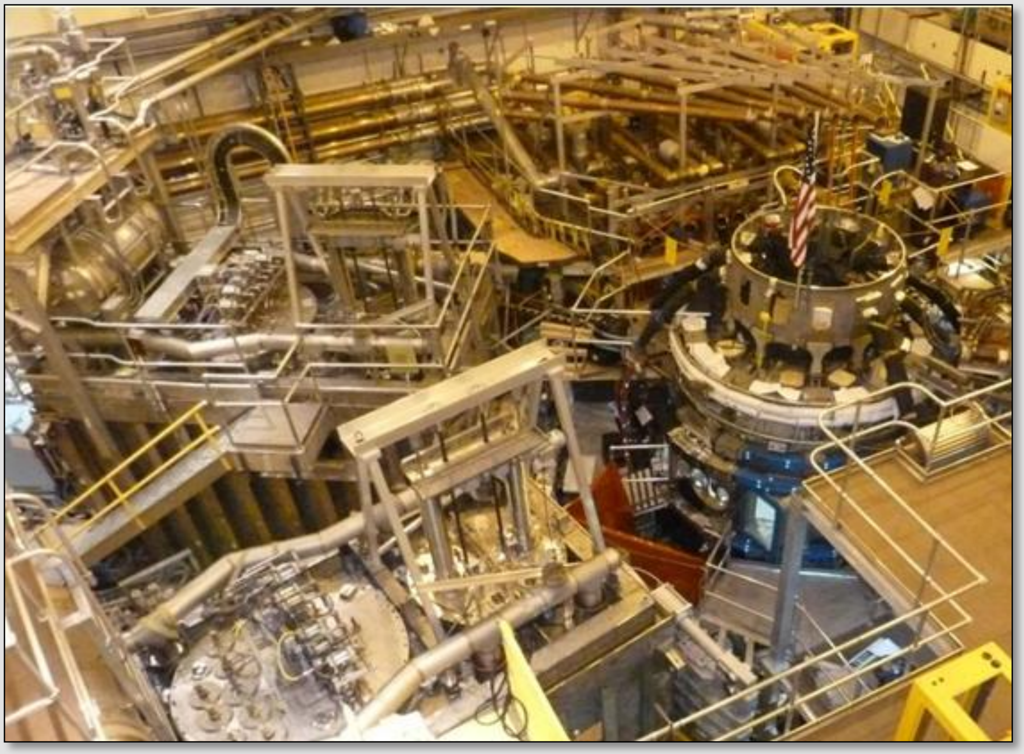
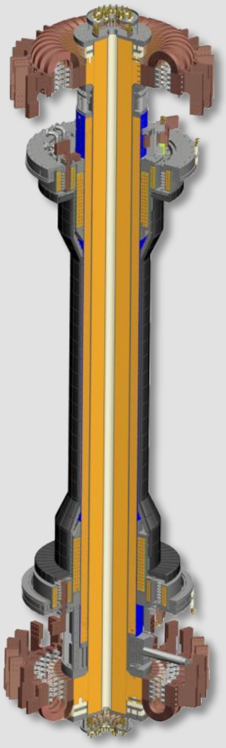
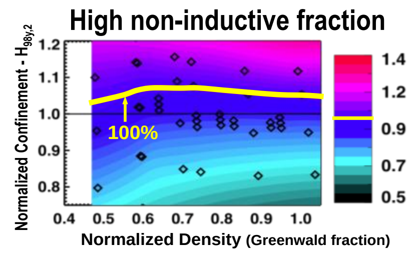
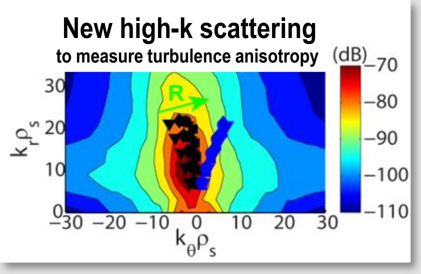
NSTX Upgrade Five Year Plan

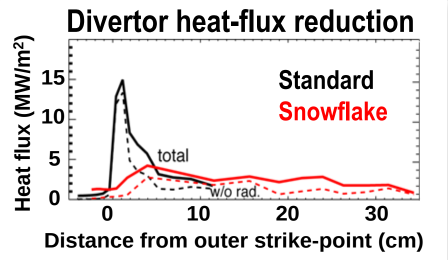
for FY2014-2018

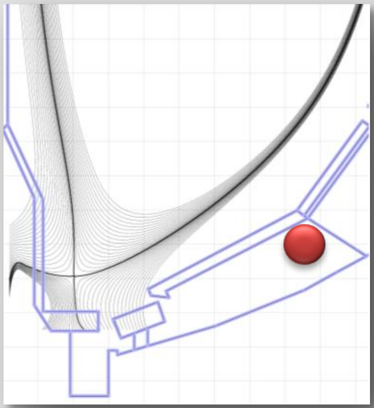


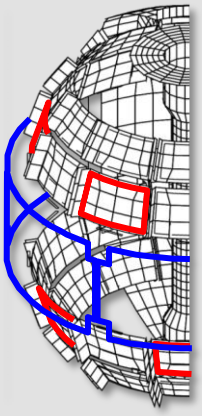


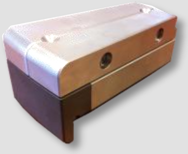


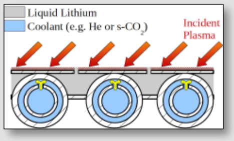












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PPPL

NSTX-U

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Executive Summary

The NSTX Upgrade 5 year research plan for FY2014-2018 will make major contributions to narrowing or closing key gaps on the development path towards fusion energy. Underpinning the proposed research program is the upgraded NSTX facility (NSTX-U) which will provide world-leading capabilities in the world fusion program. The mission elements of the NSTX-U research program are: (1) establish the physics basis for the spherical tokamak (ST) as a candidate for a Fusion Nuclear Science Facility (FNSF), (2) understand and develop novel solutions to the plasma-material interface (PMI) challenge, and (3) advance the understanding of toroidal confinement physics for ITER and beyond. Underlying all of these missions is access to a unique plasma physics parameter regime of high normalized pressure combined with reduced inter-particle collision frequency (collisionality) to address fundamental questions about plasma stability and turbulent transport, and greatly extend understanding of toroidal plasma science. *High-priority enhancements for both baseline and incremental budgets are italicized below*.

Establishing the physics basis for a Fusion Nuclear Science Facility (FNSF): An FNSF is arguably the critical major next step in the US fusion program, needed to establish the fusion nuclear science to enable design and construction of a fusion DEMO with acceptable risk. The ST is a potentially attractive candidate for an FNSF, offering the prospect of a compact design with reduced cost and tritium consumption – if the physics extrapolates successfully. NSTX-U will provide access to new physics regimes sufficiently advanced to provide the information for this critical decision on the optimal FNSF configuration. The increased magnetic field and improved beam injection geometry of NSTX-U will enable access to fully non-inductive current sustainment at high current and pressure as required for all steady-state tokamak applications. With the expected results from NSTX-U, the ST may be an attractive candidate for developing fusion component technologies such as blanket modules for thermal conversion and tritium breeding. With access to the highest magnetic field and heating and current drive power of any ST, NSTX-U will be the leading device in the world program to assess the viability of the ST for FNSF applications. The operating range of NSTX-U overlaps or connects to that of an envisioned ST-FNSF in the critical performance metrics of non-inductive bootstrap current, energy confinement enhancement factor, and normalized beta. A key challenge for the ST for the FNSF application is the need for non-inductive plasma formation and current ramp-up. NSTX experimental data has shown that auxiliary heating of helicity-injection start-up plasmas is very likely necessary to bridge the electron temperature gap between start-up (10-50eV) and temperatures projected to be necessary for over-drive ramp-up (0.3-1 keV). *Electron cyclotron heating (ECH) utilizing a 1MW 28GHz gyrotron appears particularly well-suited for heating low-temperature CHI start-up plasmas and is a high-priority facility enhancement for the 5 year period.* NSTX-U start-up and ramp-up data will be used to develop the solenoid-free tokamak/ST design needed for FNSF. If successful, it can also simplify the design of conventional reactors.

Understand and develop novel solutions to the plasma-material interface challenge: The increased heating power and compact geometry of NSTX-U will produce very high exhaust power flux prototypical of fusion reactors, requiring the development of solutions to handle these power levels at the Plasma-Material Interface (PMI). NSTX-U will explore novel solutions to the power exhaust challenge for FNSF and DEMO by testing extreme expansion of the magnetic field lines in a so-called “snowflake” divertor configuration, and by testing liquid metal plasma facing components (PFCs) to mitigate the erosion and melting problems associated with solid materials. The ability to explore very high exhaust power density, high magnetic expansion, and liquid metals in the same device is unique in the world fusion program. The operating range of NSTX-U overlaps or connects to that of an envisioned long-pulse ST-PMI or FNSF facility in the important performance metric of exhaust power flux. A critical enabling capability for accessing reduced collisionality and sustaining non-inductive current drive is control of main-ion and impurity densities. NSTX-U will continue to explore the use of lithium PFC coating techniques for enhanced plasma performance and divertor power and particle handling. In addition to increased lithium coverage, a lithium granular injector will be implemented for ELM pacing at high injection rate to control impurities and to reduce peak ELM heat flux. Presently more research is needed to determine if lithium-based particle pumping will extrapolate to the longer pulse-lengths and higher divertor heat fluxes of FNSF, or even NSTX-U. *In comparison, cryo-pumping is a mature technology and is projected to provide the necessary deuterium pumping capability for both conventional and snowflake divertor configurations in NSTX-U, and is therefore a high-priority facility enhancement for the 5 year period*. Cryo-pumping capability will also enable comparisons to deuterium pumping via lithium coatings, improving understanding of the potential longevity of lithium pumping, and of the impact of lithium on the edge and core plasma. This research will be aided by collaborative laboratory work and theoretical materials science to assess the surface chemistry and physics properties of plasma facing materials used in NSTX-U, and by testing of liquid metal solutions on the Magnum-PSI test stand in the Netherlands by NSTX-U researchers. *With incremental funding, the long-term NSTX-U plan to convert the PFCs from graphite to more FNSF-relevant metal walls would be accelerated, and tests of a flowing liquid metal divertor module would also be accelerated to develop replenishable lithium surfaces. Further, with incremental funding, divertor Thomson Scattering would be implemented to measure kinetic profiles near the divertor target to support power and particle exhaust model validation.*

Contributions to critical ITER physics issues: The unique operating regime of NSTX-U allows it to, in some cases, access directly regimes of interest for ITER that are beyond the reach of higher aspect ratio devices under normal operating conditions. One such area is Energetic Particle physics, where the new heating systems in NSTX-U will provide expanded ability to vary the velocity and spatial distribution of energetic ions in the plasma. These energetic ions can trigger bursting non-linear instabilities that can expel the same ions to the reactor walls. Similar non-linear instabilities may exist in the ITER hybrid and steady-state, reversed shear scenarios.

The requirement for stable plasma operation at high normalized beta combined with 100% non-inductive current drive for long-pulse operation motivates the development of an integrated, physics-based disruption prediction-avoidance-mitigation framework. This framework evolves from the disruption prediction system developed on NSTX, which to date identified 96% of the disruptions with sufficient warning for active mitigation. The framework and real-time control algorithms for this sophisticated system will be transferrable to that being developed for ITER. Planned NSTX-U studies of the density assimilation dependence on the poloidal position of Massive Gas Injection (MGI) for disruption mitigation could also potentially influence the design of the ITER MGI system if results are obtained early enough during NSTX-U operation.

NSTX-U will retain the NSTX set of six mid-plane non-axisymmetric (3D) field control coils which can be independently controlled to enhance plasma stability at high beta, control error fields, apply resonant magnetic perturbations for ELM control, and vary the rotation profile. Analysis for NSTX-U and data from other tokamaks (DIII-D, ASDEX-U, JET, MAST) shows that the addition of off-midplane 3D field coils in NSTX-U would enable much wider variation of the poloidal spectrum and mix of resonant versus non-resonant field components to improve the understanding of error field penetration, tearing mode triggering, resistive wall mode control, and rotation-damping by 3D fields. *To greatly expand the core and edge transport, stability, and rotation profile control in NSTX-U, an off-midplane array of 3D field coils is a high-priority facility enhancement for the 5 year period.* Understanding and controlling such 3D field effects will be critical for avoiding disruptions in both ITER and FNSF. Other specific areas of potentially strong contributions include radiative divertor solutions to the ITER-relevant heat fluxes expected on NSTX-U, and impurity transport using multiple conditioning and PFC scenarios to enable control techniques to be developed in impurity-seeded ITER plasmas.

Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement: The low aspect ratio of NSTX-U provides access to physics regimes and phenomena that are important to a moderate aspect ratio tokamak reactor, but less easily observed in the present tokamaks. Thus, NSTX-U can play a special role in the world tokamak program in model validation. Two examples include: (1) energetic particle instabilities where the high value of energetic ion velocity and pressure excite instabilities prototypical of a reactor, and (2) turbulence at high normalized pressure where magnetic fluctuations due to micro-tearing turbulence become significant and drive anomalous electron transport. Supporting electron transport theory validation is an extensive suite of profile diagnostics and a world-leading capability to measure both density turbulence from ion-to-electron gyro-scales, and magnetic fluctuations expected from microtearing modes. Boundary layer physics will be a major component of the NSTX-U program by necessity – the divertor heat fluxes will be comparable to those expected on ITER and FNSF. The strong toroidicity at low aspect ratio is found to have strong leverage in validating the theory governing the scaling of the boundary layer heat flux widths. The research program also includes novel magnetic divertor geometries such as the snowflake divertor and conventional reactor-relevant metallic PFCs. This major mission will be supported by a theory and modeling program aimed from "atoms to tokamaks," i.e., from atomistic modeling of liquid metals (and solids), by materials scientists, to scrape-off layer modeling with realistic boundaries.

NSTX-U facility and diagnostic capabilities and status, budget, user-base, and next-steps: Since the beginning of operation in FY2000, the NSTX facility has been the most scientifically and technically capable ST in the world fusion program. An upgrade to the NSTX facility was proposed in FY 2009 to provide a timely input for the FNSF construction decision, develop new solutions for the PMI, and better support ITER. The two main elements of the NSTX Upgrade Project are a new and more powerful center-stack and a tangentially-aimed 2nd NBI system. NSTX-U will double the toroidal field from ~0.5 T to 1 T, the plasma current from ~1 MA to 2 MA, the NBI heating and current drive power from ~7MW to 14MW at 90kV, and will greatly increase the plasma pulse length from 1-2 sec to 5-10 seconds. The tangential injection angles of the 2nd NBI enables much higher (~2x) plasma current drive efficiency and current profile control needed for fully non-inductive ramp-up and sustainment. NSTX-U will retain the previous 6 MW of High-Harmonic Fast Wave (HHFW) system for heating and current drive, and the total 20MW NBI and HHFW systems will allow NSTX-U to uniquely produce FNSF/DEMO relevant high divertor heat fluxes. The Upgrade Project is now in the final construction phase, is scheduled for completion in September 2014, and research operations are expected in FY2015.

The NSTX-U user facility has substantial national (245 total, 156 funded by DOE Fusion Energy Sciences (FES) grants) and international (61) researcher participation and supports many early career scientists including 13 post-docs and 33 students. The collaborating institutions will be providing and supporting approximately half of the over 50 state-of-the-art diagnostic systems on NSTX-U. Assuming the DOE-FES funding guidance for FY2014 through FY2018 (based on the FY2012 budget adjusted for inflation), NSTX-U will be able to operate for 15 weeks per year on-average. This funding level will also support the baseline facility enhancements described above. With a 10% increment above the DOE-FES funding guidance, NSTX-U will be able to support 18-20 weeks of plasma operation, and implement the majority of the major facility and diagnostic enhancements delineated in the five year plan including the incremental items described above. With incremental funding, the research budget for both PPPL and collaborators will also be enhanced by 10% to support increased facility operations and capabilities.

If the NSTX-U 5 year plan facility enhancements are implemented and the research goals achieved, the ST will be well-positioned to become a viable candidate for an FNSF, advanced approaches to mitigating FNSF/DEMO-relevant heat fluxes will have been demonstrated (for short durations), and predictive capability for next-step STs, ITER, and DEMO will have been significantly expanded. Further, NSTX-U/PPPL researchers and the wider ST community will be well-positioned to lead or contribute to any future larger-scale FNSF design activities.