Edge, Scrape-Off Layer, Power and Particle Control Physics

FY99 NSTX Research Forum

January 12-14, 1999, PPPL

Working Group 5 Report

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I. Introduction

This document summarizes the important scientific elements of NSTX research presented at the FY99 NSTX Research Forum to the Edge, Scrape-Off Layer, Power and Particle Control Physics Working Group (WG5). It will provide the scientific basis for the FY00-01 NSTX National Research Program Proposal and for the preparation of Letters of Interest and Proposals for enhanced collaboration for FY00-01. Some research elements presented at the FY98 Research Forum were not discussed at the FY99 Research Forum, but remain pertinent to the NSTX program and have been retained in this document for completeness.

Each of the items in the NSTX mission statement imply specific objectives for the Boundary Physics program (encompassing the edge, scrape-off layer, divertor, as well as power and particle control issues):

- Reaching average β_T values of 25 - 45% and bootstrap current fractions of 50 - 90% will require high power operation. The heat fluxes striking the plasma facing components (PFC's) are expected to be more than ten megawatts per square meter, greater than in moderate aspect ratio tokamaks primarily because of the relatively small major radius of NSTX. However, the peak heat flux may be reduced by radiation. Significant progress in developing both new materials and radiative regimes will have to be demonstrated if the spherical torus concept is to be extended to a volume neutron source or power plant of small capital cost.

- Maintaining a noninductively sustained current profile by radio frequency (RF) heating and coaxial helicity injection leads to requirements on the plasma conditions in front of the launching surface. The Boundary Physics program must be able to characterize and control the plasma at these locations to maximize current drive efficiency.

- Experience with existing toroidal devices has demonstrated that achieving high confinement, collisionless plasmas with high temperature and density entails controlling the boundary conditions for the core plasma. Doing so implies an ability to manipulate main ion and impurity recycling from the PFC's and to alleviate deleterious edge instabilities.

- The short connection length on the outboard side and high mirror ratio associated with the low aspect ratio of NSTX could potentially give rise to new SOL phenomena that must be understood as part of the "proof of principle" of the spherical torus.

Each of these objectives is composed of a set of boundary physics research elements. In this report, these specific elements are laid out in a phased strategy and correlated with the NSTX operation timeline. The measurement needs for each element are detailed and matched with the research proposals presented at this Forum.

This Research Forum differs from the two prior ones in that a specific set of the FY99 research elements have now been funded for execution during the upcoming NSTX run periods. The organizational entities responsible for carrying out this boundary physics-related research are the three Experimental Task Forces and the Boundary Physics Operations Group. This Working Group advises those entities primarily through this report. Additional advice resulting from electronic mail discussion amongst Working Group members may also be generated.

Particle fueling issues require further study to determine the need and schedule for pellet and compact toroid (CT) injection. Hence, the relevant material presented in this Forum is collected into Section III-4, separate from the phased Boundary Physics Program strategy.

The charge for WG5 at the FY99 Research Forum was to focus on "Phase II" research elements. However, the group as a whole felt strongly that several additional diagnostics are critical to the success of the first phase of NSTX operation and warrant immediate attention. These recommendations are summarized in Section IV.

II. Phases for NSTX Boundary Physics Program

In this section, the three phases of the NSTX Boundary Physics Program are summarized; they will be broken down into individual research elements in the subsequent section. Note that these phases overlap in time. The NSTX overall programmatic objectives and dates for these phases are given in parentheses.

Phase I: Operational Support and Wall Conditioning
(Startup and Ohmic / Low Auxiliary Power Operation: 5/99 - 4/00)

This phase begins with first plasma and, as far as boundary physics is concerned, continues throughout the life of the device. The RF heating powers in this Phase are up to 4 MW. Reliable operation entails using wall conditioning to reduce recycling and impurity fluxes as well as preventing plasma damage to the PFC's, particularly the RF antenna and coaxial helicity injector. Heat fluxes and their impact on PFC's will be measured so that scaling estimates can be made in preparation for future operation at higher heating powers. A gross characterization of the SOL and divertor plasma conditions is planned to permit comparisons with other toroidal devices.

The funded research elements will be listed and their connection to the Experimental Tasks made. Recommendations for additional diagnostics and research are made.

Phase II: Characterization of Diverted and Inner Wall Limited Edge and SOL Plasmas
(Heating and Noninductive Operations for Startup and First Stability: 5/00 - 9/01)

In this Phase, the RF heating power will increase to 6 MW and 5 MW of neutral beam injection will become available, both coincident with the beginning of focused transport and MHD experiments. *The divertor and central column materials installed for Phase I will not survive currently planned operations during this Phase without either the use of higher heat flux materials or the development of radiative techniques for dispersing the core heat exhaust over a larger area.* Accomplishing the latter objective may require that significant new hardware, such as a pumped divertor be installed.

Accurate modeling of core particle and heat transport implies a critical accounting of edge power and particle sources and sinks. Models based on these data should be further developed, benchmarked, and used to extrapolate divertor heat fluxes to full NSTX heating power. Sets of edge and divertor plasma parameters should be established for comparison with transport models.

Phase III: Unique Spherical Torus Experiments and High Power and Particle Flux Handling
(Advanced Physics: 10/01 and beyond)

The beginning of this phase coincides with the possibility of simultaneous use of neutral beam injection and RF heating, bringing the total auxiliary heating power to 11 MW, and with detailed core transport and fluctuation studies. The power and particle control techniques of the previous two phases will be extended, as required, to handle the additional heating power represented by full power, high β operation. This includes the development of edge and core radiative scenarios to reduce PFC heat fluxes, as well as the deployment of advanced methods for measuring plasma-material interactions in real time. Achieving the needed level of control will likely entail understanding and alleviating edge instabilities. The high heat fluxes in NSTX also make it a convenient plasma-material interaction testbed for the PFCs to be used in ST reactors. A pumped divertor, optimized for core performance, would provide the most effective means of controlling recycling.

The impact of unique ST features such as high mirror ratio, short connection length, and large field line curvature on edge parameters, SOL lengths, turbulence, and transport should be examined for comparisons with moderate aspect ratio devices.

III. Specific Research Elements in the Boundary Physics Program

The research elements comprising each phase of the program have been further subdivided into three physics headings for clarity and to convey a sense of continuity between the phases: A. Recycling and impurity control, B. Heat flux and power balance, C. Edge characterization. These headings also neatly summarize the mission-related Boundary Physics objectives presented in the Introduction.

The Working Group has identified and presented below the measurement needs of each phase and research element.

1. Phase I

Throughout this section, tools will be listed in connection with the goal to which they contribute. Hence, some tools are mentioned more than once. The currently FY99 funded tools are listed under the heading “Existing”. The Working Group feels that a few additional tools are needed for safe and efficient operation under Phase I; these are listed under the heading “Recommended”. These entries are further broken down into “Critical” elements (of requiring significant new expenditures) and “Low Cost”.

The connection between the Working Group and the Experimental Task groups, working in conjunction with the Boundary Physics Operational Group, which will actually carry out the research on NSTX, is illustrated in a separate “Objectives” section listing experiments relevant to each heading. The reader should consult the Experimental Task reports from this Forum for additional details of these experiments.

A. Recycling and impurity control

Goal: Enable reliable operation by utilizing wall conditioning to reduce recycling and impurity flux.

Measurement and Control Needs: Gross indicators of fuel and impurity fluxes in the divertor and SOL (e.g., the ratio of H_α to CII light), as well as means to prevent those fluxes from becoming excessive. Neutral gas pressures, particularly in the divertor region are needed to monitor conditions during the early stages of CHI. An estimate of the H/D ratio will be useful in assessing the efficiency of HHFW heating.

Tools Summary: Basic bolometry yields global radiation information and is a primary indicator of ionizing particle flows. Spectroscopy and TV cameras will identify and quantify material sources of deuterium and carbon. A schedule of increasingly aggressive wall conditioning techniques should be laid out and traversed as required to achieve the desired level of particle control. The methods envisioned for Phase I would be, in order: bakeout (at 350^o C), He glow discharge cleaning, and boronization. Wall coupons should be installed to permit evaluation of these techniques.

Tools

1) Existing

Kugel (PPPL):

- *Impurity control and wall conditioning* - The primary techniques would be bakeout of plasma facing components at 350^o C and He glow discharge cleaning.
- *Boronization* - The specific technique to be used is under investigation. The options include deuterated diborane, hydrogenated decaborane, solid target boronization, and low velocity micropellets.
- *Bolometer* - A 15-channel bolometer will be used to monitor the core and divertor. It would include both radiation sensitive photodiodes and foil detectors.

Ramsey (PPPL):

- *VIPS* - a visible spectrometer which can be used to determine the H/D ratio and C influxes. It can also be used to measure T_i in the plasma, as well as plasma rotation and flows via Doppler shifts. The instrument could be moved manually to view different locations.
- *HAIFA* - a fiber optic / interference filter array which provides the absolute brightness of impurity and fuel lines.
- *SPRED* - A VUV survey spectrometer which can be used to identify and measure impurities in the plasma from core to edge.

- *VB Array* - A visible Bremsstrahlung continuum diagnostic with a multichannel fan to yield Z_{eff} as a function of radius. The baseline plan provides for the installation of a few channels.

Skinner (PPPL):

- *Narrowband, birefringent filters* - Could be used with a simple video system to quantitatively measure the H/D ratio (using the Balmer-α line).

Wurden, Maqueda (LANL):

- *Fast visible imaging system* - An existing camera will be used in this phase to monitor recycling, impurity influxes, as well as CHI breakdown and dynamics.

Stutman and Finkenthal (Johns-Hopkins):

- *Ultra-soft X-ray arrays* - Would measure C VI and C V emission with 1 cm and 0.1 ms resolution, leading to an assessment of low-Z impurity transport. Fast tomographic measurements of radiated power are also possible.

2) Recommended

(a) *Critical*

PPPL Support (PPPL):

- *Fast pressure gauge* - Based on presentations made within the ET3 group at this Forum, a neutral pressure gauge is needed to monitor gas conditions near the CHI injector prior to and during the initial stages of injection.

(b) *Low Cost*

Kugel, Skinner (PPPL):

- *H_a and CII Cameras* - Some of the existing low cost visual TV channels could be duplicated and passed through H_α and CII filters. The raw pictures could be divided and presented to the operators as a wall conditioning diagnostic. Frames deserving of more detailed attention could be inverted via a technique and software used on Alcator C-Mod to recover the 3-D spatial pattern. The results can serve as a benchmark for modeling codes. More limited coverage with fast H_α channels viewing through dedicated telescopes is also planned with existing hardware.

Ulrickson (SNL):

- *Wall coupon holders and coupons* - The coupon holders should be installed, at least. The coupons themselves are not expensive, either. Analysis would yield information about the accumulation of eroded material and the effects of wall conditioning techniques like boronization.

Objectives

1) Operational Support
    - *Wall conditioning for reliable operation* - An experimental or machine proposal should establish procedures for arriving at satisfactory wall conditions.

2) Dedicated Runs
    - *Low-Z impurity transport study* - The ultra-soft X-ray diagnostic will be used to track impurity profiles in an effort to determine if impurity accumulation is occurring. Because neoclassical transport scales as $1/B_T^2$, impurity accumulation may be stronger than in conventional aspect ratio tokamaks.

B. Heat flux and power balance

Goals: Prevent damage to RF antennas, high risk PFC's, and coaxial helicity injector. Prepare for future operation at higher heating power by measuring heat flux scaling.

Measurement and Control Needs: Continuous, time-resolved indicators of surface temperatures. Complete power balance studies are not required at this point so that the objective can be met with less than full coverage. The location and structure of the plasma edge, particularly in relation to the RF antenna and coaxial helicity injector, should be actively monitored. CHI startup could produce erosion rates of tenths of a micron for a 5-second discharge. Tile wear should be quantified following Phase I operation to determine whether or not more durable materials are required for subsequent operations.

Tools Summary: Thermocouples in the divertor tiles will provide a record of the surface heating. Three infrared TV cameras are needed to simultaneously monitor the RF antenna, the coaxial helicity injector, some segments of the inner wall and both divertors for hot spots. In the event of suspected strong first orbit or localized anomalous fast particle losses, a camera should also be trained on the outer wall to watch for hot spots. Four or five IR windows with views suitable for monitoring all of these critical surfaces should be installed regardless of the number of cameras available. A visible TV camera would provide a qualitative indicator of the location of the plasma edge and its width. A reciprocating midplane probe should be added to measure the upstream density and temperature profiles, which would be useful for power balance and CHI injector heat flux estimates. Two low cost mechanisms for evaluating tile erosion are available, but currently unfunded.

Tools

1) Existing

    Kugel (PPPL):

    - *Infrared cameras* - Two are specified in the baseline to cover the center column, passive plates, and divertor. These would track emissions at 8-12 μm at a rate of 30 Hz.

- *Thermocouples* - The baseline list has 18 in the center column, 5 in each divertor quadrant, and 2 in each passive plate set.
- *Visible TV cameras* - Two slow (60 Hz) cameras are included in the baseline**.**

2) Recommended

(a) Critical

PPPL Support (PPPL):

- *Additional IR windows* - Should provide views of all critical surfaces.

Wurden, Maqueda (LANL):

- *Infrared imaging system* - Would be used to track heat loads on the vessel walls, the coaxial helicity injector gun, and divertor targets by measuring emissions with wavelengths of 3-5 μm. An existing system takes data at 17 ms per image, with exposure times in the μs range.

Boedo, Luckhardt (UCSD in conjunction with SNL):

- *UCSD/PBX-M fast reciprocating midplane Langmuir probe* - yields high-resolution (1.5 mm) profiles of density, temperature, and floating potential. This profile information would be very helpful in formulating power balance estimates and examining heat flux profiles on the CHI injector.

(b) Low Cost

Ulrickson (SNL):

- *Marker tiles* - "Markers" implanted in or deposited on selected divertor and center column tiles permit monitoring of erosion in the range of 10's to 100's of nm and deposition up to several microns.

Skinner (PPPL):

- *Tile measurements* - A laser range-finding device can be used to measure differences in tile height to within tenths of a millimeter. Because these measurements can be made through a vacuum vessel window, they can be performed with the machine at bakeout temperature, allowing the effects of thermal stresses on tile alignment to be determined. This technique was developed for use on ITER, and a working unit is being borrowed from ORNL for use on TFTR. With a minimal additional expenditure, it could be utilized on NSTX as well.

Objectives

1) Operational Support

- *Prevention of tile / antenna damage* - Separate experimental proposals and "piggyback" observations would be used to assess and control (through properly designed operating procedures) tile and antenna heat loads.
- *RF antenna insulator material choice* - At this Forum, members of the ET2 group asked for suggestions on materials superior to the BN currently planned. Further discussion will be required.

2) Dedicated Runs

None presented in WG5 but an experiment to measure peak heat flux scaling with input power was proposed in the Ohmic Optimization Task Force (Maingi).

C. Edge characterization

Goals: Provide preliminary indicators of the edge, scrape-off layer and divertor plasma density and temperature to permit a basic comparison with other toroidal devices, as well as to aid in evaluating and optimizing CHI, HHFW, and other Phase I experimental objectives.

Measurement and Control Needs: Values of plasma density and temperature at the divertor target for a handful of flux surfaces. Also, require the edge location, potential, density, and temperature profiles near midplane for the RF antenna. Nontrivial discharge modeling requires at a minimum SOL density and temperature profiles near midplane and measurements of density and temperature or heat flux at the target.

Given the presence LANL fast visible camera, the scaling of edge turbulence and the L-H transition should be studied in NSTX to assess the scaling of these phenomena with β and aspect ratio. The interaction between edge turbulence and CHI also needs to be characterized. The "normal" wavelength range for turbulence has $k_{\perp}\rho_s \approx 0.1$. This implies a perpendicular wavelength of 10 cm for expected NSTX edge conditions. Since this is considerably longer than the physical lengths of the edge and scrape-off layer plasma, it is anticipated that the edge turbulence in NSTX will differ qualitatively from that observed in existing tokamaks.

Tools Summary: The existing set of in-vessel Langmuir probes could satisfy this need if a few were instrumented and monitored for Phase I operation. A midplane reciprocating probe would take care of the parameters in front of the RF antenna and at midplane. The two (funded) reflectometers *may* satisfy the RF antenna needs, however. Some minor additional hardware will permit the turbulence studies to be carried out.

Tools

1) Existing

Kugel (PPPL):

- *Langmuir probes* - The baseline diagnostic set has 24 floating Langmuir probes embedded in the PFC's; there is no ex-vessel hardware to bias these probes.

Maingi (ORNL):

- *Langmuir probe hardware* - Ex-vessel hardware to bias 2 Langmuir probes.

Peebles (UCLA):

- *Edge reflectometer* - Moderate spatial and fast temporal resolution measurements of density profile just inside the last closed flux surface.

Wilgen (ORNL):

- *Scrape-off layer reflectometer* - Moderate spatial and fast temporal resolution measurements of density profile in the scrape-off layer.

Zweben (PPPL):

- *Initial turbulence studies* - Use the LANL fast visible imaging to monitor edge density fluctuations via D_α emitted during natural recycling.
- *Gas puff and optics for further turbulence studies* - A gas puff nozzle at the outer wall near Bay G and a re-entrant toroidally viewing window close by are needed to permit more detailed and controlled observations of the turbulence structure.

Porter (LLNL):

- *SOL and divertor modeling* - Plasma transport modeling with UEDGE and BOUT codes. In the absence of adequate diagnostics for modeling, the LLNL group plans to upgrade the code to handle asymmetric double-null geometries.

2) Recommended

(a) Critical

Boedo, Luckhardt (UCSD in conjunction with SNL):

- *UCSD/PBX-M fast reciprocating midplane Langmuir probe* - yields the high resolution (1.5 mm) profiles of density, temperature, and floating potential essential for achieving good RF coupling. This diagnostic could be used for cross-calibrating target Langmuir probes and the edge and SOL reflectometers.

(b) Low Cost

None presented.

Objectives

1) Operational Support

- *RF coupling to edge and SOL plasma* - Measurements of edge density profiles and potentials, along with estimates of the H/D ratio, will be provided to permit the assessment and optimization of the quality of RF coupling.

- *CHI operation and control* - Available diagnostics, including fast neutral pressure gauge, divertor Langmuir probes, and IR camera, should be used to monitor conditions of materials in and around the injector during CHI operation. Also, procedures should be established for detecting the presence of conductive deposits on the insulator and removing them, if necessary.

2) Dedicated Runs

- *Edge turbulence study with fast visible camera* - An experimental proposal will be submitted to use the fast visible camera to observe fluctuations in visible emissions at the plasma edge following injection of a small gas puff.

2. Phase II

The Working Group did not attempt to prioritize Phase II proposals during this Forum. The ordering used below lists first tools proposed by team members funded for Phase I operation; ordering amongst them roughly reflects the prioritization made during the previous Forum. Proposals made by prospective new team members follow those.

A. Recycling and impurity control

Goals: Develop methods for density control as required by high core confinement and heating powers. Also, provide a critical accounting of edge particle sources and sinks to permit accurate TRANSP modeling of core particle transport.

Measurement and Control Needs: More spatially complete measurements of the boundary plasma and fluxes will be needed to quantify sources and sinks. Methods for monitoring the evolution of first wall materials as they interact with the plasma should be established so that the impact of the wall conditioning and recycling control efforts on materials can be determined.

Tools Summary: The wall conditioning and recycling control techniques used in Phase I should be continued and extended to include tests of boronization, lithiumization, and siliconization. The use of lithium in edge control techniques should be viewed not so much as a wall conditioning tool, but as a means of directly affecting core confinement by changing the core-edge plasma boundary conditions. In fact, the benefits of lithium introduction have been observed only in already well conditioned machines. The effectiveness of these methods should be thoroughly tested; any inadequacy would lead us to recommend the installation of a divertor pumping capability for Phase III. Surface sample diagnostics, such as coupons, would provide a first cut at monitoring the impact of wall conditioning, erosion, redeposition, and hydrogen retention on the first wall materials.

Corresponding Proposals and Institutions:

Kugel (PPPL):

- *Bolometers* - Upgrade to 30 channels with three intersecting views.

Mansfield (PPPL):

- *Lithium introduction mechanisms* - the DOLLOP technique is preferred over pellet injection because of its greater efficiency and flexibility, as well as its lower cost.

Maqueda (LANL):

- *Fast visible imaging system* - Would be used in this phase to monitor pellets, DOLLOP, puffs and other plasma sources. An upgrade to the Phase I camera to provide a higher frame rate is proposed.

Ulrickson (SNL):

- *Coupon analysis* - Wall coupons will be removed and replaced during a major vacuum opening and analyzed using nuclear reaction analysis, Rutherford backscattering, SIMS depth profiling, Auger electron spectroscopy, and thermal desorption of hydrogen isotopes. The results will provide information about the accumulation of eroded material and the effects of wall conditioning techniques.

B. Heat flux and power balance

Goals: A critical accounting of all energy sources and sinks in the SOL and divertor should be attempted. Models based on those data should be further developed, benchmarked, and used to extrapolate divertor heat fluxes to full NSTX heating power. If the extrapolated heat fluxes are excessive, techniques to disperse them over a wider area, such as the radiative divertor, should be investigated.

Measurement and Control Needs: Measurements of surface heat fluxes (via surface temperatures) more complete than provided in Phase I are required. Radiated power in the edge, SOL, and divertor must be monitored. Tile erosion and redeposition resulting from Phase I operation should be assessed.

Tools Summary: Additional channels of bolometric tomography in the main chamber and divertor will allow radiation (via both photons and neutral charge exchange products) to be measured. Fast thermocouples will yield measurements of rapid changes in the surface temperature. The addition of a fourth IR TV camera will provide complete coverage of the critical surfaces, enabling power balance studies to be carried out. Analysis of marker tiles will provide an estimate of erosion and redeposition. Alternative tile materials should be tested for possible use during Phase III.

Corresponding Proposals and Institutions:

Wurden, Maqueda (LANL):

- *Infrared imaging system* - Would be used to track heat loads on the vessel walls, the coaxial helicity injector gun, and divertor targets by measuring emissions with wavelengths of 3-5 μm. If the existing LANL camera were installed under Phase I, an upgrade to a higher frame rate (partial frames at rates up to 1400 per second) would be proposed.

Kugel (PPPL):

- *Bolometers* - Upgrade to 30 channels with three intersecting views.

Maingi (ORNL):

- *Divertor bolometry* - An additional 30 channels (15 for each divertor) are proposed to permit tomographic reconstruction of the radiated power. Measurements of the radiated power would permit assessment of progress towards a radiative divertor.

Kugel (PPPL):

- *Fast thermocouples* - Monitor incident power changes on short time scales to provide edge calorimetry, as well as additional calibration for embedded thermocouples and an IR TV camera.

Skinner (PPPL), Ulrickson (SNL):

- *Wall armor station* - Divertor tile materials (such as 1-D CFC's) and coatings (deposited by plasma spray, chemical vapor deposition, or brazing) more resistant to heat flux and erosion could be tested for possible use during later phases of operation.

Ulrickson (SNL):

- *Tile analysis* - Characterized (marker) tiles will be removed during a major vacuum opening and analyzed. Tile thickness can be determined by measuring the change in the marker depth. The composition of co-deposited layers will be ascertained with ion beam analysis.

C. Edge characterization

Goals: Create a database of edge and divertor plasma parameters which can be used for comparison with models of plasma transport, leading to a greater physics understanding of the edge.

Measurement and Control Needs: Radial profiles of the density and temperature at the midplane and at the divertor target, as well as power deposition profiles at the target are needed. Available techniques for quantifying density and temperature fluctuations should be employed.

Tools Summary: All of the fixed Langmuir probes in the divertor should be instrumented to provide "downstream" measurements of density and temperature. A fast reciprocating probe at midplane will yield an upstream measurement. An edge Thomson scattering system will provide more continuous coverage of the upstream and inside-separatrix conditions. Neutral and impurity flows in the SOL and divertor can be tracked with a Fabry-Perot interferometer. A variety of modeling techniques will provide insight into the physics behind these measurements. Edge fluctuations can be monitored with the fast D_α imaging technique described under Phase I and with laser-induced fluorescence.

Corresponding Proposals and Institutions:

PPPL Support (PPPL):

- *Langmuir probes* - Instrument all remaining fixed probes.
- *Thomson scattering* - An edge Thomson scattering system will provide high-resolution density and temperature profiles.

Skinner (PPPL):

- *Balmer series spectroscopy* - Use vertical views to measure intensity of Balmer-α, β, and γ lines (e.g., using VIPS), permitting density and temperature information to be deduced.
- *Fabry - Perot interferometer* - Enables the determination of the flow velocity of neutral hydrogen in divertor and scrape-off layer through Doppler shifts in the Balmer-α emission. This information can used to infer the hydrogen ion temperature. One can also measure the shift and width of emission from ionized, puffed helium.
- *Turbulence measurements by laser-induced fluorescence* - To study ion turbulence in the edge plasma.

Maingi (ORNL):

- *Divertor bolometry* - An additional 30 channels (15 for each divertor) are proposed to permit tomographic reconstruction of the radiated power.

Porter (LLNL):

- *SOL and divertor modeling* - Plasma transport modeling with UEDGE and BOUT codes. Coupled UEDGE - DEGAS 2 simulations may also be carried out.

Stotler (PPPL):

- *DEGAS 2 neutral transport code* - Modeling support would be provided for PPPL experiments, such as those involving Fabry - Perot interferometer.

Soukhanovskii (Johns-Hopkins University):

- *FUV and XUV spectroscopy* - FUV and XUV line emission of intrinsic carbon will be used to measure at high spatial resolution ($\leq$ 1 cm) the charge state distribution and electron temperature in the edge, divertor, and SOL (possibly in 2-D).

Ulrickson (SNL):

- *Heat deposition analysis* - Given 2-D temperature profiles on divertor tiles (e.g., from infrared cameras) and the magnetic configuration, the HF3D code can be used to compute the total power deposition profile and permit an estimation of the power scrape-off length.

Boedo, Luckhardt (UCSD in conjunction with SNL):

- *UCSD/PBX-M fast reciprocating midplane Langmuir probe* - yields high-resolution (1.5 mm) profiles of density, temperature, and floating potential. An upgrade to also permit measurement of the saturation current, poloidal electric field, Mach number, as well as turbulent fluxes and the corresponding fluctuations. The Mach number profiles would aid in optimization of CHI and provide data for SOL modeling.

Krasheninnikov (MIT):

- *Kinetic transport modeling* - The large mirror ratio inherent in a spherical torus could lead to loss cone instabilities and beam-like distribution functions in a low collisionality SOL. The proposed kinetic modeling would determine the implications for parallel and perpendicular transport and yield more accurate probe interpretations and atomic physics reaction rates. The results would also serve as input into decisions on Phase III diagnostics designed to look for these kinetic effects.

3. Phase III

The Working Group has not prioritized diagnostics in this Phase.

A. Recycling and impurity control

Goals: Demonstrate control of recycling and impurity flows during full power and high β operation scenarios. Develop advanced methods for analyzing plasma-material interactions.

Measurement and Control Needs: Develop real time monitors of wall conditions to permit accurate decisions regarding the readiness of the machine for high power discharges, learn more about how wall conditioning techniques work, and provide valuable data for the establishment and validation of plasma-material interaction models.

Tools Summary: Potential approaches to real-time wall monitors are listed below along with an additional wall conditioning technique, namely, laser conditioning. Divertor pumping would provide the most effective technique for density control. If Phase II operation indicated the need for pumping, a system and plenum, containing appropriate pressure gauges, should be designed, consistent with plasma shape optimization studies, and installed during Phase III. Center stack puffing would provide additional flexibility and at the same time reduce the heat load to the center stack and divertor.

In situ, real time diagnostics in plasmas will challenge models based on coupled materials and edge plasma codes. Resulting refinements in understanding will then facilitate the technological base for PFC's in next generation machines. For example, sophisticated plasma edge codes such as DEGAS 2 and B2-Eirene have a relatively primitive characterization of PFC’s. Hogan and Hillis (both ORNL) have separately begun integrating PFC codes into the edge codes.

Such an effort provides a path to understanding the effect of Li conditioning and reliably predicting its effects in machines beyond TFTR. Likewise, the DiMES probe used on DIII-D has provided key validation of ITER erosion models and valuable information on dust generation. A DiMES-like materials sample probe could be used to test in NSTX new PFC materials such as the one-dimensional carbon fiber composite developed for ITER. This material has withstood electron beam heat fluxes of 20 MW/m^2 for 15 sec.

Corresponding Proposals and Institutions:

Maingi (ORNL):

- *Pumping upgrade design* - Design and install the pump plenum, including associated diagnostics such as total and partial pressure gauges.

Ulrickson, Watkins (SNL):

- *Coupon analysis* - Continuing the analysis initiated during Phase II, wall coupons will be removed and replaced during a major vacuum opening and analyzed using nuclear reaction analysis, Rutherford backscattering, SIMS depth profiling, Auger electron spectroscopy, and thermal desorption of hydrogen isotopes. The results will provide information about the accumulation of eroded material and the effects of wall conditioning techniques.
- *Beta backscattering* - This *in situ* analysis technique assesses metal contamination on graphite surfaces (and vice-versa).

Maingi (ORNL):

- *Filterscope array* - Expand visible spectroscopy system by allowing multiple, filtered line measurements (e.g. D_α, CII, and HeII) from each single fiber view.

Kugel (PPPL, in conjunction with Hirooka, UCSD, and Watkins, SNL):

- *Materials sample probe* - A DiMES-like probe to monitor wall conditions, test new wall materials, and provide net erosion rates for code validation.

Ramsey (PPPL):

- *SOXMOS* - An XUV, high-resolution spectrometer for Doppler shift measurements, providing T_i in the core; also gives absolute measurements of C, O influx.

Skinner (PPPL):

- *Carbon dust detector* - Monitor the accumulation of carbon dust and the hydrogen concentration therein. In a reactor, such dust could contain a significant amount of tritium.
- *Quartz crystal oscillators* - Provides a real-time monitor of the mass deposited on plasma facing components.
- *More advanced surface diagnostics* - Examples include laser desorption, colorimetry of codeposited films, and nonlinear laser spectroscopy of near-surface radicals.

- *Gas balance diagnostics* - Provide another approach to quantifying fuel retention. Examples include gas input monitor, residual gas analyzer, mass spectrometer on exhaust, sampling for off-line analysis, and pressure measurements.
- *Laser conditioning* - A CO_2 laser scans over the PFC's to locally heat surfaces, vaporizing impurities. This is an innovative method for deep (up to 100 μm) conditioning.

Skinner, Stotler (PPPL):

- *Comprehensive SOL plasma - wall code* - As sufficient data on wall conditions become available, comprehensive SOL codes could be developed. For example, a coupled UEDGE (plasma), DEGAS 2 (neutral transport and material interaction), WDIFFUSE (material state) would permit predictive modeling of plasma-wall interaction with far fewer assumptions than is currently required. The linking of these codes to calculations of erosion and redeposition, e.g., by REDEP, should also be investigated.

Nishino (Hiroshima University):

- *Center stack puffing* - Would provide a means of increasing recycling at the center stack and inner divertor, reducing the heat loads on those components.

B. Heat flux and power balance

Goals: Develop techniques for heat flux mitigation. Also, test new materials for high power, steady state operation.

Measurement and Control Needs: None beyond those listed in Phases I and II.

Tools Summary: High divertor heat fluxes in NSTX would be expected during full power operation because of its small major radius, short connection length, limited flux expansion, and relatively steep field line angle of incidence. The success of NSTX and the future viability of the spherical torus concept will require either spreading the heat load more widely over the plasma facing components or improving the heat handling capability of those components.

The short connection length in NSTX will also make it difficult to radiate significant amounts of power in the scrape-off layer and divertor. Hence, core radiation will be required if the heat fluxes to the targets are to be reduced. In present devices, such radiation can have either a deleterious or beneficial effect on confinement. The loss of H-mode due to too little power flowing into the scrape-off layer is an example of the former; the RI-mode experience on TEXTOR and the DIII-D IL- and IH-modes are examples of the latter. Highly radiative regime experiments on TFTR using Ar, Kr, and Xe injection have demonstrated increases in total radiation by a factor of three with consequent reductions in deuterium and carbon influx, but unchanged or improved confinement.

Analogous experiments on NSTX would provide an additional control knob for use in testing transport models. A related concern with the deliberate introduction of impurities into the core is the potentially strong Z-dependence of transport. DIII-D experiments in high confinement regimes have indeed observed a clear Z-dependence of impurity transport, as expected from neoclassical theory.

Because of its relatively small size, NSTX would also be ideal for testing new and completely different approaches to plasma material interactions such as the "virtual limiter".

Corresponding Proposals and Institutions:

Wade (ORNL):

- *Radiative edge regime studies* - Develop radiative divertor and mantle concepts for heat flux control in ST's.

Hill (PPPL):

- *Radiative core regime studies* - Analogous to those carried out on TFTR.

Mansfield (PPPL):

- *Virtual limiter concepts* - Represents an extension of the DOLLOP idea to its logical conclusion in which the plasma rests entirely on an aerosol cloud of lithium.

Ulrickson (SNL):

- *Tile analysis* - Continuing the analysis begun during Phase II, characterized (marker) tiles will be removed during a major vacuum opening and analyzed. Tile thickness can be determined by measuring the change in the marker depth. The composition of co-deposited layers will be ascertained with ion beam analysis.

C. Edge characterization

Goals: Study the impact of unique spherical torus features such as the high mirror ratio, large field line curvature near the edge, and short outboard connection length on edge parameters, scrape-off layer lengths, turbulence, and transport. Efforts should also be made to control edge conditions and transport through active edge biasing.

Measurement and Control Needs: Continued model development and the study of ST specific phenomena will require measuring the two-dimensional variations of density and temperature in the divertor. Methods of characterizing turbulence beyond those of Phase 2 are called for as well. Currents in the edge and SOL must be monitored during normal operation and as part of edge biasing experiments.

Tools Summary: The additional diagnostics required to study the spherical torus-specific aspects of NSTX include: a divertor reciprocating probe, a divertor Thomson scattering system, and hydrogen microsensors.

Edge instabilities such as ELM's and stationary magnetic perturbations (SMP's; including locked modes and halo currents) can have deleterious effects on confinement and, in the case of SMP's, possibly signal an incipient disruption. A variety of magnetic and tile current diagnostics would permit these instabilities to be studied in detail.

Furthermore, because of its electrically isolated inner and outer sections, active stabilization of SMP's through biasing is an attractive prospect in NSTX. Through their effect on the plasma edge potential, biasing experiments could also provide a tool for adjusting the edge density in front of the RF antenna, lowering the H-mode threshold, and controlling edge fluctuations. The end result would be improved confinement and reduced disruption frequency.

Corresponding Proposals and Institutions:

Boedo, Luckhardt (UCSD, in conjunction with SNL):

- *Fast reciprocating divertor Langmuir probe* - Would yield high resolution profiles of density, temperature, saturation current, parallel ion flow velocity (convective flows, important in radiative divertors), floating potential, poloidal electric field, as well as the corresponding fluctuations and turbulent fluxes along the path of the probe through the divertor region.
- *One-dimensional, interpretative, onion-skin modeling* - This scrape-off layer modeling would be performed with a coupled plasma-neutral transport code.

Watkins (SNL):

- *Hydrogen microsensors* - These "smart probes" monitor the flux and energy of neutrals striking the wall, including the angular dependence. One can infer the divertor T_i from the neutral energy.

Wurden, Maqueda (LANL):

- *Fast visible imaging system* - Can be used to monitor fluctuations and MHD perturbations of edge plasma.
- *Infrared imaging system* - May be able to localize fast particle losses.
- *High-speed spectroscopically resolved viewing chords* - Allows fast fluctuation studies and plasma rotation by Doppler shift of edge and coaxial helicity injector gun plasma.

Takahashi (PPPL):

- *Rogowski coils and "instrumented" tiles on center stack* - Would provide halo current measurements.
- *Mirnov coils* - The installation of sufficiently many, on the order of 100, coils would allow the mapping of halo currents with MHD modes.
- *SMP sensors inside vacuum vessel.*
- *Internal magnetic diagnostics for directly detecting islands.*

Kugel (PPPL):

- *Divertor biasing experiments* - Actively stabilize edge instabilities by divertor biasing with the coaxial helicity injector hardware. Other experiments could focus on isolating and biasing the passive shell with respect to floating divertors.

Zweben (PPPL):

- *Edge shear flow studies* - Could be imposed or controlled with edge biasing, edge RF waves, local gas puffs, or low energy NBI.

Porter (LLNL):

- *SOL and divertor modeling* - Continued modeling with UEDGE, BOUT, and DEGAS 2. Provided appropriate diagnostics are available, flows of carbon in the divertor and edge carbon density profiles could be simulated and compared with experiment.

Proposal Needed:

- *Divertor Thomson scattering* - Would permit two-dimensional maps of the electron density and temperature in the divertor region to be measured.

4. Particle Fueling

NSTX plasma offers a new plasma regime which should be approached with an array of fueling techniques, including gas puffing, NBI fueling, pellet injection, and compact toroid injection (which is facilitated by the relatively low toroidal field of NSTX).

A. Pellet injection (Schmidt, PPPL; Milora, ORNL)

NSTX plasmas are well matched to existing pellet technology. Moderate electron temperatures permit a full range of fueling depths so that pellet fueling serves as an effective density profile control technique. Deep fueling also holds the potential for a high core confinement regime, as demonstrated on standard tokamaks in plasma heated by NBI + RF and by RF alone. Pellet injection could be used as one of several perturbation techniques to study particle transport in this new regime. The establishment of core transport barriers in NSTX by other means (e.g., velocity shear stabilization, Rewoldt et al [PoP 1996]) might need to have particle sources inside the barrier, such as deep pellet injection, for efficient fueling.

Pellet penetration and fuel retention in NSTX should be enhanced as a result of the existence of a magnetic well in the ST configuration and, more importantly, its low aspect ratio, as has been recently demonstrated on ASDEX-U. However, the physics of this pellet mass redistribution process may be different in the ST magnetic geometry and should be studied.

Pellet fueling has extended density limits in standard tokamaks and would be well suited for similar experiments in NSTX. Interaction of pellets with Internal Reconnection Events (IRE) observed at the density limit in START could be an important aspect of these experiments. Pellet injection may also be able to mitigate disruptions.

The interaction of pellet fueling with ECH startup and coaxial helicity injection should also be examined. Potential start-up scenarios should include peaking density profiles early in the discharge via pellet injection; this would aid in the formation of bootstrap current.

Past experiments in tokamaks indicate that pellet fueling will be a suitable mechanism to extend plasma parameters during initial NSTX ohmic and low power RF operation as well as in plasmas heated by RF or NBI at high power, suggesting the installation and use of a pellet fueling system during initial operations. In addition, to minimize duplication and cost of support facilities the possibility of a flexible multi-purpose fueling support facility should be examined.

B. Compact toroid injection

Compact toroid injection offers the prospect of deep, fast, efficient fueling with the associated benefits of: reduced divertor pumping requirements, possible operation above the Greenwald density limit, reduction of wall hydrogen inventory, and enhancement of bootstrap current. Unlike pellets, CT injection has no contamination risk due to propellant. Another difference relative to pellet injection is that CT's provide direct injection of plasma, not neutral fuel. The application to spherical torii is of especially attractive since the low magnetic field and strong diamagnetic effect should lead to efficient central fueling and profile control. Scenarios can be developed using CT's for start-up assist to reduce transformer volt-second requirements. Potential physics experiments for CT injection into NSTX include study of magnetic reconnection processes between a cold and hot (NSTX core) plasma, and core impurity transport via doping of CT's.

Raman (Univ. of Wash.):

- The CTF-2 device is capable of injecting into 1 T fields, significantly greater than the nominal 0.3 T field of NSTX. The result should be localized, non-perturbative central fueling. With the completion of CT experiments on TdeV in June 1998, CTF-2 could be transferred to NSTX for near term operation.

Hwang (UCD):

- The existing spheromak injector at UC-Davis is capable of repetitive operation at 0.1 Hz. With a newly designed and prototyped gas valve, operation at 10 Hz should be possible. Typical injection velocities are between 15 and 20 cm per µsec. The power system would be redesigned for portability so that installation on NSTX would be simple.

IV. Recommendations for Immediate Action

The Working Group feels that the following diagnostics are critical for Phase I operation

- *Fast pressure gauge* (No Proposal)
- *Additional IR windows* (No Proposal)
- *Infrared imaging system* [Proposal received from Wurden, Maqueda (LANL)]
- *UCSD/PBX-M fast reciprocating midplane Langmuir probe* [Proposal received from Boedo, Luckhardt (UCSD in conjunction with SNL)]

These items were identified as "low cost", but will be of significant benefit to the Phase I efforts of the Boundary Physics Operations Group:

- H_a *and CII Cameras* [Proposal received from Kugel, Skinner (PPPL)]
- *Wall coupon holders and coupons* [Proposal received from Ulrickson (SNL)]
- *Marker tiles* [Proposal received from Ulrickson (SNL)]
- *Tile measurements* [Proposal received from Skinner (PPPL)]

Appendix A. FY99 NSTX Research Forum, WG 5 Activities

January 12, 1999, Tuesday
Plenary III, Plans for WG Sessions

5:05 Edge, SOL, Power and Particle Control Physics (Maingi)

January 13, 1999, Wednesday
Parallel WG Session II

1:00-5:00 WG5 Session (Agenda is Appendix B) (Stotler, Maingi)

January 14, 1999, Thursday
Plenary V, WG Session Summaries

11:00 Edge, SOL, Power and Particle Control Physics Program Summary (Maingi)

Appendix B. Parallel WG Session I Agenda

NSTX Research Forum WG5
January 13, 1999
Room EWA-153

1:00 PM	WG 5 Parallel Session Goals & Summary of FY'98 Forum	D. Stotler
1:15 PM	"Time Line for Planned Boundary Diagnostics and Opportunities for Boundary Physics Collaborations"	H. Kugel
1:30 PM	"Power and Particle Balance"	R. Maingi
1:45 PM	"Heat Flux to PFC's"	M. Ulrickson
2:00 PM	"UEDGE Modeling for NSTX"	G. Porter
2:15 PM	"Kinetic Modeling of the NSTX Scrape-Off Layer"	S. Krasheninnikov
2:30 PM	"Bridging the Gap between Wall and Plasma Physics	C. Skinner
2:45 PM	"Development of SOL and Divertor Spectroscopy Diagnostics at Johns Hopkins University"	V. Soukhanovskii
3:00 PM	Break	
3:15 PM	"Characterization of RF Coupling and Startup Plasmas	

	in NSTX Using Scanning Probes"	J. Boedo
3:30 PM	"2-D Imaging of Edge Turbulence"	S. Zweben
3:45 PM	"Repetitively Operated Spheromak-like Compact Toroid Injection for Rep-rated Plasma Fueling, Initial Plasma Startup Assist, and High-β Diamagnetic Well Trapping And Diagnostic"	D. Hwang
4:00 PM	Discussion	
5:10 PM	Adjourn	