Version 3 – August 8, 2011

# NSTX Program Letter for Research Collaboration Employing Innovative Diagnostics for FY 2012-2015

## Introduction

This NSTX[1] Program Letter provides updated information about NSTX topical research priorities and collaboration opportunities during the upcoming four years (FY2012-2015). This information is useful for the preparation of proposals in response to the Office of Science Notice *National Spherical Torus Experiment: Diagnostic Measurements of Spherical Torus Plasmas* issued August 1, 2011. New and continuing diagnostic development and implementation proposals from universities and industry are the primary emphasis of this Program Letter. This Program Letter suggests specific collaboration opportunities, as well as broader areas of research, in order to encourage proposals that address the research goals of NSTX. These research areas are described in the NSTX Five-Year Plan for 2009-13[2] and the FESAC Facilities Report[3]. The NSTX Program Advisory Committee (PAC) reviewed this Program Letter on August 1, 2011 and PAC recommendations were incorporated in this final version.[4]

## Mission of NSTX

The *programmatic* mission of NSTX is to evaluate the attractiveness of the compact Spherical Torus (ST) configuration for reducing cost, risk, and development time for practical fusion energy. The ST appears particularly attractive for: integrating Plasma Material Interface (PMI) solutions with high plasma performance (a major goal of NSTX, NSTX Upgrade[5], and the National High-power advanced-Torus eXperiment - NHTX[6]) and for an ST-based Fusion Nuclear Science Facility (ST-FNSF)[7] with goals of progressively exploring and understanding the integrated fusion nuclear environment and ultimately accessing regimes with high neutron flux and fluence at high duty-factor in an ST-based Component Test Facility (ST-CTF)[8]. NSTX also contributes to the physics basis for an ST-based Pilot Plant and DEMO devices and accesses unique plasma regimes for resolving key burning plasma physics issues anticipated in ITER. The NSTX programmatic mission thus addresses two of the long-term goals of the Office of Fusion Energy Sciences: configuration optimization, and developing a predictive capability for burning plasmas. Both ITER participation and also FNS/CTF development are included in the DOE 20-year strategic plan for the Fusion Energy Sciences Program.[9]

In support of the above programmatic mission, the *scientific* mission of NSTX is to advance fusion plasma science by understanding the special physics properties of the Spherical Torus (ST). Due to its low aspect ratio, the ST is characterized by strong magnetic field curvature and

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[1] http://nstx.pppl.gov/index.html

[2] http://nstx.pppl.gov/DragNDrop/Five_Year_Plans/2009_2013/NSTX_Research_Plan_2009-2013.pdf.

[3] http://www.ofes.fusion.doe.gov/more_html/FESAC/FacilitiesVol1.doc and FacilitiesVolume2_v3.pdf.

[4] http://nstx.pppl.gov/nstx/NSTX_Program_Letter (available August 8, 2011).

[5] http://nstx.pppl.gov/upgrade_overview.html

[6] http://nstx.pppl.gov/DragNDrop/NHTX_Information

[7] Y-K M Peng et al, Fusion Science and Technology Vol. 56, August 2009 page 957

[8] Y-K M Peng et al, Plas. Phys. Cont. Fus. **47** (2005) B263 (also http://nstx.pppl.gov/DragNDrop/CTF_Information)

[9] http://www.sc.doe.gov/bes/archives/plans/SCSP_12FEB04.pdf.

by high $\beta_T$ (the ratio of the average plasma pressure to the applied toroidal magnetic field pressure). The ST, with its unique properties, thus extends and complements the higher aspect ratio, lower $\beta_T$ tokamak in addressing the overarching scientific issues in magnetic fusion.

## NSTX Research Priorities and Key Collaboration Opportunities

This section lists the high priority topics in the NSTX Upgrade research program during FY 2012-2015 and highlights key diagnostic collaboration opportunities for research proposals. Collaboration proposals should aim to support the NSTX Upgrade research program by utilizing and/or upgrading existing high priority diagnostics and/or implementing new diagnostics. For reference, Appendix A of this letter contains a list of existing NSTX diagnostics, the associated measurement capabilities, and the person(s) responsible for the diagnostic.

Important: The NSTX Upgrade involves an extended outage period currently planned to begin in April 2012 and lasting for 2 to 2.5 years. In view of this, the normal three year collaboration grant cycle is presently planned to be extended to four years for this solicitation in order to provide collaborators an opportunity to acquire new data in the first year of NSTX Upgrade operation. Thus, it is expected that diagnostics will be implemented during the Upgrade outage and be ready for first plasma in NSTX Upgrade in 2014. With respect to plasma and device modifications, NSTX Upgrade is anticipated to provide access to plasma regimes of reduced collisionality, longer plasma duration, and increased overall plasma performance. To achieve these goals, the toroidal magnetic field, plasma current, and neutral beam injection (NBI) heating power are planned to be increased by up to a factor of two, and the pulse duration increased by up to a factor of five. The diameter of the center-stack will be increased and the minimum plasma aspect ratio will be increased from 1.3 to 1.5. Further, the NBI power will be increased through the addition of a 2nd more tangential NBI. Several diagnostic ports will be modified, and port access may also be impacted by additional structural enhancements.

**The impact of the above schedule, performance, and device changes should be assessed and incorporated into all diagnostic implementation plans. Proposals integrating the design and comparison of diagnostic measurements with theory and simulation are especially encouraged in order to maximize the predictive capability gained from new measurements.**

The NSTX research priorities and key diagnostics collaboration opportunities are organized according to the six categories used in the FESAC Priorities Plan. For each of the six scientific categories described below, the highest priority research topics are provided in approximate priority order. For each category, a key person is listed who can be contacted for further information and to assist in identifying a research contact for the "Record of Discussion" (RoD) form that must be included with each submitted proposal following review and signature by the NSTX program and project directors. The RoD documents the proposed research goals of the collaboration, collaborator off-site research tasks, on-site research support tasks and estimated effort required, on-site engineering support tasks and estimated effort required, and estimated hardware costs. Successful proposals requiring implementation of significant hardware on NSTX will further require a "Record of Agreement" (RoA) form to document hardware and interface implementation tasks and milestones. The URLs for the NSTX RoD and RoA forms are:

**RoD:** http://nstx.pppl.gov/DragNDrop/Program_PAC/Program_Letters/NSTX_Record_of_Discussion_FY2012.doc
**RoA:** http://nstx.pppl.gov/DragNDrop/Program_PAC/Collaborations/NSTX_record_of_agreement_April2009.doc

The development of stationary, high-performance, long-pulse plasmas is a high priority programmatic objective of NSTX Upgrade. A summary overview of high priority diagnostic capabilities and opportunities supporting this programmatic goal is as follows: For Macroscopic Stability research, diagnostics supporting improved measurements of the fast ion distribution and the eigenmode structure of resistive wall modes, neoclassical tearing modes, and plasma response to 3D fields are encouraged. The diagnosis of the disruption thermal quench and halo current evolution are also encouraged. For Multi-Scale Transport Physics research, diagnostics supporting improved understanding of electron and ion thermal, and impurity and particle transport are encouraged, and diagnostics for electromagnetic and intermediate-to-high-k turbulence are especially encouraged. For Plasma Boundary Interfaces research, diagnostics for measuring scrape-off-layer transport and turbulence and divertor heat flux, divertor and first wall particle sources, sinks, and transport, lithiated surface conditions, and the effects of 3D fields on the H-mode pedestal structure and particle and heat deposition on material surfaces are encouraged. For research in Waves and Energetic Particles, diagnostics supporting improved measurements of the fast-ion distribution function and the influence of MHD, including Alfvénic instabilities and fast-wave heating on the fast-ion population are encouraged. For Plasma Start-up and Ramp-up research, diagnostics supporting understanding of helicity injection plasma formation processes, coupling to auxiliary heating sources, and fast-ion confinement during NBI current ramp-up are encouraged. For Advanced Scenario Development, real-time diagnostics supporting determination of the safety factor and pressure profiles, divertor PFC temperature and heat flux profiles, and disruption onset detection are especially encouraged. Finally, diagnosis of the safety factor profile is particularly important as it supports nearly all of NSTX research.

The collaboration opportunities highlighted below were determined on the basis of what the NSTX program considers necessary to support the research priorities while also complementing ongoing contributions from university and industry, other national laboratories, and PPPL researchers. Proposals for innovative diagnostic collaboration activities beyond the ones listed in this Program Letter are also welcomed. All proposals will be considered by means of the normal DOE peer review process, according to the criteria described in the solicitation announcement.

## I. **Macroscopic Stability** – the role of magnetic structure in plasma confinement and the limits to plasma pressure in sustained magnetic configurations.

*For more information contact:* Jong-Kyu Park (jpark@pppl.gov)

Research Priorities:

I-1. *Measure and understand the role of kinetic effects in RWM stability and toroidal rotation damping to optimize RWM stability and control in ITER and future facilities.*

Background:

Significant progress has recently been made in NSTX in identifying and understanding the role of kinetic resonances in resistive wall mode stability. Substantial progress has also been achieved in the detection and active control of error fields (EF) and resistive wall modes (RWMs), and in understanding and controlling toroidal flow damping from non-axisymmetric fields. Advanced control algorithms and enhanced predictive capability (especially the effects of fast-ions on RWM stability) are under development to understand present RWM and EF results and allow extrapolation of high performance to ITER and future STs. In NSTX Upgrade, the reduced collisionality, modifications to safety factor and rotation and rotation shear profiles, and changes in the fast-ion distribution function from more tangential injection are anticipated to modify RWM stability and control.

## I-2. *Study the impact of low aspect ratio, high beta, large ion gyro-radius, magnetic shear, and flow shear on classical and neoclassical tearing mode stability.*

Background:

Neoclassical tearing mode (NTM) instabilities have been observed to limit the plasma performance in some operational scenarios of NSTX. NTMs can be triggered by energetic particle modes, edge localized modes, error fields, and can also arise from natural resistive tearing instability drive. Low-frequency (f=1-30kHz) MHD activity (including tearing activity) has also been observed to redistribute the fast ions from neutral beam injection, and this physics may be relevant to proposed "hybrid" operating scenarios for ITER. For the 2/1 NTM, the magnitude of local NTM instability drive from the bootstrap current correlates most strongly with the rotation shear rather than the absolute rotation, suggesting the importance of rotation shear on delta-prime. However, the threshold for NTM triggering by error fields has also been shown to be a function of the local rotation magnitude, potentially providing new insight into the mode coupling physics for NTM triggering. In NSTX Upgrade, the reduced collisionality, modifications to the safety factor and rotation and rotation shear profiles, and changes in the stabilizing curvature and poloidal mode coupling from increased aspect ratio may all modify the tearing mode stability.

## I-3. *Assess neoclassical toroidal viscosity, plasma equilibrium and stability response to 3D fields, and the physics and control of toroidal rotation at reduced collisionality.*

Background:

Neoclassical toroidal viscosity (NTV) models coupled to ideal 3D perturbed equilibrium solutions have shown reasonable agreement with measured plasma rotation damping in the core of NSTX plasmas and in other devices. However, the effects of rotation, rotation shear, kinetic damping, and magnetic islands on the plasma response and thus NTV remains an active area of research of importance to ITER and future ST devices – especially in the area of ELM control using 3D fields. NSTX Upgrade will substantially extend this physics through access to reduced collisionality and through modifications of the rotation and rotation shear profiles using both the 2nd NBI and through magnetic braking.

## I-4. *Characterize the dynamics of disruptions at low aspect ratio and high beta by measuring halo currents and thermal and current quench characteristics.*

Background:

NSTX has contributed plasma current quench rate and halo current data to the ITPA international database on disruptions with application to both ITER and future ST-FNSF facilities. NSTX has recently extended these studies with improved measurements of halo current distributions, fractions, and halo-peaking factors. Additional measurements are needed to understand thermal quench characteristics of the ST, and data analysis and modeling of disruptions is desired to develop a predictive capability for disruptions applicable to NSTX Upgrade and next-step STs. The uniquely low internal inductance, high elongation, high $\beta$, strongly wall-coupled plasmas of the ST could change the instability dynamics (and hence the impurity penetration and radiation evolution) of conventional mitigation techniques such as massive gas injection (MGI). The dependence of plasma density increase on poloidal injection location (midplane vs. divertor) is planned to be assessed for the first time in NSTX in the next run campaign.

Key Collaboration Opportunities in Macroscopic Plasma Physics:

- *Internal measurements of the RWM eigenfunction, internal and external measurements of the plasma response to 3D fields, and more complete measurements of the fast-ion distribution function with application to kinetic MHD models.*

- *Internal measurements of the tearing mode island structure, measurements of the safety factor profile and rotation and rotation shear profiles, and measurements and understanding of mode triggering.*

- *Diagnosis of disruption precursor onset and disruption evolution – especially the thermal quench and halo-current dynamics – including the impact of gas injection for disruption mitigation studies.*

## II. **Multi-Scale Transport Physics** – the physical processes that govern the confinement of heat, momentum, and particles in plasmas.

*For more information contact:* Yang Ren (yren@pppl.gov)

Research Priorities:

II-1. *Develop/utilize diagnostics to determine the modes (low-k, high-k, electrostatic, electromagnetic, Alfvénic) responsible for causing anomalous electron transport - with particular emphasis on the development of internal measurements of magnetic field fluctuations and intermediate-to-high-k ($k_\theta \rho_s > 1$) density fluctuations.*

Background:

NSTX results indicate that ion energy and particle transport levels are routinely at the neoclassical level, implying suppression of long-wavelength turbulence and associated anomalous transport. Such suppression is likely related to NBI-induced toroidal rotation leading to ExB shearing rates exceeding low-k turbulence growth rates. This plasma state with (controllable) suppression of long-wavelength turbulence provides an excellent environment to study short wavelength turbulence and its relationship to electron heat transport. Using a high-k scattering diagnostic, high-k fluctuations with the characteristics of Electron Temperature Gradient modes (ETGs) have been measured when the ETG critical temperature gradient is exceeded, and correlations between increased high-k fluctuation amplitude and increased electron thermal transport have been observed. Recent non-linear gyrokinetic simulations of micro-tearing modes find a nearly linear dependence of the electron thermal diffusivity on collisionality – seemingly consistent with ST global confinement trends. Global Alfvén Eigenmodes (GAE) have also been previously been correlated with anomalous electron transport in the core NSTX NBI heated plasmas. NSTX Upgrade plasmas are anticipated to have lower collisionality and different GAE instability drive, which could in turn change which modes dominate electron turbulent transport.

II-2. *Determine the role of low-k turbulence in causing anomalous energy and momentum transport, and understand the influence of plasma rotation on low-k and high-k turbulence.*

Background:

Recent NSTX results indicate that the effective angular momentum diffusivity is routinely significantly smaller than ion energy diffusivity but larger than neoclassical predictions. These results are qualitatively different than those commonly obtained in higher aspect ratio tokamaks, and may be the result of increased ExB flow shearing rates achievable in rapidly spinning low aspect ratio, high β NSTX plasmas. Further, experiments using perturbative momentum transport techniques indicate the existence of an inward momentum pinch consistent with values predicted by gyro-kinetic simulations of low-k turbulence. Externally applied 3D magnetic field perturbations lead to decreased rotation and rotation shear, and this is associated with increased inferred transport levels in the ion channel. Lithium conditioning has also recently been shown to substantially modify the near-edge rotation profile and the threshold power for access to the high-confinement mode (H-mode). Finally, some tokamak results suggest low to intermediate-k turbulence could lead to anomalous transport of energetic ions from neutral beam injection – a finding which could be tested utilizing the high and controllable ExB shearing rate conditions of NSTX plasmas. Higher field and current in NSTX Upgrade will reduce the neoclassical transport rates and could modify the relative dominance of neoclassical ion thermal transport over turbulent ion thermal transport, with implications for auxiliary power and size requirements of future ST devices.

### II-3. *Determine the relationship between the measured particle and impurity transport and simulated micro-turbulence and neoclassical transport*.

Background:

Improved density control is needed to access reduced density scenarios predicted to maximize beam-driven current in next-step ST devices. However, particle confinement is poorly understood relative to energy and momentum transport. Recent NSTX results indicate that lithium evaporated onto the lower divertor surfaces of NSTX can act as an effective pump of hydrogenic species. Impurity transport has been measured to be nearly neoclassical in NSTX and exhibits a particle pinch. ELM-free scenarios from Li surface coatings can lead to deleterious accumulation of impurities and further motivates additional research into impurity transport. Used in combination with dominant core fueling from NBI, the dependence of impurity and particle diffusivity on global plasma parameters, including rotation will be determined, and the possible relationship between anomalous impurity/particle and thermal diffusivity will be assessed. The possible relationship between the particle pinch and the momentum pinch will be investigated, and comparisons between anomalous impurity/particle transport and measured and simulated turbulence will be pursued. The higher field and current of NSTX Upgrade plasmas will reduce neoclassical particle diffusivity, which will impact the main ion and impurity evolution of all NSTX Upgrade operating scenarios.

## Key Collaboration Opportunities in Multi-Scale Plasma Physics:

- *Diagnosis of electron thermal transport and turbulence studies in a range of confinement conditions (L-mode and H-mode) to understand the source of anomalous electron transport. The development of diagnostics for investigating electromagnetic turbulence is particularly encouraged.*

- *Measurements and simulations of ion-gyro-scale turbulence and transport to understand the relationship between the flow and flow-shear and turbulence in the core and pedestal, to improve understanding of the H-mode transition, flow-damping from 3D magnetic fields and possible transport of fast-ions by low-k turbulence.*

- *Diagnosis of main ion and impurity particle transport from the edge to the core, and linkages to inward momentum pinch physics. Utilization of existing and/or any new* *main-ion and impurity edge particle sources for perturbative particle transport experiments.*

## III. *Plasma Boundary Interfaces* – the interface between fusion plasma and its lower temperature plasma-facing material surroundings.

*For more information contact:* Charles Skinner (cskinner@pppl.gov)

Research Priorities:

III-1. *Measure and interpret energy and particle transport and turbulence in the Scrape-Off-Layer (SOL), and understand the linkage between SOL parameters and the peak heat flux to the divertor to develop means for heat-flux mitigation and control.*

Background:

The transport of energy and particles in the tokamak plasma edge has important implications for the ability of the magnetic divertor to handle plasma exhaust. The SOL heat flux width parameter is particularly important, as the peak divertor heat flux scales inversely with this width. Multi-machine (including NSTX) studies of the SOL heat flux width have recently measured a strong inverse dependence of the heat flux width on plasma current and a weak dependence on magnetic field and heating power. NSTX Upgrade plasmas at high current and power are projected to have high peak heat flux values that challenge divertor PFCs. The underlying causes of the SOL heat flux scalings are poorly understood, and edge heat flux and transport and turbulence measurements remain vital to improving this understanding. To mitigate high heat fluxes, NSTX has made significant progress in developing a partially detached divertor regime for reducing peak heat flux at the divertor consistent with good H-mode confinement and acceptable density control (at high density). Further, a high flux expansion divertor – namely the “snow-flake” divertor – has demonstrated substantial reductions in peak heat flux and impurity generation. Additional research on this configuration and other novel divertor configurations is needed to determine if such techniques extrapolate to the much higher heat-fluxes and lower normalized densities of a Fusion Nuclear Science Facility and DEMO.

III-2. *Measure hydrogenic and impurity ion sources, sinks, and transport in the boundary region, measure and analyze the surface characteristics of lithiated and non-lithiated divertor and first-wall plasma facing components, and relate the surface characteristics to the particle/ion behavior under both steady-state and transient edge conditions.*

Background:

NSTX has demonstrated that evaporated lithium deposited on the lower divertor can pump deuterium, increase thermal energy confinement, and eliminate ELMs in diverted H-mode plasmas. However, ELM-free plasmas from lithiumization can also lead to impurity accumulation and increased $Z_{eff}$ and edge collisionality. Access to improved particle control and reduced collisionality requires improved understanding and control of particle sources, pumping, and transport. NSTX also implemented a liquid lithium divertor (LLD) module in 2010 to investigate the effects of liquid lithium in diverted H-mode plasmas. The LLD results indicate that a critical issue for the performance of solid and liquid lithium as a pump of hydrogenic species is the Li chemical reactions with background vacuum gases and plasma impurities. Another important observation during the LLD experiments was evidence of temperature clamping of the Mo substrate under the lithium surface as the Li was heated through and above the Li melting temperature. These results may provide insight into the potential of liquid Li for handling high heat flux and protecting solid divertor PFCs. NSTX Upgrade will continue to utilize lithium coatings for deuterium inventory control during the initial phase of Upgrade operation, and the next generation of LLD will undergo preliminary design during the Upgrade outage.

### III-3. *Measure and understand boundary plasma response to applied 3D magnetic field perturbations and other perturbations designed to control edge plasma transport and stability.*

Background:

NSTX has made significant progress in characterizing pedestal stability and developing small ELM regimes, and is actively comparing measured ELM stability thresholds to peeling-ballooning theory. With the application of evaporated lithium onto the lower divertor, long-pulse ELM-free discharges have been obtained. In these discharges, the pedestal temperature increased as did the computed edge bootstrap current density, and these edge profile changes have modified stability thresholds consistent with peeling-ballooning theory. Further, unlike the results of some higher aspect ratio tokamaks, edge 3D resonant magnetic perturbation (RMP) fields are found to be destabilizing rather than stabilizing in NSTX for reasons that are not yet understood. RMP fields have been used to purposely trigger ELMs to expel impurities from ELM-free H-mode, and the plasma boundary shape influences size of the triggered ELMs. NSTX Upgrade will have higher pedestal temperature and pressure and lower pedestal collisionality, and these differences could impact the edge bootstrap current density profile and the plasma response to 3D fields including the transient particle expulsion driven by ELMs.

## Key Collaboration Opportunities in Plasma Boundary Interfaces:

- *Measurements of plasma kinetic profiles (density, temperature, flow), neutral density profiles, and transport and turbulence in the SOL at the outboard midplane and in or near the divertor region. Diagnosis of divertor heat flux profiles, divertor plasma density and temperature, divertor neutral pressure, impurity density and radiation (especially for characterizing detachment), and measurements of divertor power and particle balance, and particles sources. Diagnostics suitable for real-time divertor radiation and PFC temperature and/or heat flux control are also encouraged.*

- *Measurements of hydrogenic and impurity ion sources, sinks, and transport in the boundary region and in-situ measurements of the divertor surface conditions with active and passivated Li coatings on carbon and/or molybdenum PFCs, with a goal of relating PFC surface conditions to particle inventories during steady-state operation, ELMs, and disruptions.*

- *H-mode pedestal profile diagnostics with increased time and spatial resolution to enhance predictive capability for the H-mode pedestal structure and stability, especially for understanding the effects of lithium and 3D fields on the pedestal thermal and particle transport including both low-Z and high-Z impurities.*

## IV. *Waves and Energetic Particles* – the use of waves and energetic particles to sustain and control high-temperature plasmas.

*For more information contact:* Gary Taylor (gtaylor@pppl.gov)

### Research Priorities:

IV-1. *Measure the transport of supra-Alfvénic fast ions due to Alfvén eigenmode avalanches and other instabilities with particular emphasis on the possible redistribution of neutral beam current drive. In addition, measure the eigenfunctions and dynamics of Alfvénic instabilities to aid in the validation of advanced numerical simulations and the development of a predictive capability for fast-ion transport relevant to FNSF and ITER.*

Background:

The capability to excite and diagnose a broad range of fast-ion driven instabilities makes NSTX a powerful research tool for understanding energetic particle physics for ITER and future ST's. NSTX researchers have mapped and diagnosed the stability space of TAE modes - from mode onset to multi-mode avalanche threshold for a range of normalized fast-ion velocities and pressures. In addition, coupling between Alfvén Cascade modes and Geodesic Acoustic Modes has been characterized, and the eigenstructure of high-$\beta$ Beta-induced Alfvén Acoustic Eigenmodes (BAAE) has been measured and successfully compared to theory. A major objective of NSTX research is to develop a predictive capability for determining the extent to which the Alfvénic MHD activity described above causes transport of energetic particles with application to ITER and an FNSF. In NSTX, successive TAE avalanche events have been measured to have an effect on the fast-ion confinement in the plasma core and to modify the NBI driven currents and resultant equilibrium q profile. Finally, the ability to largely suppress low-k turbulence in NSTX provides an excellent opportunity for comparison to previous observations (in several other fusion facilities) of fast-ion transport by electrostatic turbulence. In NSTX Upgrade, the radial transport of fast ions by *AE modes could significantly impact the beam current drive profile of the 2nd NBI and influence the ability to control current profile and support 100% non-inductive current drive.

IV-2. *Measure and simulate interactions between high-harmonic fast-waves (HHFW) and neutral beam fast-ions with application to optimizing plasma heating and current-drive by the HHFW.*

Background:

Extensive HHFW coupling and heating studies have identified surface wave excitation as a key parasitic absorption mechanism that can reduce the effective core heating efficiency, and similar physics could play a role in the coupling of ICRF to ITER plasmas. Higher magnetic field and reduced density in front of the antenna (achieved through the use of evaporated Lithium) has enabled HHFW to reliably heat electrons in deuterium H-mode plasmas. These performance improvements motivated the upgrade to the HHFW antenna system, and record ST central electron temperatures (above 6keV) have been achieved using the upgraded antenna. HHFW acceleration of NBI fast-ions has previously been observed in NSTX plasmas, and additional research is needed to understand and minimize HHFW-NBI ion interactions in conditions with reduced surface wave excitation. In NSTX Upgrade, the higher toroidal field is expected to further reduce parasitic edge losses and reduce the number of ion-cyclotron resonances present in the plasma. However, operation with increased NBI power and for longer pulses may require operation with a larger outboard gap which could decrease HHFW coupling efficiency and increase edge parasitic losses.

Key Collaboration Opportunities in Waves and Energetic Particles:

- *Measure the fast-ion distribution function and fusion products in multiple spatial dimensions and compare to classical slowing down and linear and non-linear fast-ion instability model predictions of the fast-ion confinement. Further, extend the spatial and temporal resolution of fast-ion instability eigenfunction diagnostics to improve the prediction of fast-ion transport.*

- *Utilize and/or extend the fast-ion distribution function diagnostics to measure fast-ion acceleration by the HHFW and model and characterize the heating of thermal ions and fast ions by the HHFW with application to predicting HHFW heating and current drive efficiency.*

## V. ***Plasma Start-up and Ramp-up without a Solenoid*** – the physical processes of magnetic flux generation and sustainment.

*For more information contact:* Dennis Mueller (dmueller@pppl.gov)

Research Priorities:

V-1. *Measure and optimize the formation, confinement, and heating of solenoid-free start-up plasmas created using Coaxial Helicity Injection (CHI) and other techniques such as poloidal-field ramp-up and plasma gun start-up.*

Background:

Coaxial helicity injection (CHI) has demonstrated transformer flux savings equivalent to 400kA of plasma current when CHI was added to an inductively-driven plasma current ramp. Approximately half of this current savings is due to direct poloidal flux creation, while the other half is due to reduced internal inductance of the CHI-formed ramp-up plasma. CHI coupled to induction has also been shown to be compatible with high performance H-mode operation. The Pegasus toroidal experiment has also generated high plasma current magnitudes (170kA) using plasma gun start-up. These favorable results motivate development and testing of means to efficiently heat (such as high-harmonic fast wave) and densify ST start-up plasmas to conditions compatible with non-inductive plasma current ramp-up to high plasma current. In NSTX Upgrade, helicity injection current drive is projected to scale favorably (linearly) with toroidal field strength. Thus, by doubling the toroidal field strength, the generation of 300-400kA of closed-flux plasma current should be achievable thereby providing a target plasma suitable for NBI heating and current ramp-up.

V-2. *Measure and optimize the non-inductive current ramp-up of low-current target plasmas driven by high-harmonic fast wave (HHFW) and/or neutral beam injection (NBI) heating and current drive.*

Background:

Plasma current ramp-up to conditions compatible with sustained high-performance – without reliance on a solenoid - is an important and challenging research objective for the ST. Current overdrive (from bootstrap and RF and NBI sources) is being pursued to provide current ramp-up to high performance. HHFW heating of low current H-mode discharges has achieved high poloidal beta and bootstrap current fractions up to 85%. Higher heating power and resilience to ELMs will be utilized to assess the possibility of current ramp-up using bootstrap current, RF current drive, and NBI current drive. Importantly, in NSTX Upgrade, the 2nd NBI is predicted to be absorbed by a low-current (~400kA) plasma target and ramp-up the plasma current non-inductively to 0.8-1MA.

Key Collaboration Opportunities for Start-up and Ramp-up:

- *Diagnose the early CHI equilibrium evolution – including boundary evolution and the density, temperature, impurity content, and radiated power to maximize the closed-flux plasma current formation and coupling to other heating techniques.*

- *Diagnose the HHFW coupling, heating, and current drive for plasmas formed by CHI and/or plasma guns, and measure the fast-ion confinement and Alfvén Eigenmode instability behavior during non-inductive ramp-up using the 2nd NBI of the Upgrade.*

## VI. **Advanced Operating Scenarios** – the physics synergy of external control and self-organization of the plasma.

*For more information contact:* Stefan Gerhardt (sgerhardt@pppl.gov)

Research Priorities:

VI-1. *Develop real-time diagnostics for advanced plasma control, including for example: measurements of the safety factor profile, temperature and density profiles and divertor heat-flux, radiation and/or surface temperature measurements in support of advanced operating scenarios in NSTX Upgrade.*

Background:

High non-inductive current fraction (65-70%) has been sustained for up to 3 current redistribution times in NSTX by operating with high pressure-gradient-driven current fraction in the range of 35-55% and NBI current fraction of 10-30%. In NSTX Upgrade, the decreased collisionality and more tangential 2nd NBI are together projected to enable 100% non-inductive current drive at plasma currents of 0.8-1MA. Sustaining and optimizing these high-performance scenarios will require advanced plasma control including controlling some profiles (such as the current profile) and measuring other profiles in real-time to improve real-time reconstructions of the plasma beta and in the longer term enabling real-time stability calculations. For high plasma current (~2MA) operation at high heating power (10-15MW), the projected high peak divertor heat flux on the inertially cooled divertor PFCs could limit pulse-durations to 1-2 seconds, and real-time control of divertor heat flux mitigation (flux expansion, strike-point sweeping, radiation, detachment) will become increasingly important.

VI-2. *Develop new or utilize existing diagnostics for the identification of disruption onset and/or MHD precursors for potential use in triggering controlled plasma shut-down and/or disruption mitigation techniques.*

Background:

NSTX has an extensive set of real-time in-vessel MHD diagnostics for the measurement and active feedback control of error fields, locked modes, and resistive wall modes. NSTX is initiating work on disruption mitigation using massive gas injection at several poloidal locations. Additional safe plasma shut-down algorithms are planned to be developed in NSTX Upgrade. While NSTX Upgrade is designed to withstand high current and high stored energy disruptions, the potentially deleterious effects of disruptions are best avoided, and such disruption avoidance and machine protection techniques will be needed for future FNSF devices and for ITER.

## Key Collaboration Opportunities for Advanced Operating Scenarios:

- *Develop diagnostics suitable for real-time reconstructions of the plasma current density profile, pressure profile, and for real-time measurements of the divertor temperature and control of heat flux mitigation.*

- *Develop real-time diagnostics and/or algorithms to detect the onset of plasma disruptions for triggering safe-shut-down and/or disruption mitigation.*

## *Appendix A - Table I.  NSTX Measurement Capabilities – May 2011*

(black – routine operation, blue – under active development)

| Physics Measurement | Typical range and coverage | Spatial; Temporal Resolution | Typical Precision | Available Diagnostic Techniques | Comment | Contact |
|---|---|---|---|---|---|---|
| Coil currents | | follow pulse shape. | 0.5% | Rogowski coil on buswork; Hall effect transducers at power supplies | For EFIT/LRDFIT equilibrium reconstruction | S. Gerhardt – PPPL |
| Plasma current, $I_p$, | | 0.1 ms | 1.0% | 2 Rogowski coils around plasma outside vacuum vessel | For EFIT/LRDFIT reconstruction | S. Gerhardt – PPPL |
| Equilibrium Poloidal Field and Flux | | Variable spatial resolution<br>5 kHz sampling rate | 1-3% | 2D and 3D solenoids (Mirnov coils) inside vv, flux loops inside and outside vv | For EFIT/LRDFIT reconstruction | S. P. Gerhardt-PPPL |
| Plasma Equilibrium Reconstruction | | 10 mm absolute<br>1 ms | 3 mm with RTEFIT | | Between shot analysis with the EFIT code; post-experiment analysis with EFIT and LRDFIT | S. Sabbagh – CU, J. Menard-PPPL |
| Plasma kinetic energy | > 10 kJ | 1 ms | 1 kJ | diamagnetic loop | EFIT/LRDFIT constraint, uses TF coil | M. Bell - PPPL |
| Electron density line integrals | >2x10$^{11}$ cm$^{-2}$ | 4 MHz | 2x10$^{11}$ cm$^{-2}$ | tangential interferometry, polarimetry (FIReTIP) | FIR laser with retro-reflectors in 4 tangential chords (2 additional under dev) | K. C. Lee – UC Davis |
| | | TBD (probably ~2 MHz) | | 1 mm radial polarimeter (configured as an interferometer) | 1 mm, with retroreflection from center stack | S. Kubota - UCLA |
| Electron density profile | 5x10$^{11}$ - 5x10$^{14}$ cm$^{-3}$ | 3.0 cm core, 0.9 cm edge, 2 30 Hz lasers | >3% | Thomson scattering | 60 Hz Nd:YAG, laser nearly radial on horizontal midplane, 42 of 48 channels implemented | B. LeBlanc, A. Diallo – PPPL |
| | 2x10$^{12}$– 3.5x10$^{13}$ cm$^{-3}$ | Up to 200 kHz, 21398 sweeps | ≤ 1 cm | reflectometry FM/CW | 13 – 53 GHz swept | S. Kubota - UCLA |
| | 0.02-1.6x10$^{13}$ cm$^{-3}$ | 1 kHz | | reflectometry (SOL) | 6 - 36 Ghz swept system, 1 kHz sweep rate | J. Wilgen - ORNL |

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|---|---|---|---|---|---|---|
| Real time density for density feedback control | >2x10$^{11}$ cm$^{-2}$ | 5kHz | 2x10$^{11}$ cm$^{-2}$ | tangential interferometry, polarimetry (FIReTIP) | Two fringe counter signals from mid-radius channel (Ch3: Rt=85 cm) | K. C. Lee – UC Davis |
| Electron temperature profile | 0.003 – 5 keV | 3.0 cm core, 0.9 cm edge, 2 30 Hz lasers | >3% | Thomson Scattering | 2 - 30 Hz Nd:YAG lasers nearly radial on horizontal midplane, 42 of 48 possible spatial channels implemented | B. LeBlanc, A. Diallo – PPPL |
| | 0.1-5 keV | 1 cm, < 10 kHz | 5% (rel) | tangential multi-color sxr arrays | 5 color/ 20 spatial channels, AXUV diode arrays | K. Tritz, D. Clayton – JHU |
| | | | | imaging horizontal x-ray crystal spectrometer | vertical profile ±30 cm, requires Ar injection, spherical crystal, upgraded to PILATUS II solid state detectors | M. Bitter, K. Hill – PPPL |
| Ion temperature profile | 0.02 – 5.0 keV | 3.0 cm core, 0.5 cm edge, 10 ms | ≥ 2% | toroidal CHERS | 51 channels system using C VI with heating beam, dedicated background view | R. Bell, M.Podestà – PPPL |
| | | 3.0 cm edge only, 10 ms | ≥ 2% | edge Doppler spectroscopy | 7 channels from tangential view and 6 channels from vertical view of outer midplane edge. Uses intrinsic C III and He II. | R. Bell, M.Podestà – PPPL |
| | 0.2 – 5.0 keV | 2.5 cm, 5 ms | ≥ 5% | scanning neutral particle analysis | horizontal and vertical scan, profile requires vertical scan, L-mode beam heated discharges only | S. Medley - PPPL |
| | | 5 cm, 20 ms | | imaging horizontal x-ray crystal spectrometer | see above | M. Bitter, K. Hill - PPPL |
| Plasma rotation profile | -100 km/s to +300 km/s | 3.0 cm core, 0.5 cm edge, 10 ms | ≥ 2% | toroidal CHERS | see above | R. Bell, M.Podestà – PPPL |
| | | ~ 3.0 cm edge only, 10 ms | ≥ 2% | edge Doppler spectroscopy | see above | R. Bell, M.Podestà – PPPL |
| | | 1.6 cm core, 0.6 cm edge, 10 ms | | poloidal CHERS | up and down views of heating beam and dedicated background views, 75 active channels using C VI with heating beam. | R. Bell, M.Podestà – PPPL |
| | | ~ 3.0 cm, 10 ms | | edge Doppler spectroscopy | see above | R. Bell, M.Podestà – PPPL |
| | -100 km/s to +300 km/s | 4 radial channels; up to 5kHz sampling rate | | Real-time toroidal CHERS | 4 channels measuring C VI, active and passive (background) views, fast acquisition and analysis for real-time velocity data | M.Podestà, R. Bell – PPPL |

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| | 1.0-2.0 $\times 10^{13}$ cm$^{-3}$ | 2 MHz BW | | correlation reflectometry | 28.5-40 GHz, 2 channels, configured for poloidal correlation | S. Kubota - UCLA |
| B field pitch (for determination of q(R) using LRDFIT or EFIT) | | 3 cm core, 2 cm edge, 10 ms (target 5 ms) | ≥ 0.2° | motional Stark effect based on collisionally-induced-fluorescence (MSE/CIF) | 18 channels, presently applies correction for toroidal rotation, requires heating beam source A. | H. Yuh, F. Levinton – Nova Photonics |
| | | target - 3 cm core, 2 cm edge, 10 ms | target ≥ 0.2° | motional Stark effect based on laser-induced-fluorescence (MSE/LIF) using DNB | requires compact, radial DNB | J. Foley, F. Levinton – Nova Photonics |
| | | TBD (probably ~2 MHz) | | 1 mm radial polarimeter | provides line integral constraint, in conjunction with electron density profile input | S. Kubota - UCLA |
| Magnetic field pitch angle fluctuations | | 3 cm core, 2 cm edge, 5 ms | >0.2° | motional Stark effect based on collisionally-induced-fluorescence (MSE/CIF) | 18 channels implemented, presently applies correction for toroidal rotation, requires heating beam source A. | J. Foley, F. Levinton – Nova Photonics |
| B field magnitude, P(R) | | 5 cm core, 2 cm edge, 10 ms | >5 Gauss | motional Stark effect based on laser-induced-fluorescence (MSE/LIF) using DNB | requires compact, radial DNB | J. Foley, F. Levinton – Nova Photonics |
| Profile of the radial Electric field | | 5 cm core, 2 cm edge, 10 ms | | MSE/CIF and MSE/LIF | see above; requires heating source A and DNB | F. Levinton, H. Yuh, J. Foley - Nova Photonics |
| | | 3.0 cm core, 0.5 cm edge, 10 ms | | toroidal and poloidal CHERS | see above; requires heating beam | R. Bell, M.Podestà – PPPL |
| | | 3.0 cm, 10 ms | | edge Doppler spectroscopy | may need helium | R. Bell, M.Podestà – PPPL |
| Radiation profile | | 8 cm, 0.2 ms | | toroidal bolometer array | tangential view, 16 channel AXUV diode array | S. Paul - PPPL |
| | Divertor radiation profile | 8 cm, 5 ms | | divertor bolometers | 20 gold foil bolometers: 8 viewing divertor radially from outside, 8 viewing divertor from top, and 4 viewing down from midplane | S. Paul - PPPL |
| | Lower divertor area | 1-2 cm, 10-20 kHz | | Divertor radiometer (bolometer) array, can be used with Ly-alpha filter | Vertical view, 20 channel AXUV diode array | V. Soukhanovskii - LLNL |
| $Z_{eff}$ | | line integral | 10% abs. | visible continuum sensor | single filterscope chord, $R_{TAN}$~60 cm, $\lambda=$ | C. Skinner - PPPL |
| | | 3.0 cm core, 0.5 cm edge, 10 ms | ≥ 5% in ($Z_{eff}$-1) | toroidal CHERS | see above, assumes C only impurity | R. Bell, M.Podestà – PPPL |

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|---|---|---|---|---|---|---|
| Impurity concentrations | $C^{+5}$ conc. | 3.0 cm core, 1.0 cm edge, 10 ms | 20% abs. | toroidal CHERS | see above | R. Bell, M.Podestà – PPPL |
| | H/D ratio, detachment signature, line emission | Integral; 10 ms | 5% (rel) | Visible (VIPS 2) survey spectrometer | **10** sightlines coupled via fiber to 0.5 M Czerny-Turner; 3500-11000Å, CCD detector.<br>NIR capability (8000-22000Å) under development. | V. Soukhanovskii - LLNL |
| | O/C ratio, impurity influx | Integral; 15 ms | 5% (rel) | VUV (SPRED) survey spectroscopy | 100 – 1100Å with 2 gratings, radial midplane view, microchannel plate with CCD readout | C. Skinner, S. Paul - PPPL |
| | $Z \geq 3$ ions (Li, B, C, O, Cu, Ne, Ar, Fe, Kr, Mo) | 5 cm; 5 ms for impurities | 15% abs | filtered poloidal soft x-ray arrays | 2 horizontal arrays (32 ch); discrete AXUV diode arrays | K. Tritz, D. Clayton – JHU |
| | | 1 cm, < 10 kHz | 5% (rel) | tangential multi-color sxr arrays | 5 color/ 20 spatial channels, AXUV diode arrays | K. Tritz, D. Clayton – JHU |
| | | r/a~0.08, 10 ms | 15% abs | TGI spectrometer | 12 chord transmission grating imaging spectrometer; 10Å – 300Å CCD camera | K. Tritz, D. Clayton – JHU |
| | | Integral; 12 ms | 5% (rel) | EUV spectrometer (XUES) | Flat field grazing incidence spectrometer covering 10-60 Å | P. Beiersdorfer-LLNL |
| | | Integral; 12 ms | 5% (rel) | EUV spectrometer (LoWEUS) | Flat field grazing incidence spectrometer covering 60-220 Å | P. Beiersdorfer-LLNL |
| Low (m,n) MHD modes, sawteeth, locked modes, and disruption precursors | $\Delta B/B = 10^{-4} – 10^{-1}$, (0,0)<(m,n) < (5,10) | poloidal<br>DC – 250 kHz<br>toroidal<br>DC – 2 MHz | | low frequency Mirnov coils outside plasma | 12 toroidal | E. Fredrickson, S. P. Gerhardt - PPPL |
| | | n=1,2&3 RWM Detection | | Toroidal arrays of $B_P$ and $B_R$ sensors inside the vessel. | Used for both n=1 RWM feedback and Dynamic Error Field Correction, and offline analysis | S. P. Gerhardt-PPPL |
| | | 5 cm; < 300kHz bw | | filtered poloidal sxr arrays | 2 horizontal arrays (32 ch); discrete AXUV diode arrays | K. Tritz, D. Clayton – JHU |
| | | 1 cm, < 10 kHz | 5% (rel) | tangential multi-color sxr arrays | 5 color/ 20 spatial channels, AXUV diode arrays | K. Tritz, D. Clayton – JHU |
| | | 4 cm, < 200 kHz. 1 cm, < 60 kHz | | fast tangential soft x-ray pinhole camera | uses various foils and apertures, phosphor and demagnifying image tube with Phantom Camera (typ 96 x 96 pixels) | D. Battaglia – ORNL |
| | $>2x10^{11}$ $cm^{-2}$ | 4MHz | $2x10^{11}$ $cm^{-2}$ | tangential interferometry, polarimetry (FIReTIP) | FIR laser with retroreflectors in 4 tangential chords (2 additional) | K. C. Lee – UC Davis |

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|---|---|---|---|---|---|---|
| | | TBD (probably ~2 MHz) | | 1 mm radial polarimeter (OR configured as an interferometer) | 1 mm, with retroreflection from center stack | S. Kubota - UCLA |
| | 1.1-7.0 $\times 10^{13}\,\mathrm{cm}^{-3}$ | 2.5 MHz BW | | quadrature reflectometer | 30-75 GHz, 16 channels | S. Kubota - UCLA |
| | | 500 kHz | | Neutron scintillator array | plastic scintillators with PM tubes 1-ZnS; 3 BC400 | L. Roquemore - PPPL |
| High frequency instabilities (MHD, fast ion modes) | $\Delta B/B \geq 10^{-3}$ to $10^{-7}$, $n = 0 – 30$ | 5 MHz | Toroidal and poloidal | Mirnov coils outside plasma | 3-$B_T$ in toroidal array, and 8-$B_P$ in toroidal array, 4-$B_P$ in poloidal array | E. Fredrickson – PPPL |
| | | 5 cm; < 300kHz bw | | filtered poloidal sxr arrays | 2 horizontal arrays (32 ch); discrete AXUV diode arrays | K. Tritz, D. Clayton – JHU |
| | 1.1-7.0 $\times 10^{13}\,\mathrm{cm}^{-3}$ | 2.5 MHz BW | | quadrature reflectometer | 30-75 GHz, 16 channels | S. Kubota - UCLA |
| | $>2\times 10^{11}\,\mathrm{cm}^{-2}$ | 500 kHz | $2\times 10^{11}\,\mathrm{cm}^{-2}$ | tangential interferometry, polarimetry (FIReTIP) | FIR laser with retroreflectors in 4 tangential chords (2 additional) | K. C. Lee – UC Davis |
| | | TBD (probably ~2 MHz) | | 1 mm radial polarimeter (OR configured as an interferometer) | 1 mm, with retroreflection from center stack | S. Kubota - UCLA |
| Disruption Halo Currents | 0-200 A | 10x20cm tiles, 0.1 msec resolution | | Lower Outboard Divertor Shunt Tile Array | 6 tiles in each of row 3 and 4 of the lower outboard divertor, for a total of 12 | S.P. Gerhardt, PPPL |
| | 0-80 kA | 90 Degrees toroidal, 0.5 msec | | LLD Ground Strap Rogowskis | Each LLD tray is single point grounded with a flexible copper strap; the rogowski is mounted on that strap. | |
| Core turbulence | 1.0-2.0 $\times 10^{13}\,\mathrm{cm}^{-3}$ | 2 MHz BW | | correlation reflectometry | 28.5-40 GHz, radial or poloidal correlation | S. Kubota - UCLA |
| | $2\times 10^{12}$– $3.5\times 10^{13}\,\mathrm{cm}^{-3}$ | Up to 200 kHz, 21398 sweeps | ≤1 cm | reflectometry FM/CW | 13 – 53 GHz swept; radial correlation length; broad-$k_r$ backscattering | S. Kubota - UCLA |
| | | $-20\,\mathrm{cm}^{-1} < k_r < 20\,\mathrm{cm}^{-1}$, $\Delta R \sim 5$ cm | $\Delta n/n > 0.1\%$ | high-k scattering | tangential microwave scattering at $\lambda = 1$ mm, 5 detector channels viewing $r/a \sim 0.3$-$0.8$ | Y. Ren, E. Mazzucato - PPPL |
| | $k_\perp \rho_I < 1$ | $\Delta R \sim 2$ cm; 120 cm < R< 150 cm | $\Delta n/n > 0.1\%$ | Beam Emission Spectroscopy | 2 arrays viewing heating beams with 2-D (radial and poloidal) array of 32 detector channels | D. Smith, G. McKee - UW |
| | | TBD (probably ~2 MHz) | | 1 mm radial polarimeter (OR configured as an interferometer) | 1 mm, with retroreflection from center stack | S. Kubota - UCLA |

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|---|---|---|---|---|---|---|
| | 1.1-7.0 x$10^{13}$$cm^{-3}$ | 2.5 MHz BW | | quadrature reflectometer | 30-75 GHz, 16 channels | S. Kubota - UCLA |
| | | ~ 1 cm for r/a> 0.8, <400 kHz | | gas puff imaging | Supported by gas puff manifold. Various fast cameras used | S. Zweben – PPPL |
| Edge recycling and impurity influx | | 2 kHz | | filterscopes | 5 upper divertor, 5 lower divertor, 12 midplane CS. filters include $H_{\alpha,\beta,\gamma}$ , CII, CIII, LiI, BII | V. Soukhanovskii – LLNL, T. Gray, R. Maingi – ORNL, C. Skinner - PPPL |
| | | 0.03-0.2 ms/frame | | 1D CCD cameras | 2 lower divertor, 1 midplane,<br>1 upper divertor | V. Soukhanovskii – LLNL |
| | | 1 kHz or higher | | Divertor Imaging Spectrometer - DIMS | 19 sightlines coupled via fiber to 0.61m Czerny-Turner; 3500-11000Å, CCD detector.<br>NIR capability (8000-22000Å) under development.<br>Ion temperature measurements (Doppler spectroscopy) under development. | V. Soukhanovskii - LLNL |
| | 380-590 nm range 1.0 Å/pixel dispersion | 2.5 cm chord views of LLD, Mo and ATJ tiles. 1 kHz | | Compact Spectrometer Array (CSA) | Three medium optical resolution (0.43 nm) f/4 Czerny-Turner spectrometers.<br>Absolute intensity calibrated.<br>Simultaneous monitoring of divertor D, He, C, CD, $C_2$, Li and Mo emissions. | A. McLean - ORNL |
| | | Up to 100kHz At 256x208 | | wide angle divertor fast cameras | Top view of lower divertor from Bay E (Phantom 710) and Bay J (Phantom 7.3). Equipped with narrow bandpass filters | F. Scotti, L. Roquemore - PPPL |
| | | 6 ms, 128x128 | | ENDD | Tangential view of outer midplane edge - CII filter | F. Scotti - PPPL |
| Dust monitoring | | few seconds | sens. $1\mu g/cm^2$ | electrostatic grid detector | biased fine pitch PC grid, pulse counting electronics, Bay C bottom | C. Skinner - PPPL |
| First wall deposition | | 2 sec continuous | few Angstroms | quartz microbalances | four QMBs (Bay H top, Bay H bottom, Bay I midplane, Bay B midplane), 3 shuttered, Inficon XTM/2 | C. Skinner - PPPL |
| Surface chemical state and composition | <1 micron | Outboard lower divertor. Single location intershot | | Materials Analysis Particle Probe (MAPP) utilizes multiple surface-science measurement techniques to characterize a sample material exposed to NSTX conditions | Thermal Desorption Spectroscopy (TDS), X-ray Photoelectron Spectroscopy (XPS), Low energy Ion Secondary Scattering (LEISS), and Direct Recoil Spectroscopy (DRS) | J. P. Allain - Purdue |

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| Target Langmuir probes | 1 – 40 eV<br>$10^{17}$ – $10^{20}$ m$^{-3}$ | ~2 mm electrode heads at various locations, 1-10 ms sweep resolution | | Classical interpretation yields $n_e$, $T_e$, V. Non-local interpretation yields additional $V_p$ and EEDF | Flush-mount probes embedded in carbon or molybdenum tiles (2 inner div and various CS)<br>99-electrode high-density Langmuir probe array at outer divertor with 5 mm spatial resolution | M. Jaworski - PPPL |
| Fusion source profile | | | | Si diode detectors | 2-channel prototype being tested; 8 channels planned | W. Boeglin – Florida Int'l U |
| Neutron flux monitors | | 1 ms | 5% rel.<br>25% abs. | fission chambers | 2 $U^{235}$ detectors with x26 sensitivity ratio | L. Roquemore - PPPL |
| | | 0.2 μs | <5% rel. | scintillator detectors | plastic scintillators with PM tubes 1-ZnS; 3 BC400 | L. Roquemore - PPPL |
| Core RF waves | $2x10^{12}$–$3.5x10^{13}$ cm$^{-3}$ | Up to 45 kHz, 4064 sweeps | ≤1 cm | reflectometry FM/CW | 13 – 53 GHz swept, some modifications required from standard profile reflectometry | S. Kubota - UCLA |
| RF driven surface waves | | | | high-frequency Langmuir probe | located between antenna segments, | R. Wilson – PPPL, J. Wilgen - ORNL |
| Gas pressure at several locations | | | | Penning gauges | 1 in lower divertor, 1 in upper divertor, 1 in pumping duct with spectroscopy, 1 below lower divertor with spectroscopy | R. Raman – U. Wash |
| | | | | micro-ion gauges | Bays E and C-midplane, Bay L-pumping duct, Bay C-top | R. Raman – U. Wash |
| Gas composition in vacuum vessel | typ A = 1-50/100, ΔA=1 | Approx. 1 min./1 sec. mass sweep | $10^{-11}$/$10^{-9}$ torr typical sens. | 2 Residual gas analyzers (continuous monitoring/after discharge measurements) | In Bay L pumping duct, differentially pumped system | W. Blanchard - PPPL |
| Runaway electrons | | 10 ms | 30% | hard X-ray detector | at start-up and thermal quench | L. Roquemore, K. Hill - PPPL |
| First wall filtered visible images | Phantom MIRO2 | >256x256 | 10 bit | 5.5 kHz at 32x16 | cameras share various views:<br>• top view of lower divertor<br>• tangential view of lower divertor<br>• fish eye radial view of entire | L. Roquemore,. F. Scotti, S. Zweben - PPPL |
| | Phantom 7.3-2048 | >32x32 | 14 bit | 190 kHz at 32x32 | | |
| | Phantom V4 | >64x64 | 8 bit | 50kHz at 64x64 | | |
| | Phantom MIRO4 | >64x64 | 8 bit | 60 kHz at 64x64 | | |

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| | Phantom V710 | >64x64 | 12 bit | 200 kHz at 128x128 | plasma<br>• 3 tangential midplane views including one view near pellet port<br>• view of gas puff manifold along B field | |
| First wall temperature | 20-700°C | 30 Hz<br>15° FOV<br>7 mm/pixel | 5°C abs<br><1°C rel | Standard frame rate, single-band infrared cameras | Two FLIR Omega 8-12 μm LWIR μbolometer cameras (160x128 pixels) with views of upper and lower divertors. | T. Gray, R. Maingi - ORNL |
| | 50-800°C | 1.6 kHz<br>12° FOV<br>5 mm/pixel | 5% typical | Fast, dual-band infrared camera | SBFP ImagIR HgCdTe camera (128x128 pixels). Bay H top viewing lower divertor at Bay G, H, I (R=0.2 to 1.0 m). Calibrated to 4-6 μm (MWIR) / 7-10 μm (LWIR) intensity ratio. | A. McLean, J.-W. Ahn - ORNL |
| | 20-800°C | 30 Hz<br>40° FOV<br>4 mm/pixel<br>>180° view of strike points | 5% typical | Wide-angle, two-color infrared camera | FLIR Tau 640 μbolometer camera (640x480 pixels). Re-entrant view of lower divertor from Bay H top (R=0.2 to 1.2 m). Calibrated to 8-10 μm (LWIR) / 10.5-13 μm (LWIR) intensity ratio. | A. McLean, R. Maingi - ORNL |
| | 20-1200°C | 30 Hz<br>18° FOV<br>2 mm/pixel | 5°C abs<br><1°C rel | Standard frame rate, single-band infrared camera | FLIR Tau 640 8-13 μm LWIR μbolometer camera (640x480 pixels). View from Bay B midplane of RF antenna straps at Bay D, E, and F. | P. Ryan, R. Maingi - ORNL |
| | 0-2300°C | 1 kHz<br>2 locations, 2 mm isolation | 3% typical | Fast ‘eroding’ thermocouples | Pair of high speed Type C eroding thermocouples at PFC surface. Located at R=0.64 and 0.70 m in the Gap H tile 1. | A. McLean, R. Maingi - ORNL |
| Vacuum Vessel Illumination | | | | 3 in-vessel tungsten filaments, ~ 25x5 mm helical | Provide lighting of the first-wall surfaces, Bays G and K near midplane, Bay K/L above midplane | H. Kugel - PPPL |
| Fast Lost Ions | | | | FLIP | radial array of Faraday cups | D. Darrow - PPPL |
| | | 50 kHz | 2°<br>3 cm | SFLIP | scintillator probe with energy and pitch angle resolution | D. Darrow - PPPL |
| Fast ion dynamics | $n < 5x10^{13}$ cm$^{-3}$ | 10ms, 5cm, 10keV | | s-FIDA - Spectrometer/CCD (energy resolved signal) | Vertical views from bay A/B. Tangential views from bay L/F. Based on active charge-exchange spectroscopy: requires NB injection; MPTS and CHERS data needed for analysis | A. Bortolon, W.W. Heidbrink – UCI |
| | | 20us, R=100, 120,140cm | | f-FIDA - Band-Pass Filter/PMT (energy-integrated signal) | | A. Bortolon, W.W Heidbrink – UCI |

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| Fast ion distribution | 1-100 keV | 2 msec | rel 5%<br>abs. x2 | scanning NPA | horizontal and vertical spatial distribution | S. Medley – PPPL |
|  | 35 – 100 keV | 1 msec counting window |  | solid state NPA | 4 chords $R_{TAN}$= 60, 90, 100, 120 cm, Si-diodes in current mode, with 0.15μ Al foils and apertures, <1MHz sample rate | A. Bortolon, W.W. Heidbrink - UCI |

## *Appendix A - Table II. Systems Capable of Supporting Active Diagnostics – May 2011*

(black – routine operation, blue – under active development, red – EXAMPLES of potential future diagnostics)

| System | Purpose of system | Characteristics | Used in diagnostic: | Contact |
|---|---|---|---|---|
| Heating Neutral Beam | Provide neutral population to produce beam emission for various diagnostics | D, 90 - 100 keV, ~50cm V x 20cm H, ~ 150mA/cm$^2$ neutrals entering plasma | CHERS, MSE, MSE/LIF, BES (D) | T. Stevenson - PPPL |
| Diagnostic Neutral Beam | Provide excited neutral atoms for intensity and polarimetry measurement | H, 40 keV, 1 - 2 cm dia., 30 mA neutrals entering plasma | MSE/LIF | J. Foley, F. Levinton – Nova Photonics |
| Supersonic Gas Injector | Provides low divergence, high pressure gas jet | Laval nozzle, on midplane probe | thermal atomic beam spectroscopy | V. Soukhanovskii - LLNL |
| Gas Puff Manifold | Provides neutral atoms to highlight edge density turbulence | linear manifold ⊥ to edge B field, multiple 1 mm dia holes, D, He or Ar. | gas puff imaging | S. Zweben - PPPL |
| TAE antenna | Excite stable Alvén waves to measure linear damping | 5-turn radial loop antenna, ≤ 1 kW | Fast Mirnov Coil | E. Fredrickson - PPPL |
| BEaP probes | Measure density, potential and electron temperature at LLD diagnostic tiles | 5 radial probes at Bay E and Bay K, digitized at 200 kHz | evaluates effect of BEaP electrodes on local SOL plasma | S. Zweben - PPPL |