. Evaluate various Li erosion mechanisms during disruption and ELMs and compare to various models to identify dominant mechanisms.
3. Predict erosion behavior in ITER like conditions of melted Be and W materials under disruptions and giant ELMs.

B. Study plasma contamination during ELMs

1. Develop techniques to diagnose X-point radiation enhancements during ELMs with the help of graduate students.

2. Continue to benchmark data for Li back diffusion in NSTX private flux region against numerical simulation of HEIGHTS at different ELM conditions.

3. Extrapolate conditions to ITER device and predict impurity diffusion to the X-point following ELMs. Predict the behavior of the impurity flux reaching the X-point and possible cause of disruptions during each giant ELM in ITER conditions.

C. Study SOL characteristics and behavior during ELMs

1. Continue to benchmark the SOL parameters during NSTX normal and ELMs operations at mid-plane during different ELM conditions.

2. Continue to benchmark and compare the SOL parameters during NSTX different ELMs operations and conditions to verify the numerical models.

3. Extrapolate conditions to ITER device and recommend the anticipated behavior of stronger ELMs and SOL parameters and predict ion energies arriving at the divertor plate. Evaluate the effect of much higher particle flux and energies during ELMs in ITER and predict if runaway sputtering-erosion can occur.

Summary of proposed research plan for 2011-2013

1. Continue to extrapolate conditions to ITER device and recommend and predict anticipated behavior of stronger ELMs and SOL parameters and predict ion energies arriving at the divertor plate.

2. Continue to evaluate the effect of much higher particle flux and energies during ELMs in ITER and predict if runaway sputtering-erosion can occur fro various operating scenarios.

3. Define safe operating windows for plasma instabilities for ITER relevant conditions based on comprehensive understanding of ELMs and disruptions in NSTX conditions.

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A-13. Sandia National Laboratory

Research Topic: **Liquid Lithium Divertor Experiments and Preparation for NHTX**

Principal Investigators: Richard E. Nygren

Participating Researchers: Dennis Youchison, Henry Kugel, NSTX Team

Funded under DOE Grant: Current Grant

Introduction

The general objective of this proposal is to supply NSTX with divertor hardware so that the outer strike point of a single null plasma will contact a liquid lithium surface. This objective stems from the strong affect of a lithium surface in reducing particle recycling that has been observed in experiments in both NSTX and TFTR that produced "super-shots" with lithium pellets, CDXU, T-11 and FTU and supports physics investigations identified in the NSTX Research Priorities for FY 2007-2009, i.e., item III-1. *Characterize effects of lithium wall coating on recycling and particle control* under area III. Plasma Boundary Interfaces - interface between fusion plasma and its lower temperature plasma-facing material surroundings.

Important considerations in the preparation of hardware for a liquid lithium divertor are:

1. a heating system for the lithium container(s)
2. the initial distribution and wetting of the surfaces by lithium, and mitigation as necessary of the potential subsequent spread of lithium by capillary action
3. thermal management of the lithium and container(s) during shots and plasma disruptions diagnostics for control, safe operation of the equipment and appropriate data to complement the ongoing experiments, e.g., temperature of the lithium surface.

Sandia began working in 2006 with the NSTX Team on the Liquid Lithium Divertor and received funding for a three year NSTX-Laboratory Grant in the winter of 2007 to develop a lithium tray system to install in the NSTX divertor. The system has electrical heaters and helium lines to control heat loss between shots and will be filled using the rebuilt LITER evaporators.

Sandia is providing the LLD plates, cabling for heater leads and thermocouple extensions to connection panels on the inside of the vessel, and the rack for heater controls, thermocouple signal processing and gas (helium) flow controls.

Current research contributions to NSTX

During 2007 options for the LLD design and related thermal analyses were considered by Sandia and the NSTX Team. During this time Sandia built equipment for a lithium wetting test, performed thermal analyses, procured a mockup of an open Mo mesh as a candidate technology as the lithium bearing host for the LLD and performed thermal tests on this mesh. In late 2007 and early 2008, two options for the LLD design were refined and analyzed by Sandia and the NSTX Team. The simpler design with a copper plate clad with stainless steel and covered with a flame-sprayed coating was adopted as the reference design and PPPL generated detailed drawings for the procurement of the LLD parts, which is now underway. During this same period, the specifications for the heater controls were refined and Sandia procured a three-heater copper mockup of the LLD and has started work on a new vacuum vessel for thermal tests of the mockup. This testing is extremely important for benchmarking the LLD thermal model. The results from this thermal modeling will be the basis for the thermal control program for LLD and guidance to the NSTX operators on the acceptable duration of shots for various anticipated plasmas in LLD experiments. We expect to complete installation of the LLD late in calendar 2008.

Summary of proposed research plan for 2009-13

We look forward to participating in experiments with the LLD in 2009. With appropriate funding, either through a subsequent NSTX-Laboratory Grant for 2010-2012 or new funding in Sandia’s base program, we will continue to participate in LLD experiments and work with NSTX on the design of a follow-on LLD and designs for applications in NHTX. The primary elements of an extended plan are:

- Operation of the control rack, guidance on thermal control during operation of the LLD, and interpretation of IR data, and thermal analysis of the LLD for selected shots.
- Development of a follow-on design for an upgraded LLD that has a lithium reservoir, active replenishment of the lithium-covered surface by capillary forces and thermal control and heat removal adequate to maintain steady state cooling for some plasmas.

- Operation of the control rack, guidance on thermal control during operation of the LLD, and interpretation of IR data, and thermal analysis of the updated LLD for selected shots.
- Development of a liquid lithium divertor for NHTX and projections of performance based upon experience with an upgraded LLD in NHTX.

Timeline

2009-2010:

Operate the control rack, provide guidance on thermal control during operation of the LLD, and interpret IR data based on thermal analysis of the LLD for selected shots during the first LLD campaign. Begin developing a design for an LLD upgrade. (Participation based on current grant would end at the end for FY2009.)

2010-2011:

Operate the control rack, provide guidance on thermal control during operation of the LLD, and interpret IR data based on thermal analysis of the LLD for selected shots during the second LLD campaign. Develop a follow-on design for an upgraded LLD that has a lithium reservoir, active replenishment of the lithium-covered surface by capillary forces and thermal control and heat removal adequate to maintain steady state cooling for some plasmas. Assist the NSTX Team in the specification and procurement of parts for an upgraded LLD. Begin developing a design of options for an NHTX.

2011-2013:

Continue participation in LLD experiments (operate the control rack, provide guidance on thermal control during operation of the LLD, and interpret IR data based on thermal analysis of the LLD for selected shots). Develop and participate in operation of an upgraded LLD in NSTX and use performance characteristics to assist design of NHTX Lithium options. Characterize LLD thermal performance with longer pulse duration enabled by centerstack upgrade and possible heat-flux increases (if 2nd NBI upgrade is present).

A-14. University of California at Davis

Research Topic: **Millimeter-Wave Fluctuation Diagnostics for NSTX and KSTAR**
Principal Investigator: N.C. Luhmann, Jr.
Participating Researchers: K.C. Lee, C.W. Domier, D.R. Smith (PPPL), E. Mazzucato (PPPL), H.K. Park (POSTECH), W.C. Lee (POSTECH), J.H. Kim (POSTECH)
Funded under DOE Grant: DE-FG02-99ER54518

Introduction

UC Davis, in collaboration with researchers from PPPL and POSTECH, addresses the critical issue of kinetic instabilities through a multi-pronged program of millimeter-wave diagnostics on NSTX. The focus is on the full range of MHD activity as well as ion and electron turbulence through the development of a unique suite of diagnostics. This work consists of upgrading, maintaining, and operating two diagnostic instruments on NSTX (the Far Infrared Tangential Interferometer/Polarimeter (FIReTIP) and the high-k 280 GHz collective scattering system), as well as the design and development of two new diagnostics: a 119 μm poloidal scattering system to complement the high-k toroidal scattering system, and a 3-D microwave imaging reflectometry (MIR) system to image microturbulence and internal MHD modes.

Current research contributions to NSTX

The FIReTIP system was upgraded from four-channel operation to five-channel operation for the FY07 campaign, with a sixth channel now under test in FY08. New electronics are being developed to increase the interferometry bandwidth from ~250 kHz to ~4 MHz. The ability of FIReTIP to study high harmonic fast wave (HHFW) heating will also be explored by the addition of new electronics to downconvert the ~30 MHz HHFW fluctuation signals to < 1 MHz for digitization and analysis. Even in its current form, however, FIReTIP continues to provide essential density fluctuation data for numerous physics studies.

In the area of NSTX boundary physics studies, FIReTIP data has provided strong supporting evidence for the theory of gyrocenter shift which explains the mechanism of radial electric field formation at the tokamak boundary in L/H transitions [1-3]. FIReTIP measurements of energetic particle instabilities and toroidal Alfvén eigenmodes (TAEs) have proven extremely valuable [4]; the ongoing bandwidth upgrade to ~4 MHz will allow FIReTIP to make similar measurements of higher frequency modes including compressional Alfvén eigenmodes (CAEs) and global Alfvén eigenmode (GAEs). The high time resolution of FIReTIP measurements has proven extremely useful in the study of edge localized modes (ELMs), and has allowed the identification of small (type V) ELMs which rotate toroidally in a direction opposite to the plasma current [5].

The NSTX high-k scattering system was successfully operated in the FY07 campaign, and was central to a key NSTX milestone (to study the variation of high-k turbulence with plasma conditions). In comparing L- and H-mode plasmas, a monotonically decreasing power spectra was observed during the L-mode phase and a non-monotonic power spectra during the H-mode phase. A reduction in fluctuation amplitude for upper ITG/TEM modes and moderate changes for ETG modes is observed during H-mode plasmas as indicated from electron thermal diffusivity profiles. The ion transport is close to neo-classical in the H-mode ion thermal diffusivity profiles, while the high-k scattering data reveals that the electron transport is reduced from L- to H-mode. RF-induced fluctuations were also studied with the high-k scattering system. The scattered frequency spectrum showed significant broadening during the RF heating phase where T_e is peaked at ~3 keV while T_i is ~1 keV; in cases where T_e is comparable to T_i (such as during RF and NBI heating), no spectral broadening was detected.

Modifications to the high-k scattering system electronics in May 2007 have increased the video bandwidth from 650 kHz to ~3 MHz, and have allowed the system to examine a wide range of kinetic instabilities on NSTX. Alfvén eigenmodes observed during with the upgraded high-k scattering system include an electrostatic component named Beta-induced Alfven Acoustic Eigenmode (BAAE). Plans are underway to increase the video bandwidth still further to 5 MHz for the FY09 campaign.

Summary of proposed research plan for 2009-13

FIReTIP and the high-k scattering system will continue to be employed in the study of turbulence and transport, for which the upgraded electronics with their enhanced video bandwidths should prove extremely helpful. A new component of both systems over the next 5 years will be to study HHFW-induced density fluctuations using upgraded electronics to be installed later this year.

We propose to implement two additional fluctuation diagnostics on NSTX during this time period. The first is a poloidal scattering system, similar to the high-k toroidal scattering system except in the choice of wavelength and scattering geometry. The poloidal system would employ a pair of 119 μm optically-pumped lasers similar to the lasers used in the FIReTIP system, and would considerably enhance planned turbulence physics studies by providing a measurement of the k_θ-spectrum of ETG and ITG modes. The second is a 3-D microwave imaging reflectometer (MIR) system [6,7], which would image ITG and internal MHD modes. The MIR system complements the poloidal scattering system in that each covers a different range of the k_θ-spectrum; the scattering system is more sensitive to higher wavenumbers while the imaging reflectometer is more sensitive to the lower wavenumbers.

Timeline

2009-2010:

Continue maintaining and operating the FIReTIP and high-k toroidal scattering systems on NSTX, and supporting NSTX physics studies. Get renewed funding.

2010-2011:

Continue maintaining and operating the FIReTIP and high-k toroidal scattering systems, and supporting NSTX physics studies. Undergo design reviews for the poloidal scattering diagnostic concepts.

2011-2012:

Upgrade the FIReTIP and high-k scattering systems to support the planned center stack upgrade and increased 5 second discharge length. Install and commission the poloidal scattering diagnostic on NSTX. Undergo design reviews for the 3-D MIR system.

2012-2013:

Operate the FIReTIP and toroidal/poloidal scattering systems on NSTX, and support NSTX physics studies with these diagnostics in the new center stack configuration. Install and commission the 3-D MIR system on NSTX.

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A-15. University of California at Irvine

Research Topic: **Energetic Particle Physics**

Principal Investigator: William Heidbrink

Participating Researchers: Emil Ruskov, Mario Podesta (postdoc), Deyong Liu (graduate student)

Funded under DOE Grants: DE-FG02-06ER54867 and DE-FG03-02ER54681

Introduction

The proposed work contributes to the study of fast-ion instabilities on NSTX. Energetic particle physics is an emphasis of the NSTX program for several reasons. First, fast-ion driven instabilities are observed on most beam-heated NSTX discharges. Through changes in the heat deposition, torque, and neutral-beam current profile, redistribution of the fast ions impacts the plasma performance or evolution of the discharge on virtually every high-performance shot. Second, because the beam ions are super-Alfvenic, NSTX data can play an important role in validating codes that will predict alpha-particle driven instabilities in ITER and other burning plasmas. Third, the ratio of beam-ion gyroradius to machine size in NSTX is comparable to the ratio of alpha-particle gyroradius to machine size anticipated in a spherical tokamak (ST) D-T reactor. Thus, beam-ion studies help assess the viability of the ST reactor concept.

Current research contributions to NSTX

We are responsible for the solid-state neutral particle analyzer (SSNPA) [1] and the fast-ion D-alpha (FIDA) [2] diagnostics. We regularly lead experiments in the Wave-Particle Interaction topical group and also provide diagnostic support and analysis for experiments led by our collaborators. Overall, Irvine personnel have authored five NSTX refereed journal publications and have made significant contributions to five others.

Summary of proposed research plan for 2009-13

The NSTX Energetic Particle research program strives to validate theoretical models of fast-ion instabilities and to develop the means to control their effects. The emphasis in the next five years will be on validation. The NSTX program is positioned to make a major contribution to the international effort to provide high-quality data that rigorously tests theoretical models and simulation codes. In collaboration with theoretical efforts worldwide, our goal is to develop validated codes that can predict fast-ion instabilities and their consequences in ITER. In control, our goal in the next five years is to lay the groundwork for an ambitious program that begins near the end of the five-year period.

Several instabilities are important. Attention will focus on the various Alfven instabilities, such as the toroidicity-induced Alfven eigenmode (TAE) and reversed shear Alfven eigenmode (RSAE).

The NSTX program will supply data that will test specific energetic particle (EP) physics models. The process of validation must address *all* levels of the models, including the most fundamental ones. The physics models build upon a hierarchical construction (sometimes called the "primacy hierarchy") that begins with fundamental constituents and results in fast-ion transport predictions. The elements of this hierarchy are listed in Table 1. At the lowest level are the linear wave properties of the instabilities under study. These include the polarization, frequency, spatial structure, and stability threshold. Next are the mechanisms that determine the ultimate mode amplitude, which include both wave-wave and wave-particle interactions. The wave electric and magnetic fields modify the EP distribution function (DF) and cause fast-ion transport. If these phenomena are understood for a particular case, the next level of validation testing is parametric scaling. The final validation stage is agreement with trends across multiple devices.

	Fundamental constituents ⇒ Derived Observables				
Primacy hierarchy	Linear wave properties	Nonlinear saturation	Transport	Scaling Trend	Statistics
Observables	Polarization, structure, frequency, threshold	Spectral intensity, bispectra, zonal flows/fields	EP DF & transport	Similarity experiments	ITPA database
Agent/ mechanism	EP spatial gradient, velocity anisotropy	Wave-wave, wave-particle interaction	Cross-phase, relaxation	Dimensionless scaling	Inter-machine

Table 1. Primary hierarchy for validation of EP turbulence and transport predictions.

Although the Irvine team will participate in validation at all levels, leadership will occur in two main areas. One leadership area is measurement and interpretation of the transport of confined fast ions. Another leadership area is inter-machine comparisons. Professor Heidbrink previously led two Alfven-mode similarity experiments between NSTX and DIII-D [3]. With the improvement of both fluctuation and fast-ion diagnostics on both devices, further experiments of this sort will be a major area of emphasis.

Timeline

2009-2010:

Complete the first set of papers containing FIDA data. Papers on acceleration of fast ions during HHFW and on fast-ion transport by various instabilities are anticipated. Conduct similarity experiments with DIII-D.

2010-2011:

Analyze the data from the similarity experiments. Propose new experiments based on discrepancies found through detailed comparisons with the theoretical codes that are being developed through the SciDAC Energetic Particle projects. Propose upgrades to the FIDA diagnostic.

2011-2012:

Complete much of the validation work. Begin exploring tools that can alter the linear stability or nonlinear dynamics of the fast-ion driven instabilities. Upgrade FIDA.

Contributions to the NSTX 2009-13 Five Year Plan:

UCI contributed to writing the energetic particle section of chapter 4.

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A-16. University of California at Los Angeles

Research Topic: **The Study of Alfvén Mode Physics and Turbulent Transport in NSTX**

Principal, Co-Principal Investigators: P.I. - Dr. Tony Peebles, Co-P.I.s - Prof. T Carter, Dr. D.L. Brower

Participating Researchers: Dr. Shige Kubota, Dr. Neal Crocker, Mr. Jon Hillesheim (graduate student)

Funded under DOE Grant: DE-FG03-99 ER54527

Introduction

The **N**ational **S**pherical **T**orus e**X**periment (NSTX) has opened up a wide range of exciting new physics research avenues within the overall US Fusion Energy Science Program. In particular, the study of a high-beta, high-performance plasmas in the magnetic geometry of a spherical torus (ST) has begun to provide significant new insight into Alfvén wave physics and transport/confinement research, which benefits not only the ST concept but fusion science overall. UCLA, as an active NSTX team member, has contributed to both the understanding and operation of the NSTX plasma. Application of innovative, cross-cutting measurement techniques have contributed across a broad range of research topics. A primary focus on NSTX has been the collaborative study of the plethora of Alfvén modes and their role in modifying fast-ion transport. A complementary interest is the understanding of the role that turbulence plays in governing anomalous transport in the spherical torus, and identifying the relationship to turbulent transport in other fusion plasma confinement configurations, such as the reversed field pinch and tokamak. UCLA has active research programs in both these areas on other fusion configurations (MST: RFP and DIII-D: tokamak) and is therefore well-positioned to help make these connections. During the next five years UCLA plans to play a major role in ensuring that the cross-cutting physics in Alfvén wave and turbulent transport research are clearly identified so that the overall U.S. Fusion Energy Sciences Program together with NSTX fully benefit. As a final note, in addition to the above research activities, UCLA has also contributed to NSTX operations by providing density profile information via reflectometry and line-integrated density measurement via a sensitive 1mm interferometer. The 5-year plan calls for significant upgrades to these systems, which will further enhance UCLA contributions to NSTX operations.

Current research contributions to NSTX

Alfvén Mode Studies

NSTX exhibits a wide variety of fast-ion driven modes such as compressional Alfvén modes at high frequency and energetic particle modes, such as fishbones, at low frequency. Such modes are of intrinsic interest for understanding wave particle interactions, as well as the more important concern of how such interactions impact fusion performance. Such modes can perturb fast ion orbits and, if they grow to sufficiently large amplitude, such ions may be lost to the wall or transported from the plasma. Understanding their stability, spatial structure, saturation and nonlinear interactions in existing experiments is critical in establishing a predictive capability for future burning plasma experiments. The interaction of fast ions with plasmas is also a topic of significant general interest not only in fusion plasmas, but also in the magnetosphere, ionosphere and solar wind. UCLA, as an institution, has great interest in this area of research. Understanding the wave dynamics is critical in revealing their role in fast ion confinement.

One area that received little attention was the interaction of such modes with each other through nonlinear three-wave coupling. Such interactions transfer energy between different spatial/time scales, potentially playing a significant role in mode damping, saturation, and even excitation. UCLA has performed unique local (reflectometry), and global (magnetics) measurements of nonlinear interactions via three-wave coupling between fast ion driven modes of two distinct types (see PRL, 97, 045002, July 2006). **Figure 1** illustrates the power spectra of reflectometer phase fluctuations (proportional to density fluctuations) obtained from a 50 GHz (cutoff density ~3×10^{13}cm^{-3}) O-mode quadrature reflectometry measurement localized to the core of a beam-heated NSTX plasma. As can be seen there is a rich variety of mode activity. A large amplitude, low frequency mode (~20 kHz) together with numerous harmonics are observed interspaced

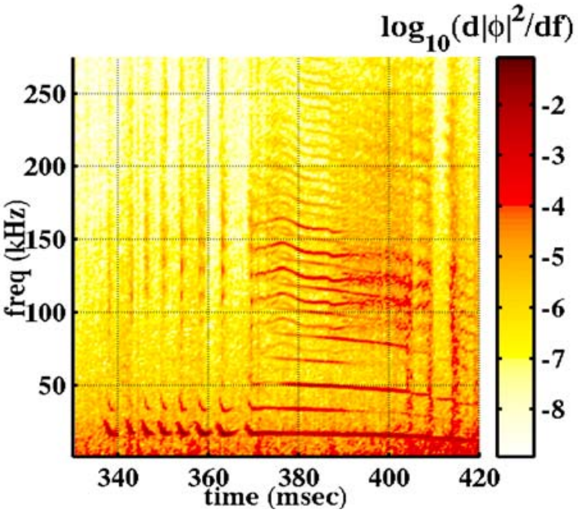

Figure 1. *Power spectra of phase fluctuations of a 50GHz O-mode reflectometer localized in the core of an L-mode NBI NSTX plasma*

with a dominantly high-frequency mode (~120 kHz) that possesses a distinctly different temporal evolution. Careful analysis (including bicoherence calculations) has established unambiguously that pairs of these high frequency modes together with a low frequency mode frequency interact nonlinearly in a three-wave coupling process. Note also that around 390ms the high frequency mode appears to mode split and take on a more "chaotic" character. As mentioned above, such nonlinear processes can transfer energy to different spatial and temporal scales and therefore improved understanding is critical in order to assess their impact on fast ion confinement – especially in next-step devices.

More recently the UCLA focus has moved towards mode structure measurement and comparison to NOVA-K predictions. Multi-channel, simultaneous reflectometry measurements have significantly helped in revealing Alfvén mode structure. These results together with a description of the beta dependence of Alfvén cascades were presented in an **Invited Talk** by Dr. Neal Crocker (UCLA) at the 2007 APS Conference in Orlando, Florida. A list of publications in this research area, where UCLA has made major contributions, is provided at the end of this section. Future plans call for a significant increase in reflectometry spatial coverage by providing 13 simultaneous channels including coverage of high-density plasmas up to $8x10^{19}m^{-3}$. A novel "comb-frequency" generator, recently successfully tested at DIII-D, will be employed so that data is obtained using the same launch and receive antennae. This upgrade will allow the temporal evolution of the ***detailed radial structure*** of various Alfvén modes to be monitored and rigorously compared with theoretical predictions. Quadrature reflectometry also provides a local measure of the absolute ***density fluctuation*** levels associated with these modes (e.g. the low frequency EPM in Figure 1 has an amplitude of ~2%).

As mentioned earlier it is also critically important to establish the ***magnetic fluctuation*** levels to assess their potential in generating fast-ion loss. UCLA, therefore, plans to add a radially-viewing polarimetry (Faraday rotation) capability to provide a measurement of the magnetic field fluctuations associated with these coherent modes. When combined with line-integrated interferometry, multichannel reflectometry and Mirnov coil data, this will provide a complete picture of the mode structure and amplitude, which can then be compared with theoretical/simulation predictions. Detailed comparison with theory will lead to improvement in predictive capability so essential for future studies.

As mentioned earlier, UCLA is interested in making cross-cutting comparisons with Alfvén wave studies in other plasma configurations. UCLA is in a unique position to pursue this avenue of research. UCLA has already made significant contributions to the study of "the sea of Alfvén modes" in DIII-D (Terry

Rhodes, Anne White) as well as to the measurement of magnetic fluctuations in MST (Co-P.I.: Dave Brower, Weixing Ding). MST is also moving quickly towards significant auxiliary heating and current drive, and is concerned about the potential role of fast-ion modes. Very little has been published about Alfvén eigenmodes in RFPs. An interesting point is that there are some significant differences between STs and RFPs that would influence the fast-ion mode spectrum, not the least of which is the q profile. There's a great deal of existing fast-ion mode theory developed for tokamaks that could be applied to RFPs, so there's a lot of theory-experiment comparison that could be performed starting with just a few relatively straightforward measurements. UCLA will play a lead role in facilitating such cross-cutting research which should aid greatly in improving understanding in this important research area.

It should also be noted that at UCLA there is also an active Alfvén mode "fusion campaign" on the Basic Plasma Science Facility (http://plasma.physics.ucla.edu/bapsf/index.html Director: Professor Walter Gekelman). The detailed goals and team members of the campaign can be found at http://plasma.physics.ucla.edu/bapsf/pages/current.html . The campaign is highly collaborative and is headed by Professor William Heidbrink (UC Irvine) who is also an active participant at both NSTX and DIII-D. The primary goal is to improve basic understanding of Alfvén waves through a collaborative theoretical/experimental research. The research will investigate Alfvén waves in a periodic mirror (providing a spectral gap similar to that found in tokamak magnetic fields) and the interaction between fast particles and Alfvén waves. Modification of a test ion beam by pre-existing Alfvén waves will be studied as well as the generation of Alfvén waves by fast particles. An intense ion beam will be injected at a variety of pitch angles into the LAPD plasma. The beam, which will spiral along the magnetic field, will match the phase velocity of Alfvén waves in the background LAPD plasma. The waves are expected to be generated by Cherenkov emission from the fast-ions. The goal is to create an analogue of TAE modes and study them in great detail. Participants include William Heidbrink, Roger McWilliams, Boris Breizman, Sergei Shaparov, Roddy Vann, Co-P.I. Troy Carter and Neal Cocker. Co-P.I., Professor Carter is also actively involved in a separate study of nonlinear interactions between colliding Alfvén waves. This research couples well to the UCLA focus at NSTX and will help in providing intellectual breadth to both efforts.

UCLA plans to more actively leverage UCLA involvement in these broad Alfvén wave/fast-ion research efforts and identify areas strongly cross-coupled to NSTX. Experimental time on the various facilities would then be pursued and results correlated to improve our overall understanding of the physics and role of Alfvén waves in hot fusion plasmas, and particularly in the spherical torus configuration.

Turbulence & Transport

Historically, long wavelength turbulence was thought to play a *secondary* role in the transport properties of NSTX discharges. For example, an early paper by Rewoldt *et al.* indicated that linear growth rates reduced dramatically for both the trapped electron η_i mode (low beta considered) and kinetic ballooning mode (high beta considered) as aspect ratio was reduced. This result was thought to be primarily due to the reduction in bad curvature available to drive such modes. Note, however, that this effect is mitigated as you penetrate deeper in to the core plasma. (i.e. the effect of aspect ratio would be much weaker at r/a =0.5 than r/a~0.8) as was shown by Rewoldt. Gyrokinetic calculations have indicated that linear growth rates are extremely sensitive to a wide range of parameters including electron to ion temperature ratios, ExB flow shear, magnetic shear, temperature and density gradients, beta, beta-prime, aspect ratio, etc. Using actual NSTX profiles linear growth rates for long wavelength ITG-like turbulence are found to be much lower than for shorter wavelength ETG-like modes. In addition, ExB shear flow suppression is generally predicted to be effective for ITG-like modes in NBI heated plasmas while ineffective to the shortest wavelength ETG modes.

To date UCLA has focused attention on longer wavelength turbulence measurements. For example, UCLA has installed a tunable correlation reflectometer to measure turbulent correlation lengths in the core NSTX plasma. In addition, local quadrature reflectometry measurements in the core plasma have allowed determination of local turbulent spectra and estimates of fluctuation levels. Turbulent correlation lengths are found to increase significantly from the edge to the core plasma. The values in the outer plasma (ρ ~0.8) when normalized to the gyroradius ρ_s are similar to those observed in DIII-D – approximately $5\rho_s$. However, deeper in the core plasma (ρ ~0.6) the normalized correlation lengths rise to normalized values significantly larger (~$17\rho_s$) than seen for example in DIII-D. This is surprising. UCLA has spent considerable effort in confirming that these long correlation lengths are not related to the presence of global modes in the NSTX plasmas. Data taken in Ohmic plasmas, stable Helium conditioning and RF only plasmas - devoid of MHD activity - are also found to have similar correlation length characteristics. The source of these long correlation lengths remains unknown and is under active study. New information has recently come to light with an upgrade of the fast sweep density profile reflectometer. The system now generates phase delay versus position (rf frequency) information every 10μs. This can be used to determine correlation length as well as density profiles with high temporal resolution. Recent analysis indicates that there is some evidence that the turbulent correlation length is intermittent. Long correlation lengths are still seen but interspersed are periods when shorter correlation lengths are observed. This is potentially a very interesting observation. In order to confirm, or not, this possibility UCLA plans to install a multichannel (13 channels) "comb frequency" reflectometry system to study the temporal evolution of correlation length. If the correlation is intermittent this will be clearly confirmed by this new system. This system, with suitable antenna modifications, can also be utilized as a Doppler backscattering system to locally probe intermediate-k (TEM-scale) turbulence and ExB flow. Turbulence data can also be obtained at DIII-D to cross-check and confirm any differences in correlation length scaling, flows, intermediate-k response, etc.

It should be noted that the recently upgraded fast sweep (10 μs) profile reflectometer will also be able to contribute to boundary physics studies such as the study of ELMs, ELM suppression and the L-H transition. When the toroidal field is increased to 10 kG this will significantly enhance the profile measurement capability. High resolution density profiles would then be available all the way from the core to the vessel wall. This will aid significantly in analysis of HHFW coupling to the edge plasma. Currently the low toroidal field limits measurements down to densities above $2 \times 10^{12} \mathrm{cm}^{-3}$. This compromises accurate profile inversion in the very edge plasma. The FM system will also be upgraded in frequency in order to access higher core densities.

On the longer timescale UCLA plans to install a multichannel 600 GHz (λ ~0.5 mm) Faraday rotation radial view measurement system. The primary goal of this system will be to provide magnetic fluctuation measurements in similar fashion to that demonstrated by UCLA (Co-P.I., David Brower, Weixing Ding) at MST. The system will contribute to both the study of Alfvén instabilities as well as magnetic turbulence. The system will also provide high bandwidth (40 MHz), high-resolution interferometry data which will be able to *directly probe* the fast waves (electrostatic component) generated by the HHFW.

Summary of proposed research plan for 2009-13.

2009-2010:

Install multichannel "comb-frequency" quadrature reflectometer system (13 channels: 8 widely space channels and 5 closely spaced channels with tunable center frequency) for detailed study of Alfvén wave mode structure, time resolved turbulent correlation length. Perform cross-cutting comparison experiments with DIII-D (e.g. check correlation length scaling using identical system hardware). Separately it is planned to upgrade the operating frequency range of the FM density profile reflectometer to access higher density plasmas.

2010-2011:

Modify launch/receive antennas to optimize for multichannel Doppler backscattering measurement of intermediate-k turbulence and ExB flow. Perform core measurements of low and intermediate-k turbulence at L-H transition. On DIII-D, turbulence reductions are observed at the L-H transition even in the core plasma. Investigate other cross-machine comparisons. Begin design and fabrication of multichannel, radially-viewing 600GHz Faraday rotation (i.e. polarimetry) system for magnetic fluctuation measurements.

2011-2012:

Install multichannel Faraday rotation system. This system will be capable of directly measuring magnetic fluctuation levels associated with Alfvén waves, as well as tearing modes, and potentially magnetic turbulence. The system will also provide large bandwidth (40MHz) high-sensitivity line averaged (along a midplane radial view) interferometry data which will allow direct probing of the strength of HHFW generated fast waves toroidally away from the launch antenna. This will be important in correlating with fast wave current drive efficiency. After installation of the new center stack, the existing high-k backscattering system will become fully operational. Higher-field operation (10 kG) will create an extremely effective internal beam dump (to absorb forward scattered light from large scale fluctuations) at the $2f_{ce}$ resonance. Currently, at 5.5kG, this is located close to inside wall and is therefore ineffective.

2012-2013:

Bring Faraday and high-k backscattering systems into operation to complement multichannel low- and intermediate-k density turbulence measurements. Investigate cross-cutting research with tokamak

(DIII-D) and RFP (MST) community especially in Alfvén wave research areas and the role that magnetic fluctuations, including tearing modes, play in these varying fusion plasma configurations.

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A-17. University of California at San Diego

Research Topic: **Edge Heat and Particle Transport (radial and parallel) and divertor physics**
Principal, Co-Principal Investigators: J. Boedo (PI)
Participating Researchers: J-W Ahn, J. Boedo, S. Mueller, G. Tynan, D. Rudakov, H. Ji, S Zweben
Funded under DOE Grant: DE-FG02-03ER54731

Introduction

Power loads to the divertor are a critical element of the development of the tokamak concept as a fusion power plant and due to the small aspect ratio, the ST concept is particularly sensitive to the power deposition in the walls. Additionally, particle exhaust, wall erosion and impurity generation and transport are crucial items in any tokamak, but even more in a ST due to tight tolerances. Therefore UCSD proposes a 5 year program that makes contributions to studying most, if not all, the processes involved in controlling or mediating particle and heat transport in the boundary/SOL. NSTX has several activities in it's 5 year plan to study and eventually manipulate heat loads in the divertor and they include divertor detachment and the Liquid Lithium Divertor (LLD). UCSD will therefore contribute by studying both particle and heat turbulent radial transport, blob generation and dynamics, ELM dynamics and parallel transport. Among the contributions to NSTX, UCSD will install a second reciprocating probe in the divertor region to enable divertor parameter studies during detachment and operation of the LLD. Development of magnetic sensors has been completed to study electromagnetic turbulence, thought to be relevant at high beta, and fast Te and possibly Ti diagnostics are in development. The probe has capabilities to measure Reynolds stress, a mechanism argued to be involved in the L-H transition in generating self-organized flows.

Current research contributions to NSTX

UCSD has built, installed and commissioned a fast scanning probe for boundary physics studies, the probe capabilities are summarized below. There are NSTX needs for a second probe in the divertor region for LLD and detachment studies and the expected capabilities are also summarized below.

$n_e, T_e, V_{fl}, I_{sat}, E_\theta$ profiles. With 1 ms time resolution and 1.5 mm spatial resolution. So far, one plunge per discharge. Profiles obtained in 60 ms. These are used for profile studies, decay length studies, perpendicular and parallel transport model validation. Also DC (low freq) convective cells studies. Relevant edge physics and divertor physics.

$V_{fl}, I_{sat}, \tilde{E}_\theta, \tilde{\Gamma}_r$ profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 60 ms. Plans to add $\tilde{T}_e$ measurement with 400 kHz time resolution and 1.5 spatial resolution. These are used for turbulent particle and heat transport evaluation and to determine the conduction and convection heat channels, which have applications for edge physics, L-H transition physics, turbulent transport physics, intermittency. Relevant for L-H transition physics, edge physics and divertor physics.

We recently added 3 magnetic coils to add $\tilde{A}_r, \tilde{A}_\theta$ measurements to evaluate the importance of electromagnetic turbulence on particle and heat transport in an ST. Relevant since these channels will emerge at high beta. Relevant for L-H transition physics, edge physics and divertor physics. The data is being evaluated in the framework of a collaboration with Korea.

Summary of proposed research plan for 2009-13

We propose to contribute to the NSTX program by measuring edge/SOL profiles in order to increase understanding of perpendicular particle and heat transport and their connection to the divertor parameters, understand ELM-mediated transport and parallel heat and particle transport. Will also install a divertor probe to aid divertor detachment and LLD work. Some of these venues of research are ongoing and the primary elements of our plan are:

- Runtime to be discussed, but of the order of 1 day per campaign
- Need boundary simulation capability
- Will build, commission and install X-point probe
- Will develop and install fast Te diagnostic for heat flux studies
- Will develop a Ti diagnostic for the boundary (either RFA or new diagnostic)

Timeline

2009-2010:

Install new shaft and head with expanded capabilities. Continue work on parallel heat conductivity. Complete intermittency-mediated transport and SOL scaling work and comparison to DIII-D. Help characterize plate-based LLD. Design and build divertor probe. Start electromagnetic transport studies with new set of coils. Finish construction of fast Te diagnostic.

2010-2011:

Install, commission fast Te diagnostic, perform first heat conduction measurement. Continue LLD support. Evaluate scaling of EM transport using optimized set of coils. Contribute to SOL width studies by using new capabilities. R&D on Ti measurement should be completed. Focus on one concept.

2011-2012:

Install X-point probe at NSTX. Commission and make first measurements: $n_e, T_e, V_{fl}, I_{sat}, E_\theta$ profiles. With 1 ms time resolution and 1.5 mm spatial resolution. So far, one plunge per discharge. Profiles obtained in 60 ms. These are used for profile studies, decay length studies, perpendicular and parallel transport model validation. Also DC (low freq) convective cells studies. Relevant edge physics and divertor physics.

$V_{fl}, I_{sat}, \tilde{E}_\theta, \tilde{\Gamma}_r$ profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 60 ms. Plans to add $\tilde{T}_e$ measurement with 400 kHz time resolution and 1.5 spatial resolution. These are used for turbulent particle and heat transport evaluation and to determine the conduction and convection heat channels, which have applications for edge physics, L-H transition physics, turbulent transport physics, intermittency. Relevant for L-H transition physics, edge physics and divertor physics.

Mach profiles in the divertor. Heat flux driven by large flows account for most of the divertor heat flux in detached discharges. Compare lithium and carbon divertor. Study poloidal asymmetries and the physics of blob detachment and its influence on decay lengths. Study X-point driven turbulence as a possible tool to manipulate SOL decay length. Continue Ti diagnostic construction.

2012-2013:

Ti diagnostic installation and commissioning, first measurements. Continue LLD studies. Work on active SOL decay length control by using biasing and electrical blob detachment. Continue poloidal asymmetries work and electromagnetic transport work.

Contributions to the NSTX 2009-13 Five Year Plan:

Contributed to Section 3.5.1.3 for the SOL turbulence and width program.

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A-18. University of California at San Diego

Research Topic: **Edge Plasma Simulations in NSTX and CTF: Synergy of Lithium-Coating, Non-diffusive Anomalous Transport and Drifts**

Principal, Co-Principal Investigators: A.Yu. Pigarov (PI), S.I. Krasheninnikov (co-PI)

Participating Researchers: A.Yu. Pigarov, graduate student (TBN), S.I. Krasheninnikov

Funded under DOE Grant: DE-FG02-08ER54989

Introduction

In the Lithium Wall concept [1-3] for fusion devices, the usage of lithium as plasma facing components allows the handling of frequent transient high heat power loads and the active control of plasma density and hydrogen isotope retention. Lithium Wall (LW) can also improve the core plasma performance and increase fusion power [1]. As has been shown very recently on NSTX, lithium coatings can reduce the particle recycling [4,5] and even eliminate the ELM activity [5,6]. The LW concept can be studied on NSTX with Liquid Lithium Divertor module planned for installation and on the next-step NHTX and CTF tokamaks.

Although a number of experiments related to the application of lithium technology in fusion devices increases year-to-year and there was significant progress in understanding the possible impact of lithium coatings/liquid on tokamak plasma performance, there are many issues in the LW concept that remain to be understood in detail. The physical processes of lithium-plasma interaction (e.g., lithium sputtering, evaporation, and hydrogen isotope retention) depend largely on plasma conditions and more work is needed for their characterization. Moreover, the behavior of edge plasma, radial gradients of edge plasma parameters and electric field, parallel plasma flows, and properties of intermittent non-diffusive cross-field transport have not been investigated yet for the low-recycling regimes envisaged to occur in the tokamaks with large area of plasma facing components covered with lithium. In addition, we see that engineering, plasma-lithium interaction, and plasma physics issues are strongly coupled. We highlight that numerical simulation based on edge-plasma transport code UEDGE is a powerful tool to consider these issues together and to perform multi-parameter analysis for Lithium Wall.

Summary of proposed research plan for 2009-13

We will work on sophisticated edge-plasma transport modeling in NSTX to develop a better understanding of basic boundary-plasma physics, in particular, in the low-recycling regimes expected in the presence of lithium coating/liquid and we will work closely with NSTX team on simulation of experimental data.

The main goal of the proposed theory research is to study the synergy of lithium coating/liquid, asymmetric ballooning-like anomalous non-diffusive cross-field transport, and classical plasma drifts. These are three main ingredients affecting the edge plasma transport and strong synergistic effects are expected in many aspects of basic edge-plasma physics. We will analyze the resulting plasma flow patterns, material migration, and impurity penetration into the core for NSTX. We will provide a support in modeling for experiments with Lithium Liquid Divertor (LLD) module planned on NSTX, in particular, the contributions will be made to assessment of edge plasma parameters in the low-recycling regimes, estimation of heating and net erosion of lithium components, and evaluation of hydrogen pumping/retention in lithium.

For the next step tokamaks, NHTX and CTF, we plan to analyze the hydrogen pumping, plasma contamination with lithium impurities, and power handling capabilities in the Lithium Wall concept. For NHTX and/or CTF, we intend to compare the plasma performance in conventional operation regime with all-carbon wall and in alternative regime with Lithium Wall.

In the period FY09-11 covered by the DoE grant DE-FG02-08ER54989, we will use the multi-fluid, multi-ion species, two-dimensional code UEDGE to simulate transport of plasma, neutrals, and impurities in the edge, scrape-off layer, and divertor for NSTX, NHTX and CTF tokamaks. This code has existing capabilities that suit our research. Improvements will be made in UEDGE mainly for better description of lithium impurity sources and hydrogen recycling which depend on surface temperature, thermostat temperature, irradiation dose, and liquid flow speed.

We have also developed the Wall and Plasma Surface Interaction (WallPSI) code which is the 1-D multi-scale multi-species code for particle and heat transport inside plasma-facing components [7]. The code is in the process of benchmarking against vast experimental data on hydrogen retention, permeation, and erosion rates for major fusion related materials. WallPSI is a part of ongoing SciDAC project on Framework Application for Core-Edge Transport Simulations (FACETS) [8]. Initially this work includes coupling of core plasma codes, 2-D edge-plasma code UEDGE, and WallPSI. The coupling of WallPSI to UEDGE will be through assigning on instance of WallPSI to each wall facing cell of UEDGE. The project goal is to provide detailed core to wall transport modeling of tokamak fusion reactors. In the period FY11-13, we plan to modify and validate WallPSI code in a way necessary to model discharges with LW and use the coupled WallPSI/UEDGE codes for further studies of the Lithium Wall concept.

Contributions to the NSTX 2009-13 Five Year Plan:

This work also contributes to chapter 5 on boundary physics.

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A-19. University of Colorado at Boulder

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

Principal Investigator: Tobin Munsat

Funded under DOE Grant: 1R01GM083953-01

Introduction

The goal of this project is to perform analysis on data from the NSTX Gas Puff Imaging (GPI) diagnostic in a twofold effort to (a) quantitatively characterize the convective "blob" transport in the NSTX edge and (b) assess the existence and characteristics of sheared and zonal flows as visible in the viewing window of the GPI instrument. Analysis of this type and advanced understanding of the topics in this proposal is critical to the evaluation the plasma-boundary interface in fusion plasmas, and can have significant impact on next-step devices.

Current research contributions to NSTX

This collaboration has just been funded, but draws upon the development (complete) of the HOP-V code, written by the Principal Investigator for this purpose [1]. We have already created an extensive library (>400 shots) of derived velocity fields for use in this study.

Summary of proposed research plan for 2009-13

The research objectives will be achieved through the derivation of detailed velocity maps of cross-field plasma motion, resolved in both space and time, using the HOP-V (Hybrid Optical-flow Pattern-correlation Velocimetry) code, specifically written by the principal investigator for this purpose. Statistical analysis of the derived velocity fields will enable the identification of a wide variety of flow properties, including flow shear, the relationship between flow evolution and H-mode behavior, the connection between flow, filament birth and evolution, and NSTX operating parameters/regimes, and the identification of zonal flows, among others. Furthermore, the evolution of the velocity fields can be used to assess convective edge transport, which can then be compared over a range of conditions to theoretical models and computed predictions. Indeed, a series of theoretical predictions of blob behavior already exist or are in the development stage, and the derivation of velocity maps from the GPI measurements is the key to connecting these models to the experimental observations.

The HOP-V velocimetry code developed for this project uses a hybrid optical-flow / direct-pattern-correlation technique which overcomes the limitations of many common velocimetry approaches. Advantages include the freedom from a-priori knowledge of any aspect of the velocity behavior, freedom from the “aperture effect” which limits many algorithms to deriving velocity only along density gradients, and freedom from imposed (arbitrary) definition of identifiable structures. The hybrid code derives “dense” velocity fields at the spatial and temporal resolution of the underlying image frames, which in this case is 64x64 pixels, 300 timepoints, taken at 4 μs per frame at a spatial resolution of ~4 mm.

The Principal Investigator has established contacts with both S. Zweben, who heads the GPI project and coordinates many of the associated efforts, and with Lodestar Research, Inc., who are responsible for many of the most relevant theoretical models of convective blob transport in the plasma scrape-off layer.

There are no explicit run-time requirements for the initial funded three-year span of the project, for which data is already in hand. Additional image data will be collected by the on-site GPI team, with which we have close contact, and may evolve as the analysis is completed.

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A-20. University of Illinois at Urbana-Champaign

Research Topic: **LLD and SOL Interactions on NSTX**

Principal, Co-Principal Investigators: David N. Ruzic

Participating Researchers: M. A. Jaworski (post-doctoral researcher)

Funded under DOE Grant: DE-PS02-07ER07-29

Introduction

The implementation of the Liquid Lithium Divertor (LLD) in NSTX presents unique opportunities in plasma-material interactions studies. The addition of a large area pumping surface provides the possibility of improved density control and new machine operating regimes. Lithium's high evaporation rates at relatively low temperatures presents a challenge to successful implementation and directly influences the particle pumping capabilities of the LLD. It is expected that as the temperature of the LLD increases, a transition between low and high recycling will occur impacting power deposition and particle fluxes. Due to the numerous temperature dependent properties of lithium (e.g. sputtering, ion-burial, and evaporation), the LLD-SOL interactions are expected to be complicated and represent a coupling at the plasma-wall interface.

To accomplish the stated goal of a quantitative understanding of plasma-LLD interactions, a comprehensive set of diagnostics will be utilized. Available NSTX diagnostics will be used such as the D_α camera to view D_α light emissions that correlate to the wall recycling of the LLD. Other diagnostics of use will be bolometers and a fast-framing camera to measure the radiated power of the plasma and any bulk motion in the LLD lithium surface respectively. In addition to the large set of diagnostics already on NSTX, this proposal seeks first to provide input into the design of a diagnostic array to be installed at one of the toroidal breaks in the LLD. The array is being fabricated by PPPL, and will consist of graphite armor with embedded, flush mounted Langmuir probes (LP's) spaced radially to monitor edge plasma density and temperature. To measure these parameters, the group at the University of Illinois at Urbana-Champaign (UIUC) has specified that the LP's be installed in sets of three at each radial location, so they can be operated in a "triple probe" configuration. Embedded thermocouples will provide feedback on the heat load experienced at the LLD radial position during each NSTX discharge.

Measurement of the lithium and deuterium flux at the interface between the LLD and the plasma will be provided by an array of photodiodes. A set already exists with a view perpendicular to the surface of the LLD, and a tangential array will eventually be added. A measurement of the deuterium and lithium fluxes will provide a detailed understanding of the recycling coefficient of the LLD during each discharge as a function of the incident heat flux as measured by the embedded thermocouples. These data will help calibrate infrared measurements of the LLD, which will be difficult due to lithium's reflectivity and chemical interactions with impurities. Together, these measurements will lead to a greater understanding of edge plasma behavior and its influence on the gross performance of the machine as a whole.

Current research contributions to NSTX

At present, UIUC personnel provide design consulting for the LLD diagnostic module to be installed during the summer of FY08. This consultation covers the implementation of the divertor tile Langmuir probes, data acquisition and probe biasing, as well as thermocouple implementation. Beginning in FY09, UIUC will station a post-doctoral researcher at PPPL to participate in the operation of the diagnostic module, data collection and analysis with a focus on the proposed research plan.

Summary of proposed research plan for 2009-13

The primary UIUC research interest is the interaction between the SOL plasmas produced in NSTX and the LLD. The UIUC group will fabricate and install the signal detection and biasing electronics for the dense "triple probe" array of edge LP's embedded between the LLD segments. The density and temperature data obtained with this array will be used to quantify the SOL-LLD plasmas at the divertor edge, using "state-of-the-art" SOL models. With the proposed machine upgrades, scaling studies will be carried out comparing current NSTX level fields (0.5T) to the upgraded levels (1T) with the goal of extrapolation to a Next-Step ST system. The data and analysis obtained with the LLD on NSTX, while most applicable to the ST system, will provide key experience on the performance of liquid lithium PFCs applicable to other confinement schemes.

Timeline

2009-2010:

Operation of the edge diagnostics will begin in this run campaign. Extensive data collection will occur during the NSTX run campaign and edge characterization will take place while model development and extension occurs of the LLD-SOL interface.

2010-2011:

Following the initial model development describing LLD-SOL interface, dedicated XPs will be proposed for this run campaign testing the limits of the model and pumping ability, as well as temperature limitations of the liquid lithium surfaces. Model refinement and extension will be carried out based on this data. Pertinent information for the second iteration of the LLD will be provided based on the model to date. Diagnostic upgrades will be proposed for the following research campaign based on present experience.

2011-2012:

With the introduction of an LLD that potentially includes flowing lithium for active cooling, the SOL-LLD plasma and models will be tested for such a module design. Characterization of the new SOL parameters will be necessary for future scaling studies at higher toroidal field and plasma currents after the planned center stack (CS) upgrade. XPs will be proposed to test the power handling limits of the new LLD design.

2012-2013:

Analysis of the new plasma parameters and machine operation will occur this year after the planned CS upgrade. The ability to extrapolate the model developed in the previous years will be tested during operation at higher fields and plasma currents. Additionally, power handling will again be tested while the edge is characterized for various LLD temperatures. This model development will be applied with special focus to increased power handling for the proposed NBI upgrade.

2013:

After several years of research on the LLD-SOL interactions on NSTX with and without the proposed upgrades, a model will have been developed describing the pumping capabilities of the active lithium surfaces of the LLD over a range of magnetic fields and plasma currents. The impact of these models toward scaling to a Next-Step ST design will be assessed and the feasibility of liquid lithium in these scenarios evaluated from a firm experimental basis.

Summary of Additional Off-site Research Activities

In addition to the research undertaken at NSTX, UIUC is home to an active research group which can contribute to the NSTX mission. Two experiments in particular, the Ion-Interaction Experiment (IIAX) and the Solid/Liquid Lithium Divertor Experiment (SLiDE) will provide a laboratory basis for relevant parameters. The IIAX experiment has a long history of making fundamental sputtering yield measurements form exotic surfaces, including liquid lithium and lithiated graphite. The SLiDE machine utilizes an electron beam to mimic divertor heat fluxes onto a liquid lithium tray for studies of lithium behavior and power handling in fusion relevant conditions. Experimental results from both of these machines will support the NSTX mission and Next-Step ST designs.

A-21. The University of Tulsa

Research Topic: **Energetic Particle and Flow Shear Effects in Resistive MHD Instabilities**
Principal, Co-Principal Investigators: Dylan P. Brennan
Participating Researchers: Ryoji Takahashi, 2 graduate students
Funded under DOE Grants: DE-FG02-08ER54950 and DE-FG02-07ER54931

Introduction

The main thrust of our research plan is to simultaneously address linear dispersion relation analyses, modified Rutherford equation modeling, and nonlinear evolution computations for the onset and evolution of resistive MHD instabilities in comparison to cases selected from the NSTX and DIII-D experiments. The specific sub-topics we are currently focused on are the effects energetic particles and toroidal flow shear have on this physics.

One part of the work will focus on the use of the PEST-III code to compute the ideal MHD outer region solution for multiple rational surfaces using model equilibria based on experimental equilibrium reconstructions, and the subsequent use of the PEST-III results both in linear dispersion relation solutions including coupled modes, and modified Rutherford modeling for a single island evolution through to saturation. The ideal MHD outer region solution from the PEST-III code will be computationally matched to the resistive inner layer solutions[1] at each rational surface to determine the stability of both tearing and interchange resistive mode parities. An effort is underway to develop the energetic particle effects and toroidal flow shear into the PEST-III and inner layer computations. The tearing parity solutions (Δ') will also be used within the modified Rutherford equation to study the evolution of resistive modes to saturation [2,3] in comparison to experiment and simulation.

Another part of the work will employ the NIMROD code [4] for nonlinear numerical studies of coupled resistive mode evolution. NIMROD currently has complete handling of energetic particle and toroidal flow shear effects.

Recent studies [5,6,7] have found that in DIII-D discharges where the β_N approaches the ideal kink limit for the n=1, the free energy available to the tearing mode, or the linear stability index Δ', increased rapidly causing the m/n=2/1 tearing mode to onset. This mechanism was shown to operate even in the presence of coupling between multiple modes [6,2]. Most recently, in a high β_N DIII-D discharge, a strong, but non-resonant m/n=1/1 perturbation was found to be dominant in the core and coupled to the 2/1 mode, which was driven unstable by the approach to 1/1 resonance [7].

Obtaining a clear and accurate understanding of the physics of onset and evolution of resistive MHD modes in NSTX is especially important considering the planned increase to magnetic field and current in the experiment. To date, stability analyses of the level of accuracy described above have not been performed with NSTX equilibria. It is an open and important question whether similar mechanisms are operating in NSTX discharges, and how their influence on the mode onset and evolution compares with those at higher aspect ratio. This is even more important when considering the added physics involved with toroidal flow shear and energetic particles.

Current research contributions to NSTX

Only the initial stages of the NSTX specific research has begun, with an increasing amount of such research expected over the coming years. A single equilibrium reconstruction from NSTX shot 123970 from the LRDFIT code has been adapted for use in PEST-III, NIMROD, etc. in late 2007. This discharge developed a 2/1 NTM shortly after the time of this reconstruction. The effort has begun to generate an appropriate series of model equilibria based on this and other reconstructions.

Equilibria which model the state of the experimental discharges after the proposed upgrade to the experiment, including higher field and current, are also being considered.

Summary of proposed research plan for 2009-13

We propose to study the effects of toroidal flow shear and energetic particles on low order rational MHD modes in NSTX and DIII-D equilibria.

Experimental discharges from NSTX that exemplify the physics of energetic particle and flow shear effects in the onset and evolution of resistive MHD instabilities will be studied and compared with results from simulation and modeling. Analyses with NIMROD can be complimented with a coupled rational surface analysis of the linear mode onset physics, and the modified Rutherford equation analyses described above, to clarify the effect aspect ratio has as the system evolves to instability. A thorough theoretical and computational analysis of how these effects depend on aspect ratio will give us insight to further develop our theoretical description of the physics of these instabilities.

Recently, results have been published showing numerical computation of mode onset and evolution which include flow shear as measured in DIII-D experimental discharges [2]. Systematic studies of flow shear effects on coupled resistive MHD modes have also recently been presented at EPS 2008 [8]. In these cases case a n=1 mode is dominant in the core and drives an n=2 mode through nonlinear coupling. Here the growth rates of the n=1 and n=2 modes are both increased with flow, but the relative amount of drive to the n=2 mode is decreased. The increased growth rates with increased flow is due to inner layer effects, while the toroidal coupling is reduced with flow, and thus the relative amount of flux driven in the n=2 is reduced. Even for moderate toroidal flow shear, the inner layer solutions can be affected, the relative rotation between rational surfaces can significantly affect the coupling, and the resultant nonlinear state will not be well described by linear models.

The combined application of these tools in comparison to the onset of resistive instabilities in DIII-D and NSTX will be extremely fruitful in our efforts to better understand this physics, and what to expect from future experiments. In particular, the results presented at EPS showed that toroidicity strongly affected behavior of the poloidal spectra of the n=1 and 2 modes in this nonlinear evolution when compared with a standard large aspect ratio expansion model in cylindrical geometry. Furthermore, recent experiments on NSTX [9] have shown that a 1/1 mode component interacts with the 2/1 mode in what may be a similar mechanism to that detailed in DIII-D hybrid discharges [7]. How the rotational shear modifies the onset in the NSTX experiments, within the context of the influence of this coupling, and how the lower aspect ratio affects this physics in comparison to DIII-D, will be addressed in this research.

Another part of the work will focus on the application of the delta-f and PIC methods already developed into the NIMROD code [10] to analyses of energetic particle effects on resistive mode onset and evolution in NSTX and DIII-D discharges. Assuming a low density of energetic particles ($n_h \ll n_0$) and quasineutrality, the modification made to the MHD equations to include the energetic particle effects is to include an energetic particle pressure tensor into the momentum equation:

$$\rho \frac{\partial V}{\partial t} + V \cdot \nabla V = J \times B - \nabla \cdot p_b - \nabla \cdot p_h$$

where p_b is the background pressure tensor, p_h is the "hot" particle pressure tensor that is assembled from a PIC δf method. Here f is the velocity distribution function over the computational grid and $f=f_{eq}+\delta f$ where f_{eq} is the equilibrium or steady state distribution and at each timestep $p_h=p_{h0} + \delta p$ where $\delta p = \int m(v - V_h)^2 \delta f(r,v) d^3v$ is integrated over the volume. The δf evolves along the phase space characteristics (or trajectories) using the Vlasov equation. This is similar to a Monte-Carlo method in that statistics are used to calculate the moments of the distribution function.

The NIMROD PIC code has has been successfully benchmarked against both the NOVA-K and M3D codes for the transition of an m/n=1/1 internal kink mode to the Fishbone instability, which has a complex eigenvalue, as the fraction of energetic particle β to the total β is increased. With this formulation we can impose hot particle distribution functions on the resistive single fluid and two fluid MHD computations, calculate the effects, and compare with simple model described above for the effect on the outer ideal MHD region of a linear resistive MHD calculation. The combined application of these tools in the analyses of the onset and evolution of resistive instabilities in NSTX and DIII-D will be extremely fruitful in our efforts to better understand this physics. The addition of the kinetic effects of a non-Maxwellian distribution in the linear resistive stability codes will provide the basis for the study of a series of experimentally relevant cases. The accompanying inclusion of the hot particle effects in linear and nonlinear computations with NIMROD for the same cases will produce important scientific results and contribute to our understanding of what to expect from future burning plasma experiments.

The primary elements of our plan are:

- PEST-III / Inner Layer analyses of model NSTX equilibria and (possibly) equilibrium reconstructions.
- Quasilinear modified Rutherford analyses of mode onset and evolution.
- Nonlinear initial value computations of coupled mode evolution using NIMROD.

Timeline

2008-2009:

Begin applications of the δf code developed into NIMROD on model equilibria. Develop an analysis of resistive mode onset in selected NSTX cases, possibly including accurate equilibrium reconstructions and linear analyses. Begin linear analyses of flow inclusive equilibria with NIMROD in comparison to results from PEST-III.

2008-2009:

Extend the previous analyses to focus on aspect ratio effects using model equilibria in comparison with experimental cases. Study the nonlinear coupling between modes in nonlinear simulations.

2010-2013:

Study linear onset and nonlinear evolution of resistive modes in tokamaks, in comparison to experimental cases, including kinetic effects of energetic particles and flow shear effects, using reduced analytic models, linear codes, and NIMROD.

Contributions to the NSTX 2009-13 Five Year Plan:

Contributed to Section 2.1.1 Tearing Mode / NTM Physics

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A-22. University of Washington at Seattle

Research Topic: **A) Solenoid-free Plasma Startup using Coaxial Helicity Injection, B) Deep Fuelling and Momentum Injection using Compact Toroid Fuelling**

Principal for CHI (Co-Pi for CT - Thomas R. Jarboe), Co-Principal Investigator (Principal for CT - Roger Raman)

Participating Researchers: Brian A. Nelson, Dennis Mueller, Henry W. Kugel, Steve Jardin, Michael Bell and others from PPPL, LLNL, ORNL

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Introduction

The primary goal of our research is (1) to incorporate CHI started discharges for integration with non-inductively driven discharges so that nearly full non-inductive startup and ramp-up current can be demonstrated on NSTX, (2) Demonstrate deep localized fuelling using Compact Toroid Injection with simultaneous momentum injection for eventual use in low wall recycling discharges.

Current research contributions to NSTX

CHI research in NSTX has made considerable progress in developing transient CHI as a viable method for solenoid-free plasma start-up. These are (a) the generation of closed flux current in HIT-II and the very successful coupling of this current to induction from the central solenoid including CHI current generation with a pre-charged central solenoid [1], (b) the generation of 100kA closed flux current in HIT-II and demonstration of CHI plasma quality similar to that produced inductively [2,3], (c) the successful CHI generation of a record 160kA of closed flux current in NSTX demonstrating the high current capability of this method in a large ST [4,5,6] and (d) Successful coupling of CHI started discharges to induction from the central solenoid with the discharge transitioning to an H-mode demonstrating compatibility of this startup method with high-performance plasma operation [7]. The 160kA result was recently accomplished using the transient CHI method, first developed on the HIT-II ST [8].

In the area of Compact Toroid Injection we have informed the ST community through several presentations and two recent journal papers that describes the need for this advanced fuelling system for steady-state ST operation. The first paper [9] describes the importance of feed-back controlled density profile control and momentum injection benefits for sustaining high-bootstrap current fraction discharges under steady state operation. The second paper [10] describes the improved tritium usage and reduced tritium losses to the walls that could be realized as a consequence of CT fuelling.

Summary of proposed research plan for 2009-13

<u>(A) Coaxial Helicity Injection:</u>

(1) In this approach a transient CHI equilibrium will be produced and induction from the central solenoid will be added to this startup plasma to demonstrate compatibility of the CHI discharge with plasmas conventionally produced using the inductive method. In subsequent experiments, the CHI-started plasma will be driven inductively using a combination of outer poloidal field coils in conjunction with RF and NBI to ramp the initial startup current to a level where it can be non-inductively driven by neutral beams and by High Harmonic Fast Waves.

(2) The CHI process initially drives current in the edge, whereas other non-inductive methods drive current in the interior of the plasma. This unique capability of CHI will be used to drive steady-state current at the edge of a pre-formed inductive discharge in NSTX for the purpose of improving the edge current profile and controlling edge SOL flows for the purpose of altering the SOL density.

(3) Recent work on HIT-II has shown poloidal flux amplification when CHI is operated at low toroidal field. In dedicated experiments the physics of relaxation current drive will be studied as this has the potential of increasing the CHI produced current beyond what is possible using transient CHI.

Coupling to OH: Work conducted during 2008 in NSTX has conclusively demonstrated the coupling of CHI started discharges to inductive drive from the central solenoid. The remaining steps are (1) to increase the magnitude of this current to about 500kA, using higher voltage capability and higher TF of up to 1T (2) to heat the CHI started discharge with 350kW of ECH so that the electron temperature is increased above 200eV, 3) at this temperature, HHFW should be able to further increase the temperature to about 1keV, 4) At 500kA NBI should be able to ramp the current up to several hundred kA and to sustain it noninductively.

Coupling to a pre-charged OH coil: During 2008, preliminary work with a pre-charged solenoid showed a CHI discharge could be initiated under conditions when the OH introduces fringing error fields. These discharges will be improved to enable start up under this condition.

Edge current drive for a high beta NSTX discharge: The goals are to determine the magnitude of edge current that can be added without confinement degradation. Since CHI current drive is applied to the edge region, it is possible that this current drive method can be used to modify the bootstrap current drive profile by providing current drive in regions where conventional methods cannot provide current drive. Initial experiments will use the transient CHI capacitor bank to apply voltage to the lower divertor legs of a reference inductive discharge. The purpose is to try to duplicate the experiments conducted on HIT-II, but with much improved diagnostics. The next step will be to reproduce these experiments using the DC power supply so that the duration of the edge current can be prolonged. Another purpose of these experiments is to alter the SOL flows to control the SOL plasma density. In a related experiment, the capability of the CHI system to be able to bias the SOL of a pre-formed LSN discharge will be used to control edge particle flows. Previous experiments in other machines have clearly shown that edge biasing can be used to favorably improve edge flows and possibly control the particle content in the closed flux region. For example, in NSTX high performance H-mode discharges, it is well known that the electron density continues to increase, until MHD eventually terminates the discharge. From previous experiments in tokamaks, it is well known that anti-CHI biasing of the lower divertor electrodes can result in pumping of the SOL as the E x B flows are directed into the divertor region. Reducing the SOL density has the potential to increase the edge pedestal temperature during H-mode discharges.

Steady-state CHI for poloidal flux amplification: This study is needed to investigate the high current potential of CHI under steady state operation. Experimental data produced as part of this work is needed in conjunction with computational modeling work carried out by X. Tang of LANL and C. Sovenic of the University of Wisconsin to develop an understanding of relaxation current drive physics. Steady state CHI experiments thus far have succeed in attaining 390kA of CHI generated toroidal current in 330ms discharges using about 28kA of injector current. CHI discharges have been obtained without relying on the central solenoid. These discharges will provide data for a more complete understanding of dynamo current drive physics, which was described in the previous section. The edge plasma in these discharges will also be diagnosed in detail using the edge dynamo probe, ion Doppler spectroscopy and edge fluctuation measurements.

(B) Compact Toroid Injection:

The first year will be spent preparing the injector, which is currently in storage at PPPL, for installation on NSTX. After that the injector will be re-commissioned and the CT injector – NSTX control interfaces implemented.

The primary objective during the second and third years after installation on NSTX will be to develop tools needed for the non-inductive sustained operation phase. This involves:

- Demonstration of localized deep fueling.
- Demonstration of the ability to alter the fuel mass and deposition location.
- Demonstration of the ability to fuel advanced confinement mode discharges by injecting CTs into H-mode discharges.
- Measure momentum injected by the CT by configuring it for tangential injection in NSTX.
- After initial results on pulsed power system requirements are obtained, we will design the pulsed power system for a high repetition rate CT injector for NSTX. These would be used to conduct multi-pulse CT injection experiments.

Timeline

2009 – 2010:

- CHI: Use Lithium to improve CHI performance. Improve CHI voltage capability to 2kV.

2010 – 2011:

- CHI: Using the 350kW ECH system, the absorber field null capability and the full 2kV capability we will increase the magnitude of the CHI started currents. Test edge current drive.
- CT: Off-line testing of the CT injector.

2011 – 2012:

- CHI: Operate at 1T. Couple to HHFW and then to NBI. Use metal divertor plates to improve CHI current startup capability. Test relaxation current drive.
- CT: Demonstration of momentum injection.

2012 – 2013:

- CHI: Maximize solenoid-free startup currents using synergism with outer PF coil startup.
- CT: Test of localized core fuelling.

2013:

- CHI: Use CHI startup for full integration with nearly full non-inductive operation, which includes startup with CHI, reaching Ip ~500kA with or without HHFW current boost followed by ramp-up with NBI to currents levels where it is non-inductively sustained.
- CT: Initial test of multi-pulse operation for the eventual goal of fuelling low recycling discharges.

Contributions to the NSTX 2009-13 Five Year Plan:

We wrote the section on Solenoid-Free startup of (Chapter 6.4) in the NSTX 5yr plan document. This work also contributes to the chapters on boundary physics and Integrated operations.

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