

Divertor, Scrape-Off Layer, Power and Particle Handling

FY98 NSTX Research Forum

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Working Group 5 Report

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I. Introduction

This document summarizes the important scientific elements of NSTX research presented at the FY98 NSTX Research Forum to the Divertor, Scrape-Off Layer, Power and Particle Handling Group. It provides a context for the preparation of individual pre-proposals and Letters of Interest, due Jan. 20, 1998.

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 handling 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 (PFCs) 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 which 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 initial NSTX operation timeline. The measurement needs for each element will be detailed and matched with the research proposals presented at this Forum. Areas not covered in this plan are identified as "needed proposals".

A specific conclusion of this Working Group is that particle fuelling issues need further study to determine the need and schedule for pellet and compact toroid injection. Hence, the relevant material presented in this Forum is collected into Section III-4, which is separate from the phased Boundary Physics Program strategy.

II. Phases for NSTX Boundary Physics Program

In this section, the three phases of the NSTX Boundary Physics Program are summarized as follows; they will be broken down into individual research elements in the subsequent section. Note that these phases overlap in time.

Phase 1: Operational Support and Wall Conditioning

This phase begins with first plasma and continues throughout the life of the device. The auxiliary input heating powers in this Phase are up to 2 MW. Reliable operation entails using wall conditioning to reduce recycling and impurity fluxes and preventing heat flux damage to the plasma facing components, particularly the RF antenna and coaxial helicity injector. Heat fluxes 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.

Phase 2: Characterization of Diverted and Inner Wall Limited Edge and SOL Plasmas

In this Phase, auxiliary heating power will increase to 6 MW coincident with the beginning of focussed transport and MHD experiments. Control of particle and heat flows beyond that afforded by the Phase 1 tools will be needed to handle the increased power. A pumped divertor, optimized for core performance, would provide the most effective means of controlling recycling.

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 divertor transport models.

Phase 3: Unique Spherical Torus Experiments and High Power and Particle Flux Handling

The beginning of this phase coincides with the introduction of neutral beam injection, 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. These high heat fluxes also make NSTX a convenient plasma-material interaction test-bed for the PFCs to be used in ST reactors.

The impact of the 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 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 1 (Begins ~4/99)

Throughout this section, tools will be listed in connection with the goal to which they contribute. Hence, some tools are mentioned more than once. Shortfalls in the baseline diagnostic set are highlighted in this Phase.

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, as well as means to prevent those fluxes from becoming excessive.

Tools Summary: Basic bolometric yields global radiation information and is a primary indicator of ionizing particle flows. Spectroscopy 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 1 would be, in order: bake-out (at 350° C), glow discharge cleaning with He, and boronization.

1) Tools included in baseline set:

Kugel (PPPL):

- *Impurity control and wall conditioning* - The primary techniques would be bake-out of plasma facing components at 350° 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-light spectrometer that yields 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.

- *Plasma Camera* - Would be used to view the entire plasma with spectral and spatial resolution; would permit absolute line brightness measurements for fuelling and recycling studies. Discussions are underway regarding whether to outfit one of two baseline TV cameras with filters to serve this purpose, or to use a third camera, such as that proposed by LANL (listed in Phase 2).
- *SPRED* - a VUV survey spectrometer that can be used to identify and measure impurities in the plasma from core to edge.

Stutman and Finkenthal (Johns-Hopkins):

- *Ultra-soft X-ray array* - Would measure C VI and C V emission with 1 cm and 0.1 ms resolution.

2) Shortfall: None.

3) Proposals not included in baseline set:

Ramsey (PPPL):

- *VB Array* - a visible Bremsstrahlung continuum diagnostic with a multichannel fan to yield Z_{eff} as a function of radius.

B. Heat flux and power balance

Goal: Prevent damage to RF antennas, high-risk plasma facing components, 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. However, 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 also be actively monitored.

Tools Summary: Thermocouples in the divertor tiles will provide a sufficient record of the surface heating. Three infrared TV cameras are needed to simultaneously monitor the RF antenna, the coaxial helicity injector, and some segments of the inner wall and divertor for hot spots. A visible TV camera would provide a qualitative indicator of the location of the plasma edge and its width.

1) Tools included in baseline set:

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 cameras are included in the baseline.

2) Shortfall: 1 IRTV camera system .

3) Proposals not included in baseline set:

Maqueda (LANL):

- *Infrared imaging system* - Would be used to track heat loads on the vessel walls, the coaxial helicity injector gun, and divertor targets. The proposed device would measure emissions with wavelengths of 3-5 μm and could be gated down to 10 μs , or possibly even faster

C. Edge characterization

Goals: Provide gross indicators of the edge, scrape-off layer and divertor plasma density and temperature to permit a basic comparison with other toroidal devices.

Measurement and Control Needs: Values of plasma density and temperature at some location along a flux surface for a handful of flux surfaces.

Tools Summary: The existing set of in-vessel Langmuir probes could satisfy this need if a few were instrumented and monitored for Phase 1 operation.

1) Proposals included in baseline set:

Kugel (PPPL):

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

2) Shortfall: ex-vessel hardware to bias 4 Langmuir probes

3) Proposals not included in baseline set: none

2. Phase 2 (Begins ~10/99)

The Working Group has made an attempt at prioritizing the proposals listed under each heading in this Phase, with the most essential tools listed first. However, no attempt was made to rank diagnostics across headings, recycling control vs. power balance for example.

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: Divertor pumping would provide the most effective technique for density control. A pumping system and plenum, containing appropriate pressure gauges, should be designed, consistent with plasma shape optimization studies, and installed during Phase 2. In addition, the wall conditioning and recycling control techniques used in Phase 1 should be continued and extended to include tests of boronization, lithiumization, and siliconization. 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.

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. This is in view of the fact that the benefits of lithium introduction have been observed only in already well conditioned machines. The DOLLOP experiments on TFTR also exhibited a narrowing of the plasma current distribution, resulting in a more stable plasma. Sawteeth were eliminated in many of these discharges.

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.
- *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.

Kugel (PPPL, UCSD):

- *Materials sample probe* - Would monitor wall conditions, test new wall materials, and provide net erosion rates to be used in code validation.

Watkins (SNL):

- *Surface sample analysis* - As needed samples would be taken from internal components and coupons to determine D implantation, erosion / redeposition, and the effects of surface conditioning.

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.

Measurement and Control Needs: More complete measurement of surface heat fluxes (via surface temperatures) than provided in Phase I are required. Radiated power in the edge, SOL, and divertor must be monitored.

Tools Summary: An additional 15-30 channels of bolometric tomography will be needed to account for radiation (via both photons and neutral charge exchange products). Fast thermocouples will provide 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.

Corresponding Proposals and Institutions:

Proposals Needed:

- *Fourth IR TV camera* - The four cameras would continue watching the center stack, the upper and lower divertors (including the coaxial helicity injector gun), and the RF antenna.

Maqueda (LANL):

- *Infrared imaging system* - Would be used to track heat loads on the vessel walls, the coaxial helicity injector gun, and divertor targets. The proposed device would measure emissions with wavelengths of 3-5 μm and could be gated down to 10 μs , or possibly even faster

Maingi (ORNL):

- *Bolometers* - Add 15-30 channels with three intersecting views.
- *Model development and testing* - Benchmark edge plasma and neutral models with data to support extrapolation to higher power operation.

Kugel (PPPL):

- *Fast thermocouples* - monitor incident power changes on short time scales. The possibility of including these in the baseline list, for cost efficiency and need (e.g., to provide a calibration for an IR TV camera), is being investigated.

•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 greatest physics understanding of the edge.

Measurement and Control Needs: Radial profiles of the density and temperature at the mid-plane and at the divertor target are needed. Available techniques for quantifying density and temperature fluctuations should be employed, and the multi-dimensional structure of edge turbulence mapped out.

The "normal" wavelength range for turbulence has $k_{\perp}\rho_s \sim 0.3$. This implies a perpendicular wavelength of 20 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 those observed in existing tokamaks. Specific turbulence experiments should be directed at the relationship between transport barrier formation and the H-mode pedestal, and the connection between edge turbulence and MHD second stability.

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 needs to be installed at mid-plane to 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. Fluctuations in the edge may be monitored with fast D_α imaging and a fast visible camera.

Corresponding Proposals and Institutions:

Moyer (UCSD in conjunction with SNL):

- *Fast reciprocating mid-plane Langmuir probe* - yields high resolution profiles of density, temperature, saturation current, floating potential, and poloidal electric field, as well as the corresponding fluctuations and turbulent fluxes.

Proposals Needed:

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

Maqueda (LANL):

- *Fast visible imaging system* - Can be used to monitor fluctuations and MHD perturbation of edge plasma.

Zweben (PPPL):

- *Turbulence studies* - Diagnostics such as the LANL fast visible imaging system can be used to monitor edge density fluctuations via D_α emissions. Inducing those emissions with an outboard gas puff would allow large major radius fluctuations to be compared with those at small major radius as the effects of the gas puff propagate along the field lines to the inboard side of the plasma. Such measurements would need to be coordinated with other edge parameter and fluctuation measurements to facilitate interpretation. One objective would be to evaluate the standard shearing criterion using edge poloidal rotation measurements.

Skinner (PPPL):

- *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 be used to infer hydrogen ion temperature. One can also measure the shift and width of emission from ionized, puffed helium. The requisite neutral transport modeling support would be performed with DEGAS 2.
- *Turbulence measurements by laser-induced fluorescence* - To study ion turbulence in the edge plasma.

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.

3. Phase 3 (Begins ~6/2000)

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, beyond those considered in Phase 2, namely, laser conditioning.

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 PFCs in next generation machines. For example, sophisticated plasma edge codes such as DEGAS 2 and B2-Eirene have a relatively primitive characterization of PFCs, although John Hogan (ORNL) has begun integrating PFC codes like CASTEM2000 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/m² for 15 sec.

Corresponding Proposals and Institutions:

Maqueda (LANL):

- *High-speed spectroscopically resolved viewing chords* - Allows fast fluctuation studies and plasma rotation by Doppler shift of edge and coaxial helicity injector gun plasma.

Watkins (SNL):

- *Surface sample analysis* - Extend program begun in Phase 2 of taking surface samples from internal components and coupons to determine deuterium implantation rates, erosion / redeposition, and the effects of surface conditioning.
- *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 , C-II, He-II) from each single fiber view

Kugel (PPPL, UCSD):

- *Materials sample probe* - Would monitor wall conditions, test new wall materials, and provide net erosion rates to be used in 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):

- *Quartz crystal oscillators* - Provides a real-time monitor of the mass deposited on plasma facing components.
- *Advanced surface diagnostics* - Examples include laser desorption, colorimetry of codeposition rates, and nonlinear laser spectroscopy of near-surface radicals.
- *Gas balance diagnostics* - Provides 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 PFCs to locally heat surfaces, vaporizing impurities. This is an innovative method for deep (up to 100 μ m) conditioning.

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 1 and 2.

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 flux to the targets is 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* - An extension of the DOLLOP idea to its logical conclusion where the plasma rests entirely on an aerosol cloud of lithium.

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 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 ELMs and stationary magnetic perturbations (SMPs; including locked modes and halo currents) can have deleterious effects on confinement and, in the case of SMPs, 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 SMPs 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:

Moyer (UCSD in conjunction with SNL):

- *Fast reciprocating divertor Langmuir probe* - Would yield high resolution profiles of density, temperature, saturation current, parallel ion flow velocity (convection), 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, onionskin 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.

Maqueda (LANL):

- *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.

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 Fuelling

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 (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 fuelling depths so that pellet fuelling 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. The pellet source function would be one such source.

Pellet penetration 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 near the density limit in START, could be an important element of these experiments. Pellet injection may also be able to mitigate disruptions.

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

Past experiments in tokamaks indicate that pellet fuelling 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. This suggests the installation and use of a pellet fuelling system during initial operations. In addition, to minimize duplication and cost of support facilities the possibility of a flexible multi-purpose fuelling support facility should be examined.

B. Compact toroid injection

Compact toroid injection offers the prospect of deep, fast, efficient fuelling 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 a propellant. Another difference relative to pellet injection is that CTs provide direct injection of plasma, not neutral fuel. Scenarios can be developed using CTs for startup assist to reduce transformer volt-second requirements. Potential physics experiments for CT injection into NSTX include study of magnetic reconnection processes between a cold (CT) and hot (NSTX core) plasma, and core impurity transport via doping of CTs.

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-perturbing central fuelling. 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 penetration into 0.1 T fields. A second-generation rep-rated gas valve should yield 1000 repetitions at 0.2 Hz. An upgrade of the injector to enable 0.5 T injection is proposed. The power system would be redesigned for portability so that installation on NSTX would be simple.

IV. Recommendations for Immediate Action

Two items should be added to the baseline diagnostics:

- (i) A third IR TV camera to permit simultaneous monitoring of the RF antenna, the coaxial helicity injector, and some segments of the inner wall and divertor for hot spots;
- (ii) Instrumentation for 4 of the fixed Langmuir probes to allow a basic comparison of the divertor plasma density and temperature with other toroidal devices. Also, the VB array is not in the baseline, but could be added with minimal expense.

A particle fuelling study group should be convened in the near future to determine the need and schedule for pellet and compact toroid injection. This small (5 or 6) group should include experts on each of these injection methods, a boundary physics expert, a core transport expert, and an NSTX manager. To ensure action, the group should plan to complete its work within the next six months.

Appendix: Working Group 5 Agenda

NSTX Research Forum WG5, Thursday, December 4, 1997
Room B233

8:00 am	Discussion of agenda and goals	Stotler
8:10 am	I. Support for the NSTX start-up period "Wall Conditioning" "Power Accountability" "Edge Spectroscopy on NSTX" "Power and Particle Balance"	H. Kugel, D. Mueller H. Kugel, R. Maqueda A. Ramsey R. Maingi
9:20 am	II. Characterization of basic plasma boundary properties "Langmuir Probes: Arrays and Reciprocating Probes" "Edge Flows (F-P Interferometer)" "Edge Turbulence and H-modes on NSTX" "Theory of NSTX Edge plasma" "Fast Camera and High-Speed Fiber Scopes" "Halo Currents, Edge Phenomena, and Stationary Magnetic Perturbations" "Real Time Wall Monitors: Traditional and New" "DiMES Probe for NSTX" "Applications for DEGAS 2 on NSTX" "Impurity Transport in Enhanced Confinement Plasmas"	J. Watkins, R. Moyer C. Skinner S. Zweben J. Drake (S. Zweben) R. Maqueda H. Takahashi H. Kugel, J. Watkins C. Skinner D. Stotler M. Wade
11:00 am	III. Investigation of unique ST boundary plasma issues and development of specific power and particle control scenarios for NSTX "Active Edge Stabilization" "Laser Conditioning" "Highly Radiative Regimes for Heat Dispersal, Reduction of Impurity Influxes, and Tests of Local Transport Theory" "DOLLOP and Virtual Limiters" "Fuelling Scenarios for NSTX" "Compact Toroid Fueling"	H. Kugel C. Skinner K. Hill D. Mansfield G. Schmidt D. Hwang, R. Raman
Last 5 min.	Review diagnostic needs presentation for Plenary Session IV	H. Kugel