NSTX-PMI: An Upgrade to NSTX-U for a PMI-Centered Mission

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Overall mission

Develop, understand, and demonstrate advanced strategies for controlling the plasma-material interface that are compatible with high performance fusion core plasmas

The ability of the facility to contribute to world-leading science

Grade: A - central

Taming the plasma-material interface is a grand challenge in magnetic fusion energy. The components of a fusion reactor directly facing the plasma present a *materials science* challenge:

(a) reliable operation for months to years, and over a range of temperature (500-1500 K),
(b) transfer of very high heat fluxes (about one-tenth that at the surface of the sun: 5-10 MW/m^2) to active coolants,
(c) maintenance of structural integrity during continuous and transient plasma wall interactions,
(d) sufficiently low retention of the fusion fuel (or should have the ability to actively remove the fuel),
(e) and acceptably low degradation of material properties under intense neutron radiation.

Taming the plasma-material interface also presents a *plasma physics* challenge: any plasma-material interface (PMI) solution must also be compatible with high edge and core plasma confinement and stability necessary for high fusion performance. There is presently no demonstrated PMI solution that meets the above requirements even for short durations. Obtaining a solution is a combined challenge in plasma physics and materials science.

Here we propose to upgrade NSTX-U to NSTX-PMI as a *cost-effective* way to develop and demonstrate candidate solutions for taming the PMI. This research problem must be solved to realize magnetic fusion energy, independent of magnetic configuration. This research would also significantly reduce risk and accelerate possible next-step fusion devices such as a fusion nuclear science facility (FNSF) or a steady-state PMI facility. Given the importance and interdisciplinary nature of this research, the user community is expected to be comparable or larger than that of NSTX-U (~300 total users), albeit with a broader range of expertise. The user community would encompass both plasma physicists and material scientists.

The planned research program for NSTX-U for 2014-2018 will provide unique capabilities in the world program to integrate high confinement and normalized pressure, high non-inductive current fraction, very high exhaust power density, high magnetic expansion, and initial examination of Mo/W plasma facing components (PFCs) and liquid metal PFCs in the same device for short durations (few seconds). However, the surrounding PFCs will not be thermally equilibrated in NSTX-U. We therefore propose to upgrade NSTX-U as follows:

(1) to longer pulse durations with intense heat flux to better evaluate PFC materials under nearly stationary thermal conditions more prototypical of a fusion reactor, and

(2) to test and investigate novel boundaries that offer breakthrough solutions such as liquid metal walls and expanded magnetic flux geometries.

As the PFCs themselves are an essential part of the research, we describe first the two classes of PFCs we propose to evaluate, and then the needed facility upgrades.

<u>*Gas cooled PFC materials*</u>

Tungsten (W) is considered the most viable 'high-Z branch' refractory metal for the PFC material in future machines such as ITER, because of its material properties such as high melting point and thermal conductivity, low sputtering yield and fuel retention rate, resilient thermal properties to the neutron irradiation, and absence of co-deposition and long-term activation. Several tokamaks have changed their PFC material from Carbon to W. However, these devices rely on inertially cooled PFCs, and are presently incapable of "hot-wall" operation. Due to the very high heat flux and extended pulse length (10 – 20 sec) in the proposed upgrades, NSTX-PMI would provide an excellent test of actively-cooled tungsten PFCs. This extended pulse length is estimated to be sufficient for thermal equilibration of solid or liquid PFCs. Because of the need to run the 'hot' wall while maintaining compatibility with liquid metals described below, water cooling is unsuitable and a gas cooled PFC design would be implemented. This requires high mass flow rate for adequate heat removal, which means high density at acceptable flow velocities and therefore high pressure. This requires a parallel and coordinated program of side lab experiments and component development. With an upgraded PMI diagnostic set, NSTX-PMI would provide measurements of W PFC performance, such as gross and net erosion rates, which will be needed to validate leading PMI models, enabling believable projections and designs for PFCs in next-step experiments.

To achieve this, all NSTX-U PFCs would be converted from graphite to W to enable clear comparisons between W and liquid metals. The W PFCs will also serve as a solid metallic substrate for liquid metals (see next item).

Liquid metals: Liquid metal boundaries are self-regenerating, thus resistant to erosion, immune to neutron damage, self-regenerating, and fatigue from thermal cycling. They are compatible with heat removal requirements with sufficient flow or by using thin layers on an underlying heat-removing substrate. Several liquid metals (Li, Ga, Sn) are leading candidates for the PFC of a confinement device, though each presents technological challenges. Li is attractive, with low Z=3 and chemical compatibility with iron and vanadium alloys as well as the refractory metals (such as W). Li evaporates at temperatures above 800 K, however and experiments demonstrating compatibility with good core confinement have not yet been conducted at elevated temperatures. Li further provides the possibility of controlling the fuel inventory of the fusion device through a strong chemical affinity for hydrogen. A liquid lithium boundary, absorbing to incident particles, offers the possibility of a reduced turbulence, improved confinement plasma regime, which could revolutionize the approach to the PMI, but only if it can be shown to be scientifically feasible from a materials, plasma physics, and fluid dynamics perspective.

Sn and Ga are both high-Z (Z=50 and 31 respectively) liquid metal options. Both have very low evaporation rates even up to temperatures as high as 1400 K. Both materials create technological challenges as they are incompatible with iron-base alloys, requiring the use of refractory substrates. Of the two metals, Sn has lower sputter yields. No diverted machine has operated with a high-Z liquid metal divertor target, and so compatibility with good core confinement would remain a central theme. The Sn-Li eutectic alloy is a 4^{th} option. Evaporation rates are reduced compared to pure Li; however there is evidence that the surface of the liquid metal is composed primarily of Li – potentially retaining the low-Z aspect of pure Li.

To test flowing liquid metals as a means of providing a replenishable PFC surface and for evaporative/radiative heat-flux mitigation, prototype capillary-restrained and slow-flowing thin-film liquid metal PFC modules will be developed and implemented in NSTX-PMI. Pending successful tests of the modules, a full toroidal coverage flowing liquid metal PFC will be implemented and tested.

Necessary Facility Upgrades - the upgrade from NSTX-U to NSTX-PMI will be accomplished by implementing the following facility and diagnostic capabilities:

1. To provide access to high power density with nearly thermally equilibrated divertor and wall conditions, the neutral beam injection pulse-length at full power (15MW) would be extended from 1-2s to 10-20s by upgrading the NBI ion dumps, scrapers, ducts, and ports.
2. Since plasma surface interactions are highly temperature sensitive, and PFC recrystalization or melting temperature limits must not be exceeded. Given the increased divertor energy throughput (up to ~300MJ), the divertor PFCs would be upgraded to be actively gas-cooled during a shot, including active heating between pulses to maintain divertor PFC temperature.
3. To increase the first-wall PFC temperature to a fusion-relevant range and enable controlled melting/solidification of liquid metals, the first-wall structural supports of NSTX-U would be upgraded to be actively heated to up to 600-700 K using the NSTX-U bake-out system.
4. To support the development of a predictive capability for the divertor and first-wall performance, the NSTX-PMI diagnostic set would be expanded to include: edge Thomson scattering for enhanced spatial resolution in the pedestal region, divertor Thomson scattering for plasma density and temperature near the divertor target, full-toroidal-coverage front-face temperature and heat flux measurements, high spatial resolution bolometry and absolute intensity calibrated spectroscopy for radiation and power-balance, an upgraded in-situ materials probe moved closer to the divertor strike-point, and wide-coverage surface diagnostics to measure surface composition and material migration.

<u>The readiness of the facility for construction</u>

Grade: B - Scientific/engineering challenges to resolve before initiating construction

High-Z tiles – Grade B: PPPL has recent experience in analysis, design, and fabrication of TZM divertor tiles for NSTX and this expertise would be applied to NSTX-PMI. Water-cooled W monoblock will be tested on EAST and similar designs could be implemented on NSTX-PMI. W coated C tiles have been successfully utilized on ASDEX-U at low temperature. Gas-cooled W or TZM PFCs are needed for compatibility with liquid metal PFCs, and would require significantly more R&D.

Flowing liquid metal (LM) PFCs – Grade B: Component mission/performance requirements have been defined, and prototype flowing thin-film Li PFCs have been tested on HT-7, and capillary systems tested on FTU and several Russian tokamaks and linear/e-beam test facilities. However, substantial flowing lithium loop R&D must be carried out prior to implementing a flowing liquid metal PFC in NSTX-PMI.

NBI pulse-length upgrade – Grade B: NBI ion dump, scraper, duct, and port upgrade designs were carried out for very long pulses (~1000s) for the TPX experiment, and KSTAR is using similar long-pulse NBI technology and could contribute to NSTX-PMI NBI pulse-length extension design (target: 10-20 sec).

Hot first-wall and divertor upgrade – Grade B: The disruption and thermal loading analysis of the first-wall passive plates carried out for NSTX-U would be extended to higher operating temperature, and structural requirements determined for operating at higher wall temperature.

PMI diagnostics – Grade B: Each of the proposed diagnostics has been utilized before on NSTX/NSTX-U or other tokamaks, so this is largely an interface problem, although the higher PFC temperature and potential window coatings could introduce new challenges.

Estimated construction and operations cost of the facility

Notional start year:	Design work FY14-17, construction and installation FY18-19
Construction costs:	Total project cost (TPC) = $60-120M
Operations costs:	$35-40M/yr (operations), $25→30M/yr (science) for FY19 → FY23
Termination costs:	N/A

Context of facility relative to world efforts

NSTX-PMI would be the only facility in the world with a broadly based liquid metal PFC program, at divertor loading parameters P/R~16 and P/S~0.5 amongst the highest in the world.

Scientific community considerations

The FESAC Priorities, Gaps and Opportunities Report (2007) identified "Taming the Plasma Material Interface" as one of the three highest priority research areas to be addressed for next-step devices for fusion energy science. In the report of the FESAC Toroidal Alternates Panel (2008), the report identified several technical challenges for the ST configuration and prioritized mitigating first-wall heat flux as very high (second highest) priority for the ST – consistent with the high importance of PMI for magnetic fusion generally. In the Report of the Research Needs Workshop (ReNeW) (June 2009), one of the five research themes used in organizing the research needs for the U.S. fusion research program is "Theme 3: Taming the plasma-material interface". This theme contains three thrusts (Thrusts 9-11), and all three thrusts of this theme are strongly supported by the proposed NSTX-PMI. A fourth thrust: "Thrust 12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma" is a central goal of NSTX-PMI, and NSTX-PMI results could help provide prototypical PMI solutions for subsequent and far more extensive testing in a dedicated steady-state PMI integration facility should such a facility be built and operated. This NSTX-PMI proposal is also highly responsive to the FESAC report on Materials Science and Technology Research Opportunities (2012) which recommends for taming the PMI that: "P1. Significant confinement plasma science initiatives are required to provide any confidence in the extrapolated steady and transient power loadings of material surfaces for a FNSF/DEMO" and "P2. The leading FNSF/DEMO candidate solid material to meet the variety of PFC material requirements is tungsten due to its projected erosion resistance, high melting temperature and high thermal conductivity."