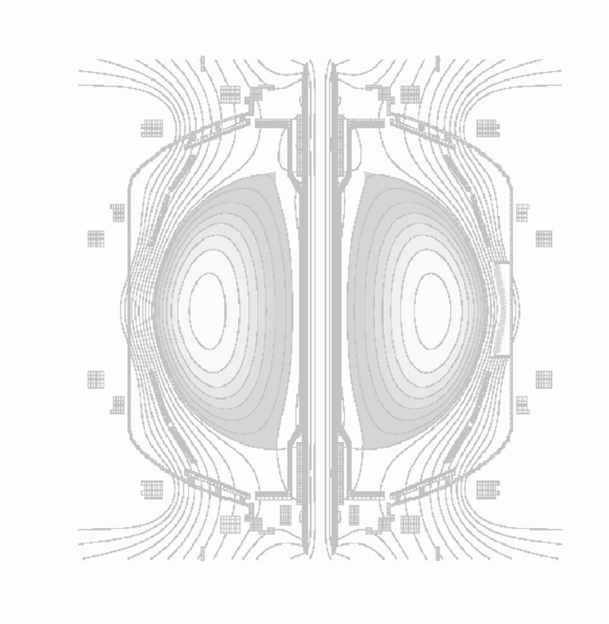

Appendix

NSTX Collaboration Research Plans

The NSTX National Research Program is carried out by a broadly based research team, which has grown since the start of NSTX experimental operations in FY 2000. NSTX research collaborations have made substantial contributions to Innovative Confinement Configuration research in Fusion Energy Sciences. 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 17 universities, national laboratories (including PPPL), and private industry, most of which participated in the team building effort since FY 1998, obtaining direct collaboration funding from DOE. About 45% of the NSTX scientific staff in full time equivalent (FTE) and 60% 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 review 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 1-3 years, and new ideas that extend the work to FY 2008. 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 2004-2008 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 150 active research users of NSTX including graduate students and post doctoral researchers, 75 are from these collaborating institutions, 52 are from PPPL, and 23 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 87 FTE's. 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 FY 2000.

A.2 NSTX National Collaboration Research Capabilities and Plans

The capabilities and plans of the NSTX national collaboration research is organized by the collaborating institutions list below:

A-I. *Columbia University*
A-II. *CompX*
A-III. *General Atomics*
A-IV. *Johns Hopkins University*
A-V. *Los Alamos National Laboratory*
A-VI. *Lawrence Livermore National Laboratory*
A-VII. *Lodestar Research Corporation*

A-VIII. Massachusetts Institute of Technology
A-IX. Nova Photonics, Incorporated
A-X. Oak Ridge National Laboratory – UT-Battelle
A-XI. University of California at Davis
A-XII. University of California at Irvine
A-XIII. University of California at Los Angeles
A-XIV. University of California at San Diego
A-XV. University of Washington
A-XVI. University of Wisconsin-Madison

The success of a 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. Chapter 7 provides information on how the new NSTX national research team was built in FY 1998-1999 to begin research in FY 2000, how the national team successfully works together to advance NSTX research goals, and how NSTX research collaboration should be enhanced and expanded in the future to meet the challenges of producing an expanded scientific database for practical fusion energy through the investigations in Innovative Confinement Configurations, such as the ST.

A-I. Columbia University

Research Topic:	**Study of MHD Instability and Active Mode Control in NSTX**
Principal, Co-Principal Investigators:	S.A. Sabbagh, G. A. Navratil
Participating Researchers:	J. Bialek, A. Sontag, W. Zhu (graduate student)
Funded under DOE Grant:	DE-FG02-99ER54524

The general goal of the proposed work by the Columbia group, in collaboration with PPPL and the NSTX Research Team, is to develop the science understanding of spherical torus plasma stability at the highest level of β_N that can be reliably achieved in the device at high bootstrap current fraction and high β_t.

The plan to reach this goal has emerged from our original collaborative research on NSTX that dates back to the conceptual design phase of the machine. Reaching the goal requires a parallel effort of plasma stability tool development, an active experimental program, the coupling of theory to experiment, and the design and implementation of plasma stabilization hardware on NSTX. The original plan of physics analysis aimed solely for this purpose has expanded to allow distribution of the results to all NSTX Research Team members based on the many requests for these results. In addition, reliable generation of these results *between-shots* and with *high frequency* has been useful to the NSTX Research Team, and is now a strong directive for the implementation of future analysis systems that we are developing.

To further understand the stability physics and optimize the achievable beta in NSTX, we plan to extend our present research through the term of NSTX research. The research includes computing accurate, between-shots experimental equilibrium reconstructions and stability analysis utilizing magnetic and kinetic data, continually upgrading the physics included in this work, leading experiments on NSTX aimed at understanding the physics of high beta, global mode stabilization, and the design and application of passive and active MHD mode control techniques on NSTX. This work will be based on the Columbia Group's extensive experience in our present experimental and theoretical studies of high-beta plasmas in NSTX, our experimental studies of wall stabilized, high-beta plasmas in DIII–D, and Columbia's HBT-

EP experiment. We bring to bear an expanding set of integrated analysis tools including reconstructed plasma equilibrium (NSTX EFIT), stability (DCON), global mode control for mode control in 3-D (VALEN). Parallel processing of equilibrium and stability (PHOENIX) has allowed between-shots processing and the construction of an extensive database of results available to the full team.

Summary of proposed research plan

The proposed work directly addresses several major research elements under the category of Macroscopic Stability defined on page 21 of the NSTX Research Program Letter FY 2002 – 2005:

- MHD operation, kink-ballooning stability limits
- β-limiting phenomena and parametric dependence
- Passive and active mode control (feedback)
- Modeling and fast reconstruction of high beta equilibrium and macroscopic instabilities
- resistive wall mode stability
- wall stabilization / potential feedback stabilization system needs

Each of these subject areas has been given high programmatic emphasis as both research elements and areas of emphasis for collaboration in this document. In addition, the analysis mentioned (i.e. equilibrium reconstruction) supports many other research topics comprising the NSTX research program. Our intended research and goals follow the NSTX research timeline specified in Chapter 3.1 MHD:

***Year 2004*:**

- Continue experimentation and analysis of plasmas above the NSTX ideal no-wall beta limit with the goal of firmly establishing and understanding the consequences of exceeding this limit without feedback stabilization.
- Propose and execute high beta experiments on NSTX focused on examining the effect of equilibrium profile control and toroidal rotation at low aspect ratio on MHD stability limits.

- Perform experimentation investigating the dissipation mechanism, rotation damping, and critical rotation frequency of the RWM in ST geometry as a natural progression of present experiments characterizing the RWM (continues into 2005).

- Perform experimentation to generate and measure resistive wall modes with toroidal mode number greater than 1.

- Continue stability analysis to determine optimal, yet practical approaches toward the conceptual design target of the device based on existing NSTX equilibria (continues into following years).

- Continue to improve automated, time evolving equilibrium reconstruction and stability analysis between-shots, anticipating that ion and electron temperature, and Z effective information will be available, to have immediate knowledge of the beta margin reached above the no-wall limit, and to expand the already significant database of results.

- Reduce the processing time for between shots equilibrium analysis, as requested by NSTX machine operators and researchers.

- Determine the impact of toroidal rotation and other potentially significant physics effects on existing equilibrium reconstruction analysis.

- Expand existing stability analysis tools to support further RWM study (i.e. perform MARS analysis of the resistive wall mode with toroidal rotation and dissipation).

- Continue to distribute equilibrium reconstructions to the NSTX Research Team in a common public database format, and expand these distributed results to include stability calculations.

- Continue to provide supporting work and analysis for the NSTX real-time EFIT plasma control system, proposed by D. Gates at PPPL. Dr. Gates is working in collaboration with Dr. John Ferron, who has implemented an EFIT-based control system on DIII-D.

- Continue to provide MHD analysis support of planned upgrades of NSTX, including possible passive plate modifications.

- Model effects of passive stabilizer time constant and 3D geometry effects on an improved passive stabilizer design / active mode control system.

- Work iteratively with NSTX engineers and design technicians on a practical, effective design of an active feedback control system utilizing internal control coils.

- Support the implementation and maintenance of the improved RWM in-vessel magnetic sensor set.

- Perform the initial high beta experiments on NSTX to support the design or upgrade of passive stabilization and active feedback control systems optimized for ST geometry (continues into the next year).

- Determine if the expected theoretical differences between the resistive wall mode in low vs. moderate aspect ratio geometry are supported by experiments by conducting similarity experiments with the DIII-D group.

- Upgrade the present VALEN code to include the effects of rotation, analysis of multiple modes, and simulation of diagnostics (continues throughout the five year period).

***Year 2005*:**

- Perform experiments utilizing passive stabilization techniques and current profile control to extend the length of pulses to greater than $10^*\tau_{\mathrm{wall}}$ with β_N above the no-wall limit at reduced toroidal field (less than 0.4 T).

- Perform experiments to study the physics of global MHD modes at maximum β_N and low l_i using all means of equilibrium optimization and global mode stabilization available (continues into following years).

- Attempt and study plasma operation in the theoretically expected second stability regime of the resistive wall mode.

- Complete experimentation required to fully document the effect of coupling unstable low aspect ratio plasmas to stabilizing conducting structure.

- Conduct experiments that follow theoretically optimal paths to wall-stabilized, high β_N configurations

- Determine the impact of toroidal rotation and other potentially significant physics effects on existing stability analysis.

- Implement internal magnetics measurements or other techniques into between-shots equilibrium reconstructions to more accurately measure the safety factor profile (contingent upon availability of MSE diagnostic data).

- Experimentally access the second stability region to high-n ballooning modes in the ST by exploiting the synergistic stabilizing effects of low aspect ratio and high central safety factor (requires internal magnetic measurements).

- Complete the design of an optimized, active mode control system. If resistive wall modes with toroidal mode number greater than one are experimentally observed, include stabilization of these modes in the design.

- Explore the role of enhanced toroidal rotation velocity on RWM stabilization through larger E_r caused by increased energetic particle loss in the ST.

- Design multi-n capability active feedback coil geometry to permit control of toroidally localized ballooning mode structure in low-n MHD.

- Support installation of an optimized active mode control system (dependent on NSTX active feedback implementation schedule).

***Years 2006-2008*:**

- Demonstrate active stabilization of the resistive wall mode using an optimized feedback system (depending on availability of stabilization system implementation).

- Operate stable plasmas approaching the conceptual design target of $\beta_N \sim 8$ for many wall times (depending on availability of stabilization system implementation).

- Utilize active feedback system to study the physics of the resistive wall mode and other relevant global modes near the conceptual design target β_N.

- Continue development of between-shots analysis capability as required. Possible upgrades include incorporation of fast particle data into equilibrium reconstructions (requires availability of fast particle diagnostic), the addition of resistive stability criterion evaluation, and more rapid input data pre-processing.

- Attempt rotation control using active means, and compare expected theoretical rotation dynamics with experiment.

- Explore the existence of toroidally localized kink/ballooning modes (with n up to 6) and associated RWMs created through error fields or island activity.

- Determine the effect of FLR or other stabilization mechanisms of high-n modes in ST geometry by attemping to significantly violate the Mercier and high-n ballooning limits.

- Generate diamagnetic plasmas above the no-wall limit with central local β exceeding unity.

- Utilize the implemented multi-n control coil system to create a spectrum of static m/n error fields to determine the effect on the RWM including increased toroidal rotation through enhanced stochastic losses of energetic particles.

A-II. CompX

Research Topic: **CQL3D Modeling of RF Heating and Current Drive**

Principal Investigator: Robert Harvey

Introduction

Computational modeling of electron Bernstein wave, high harmonic fast wave, and neutral beam injection auxiliary heating and current drive in support of NSTX is being carried out. The primary tools are the CQL3D [1] Fokker-Planck-transport code and the GENRAY [2] RF ray tracing code. Electron Bernstein wave (EBW) power is proposed as a means for start-up and for localized current drive (CD) in over-dense ($\omega_{pe} > \omega_{ce}$) NSTX plasmas. High harmonic fast wave (HHFW) and neutral beam injection (NBI) are in operation on NSTX and provide broader profiles of bulk heating and current drive.

CQL3D provides a general model of non-thermal RF-QL/collisional effects on heating and current drive in toroidal plasmas, being bounce-averaged, 2D-in-velocity, 1D-in-noncircular-radius, multi-species, and time-dependent. It is coupled to the GENRAY general ray-tracing code; non-thermal distribution functions and self-consistent RF damping are obtained by iteration. GENRAY calculates ray trajectories in noncircular and non-axisymmetric toroidal geometry for several dispersion relations, including the full Stix [3] hot plasma expression. Radial transport and orbit losses are included in CQL3D.

The following sections report modeling results obtained in the first year of contract work in support on NSTX on EBW and HHFW heating and current drive, plans for additional work to be carried out under the present contract, and considerations for future research on NSTX.

EBW

The GENRAY WKB ray tracing code models the flow of EBW power into the noncircular NSTX equilibrium plasma. Coupled to the CQL3D code, it provides a comprehensive model of EBW power deposition and current drive [4].

Figure 1 shows rays of EBW launched near poloidal angle 65 degrees, into a high beta equilibrium. A narrow spectrum of rays around $n_{||} = 0.0$ gives damping over a small radial region near the $q = 2$ surface at radius r=0.5a. The strong $n_{||}$ - variation with distance along the ray into the plasma is characteristic of the high poloidal magnetic field in the NSTX device. As the ray energy which is injected between the first and second electron cyclotron harmonics propagates into the device, the ratio of Doppler shifted resonance velocity, $v_{||} = (\omega - 2\omega_{ce})/k_{||}$, to thermal velocity decreases sharply; strong damping shown in Fig 1(d) sets in with resonance velocity near $3v_{Te}$.

The Fokker-Planck code provides a means for calculating the EBW deposition and current drive and gaining insight into the RF physics. The quasilinear operator is determined for each short element of the RF rays and contributions are summed in flux surface bins covering the plasma cross-section. Figure 2 shows the diffusion coefficient in momentum-per- rest-mass space, u^2Duu, contoured in $u_{||};u_{\perp}$-space in the radial bin at r=0.5a. Three cyclotron harmonic interactions are included, but the 2nd harmonic interacts with the lowest velocity particles and is dominant. Notice that the $J_1(k_{\perp}u_{\perp}/\omega_{ce})$ quasilinear term gives peak diffusion in the vicinity of the trapped-passing boundary. This is near the optimal location for Ohkawa current drive, which results from passing particles being diffused into the trapped-particle region of velocity space. The solution of the Fokker-Planck equation balancing the RF diffusion and the collisional effects results in electron flow in velocity space, as shown in Fig. 3(a). This clearly shows that the passing particles are diffused into the trapped region. Fig. 3(b) gives the electron distribution at r=0.5.

Varying the launched $n_{||}$ gives driven current shown in Fig. 3.3.11 of the proposal. In all these cases, the secular variation of $n_{||}$ as shown in Fig. 1 results in $n_{||}$ having positive values in the region of strong damping. Efficient current drive is obtained over a broad range of plasma radius, r/a=0.4-0.7, by varying the launched $n_{||}$ spectrum from -1.0 to +2.0. Ohkawa current is dominant. For even more negative values of launched $n_{||}$, the ray propagates further into the high aspect ratio central plasma giving dominant current drive due to the Fisch-Boozer mechanism. This current is in the opposite direction.

EBW work to be completed within the next two years in close collaboration with NSTX staff includes (a) broad scoping assessment of EBWCD to determine optimal current drive wave and plasma conditions, (b) parallelization of GENRAY, (c) calculations of non-thermal EBW emission, (d) examination of EBW startup scenarios, and (e) examination of radial transport effects on EBWCD and heating localization.

A particularly exciting possibility for future work is solenoid-free startup studies on NSTX/ST plasmas using EBWCD. Another opportunity, when the NSTX experiment moves into regimes of high EBW power, is that radial transport of the RF induced fast electrons can be expected to play a role in thermal electron energy transport, as in the present high power ECH experiment in the TCV tokamak [5]. Fokker-Planck-transport modeling will be useful in the study of the electron transport.

HHFW

Modeling similar to the above EBW is carried out for the high harmonic fast wave (HHFW). GENRAY data for HHFW is input to the CQL3D Fokker-Planck code, and together with a fast ion source given by the well-known NFREYA neutral beam model, the resultant self-consistent damping of the HHFW rays and distortion of the ion distributions are obtained. Fig. 4 shows (a) the HHFW ray paths for a particular NSTX shot [6], (b) the deuterium distribution function at r=0.5a, and (c) the power deposition on the deuterium species. Fluxes into the banana loss regions can be calculated at each radius and may be detected at the plasma edge. Power deposition results are very similar to those obtained in the HPRT, CURRAY and AORSA modeling [6], with 65 percent of the power to electrons, 35 percent to the deuterium ions. Benchmarking activity is ongoing.

The distributions are calculated using the zero-banana width approximation. The distribution at a given radius represents ions with that average radial position. First order, finite-banana-width corrections are included through the ion loss term. Presently, ion orbit width is given by a simple analytic expression. Additional work within the present contract will include numerical orbit calculations of the loss orbits. Future proposed work will include banana regime corrections of the ion bootstrap current due to the non-thermal ions, and effects of neoclassical radial transport. A diagnostic calculation of the time-dependent neutron rate is provided. Simulation of neutral-particle flux spectra (NPA) is work in progress with A. Rosenberg, PPPL.

The WKB ray tracing description of the waves may be limiting is some cases. In a typical situation there are only 10 wavelengths across the minor radius of the plasma. Mode conversion is not modeled accurately, if at all, in the WKB approach. As part of the Scientific Discovery through Advanced Computing (SciDAC) initiative, CQL3D is being coupled to ICRF full wave codes, such as AORSA. RF diffusion coefficients are obtained by integration of the gyro-orbits. This treatment will provide a quite complete modeling of both finite banana effects and the problem of gyro-orbits crossing more than one cyclotron harmonic, which are important for fast ions in the low magnetic field, high beta NSTX device.

Future work involves application of these models for interpretation of the NSTX experiment. Both electron and ion modeling is necessary for a full calculation of the current drive. The DC electric field is synergetic with the quasilinear interaction of HHFW and electrons. Fast ion distributions may be coupled to MHD stability and microstability codes. Comprehensive deposition and current drive modeling will require setting up systematic methods for transferring data to the codes, and comparison with experimental diagnostics.

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[3] T.H. Stix, Waves in Plasmas, AIP, NY (1992).

[4] C.B. Forest, P.K. Chattopadhay, R.W. Harvey, and A.P. Smirnov, “Off-mid-plane Launch of Electron Bernstein Waves for Current Drive in Overdense Plasmas”, Phys. of Plasmas 7, 1352 (2000).

[5] R.W. Harvey, O. Sauter, R. Prater, and P. Nikkola, "Radial transport and electron-cyclotron-current drive in the TCV and DIII-D tokamaks ", Phys. Rev. Lett. **88**, Article 205001 (2002).

[6] A. Rosenberg, 15th Top. Conf. on Radiofrequency Power in Plasmas, Grand Teton National Park [also plasma profiles and ancillary data for NSTX shot 108251] (2003).

Figures

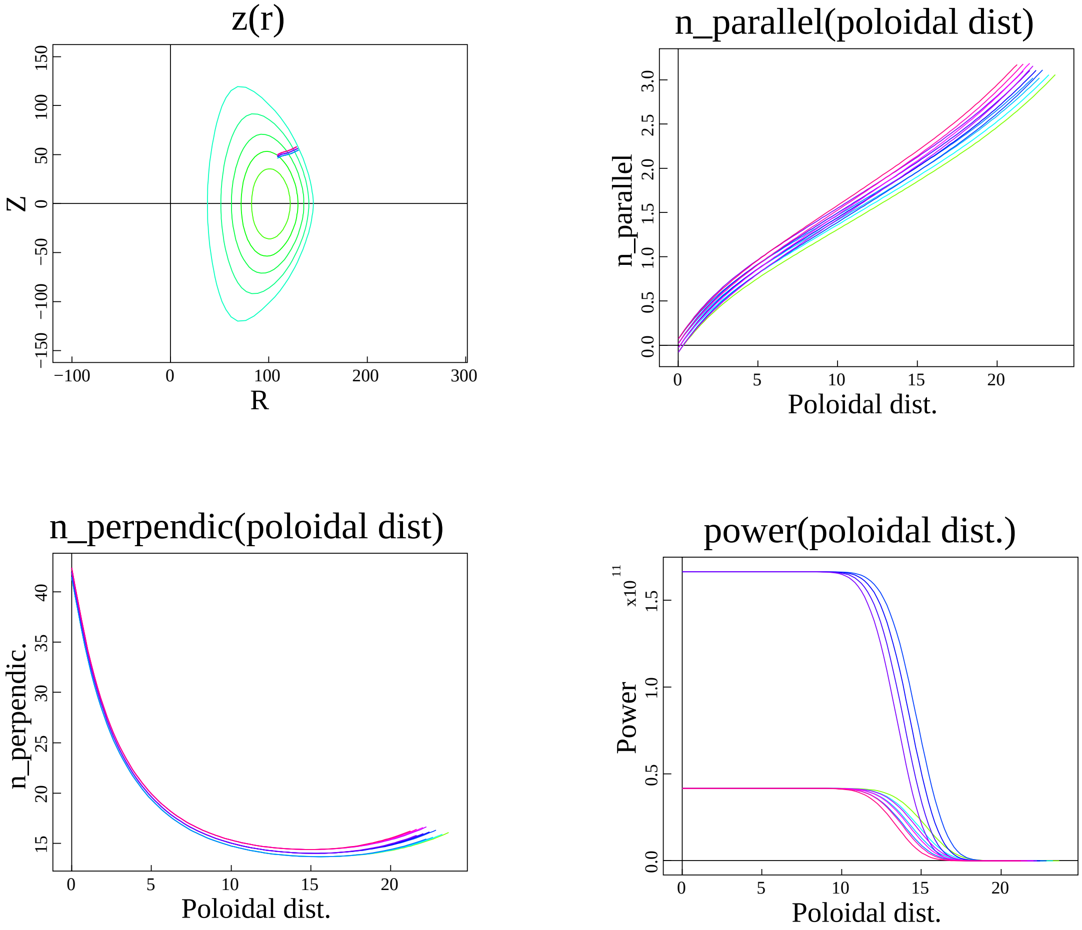

Figure 1: EBW ray trajectories: Poloidal projection, and $n_{||}$, $n_{\perp}$, *and power versus distance in the poloidal plane.*

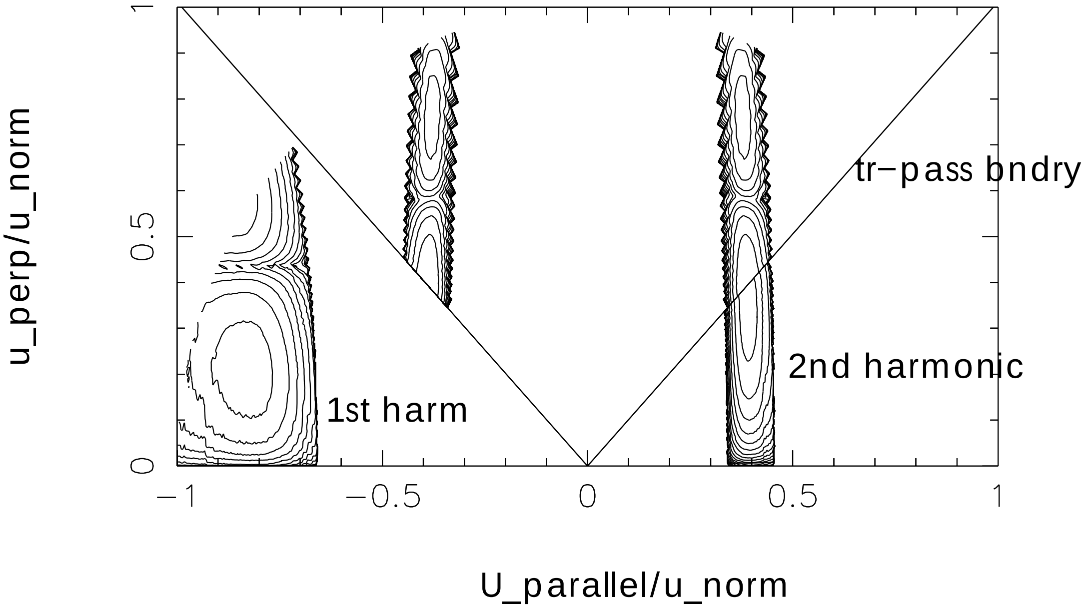

Figure 2: Contours of QL diffusion coefficient versus $u_{\|}$;$u_\perp$. Normalization corresponds to 30 keV. The 2nd harmonic diffusion interacts with electrons at 3 v_{Te} and greater.

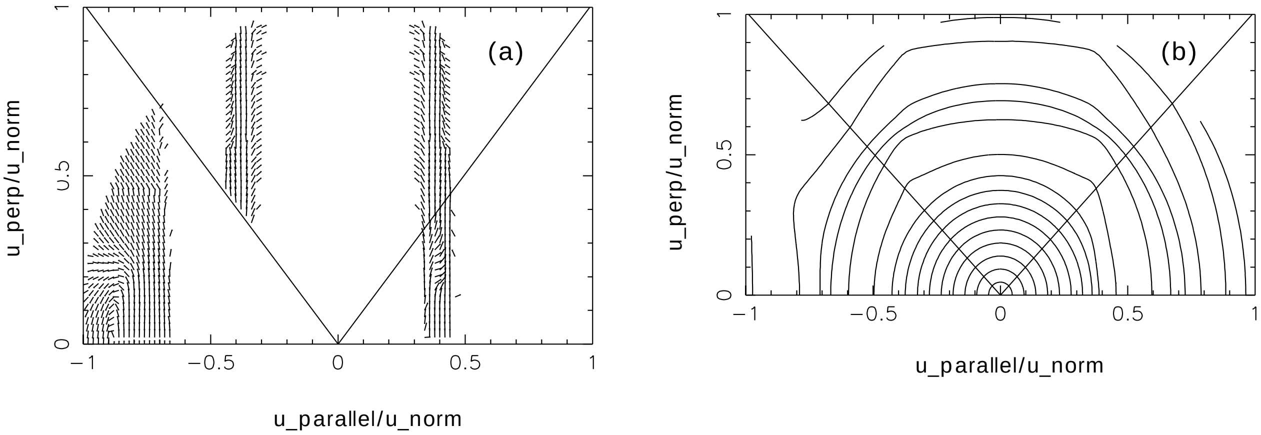

Figure 3: (a) Vectors of log of EBW induced flux in velocity space. (b) Contours of the resulting steady state electron distribution function.

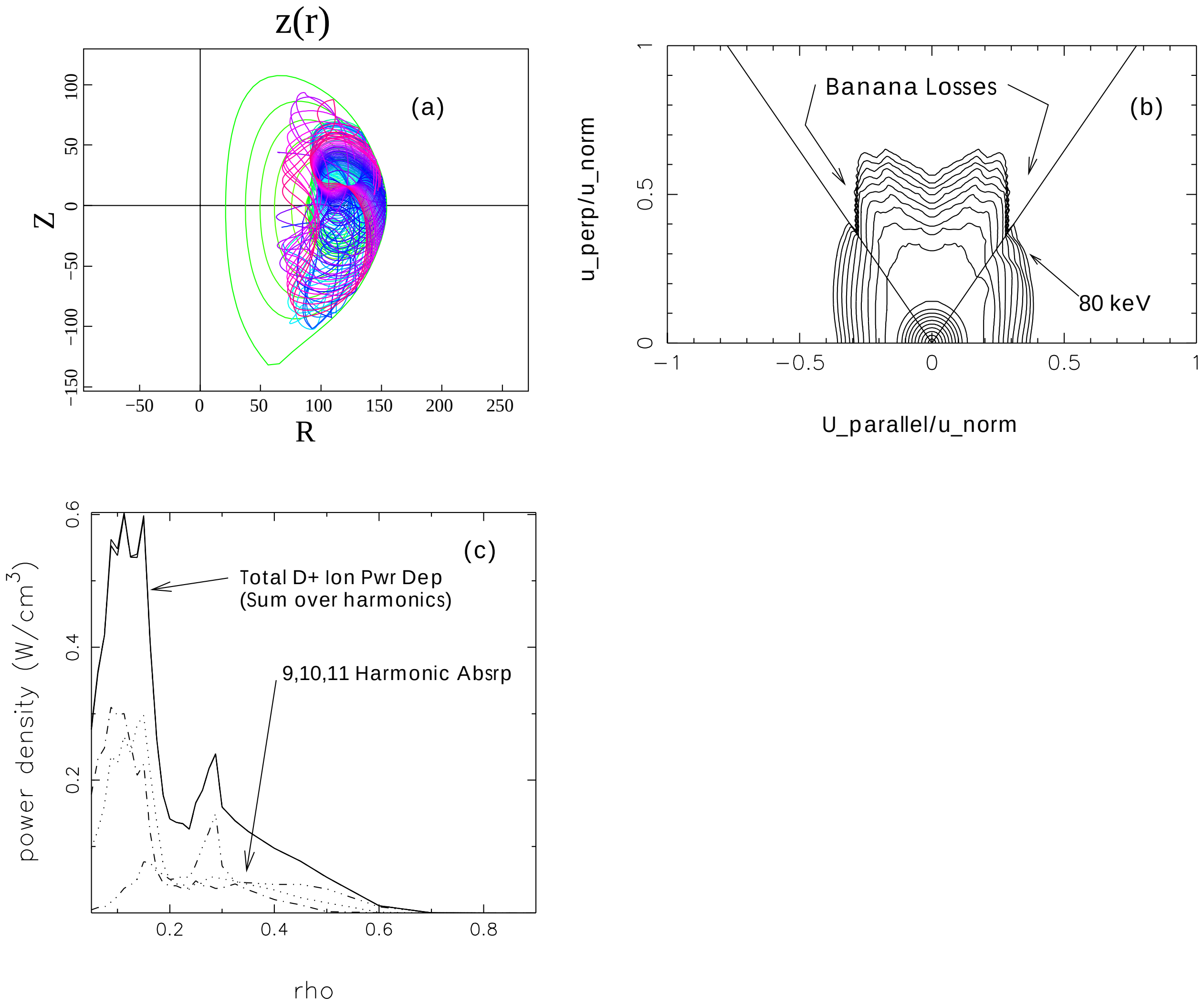

Figure 4: (a) HHFW ray trajectories in NSTX shot 108251. (b) Contours of deuterium distribution function at radius r=0.3a. The velocity normalization u_norm corresponds to 0.5 MeV. 80 keV neutral beam injected ions, and the banana loss regions, are indicated. (c) Radial profile of HHFW deposition due to the 9th, 10th, and 11th harmonic interaction.

A-III. General Atomics

General Atomics contributes to the NSTX program in three topical areas: plasma control, coaxial helicity injection (CHI), and RF physics. An overview is given here of both the work presently under way as part of the currently funded project period (which extends to 2/28/05) and work that will be proposed as part of a project continuation. The current work is supported by the U.S. Department of Energy under Contract No. DE-FG03-99ER54522.

I. NSTX-General Atomics Collaboration on MIMO Plasma Control

The principal goal of the plasma control collaboration between NSTX and DIII-D/General Atomics is to design and study model-based Multiple-Input-Multiple-Output (MIMO) control capability for the NSTX plasma control system. Accurate and robust control can be provided with high confidence through systematic multivariable design and simulation methods using the validated dynamic models which will be developed. Use of methods, tools, and plasma control software already developed for use on the DIII-D tokamak will greatly shorten the development cycle and allow design of initial controllers for NSTX much more rapidly and with much higher confidence levels than if such capability were developed independently. Employing extensive controller simulation with validated models prior to operational implementation can also dramatically reduce the need for costly experimental time to develop and improve control performance.

General Atomics researchers involved in the NSTX MIMO control task are J. Ferron, J. Leuer, M. Walker, R. Deranian, and D. Humphreys. Key collaborating researchers at NSTX are D. Gates, J. Menard, and S. Sabbagh.

The plasma control collaboration presently under way is funded and scoped through mid-FY05. Installation and extensive development of the NSTX Plasma Control System (PCS) were accomplished during pevious collaborative research tasks. The PCS now in routine use at NSTX is based on the system presently in operation at DIII-D. This enables direct use in the NSTX system of the MIMO control facilities being implemented in the DIII-D version of the software. Electromagnetic models and control simulations for NSTX are presently being implemented using the GA TokSim system in

Matlab/Simulink. Analysis of NSTX vertical stability and design of vertical controllers is underway as a first step toward development of full MIMO control algorithms. The scope of the present three-year effort includes development of the design and simulation tools to allow NSTX researchers to produce and test MIMO control algorithms. The initial target for such designs will be a limited set of NSTX equilibria and operating regimes.

Implementation, testing, and closed-loop system validation on NSTX is not included under the scope of the present task. Continuation of this effort beyond mid-FY05 can focus on support of controller implementation and testing in experimental operations, validation of open loop system models and closed loop control performance, optimization and tuning of control action to match specific experimental needs, as well as development of MIMO controllers for a larger set of fiducial equilibria and operating regimes.

II. NSTX-General Atomics Collaboration on CHI Research

General Atomics (GA) participates in Coaxial Helicity Injection (CHI) non-inductive current drive research at NSTX in the persons of Michael Schaffer and Lang Lao. CHI plasmas are characterized by large electric currents on open magnetic surfaces and their relaxation or spreading to interior, preferably closed, surfaces. The principal GA research topic has been equilibrium reconstruction, by modified versions of the GA-developed MFIT and EFIT codes, for NSTX experimental guidance and to help determine whether closed surfaces exist. Dr. Schaffer also brings physics, operational and hardware design knowledge learned in closely related prior electrical bias experiments on the OHTE and DIII–D devices. Schaffer also has extensive experience with helicity concepts, theory and experiments. Dr. Lao authored the MFIT and EFIT codes and knows them in detail. General Atomics' goal in CHI research at NSTX is to assist with the physics understanding and application development of CHI for NSTX.

During the NSTX 5-Year Plan period, General Atomics plans to continue to support CHI experiments and theory at NSTX. The tasks envisioned include routine running of the fitting codes; improvement and upgrade of the EFIT code for more accurate and robust fitting of the open-surface current distribution; helicity theory; helicity transport measurements (with the UCSD reciprocating probe) and interpretation; and CHI hardware design. Additionally, Dr. Schaffer has devised several new helicity injection concepts, some of which might be incorporated advantageously into NSTX in the future.

III. NSTX-General Atomics Collaboration on RF Physics

General Atomics participates in both the High Harmonic Fast Wave (HHFW) and electron Bernstein wave (EBW) areas of the NSTX research program. Up to the present, the GA participant has been R.I. Pinsker. The first task performed by Dr. Pinsker in the HHFW area was to port the GA impedance matching code TOONS to PPPL, and, working with ORNL personnel, produce the tool used to set the many tuning elements in the most complex transmission line system used to date. Dr. Pinsker has participated in many of the early HHFW experiments on NSTX. More recently, the focus of the GA participation has shifted largely to the EBW area, with a detailed study of the coupling to the EBW via the method of direct X-mode launch with mode conversion to EBW. A computer code has been developed to predict the coupling with phased waveguide antennas, and regimes of improved coupling have been identified.

GA plans to continue the participation in both of these areas during the next 5-year period. In the HHFW area, a topic of great mutual interest to the NSTX and DIII-D programs is in the area of reliable high-power operation of large antenna arrays. If continued experiments on this topic are able to clarify the causes of high-voltage antenna breakdown, a new antenna design might be developed to significantly improve the reliable high power capability of the NSTX HHFW system, utilize a larger fraction of the available generator power, and/or decrease the toroidal width of the structure to allow more diagnostic access. GA expects to continue to collaborate with ORNL personnel and with the rest of the NSTX team on this research topic. Another topic that is of interest to both the DIII-D and NSTX groups is the absorption of FW power at high ion cyclotron harmonics. Similarity studies between NSTX and DIII-D are possible in which the ratio of the FW frequency to the toroidal magnetic field is fixed (the different aspect ratios of the two machines are not relevant in this case.)

In the EBW area, GA envisions designing an antenna which builds on both the experimental results obtained by the NSTX team in emission studies and the theoretical results obtained in our recent work. Such a coupler might look rather like a lower hybrid grill rotated by an angle of about 90 degrees. Some aspects of such a coupler could be tested without a high-power rf source, either by emission studies or with a low power source. Increased participation in the initial EBW experiments is also planned.

A-IV. Johns Hopkins University

The research topics of the Johns Hopkins University Plasma Spectroscopy group on NSTX are aimed in the following two directions: **the development of (I) ultrasoft X-ray (USXR) based MHD, transport, equilibrium and current profile diagnostics, and (II) the associated computational and physics analysis tools to be used in the investigation of MHD and transport in NSTX.**

Presently the JHU researchers on-site are: one research scientist (D. Stutman), one assistant research scientist (K. Tritz) and one graduate student (L. Delgado Aparicio). We plan to add to this group a graduate student beginning 2005.

The NSTX JHU research is funded throughout the April 2003-March 2006 period, with the following research goals:

1) *Completion of the poloidal USXR imaging system for multi-spectral tomographic capability on NSTX and development of tomographic algorithms and codes for routine analysis of the data*

2) Application of a 2-D Micro-Pattern Gas Detector (MPGD) and of the USXR systems to the estimate of the central safety factor

3) Steady-state and time-dependent measurements of particle and energy transport using the USXR systems, a Transmission Grating Imaging Spectrometer (TGIS) and the MPGD detector

For the 2006-2009 period we plan to extend the JHU contribution to the:

4) Implementation of a 100 kHz, continuously sampling 2-D tangential USXR system for fast and continuous imaging of core and peripheral MHD activity in NSTX

5) Implementation of multiple-energy MPGD arrays for fast 2-D measurements of T_e perturbations

Thus, the planned JHU research will contribute to all the major NSTX activities as described in the 5-year plan, with emphasis on *MHD*, *transport* and *non-inductive operation*. The main elements of the plan are briefly described in the following. Since the present level of funding is far below that requested in our recent proposal, most of the diagnostic development activities will require supplemental funding.

Overview of diagnostic implementation and research

1) *Completion of the poloidal USXR imaging system for multi-spectral tomographic capability on NSTX and development of tomographic algorithms and codes for routine analysis of the data*

The multi-spectral (0.01-10 keV) USXR system installed and operated by JHU on NSTX provides fast imaging capability for operating scenarios ranging from Coaxial Helicity Injection, to the highest performance auxiliary heated plasmas [1]. Figure 1 shows for example the MHD picture recorded by the system prior to the beta collapse in the long-pulse, high-β_N discharge discussed in section 3.1.2 of the NSTX 5-year plan. The ≈ 25 kHz n=1 mode discussed in §3.1.2 appears as an internal m=1 perturbation associated with an additional peripheral mode, possibly supporting the hypothesis of a double tearing reconnection as the cause for the collapse. By providing both the poloidal structure and the radial localization of MHD perturbations, the USXR arrays can thus be a powerful complement to the magnetic sensor system.

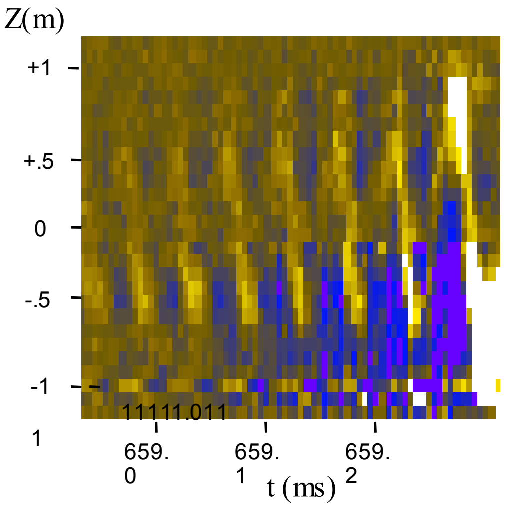

Fig. 1 MHD activity seen by horizontal USXR arrays prior to beta collapse in long-pulse $\beta_N \approx 6$ NSTX discharge 109063.

We plan to enhance the present imaging system by adding tomographic reconstruction capability for higher poloidal number (m=2-3) emissivity perturbations. This will allow mapping the mode structure and localization without assumptions about the flux surfaces, as well as independent measurements of the plasma shape and position. The study of higher-m perturbations will be central to the MHD research, due to the planned operation at central safety factor above one (§3.1.2).

Another reason for the modification and the upgrade of the present USXR system is the re-positioning of the secondary stabilizing plates planned for 2004-2005 (§2.1.2), which could obtrude the views of all the present vertical arrays.

For tomographic inversion of a mode of poloidal number ‘m’, the Nyquist criterion requires at least 2m viewing directions. Since the present system has only two sets of directions (m=1 capability), the present arrays will be reconfigured and new arrays added for supplementary viewing directions and m=2-3 reconstruction capability (Fig. 2). To solve at the same time the field of view problem created by the stabilizing plate re-positioning and to provide flexibility for future NSTX design modifications, we will build in-vessel arrays based on the re-entrant design tested on NSTX during the last operation period.

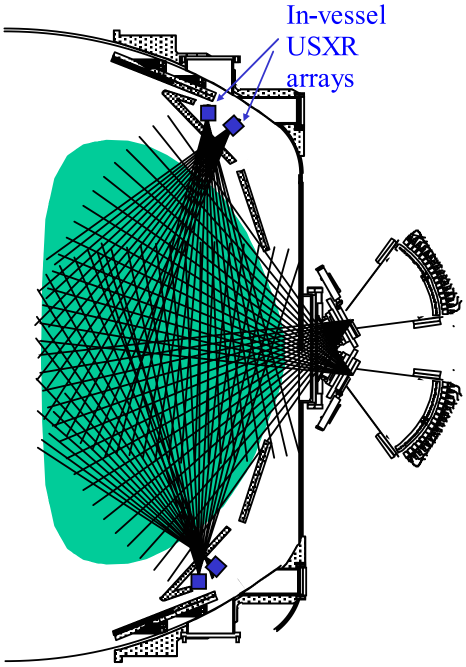

Fig. 2 Planned configuration of NSTX USXR system for m=2-3 tomography, with stabilizing plates re-positioned.

Another important upgrade of the USXR system will be to increase the sampling rate from 200 to 600 kHz. This is first requested by the high toroidal rotation observed in NSTX, which Doppler shifts the frequency of modes rotating with plasma into the 30-50 kHz range. At the same time, high-m mode structure analysis requires sampling at nearly ten times the frequency of the fundamental mode.

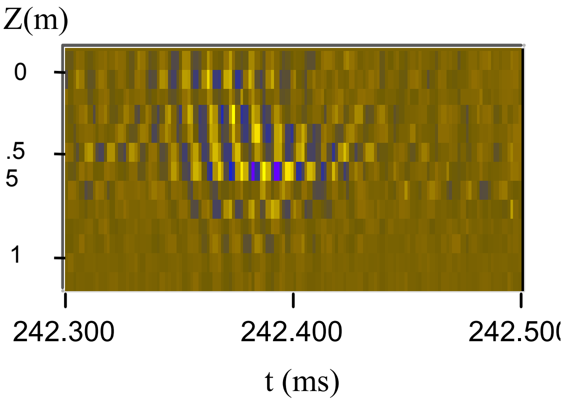

Fig. 3 100 kHz TAE mode seen by horizontal USXR array in discharge 109075, in a 600 kHz sampling test.

In addition, this upgrade will also enable the imaging and spatial localization of 80-150 kHz TAE modes induced by fast particles (§3.1.1), with possible applications to q-profile estimates by ‘MHD spectroscopy’ (see Fig. 3).

Finally, an essential task in the completion of the poloidal system will be the development of tomographic algorithms and MDS/IDL based data visualization and analysis routines for the general use of the NSTX researchers. The Cormack-Granetz algorithm developed at MIT will be implemented on NSTX, in collaboration with Dr. R. Granetz from C-Mod. Later on, we will improve the reconstruction capability on NSTX by implementing Singular Value Decomposition (SVD) in the tomographic inversion process, as well as cross-correlation and other algorithms that address the noise problem.

2) Application of a Micro-Pattern Gas Detector (MPGD) and the USXR systems to the estimate of the central safety factor

A recently developed, 2-D energy resolved Micro-Pattern Gas Detector (MPGD) was installed and tested on NSTX, within the collaboration between the JHU Plasma Spectroscopy group, the FTU group (Dr. D. Pacella, ENEA, Frascati, Italy) and PPPL. The results show that this photon-counting detector can image with excellent signal-to-noise performance the shape of the X-ray (1.5 keV ≤ E ≤ 10 keV) emission from the NSTX core [2]. In addition, we showed that good electron temperature measurements could be performed with the MPGD, by independently scanning the counting thresholds for each pixel (Fig. 4). This capability can be extended to fast (0.1 ms) time scales by using multiple, fixed threshold pixels. Thus, using the MPGD in conjunction with the tomographic USXR system opens new possibilities for flux surface imaging, as well as for the measurement of fast T_e perturbations.

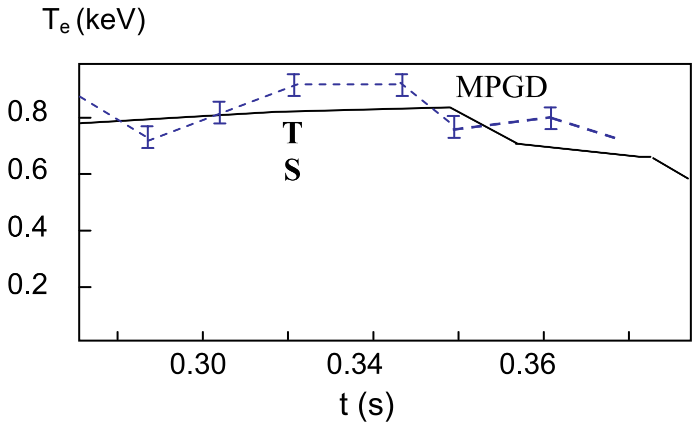

Figure 4. Line-integrated electron temperature measurement obtained using a central pixel of the test MPGD on NSTX and consecutively scanning the counting threshold over five energy ranges. Also shown the Thomson scattering $T_e(0)$.

The MPGD detector will be first operated in a tangentially viewing configuration for the measurement of the central flux surface shape. As was recently shown, in a spherical torus this measurement can put a strong constraint on the magnetic reconstruction, enabling thus a good estimate of the central safety factor [3]. Together with the slow tangential SXR camera to be implemented under the NSTX/U. Wisconsin collaboration (§2.5), the MPGD could thus provide a q(0) diagnostic, which would be extremely valuable for NSTX, where the MSE q-profile measurement is at an early experimental stage.

In addition, we will try to improve the accuracy of the flux surface imaging technique by using the 2-D energy resolving capability of the MPGD device, for a measurement of the electron temperature iso-surfaces. As opposed to the SXR iso-emissivity surfaces, the temperature iso-surfaces should not be affected by poloidal asymmetries in the impurity or electron density (§3.3.1), since the parallel electron transport is very fast. In addition, this technique can obviate the fact that the SXR emissivity profiles are hollow in high performance NSTX discharges, which may lead to reduced accuracy in the shape measurement with regular SXR imaging.

Later on, the MPGD could be reconfigured into a multi-energy linear imaging system and positioned in a poloidal view, for measurements of the electron temperature profile and its perturbations with high time resolution (≈ 0.1 ms). This project would aim to demonstrate on NSTX, a space resolved fast electron temperature diagnostic, similar to ECE imaging on tokamaks. The linear MPGD is also of interest for measurements of the tangential T_e profiles, which could provide a superior constraint in the current profile reconstruction in a ST [3].

3) Steady-state and time-dependent measurements of particle and energy transport using the USXR systems, a Transmission Grating Imaging Spectrometer (TGS) and the MPGD detector

Another main research direction of our group on NSTX is the study of impurity transport. Thus, a non-perturbative transport technique based on neon injection and USXR imaging and spectroscopy was developed and applied for measurements of the particle diffusivity profile in beam heated L-mode discharges [4]. In addition, by combining low spectral resolution imaging with the USXR system and high resolution USXR spectroscopy we showed that it is also possible to characterize the intrinsic impurity content and estimate the Z_{eff} profile in NSTX [5].

We plan to continue and enhance such measurements by implementing on NSTX an imaging Transmission Grating spectrometer developed by our group under the Advanced Diagnostic Program. This instrument will image with ≈ a/20 spatial resolution the line and continuum emission from the entire NSTX plasma [6]. Together with the USXR tomographic system, the upgraded CHERS system and atomic physics modeling [5], this diagnostic will enable measurements of the impurity density, P_{rad} distribution and Z_{eff} profile in most NSTX operating scenarios. This will enable a cross-validation of the visible continuum Z_{eff} profile measurements planned for NSTX. In addition, 2-D measurements like those enabled by USXR tomography might be essential in NSTX, where significant poloidal asymmetries are observed in both the impurity and the electron density during high performance discharges (Ref. 5 and §3.1.1). In addition, both neon injection and low-Z impurity pellets will be used in conjunction with the above systems for perturbative impurity transport studies in the main NSTX operation regimes. In conjunction with the low-k turbulence diagnostic planned on NSTX (§2.5), such measurements might help elucidate the mechanisms behind the good ion confinement observed in NSTX.

Furthermore, we plan to use the energy and space resolved MPGD detector and the tomographic USXR system for perturbative measurements of the electron heat diffusivity in various operating scenarios. Both MHD events (e.g., ELMs) and pellet injection will be used for 'cold pulse' perturbations. In conjunction with the planned high-k turbulence diagnostic (§2.5), such studies may help understanding the causes for the strong electron transport in NSTX.

Finally, we will continue our involvement in the overall NSTX transport research, by performing dedicated experimental proposals aimed at understanding and improving the confinement. A research direction our group proposes to continue is the study of high performance L-mode discharges. Experiments we performed in 2002 show that high confinement and broad pressure profiles may be obtained also in L-mode edge plasmas. We believe it is important to pursue *scenarios alternative to the H-mode* in the ST development, through which pedestal instabilities or the high divertor heat load with H-mode profiles, might be avoided.

4) Implementation of a 100 kHz, continuously sampling 2-D tangential USXR system for fast and continuous imaging of core and peripheral MHD activity in NSTX

In the time frame of our next grant cycle (2006-2009) we plan the development of a 1400 channel, fast and continuously sampling (up to several seconds) two-dimensional tangential USXR system. The proposed system is based on the 'large pixel-count' optical array designed by our group under the Advanced Diagnostic Program. This project was favorably reviewed in our last (2002) NSTX proposal, but was deferred from the 2003-2006 research plan due to budgetary constraints.

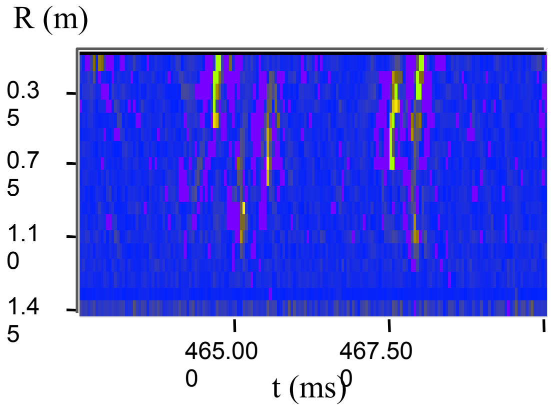

Fig. 5 Edge-localized modes seen in high β_N discharges (109063) and having large amplitude at the inboard.

Such a system is deemed necessary for NSTX in order to resolve MHD structures that evolve on time scales very different from the plasma rotation, like the Resistive Wall Mode, or structures with short poloidal wavelength, like high-m external kinks and ELMs [7]. Our observations indeed confirm the necessity for a fast tangential imaging system. An example is illustrated in Figure 5, which shows the vertical USXR image of an edge-localized mode prevalent in high β_N NSTX discharges. As seen, most of the perturbation appears at the far inboard side, making very difficult an interpretation based on a poloidally viewing system.

A fast, sensitive and continuously sampling 2-D tangential array viewing most of the plasma could resolve such high-m instabilities and decouple the measurements from plasma rotation. The essential requirement for continuous sampling over extended periods of time comes from the practically random character of major MHD events in NSTX, like for example the beta crashes in high-β H-modes discussed throughout the MHD chapter in the 5-year plan.

We plan also to develop computational tools for the integrated analysis of the data from the continuously sampling tangential and poloidal USXR arrays and that from the 1 MHz tangential SXR camera to be implemented by PPPL for ultra-fast, burst type MHD measurements.

Finally, 1-D and 2-D prototype optical arrays will be tested on NSTX throughout the 2003-2006 grant period, in preparation for the implementation of the large-pixel count array.

5) Implementation of multiple-energy MPGD arrays for fast tomographic measurements of T_e profile perturbations

As earlier mentioned, ECE measurements are not possible in NSTX due to its low magnetic field. This creates a strong need for alternate diagnostics capable of measuring of fast (≤ 100 µs) T_e perturbations with good spatial resolution. Linear MPGD pinhole cameras having parallel columns of pixels with different threshold energy could provide such measurements. For the 2006-2009 grant period, we therefore also consider developing linear MPGD cameras having several tens of pixels and viewing the plasma vertically and horizontally in a poloidal cross section. This could provide 2-D tomographic measurements of fast temperature perturbations in NSTX, enabling a host of MHD and transport studies.

A current profile diagnostic based on tangential T_e profiles obtained with multi-energy linear arrays will also be considered. Tests of these techniques will be performed during the 2003-2006 grant period.

Implementation plan

2003-2004

1. reconfiguration and upgrade of the existent USXR system for partial tomographic capability
2. implementation of the MIT tomographic code and of MDS/IDL data analysis/visualization tools
3. upgrade of one USXR array to 600 kHz sampling rate
4. installation of a second vertical array at Bay J, for fast measurements of toroidal plasma displacements and T_e perturbations in support of RWM research (*16 amplifiers supplemental*)
5. measurements of X-ray iso-emissivity and of iso-temperature surfaces with the tangential MPGD detector (*supplemental*)
6. construction,, installation and operational tests of a photometrically calibrated Transmission Grating Imaging Spectrometer (*supplemental*)
7. test of a prototype l-D optical array

2004-2005

8. design and construction of in-vessel USXR camera(s) (upper arrays in Fig. 2) for tomographic capability and as replacement for the vertical arrays after stabilizing plate re-positioning (*supplemental*)
9. upgrade of additional USXR arrays to 600 kHz sampling rate (*supplemental*)

10. implementation of MPGD X-ray imaging constraint in a magnetic reconstruction code for q(0) determination

11. integration of the USXR array data with Transmission Grating spectrometer data and CHERS data for impurity content, Z_{eff} profile and impurity transport measurements

12. development of SVD enhanced tomography for the NSTX geometry

<u>*2005-2006*</u>

13. construction and installation of additional in-vessel USXR cameras (lower arrays in Fig. 2) for m=2-3 tomographic capability (cameras are *supplemental,* with the exception of amplifiers and data acquisition for one camera*)*

14. reconfiguration of the MPGD for poloidal measurements of fast T_e perturbations (*supplemental*)

15. MHD and transport studies using the full set of USXR diagnostics

16. test of a prototype 2-D optical array

<u>*2006-2009*</u>

17. construction, installation and operation of the 2-D tangential USXR system

18. construction, installation and operation of MPGD based fast T_e tomographic system

19. current profile diagnostic based on tangential multi-energy T_e measurements

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7. NSTX Measurement Needs (http://nstx.pppl.gov/nstx/Research_Program)

A-V-a. Los Alamos National Laboratory – Hypervelocity Dust Injection

Research Topic: **Hypervelocity Dust Injection for NSTX internal magnetic field measurements**

Principal, Co-Principal Investigators: Zhehui "Jeff" Wang, Glen A. Wurden

Summary

Making an internal magnetic field measurement is one of the most difficult and challenging diagnostics in high-temperature (>100 eV) fusion-relevant plasmas, such as NSTX. Simple magnetic probes (B-dot loops) burn-up, and/or perturb the plasma. Complicated neutral beam techniques (such as Motional Stark Effect) are expensive, and difficult to implement (especially at low magnetic field). We propose to measure the direction of the internal magnetic field in NSTX plasmas through injection and visualization of multiple hypervelocity (up to 10 km/s) dusts (radius 1-20 µm). Visualization and mapping of 2-D and 3-D internal magnetic field structure should be possible through optical imaging of plumes induced by the injected dusts, which can provide a source of neutral and ions particles far from the edge of the plasma. Our recent study [Wang and Wurden, Rev. Sci. Instrum. **74**, 1887, (2003)] indicates that the proposed dust injection would be simpler to use, have excellent time-resolution, be essentially non-invasive, more resilient, and cheaper to implement than existing internal magnetic field measurement techniques (internal magnetic probes, neutral beams, or macro-pellets). Existing (ancient) LANL hardware for micron dust acceleration would allow us to achieve 125 kV electrostatic acceleration of micron-sized dust to 1-10 km/s with modest further investment. Besides spherical tokamaks like NSTX, the proposed diagnostic would be also applicable to other magnetic confinement devices, in particular innovative confinement concepts, such as the RFP, spheromak, and FRC's (basically, in plasmas where the internal magnetic field is substantially modified by the plasma current). By the end of the three-year project, having prototyped this new diagnostic concept, we expect to obtain 2-D internal magnetic field pitch angle information, at multiple locations simultaneously inside the NSTX plasma.

Proposed research plan

***<u>Year 2004</u>*:**

- Design, resurrect, assemble dust accelerator at LANL
- Test operation of dust sources in vacuum

***Year 2005*:**

- Characterize dust acceleration and acceleration performance
- Inject dust into a LANL plasma to confirm cloud size physics
- Prepare the prototype remote controls for NSTX interfacing

***Year 2006*:**

- Take "turn-key" dust accelerator system to PPPL. Install the dust accelerator on NSTX, with suitable optical views of the dust beam line.
- Add high resolution LANL camera to the existing NSTX optical systems, to obtain detailed images of the lithium or carbon dust ablation clouds, and hence the direction of the internal magnetic field.
- Study penetration of the micron sized dusts in NSTX plasmas.

***Year 2007-8*:**

- Consider spectroscopic measurement of the dust clouds, in particular, Zeeman spectroscopy, to also obtain the magnetic field strength (in addition to direction).
- Consider a higher voltage accelerator, (~200-300 kV) to allow penetration into even higher performance NSTX discharges.

A-V-b. Los Alamos National Laboratory – Coaxial Helicity Injection Modeling

<u>1) Current research topic:</u> Modeling of coaxial helicity injection.

<u>2) Participating researchers:</u> X.Z. Tang, with A.H. Boozer (Columbia University).

<u>3) Collaboration research expertise and goals:</u> Analysis of the equilibrium, stability, and nonlinear dynamics of coaxial helicity injection plasma; 3D numerical MHD and two-fluid simulations of CHI in a toroidal geometry. Our goals are to model and quantitatively assess the physics of CHI current drive in NSTX, and to develop predictive numerical modeling capabilities towards CHI current drive operation on NSTX.

<u>4) Areas of contribution in the NSTX 5-year plan:</u> The primary area is Section 3.4, Co-axial Helicity Injection. A secondary area is Section 3.1, MHD.

<u>5) Presently DOE-funded activities and duration:</u> This work is currently under DOE review for funding considerations. The work has been leveraged upon a LANL funded LDRD project on helicity injection by astrophysical accretion disks. We find that the operational regime of CHI is defined by a normalized voltage $v = \left(\mu_0 V / \eta B\right)\left(\chi_0 / 2\pi\Psi_0\right)$, with V the injector voltage, B a nominal toroidal field, χ_0 the injector poloidal flux and Ψ_0 the vacuum toroidal flux. If $v > 1$, CHI plasma quickly develops a hollow current profile susceptible to 3-D line-tied kink instabilities. ["Numerical studies of a steady state axisymmetric CHI plasma," LA-UR#03-1958, submitted to Physics of Plasmas (2003)] The subtle physics of finite plasma inertia affecting the plasma potential is understood in terms of two distinct Pfirsch-Schlüter effects. ["Equilibrium and resistive steady state of an axisymmetric CHI plasma," LA-UR#02-7903, submitted to Physics of Plasmas (2002)]. 3-D MHD simulation with massively-parallel CHIP code demonstrates significant current penetration into the plasma core, yielding substantial closed flux in the n=0 component of the saturated 3D CHI plasma. We have elucidated the physics basis for non-inductive CHI plasma startup and its transition to secondary current drive with a transient CHI plasma. Two approaches are identified, along with their strength and weakness. The first uses forced 2D reconnection of a stable CHI plasma by pinching off the injector flux or modulating the voltage. The plasmoid thus formed has closed flux surfaces but little current in the core, so the q profile is opposite of the eventual ST q profile. A second approach overcomes this difficult by ramping down a 3D saturated CHI plasma with substantial current penetration into the core. The slowly decaying n=0 component has an ST-like q profile, thus reducing the load on secondary current drive and has far greater room for profile optimization during the CHI stage. These ideas were presented at the NSTX 5-year planning meeting, with constructive impact on the experimental planning. Part of it (2D handover) has been successfully demonstrated recently on HIT-II.

6) Extending research contributions to 5 years: Pending the approval of our NSTX collaborative research proposal on predictive CHI modeling, we plan further application and improvement of LANL's parallel, full-torus CHI simulation code CHIP such as direct import of NSTX magnetic diagnostic data into the code as boundary condition for precise after-shot analysis, scoping the operational regime of CHI on NSTX, scenario studies of transient CHI plasma for non-inductive startup on NSTX, and assessment of transport degradation in a steady state 3-D CHI plasma. NSTX collaborative research funds would also allow us to continue working closely with on-site NSTX experimentalists.

A-VI. Lawrence Livermore National Laboratory

Research Topic: **Boundary, pedestal, and divertor physics**

Researchers: Gary Porter, Marv Rensink, Tom Rognlien, X. Xu, Steve Allen, Bill Nevins

Overview and Proposed Scope

The focus of the Lawrence Livermore National Laboratory (LLNL) collaboration on NSTX is to provide experimental and modeling expertise in the area of boundary, pedestal, and divertor physics. We will apply the techniques gained in LLNL's other fusion endeavors to the NSTX device. To date, the NSTX effort has provided modeling support, with a limited role in diagnostics and experiments. A computer, frame grabber, and analysis software for the IRTV measurement of heat flux have been provided for experiments. In computational modeling, the fundamental characteristics of the boundary plasma have been studied with the UEDGE code. A unique modeling contribution has been the calculations of the boundary turbulence using the BOUT code. An important initial component of our program was to upgrade both the UEDGE and BOUT codes to permit modeling of double null and asymmetric single null plasmas, anticipated to be an important operating mode of NSTX. This was successfully done and has been published [1, 2].

In the next five year period, we propose a modest expansion of the scope of the collaboration: to provide on-site (several months at PPPL) experimental staff for data analysis and processing for comparison of edge data with the UEDGE and BOUT codes. This is a step in the direction of a "full service" collaboration (diagnostics, modeling, technical support) that LLNL uses on other devices, such as DIII-D. Ideally, a modest increase in funding (about 1 FTE) would allow both the experimental work, along with a continuation of the modeling work. We propose to start down this path (with the present flat budget) by using a staff member, perhaps a post-doc, to do both the data analysis and modeling. With the new double-null capabilities, and the continued support of the LLNL theory group for the codes, this should be possible. It should be noted, however, that if further code development (on the scope of what we have done in adding the DN capability) is required, and the transition to a staff member– (from a post-doc, after a year or so), would require additional funding.

We are also interested in collaborating in the area of visible spectroscopy, by using small portable spectrometers (from Ocean Optics; Steve Paul of PPPL has a detailed plan). We have a few of these in use at DIII-D, and by adding a few more and using the same type of data acquisition, we could provide multiple chords of visible spectroscopy. These data are important in understanding the impurity levels in the edge plasma of NSTX, and would be a high leverage activity with our work on other machines.

Proposal for future modeling work

The LLNL proposal for modeling work in the NSTX 5-year plan focuses on two important extensions of our past program: 1) simulations validation by detailed incorporation of the data from new SOL and divertor diagnostics as they become available, and 2) coupling of the boundary turbulence calculations by BOUT with the SOL/divertor fluid model in UEDGE through theory based profiles of transport coefficients. At LLNL we have a long history of successful validation of UEDGE simulations by comparison with experimental measurements for conventional tokamak geometries such as DIII-D, JET and JT-60. We propose to extend this fundamental work to spherical tokamak geometry by detailed comparison with NSTX and MAST data. Working relationships already exist between LLNL and MAST personnel so that SOL and divertor data from MAST should be available to complement the UEDGE validation efforts on NSTX. Significant understanding of the role of aspect ratio in the behavior of the SOL and divertor plasmas should be achievable with a single simulation code that is validated in a wide aspect ratio range. This should allow the boundary plasma advantages and disadvantages of spherical tokamak vs. conventional tokamak operation to be identified.

The second objective is to bring into the NSTX collaboration the results of internally funded work (LDRD program) in progress at LLNL to couple the BOUT turbulence calculations with the UEDGE fluid model. One of the objectives of LDRD project is to generate spatial profiles of transport coefficients, from the BOUT calculated turbulence induced fluxes, that can be used in the UEDGE simulations. Since there are no good plasma profile measurements at the boundary plasma region, it is hard to make quantitative comparisons of turbulence with experimental measurements. We plan to make many BOUT runs using a profile scan to study the sensitivities of the turbulence. The new version of BOUT will also be able to study the plasma profile evolution by specifying sources from the core boundary and specifying neutral profiles or using those given by the initial UEDGE solution. The resulting plasma solution from the UEDGE calculations with these BOUT transport coefficients will then be used as the background plasma for the next iteration of the BOUT calculation and this cycle will be iterated to convergence. At the completion of the LDRD project, the coding systems that perform this iteration will be available for application to NSTX discharge simulations. We anticipate that theory based profiles of the transport coefficients will produce UEDGE solutions that match NSTX data better than present simple models of the transport.

Finally, it may be possible to extend the simulations capability to lower collisionality regimes consistent with advanced NSTX operation if planned LDRD work at LLNL is funded. We plan to significantly improve our ability to model kinetic effects in the edge pedestal, SOL and divertors as part of a future LDRD project. This capability would allow low density, low collisionality operation of NSTX to be modeled much more accurately. The simulation codes calculations of kinetic effects from fast particles, eg. those expelled from the pedestal during ELMs, interacting with the divertor targets can then be validated against experimental measurements to provide physics understanding of the role of fast particles in the plasma materials interaction in spherical tokamaks.

Detailed Results from previous studies

UEDGE SOL Fluid Simulations

The UEDGE code has been used to study the expected behavior of the NSTX boundary plasma as a function of the heating power. The results indicated the development of high carbon impurity content at high heating powers due to sputtering from plasma facing surfaces. UEDGE simulations were performed on NSTX discharges with the best available boundary data as provided by the NSTX team. We found the transport diffusivities that produced the best match of calculated and measured midplane SOL profiles were somewhat higher than those found in a conventional tokamak, and the steep gradient region of the boundary plasma extended further inward in flux space. We have used the code to study operational boundaries for divertor detachment, and thus to guide the design of detachment experiments expected to be performed in NSTX in the near future.

Simulations of balanced double-null configurations in NSTX show a substantial up/down asymmetry in the plasma profiles on the divertor plates. Peak densities can differ by more than a factor of two. For the toroidal field in the standard direction, the lower divertor has higher density at the inboard plate as in a single null. However, in the upper divertor the density is slightly higher at the outboard plate. These asymmetries can be attributed to ExB particle fluxes produced by radial electric fields in the private flux regions that transport particles in opposite directions for the upper and lower divertors. Most of the power from the core goes to the outer divertor plates, independent of the toroidal field direction.

Parallel electrical currents flowing in the outboard scrape-off-layer alter the heat flux profiles on the divertor plates. The strength of the cross-field drifts that cause the up/down asymmetry increases with the core power due to higher temperatures and electric fields. Stronger anomalous transport produces weaker radial gradients, so the radial electric field and radial shear that may contribute to turbulence suppression are correspondingly weaker also. A preliminary fit between the simulation results and experimental edge density profiles indicates that the radial particle diffusivity at the outboard midplane is about 2 m**2/sec. This is consistent with 3-d turbulence simulations of NSTX from the BOUT code (see below).

We attempted to benchmark the UEDGE model with respect to edge plasma data from a single high-power beam-heated ELM-free H-mode plasma, shot 109053. The plasma configuration is lower single-null with a small inner gap. The midplane Thomson data suggests that EFIT flux surface reconstruction is not accurately determining the flux surface position near the separatrix. Peak divertor heat flux from the simulation (24 MW/m**2) is about 3 times larger than the measured peak heat flux. The simulation shows that intrinsic carbon impurities from physical and chemical sputtering in the divertor produce z-effective=1.3 on close flux surfaces just inside the core; this is significantly lower than the measured z-effective=2.8. These discrepancies in the peak heat flux and z-effective might be resolved by better spatially resolved measurements of edge plasma at the midplane and impurity radiation in the divertor. A source of uncertainty in the model is the rate of pumping of hydrogenic neutrals by the outer wall; this can have a significant effect on the impurity radiation and core carbon content due to sputtering. This benchmarking effort is an ongoing project that will require detailed edge plasma measurements for a variety of plasma conditions including L-mode and H-mode, singe-null and double-null, and scans of density and heating power.

BOUT Fluid Turbulence Simulations

BOUT simulations of boundary plasma turbulence in NSTX have been carried out. The main results specific to NSTX are:

(1) The X-point geometry affects the poloidal mode structures and drift-Alfvén mode becomes robustly unstable due to low magnetic field [3]. The rms fluctuations are confined outboard between the top and bottom x-point regions along the field line due to the very strong poloidal magnetic shear structure. Filament-like structures have been observed both in BOUT and Gas Puff Imaging (GPI) measurements. In the direction parallel to the magnetic field, the correlation length is very long (~10 meters) while in the direction perpendicular to the magnetic field the correlation length is only a few centimeters. The typical fluctuation parameters obtained are a correlation time ~ 15-30 microsecond at the midplane, which is in agreement with probe and GPI. The frequency spectra of the mid-plane fluctuating density from GPI measurements and BOUT simulations in L-mode shows reasonable agreement. Images of the edge turbulence in the poloidal vs toroidal plane provides a direct visualization of "quasi-2D" structures in boundary turbulence. An animation of the data shows large scale, transient, and coherent structures (localized in time and in space) convecting upward through the observation domain at several kilometers per second and reversing outside the separatrix.

(2) A strong poloidal asymmetry of particle flux is observed in BOUT near the separatrix. Particle transport perpendicular to the magnetic field results from correlated fluctuations of the plasma drift velocity and density fluctuation. A strong poloidal asymmetry of the turbulent flux of particles comes from the divergence of the plasma drift velocity as poloidal magnetic field B_p approaches zero due to the X-point null.

(3) Radial "streamers" at the separatrix have been observed in the BOUT simulations. The spatial and temporal spectra of the turbulence in the BOUT model are in general agreement with the edge density fluctuations observed by GPI in NSTX experiments [4]. Detailed comparison with results from dedicated NSTX experiments are in progress.

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A-VII. Lodestar Research Corporation

1) Current research topic and participating researchers: Lodestar is currently engaged in research on **edge and scrape-off-layer instability and transport physics for NSTX**. Participating researchers at Lodestar are Jim Myra and Dan D'Ippolito. The work is in collaboration with Stewart Zweben and Daren Stotler (PPPL), Ricky Maqueda (LANL) and Jose Boedo (UCSD). Additionally, much of the work leverages off of other theory program collaborations which Lodestar maintains, including LLNL (X.Q. Xu) and UCSD (Sergei Krasheninnikov, G. Q. Yu and A.Y. Pigarov).

2) Collaboration research expertise and goals: Work is presently underway to model and interpret data from edge turbulence diagnostics, primarily Gas Puff Imaging (GPI). The goal is to elucidate the physics of observed density "blobs" (localized coherent density enhancements) in the scrape-off layer (SOL). The blob model[1,2] presents a new paradigm for understanding non-diffusive transport in the SOL. The work also builds on past experience with edge and SOL turbulence, such as the BAL stability code and the physics of resistive X-point modes.[3]

3) Areas of contribution in the NSTX 5-year plan: Blob (i.e. large scale intermittent convective transport) research will contribute to both the energy and science goals of the NSTX program in Transport and Turbulence (Chap. 3.2) and Boundary Physics (Chap. 3.5). The work will assess the role of edge convection relative to the standard diffusive transport paradigm (Chap. 3.2.2) by providing theory and modeling support for the interpretation of GPI and probe data. The goal is an understanding of the observed intermittent edge and SOL transport phenomena (Chap. 3.5.5) using the latest theoretical models.[1,2] The work will have potential impacts on power handling and particle control (Chap. 2.3.3), H-mode transition physics (Chap. 3.2.3) and edge rf-antenna interactions (Chap. 2.4.2).

4) Presently DOE-funded activities and duration: Work is funded through a project that extends to 8/14/05. We are presently extracting density and temperature from the raw GPI emission data using a new analysis technique. Comparison of this processed data with plasma models (initially 2D blob evolution codes) will permit an investigation of the role and interplay of diffusive and convective transport through background plasma effects on blob velocity, rotation, and stability.

5) Extending research contributions to 5 years: Extended research goals include a more comprehensive understanding of non-diffusive transport. This will be used, together with edge instability modeling of resistive X-point modes by the BAL code, to understand NSTX experiments on the scaling of edge and SOL turbulence. Ultimately, the research is expected to lead to a better understanding of the fundamental physics of edge turbulence, the SOL width, and how it can be controlled to optimize plasma exhaust and particle control issues.

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A-VIII-a. Massachusetts Institute of Technology – High Harmonic Fast Wave

1) Current Research Topics and Participating Researchers:

Currently MIT is carrying out **studies of high harmonic fast wave (HHFW) heating and current drive** experiments in NSTX using an ion finite Larmor radius (FLR) code (TORIC), coupled with an adjoint module for the current drive efficiency. We have also assisted in the implementation of this module in the transport analysis code TRANSP. Participating researcher at MIT is Paul Bonoli, who cooperates with Marco Brambilla of IPP, Garching and John Wright of MIT. This work is collaboration with C.K. Phillips, J.R. Wilson, and S. Kaye of PPPL.

2) Collaboration Research Expertise and Goals:

The MIT / IPP / PPPL collaboration on TORIC has resulted in significant advances in full-wave ICRF modeling over the past decade. Most recently the TORIC field solver was implemented on a massively parallel architecture to successfully simulate mode converted ICRF waves in toroidal geometry [see E. Melby et al., PRL **90**, 155004-1 (2003)]. Thus, the research expertise with this field solver is considerable.

The goals of this collaboration are to benchmark the TORIC – adjoint module against HHFW heating and current drive experiments in NSTX. The benchmarked code will be used to scope out effective current profile control and maintenance scenarios for NSTX. It is anticipated that a further outcome of this collaboration will be a reliable rf heating and current drive module for use within TRANSP.

3) Areas of Contribution in the NSTX Five Year Plan:

Chapter 3.2: Transport and Turbulence

Chapter 3.3: High Harmonic Fast Wave Heating – EBW

Chapter 3.4: Non-Ohmic Startup

Chapter 4: Integrated Scenario Modeling

4) Presently DoE – Funded Activities and Duration:

This portion of the MIT NSTX Collaboration is presently funded under a Three Year DoE Grant (No. DE-FG02-99ER54525) that runs from March 15, 2002 to March 15, 2005. The Grant is titled "Modeling of High Harmonic Fast Wave Heating in the NSTX Device Using the TORIC Code".

5) Extending Research Contributions to Five Years:

Recently an all-orders version of the TORIC ICRF solver was developed by the code's original architect M. Brambilla and was benchmarked against HHFW heating experiments in NSTX where a small concentration of background hydrogen (H) was present [M. Brambilla, Plasma Phys. Cont. Fusion **44**, 2423 (2002)]. We plan to implement this all-orders version of TORIC at PPPL and MIT, then apply the code to NSTX discharges where background levels of (H) are present along with fast ions from neutral beam injection (NBI). Comparisons will be made with the 1-D integral wave code METS and with experimental observations on NSTX.

We also plan to implement modules for dielectric tensor response in the presence of non-Maxwellian ions, that have been developed by PPPL (C.K. Phillips and A. Pletzer) through the US rf SciDAC Initiative. Although implementation will likely be funded on the MIT side through the rf SciDAC Initiative, the resulting module will be benchmarked extensively against NSTX discharges through this collaboration. Again, the ultimate goal of this work will be to identify viable current profile control scenarios for NSTX, where parasitic absorption of HHFW power on fast ions can be minimized.

A-VIII-b. Massachusetts Institute of Technology – Electron Bernstein Wave

1) Current research topics and participating researchers:

Massachusetts Institute of Technology is engaged in **modeling and computational research in heating and current drive in NSTX with electron Bernstein waves (EBW).** Participating researchers at MIT are Dr. Abhay K. Ram and Professor Abraham Bers. The work is in collaboration with Gary Taylor and Cynthia Phillips (PPPL).

2) Collaboration research expertise and goals:

This research for the period 2003 to 2008 will have two primary goals. The first goal will be to provide a theory-based understanding of EBW experiments being pursued on NSTX. The second goal will be to build a modeling and computational capability to support future EBW experiments being contemplated for NSTX. The research capability of the group will be applied during the next five years to address issues on: mode conversion coupling to EBWs from externally launched electromagnetic waves, the propagation and damping of EBWs in NSTX plasmas, plasma current generation by EBWs, and the interaction of EBWs with MHD instabilities, e.g., neoclassical tearing modes, in NSTX.

3) Area of contribution in the NSTX 5-year plan:

This work will contribute directly to NSTX research plan described in Chapter 3.3 (Wave-Particle Physics, Heating, and Current Drive) and Chapter 3.1 (MHD).

4-5) Presently DOE-funded activities and extending research contribution to 5 years:

A. Coupling of Power to Electron Bernstein Waves

The emission experiments on NSTX and CDX-U have been useful in validating the scaling of mode conversion from EBWs to the extraordinary X mode. We have shown that, based on general physical principles, in a dissipation-free mode conversion region the emission and excitation coefficients for the EBWs are the same. We have also provided an analytical basis for understanding the effect of density gradients in optimizing the coupling of power from X modes to EBWs. Thus, the passive emission experiments on NSTX and CDX-U provide a basis for understanding the active mode conversion excitation of EBWs from externally launched electromagnetic waves in the electron cyclotron range of frequencies. Our short term goal is to provide a user-friendly mode conversion code that implements our theoretical model for mode conversion excitation of EBWs from X or ordinary O modes. This code could be used for appropriate experimental scenarios not only to benchmark against experimental observations but also to predict the various mode conversion coefficients in any anticipated experimental configurations.

The emission experiments being passive do not provide any information on any nonlinear parametric processes that could occur in the mode conversion region. In NSTX this region is calculated to be near the edge within about a free-space wavelength of the externally excited electromagnetic wave. The electric fields within the mode conversion could get large enough, when coupling powers of the order of 1 MW, so as to lead to parametric coupling to other plasma waves. Part of our long range five-year plan is to study possible parametric interactions that can take place in the coupling region, and their effect on the mode conversion excitation of EBWs. Some of the previous theories on parametric interactions need to be revisited since the magnetic field geometry in NSTX is sufficiently novel and different from conventional tokamaks.

B. Propagation and Damping of Electron Bernstein Waves

In conventional electron cyclotron heating and current drive it has been recognized that weakly relativistic effects play an important role in determining the ray paths and absorption of the waves. The weakly relativistic effects lead to significant and important deviations from a non-relativistic treatment of the plasma dielectric. The weakly relativistic formulation for a Maxwellian plasma entails an expansion in $k \perp \rho_e$ and is appropriate for waves having $k \perp \rho_e << 1$ as in conventional electron cyclotron waves. However, as we have shown before, for EBWs $k \perp \rho_e \underset{\sim}{>} 1$. This precludes using the weakly relativistic formulation, and a fully relativistic treatment of the plasma dielectric is required. We have started to implement a fully relativistic treatment of the plasma dielectric tensor. In the next five years we intend to include this into a ray tracing code (with a quasilinear description of the wave-particle interaction) so as to be able to determine the ray paths and the corresponding damping characteristics of EBWs in NSTX plasmas.

C. Current Drive by Electron Bernstein Waves

A principal role for EBWs in NSTX, in any future experiments, will be to generate non-inductive plasma currents for current profile control and achieving long pulse operations. Towards this end we will be making use of the aforementioned ray tracing code and implement a quasilinear-drift kinetic equation code for NSTX-type geometries to determine the magnitude of the current that can be generated by EBWs for various wave parameters, plasma parameters, and launch angles of the wave. This research that will be carried out over the next five years will also make use of the relativistic formulation of the plasma dielectric for evaluating the wave polarizations that are incorporated in the quasilinear diffusion coefficient.

The conventional drift-kinetic equation is derived in the thin-banana approximation for the electron distribution function. This approximation may not be valid in the outer half of the NSTX plasma where the electrons could drift significantly far off a flux surface. Part of our goal will be to consider the generalization of the drift kinetic equation, including collisions and quasilinear diffusion, to finite banana widths which is more appropriate for NSTX operations.

D. Current Drive by Electron Bernstein Waves in the Presence of the Bootstrap Current

In the past, the bootstrap current and the RF generated current have been treated independently of each other. However, as we have shown, from a kinetic phase-space point of view, it is clear that each of these currents entails distortions of the particle distribution function in velocity space. Furthermore, the two currents depend upon the profiles in configuration space.

So even though the sources for generating these currents are essentially distinct (but not entirely independent), the currents generated simultaneously by these means are, in general, not independent. Initial indications are that there are synergistic effects for lower hybrid current drive and for electron cyclotron current drive; hopefully, there may be synergistic effects for EBW current drive as well. We plan to study the kinetic interaction of these currents — the velocity space interaction of bootstrap current and the EBW driven current. These studies would be useful for current profile control as well as a control on the growth of neoclassical tearing modes.

A-IX. Nova Photonics, Incorporated

Part I. – Motional Start Effect Diagnostics (MSE) and Laser Visualization of Turbulence

Principal Investigator: **Dr. Fred M. Levinton**

Other Participants: Howard Yuh (Physicist, starting 10/03), D. DiCicco (Technician), D. Card (Technician), K. Hirst (Technician), V. Corso (Mechanical designer).

The Nova Photonics, Inc. has begun a three year (March 1, 2003 - Feb. 28, 2006) renewal of our collaboration on the National Spherical Torus Experiment (NSTX). This collaboration consists of three main tasks, **1) complete installation and begin operation of the MSE-Collisionally Induced florescence (CIF) system** that is presently being installed on NSTX; **2) install the MSE-Laser Induced Florescence (LIF) diagnostic** that is currently being developed and supported by the Advanced Diagnostic Development Program of OFES; **3) install a megahertz Planar Laser-Induced Fluorescence (PLIF) diagnostic** for visualization of turbulence, currently supported by a OFES/SBIR Phase II Grant.

1) MSE-CIF Diagnostic on NSTX

Task 1 is to complete the installation of the MSE-CIF diagnostic. The collection optics, polarimeter, and fiber optics, for 19 channels, have been installed on the machine. Presently the birefringent filter is in the final shakedown and testing phase. We plan to begin shakedown with four filter/detector channels when NSTX begins operation next year, and complete installation of an additional six channels (for a total of 10 channels) in Q2 2004. During the following year we plan to increase the number of spatial channels to 19, providing coverage from the geometric axis to the outer plasma edge with a resolution of 2-3 cm. The present MSE-CIF design inherently has very good spatial resolution. A possible future upgrade (FY07-08), if we have sufficient signal-to-noise, would be to divide up channels in the outboard region to provide increased spatial resolution (~1 cm). Participation in the NSTX collaboration would not only include operation of the diagnostic, providing calibrated MSE-CIF magnetic field pitch angle data for the NSTX project, but extensive participation in the NSTX research program.

2) MSE-LIF Diagnostic on NSTX

Task 2 is to install a MSE-LIF diagnostic on NSTX. This is presently being developed under a separate grant from the Advanced Diagnostic Development Program of OFES. The MSE-LIF development is continuing with our neutral beam test stand and helicon plasma source. When the diagnostic development phase has been completed, in about one year, we plan to install the system on NSTX in FY05. The MSE-LIF diagnostic, like the MSE-CIF system, will view the outboard half of the plasma with good spatial resolution. It will begin with 10 channels with the possibility of being increased to 18 in the future (FY07-08). The diagnostic can provide a measurement of the magnetic field pitch angle, however unlike the MSE-CIF system, the geometry is such that this measurement is not sensitive to Er effects. Therefore, with the two diagnostics combined they will be able to separate out the radial electric field and provide a measurement of E_r. In addition to these measurements, by scanning the detailed laser wavelength the Stark shifted spectrum can provide a measure of the plasma diamagnetism. This would provide a sensitive measure of the plasma pressure, which is very valuable for equilibrium, stability, and transport studies.

3) Laser Visualization of Turbulence

Task 3 is to install a PLIF diagnostic system for visualization of edge turbulence structures in the NSTX plasma. This project was begun several years ago as a SBIR Phase I and then later as a Phase II project. A high power tunable alexandrite laser was used to excite an argon ion transition and fluorescence, which is viewed with an intensified CCD camera. Based on the successful development of the PLIF visualization, a new SBIR Phase II project was begun about two years ago to extend the capability of this technique to capture 10-20 images with a temporal resolution of a few microseconds and follow the evolution of the turbulence. This is to be accomplished with the development of a burst alexandrite laser to deliver 10-20 pulses within the period of a single flash-lamp pulse, which is ~150 µsecs. The laser is to be used with an ultra-fast CCD camera, developed by Princeton Scientific Instruments Inc. (PSI) that can capture 28 frames at a maximum frame rate of 1 MHz. The combination makes for a powerful tool to study edge turbulence in NSTX with high spatial resolution (Section 3.2.3 and 3.5.5). After development and testing of this diagnostic we plan to install the system on NSTX and utilize the existing Gas Puff Imaging (GPI) viewing port and the ultra-fast CCD camera. A key advantage of the PLIF technique over passive emission of light from the plasma is the integrated path length can be kept very small to provide a spatial resolution of ~ 1 mm.

Key Contributions in NSTX Research

The MSE-CIF diagnostic, when combined with the MSE-LIF system, can provide profiles of the magnetic field pitch angle, E_r, and pressure. This set of data will contribute toward several of the NSTX goals over the next 5 years in almost every topical area. In the area of current drive the MSE diagnostic will be able to measure the location and effectiveness of driven currents to aid in the development and understanding of the HHFW and EBW current drive scenarios (Sections 1.3 & 3.3.4). The coaxial helicity injection (CHI) system is being developed for plasma current startup. Two goals of CHI development, which can be supported with the MSE diagnostics (section 3.4.6) are demonstration of closed flux surfaces during startup (section 3.4.3) and control of edge currents during a sustained discharge (Section 3.4.4).

A key focus of the NSTX program is achieving high beta. This is required to demonstrate the ST as an economically attractive fusion reactor concept. The maximum achievable beta is often limited by MHD stability, which depends strongly on the q-profile and pressure profile for reliable MHD stability calculations. The MSE diagnostics can also be utilized for development of theoretically optimal profiles such as high q(0) or reversed shear (section 3.1.2) as well as the study of fast ion physics of the TAE and CAE modes(section 3.1.2).

NSTX offers new opportunities in the exploration of the transport and turbulence physics that governs toroidal confinement devices. With magnetic fields about a factor of 10 lower than conventional tokamaks and a regime of dimensionless parameters (such as beta) quite different from the previously studied, NSTX can provide new and important insight into the physics of energy, particle, and momentum transport. The MSE diagnostics can provide important information on how q(R) and E_r relate to transport in this regime (section 3.2.3). The PLIF diagnostic can further provide direct measurements of the short-wavelength turbulence properties (as small as ~ 1 mm in size scale) to enable comparison with theory of possible electron gradient driven turbulences.

Several “Integration and control” goals have been identified in recent IPPA and FESAC reports. These include integrating high beta stability and confinement with self-consistent boot-strap operation. Development of advanced plasma control capability will provide the tools for achieving these goals. This will include implementation of the MSE measurements into the real-time control system (section 3.1.2 and 3.6.3).

Part II. – Edge and SOL Studies

Principal Investigator: **Ricardo Maqueda**

Participant: Stewart Zweben (PPPL)

Nova Photonics proposes to augment its collaborative effort on NSTX with the study of edge turbulence, intermittency, and other edge phenomena such as ELMs, recycling, and impurity generation and transport. This collaboration, based on fast visible imaging, continues the work carried out in recent years by Ricardo Maqueda (formerly at LANL) and Stewart Zweben (PPPL), who developed the new diagnostic, Gas Puff Imaging (GPI[1,2]), to NSTX and C-Mod. This diagnostic is expected to be an important tool in the study of edge turbulence and intermittency (see Sections 3.2.3 and 3.5.5). The experiments proposed are also intended to be part of the basis for comparison with simulations and theory relating to edge turbulence in magnetically confined devices (BAL, BOUT, UEDGE, etc.) as well as comparison with similar experiments in other devices (Alcator C-Mod[3] and, possibly, DIII-D). The proposed experiments can be divided in two groups: characterization and control. The characterization effort will continue in line with the recent experiments[2] where the GPI diagnostic, as well as other edge turbulence diagnostics in NSTX, were employed to characterize as best as possible the important physical phenomena of turbulence and intermittency. It is believed that this measurement is critical to making significant progress in the next 5 years in understanding the following topics:

- L-mode edge turbulence.
- The origin of the L-H transition.
- The density limit.
- Turbulence transport across the edge and through the SOL.

Over longer term, the goal of this research is the control of the edge turbulence, and thereby the control the edge profiles and the transport across the separatrix and edge barriers. Control actuators that may lead to such desired control will be explored with several possible experiments already identified for NSTX.

One such control mechanism to explore may be the use of biasing to modify the edge radial electric field profile. This can be relatively easily accomplished in NSTX by applying a DC voltage across the CHI electrodes present on the lower divertor plates, in L-mode and H-mode confinement regimes in lower single null discharges. The HHFW auxiliary heating/current drive system could also be used to modify the edge profiles in an attempt to control the edge turbulence.

The optical elements of the gas puff imaging diagnostic will also be used to study of physical phenomena on the edge by imaging the natural emission (i.e., without puffing) while averaging over the turbulence time-scale (~10 μs) with long frame exposures. [Eventually, FY07, we would like to have tangential access to the divertor region for visible 2-D imaging.] By capturing simultaneous 2-color images, and modeling the spectral line emission ratio, it is possible to obtain high-resolution profile information (temperature and density) as well as follow the evolution of these profiles as fast as the frame rate of the imaging camera permits. Filters tuned to D_2 Balmer lines (fuel imaging), low ionization carbon lines, or low ionization boron or lithium lines will be selected for recycling, impurity generation and wall conditioning studies, respectively.

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A-X. Oak Ridge National Laboratory – UT-Battelle

Introduction

Scientists from ORNL have collaborated and made major contributions to the design, operation, and experimental program of NSTX since its inception. We propose to continue this productive collaboration by conducting a research program focused on ST- and NSTX-specific physics issues geared toward scenario development for high performance and long pulse discharges. Our proposed program mirrors elements of the NSTX 5-year research plan in areas which ORNL is expected to play a key role.

The proposed topics of research are:

1) **Transport studies and transport barrier optimization**. These include i) test of neoclassical transport modeling predictions, ii) H-mode access physics and optimization, iii) particle and impurity control, including cryopump design, and iv) power handling during long pulse operation.

2) **Current drive studies in HHFW-heated discharges**. Concomitant with the current drive studies is a plan for improved RF power launching and deposition studies and modeling, as well as a detailed look at RF-edge interactions.

3) **Studies of the synergy of NBI + RF heating**, emphasizing RF fast-ion interaction.

4) **Electron Bernstein Wave** (EBW) current initiation and ramp up studies. **(new)**

5) **Pellet injection** studies on NSTX with injection from the low field side and the top. **(new)**

6) **Application of modeling** capabilities of the ORNL theory group to the work described above, e.g. use of the **AORSA** code for power deposition and current drive studies **(new)**, and development of low-A neoclassical **transport models** to support physics analysis.

In addition, ORNL will continue to support HHFW system operation, edge density/turbulence measurements using the microwave reflectometer, and machine operation via ECH startup support, as well as day-to-day operation of D_α diagnostics and infrared cameras.

Participants of this collaboration for FY 2004-2008 from ORNL are expected to be: R. Maingi, C. Bush, D. Swain, P. Ryan, J. Wilgen, T. Bigelow, L. Baylor, W. Houlberg, D. Rasmussen, P. Mioduszewski, D. Batchelor, M. Carter, and E. F. Jaeger. The work has been carried out in close collaboration with V. Soukhanovskii, J. R. Wilson, G. Taylor, H. Kugel, S. Kaye, C. K. Phillips, B. Leblanc and A. Rosenberg of PPPL. D. Swain, P. Ryan, and R. Maingi have served successfully as Experimental Task Group leaders or deputies. R. Maingi served successfully as Run Coordinator for FY 2002.

An Integrated Approach of Research Collaboration

Research in pulse maintenance and RF current drive involves the most critical issues for Spherical Tori (ST), even more so than conventional aspect ratio devices. Due to their compact design, ST has only a small space for a central ohmic solenoid, which translates to limited volt-second capability and inductive pulse-length. A major NSTX goal for FY 2004-2008 is to explore the $\beta_t \sim 40\%$ regime for pulse lengths longer than the current diffusion time ($\tau_{pulse} > \tau_{skin}$), which will be difficult to achieve with inductive current drive only. In practice, NSTX generally achieves pulse lengths < 0.5 sec. in low confinement mode (L-mode) plasmas with 1 MA plasma current, and up to 1 sec. in high confinement (H-mode) plasmas. In those plasmas with $T_e^0 \sim 1$ keV, $\tau_{skin} \sim 250$-300ms and flattop $\tau_{pulse} \sim 1.6\tau_{skin}$ has been achieved. τ_{skin} could reach up to 1-2 seconds, however, depending on the plasma profiles and low impurity content, particularly if T_e^0 were increased to ~ 3-4 keV by maintaining appropriate edge densities. Thus most present NSTX experiments, without an adequate control of the edge density, so far did not achieve quasi-steady current profiles, or equilibration of plasma/wall interactions, which require an even longer time scale.

We propose to carry out a research collaboration program focused on ST and NSTX specific physics issues geared toward scenario development for high performance, long pulse discharges. Three existing lines of research are considered. 1) The first research topic addresses transport characterization and transport barrier optimization, which includes H-mode/boundary optimization and density profile control, as well as testing of neoclassical transport predictions. 2) The second research topic addresses current drive physics in HHFW-heated discharges. Concomitant with the current drive studies is a plan for improved RF power deposition measurements and modeling, as well as a detailed examination of RF-edge interactions. 3) Finally, the third research topic addresses the synergy of NBI + RF heating. An important element of this topic is the RF interaction with the fast ions generated by NBI. These components of research have the longer term goal of minimizing flux consumption and maximizing the pulse length with good performance. To carry out these collaborative investigations effectively, it will be most effective to participate also in three new topics: 4) EBW current initiation and ramp up, 5) pellet injection, and 6) RF modeling accounting for the NSTX HHFW launcher and plasma edge configurations and neoclassical transport modeling accounting for the high beta and strong flow of the ST plasmas. These capabilities also leverage existing ORNL expertise and equipment to provide the required support for the planned RF experimental efforts.

1) Transport Studies and Transport Barrier Optimization

The first topic includes test of 1) neoclassical transport modeling predictions, 2) H-mode access physics and optimization, 3) particle control, including density (profile) and impurity control, and 4) power handling on the divertor surfaces. Most tokamaks are able to access neoclassical ion transport in limited regions in radius, making neoclassical transport studies difficult. On the other hand, NSTX plasmas appear to have neoclassical ion confinement naturally in many plasma regimes and over broad region in radius. This provides a nearly ideal test-bed for many elements of neoclassical transport models. H-mode discharges constitute an important operational scenario for achievement of NSTX programmatic goals, and H-mode access and optimization research helps lay the foundation for many parts of the NSTX program, including high β and long pulse studies.

We propose to carry out collaborative studies in the areas of H-mode access and pedestal/ELM characterization. Many of the NSTX long pulse H-modes suffer from uncontrolled electron density rise, underscoring the need for particle control research. In addition, density control is desirable not only to improve the current drive efficiency in NSTX, but also to enable controlled studies of the density dependence of transport, stability, and boundary physics. We propose to lead the study of particle flux and core fueling, and lead the physics design of the planned in-vessel cryopump systems. We also propose to lead the design and installation of a pellet injector to enable density profile control.

Research on heat flux profiles and power balance is motivated both by NSTX near term needs and longer term ST design needs. ST has the potential to be designed as compact devices, which can have high power densities given sufficient heating power. Previous calculations and recent measurements have shown that divertor tile heating could restrict NSTX pulse lengths to ~ 2-3 seconds at the highest heating power. The pulse length goal in NSTX is to achieve several current diffusion times, τ_{skin}. While the current diffusion time $\tau_{skin} \sim 250$-300 ms with the typical H-mode plasma profiles with $T_e^0 \sim 1$ keV, an increase in T_e to 3-4 keV will increase τ_{skin} to ~ 1-2 sec. Such an increase in T_e could occur when the edge electron density is reduced by active pumping as planned for NSTX, in which case tile heating could hamper achievement of programmatic goals. We propose to lead the studies on dependence of the heat flux profile on engineering parameters (i.e. plasma current, NBI power, etc.) and shape parameters (triangularity, flux expansion, etc.).

2) Current Drive Studies in HHFW-Heated Discharges

The second topic includes: 1) HHFW current drive research and 2) RF-edge interactions. Phased-array experiments were performed in the 2-4.5 MW range to investigate the current drive capabilities of the HHFW antenna arrays. These experiments were preceded by detailed loading studies which helped optimize coupling. The RF-driven portion of the plasma current was calculated from the difference in loop voltage between co-CD and counter-CD phasing. The advent of direct measurement of current density profiles via the Motional Stark Effect diagnostic (in FY 2004) will allow more precise determination of current drive effectiveness and permit more rapid development of optimized current drive scenarios. Thus, we propose to continue leading the collaborative HHFW current drive studies, e.g. quantify the current drive efficiency and radial distribution as a function of power, density, temperature, and spectral wave number. Increasing the reliability, repeatability, effectiveness and power capability of the HHFW heating and current drive system requires improved understanding of the interaction of the RF fields with the edge plasma. The ability to operate the antenna array reliably at high power levels is dependent on the power flow through (and the power deposition in) the plasma edge region. RF-enhanced particle flux, neutral pressure rise, and large ion/electron temperature increases in the vicinity of the antenna need to be measured, modeled, understood and, if necessary, ameliorated. We propose a collaborative program to investigate RF-edge interactions, which requires the addition of new diagnostics in the antenna region and upgrades of existing diagnostics, e.g. SOL reflectometers.

3) Support Studies of Synergy between HHFW and NBI Heating

The third topic considers the compatibility and optimization of simultaneous RF and NBI heating. ORNL will continue its support of the experiments studying HHFW/NBI interaction by using the AORSA-2D code to calculate distribution of rf power absorption by the fast beam ions. Current drive scenarios consistent with future long-pulse environments, such as neutral beam-driven plasmas, H-mode plasmas, increased beta, large bootstrap current fractions, and double-null divertor configurations, will be studied and optimized. The eventual goal will be to tailor the HHFW current drive profiles using active feedback control of the power and phasing of the antenna array to enable long-pulse high performance plasma research on NSTX. Additional discussion of the crucial importance of NSTX plasma modeling using the AORSA-2D code is provided under 5) Modeling Support in RF and Transport Studies.

4) EBW Current Initiation and Ramp Up

Electron Cyclotron Wave and Electron Bernstein Wave (ECW/EBW) heating and current drive can be utilized for several important NSTX 5-year research goals, including plasma and current initiation, current ramp up, steady state heating and current drive to tailor the current profile for improved ideal MHD beta limit, and Neoclassical Tearing Mode (NTM) suppression. In support of these goals, we propose to participate in the development of EBW receiver/launcher and transmission technology and physics applications. ORNL proposes to implement a phased program including a possible initial (FY 2004-2005) medium power system for current initiation and ramp up tests at ~15 GHz in frequency and 40-100 kW in power. This will be aimed at tests of ECH/EBW current initiation scenarios to ensure beginning in FY 2005 the success of the outboard poloidal field null technique (to provide the needed electron heating) as well as the inboard poloidal field mirror technique (to enable bootstrap current initiation) without using the central solenoid. The new data will enable launcher designs for effective current initiation and ramp up using subsequent high power systems (1-3 MW) to be provided by new prototype gyrotrons at similar frequencies planned by NSTX for FY 2006-2008. The tasks will also include EBW emission measurements and modeling to guide the choices of the appropriate Gyrotron frequency and the optimum launcher design.

The collaborative research will commission an existing, self-contained, medium power, 15.3-GHz Gyrotron at ORNL in 2004. It will be capable of 40 kW injected power for 200 ms for preliminary experiments on NSTX in 2005 with O-X-EBW fixed angle launch with external polarization control. The power supply could be upgraded subsequently by installing a larger high voltage power supply. One option under consideration for the high voltage supply upgrade would be the PPPL DNB power supply combined with an ORNL Modulator/Regulator. This approach would also provide enough MVA to drive the new 1 MW prototype Gyrotron for operation beginning in FY 2006.

5) Pellet Injection Studies

We propose to lead the physics and engineering design and implementation of an existing deuterium pellet injector for improved central fueling and density profile control on NSTX, as well as for perturbative transport and density limit studies. The injection system for NSTX will initially consist of a single barrel pipe gun (single pellet, v~100-1400 m/s). A future more versatile injector based on the pellet injector in a suitcase design is also proposed that will consist of a 4-barrel pipe-gun injector that can inject up to 4 pellets with the same size and speed range as the single shot injector. Injection locations will initially be through an outboard mid-plane port or a vertical port toward inboard side of the magnetic axis.

The initial single pellet injector will be used in preliminary scoping studies on pellet ablation and deposition physics in NSTX plasma, confinement at high density, transport from pellet density perturbations, and the modification of ETG-related turbulence and transport via the formation of peaked density profile and internal transport barrier. The pellets can be combined with an imaging system to map the inclination angle of the pellet cloud, which in turn can be used to measure the magnetic field pitch angle of the plasma equilibrium. We propose to utilize existing NSTX imaging hardware to view the pellet clouds for this purpose. In addition, the magnetic well formed in NSTX from high beta plasmas will be particularly interesting for studying the pellet deposition when injected from the low field side. This configuration provides a negative ∇B toward the magnetic axis, which is predicted to cause the pellet mass to drift toward the magnetic axis and result in improved fueling efficiency.

6) Modeling Support in RF and Transport Studies

ORNL theory division proposes to provide modeling and analysis support for the collaborative experimental program discussed above. We will continue to support transport analysis of NSTX plasmas by upgrading the neutral beam current drive, plasma rotation and fueling models in the NCLASS code. In addition, we will provide modeling support for pellet injection experiments, including pellet ablation and deposition physics. Also, we will provide theoretical support for analysis of HHFW heating and current drive experiments, as well as for the design of the new ECW/EBW launchers.

Finally, we propose to adapt existing RF codes to model NSTX parameters, e.g. the AORSA-2D full wave RF solver, which is required to model HHFW heating and current drive on NSTX with sufficient accuracy and reliability. Common 2D full wave solvers makes a finite Larmor radius expansion to the 2nd order in $k_\perp\rho$, which is assumed to be << 1 for validity of the expansion. Here $k_\perp$ is the perpendicular wave number, and ρ is the ion gyroradius. This approximation is however routinely violated in NBI heated NSTX plasmas, where for HHFW $k_\perp\rho_i$ is > 1 for thermal ions and >> 1 for beam ions. Furthermore because wave-particle interactions at the *n*-th cyclotron harmonic enter the plasma response via order $(k_\perp\rho)^{(2n-2)}$, the small Larmor radius expanded codes therefore fail to characterize wave-plasma interactions at higher than the 2nd cyclotron harmonic. Finite Larmor radius codes and ray tracing codes, which typically calculate the ray trajectory assuming cold plasma theory, are sometimes used to model dissipation from higher harmonic waves. However, the code does not calculate $k_\perp$ with sufficient accuracy, leading to mistaken calculations of wave absorption by the plasma, which scales as $(k_\perp)^{2n}$.

The AORSA-2D code makes no approximation of small $k_\perp\rho$, treats arbitrary cyclotron harmonics accurately, and launches the waves from spatially distributed current sources that can more accurately model the actual antenna. It is therefore crucial to adapt and apply the AORSA-2D code to help benchmark other key HHFW modeling codes, and enhance the reliability of HHFW modeling in NSTX plasmas. This effort leverages progress made in frontier code development through the SciDAC project.

A-XI. University of California at Davis

1) Current research topic: Far InfraRed Tangential Interferometer/Polarimeter (FIReTIP)

2) Participating researchers: N.C. Luhmann, Jr., K.C. Lee, C.W. Domier

3) Collaboration research expertise and goals:

The Plasma Diagnostics Group of Prof. N.C. Luhmann, Jr., has considerable expertise in the design, development and operation of millimeter-wave and far-infrared (FIR) plasma diagnostics. This expertise, coupled with an unparalleled inventory of millimeter-wave and FIR sources and electronics, is currently being applied to the completion and implementation of a multi-channel FIR Tangential Interferometer/ Polarimeter (FIReTIP) system for NSTX, and to using this system to contribute to numerous areas of NSTX physics studies. Design activities are underway for a high-k collective scattering system to study the important Electron Temperature Gradient (ETG) instability as well as the Ion Temperature Gradient (ITG) instability at low scattering angles. A Microwave Imaging Reflectometer (MIR) system for ITG turbulence studies will be developed since collaborative studies by PPPL and UCD researchers have demonstrated the serious limitations of conventional, non-imaging 1-D reflectometer systems.

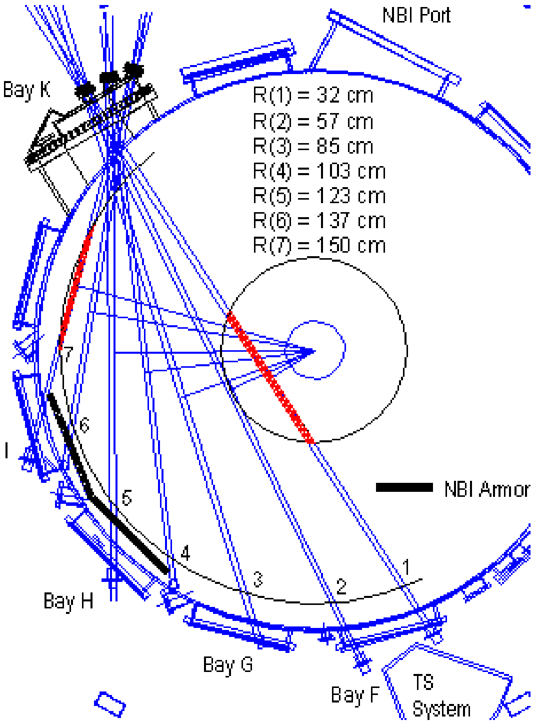

Fig. 1 Top view of the seven channel FIReTIP diagnostic system.

4) Areas of contribution in the NSTX 5-year plan:

3.1.2 MHD – Research plans for FY2003-FY2008

3.2.3 Transport and Turbulence – Experimental studies

3.5.4 Boundary Physics – H-mode transition, pedestal, and ELM physics

5) Presently DOE-funded activities and duration:

In collaboration with PPPL researcher Dr. H.K. Park, UC Davis is developing a seven channel FIReTIP system for NSTX to provide temporally and radially resolved toroidal field profile [B_T(r,t)] and 2-D electron density profile [n_e(r,t)] data. The system, when completed, will comprise an integral part of physics analyses such as confinement and stability. At the same time, the real time density information provided is crucial for NSTX plasma operations and plasma density control.

The FIReTIP collaboration was recently renewed and extends until March, 2006, during which time UC Davis will design and fabricate optics/supports to extend the current 4 channel FIReTIP system to a total of 7 channels for optimum plasma coverage for profiles of density and toroidal field as NSTX ports become available (the 3 additional channels require NBI armor penetration). The present FIReTIP system has demonstrated the highest IF frequency ever used in the FIR range. A second Stark-effect FIR laser will (a) increase FIR output power to support the increased channel count, and (b) be used as a probe beam to achieve higher IF frequencies (4.5 and 12.0 MHz) and thus greatly improved time response beyond that available from other FIR interferometry/polarimetry systems. Upgraded phase comparator electronics will be fabricated for the study of rapidly changing density profile changes (<1 μs resolution) and low-to-high frequency turbulence (≤800 kHz). We note that this far exceeds the best reported results from any existing FIR system, such as the POLARIS system installed by UCLA on the Madison Symmetric Torus RFP in which IF frequencies of 600 and 900 kHz are reported with a 4 μs time response and a 100 kHz bandwidth. It should also be noted that the UCLA results were obtained via direct digitization of the mixer output signals, providing phase data only through extensive computations employing a digital phase comparator technique. FIReTIP phase data, on the other hand, are immediately available as real-time signals (note that application of the digital phase comparator approach to FIReTIP would yield >5 MHz bandwidths, should the necessary data acquisition hardware be made available).

The FIReTIP system will be employed in support of NSTX physics goals, in particular to study transient edge dynamics associated with gas puffing and L/H transitions. Density and magnetic field profile reconstruction routines will be developed, and UC Davis will work with PPPL staff to incorporate these profiles into routine NSTX physics analyses such as EFIT.

6) Extending research contributions to 5 years:

UC Davis proposes to augment its collaborative effort on NSTX with the development of two new millimeter-wave density fluctuation diagnostics in cooperation with PPPL researchers Ernesto Mazzucato, Tobin Munsat, and Hyeon Park. The first is a five channel 280 GHz collective scattering system to measure density fluctuations with a broad radial wavenumber range ($k_r \cong$ 0–20 cm^{-1}). Such high-*k* fluctuations are predicted as a result of ETG instabilities in toroidal plasmas, but have heretofore never been directly observed. Simultaneous measurement of five wavenumbers will allow us to distinguish ETG modes from ITG spectra. A 354 GHz gyrotron upgrade (150 W, 0.5 s) will extend the continuous wavenumber coverage to 25 cm^{-1}, or to 60 cm^{-1} using an 800 GHz gyrotron should the 280 GHz data support the need for the increased wavenumber response (both options are possible through a collaboration with Fukui University).

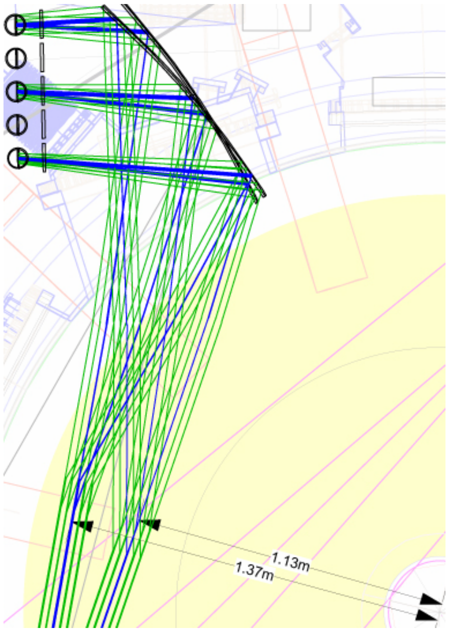

Fig. 2 Top view of the high-k collective scattering system.

The technique involves illuminating the plasma with a high power (≥100 mW) collimated µwave beam. Coherent density fluctuations, such as those arising from short wavelength ETG modes with $k_\perp \rho_i >> 1$, act as a plasma grating to scatter a small portion of this beam at frequencies and wavenumbers that are matched to those of the incident beam. The scattered signal amplitude is proportional to the density grating amplitude, and thus provides a means of monitoring such fluctuations. The frequency/wave-number matching condition allows the wavenumbers of the density fluctuations to be inferred from scattered signals collected at multiple scattering angles. A critical aspect to the identification of ETG-driven turbulence (for example to distinguish ETG spectral behavior from the high-wavenumber ITG tail), is the simultaneous collection of multiple wavenumber channels, rather than a single wavenumber detection system. The proposed scattering system provides for variability in the 5-channel spectral window as well as scanability of the scattering volume over a significant fraction of the plasma cross-section.

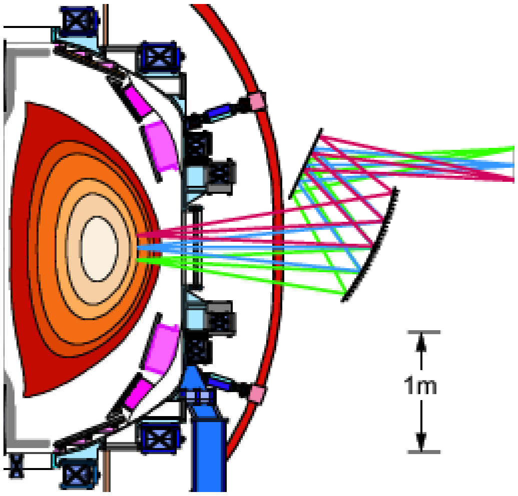

Fig. 3 Schematic illustration of the proposed MIR diagnostic for NSTX.

The second millimeter-wave plasma diagnostic is a microwave imaging reflectometer (MIR) system. While the collective scattering system is intended for the study of short wavelength ETG instabilities, the MIR system is ideal for the study of long wavelength ITG-driven turbulence with $k_\perp \rho_i < 1$. The MIR system would utilize large diameter optics coupled with a moderate-sized vacuum window to achieve ~20 cm poloidal coverage with ~1 cm resolution, leading to a $k_\perp$ resolution of 0.3–3 cm^{-1}.

In MIR, a probing beam illuminates an extended region of the plasma cutoff layer, with the curvature of the illuminating beam matched to that of the cutoff surface. The "virtual cutoff layer" is then imaged onto a planar mixer array. This is the effective surface, located behind the actual cutoff surface, where the waves appear to emanate from due to refraction. Imaging the density fluctuations virtually eliminates the complicated interference patterns that result from conventional reflectometry, allowing for a clear picture of density fluctuations over the illuminated cutoff surface, while providing a measurement of the poloidal wavenumber spectrum. As shown by Mazzucato [*Rev. Sci. Instrum.* **69**, 1691 (1998)], and demonstrated in detailed laboratory experiments as well as preliminary TEXTOR measure-ments [*Rev. Sci. Instrum.* **74**, 1426 (2003)], one can expect interference to play a significant role in the reflected field pattern if non-imaged measurements are taken beyond a distance $D_{diff} \approx 2k_0/[\Delta k_\theta^2(1+\sigma_\varphi^2)]$, where $\sigma_\varphi \approx <\Delta\varphi^2>^{1/2}$ and Δk_θ is the width of the poloidal mode spectrum. In the case of a single-channel reflectometer, a 1% fluctuation level with $\Delta k_\theta = 1$ cm^{-1} could lie within the low diffraction region while increasing the fluctuation level to 5% or increasing the spectral width of the fluctuations could be expected to yield considerable interference. The advantages of the MIR approach are thus a series of reliable localized (poloidally distributed) density fluctuation measurements and a measurement of the poloidal wavenumber spectrum, both of which are of crucial importance in turbulence measurements where neither the amplitude nor wavenumber spectra is known a priori.

Table 1 below summarizes the research and measurement goals of the collaboration tasks by the UCD group, the physics relevance of the tasks, and the diagnostic techniques used to accomplish the goals.

Table 1 Current Research and Measurement Goals (Existing Program Refinement, upgrades)

Research Goal	**Physics Relevance**	**Technique**
Measure the spatial and temporal evolution of the plasma density $n_e(r,t)$ and toroidal field $B_T(r,t)$ profiles.	Detailed profile reconstructions will provide a significant resource for improved EFIT. Profiles are complementary to that of Thomson scattering (TS), thus allowing for easy TS calibration.	Reconstruction of seven chord FIReTIP data yields $n_e(r,t)$ and $B_T(r,t)$ with <1 μs time resolution. Not limited to plasma edge as in FM reflectometry.
Real-time plasma density control.	Real time integrated density data for each chord offer numerous possibilities for developing real-time control focused on a variety of different NSTX plasma regions.	Real-time FIReTIP density outputs will be wired to the gas control system to program plasma density and interlock systems of the heating systems.
Monitor localized electron densities with a sufficiently high time (1 μs) resolution.	Confinement, transition physics (L/H), ELMs, microturbulence, MHD (TAE, CAE) and fluctuation studies via gas (Ar) puff. High frequency n_e fluctuations associated with MHD activities (CAE, TAE) at different tangencies is complementary to the X-ray and magnetic measurement.	The FIReTIP chords sample plasmas at different tangencies with high sensitivity and temporal resolution. Comparison study between chords provide a semi-localized measurement of density fluctuations.
Measure the spatial distribution and temporal evolution of density fluctuations associated with rf waves.	Fast wave heating has been effective on NSTX. Detailed understanding of the physics is not yet at-hand. Comparison of experimental data with theory should improve understanding.	The integrated FIReTIP chords sample the plasma with high temporal resolution (<1 μs) at different tangencies, and, unlike conventional fixed frequency reflectometry, will provide absolute measurement of high frequency density fluctuations.
Measure high k, short wavelength ETG turbulence in NSTX. (2003-4)	Theoretical predictions indicate that short wavelength T_e gradient modes are dominant in NSTX plasmas. Longer wavelength ITG turbulence and/or streamers may co-exists near the edge.	Five channel collective scattering at 280 GHz to measure density fluctuations with a broad range of radial wavenumbers ($k_r \leq 0$–$20\ \mathrm{cm}^{-1}$) and wide bandwidth (3 MHz).

Visualize low k, long wavelength ITG turbulence in NSTX. (2004-5)	The measured 2-D image of low k (long wavelength) turbulence can be compared with theoretical predictions for different plasma operations. In addition, measurements can be contrasted with that of the tokamaks.	The wide bandwidth (3 MHz) MIR system will achieve ~20 cm poloidal coverage with ~1 cm resolution and a $k_\perp$ resolution of 0.3–3 cm^{-1}. A similar system installed on TEXTOR allows for direct inter device comparisons.

A-XII. University of California at Irvine

Research Area: **Energetic ion confinement and instabilities**

Researchers: Professor William Heidbrink and students

Expertise: Fast ion diagnostics and experiments in magnetic fusion devices

Current Funded: Through 8/14/04

Recently Completed Research: As briefly described in Sec. 3-2 of the proposal, the confinement of beam ions was studied using short neutral beam pulses. In the absence of MHD, the neutron data show the expected dependencies on beam injection angle and plasma current; the average jump in the neutron signal is 88+-39% of the expected jump. The decay of the neutron and neutral particle signals following the beam pulse are consistent with Coulomb scattering rates, implying an effective beam-ion confinement time in excess of 100 ms. A paper describing these results is submitted to Nuclear Fusion. “An Alfvén eigenmode similarity experiment” is in press with Plasma Physics Controlled Fusion. Two figures from this comparative study between beam-ion driven instabilities in NSTX and DIII-D appear as Figs. 26 and 27 in Sec. 3-1 of the proposal. An important result of this study is that the toroidal mode number of the most unstable TAE scales as theoretically predicted, supporting the expectation that the mode number of any unstable TAEs in ITER will be high (~15).

Currently Planned Research: Our next two projects are motivated by the successful TAE similarity experiment between NSTX and DIII-D. The first of these, which will be conducted in collaboration with Eric Fredrickson (with theoretical support by Nikolai Gorelenkov), is a similarity comparison of CAE and GAE activity in the two tokamaks. The second study is motivated by the observation that rapid frequency chirping is extremely common in NSTX but rare in DIII-D. If we can understand the origin of this difference, we will better understand the mechanisms that control nonlinear saturation of beam-driven instabilities.

Extended Research Plans: Our main goal for the 5-year period is to develop accurate beam-ion profile diagnostics. These will contribute to both confinement studies of energetic ions (Sec. 3-2) and studies of beam-ion driven instabilities (Sec. 3-1). Several techniques are under consideration, including a neutron collimator, a 3-MeV proton camera, and a technique based on D-alpha light emitted by re-neutralized beam ions. We hope to station a UCI graduate student at Princeton, who will work under the joint supervision of Doug Darrow and Bill Heidbrink on one of these diagnostic systems. In addition to hardware costs (which are already included in Princeton's proposal), this effort will require an extension to UC Irvine's grant and a funding increase to support the Ph.D. student. A secondary goal is to include MAST data in our comparative study of beam-ion driven instabilities.

A-XIII. University of California at Los Angeles

1) Current research topics and participating researchers

The **N**ational **S**pherical **T**orus **Ex**periment (NSTX) has opened up a wide range of exciting new physics research avenues and plasma operating regimes within the overall US Fusion Energy Science Program. In particular, the study of a high beta, high performance plasma in the magnetic geometry of a spherical torus (ST) offers to provide significant insight into transport, stability and wave physics issues which will benefit not only the ST concept but fusion science in general. UCLA, as an active NSTX team member, currently contributes to both the operation and understanding of the NSTX plasma through application of cross-cutting measurement techniques that address a wide range of research needs. These measurement capabilities and physics relevance are listed below in Table 1.0.

Table 1.0 Current measurement capabilities and physics relevance

Measurement Capability	**Physics Relevance**
(1) Edge density profile via FM reflectometry – 50 microseconds temporal response	Confinement – L-H transition, ELMs, pedestal width and height, etc
(2) Turbulence correlation length of long wavelength modes via correlation reflectometry	Turbulence & transport; direct comparison with gyrokinetic code predictions: direct comparison with data from DIII-D
(3) Internal magnetic field strength via dual-mode reflectometry	Stability in high beta device, EFIT reconstruction.

UCLA is also actively involved in DIII-D, MST and HSX research programs and so is uniquely positioned for *to perform* detailed cross comparison with these alternative magnetic configurations. It is expected that these comparisons will enhance our understanding of turbulence driven transport as well as other areas of fusion science. The participating researchers are Tony Peebles, P.I., David Brower, Co-P.I., Shige Kubota, Participating Investigator, Neal Crocker, Postgraduate Researcher, Mark Gilmore (now at UNM).

2) Collaboration research expertise and goals

UCLA has pioneered the development of a wide-range of millimeter-wave measurements and, more importantly, applied them to improve our understanding of fusion science on both mainline and emerging plasma devices. Examples include (1) investigation of the role of sheared ExB flow on turbulence for both the H-mode edge and internal transport barriers (2) the pivotal role played by low wave-number ITG turbulence in governing ion thermal transport, (3) edge density profile measurements on DIII-D and their role in ELM, L-H transition and pedestal physics and (4) the role of current density and magnetic fluctuations on transport in the MST reversed field pinch.

UCLA is currently enhancing measurement capabilities on NSTX to address a number of important science questions. Our goals for the next five years are to contribute to generation of answers to the following questions:

(1) Does short wavelength e.s. turbulence dominate the core of NSTX plasmas?

(2) What is the role of longer wavelength e.s. turbulence (e.g. ITG turbulence)?

(3) How do the turbulence characteristics vary between different fusion devices e.g. DIII-D and NSTX?

(4) Can emerging gyrokinetic simulations accurately predict turbulence and transport characteristics in NSTX?

(5) Do current density and low k magnetic fluctuations play a significant role in transport at high beta in NSTX?

(6) Do CAE modes channel energy to thermal ions via a stochastic process?

(7) What is the magnetic field structure (i.e. q profile) in NSTX? Concerns regarding the viability and availability of MSE indicate that additional measurements are essential.

(8) Can the HHFW heating and current drive on NSTX be fully understood in terms of theoretical full-wave models? Are rf waves launched directionally as the antenna phasing is modified?

(9) What is the physics of ELMs, the L-H transition and the pedestal in a spherical torus?

UCLA will provide a wealth of information towards resolving many of these critical issues. UCLA has an excellent record of accomplishment in addressing important research needs on a wide range of fusion devices (e.g. DIII-D, NSTX, MST, HSX, etc). It is planned to fully leverage this experience and deliver to NSTX crucial measurements essential for understanding transport, stability and wave physics in a high beta spherical torus. Understanding the science of the spherical torus will require improved measurement capability coupled with detailed comparison both with theoretical/computational modeling and with data from other fusion concepts. UCLA is well positioned to make major contributions as part of the NSTX Team. However, the additional resources need to be allocated to achieve scientific progress in a timely manner.

3) Areas of contribution in the NSTX 5-year plan

UCLA will contribute to a wide range of areas outlined in the **NSTX 5 year plan** as described in **Sections 3.1, 3.2, 3.3 and 3.5**

4) Presently DoE-funded funded activities and duration (3/1/03 – 2/28/06)

Table 1.1 Current Research and Measurement Goals (Existing Program Refinement, upgrades)

Measurement	**Physics Relevance**	**Technique**
Continuation and refinement of existing research program involving reflectometry measurements of **density profile, turbulent correlation length and internal magnetic field structure**. Proposed refinements include improved spatial and temporal coverage combined with between-shot availability.	Relevance to confinement, transport and stability studies on NSTX. e.g. comparison with gyrokinetic simulations such as GYRO (9): investigation of the physics of edge pedestal formation. Existing hardware has also been utilized to internally probe compressional Alfvén waves.	Frequency modulated (FM) reflectometry (50µs time resolution) for profile measurement. Dual mode (O-X) and O-mode correlation reflectometry for magnetic field strength, magnetic field pitch angle, and turbulent correlation length measurement.

Establish the existence (or not) of **high k, short wavelength ETG turbulence** in NSTX. Compare fluctuation levels, spectra etc. in discharges where theory predicts large variation in the level of ETG mode turbulence. (2003-4)	Theoretical predictions indicate that short wavelength electron temperature gradient modes are dominant in the core of NSTX plasmas. Longer wavelength ITG turbulence is expected to exist near the plasma edge.	Collective scattering in a **back scattering geometry at ~100 GHz** to provide the clearest and most sensitive method of detecting the existence of ETG modes. The antennae and port already exist for such a scattering geometry.
Measure the spatial distribution and temporal evolution of **internal density fluctuations associated with rf waves**. Primary goals will be to measure the antenna directionality and determination of perpendicular wave number. Other goals involve the **local study of CAE/TAE modes (2004)**	Fast wave heating has been effective on NSTX. Detailed understanding of the physics is not yet at-hand. Comparison of experimental data with theory should improve understanding. Study of CAE mode amplitudes will establish whether they are responsible for ion heating.	Multiple (7) fixed frequency **reflectometers employing quadrature detection** to determine the reflectometer phase. At small density fluctuation levels, this phase information can be utilized to determine local fluctuation levels.

5) Extending research contribution to 5 years

On the longer time-scale, it is planned to design, fabricate, install and operate a far-infrared polarimeter/interferometer to obtain information regarding current density on axis, magnetic fluctuations. We view this as extremely important from both the transport and stability perspectives. The information gained from this system cannot be obtained from the toroidally viewing FIRE-tip system. The following table provides additional information.

Measurement	**Physics Relevance**	**Technique**
Determine the **current density on axis**, $\tilde{J}_o(t)$. The magnetic axis is also identified. Measure fluctuations, J_o, with a bandwidth of up to 3MHz.	Knowledge of J_o on axis is currently lacking in NSTX. This diagnostic will provide this crucial information and serve to significantly constrain EFIT. The $J_o(t)$ measurement can follow temporal dynamics with a time resolution of ~0.3 μs and so can study fast reconnection events such as sawteeth.	Measure equilibrium Faraday rotation angle via polarimetry. The slope of the Faraday rotation angle provides direct information on J_o. In the highly shaped NSTX plasma, such information can significantly constrain EFIT. The existing Fire-Tip system cannot provide this information.
Measure **long wavelength ($k < 1$ cm^{-1}) radial magnetic field fluctuations of both turbulent and coherent modes** Set maximum fluctuation levels and investigate potential role in anomalous transport and CAE mode anomalous ion heating.	In high beta devices such as NSTX, the potential role of magnetic fluctuations in anomalous transport becomes more significant. On NSTX it is essential to develop and field techniques capable of addressing this issue. The system would also measure fluctuation amplitudes of coherent modes such as MHD, CAE, TAE modes, etc.	Utilize a sensitive fast polarimeter system to study radial magnetic field fluctuations by probing a radial chord through magnetic axis. Magnetic fluctuation levels as low as 0.01% will be measured with a bandwidth of 3 MHz. A similar system has been demonstrated by UCLA on MST.
Measurement of **total (line average including high field region) absolute fluctuation content (ň/n) of low k (ITG)** turbulence. The system would provide a density fluctuation monitor that enables comparisons over a wide range of discharges and between machines.	The measured fluctuation content of low k turbulence can be compared with theoretical predictions for different plasma operations such as L, H mode. In addition, measurements can be contrasted with different fusion devices.	An extremely sensitive, fast, interferometer would be installed to monitor ($\tilde{\phi}/\phi$) and thereby (ň/n) with a bandwidth of 3 MHz. Similar systems have been installed on MST, HSX and DIII-D allowing direct inter machine comparison of low k turbulence content.

A-XIV-a. University of California at San Diego – High Harmonic Fast Wave

1. Current Research Topic and Participating Researchers:

UCSD is currently engaged in the **modeling of high-harmonic fast wave (HHFW) heating and current drive** using the CURRAY ray tracing code. **Tak Kuen Mau** is the sole participating scientist in this project, and the work is carried out in collaboration with all HHFW team members on NSTX, including theorists and experimentalists. In addition, there is collaboration with the computation group at PPPL to implement CURRAY into the TRANSP analysis code.

2. Collaboration Research Expertise and Goals:

The project involves the prediction and analysis of NSTX experiments on HHFW heating and current drive. To achieve this, CURRAY is being implemented into TRANSP to analyze and simulate time evolution of HHFW-heated discharges [1], to investigate the formation of H-mode discharges [2] and to estimate the amount of driven current [3]. Specifically, the adjoint technique is employed in calculating the HHFW-driven current profile, which becomes important at high beta. HHFW interaction with energetic beam ions has also been studied through comparison with the HPRT ray tracing code at PPPL. Extensive benchmarking of CURRAY with HPRT and full wave codes (AORSA, TORIC) has also been carried out. The goal of this research is to build up the analysis tool needed to perform between-shots analysis of future high-beta, high bootstrap fraction and long-pulse discharges.

3. Areas of Contribution in the NSTX 5-Year Plan:

HHFW modeling with CURRAY will contribute to the scientific and operational goals of the NSTX 5-year program in Wave-Particle Physics, Heating and Current Drive (Ch. 3.3), and Integrated Scenario Modeling (Ch. 4). It may also find applications in Integration and Control (Ch. 3.6). The goal is to help understand experimental observations of high performance discharges involving HHFW power using either time-slice analysis with stand-alone CURRAY or time dependent analysis with the TRANSP/CURRAY combination.

4. Presently DOE-funded Activities and Duration:

The project is currently funded through April 14, 2005. Activities include the use of CURRAY to calculate heating and driven current profiles of NSTX discharges, comparison of CURRAY results with other codes to validate its accuracy, and implementation of CURRAY into TRANSP. The capability to model HHFW interaction with energetic beam ions is also being improved and implemented in order to study its effect on current drive efficiency on NSTX, particularly for high-beta discharges.

5. Extending Research Contributions to 5 Years:

The goal of extended research is to gain a more comprehensive understanding of what pivotal roles HHFW power can play in advanced performance discharges, and make improvements in CURRAY to facilitate this. One particular goal is to assess the effect of energetic beam ion absorption of HHFW on current drive in discharges where both RF and NBI power are applied, and how the effect can be minimized with a suitable launch spectrum. The adjoint technique employed in CURRAY to calculate the current drive efficiency will be extended to include the effect of a transient DC electric field. Careful benchmarking with full wave codes and/or quasilinear kinetic codes will be carried out to validate and improve on the CURRAY physics models. The effect of edge turbulence on the wave propagation and energy flow path may be studied using a Monte Carlo ray tracing approach. Mode conversion to IBW at high beta may also need to be modeled.

References:

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A-XIV-b. University of California at San Diego – Edge and SOL Studies

1) Current research topic(s):

UCSD is carrying out **edge and SOL physics studies** using a newly installed fast reciprocating probe. The main aim of the work at the moment is to produce high spatial resolution profiles for the edge simulation codes (such as UEDGE) and to start characterization of the edge/SOL turbulence and transport.

Measurement	**Physics Topic Addressed**
Profiles of n_e, T_e with 1.5 mm spatial resolution and 1 ms time resolution. Profiles are obtained in 80 ms.	• Scaling of SOL dimensions • Heat and particle flux to divertor and scaling • Input to UEDGE modeling
E_r profiles, profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 80 ms	• L-H transition physics • Edge barrier formation • Ion losses physics
$\tilde{E}_r, \tilde{I}_{sat}, \tilde{E}_r, \tilde{\Gamma}_r$, profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 80 ms	• Basic turbulence characterization in a ST • Particle and heat transport in the edge/SOL • Scaling of turbulence • Intermittent transport in the edge/SOL • Compare to BOUT predictions
$\tilde{V}_r \tilde{V}_\theta$, profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 80 ms	• Reynolds Stress, self-generated flows, energy cascades in plasma turbulence, L-H transition physics

The expertise and involvement that UCSD has on other programs (such as DIII-D and TCV among others) will also allow direct comparison of NSTX results to those form other devices. UCSD has also access to a large database of edge data from various devices including TEXTOR and CCT.

2) **Participating researchers:**

J. Boedo, N. Crocker (now at UCLA), H. Kugel (PPPL), G. Tynan (UCSD), R. Maingi (ORNL), S. Zweben (PPPL), R. Maqueda

3) **Collaboration research expertise and goals:**

The UCSD team has a broad expertise in edge/SOL physics that is brought to the NSTX collaboration. Among the recent accomplishments are:

- Discovery that ExB drifts are important in the DIII-D edge and divertor, resulting in accelerated implementation of drifts in simulation codes.
- Quantification of divertor ExB flows and realization the unexplained in-out divertor asymmetries could be understood by this mechanism
- Discovery that divertor plasma flows at sound speed toward the target plates in detached divertor conditions. This discovery has important consequences for divertor particle and heat balance.
- Discovery that convective intermittent transport is present in the DIII-D boundary and quantification that ~50% of the radial transport is driven by this mechanism in the edge/SOL.
- Scaling studies reveled that the intermittency, and concomitant transport, increase with pedestal density.

UCSD will shift emphasis from profile characterization and scaling to edge/SOL mass and momentum transport and turbulence simulation benchmarking. A series of small upgrades are also being considered. The goals are:

- Characterization of edge/SOL radial turbulent transport. Compare to BOUT predictions.

- Quantification of intermittency and its contribution to the total radial transport. Compare to BOUT.
- Add fast (500 kHz) Te capability to measure radial heat transport.
- L-H transition physics. Investigate changes in turbulent transport.
- Measurement of the Reynolds Stress term ($\tilde{V}_r\tilde{V}_\theta$) and search for self-generated flows in the boundary.
- Characterization of the radial electric field Er and edge transport barrier formation. Correlate to existing theories. Compare to BOUT predictions.
- Add magnetic sensors to look for the importance of electromagnetic turbulence in the ST configuration.
- Install a divertor probe (incremental funding) to investigate divertor physics and poloidal asymmetries of turbulence.

4) Areas of contribution in the NSTX 5-year plan:

Measurement	**Physics Topic/Activity**
Profiles of n_e, T_e with 1.5 mm spatial resolution and 1 ms time resolution. Profiles are obtained in 80 ms.	• Edge modeling • Edge scaling • RF edge physics
E_r profiles. 1 MHz time resolution and 1.5 mm spatial resolution. Profiles obtained in 80 ms.	• L-H transition physics • Edge barrier formation • Ion loss physics • Radial conductivity

$\widetilde{E}_\theta, \widetilde{I}_{sat}, \widetilde{T}_e, \widetilde{E}_r, \widetilde{\Gamma}_r$ profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 80 ms	• Edge physics • L-H transition physics • Turbulent transport physics
$\widetilde{V}_r \widetilde{V}_\theta$ profiles with 1 MHz time resolution and 1.5 mm spatial resolution. Profiles obtained in 80 ms	• Turbulent transport physics • L-H transition physics

5) Presently DOE-funded activities and duration:

The present activities were outlined in sections 3 and 4 above. The present grant is funded through 08/2003. A renewal proposal has been submitted that will hopefully extend the activities to 08/2006

6) Extending research contributions to 5 years:

The medium range goal is to continue the studies outlined above and add magnetic fluctuations capabilities in order to evaluate electromagnetic turbulent transport at high beta. A long range goal is to extend the study of edge/SOL physics to the divertor. This goal is crucial as NSTX moves into higher power regimes and starts exploring divertor heat flux mitigation techniques such as gaseous divertors. Part of the goal is to install a divertor probe to characterize the divertor plasma.

Medium range Measurement	**Physics Topic/Activity**
$\widetilde{T}_e, \widetilde{\Gamma}_r, \widetilde{Q}_r$ profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 80 ms	Include T_e fluctuations on turbulent particle and heat measurements • Edge physics • L-H transition physics • Turbulent transport physics

$\widetilde{T}_e, \widetilde{B}, \widetilde{\Gamma}_r, \widetilde{Q}_r, \widetilde{A}_r$	Include magnetic fluctuations on particle and heat transport measurements • Edge physics • L-H transition physics • Turbulent transport physics

Long range Measurement: Divertor Probe	**Physics Topic/Activity**
Profiles of n_e, T_e with 1.5 mm spatial resolution and 1 ms time resolution. Profiles are obtained in 80 ms.	Edge physics. Divertor physics • Edge modeling • Heat flux scaling Heat and particle control
Parallel divertor flows by using Mach probes	L-H transition physics • Edge barrier formation • Ion loss physics • Radial conductivity
$\widetilde{E}_\theta, \widetilde{I}_{sat}, \widetilde{T}_e, \widetilde{E}_r, \widetilde{\Gamma}_r$ profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 80 ms	Edge physics • L-H transition physics • Turbulent transport physics Divertor physics
$\widetilde{E}_\theta, \widetilde{I}_{sat}, \widetilde{T}_e, \widetilde{E}_r, \widetilde{\Gamma}_r$ profiles with 1 MHz time resolution, 1.5 mm spatial resolution. Profiles obtained in 80 ms	Edge Physics Transport and Turbulence • Poloidal asymmetry of turbulence • Comparison to BOUT Energy and Particle Control

A-XIV-c. University of California at San Diego – Far-SOL Transport Modeling

1) **Current research topic(s):** Modeling of far-SOL plasma transport in NSTX

2) **Participating researchers:** A.Yu. Pigarov, S.I. Krasheninnikov, G. Yu (graduate student)

3) **Collaboration research expertise and goals:** The multi-fluid two-dimensional UEDGE code simulations of plasma, impurity, and neutral gas transport in the far SOL region of NSTX spherical tokamak and corresponding analysis of experimental data. The goal is the understanding of the effect of fast anomalous non-diffusive transport on radial plasma profiles in the SOL, on particle recycling in the main chamber and core plasma fueling, on intrinsic impurity particle sources and core plasma contamination by impurities, on particle and heat power loads to the divertor plates, and on divertor plasma detachment.

4) **Areas of contribution in the NSTX 5-year plan:** Chapter 3, Section 3.5: Boundary Physics

5) **Presently DOE-funded activities and duration:** The group is funded to carry out the follow research:

(i) The validation of our theoretical models of anomalous intermittent non-diffusive cross-field transport which was observed on many tokamaks including the NSTX, stellarators, and linear-plasma devices;

(ii) Thorough understanding of the effect of fast anomalous non-diffusive transport on radial plasma profiles in the inner/outer SOL, on particle recycling in the main chamber, on core plasma fueling, on intrinsic impurity particle sources and core plasma contamination by impurities, on particle and heat power loads to the divertor plates, and on divertor plasma detachment;

(iii) The development of an initial database of cross-field plasma transport parameters (diffusivities and convective velocities) in L and H mode discharges, an analysis of the main trends of plasma transport parameter variation with global discharge parameters, toroidal magnetic field strength Bt, and plasma radii (note, that among major US tokamaks, the NSTX tokamak provides a unique set of edge plasma data correspondent to the low values of Bt, for which enhanced cross-field transport and ExB drifts are expected), and the cross-tokamak comparison of cross-field transport properties.

DOE research grant: DE-FG03-02ER54680 at UCSD, duration: 8/15/02-8/14/04

6) Extending research contributions to 5 years: The UEDGE code modeling of the temporal evolution of edge plasma profiles in transition between L and H modes on NSTX and the pedestal asymmetry. Analysis of the combined effect of anomalous plasma cross-field convection, neutral particle recycling and gas puffing, and impurities on the development of hollow density profiles (the so-called, "ears").

A-XV. University of Washington

Research Topic: **Coaxial Helicity Injection and Compact Toroid Injection**

Researchers: Roger Raman, Thomas R. Jarboe, Brian Nelson, and Aaron Redd

A) Coaxial Helicity Injection research

Plasma start-up: During 2002 and 2003, important new progress was made on the HIT-II experiment at the University of Washington, that provides a physics solution for non-inductive current initiation in a ST. This is based on a new method, referred to as Transient CHI discharge, used for initiating the CHI discharge [1]. Plasma start-up using transient CHI plasma has three steps. These involve (1) establishing a sufficiently high quality CHI discharge, (2) forcing reconnection and (3) applying induction from the central solenoid. Three new results came out of this new method. First it was shown that CHI produces closed flux plasma, second it was shown that the plasma was of sufficiently high quality to couple to an inductive discharge without degrading the inductive discharge. Third it was shown that CHI improved the performance of the inductive discharge by saving transformer volt-seconds. Because the method did not rely on any time changing poloidal field coil currents, and requires only the application of a short (few ms) voltage pulse to a pre-established vacuum magnetic flux condition, the method is very well suited to reactors where the poloidal field coils will be located outside blanket structures, which would not allow the possibility of rapidly changing magnetic fluxes inside the vessel. The method is fully adaptable to NSTX and requires a demonstration on NSTX. In regard to plasma start-up, our plans are as follows:

During FY 03 we will investigate the possibility of building a small capacitor based power supply, as on the HIT-II experiment, for transient CHI discharge initiation on NSTX. The present NSTX DC power supplies used for applying the CHI voltage are not fast enough because of external inductances and the nature of the thyristor switches that does not allow the CHI current to be rapidly ramped up or the current to be rapidly reduced to zero, an operating feature necessary for transient CHI discharge initiation.

During FY 04 CHI operations, our primary goal is to demonstrate transient CHI startup by successfully coupling a CHI produced discharge to induction.

During FY 05, we plan to improve the temperature of the initial CHI discharge by injecting a short pulse of NBI and HHWF, to the CHI discharge as it is being initiated. This should result in improved volt-seconds savings. We will then use these improved CHI plasmas, to investigate the use of the outside PF coil system on NSTX to inductively ramp the CHI current to higher levels (300 to 500kA). At these current levels, these plasmas are expected to be suitable for full non-inductive current sustainment using HHFW and NBI.

During FY 06, using discharges developed during FY 05, we will conduct a demonstration of non-inductive current startup using CHI and transfer to non-inductive current drive systems. A second parallel objective will be to increase the initial current generation levels of transient CHI discharges. In principle, very high currents (> 300kA) are possible using CHI alone, but producing such high current plasmas that also have a sufficiently high plasma temperature depends on electrode physics and technology. Data on NSTX divertor plates (used as electrodes during CHI) is evolving, and information on this is expected from high divertor loading single null discharges. The possibility of a tungsten divertor plate is also being considered for the NSTX program. Through an improved understanding of divertor technology (during FY 04 and 05), in FY 06 and 07, we should be able to optimize the current production capability of transient CHI.

Steady-state CHI research: The motivation for steady-steady CHI research are (1) to drive some edge current to a pre-establish high current discharge (2) to favorably control edge SOL flows (3) possible control of edge plasma rotation for transport barrier sustainment and (4) investigate if higher levels of useful CHI current can be produced, than what can be produced using transient CHI for plasma startup. High beta stability analysis of ST plasmas shows that the presence of some edge current drive allows an ST discharge to improve its beta limits [2]. CHI is particularly well suited for this application, whereas other conventional current drive methods drive current in the interior. There is existing evidence from edge biasing studies that voltage application to the SOL can be used to improve the discharge properties of lower single null plasmas, including controlling the edge SOL flows. But these earlier studies in tokamaks did not investigate the possibility of edge current drive or edge rotation, as these aspects of CHI were not well known to the tokamak community. Also, these earlier tokamak experiments (such as on DIII-D) did not have access to good edge rotation measurement diagnostics.

Assessing the usefulness of CHI for edge current drive and controlling SOL flows, requires good capability to control the edge boundary shape and precise control of the SOL footprints. NSTX is a new machine, with the capability for good boundary shape control to be developed during FY 04 and 05 by the Integrated Scenario Development group. This capability is expected be become available as a result of Real-time EFIT that is being developed in collaboration with DIII-D. Because of this we expect the full capability of edge current drive and edge SOL flows to be developed during the FY 06 to 07 period.

Thus far good progress has been made in the area of high current production using steady state CHI [3,4]. Long pulse (330ms), high current (400kA) discharges have been produced. While equilibrium reconstruction results using the EFIT and ESC are consistent with the generation of closed flux surfaces, these results require internal electron pressure profile measurements before one can conclude that in these long pulse discharges the edge driven CHI current has indeed produced closed flux surfaces. These pressure measurements require the presence of a stable plasma discharge for diagnosing. Because of the highly dynamic nature of the CHI discharge these measurements have not been possible. Stabilizing the steady-state CHI discharge requires (1) development of a new feedback control algorithm and (2) possibly energizing the newly installed absorber PF coils for reducing the absorber stray fields. During FY 05, we will reestablish the 300kA discharges and investigate the capability of the newly installed absorber to maintain a 300kA current flattop for about 100ms, to enable diagnosing of these plasmas, initially without relying on active feedback control. If by FY 05, it is felt that sufficiently high currents are not achieved by the transient start-up methods, the active feedback control of steady state CHI discharge will be developed during FY 06 to improve the CHI produced current. Related development experiments are planned on the HIT-II experiment during FY 03 and 04.

During FY 07 and 08, the methods developed will be used for volt-seconds savings to a high confinement, high bootstrap fraction discharge, that will be sustained noninductively for periods of time longer that a current diffusion time.

B) Compact Toroid Injection research

In present experiments, neutral beams or RF are used for plasma heating. An added benefit of NBI heating is that the tangentially injected beams transfer momentum to the plasma and provide plasma rotation. The velocity shear helps sustain transport barriers. In a reactor, fusion product alphas will provide the needed heating thus neutral beam heating will not be needed during the sustained operation phase. Alphas being isotropic cannot provide preferential plasma rotation and velocity shear. A fueling system that can also provide a source of toroidal plasma rotation, while fueling the discharge as needed would be highly desired.

The long-term plans for the ST program are to produce a high beta, high bootstrap current fraction discharge and to eventually sustain it for steady-state operation. Operation under these conditions requires maintaining the optimized plasma profiles. Unfortunately, at this time there is no viable fueling system to meet the fueling needs of such discharges, as fueling these discharges requires the injection of small amount of fuel where needed and as often as needed without destroying the optimized profiles.

CT fueling has the potential to meet this need while imparting toroidal momentum, however, the CT technology is largely undeveloped.

Perkins [5] and Parks [6] proposed injecting compact toroids of dense plasma into tokamaks to achieve deep fueling. Experiments on TdeV at a toroidal field of 1.4T have shown that a CT can beneficially fuel a tokamak discharge without adversely perturbing it [7]. CTs have also been used to trigger H-modes in ohmic tokamak discharges [8]. The possibility of inducing H modes in new ST configurations such as the "Natural Divertor" configuration on MAST will ease the divertor power loadings during high performance steady state operation.

CT systems are also fully electrical, with the only moving part being the high reliability gas valve. Electrical systems are generally more reliable than mechanical systems. In addition, in a CT injector, because of the electrical nature of the injector it is relatively easy to alter the fuel mass and deposition location on each pulse as desired by the plasma control system. Altering the accelerator voltage alters the CT kinetic energy density, thereby changing the depth of penetration and the fuel deposition location. Changing the amount of gas puffed into the injector region alters the mass of the CT. Changing the fuel composition is also easy as some of the gas injection valves could be controlled by the operating system to dope the fuel with needed isotopes.

The CT injector used in the TdeV experiments is at present in storage at PPPL. The estimated cost of duplicating this system is about $1.5M and two years. Present plans for CT Injection into NSTX calls for off line testing of this injector during FY 05 and 06, with a possible target injection date in NSTX during FY 08. Considering that the lead scientist (R Raman) is on site at NSTX, it would be beneficial to ramp up the CT development work starting from FY 03, to possibly enable an earlier CT injection target date on NSTX.

During FY 03, we would like to begin calibrating the gas injection system on the CT injector. At the time the CT injection program was discontinued on TdeV due the termination of the entire Federally supported Canadian Fusion program, a new improved gas injection system was under development. This system was designed to give more precise control over the injected gas, while minimizing the amount of gas injected. The amount of time needed to fully commission this system is expected to take a few months. To conduct this work, none of the CT power supplies need to be energized, nor does the injector need to be fully reassembled. This work can be conducted during the next 16 months, as time permits, without impact on any other work. Completion of this work before initiation of the off-line CT testing will make the off-line CT development work more efficient.

Our plans in regard to CT injection into NSTX are as follows:

- FY 03, 04: Improve the fast gas injection system for the CT injector to maximize gas coupling to the CT.

- FY 04 and FY 05 : Conduct off-line testing of the injector with the aim of completing this testing as soon as possible, depending on allowed resources. Investigate the possibility of constructing a high-rep rate power supply module for initial high rep-rate feasibility studies into a dummy load.

- FY 06 to 08: Conduct experiments on NSTX to establish (1) toroidal momentum injection, (2) demonstration of localized core fuelling including variable mass and fuel deposition location. This information is needed for a future multi-pulse injector, (3) prompt H-mode initiation capability and (4) transport studies using impurity doped CTs. Demonstrate, depending on allowed resources, high rep-rate capability at higher power levels into a dummy load and outline the design of the high rep-rate power supply for future NSTX CT injector needs.

We note that this plan calls for an earlier CT injection target date (FY 06) on NSTX than the plan outlined in the NSTX 5-year plan document. In principle, depending on the allowed resources, CT injection experiments on NSTX could start as early as FY 05.

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A-XVI. University of Wisconsin-Madison

1) Current research topics and participating researchers: The University of Wisconsin-Madison is engaged in research on the neoclassical modeling of plasma rotation and plasma confinement physics for NSTX. Participating researchers at the University of Wisconsin are K. C. Shaing and J. D. Callen. The work is in collaboration with R. Bell (PPPL), E. Synakowski (PPPL), W. A. Houlberg (ORNL), S. A. Sabbagh (Columbia U.), and M. Peng (ORNL).

2) Collaboration research expertise and goals: Several research topics are either planned or currently in progress: a) In collaboration with W. A. Houlberg (ORNL), a neoclassical theory is being developed to include the effects of the neutral beam injection on ion energy confinement. The goal is to provide an explanation of the observed extremely good ion confinement. b) On a related issue, we are comparing the experimentally inferred toroidal momentum diffusivity in the absence of magnetohydrodynamic (MHD) activity with that predicted by neoclassical theory. c) We plan to compare theoretical predications and experimental observations of the toroidal plasma rotation when there is a resistive wall mode (RWM) present.

3) Area of contribution in the NSTX 5-year plan: Research topics a) and b) contribute to the understanding of ion energy confinement and plasma rotation described in 3.2.2, while topic c) is related to the understanding of the plasma rotation in the presence of a resistive wall mode described in 3.1.1 and the appendix on Columbia U. collaboration.

4) Presently DOE-funded activities and duration: Work is funded through a grant that extends to 8/14/05. We are presently working with W. A. Houlberg on the development of a neoclassical theory to include the effects of the neutral beam injection on the ion energy confinement and comparing the experimentally inferred toroidal momentum diffusivity with that predicted by neoclassical theory. Analytical theory (supported by a separate theory grant from DOE) for the toroidal momentum dissipation in the presence of the resistive wall mode is also developed and is being adapted for modeling plasma rotation in the presence of the resistive wall mode in NSTX.

5) <u>Extending research contribution to 5 years:</u> The extended goal is to develop a comprehensive capability to model plasma rotation (with or without MHD activities) and plasma confinement for NSTX plasmas. This will be accomplished by comparing various advanced neoclassical theoretical models with experimental observations.