Version 8 - August 30, 2008

NSTX Program Letter
for Research Collaboration Employing Innovative Diagnostics for FY 2009-2011

Introduction

This NSTX Program Letter provides updated information about NSTX topical research priorities and collaboration opportunities during the upcoming three years (FY2009-2011). This information is useful for the preparation of proposals in response to the Office of Science Notice *National Spherical Torus Experiment - Innovative Measurements of Spherical Torus Plasmas* which was issued in August 2008. 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 recently peer reviewed NSTX Five-Year Plan for 2009-13[1] and the FESAC Facilities Report[2]. In the Appendix to this Letter, these areas are cross-referenced to the ten-year goals in the FESAC Priorities Report as background information. The NSTX Program Advisory Committee reviewed this Program Letter on August 28, 2008. Its advice was incorporated in the final version.[3]

Mission of NSTX

The *programmatic* mission of NSTX is to evaluate the attractiveness of the compact Spherical Torus (ST) configuration in reducing cost, risk, and development time for practical fusion energy. The ST appears particularly attractive for: integrating DEMO-relevant Plasma Material Interface (PMI) solutions with high plasma performance (mission of the National High-power advanced-Torus eXperiment - NHTX[4]) and producing DEMO-relevant neutron flux and fluence at high duty-factor in an ST-based Component Test Facility (ST-CTF)[5]. NSTX also contributes to the physics basis for an ST-based DEMO device 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 CTF development are included in the DOE 20-year strategic plan for the Fusion Energy Sciences Program.[6]

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 by high β_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 β_T tokamak in addressing the overarching scientific issues in magnetic fusion.

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

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

[3] http://nstx.pppl.gov/nstx/NSTX_Program_Letter (available September 2, 2008).

[4] http://www.pppl.gov/pub_report//2007/PPPL-4252.pdf and http://nstx.pppl.gov/DragNDrop/NHTX_Information

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

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

NSTX Research Priorities and Key Collaboration Opportunities

This section lists the research topics of high priority in the NSTX Program during FY 2009-2011 and then highlights key collaboration opportunities for which research proposals are solicited. The NSTX research priorities and key collaboration opportunities are organized according to the six categories used in the FESAC Priorities Plan. For each category a key person is listed who should be contacted for further information prior to submitting collaboration proposals.

The list of research priorities is guided by the NSTX programmatic and scientific missions and by its schedule of milestones, subject to anticipated funding during FY 2009-2011. For each of the six scientific categories described below, the numbered research priorities are listed in priority order. Proposals addressing high priority research areas including understanding the impact and operation of the Liquid Lithium Divertor, the linkage between scrape-off-layer transport and divertor heat flux, identifying modes responsible for electron and ion turbulent transport, and the utilization of the upgraded High Harmonic Fast Wave system for plasma heating and current ramp-up are especially encouraged. The key diagnostic 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 diagnostic contributions from other national laboratories and by PPPL researchers. A table of existing NSTX diagnostic capabilities is provided in Appendix A to inform collaboration proposals. Proposals for innovative collaboration activities beyond the ones listed in this Program Letter are also welcomed; such proposals might be motivated by the list in Appendix B. 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 Plasma Physics* – the role of magnetic structure in plasma confinement and the limits to plasma pressure in sustained magnetic configurations.

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

Research Priorities:

I-1. *Determine the physics of RWM stabilization, by both passive and active means, and apply this understanding to reliably sustain high-beta low-aspect-ratio plasmas.*

Background:
Significant progress has been made in NSTX in the detection and active control of error fields (EF) and resistive wall modes (RWMs), understanding passive RWM stability, and in understanding and controlling toroidal flow damping from non-axisymmetric fields. More advanced control algorithms and enhanced predictive capability are sought to understand present RWM and EF results and allow extrapolation of performance to ITER and future STs. In particular, the high-β, near-Alfvenic toroidal flow velocities from NBI, the ability to control the toroidal flow velocity with magnetic braking, and the strong toroidicity of NSTX provide an excellent test-bed for validating models of RWM control and mode damping.

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

Background:
Recent research has revealed the importance of neoclassical tearing instabilities in limiting the plasma poloidal β and bootstrap fraction in NSTX. Low-frequency (f=1-30kHz) MHD activity (including tearing activity) has also been observed to redistribute the fast ions from neutral beam injection, but the mechanism by which this occurs is not yet quantitatively understood. Such physics may be relevant to proposed "hybrid" operating scenarios for ITER. Strong rotation and rotational shear, enhanced stabilization effects from curvature and large ρ*, and enhanced poloidal mode coupling may all play a significant role in modifying tearing mode stability in NSTX.

I-3. *Characterize the effects 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 data to the ITPA international database on disruptions with application to ITER. Low aspect ratio data has improved the understanding of the quench rate scaling for all aspect ratios, and NSTX has recently extended these studies with improved measurements of halo current fractions and halo-peaking factors. Additional research is 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 next-step STs – in particular for low internal inductance, high elongation, high β, strongly wall-coupled plasmas of STs.

I-4. *Develop understanding of non-axisymmetric field induced plasma viscosity for both resonant and non-resonant fields, and apply results to optimize error field correction and for rotation profile control*

NOTE: For I-4 above, plasma rotation modification by 3D fields also impacts the transport and turbulence and boundary physics scientific areas of NSTX as described below.

Key Diagnostic Collaboration Opportunities in Macroscopic Plasma Physics:

- *Develop and/or improve internal measurements of the RWM mode magnetic field and plasma displacement profile to compare to ideal and non-ideal simulations of the RWM to test mode stabilization theory. Assess the feasibility of non-magnetic sensors for diagnosis of 2D and 3D magnetic field structure and for control of the plasma boundary.*

- *Develop and/or improve internal measurements of the NTM mode magnetic field and/or plasma displacement profile to determine saturated island widths to compare to simulations and test tearing mode stability theory.*

- *Provide high resolution (space & time) kinetic profile data (q, rotation, temperature, density, etc.) to characterize the observed instability growth and disruption evolution – especially the thermal quench, and support computational stability analysis of the observed instabilities.*

NOTE: High resolution kinetic profiles and internal measurements of 3D magnetic fields and/or plasma displacement underpin the development of a predictive capability for non-axisymmetric-field-induced plasma viscosity.

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

For more information contact: Stan Kaye (skaye@pppl.gov)

Research Priorities:

II-1. *Determine the modes (low-k, high-k, electrostatic, electromagnetic, Alfvénic) responsible for causing anomalous electron transport.*

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 the recently implemented 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 the possible correlation between increased high-k fluctuation amplitude and increased electron thermal transport is being investigated. Micro-tearing and Global Alfvén Eigenmodes (GAE) have also been correlated in a preliminary way with anomalous electron transport in NSTX, and Collisionless Trapped Electron Modes (CTEM) will also be studied.

II-2. *Determine the role of low-k turbulence in causing anomalous ion 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. 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, recent 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.

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

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 (albeit transient) pump of hydrogenic neutrals, and the liquid lithium divertor (LLD) is expected to significantly enhance this pumping. Used in combination with dominant core fueling from NBI, the dependence of particle diffusivity on global plasma parameters will be determined, and the possible relationship between anomalous

particle and thermal diffusivity will be assessed. Impurity transport has been measured to be near neoclassical levels in NSTX and also exhibits a particle pinch. The possible relationship between the particle pinch and the momentum pinch will be investigated, and comparisons between anomalous particle transport and measured and simulated turbulence will be pursued.

Key Diagnostic Collaboration Opportunities in Multi-Scale Plasma Physics:

- *Develop and/or enhance measurements of magnetic fluctuations possibly associated with micro-tearing and GAE modes. Measure intermediate wavelength electrostatic ITG/TEM turbulence in both L-mode and H-mode (i.e. compatible with high density, and possibly hollow density profiles) plasma conditions. Design and/or develop diagnostics to measure the poloidal component of high-k turbulence to complement/extend the existing high-k-radial microwave scattering system and measure the turbulence polarization. Relate turbulence fluctuation measurements to measured and simulated electron energy transport.*

- *Measure the long and intermediate wavelength electrostatic and electromagnetic components of ITG/TEM turbulence in L-mode and H-mode plasma conditions and relate to measured and simulated ion energy and momentum transport.*

- *Improve diagnostic coverage and resolution of the edge plasma (e.g., T_e. T_i, n_e, n_{imp}, B, flows) impurity transport and particle pinch, and measure long and intermediate wavelength turbulence and relate to measured and simulated particle transport.*

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

For more information contact: Bob Kaita (rkaita@pppl.gov)

Research Priorities:

III-1. *Measure and understand the impact of a liquid lithium divertor (LLD) on particle control, energy confinement, and H-mode pedestal transport and stability. Further, analyze the LLD surface characteristics and the interactions between the LLD and the edge plasma, including the transport of lithium from the edge to the core under both steady-state and transient edge conditions.*

Background:
NSTX has demonstrated that evaporated lithium deposited on the lower divertor can improve particle control, increase thermal energy confinement, and eliminate ELMs in diverted H-mode plasmas. To investigate the effects of liquid lithium in diverted H-mode plasmas, NSTX will be implementing a liquid lithium divertor (LLD) module. Substantial additional diagnosis of edge plasma conditions is needed to support analysis and experimentation aimed at understanding and optimizing LLD performance and for characterizing the interactions between the LLD and the edge plasma and plasma-material interactions during steady-state operation, ELMs, and disruptions.

III-2. *Characterize the parallel and cross-field transport of heat and particles in the Scrape-Off-Layer (SOL), and understand the linkage between SOL transport and turbulence and the peak heat flux to the divertor.*

Background:
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). However, it is unclear if such techniques extrapolate to the much higher heat-fluxes of CTF, demonstration power plants, and reactors. Additional understanding of the scalings and underlying causes of SOL transport (in particular cross-field transport) is needed to develop a predictive capability for the peak divertor heat flux for divertor design for next-step devices.

III-3. *Understand the H-mode pedestal characteristics that provide access to small ELM and ELM-free regimes in the ST, and understand how boundary modifications including plasma shaping, 3D fields, and lithium impact pedestal transport and ELM stability.*

Background:
NSTX has made significant progress in characterizing pedestal stability and developing small ELM regimes, and is beginning to compare measured ELM stability thresholds to theory. Recently, 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 are likely impacting pedestal stability. Further, unlike the experience of some higher aspect ratio tokamaks, edge 3D resonant magnetic perturbation (RMP) fields are found to be destabilizing rather than stabilizing in NSTX. 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. Additional research and diagnostics are needed to better understand the influence of Li, RMP, and boundary shaping on ELM stability.

Key Diagnostic Collaboration Opportunities in Plasma Boundary Interfaces:

- *Improve the spatial and temporal resolution of pedestal and scrape-off-layer kinetic profiles to enhance stability and transport analysis in the presence of Li from wall coatings and the liquid lithium divertor (LLD) module. In particular, improve measurements of electron and ion density and temperature, plasma flow, current density, impurity concentration, radiation, and turbulence. These measurements are needed for all three of the Research Priorities for Plasma Boundary Interfaces described above. Innovative diagnostic approaches for relating mid-plane edge parameters to the divertor heat flux, and measurements of possible non-Maxwellian features of the edge plasma distribution function are particularly encouraged.*

- *Improve diagnosis of the plasma-material interface with particular emphasis on measurement of the transport of Li and other impurities to the plasma edge and core during quiescent edge conditions and in the presence of ELMs, and characterize the migration of Li from the LLD to other plasma facing components in response to ELMs and disruptions.*

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. *Study the range of observed energetic-particle-driven instabilities (for example Toroidal Alfvén Eigenmode (TAE) avalanches) and their possible role in redistribution of neutral-beam-driven current.*

Background:
The capability to excite and diagnose a broad range of fast-ion driven instabilities makes NSTX a powerful 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 Alfven Cascade modes and Geodesic Acoustic Modes has been characterized, and the eigenstructure of high-β Beta-induced Alfven Acoustic Eigenmodes (BAAE) has been measured and successfully compared to theory. A major research objective of NSTX research is to develop a predictive capability for determining the extent to which the Alfvenic MHD activity described above causes transport of energetic particles with application to ITER and CTF.

IV-2. *Study and optimize high-harmonic fast-wave (HHFW) heating and current drive in deuterium H-mode plasmas, with emphasis on understanding and minimizing parasitic loss mechanisms including: interactions between the HHFW and Neutral Beam Injection (NBI) fast ions, surface wave excitation, and other RF-induced changes to the plasma edge.*

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. Surface wave excitation can occur for plasma conditions in which the fast wave can propagate close to the antenna and/or wall. Similar physics could play a role in the coupling of ICRF to ITER plasmas. Recently, higher magnetic field and reduced density in front of the antenna (achieved through the use of evaporated Lithium) have enabled HHFW to reliably heat electrons in deuterium H-mode plasmas for the first time. These performance improvements have motivated upgrades to the HHFW antenna system to increase the heating power in high-performance NBI-heated discharges and for assessing plasma current ramp-up using HHFW-heated bootstrap current overdrive. 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. Other RF-induced changes in the edge plasma such as RF-driven sheaths and parametric decay instabilities may also impact HHFW heating efficiency in high-performance H-mode plasmas.

IV-3. *Measure and understand Electron Bernstein Wave (EBW) emission from over-dense plasmas with emphasis on maximizing mode conversion efficiency by minimizing collisional damping and conversion efficiency fluctuations.*

Background:
Recent experiments have demonstrated for the first time that significant electron Bernstein, X-mode, O-mode (B-X-O) mode conversion can be achieved in H-mode plasmas. The highest mode conversion efficiency in H-mode (50-60%) was achieved in the presence of evaporated Lithium which increased the temperature at the mode conversion layer which is predicted to reduce

collisional damping of the EBW. Additional research and measurements are needed to better understand and further increase the EBW transmission efficiency in H-mode to ultimately enable high mode conversion efficiency for EBW heating and current-drive applications.

Key Diagnostic Collaboration Opportunities in Waves and Energetic Particles:

- *Measure of the mode magnetic field and/or plasma displacement profile of fast-ion-driven instabilities and measure several moments of the fast-ion distribution function to test linear and non-linear fast-ion instability simulations and develop a predictive capability for fast-ion transport by fast-ion-driven instabilities for CTF and ITER.*

- *Measure HHFW wave-fields and RF-induced changes in the plasma core and edge to test fast wave heating and coupling simulation codes, measure fast-ion acceleration by the HHFW and develop means to modify and minimize the interaction between the HHFW and NBI fast-ions, and characterize the impact of HHFW power on the edge plasma and structures near the HHFW antenna.*

- *Perform additional measurements and experiments to determine the correlation between edge density fluctuations and fluctuations in the B-X-O transmission efficiency. Assess the dependence of B-X-O transmission efficiency on wave frequency, mode conversion location, plasma boundary shape, etc. in order to increase the time-average B-X-O transmission efficiency in H-mode from 50-60% to the 80-90% level needed for effective EBW heating and current drive.*

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

For more information contact: Mike Bell (mbell@pppl.gov)

Research Priorities:

V-1. *Develop and characterize efficient plasma current start-up utilizing techniques such as coaxial helicity injection, plasma guns, and poloidal-field ramp-up incorporating the impact of increased divertor pumping and increased ECH pre-ionization and heating power.*

Background:
Coaxial helicity injection (CHI) has created closed-poloidal-flux plasma current of up to 160kA on NSTX, and recently demonstrated transformer flux savings when CHI was added to an inductively-driven plasma current ramp. CHI coupled to induction has also been shown to be compatible with high performance H-mode operation. Given the importance of solenoid-free plasma formation to the ST concept, all viable plasma start-up techniques (consistent with NSTX device constraints) will be considered for testing in NSTX. Plasma gun startup has produced plasma currents up to 80kA in the Pegasus experiment, and flux closure and core temperature increases have also been observed. These favorable results motivate testing of plasma guns on NSTX to determine the size and field scaling of gun start-up in STs. Additional areas of research include an assessment of the impact of reduced divertor radiation during CHI using a metallic divertor, and the role of increased ECH pre-ionization power on CHI, gun startup, vertical-field current ramp-up – including synergies between these start-up techniques.

V-2. *Assess non-inductively-driven plasma current ramp-up utilizing high-harmonic fast-wave heating and current-drive with increased RF power and with improved resilience to variations in plasma edge density.*

Background:
In addition to the goal of creating closed-flux plasma current without a solenoid, ramping the current to values compatible with sustained high-performance - without a solenoid - is also an important 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 and RF current overdrive.

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

- *Measure CHI plasma density, impurity content, and radiated power to characterize CHI start-up power balance with and without additional heating power (ECH and HHFW) in the presence of a metallic outboard divertor and lithium. Implement initial low-current plasma gun system on NSTX and measure the gun-formed plasma current formation efficiency and scaling with device size and magnetic field. Image the rapid time evolution of solenoid-free start-up plasmas to understand and optimize plasma current formation.*

- *Measure HHFW wave-fields in the plasma core and edge to assess HHFW coupling and heating efficiency during the plasma current ramp-up, measure the production/acceleration of fast ions by HHFW, and measure/infer the sources of non-inductive current drive during the RF-driven current ramp-up.*

VI. *Physics Integration* – the physics synergy of external control and self-organization of the plasma.

For more information contact: Dave Gates (dgates@pppl.gov)

Research Priorities:

VI-1. *Achieve and maintain high-performance plasmas with reduced density and collisionality. Use the LLD to produce discharges with high non-inductive current fraction – in particular changes in the neutral beam current drive efficiency, core and pedestal confinement and stability, edge bootstrap current density, and plasma impurity content.*

Background:
High non-inductive current fraction (up to 65%) has been sustained in NSTX discharges at high plasma density by operating with a high pressure-gradient-driven current fraction up to 55% and NBI current fraction of 10%. Next-step ST devices sustained by non-inductive current drive are projected to operate with higher beam current fractions of 30-50% by operating at lower normalized density and collisionality. The liquid lithium divertor will be tested as a means of reducing plasma density in NSTX and increasing the NBI current drive and the total non-inductive current fraction. Modifications to plasma core and edge confinement, stability, and impurity content will be assessed in plasmas with reduced density and high non-inductive fraction, and increasingly sophisticated plasma control techniques will be developed to sustain high plasma performance while avoiding disruptions.

Key Collaboration Opportunities for Physics Integration:

- *Measure the plasma current density profile evolution and kinetic profiles to infer changes in non-inductive current drive sources at reduced density, measure possible beam current-drive redistribution from MHD activity and fast-ion instabilities, and measure the energy, momentum, and particle confinement properties and the full spectrum of plasma turbulence of discharges optimized for high non-inductive current drive fraction and long pulse duration.*

- *Develop real-time diagnostics and analysis tools for the plasma beta, rotation, and current profile to improve plasma control to sustain high plasma performance and to avoid and/or mitigate disruptions.*

Appendix A - Table I. NSTX Measurement Capabilities – August 2008

(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	For EFIT equilibrium reconstruction	S. Gerhardt – PPPL
Plasma current, I_p,		0.1 ms	1.0%	2 Rogowski coils around plasma outside vacuum vessel	For EFIT reconstruction	S. Gerhardt – PPPL
Plasma position		10 mm absolute 1 ms	3 mm with RTEFIT	2D and 3D solenoids inside vv, flux loops inside and outside vv	For EFIT reconstruction	S. Gerhardt – PPPL
Plasma kinetic energy	> 10 kJ	1 ms	1 kJ	diamagnetic loop	EFIT constraint, uses TF coil	M. Bell - PPPL
Electron density line integrals	>2x10^{11} cm^{-2}	500 kHz	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
		500 kHz		1 mm radial interferometer	1 mm reflected 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, 30 of 48 channels implemented	B. LeBlanc - PPPL
	2x10^{12}– 3x10^{13} cm^{-3}	Up to 100 kHz, 9273 sweeps	~ 1 cm	reflectometry FM/CW	13 – 50 GHz swept; radial correlation lengths (can be used simultaneously with correlation reflectometry	S. Kubota – UCLA
	.02-1.6x10^{13} cm^{-3}	1 kHz		reflectometry (SOL)	6 - 36 Ghz swept system, 1 kHz sweep rate	J. Wilgen – ORNL
	0.1-1.6x10^{13} cm^{-3}	1.5 mm, 2 ms per point, 60 ms per profile		fast scanning midplane probe	18 cm below midplane, τ_{insert}<100 ms, τ_{dwell} =2-50 ms, 10 tips	J. Boedo – UCSD
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, 30 of 48 possible spatial channels implemented	LeBlanc - PPPL
				fast scanning midplane probe	see above	J. Boedo - UCSD
	0.1-5 keV	4 cm, < 100 kHz	5% (rel)	tangential multi-color sxr arrays	3 color/ 16 spatial channels, CsI:Tl phosphor and PM arrays	L. Delgado - JHU

				imaging horizontal x-ray crystal spectrometer	vertical profile ±30 cm, requires Ar injection, spherical crystal, being upgraded to PILATUS II solid state detectors	M. Bitter - 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 - 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 - 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 - PPPL
		~ 3.0 cm edge only, 10 ms	≥ 2%	edge Doppler spectroscopy	see above	R. Bell - 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 - PPPL
		~ 3.0 cm, 10 ms		edge Doppler spectroscopy	see above	R. Bell - PPPL
	1.1-2.0 x10^{13}cm^{-3}	variable		correlation reflectometry	30-40 Ghz (core access for peaked low density profiles). Radial or 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)	16 of 19 channels implemented, presently applies correction for toroidal rotation, requires heating beam source A.	F. Levinton, H. Yuh - NOVA
		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	F. Levinton, J. Foley - NOVA
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

		3.0 cm core, 0.5 cm edge, 10 ms		toroidal and poloidal CHERS	see above; requires heating beam	R. Bell - PPPL
		3.0 cm, 10 ms		edge Doppler spectroscopy	may need helium	R. Bell - PPPL
	10V–30kV/m	1.5 mm, 1 μs		fast scanning midplane probe	see above, edge only	J. Boedo - UDSD
Radiation profile		8 cm, 0.2 ms		toroidal bolometer array	tangential view, 16 channel AXUV diode array	S. Paul - PPPL
		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
Z_{eff}		line integral	10% abs.	visible continuum sensor	single filterscope chord, R_{TAN}~60 cm, λ=	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 - PPPL
Impurity concentrations	C^{+5} conc.	3.0 cm core, 1.0 cm edge, 10 ms	20% abs.	toroidal CHERS	see above	R. Bell - PPPL
	H/D ratio, detachment signature, line emission	Integral; 10 ms	5% (rel)	Visible (VIPS) survey spectrometer	several sightlines coupled via fiber to 0.5 M Czerny-Turner; 3500-11000Å, CCD detector	C. Skinner, S. Paul - PPPL
	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
	$Z\geq6$ ions (C, O, Cu, Ne, Ar, Kr)	5 cm; 5 ms for impurities	15% abs	filtered poloidal soft x-ray arrays	1 vertical array (16 ch); 2 horizontal arrays (32 ch); discrete AXUV diode arrays	K. Tritz - JHU
		r/a~0.08, 100 ms	15% abs	TGI spectrometer	12 chord transmission grating imaging spectrometer; 10Å – 300Å CMOS detector	D. Stutman - JHU
		Integral; 90 ms	5% (rel)	EUV spectrometer (XUES)	Flat field grazing incidence spectrometer covering 10-60 Å	P. Beiersdorfer- LLNL
		Integral; 90 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 DC – 250 kHz toroidal DC – 2 MHz		low frequency Mirnov coils outside plasma	12 toroidal, 24 poloidal	E. Fredrickson - PPPL
		5 cm; < 300kHz bw		filtered poloidal sxr arrays	1 vertical array (16 ch); 2 horizontal arrays (32 ch); discrete AXUV diode arrays	K. Tritz - JHU
				fast tangential soft x-ray pinhole camera	uses various foils and apertures, phosphor and demagnifying image tube with PSIV camera ($5x10^5$ frames/sec for 300 frames)	B. Stratton - PPPL
		4 MHz		quadrature reflectometer	30, 42, 49 GHz	S. Kubota - UCLA
		500 kHz		Neutron scintillator array	plastic scintillators with PM tubes 1-ZnS; 3 BC400	L. Roquemore - PPPL
				dynamo probe on fast scanning midplane probe		J. Boedo - UCSD
	>20 kA total poloidal halo current	toroidal arrays of six coils at two poloidal angles, <1 kHz	5-10 kA	Wall halo-current sensors	Arrays measure magnitude and toroidal peaking of poloidal halo currents in vessel wall just outside of the CHI gap and just outside the outboard divertor.	S. Gerhardt – PPPL
High frequency instabilities (MHD, fast ion modes)	$\Delta B/B \leq 10^{-2}$, $\Delta n/n \leq 10^{-2}$, $n = 10 – 50$, $\Delta\phi \leq 10^{-2}$	5 MHz		Mirnov coils outside plasma	B_T and B_P	E. Fredrickson – PPPL
		5 cm; < 300kHz bw		filtered poloidal sxr arrays	1 vertical array (16 ch); 2 horizontal arrays (32 ch); discrete AXUV diode arrays	K. Tritz - JHU
	1.1, 1.5, 2.2, 2.5. 3.1 $x10^{13}cm^{-3}$	4 MHz		quadrature reflectometer	30, 35, 42, 44.5, 50 GHz	S. Kubota - UCLA
	$>2x10^{11}$ cm^{-2}	500 kHz	$2x10^{11}$ cm^{-2}	tangential interferometry, polarimetry (FIReTIP)	FIR laser with retroreflectors in 4 tangential chords (2 additional)	K. C. Lee – UC Davis
	$>2x10^{11}$ cm^{-2}	500 kHz	$2x10^{11}$ cm^{-2}	1 mm radial interferometer	1 mm reflected from center stack	S. Kubota - UCLA
Core turbulence	1.1-2.0 $x10^{13}cm^{-3}$	variable		correlation reflectometry	30-40 Ghz (core access for peaked low density profiles). Radial or poloidal correlation	S. Kubota - UCLA

	$2x10^{12}$– $3x10^{13}$ cm^{-3}	Up to 100 kHz, 9273 sweeps	~ 1 cm	reflectometry FM/CW	13 – 50 GHz swept; radial correlation lengths (can be used simultaneously with correlation reflectometry	S. Kubota - UCLA
		$-20\ cm^{-1} < k_r < 20\ cm^{-1}$, ΔR ~ 5 cm	Δn/n >0.1%	high-k scattering	tangential microwave scattering at λ= 1 mm, 5 detector channels viewing r/a ~ 0.3-0.8	E. Mazzucato - PPPL
	$k_\perp \rho_i < 1$	ΔR ~2 cm; 120 cm < R< 150 cm	Δn/n >0.1%	Beam Emission Spectroscopy	2 arrays viewing heating beams with 2-D (radial and poloidal) array of 32 detector channels	G. McKee-UW, B. Stratton-PPPL
Edge turbulence	10% -100% Δn_e, $\Delta\phi$	1.5 mm, 1 µs		fast scanning midplane probe	see above	J. Boedo - UCSD
	ΔT_e	1.5 mm, 1 µs		fast scanning midplane probe	see above	J. Boedo - UCSD
		~ 1 cm for r/a> 0.8, <500 kHz		gas puff imaging	Supported by gas puff manifold. Various fast cameras used	S. Zweben – PPPL, R. Maqueda - NOVA
	B, ΔB .01 – 100G	1 mm, 2 µs		dynamo probe tip on fast scanning probe	all components	J. Boedo - UCSD
	$k_\perp \rho_i < 1$	ΔR ~2 cm; 120 cm < R< 150 cm	Δn/n >0.1%	Beam Emission Spectroscopy	see above	G. McKee-UW, B. Stratton-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, R. Maingi – ORNL, C. Skinner - PPPL
		0.2 ms/frame		1D CCD cameras	2 lower divertor, 1 midplane CS, 1 radial horizontal view of lower divertor	V. Soukhanovskii – LLNL
		1.5 cm sightline separation		high resolution divertor fiber view	32 channels viewing inner and outer divertor from top, channel separation at divertor 1 – 3 cm. Used with filterscopes and visible spectrometers	V. Soukhanovskii - LLNL
Edge and SOL flows	Mach .1-2	1.5 mm, 1 µs		fast scanning midplane probe	see above	J. Boedo - UDSD
		1 mm, 2 kHz		Shifted-Wavelength Interference Filter Technique (SWIFT)	uses fiber views of gas puff manifold , requires helium injection	S. Paul - PPPL
Dust monitoring		1 kHz	sens. 1µg/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		quartz microbalances	four QMBs (Bay H top, Bay H bottom, Bay I midplane, Bay B midplane), 3 shuttered, Inficon XTM/2	C. Skinner - PPPL

Spectroscopic n_e , T_e in divertor		1.5 cm sightline separation		visible filterscopes viewing lower divertor	see above	V. Soukhanovskii - LLNL
n_e , T_e at target	3 - 50 eV			Langmuir probes	flush-mount probes embedded in carbon tiles (3 inner div, 4 outer div.- upper and lower, 8 on CS)	C. Bush - ORNL
Neutron source profile				neutron collimator	one-channel prototype being tested	L. Roquemore - PPPL
Neutron flux monitors		1 ms	5% rel. 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
RF driven surface waves				high-frequency Langmuir probe	located between antenna segments,	R. Wilson – PPPL, J. Wilgen - ORNL
Mode conversion efficiency of EBW emission				EBW radiometer	2 obliquely-viewing antennas ; 2 radiometers covering 8-18 GHz and 18-36 GHz	G. Taylor- PPPL J. Kaughman. 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: • top view of lower divertor • tangential view of lower divertor	L. Roquemore - PPPL
	Phantom 7.3-2048	>32x32	14 bit	190 kHz at 32x32		L. Roquemore - PPPL
	PSI V	64x64	12 bit	300 frames at 250 kHz		S. Zweben - PPPL
	Photron	>64x64	8 bit	<40 kHz		N. Nishino – U. Hiroshima

	Phantom	>64x64	12 bit	120 kHz continuous	• fish eye radial view of entire plasma • 3 tangential midplane views including one view near pellet port • view of gas puff manifold along B field	R. Maqueda - NOVA
First wall temperature	20-1200°C	30 Hz, 1 kHz; 15° FOV	5°C abs <1°C rel	IR Cameras	2 FLIR Omega and 1 FLIR Alpha compact µbolometer cameras (30 Hz) and one fast IR camera(1 kHz) with views of lower divertor, CS, and beam armor	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
		1 kHz		SFLIP	scintillator probe with energy and pitch angle resolution	D. Darrow - PPPL
Fast ion dynamics	$n < 5x10^{13}$ cm^{-3}	10ms, 5cm, 10keV		Spectrometer	Vertical views from bay A/B. Based on active charge-exchange spectroscopy: requires NB injection; MPTS and CHERS data needed for analysis	M.Podestà, UCI
		20us, R=100, 120,140cm		Energy-integrated signal		M.Podestà, UCI
Fast ion distribution	1-100 keV	2 msec	rel 5% 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 with 0.15µ Al foils and apertures, pulse height analysis	D. Liu, W. Heidbrink – UC Irvine

Appendix A - Table II. Systems Capable of Supporting Active Diagnostics - August 2008

(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	F. Levinton, J. Foley NOVA
Impurity Pellet Injector	Provide impurity population to enhance signals	solid pellets or dust, .5 – 10 mg per sabot, < 200 m/s, ≤ 8/pulse	pellet plume detector	H. Kugel - PPPL
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 SWIFT	S. Zweben - PPPL

Appendix B: FESAC Priorities Panel 10-Year Goals (as additional background information)	**Relevant NSTX Research**
Macroscopic Plasma Physics	
1. Understand the coupled dependencies of plasma shape, edge topology, and size on confinement in a range of plasma confinement configurations.	1. I-1
2. Identify the mechanisms whereby internal magnetic structure controls plasma confinement.	2. I-2,3
3. Identify the effects and consequences on confinement of large self-generated plasma current.	3. V-2, VI-1
4. Learn how to control the long scale-length instabilities that limit plasma pressure.	4. I-1, 2
5. Understand and control intermediate to short wavelength modes responsible for limiting the plasma pressure, particularly at the edge, and extrapolate their effects to the burning plasma regime.	5. III-2,3
6. Understand the equilibrium pressure limits in a range of magnetic configurations, including the effects of islands, stochastic magnetic fields, and helical states.	6. I-2, III-3
7. Understand and demonstrate the use of self-generated currents and mass flows to achieve steady-state high-pressure confined plasmas and improve fusion energy performance.	7. VI-1
8. Understand how external control can lead to improved stability and confinement in sustained plasmas in a range of magnetic configurations.	8. I-1,2, III-3
9. Understand the pressure limits and confinement properties in configurations where magnetic turbulence controls the distribution of the equilibrium magnetic field and for similar configurations with reduced turbulence. Assess their prospects for study in more collisionless plasma regimes for possible extrapolation to practical sustained burning plasmas.	9. V-1
Multi-Scale Transport Physics	
1. Develop predictive capability for ion thermal transport using simulations validated by comparison with fluctuation measurements.	1. II-2
2. Identify the dominant particle transport mechanisms, including the conditions under which pinch/convective processes compete with diffusive processes.	2. II-3
3. Identify the dominant mechanisms for momentum transport and their relationship to thermal transport.	3. II-2
4. Understand generation of flow shear, regulation of turbulence, and self-consistent profile dynamics and local steepening, and to identify conditions and thresholds for edge and core barrier formation.	4. II-1, 2, 3
5. Identify the dominant electron thermal transport mechanisms, including the role of electromagnetic fluctuations, short-scale versus long-scale turbulence, and spectral anisotropy.	5. II-1
6. Identify the dominant driving and damping mechanisms for large-scale and zonal flows, including turbulent stresses and cascades.	6. II-1, 2
7. Identify the dominant mechanisms by which turbulence generates and sustains large-scale magnetic fields in high-temperature plasma.	7. V-1
8. Identify the mechanisms and structure of magnetic reconnection, including the role of turbulent and laminar processes, energy flow, and the production of energetic particles.	8. I-2, V-1,2
9. Identify the conditions for onset of island growth and the factors controlling saturation and coupling with transport.	9. I-2
Plasma Boundary Interfaces	
1. Predict the expected magnetohydrodynamic stability and plasma parameters for the ITER H-mode edge pedestal with high confidence. This is a time-sensitive issue	1. III-1,3

Appendix B: FESAC Priorities Panel 10-Year Goals (as additional background information)	**Relevant NSTX Research**
relevant to the success of ITER	
2. Identify the underlying driving mechanisms for mass flow and cross-field transport in the scrape-off-layer plasma, in H-mode attached and detached plasmas.	2. III-2, 3
3. Resolve the key boundary-physics processes governing selection of plasma-facing components for ITER. This is a time-sensitive issue relevant to the success of ITER.	3. III-1,3
4. Complete the evaluation of candidate plasma-facing materials and technologies for high-power, long-pulse fusion experiments. This is a time-sensitive issue relevant to the success of ITER.	4. III-1,2,3
Waves and Energetic Particles	
1. Develop the capability to design high-power electromagnetic wave launching systems that couple efficiently and according to predictions for a wide range of edge conditions.	1. IV-1, 3
2. Produce, diagnose in detail, and model with nonlinear, closed-loop simulations the macroscopic plasma responses produced by wave-particle interactions, including localized current generation, plasma flows, and heating, in both axisymmetric and non-axisymmetric configurations.	2. IV-1,2,3
3. Develop long-pulse radio-frequency wave scenarios for optimizing plasma confinement and stability and to benchmark against models that integrate wave coupling, propagation, and absorption physics with transport codes (including microturbulence and barrier dynamics) and with magnetohydrodynamic stability models.	3. IV-1,3, V-2, VI-1
4. Improve analysis and models to match the experimental measurements and scale the understanding to predict the dynamics of energetic particle-excited modes in advanced regimes of operation with high pressure, inverted magnetic shear, and strong flow.	4. IV-2
5. Identify the character of Alfvén turbulence and the evolution of the energetic particle distribution in a nonlinear system, which can be used to predict alpha-particle transport in a burning tokamak experiment; and to evaluate and extrapolate energetic particle behavior in present-day confinement systems to reactor parameters.	5. IV-2
Fusion Engineering Science	
1. Deliver to ITER the blanket test modules required to understand the behavior of materials and blankets in the integrated fusion environment.	1.
2. Determine the "phase space" of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency and power extraction can be attained.	2.
3. Develop the knowledge base to determine performance limits and identify innovative solutions for the plasma chamber system and materials.	3. III-1, 2, 3
4. Develop the plasma technologies required to support U.S. contributions to ITER.	4. I-1, III-3, IV-1
5. Develop the plasma technologies to support the research program.	5. I-1, III-1, IV-1,3, V-1,2