NSTX Upgrade Program Letter for Research Collaboration Employing Innovative Diagnostics for FY 2016-2018

Introduction

This NSTX Upgrade (NSTX-U)[1] Program Letter provides updated information about NSTX-U research priorities and collaboration opportunities during the upcoming three years (FY2016-2018). This information is useful for the preparation of proposals in response to the Office of Fusion Energy Sciences Notice: *National Spherical Torus Experiment – Upgrade: Diagnostic Measurements of Spherical Torus Plasmas* issued July 2015. 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-U. These research areas are described in the NSTX-U Five-Year Plan for 2014-18[2], recent NSTX-U Program Advisory Committee (PAC) presentations[3], and the FESAC Facilities Report[4]. The NSTX-U PAC reviewed this Program Letter on June 23, 2015 and PAC recommendations were incorporated in this final version.[5]

Mission of NSTX-U

The *programmatic* mission of NSTX-U 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 the NSTX Upgrade Project[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-U also contributes to the physics basis for an ST-based Pilot Plant[9] and DEMO[10] devices and accesses unique plasma regimes for resolving key burning plasma physics issues anticipated in ITER. The NSTX-U programmatic mission thus addresses two of the strategic goals of the Office of Fusion Energy Sciences[11]: developing predictive capability and designing/deploying materials needed to support a burning plasma environment. In support of these goals, the NSTX-U facility has been judged as "absolutely central" as described in the recent FESAC report on the "Prioritization of Proposed Scientific User Facilities" for FES for 2014-2024.[12]

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[1] http://nstx-u.pppl.gov
[2] http://nstx.pppl.gov/DragNDrop/Five_Year_Plans/2014_2018/chapter_text/full_text/NSTXU_5YearPlan_text.pdf.
[3] http://nstx-u.pppl.gov/program/program-advisory-committee/pac-35
[4] http://www.ofes.fusion.doe.gov/more_html/FESAC/FacilitiesVol1.doc and FacilitiesVolume2_v3.pdf.
[5] http://nstx.pppl.gov/DragNDrop/Program_PAC/Program_Letters/ (available July 7, 2015).
[6] http://nstx-u.pppl.gov/nstx-upgrade
[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://nstx.pppl.gov/DragNDrop/Publications_Presentations/Publications/2011%20Papers/Menard_NF.pdf
[10] http://www.sciencedirect.com/science/journal/09203796/65/2
[11] http://science.energy.gov/fes/
[12] http://science.energy.gov/~/media/fes/fesac/pdf/2013/FESAC_Facilities_Report_Final.pdf.

In support of the above programmatic mission, the *scientific* mission of NSTX-U 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. Proposals that support collaborative research leveraging unique ST parameter regimes relative to other configurations and devices are strongly encouraged, and the NSTX-U research team carries out a substantial number of the ITPA joint experiments and/or joint data analysis activities each year. Example ongoing ITPA joint experiment / activity topics that particularly benefit from access to the unique ST parameter regime include: experimental identification of ITG, TEM, ETG turbulence and comparison with numerical simulation (TC-10), the ρ^* scaling of intrinsic torque (TC-17), the impact of resonant magnetic perturbations on transport and confinement (TC-24), the relative importance of thermal and energetic ion kinetic and rotation/rotation shear effects on global mode stabilization physics and control (MDC-21) and active disruption avoidance (MDC-17), critical edge parameters for achieving L-H transitions (PEP-26), and ELM control by pellet pacing in ITER-like conditions (PEP-30). Potential NSTX-U collaborators are strongly encouraged to propose and participate in these and other cross-device activities. For more information on past participation and future collaboration opportunities in ITPA involving NSTX-U, please contact the ITPA coordinator for NSTX-U: Stan Kaye (kaye@pppl.gov).

NSTX-U Research Priorities and Key Collaboration Opportunities

This section lists the high priority topics in the NSTX Upgrade research program during FY 2016-2018 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-U diagnostics, the associated measurement capabilities, and the person(s) responsible for the diagnostic.

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.

Upgrade Summary and Near Term Schedule:

NSTX Upgrade operation is expected to resume in fall of 2015. NSTX Upgrade is anticipated to provide access to plasma regimes of reduced collisionality, longer pulse duration, and increased overall plasma performance. To achieve these goals, the toroidal magnetic field, plasma current, and neutral beam injection (NBI) heating power have been increased by up to a factor of two, and the pulse duration will be increased by up to a factor of five. The diameter of the center-stack has been increased and the minimum plasma aspect ratio increased from 1.3 to 1.5. Further, the NBI power has been increased through the addition of a 2nd more tangential NBI. Several diagnostic ports have been modified, and port access may also be impacted by additional structural enhancements.

NSTX-U capabilities during the first few years of operation are presently planned as follows:

- It is expected NSTX-U will achieve field and current values 50% above NSTX values (i.e. up to 0.75T and 1.5MA) by the end of the first full year of operation (FY2016).
- Field and current values up to 100% higher than NSTX (i.e. up to 1T and 2MA) are expected by the end of the second full year of operation (FY2017).
- Pulse durations of up to 3-5s are also anticipated during the first 2 years of operation, but achievable pulse-lengths will depend on the effectiveness of particle control techniques and on the performance of the upgraded magnets and structural supports of NSTX-U.
- During the operational years of NSTX-U relevant to this letter (2016-2018), the new 2nd NBI should be available for the entire period.
- A new second switching power amplifier for independent control of all 6 mid-plane 3D field coils will be commissioned by the end of the first full run year.
- The divertor and first-wall will utilize graphite PFCs for the first run year, and a row of molybdenum tiles are planned for the lower outboard divertor for the 2017-2018 runs.
- Lithium coating coverage will be extended to the upper divertor and first-wall by 2016, and a granule injector for ELM control will be implemented during the first run-year.

Additional major facility enhancements have been proposed as part of the NSTX-U 5 year plan and will be implemented if sufficient resources are available. These enhancements include:

- A lower outboard divertor cryo-pump for improved density control is planned and would be available by the end of 2018.
- A partial to full set (12 to 24 coils) of off-midplane in-vessel non-axisymmetric control coils (NCC) is planned and would be available by the end of 2018.
- A 1MW, 28GHz gyrotron for ECH/EBW heating and current drive is planned and would be available by the end of 2017.

Note that the cryo-pump and NCC are presently highest priority and would nominally be installed during an extended outage that would be completed in late FY2018 or early FY2019.

The impact of the above schedule, performance, and device changes should be assessed and incorporated into all collaboration proposals.

The NSTX-U research priorities and key 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. It should be noted that proposals will be evaluated based on overall scientific quality at least as much as their relevance to the priorities indicated in this Letter. 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-U 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. Since the remaining available port-space is very limited on NSTX-U, the RoD author and research contact should also discuss and document port-space requirements for the proposed diagnostic (see Appendix B). Successful proposals requiring implementation of significant hardware on NSTX-U will further require a "Record of Agreement" (RoA) form to document hardware and interface implementation tasks and milestones. The URLs for the RoD and RoA forms are:

RoD: http://nstx.pppl.gov/DragNDrop/Program_PAC/Program_Letters/FY2016_Diagnostics/
RoA: http://nstx.pppl.gov/DragNDrop/Program_PAC/Collaborations/NSTX-U_record_of_agreement_Sept2012.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 capabilities and opportunities supporting this programmatic goal is provided here:

- Macroscopic Stability: Diagnostics aimed at measuring and understanding the impact of varied rotation, rotation shear, and fast-ion density profile on resistive wall modes, neoclassical tearing modes, and mode locking. Measurement of the plasma response to 3D fields is encouraged, as is the diagnosis of the disruption thermal quench, halo currents, and the development of disruption avoidance and mitigation techniques.
- Multi-Scale Transport Physics: Diagnostics supporting improved understanding of confinement scaling, electron and ion thermal, momentum, and impurity and particle transport at higher field and current are encouraged.
- Plasma Boundary Interfaces: Diagnosis of scrape-off-layer heat flux and particle control utilizing advanced divertors, edge response to non-axisymmetric perturbations, characterization of surface conditions and evolution for both low and high-Z PFCs, and material migration are encouraged.
- Waves and Energetic Particles: Measurements of fast ion distributions and Alfvén Eigenmode stability and fast-ion transport with varied instability drive are encouraged, as are measurements to elucidate the underlying physics of fast-wave power losses in the edge and interactions with fast ions.
- Plasma Start-up and Ramp-up: Measurements supporting Helicity Injection (HI) current formation and the underlying reconnection physics and plasmoid dynamics are encouraged.
- Advanced Scenario Development: Real-time diagnostics and algorithms for controlling internal profiles, divertor PFC temperature and heat flux profiles, and for plasma-internal precursor detection are especially encouraged.

Collaboration proposals integrating the comparison of experimental measurements with theory and simulation are especially encouraged to maximize the development of new predictive capability.

The collaboration opportunities highlighted below were determined on the basis of what the NSTX-U program considers necessary to support 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. *Study the plasma response to 3D magnetic field perturbations to better understand the role of kinetic effects (such as drift-kinetic damping, plasma rotation, and fast-ion population) in tokamak macroscropic equilibrium and stability.*

Background:

Magnetic feedback control with midplane 3D coils was used successfully and routinely on NSTX to control Resistive Wall Modes (RWMs) by detecting dual-field components of the dominant n=1 mode using poloidal and radial sensors. This capability will be retained on NSTX-U, but advanced capability including multi-mode and state-space control based on plasma response and full eddy current models are desired to improve RWM stability and to maintain high β_N and β_N / l_i above the no-wall stability limit for longer pulse-lengths. Previous NSTX research has established a new understanding of RWM and Ideal Wall Mode (IWM) kinetic stability by making quantitative correlations between experiment and theory/simulation. Rotation and rotation shear are key components to controlling and improving RWM and IWM kinetic stability, and both RWM control and rotation control will be more extensively tested utilizing independent control of each mid-plane 3D field coil (enabled by new switching power amplifiers – SPAs) and utilizing the second NBI system in various NSTX-U regimes including low ν^* and with different fast-ion populations. Rotation profile control can also modify internal mode stability including both internal kink and neoclassical tearing modes (NTMs). Tests of RWM and IWM theory with perturbative, self-consistent, and non-linear simulations will be important to achieve predictability for FNSF and ITER.

Opportunities:

- Perform internal measurements of the RWM and IWM eigenfunctions, 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. Perform experiments, analysis, and simulation to understand RWM kinetic stabilization, and IWM, internal kink, and NTM stabilization.

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 and neoclassical toroidal viscosity.*

Background:

NSTX research highlighted the importance of plasma response effects in the application of 3D fields to tokamaks. The understanding of resonant and non-resonant error field effects was improved using ideal perturbed equilibria for rotating plasmas, and error-field correction was successfully utilized using midplane coils. However, extrapolations to the next-step devices remain uncertain due to the complexity of parametric dependencies on collisionality and rotation. Locking physics understanding has improved in the core, but other layer dynamics (especially in the plasma edge) remains to be resolved to understand resonant 3D field effects. 3D neoclassical transport, such as neoclassical toroidal viscosity (NTV), is the key concept to understanding non-resonant 3D field effects and magnetic braking. NSTX research led to several NTV experimental and theoretical discoveries, and will be actively used and controlled to modify rotation and rotation shear to test and improve macroscopic stability. NTV physics itself, including kinetic resonance effects (such as superbanana-plateau behavior) should be more deeply investigated to optimize rotation feedback control and achieve predictive capability and optimized 3D field control in FSNF and ITER. Finally, expanded 3D field capability is essential to support better understanding and control of both resonant and non-resonant field components, and a new 3D coil set (non-axisymmetric control coils - NCC) is being designed and analyzed to assess new 3D physics capabilities.

Opportunities:

- Perform internal measurements of the rotating tearing mode and low-frequency/static island structure, measurements of the safety factor profile and rotation and rotation shear profiles, and measurements and understanding of mode triggering.

I-3. *Characterize the dynamics, avoidance, and mitigation of disruptions at low aspect ratio and high beta*

Background:

Multiple techniques for disruption detection and avoidance were explored in NSTX, and this research will continue on NSTX-U. Particular research success on NSTX was found in the areas RWM control, RFA analysis, and disruption prediction algorithms. In the future, global and kinetic stability physics and control models, with expanded sensor input, will be applied for disruption prediction; real-time implementation of these physical models and measurements will be attempted to improve disruption avoidance. The plasma dynamics resulting from the interplay of different stability controllers will be measured and simulated. In the area of disruption mitigation, it is critical to develop novel techniques of rapidly injecting large quantities of radiating material into the plasma, as this is the process being developed for mitigation in ITER. Examples of novel technologies may include massive gas injection (MGI) from multiple poloidal locations (divertor, off-midplane, midplane) or other means of achieving mass injection. Simulation capability that can produce validated models of these mitigation technologies shall be pursued where possible. NSTX also made significant progress in understanding halo current dynamics, including measurements of halo current rotation in the outer divertor. However, measurement and understanding of the global current structure and dynamics remains to be developed. Measurements of thermal loading during disruptions were not pursued on NSTX, but will be important in NSTX-U for projecting the transient thermal loading during disruptions in next-step STs. The knowledge gained in this research will improve knowledge of the physics and technologies required for disruption prediction, avoidance, mitigation (PAM) system in STs and tokamaks including ITER.

Opportunities:

- Diagnose disruption precursor onset and disruption evolution – especially the thermal quench and halo-current dynamics – including the impact of gas injection for disruption mitigation studies.
- Implement greater toroidal coverage measurements (up to 4 toroidal locations) of radiated power profiles to diagnose mode-induced toroidal asymmetries
- Develop and apply various MHD spectroscopy, observer techniques, and real-time profile controllers.

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

For more information contact Walter Guttenfelder (wgutten@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 energy transport*

Background:

NSTX results indicated 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. Non-linear gyrokinetic simulations of micro-tearing modes found a nearly linear dependence of the electron thermal diffusivity on collisionality – seemingly consistent with ST global confinement trends. Global and Compressional Alfvén Eigenmodes (GAE/CAE) 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/CAE instability drive, which could in turn change which modes dominate electron turbulent transport.

Opportunities:

- Develop, deploy, and utilize new diagnostics for investigating electromagnetic turbulence
- Implement and utilize a range of turbulence diagnostics to identify turbulence most correlated with electron thermal transport, and compare these measurements to appropriate simulations (linear and nonlinear gyrokinetic and Alfvénic)

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 turbulence*

Background:

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.

Opportunities:

- Measure and simulate ion-gyro-scale turbulence to understand the relationship between the flow and flow-shear and ion energy transport 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.

For II-1 and II-2 above, turbulence and transport diagnostics relevant to both the core plasma and H-mode pedestal region are encouraged.

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. NSTX results indicated that lithium evaporated onto the lower divertor surfaces of NSTX can act as an effective pump of hydrogenic species. Ion impurity transport was measured to be nearly neoclassical in NSTX and exhibited a particle pinch. ELM-free scenarios using lithium surface coatings often led to deleterious accumulation of impurities, and such results motivate additional research into impurity transport. Electron particle transport is also a very important consideration since the transport rates almost certainly exceed neoclassical, and the observed specific transport properties could help discriminate among different transport mechanisms. 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.

Opportunities:

- Diagnose electron, main ion, and impurity particle transport from the edge to the core, and linkages to inward momentum pinch physics.
- Utilize existing and/or any new main-ion and impurity edge particle sources (for example granule injectors and laser blow-off) for perturbative particle transport experiments.
- Perform cross-device comparisons of momentum and impurity transport

II-4. *Compare turbulence measurements with theory and simulation using a suite of micro-turbulence codes and advanced turbulence diagnostics*

Background:

It is important for both spherical and conventional tokamaks to develop reduced transport modeling capability to predict plasma profiles, which determine confinement scaling, MHD stability, and current profiles (from bootstrap and NBI/RF driven current). The validated transport models can be used to predict confinement scaling (to compare with results of II-1) and can also be used in self-consistent integrated modeling scenarios to study and develop advanced operating regimes, such as steady-state fully non-inductive scenarios. The highest priority focus is on electron temperature profile as it is potentially influenced by a large number of mechanisms. Ultimately, it is also desired to predict density and toroidal flow profiles self-consistently, as both profiles influence the underlying transport mechanisms. In addition, increasing emphasis will be placed on studying and modeling global, or non-local, effects due to the relatively larger ratio of gyroradius to machine size typical of spherical tori.

Opportunities:

- Validate transport models with NSTX and NSTX-U data and test the accuracy of transport solvers with priority on predicting electron temperature profiles.
- Assess the ability to predict flow and density profiles as model fidelity improves.
- As global turbulence simulations become more readily available, assess the influence of non-local effects.

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

For more information contact: Rajesh Maingi (rmaingi@pppl.gov)

Research Priorities:

III-1. Measure 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 in order 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. While heuristic models and some first-principles models have made progress in understanding the underlying causes of the SOL heat flux scalings, edge heat flux and transport and turbulence measurements remain vital to improving this understanding. To mitigate high heat fluxes, NSTX 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, high flux expansion divertors – namely the “snow-flake” and X divertors – have demonstrated substantial reductions in peak heat flux and impurity generation. Additional research on these 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.

Opportunities:

- Measure plasma kinetic profiles (density, temperature, flow), neutral density, and transport and turbulence in the SOL at the outboard midplane and in or near the divertor region.
- Diagnose divertor heat flux profiles, divertor plasma density and temperature, divertor neutral pressure, impurity density and radiation (especially for characterizing detachment), and measure divertor power and particle balance, and particles sources.
    - Utilize such diagnostics for power exhaust control – see Section VI-1.
- Participate in measurements, experiments, analysis, and edge fluid and/or kinetic plasma/neutral transport simulations to validate cryo-pump physics design activities, perform initial density control studies, and assess compatibility with H-mode pedestal and core performance and divertor power exhaust scenarios.

III-2. *Measure and analyze the surface characteristics of low-Z and high-Z plasma facing components (PFCs) including lithiated and non-lithiated divertor and first-wall PFCs, and relate these characteristics to the core and edge plasma confinement and stability 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. It is further noted that lithium has a significant evaporation rate at modest temperatures, leading to questions about maximum operating temperatures in long-pulse scenarios. Interestingly, experiments in FTU at elevated temperatures ~550˚C showed a strong evaporation into the local plasma, simultaneously with reductions in limiter heat fluxes. This suggests a potentially attractive operating regime may exist where strong local evaporation leads to a continuously vapor-shielded PFC. An experimental determination of the ultimate temperature limits for a liquid lithium PFC in the diverted configuration with good core performance is envisioned. NSTX Upgrade will continue to utilize lithium coatings for deuterium inventory control during the initial phase of Upgrade operation, a row of high-Z tiles will be implemented to provide a different substrate for lithium studies (albeit in a mixed material environment), and initial vapor shielding studies will be performed using lithium on the high-Z tiles.

Opportunities:

- Measure 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 high-Z PFCs, with a goal of relating PFC surface conditions to particle inventories during steady-state operation, ELMs, and disruptions.
- Utilize surface analysis diagnostics to identify in-situ between-shot chemical states and compositions of the coatings, and connect these results to stand-alone surface-science studies and to possible changes in plasma performance – for example changes in wall recycling and/or plasma confinement and stability.

III-3. *Measure and understand boundary plasma response to applied 3D magnetic field perturbations, high-frequency mass injection (pellets or granules), and other perturbations designed to control edge plasma transport and stability.*

Background:

NSTX made significant progress in characterizing pedestal stability and developing small ELM regimes, and continues to actively compare 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 were 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.

Opportunities:

- Diagnose H-mode pedestal profiles 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.
- Image/diagnose, analyze, and model/simulate granule/pellet trajectories, ablation, and subsequent particle transport and background plasma response.

III-4. Measure and understand the physics of material erosion and re-deposition in tokamaks.

Background:

The edge plasma of fusion devices continuously interacts with incoming neutral atoms resulting in a charge-exchange flux of high-energy neutrals that will impinge and sputter the first-wall, limiting its lifetime. Wall erosion is projected to result (for example) in thousands of kg per year of circulating material in a fusion power reactor. The eventual fate of the eroded material is presently unknown, and requires further study. An extensive set of spatially- and time-resolved photometrically calibrated spectroscopic measurements will be available on NSTX-U for evaluation of impurity fluxes. To interpret the measurements, knowledge of accurate atomic physics factors, such as ionizations per photon and photon emission coefficients, is needed for common NSTX-U impurities originating from plasma-facing component materials, surface contamination, or those seeded externally. The high power densities and particle fluxes achievable in NSTX-U should provide readily measurable erosion, and this is important for both understanding NSTX-U impurity generation and for projecting to future devices.

Opportunities:

- Perform measurements, experiments, analysis, and simulations to assess shot-to-shot erosion and re-deposition including (for example) interpretation of microbalance diagnostics. Evaluate the impact of high-Z PFCs on erosion and migration as such PFCs are introduced into NSTX-U.

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

For more information contact: Mario Podesta (mpodesta@pppl.gov)

Research Priorities:

IV-1. *Measure the distribution and transport of supra-Alfvénic fast-ions and the eigenfunctions and dynamics of Alfvenic instabilities to aid in the validation of advanced numerical models of fast-ion confinement relevant to ITER and FNSF (Fusion Nuclear Science Facility)*

Background:

A primary goal for Energetic Particle research on NSTX-U is to develop capabilities that enable reliable and *quantitative* predictions on properties of - and fast ion response to - unstable modes in future devices such as ITER and FNSF. For instance, although good progress has been made in understanding linear stability thresholds, self-consistent and reliable predictions of Alfvénic mode properties at saturation (e.g. stationary vs. bursting dynamics) still require extensive work from both experimentalists and theory/code developers. EP research on NSTX-U will benefit from the expanded range of plasma regimes enabled by the twofold increase in toroidal magnetic field and the addition of a second NBI system with more tangential injection. Knowledge of the fast ion distribution resulting from different NBI geometries (from more perpendicular to more tangential) is crucial to understand the device performance in terms of NB current drive and heating efficiency and the stability of the plasma to fast-ion-driven modes. When used in combination with NBI, RF injection can also result in large deviations of fast ion behavior from what is predicted by classical models. An initial characterization of the fast ion distribution performed in MHD-quiescent NSTX-U plasmas will be extended to higher performance scenarios, in which either RF injection or instabilities are expected to cause a departure of the fast ion behavior from classical. In this scenario, modes that - based on previous results from NSTX and other devices - can induce substantial redistribution and/or loss of fast ions will be targeted first. These include TAEs, Reverse-Shear AEs (RSAEs) and Energetic Particle modes (EPMs), as well as higher frequency Global/Compressional AEs. Experimental studies will benefit from the suite of fast ion diagnostics installed on NSTX-U. Two Fast Ion D-Alpha (FIDA) systems will provide time, space and energy resolved measurements of the fast-ion distribution; a vertical FIDA system more sensitive to trapped or barely co-going particles and a tangential FIDA system that measures co-passing fast-ions. FIDA measurements will be complemented by an upgraded solid-state Neutral Particle Analyzer array that measures co-passing and trapped fast-ions. Additional diagnostics supporting studies of fast-ion dynamics include neutron rate counters and a scintillator-based Fast Lost Ion probe.

Opportunities:

- Measure the fast-ion distribution function and fusion products in multiple spatial dimensions and with increased time resolution, and compare to classical slowing down and linear and non-linear fast-ion instability model predictions of the fast-ion confinement.
  - Assess the impact of fast ion transport and redistribution by Alfvén Eigenmodes on NB current drive and assist in 100% non-inductive scenario development.
- Extend the spatial and temporal resolution of fast-ion instability eigenfunction diagnostics to improve the prediction of fast-ion transport.
  - Compare measured mode properties (ω, k spectrum, radial structure) with predictions from both linear and non-linear codes such as NOVA, M3D-K, HYM.

- Using the above diagnostic capabilities, lead or assist in linear and non-linear Alfvén Eigenmode simulations for NSTX-U scenarios and compare with experiments.

IV-2. *Measure and simulate high-harmonic fast-wave (HHFW) power loss mechanisms including interactions with the plasma edge and neutral beam fast-ions with application to optimizing plasma heating and current-drive by the HHFW.*

Background:

High-harmonic fast wave (HHFW) coupling and heating studies on NSTX have identified a major loss of RF power that occurs along open field lines that pass in front of the antenna over the width of the scrape-off layer (SOL), and this RF power loss mechanism can significantly reduce the effective core heating efficiency. The fast wave heating efficiency was found to depend on the location of the critical electron density for the onset of perpendicular fast wave propagation (n_{ec}). 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 allowed fast waves to reliably heat electrons in deuterium H-mode plasmas in NSTX. These performance improvements motivated an upgrade to the 12-strap HHFW antenna system to a configuration with an RF feed at the top and bottom of each strap and a ground in the middle of the strap, instead of one RF feed at the top and a ground at the bottom. This upgrade was implemented to reduce the voltage on the antenna needed for a given coupled power. Record ST central electron temperatures (above 6 keV) have been achieved using the upgraded fast wave antenna, but the performance of the antenna upgrade has never been evaluated with little or no lithium coating present and following a boronization. Fast wave acceleration of neutral beam injection (NBI) fast-ions has previously been observed in NSTX plasmas, and additional research is needed to understand and minimize interactions between fast waves and NBI ions in conditions with reduced fast wave power losses in the SOL. In NSTX-U the increased magnetic field strength will enable greater exploration of the effects of the location of n_{ec}, while more detailed diagnostic measurements will confirm whether or not strong RF fields are present in the SOL. Further, SOL density control tools such as lithium coatings and divertor cryo-pumping will influence the location of n_{ec}. 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 that could decrease fast wave coupling efficiency and increase RF power loss in the SOL. HHFW acceleration of NBI fast-ions has also previously been observed in NSTX plasmas and is an additional mechanism that can reduce core electron heating and current drive. Further research is needed to understand and minimize HHFW-NBI ion interactions in conditions with reduced surface wave excitation.

Opportunities:

- Implement/utilize new or upgraded diagnostics (such as RF probes, IR cameras) to assess the performance of the fast wave antenna after boronization and with lithium coatings.
    - Assess antenna performance over a wide range of antenna phase and plasma current, toroidal field, and density.
    - Compare measurements to RF code predictions for RF power flows in the SOL.
- Utilize and/or extend the fast-ion distribution function diagnostics to measure fast-ion acceleration by the HHFW.
- Develop and validate models to 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)

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 approximately 200kA of plasma current 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. These favorable results motivate experiments and modeling with the goal of further increasing the helicity injection current. In NSTX Upgrade, helicity injection current drive is projected to scale favorably (linearly) with toroidal field and poloidal flux supplied by the injector coils. The toroidal field and injector flux will increase two-fold in NSTX-U. Thus, the generation of 400kA of closed-flux plasma current should be achievable and is projected to provide a plasma current suitable for NBI heating and current ramp-up. Recently, the formation of plasmoids has, for the first time, been demonstrated in simulations of NSTX CHI experiments, and preliminary (low resolution) camera images from NSTX experiments are qualitatively consistent with the simulations. Plasmoid instability could be the leading mechanism for fast flux closure, and thus understanding plasmoids may be necessary to predict how transient CHI scales as it is extrapolated to future (larger) devices with considerably larger amounts of poloidal flux, such as an ST-based Fusion Nuclear Science Facility.

Opportunities:

- 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.
  - Exploit upgraded NSTX-U capabilities including higher toroidal field, the new injector coils, and higher injector voltage (≤ 2-3 kV)
- Diagnose the reconnection region of transient CHI plasmas (flows, electric fields, current density), and improve diagnosis of non-axisymmetric features of CHI plasmas including plasmoid instabilities.
- Perform experiments, analysis, and simulation with the goals of increasing the closed-flux plasma current generated by CHI and improving understanding of reconnection processes.

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 a critical research objective for the ST. Current overdrive (from bootstrap and RF) is being pursued to provide non-inductive current ramp-up to current values compatible with efficient NBI absorption, heating, and current drive. In particular, in NSTX Upgrade, TRANSP/TSC simulations indicate the new 2nd NBI is predicted to be absorbed by a low-current (~400kA) plasma target and to be capable of ramping-up the plasma current non-inductively to 0.8-1MA. HHFW heating of low current H-mode discharges has achieved high poloidal beta and bootstrap current fractions up to 85% at 250-

300kA and central electron temperatures as high as 3keV. Higher HHFW heating power and resilience to ELMs will be pursued to optimize heating of plasma targets suitable for NBI ramp-up.

Opportunities:

- Diagnose the HHFW coupling, heating, and current drive for plasmas formed by CHI and for low-current ohmic plasmas that will serve as target plasmas for overdrive experiments.
- Measure the fast-ion confinement, Alfvén Eigenmode instability behavior, neutral beam current drive profile evolution, and total current profile evolution during non-inductive ramp-up using the new 2nd NBI of NSTX-U combined with HHFW.
- Participate in experiments, analysis, and simulation for plasma current overdrive.
  - Measurements and experiments that support time-dependent simulations of the impact of early auxiliary electron heating and the dynamics and stability of the plasma current ramp-up phase would be especially valuable.

VI. Advanced Operating Scenarios and Control – 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 control of NSTX-U advanced operating scenarios*

Background:

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 the current profile and/or rotation profile, and will also require 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. During the first few years of NSTX-U operation, emphasis will be placed on re-establishing baseline operating scenarios, extending scenarios to higher field, current, and pulse length, demonstrating 100% non-inductive current drive for at least a current redistribution time, and optimizing axisymmetric control - especially power exhaust and current and rotation profile control.

Opportunities:

- Develop diagnostics suitable for real-time reconstructions of the plasma current density profile and pressure profile.
  - Participate in scenario development for NSTX-U emphasizing control of high-elongation scenarios which may challenge vertical stability in NSTX-U.
- Develop diagnostics suitable for real-time measurements of divertor surface temperature and/or divertor radiated power for closed loop heat flux control.
  - Contribute to the development of control of strongly-shaped multiple x-point equilibria typical of snowflake and/or X-divertor configurations.

- 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 systems.*

Background:

NSTX-U will have an extensive set of real-time in-vessel magnetic diagnostics for the measurement and active feedback control of error fields, locked modes, and resistive wall modes. However, these external measurements may not be sufficient to detect internal disruption precursors, and therefore internal electromagnetic fluctuation diagnostics may be suitable or potentially essential for reliable disruption precursor identification. Further, additional safe plasma shut-down algorithms are being developed for 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. In addition to new diagnostics, real-time control algorithms will be required to both predict impending disruptions and automate the control response once a disruption is declared to be imminent.

Opportunities:

- Develop and utilize internal real-time diagnosis of electromagnetic (or electrostatic if applicable) fluctuations/perturbations associated with disruption precursors.
- Implement wide-angle infrared camera diagnostics to measure inner-vessel temperature evolution to identify any hot-spots, and assist in disruption energy accountability studies.
    - Utilize the results obtained to assess if any real-time global temperature diagnostics are required at high power, current, and/or long-pulse.

These diagnostic opportunities have strong synergy with the goal of improved understanding of MHD as described in Section I (Macroscopic Stability) of this letter.

Appendix A

NSTX-U Equilibrium Diagnostic Measurement Capabilities – January 2015

(black – available for experiments, blue – under active development)

Physics Measurement	Typical range and coverage	Spatial; Temporal Resolution	Typical Precision	Available Diagnostic Techniques	Comment	Contact
Coil currents	0-130 kA	follow pulse shape.	1.0%	Rogowski coil on buswork; Hall effect transducers at power supplies	For EFIT/LRDFIT equilibrium reconstruction	S. Gerhardt – PPPL
Plasma current, I_p,	0-2 MA	2-5 kHz sampling rate	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 2-5 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 1 ms		Solutions of the Grad-Shafranov Equation Constrained by Measurements	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	S. Gerhardt - PPPL
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	10 channels, Requires compact, radial DNB	Y. Sechrest, 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
	Compact array of microwave receiving antennas. Two antennas can be configured to launch microwaves for imaging reflectometry.	Measures plasma emission up to 40 GHz with sub-millisecond time resolution.		Synthetic Aperture Microwave Imaging (SAMI)	Measures EBW emission as a function of poloidal and toroidal angle, allowing high radial resolution measurements of edge magnetic field pitch. Also can be configured for imaging relectometry to measure edge plasma flows.	G. Taylor – PPPL R. Vann – University of York, UK
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	10 channels, Requires compact, radial DNB	Y. Sechrest, F. Levinton – Nova Photonics

NSTX-U MHD Instability Diagnostic Measurement Capabilities – January 2015 (black – available for experiments, blue – under active development)						
Physics Measurement	Typical range and coverage	Spatial; Temporal Resolution	Typical Precision	Available Diagnostic Techniques	Comment	Contact
Low (m,n) MHD modes, sawteeth, locked modes, and disruption precursors	$\Delta B/B = 10^{-4} - 10^{-1}$, (0,0)<(m,n) < (5,10)	2 MHz		Mirnov coils outside plasma, known as the "high-n" array	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	C. Myers-PPPL
		5 cm; < 300kHz bw		Filtered poloidal SXR arrays	2 arrays (32 ch); discrete AXUV diode arrays	K. Tritz, J. M. Burgos – JHU
		1 cm, < 10 kHz	5% (rel)	Tangential multi-color SXR arrays	5 color/ 20 spatial channels, AXUV diode arrays	K. Tritz, J. M. Burgos – JHU
	>2x10^{11} cm^{-2}	4MHz	2x10^{11} cm^{-2}	Tangential interferometry, polarimetry (FIReTIP)	FIR laser with retroreflector in 1 tangential chord at R_{TAN}=0.64 m	C. Domier – UC Davis, Y. Ren - PPPL
	Cut-off 1.1-7.0 x10^{13}cm^{-3}	2.5 MHz BW $\Delta r \sim$ 1cm		Quadrature reflectometer (MHD density fluctuation)	30-75 GHz, 16 channels	S. Kubota - UCLA
		250 kHz		Neutron scintillator array	Plastic scintillators with PM tubes 1-ZnS; 3 BC400	D. Darrow - 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, known as the "high-f" array	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, J. M. Burgos – JHU
	1.1-7.0 x10^{13}cm^{-3}	2.5 MHz BW		Quadrature reflectometer	30-75 GHz, 16 channels	S. Kubota - UCLA
	>2x10^{11} cm^{-2}	500 kHz	2x10^{11} cm^{-2}	Tangential interferometry, polarimetry (FIReTIP)	FIR laser with retroreflector in 1 tangential chord	C. Domier – UC Davis, Y. Ren - PPPL
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.	Y. Sechrest, F. Levinton – Nova Photonics
Disruption Halo Currents	0-1000 A	~10x~20cm tiles, 0.1 msec resolution		Shunt Tile Arrays	10 tiles in outboard divertor and 18 on center column	S.P. Gerhardt, PPPL

NSTX-U Electron Diagnostic Measurement Capabilities – January 2015 (black – available for experiments, blue – under active development)						
Physics Measurement	Typical range and coverage	Spatial; Temporal Resolution	Typical Precision	Available Diagnostic Techniques	Comment	Contact
Electron density line integral	>$2x10^{11}$ cm^{-2}	4 MHz	$2x10^{11}$ cm^{-2}	Tangential interferometry, polarimetry (FIReTIP)	FIR laser with retro-reflector in 1 tangential chord with R_{tan}=0.64 m	C. Domier – UC Davis, Y. Ren - PPPL
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, M. Coury – PPPL
	0.02-$1.6x10^{13}$ cm^{-3}	1 kHz		Reflectometry (SOL)	6 - 36 Ghz swept system, 1 kHz sweep rate	C. Lau - ORNL
Real time density for density feedback control	>$2x10^{11}$ cm^{-2}	5kHz	$2x10^{11}$ cm^{-2}	Tangential interferometry, polarimetry (FIReTIP)	FIR laser with retro-reflector in 1 tangential chord with R_{tan}=0.64 m	C. Domier – UC Davis, Y. Ren - PPPL
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, M. Coury – PPPL
	0.1-5 keV	1 cm, < 10 kHz	5% (rel)	Edge (r/a: 0.6-1.1) tangential multi-color SXR arrays	5 color/ 20 spatial channels, AXUV diode arrays	K. Tritz, J. M. Burgos– JHU
	0.1-5 keV	3 cm, < 10 kHz	5% (rel)	Core (r/a: 0-1.1) tangential multi-color SXR arrays	5 color/ 20 spatial channels, AXUV diode arrays	K. Tritz, J. M. Burgos– JHU

NSTX-U Ion Diagnostics Measurement Capabilities – January 2015 (black – available for experiments, blue – under active development)						
Physics Measurement	Typical range and coverage	Spatial; Temporal Resolution	Typical Precision	Available Diagnostic Techniques	Comment	Contact
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
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
	-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
	ExB flow Core plasma	5MHz BW $\Delta r \sim 1$cm		Quadrature Doppler Backscattering (DBS)	1 Channel, 96 GHz (2015) 4 Channels (2016)	S. Kubota - UCLA
		Measures plasma emission up to 40 GHz with sub-millisecond time resolution.		Synthetic Aperture Microwave Imaging (SAMI)	Compact array of microwave receiving antennas. Two antennas can be configured to launch microwaves for imaging reflectometry. Measures EBW emission as a function of poloidal and toroidal angle, allowing high radial resolution measurements of edge magnetic field pitch. Also can be configured for imaging relectometry to measure edge plasma flows.	G. Taylor – PPPL R. Vann – University of York, UK
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, Y. Sechrest - 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		2-3 cm, 0.2 ms		Toroidal bolometer array	Tangential view, 40 channels (AXUV diode arrays)	L. Delgado-Aparicio - 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	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
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, survey, impurity studies	Integral; 10 ms	5% (rel)	Ultraviolet-visible survey spectrometer VIPS-2	**3 (10)** sightlines coupled via fiber to 0.5 M Czerny-Turner; 350-1100 nm, CCD detector.	V. Soukhanovskii - LLNL
	Z≥3 ions (Li, B,	5 cm; 5 ms	15% abs	Filtered poloidal soft x-ray	2 horizontal arrays (32 ch); discrete	K. Tritz, J. M.

	C, O, Cu, Ne, Ar, Fe, Kr, Mo)	for impurities	15% abs	arrays	AXUV diode arrays	Burgos– JHU
		1 cm, < 10 kHz	5% (rel)	Tangential multi-color SXR arrays	5 color/ 20 spatial channels, AXUV diode arrays	K. Tritz, J. M. Burgos – JHU
		r/a~0.08, 10 ms	15% abs	TGI spectrometer	12 chord transmission grating imaging spectrometer; 10Å – 300Å CCD camera	K. Tritz, J. M. Burgos – JHU
		Integral; 12 ms	5% (rel)	EUV spectrometer (XEUS)	Flat field grazing incidence spectrometer covering 5-60 Å	P. Beiersdorfer-LLNL
		Integral; 12 ms	5% (rel)	EUV spectrometer (LoWEUS)	Flat field grazing incidence spectrometer covering 220-400 Å	P. Beiersdorfer-LLNL
		Integral; 12 ms	5% (rel)	EUV spectrometer (MonaLisa)	Flat field grazing incidence spectrometer covering 60-220 Å	P. Beiersdorfer-LLNL

NSTX-U Turbulence Diagnostic Measurement Capabilities – January 2015 (black – available for experiments, blue – under active development)						
Physics Measurement	Typical range and coverage	Spatial; Temporal Resolution	Typical Precision	Available Diagnostic Techniques	Comment	Contact
Turbulence	$k_{\perp}\rho_{I}<1$	ΔR ~2 cm; r/a~0.4 to SOL	$\Delta n/n$ >0.1%	Beam Emission Spectroscopy	2 arrays viewing heating beams with 2-D (radial and poloidal) array of 48 detector channels	D. Smith, G. McKee - UW
	$k_{\perp}\rho_{I}$ ~ 0.5-10 Density turbulence	5MHz BW Δr ~ 1cm		Quadrature Doppler Backscattering (DBS)	1 Channel, 96 GHz (2015) 4 Channels (2016)	S. Kubota - UCLA
	Cut-off 1-7 x10^{13}cm^{-3} $k_{\perp}\rho_{I}<1$	2.5 MHz BW Δr ~ 1cm		Quadrature reflectometer	30-75 GHz, 16 channels	S. Kubota - UCLA
	T_e < 200 eV	~ 1 cm for r/a> 0.8, <400 kHz	12 bit	gas puff imaging (GPI)	Supported by gas puff manifold. (Phantom 710 camera)	S. Zweben – PPPL

NSTX-U Boundary Diagnostics Measurement Capabilities – January 2015

(black – available for experiments, blue – under active development)

Physics Measurement	Typical range and coverage	Spatial; Temporal Resolution	Typical Precision	Available Diagnostic Techniques	Comment	Contact
Edge recycling and impurity influx		2 kHz	5% (rel)	EIES (filterscopes)	5 upper divertor, 5 lower divertor, 5 midplane inner wall. Filters include D-alpha, CII, CIII, He I, HeII, LiI, LiII, BII, OII	V. Soukhanovskii – LLNL
		36 kHz	5% (rel)	Filtered 1D CCD arrays	3 lower divertor, 2 inner wall, 2 upper divertor. Filters include D-alpha, D-beta, D-gamma, CII, CIII, CIV, LiI, LiII, HeI, HeII	V. Soukhanovskii – LLNL
		1 kHz or lower	5% (rel)	Divertor Imaging Spectrometer - DIMS	19 sightlines coupled via fiber to 0.61m Czerny-Turner; 350-1100 nm, CCD detector. Divertor ion temperature measurements (via Doppler broadening) under development.	V. Soukhanovskii - LLNL
		2 kHz or lower	5% (rel)	Divertor vacuum ultraviolet spectrometer SPRED	1 sightline; two gratings: 102-310 Å and 165-1650 Å , CCD detector. Real-time divertor feedback control signal under development.	V. Soukhanovskii - LLNL
		1 kHz or lower	5% (rel)	Divertor Control Spectrometer - DICS	26 sightlines coupled via fiber to 0.3m Czerny-Turner-Schmitt; 300-1100 nm, CCD detector. Real-time divertor feedback control signal under development.	V. Soukhanovskii - LLNL
		0.1 kHz	5% (rel)	Near-infrared spectrometer - NIRS	1 sightline via fiber, 3 NIR-optimized gratings, 0.5 m Czerny-Turner, InGaAs LN-cooled detector, 800-2400 nm. Presently at DIII-D.	V. Soukhanovskii - LLNL
		500 kHz or lower	12 bit	Divertor Control Camera	Horizontal divertor view with Phantom V1211. Real-time divertor feedback control signal under development.	V. Soukhanovskii, F. Scotti - LLNL
		Up to 100 kHz at 256x208 resolution	12 bit, 14 bit	Downward facing wide angle divertor fast cameras	View of lower divertor from Bay E-top (Phantom 710) and Bay J-top (Phantom 7.3).	F. Scotti – LLNL
		Up to 8 kHz at 256x256 resolution	12 bit	Upward facing wide angle divertor fast camera	View of upper divertor from Bay H-bottom (Miro 4).	F. Scotti – LLNL
		30 Hz, VGA resolution	8 bit	Two-color radiation-hardened intensified CIDTEC camera	View of lower divertor from Bay I-top	F. Scotti – LLNL
		30 Hz, VGA resolution	8 bit	Radiation-hardened intensified CIDTEC camera	Midplane view	F. Scotti – LLNL
		6 ms, 128x128	12 bit	Edge Neutral Density Diagnostic (ENDD)	Tangential view of outer midplane edge – Bay G CII filter	F. Scotti – LLNL
		190 kHz at 32x32	14 bit	Lower divertor tangential camera	Tangential image of lower divertor from Bay F (Phantom 7.3)	R. Maqueda – X Science
	350-900 nm range 0.08nm/pixel dispersion	5ms		Imaging Spectrometer at bay G bottom viewing upper Divertor (R=0.3-0.9m) and at bay J middle viewing central stack (Z=0-1.5m)	Monitor upper divertor and center stack with 16 sightlines separately (not simultaneously for both views) 16 sightlines via fiber to IsoPlane SCT 320 spectrometers and 512*512 detector CCD, monitor ratios of spectrally close C and Li lines	K.F. Gan-UTK, T.K. Gray-ORNL
Dust monitoring		Few seconds	1 mg/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	several Angstroms	Quartz microbalances	Four QMBs (Bay E top, Bay F bottom, Bay I midplane, Bay B midplane), 3 shuttered, Inficon XTM/2	C. Skinner - PPPL
Surface	<1 micron	Outboard		Materials Analysis Particle	Thermal Desorption Spectroscopy	J. P. Allain – U.

chemical state and composition		lower divertor. Single location intershot		Probe (MAPP) utilizes multiple surface-science measurement techniques to characterize a sample material exposed to NSTX conditions	(TDS), X-ray Photoelectron Spectroscopy (XPS), Low energy Ion Secondary Scattering (LEISS), and Direct Recoil Spectroscopy (DRS)	Illinois Urbana-Champaign
Target Langmuir probes	1 – 40 eV $10^{17} – 10^{20}$ m^{-3}	~1mm electrode heads poloidally distributed along center stack and outboard divertors		Classical interpretation yields n_e, T_e, V. Non-local interpretation yields additional V_p and EEDF	Proud probes distributed poloidally throughout machine. Up-down symmetric on outboard divertor target, inboard divertor targets and center stack column. Operated as swept probes and in Isat mode.	M. Jaworski - PPPL
Gas pressure at several locations				Penning gauges	1 in lower divertor, 1 in upper divertor, 1 in lower divertor with spectroscopy, 1 in inner lower divertor (organ pipe)	R. Raman – U. Washington, V. Soukhanovskii - LLNL
				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
Plasma TV (discharge monitoring)	Fisheye-view of vessel interior, complementing views from bays B and I	~1cm spatial resolution		Qualitative discharge and operations monitoring via in-vessel imaging.	Plasma TV (Miro 2)	M. Jaworski, S. Zweben
					RF antenna view (Phantom 4.1)	R. Perkins
First wall temperature	50-800°C	1.6 kHz 12° FOV 5 mm/pixel	5% typical	Fast, dual-band infrared camera at Bay G bot viewing upper divertor (R = 0.2 – 1.0 m). Calibrated to 4-6 µm (MWIR) / 7-10 µm (LWIR) intensity	SBFP ImagIR HgCdTe camera (128x128 pixels)	T.K. Gray, J.-W. Ahn - ORNL
	50-800°C	1.6 kHz 12° FOV 5 mm/pixel	5% typical	Fast, dual-band infrared camera at Bay H top viewing lower divertor (R = 0.2 – 1.0 m). Calibrated to 4-6 µm (MWIR) / 7-10 µm (LWIR) intensity	SBFP ImagIR HgCdTe camera (128x128 pixels)	T.K. Gray, J.-W. Ahn - ORNL
	20-800°C	30 Hz 40° FOV 4 mm/pixel >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.	J-W. Ahn - ORNL
	20-1200°C	30 Hz 18° FOV 2 mm/pixel	5°C abs <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.	R. Perkins – PPPL, T.K. Gray - ORNL
	0-2300°C	1 kHz 2 locations, 2 mm isolation	3% typical	Fast 'eroding' thermocouples	2 high speed, Type C eroding thermocouples at PFC surface. Located in the row 1 tile in the upper and lower inboard, horizontal divertor	T.K. Gray - 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	W. Blanchard - PPPL
RF driven surface waves				High-frequency Langmuir probe	Located between antenna segments,	R. Perkins – PPPL, C. Lau - ORNL

NSTX-U Energetic Particle Measurement Capabilities – January 2015

(black – available for experiments, blue – under active development)

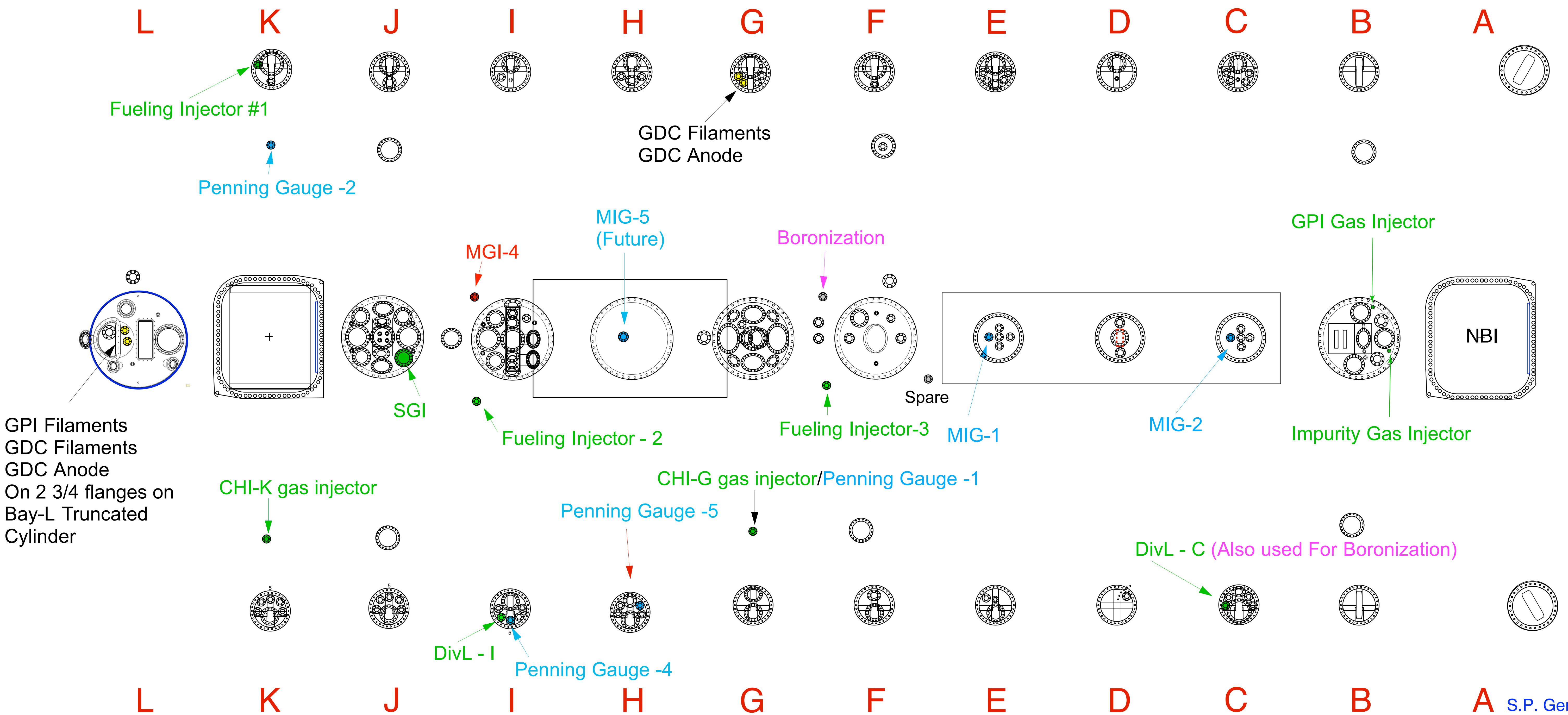
Physics Measurement	Typical range and coverage	Spatial; Temporal Resolution	Typical Precision	Available Diagnostic Techniques	Comment	Contact
Fusion source profile				Si diode detectors	6-8 channels planned	W. Boeglin – Florida Int'l U
Neutron flux monitors		1 ms	5% rel. 20% abs.	Fission chambers	4 U^{235} detectors with x26 sensitivity ratio	D. Darrow - PPPL
		4 μs	<5% rel.	Scintillator detectors	Plastic scintillators with PM tubes 1-ZnS; 3 BC400	D. Darrow - PPPL
Runaway electrons		10 ms	30%	Hard X-ray detector	At start-up and thermal quench	L. Delgado-Aparicio- PPPL
Fast Lost Ions				FLIP	Radial array of Faraday cups	D. Darrow - PPPL
		50 kHz	2° 3 cm	SFLIP	Scintillator probe with energy and pitch angle resolution	D. Darrow - PPPL
Fast ion dynamics and Fast ion distribution	$n < 5x10^{13}$ 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	D. Liu, G.Z. Hao, W.W. Heidbrink – UCI
		20μs, R=100, 120,140cm		f-FIDA - Band-Pass Filter/PMT (energy-integrated signal)		D. Liu, G.Z. Hao, W.W. Heidbrink – UCI
		10μs in current mode, 5cm, three energy bands [>25, >45, >65] keV		Solid state NPA system (t-SSNPA: subsystem at Bay I for active tangential views, r-SSNPA: subsystem at Bay L midplane for active radial views p-SSNPA: subsystem at Bay B for background passive signals)	15 tangential views with R_{maj} between 90-130 cm; 15 radial views with R_{maj} between 120-145 cm; 15 passive views; Si- diode arrays in current mode, 500kHz sample rate, ~100kHz bandwidth ; requires NB injection; MPTS and CHERS data needed for analysis	D. Liu, G.Z. Hao, W.W. Heidbrink – UCI

NSTX-U Systems Capable of Supporting Active Diagnostics – January 2015 (black – available for experiments, blue – under active development)				
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	Y. Sechrest, 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
Laser Blow-Off Impurity Injector	Provides low divergence source (pulse) of atomic impurities for transport studies	Midplane location, multi-pulse, multi-slide, 1 J laser outside NTC	Impurity spectroscopy	P. Beiersdorfer, 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 Alfvén waves to measure linear damping	5-turn radial loop antenna, ≤ 1 kW	Fast Mirnov Coil	E. Fredrickson - PPPL

Appendix B - to be updated...

Port Assignment for FY 2015 (Pressure measurement, gas delivery, GDC)

Many Port Cover Details Are Incorrect...See Diagnostic Drawing



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10-24-2014

Gauges and Injectors on Inner Vessel (see ED1324)

MGI #1: Lower 180 Degree Organ Pipe
MGI #2: Lower 15 Degree Organ Pipe
MGI #3: Upper 345 Degree Organ Pipe
Penning #3: Lower 240 Degree Organ Pipe

CS-Mid-125: 0.125" tube, Bay C
CS-Mid-250: 0.25" tube, Bay I
CS-Shoulder-125: 0.125" tube, Bay J
CS-Shoulder-250: 0.25" tube, Bay D (also boronization)

Gauges onTVPS Pumping Ducts :

Ion Gauge -1
Ion Gauge-2
Capacitance Manometer 1 (1 Torr)
Capacitance Manometer 2 (10 Torr)
Capacitance Manometer 3 (1000 Torr)
MIG-4 (On Duct...or maybe not any more...)
MIG-3 (On Bay K Spool Piece Flange, midplane)

Definitions

MGI - Massive Gas Injector
MIG - Micro Ion Gauge
DivU - Upper Divertor injector
DivL- Lower Divertor injector

GPI - Gas Puff Imaging
CHI - Co-axial Helicity Injection
SGI - Super Sonic Gas Injector
Penning Gauge