High-Power Divertor-Tokamak Experiment (HDTX)*

Mission (absolutely critical, A) – Develop the scientific understanding and key innovations urgently needed to achieve a viable solution for the interaction of high-power fusion plasmas with surrounding surfaces at reactor-relevant conditions and time scales.

I. Research Summary – While fusion energy could serve as a limitless energy source, it is widely recognized that a solution to the interaction of the plasma with surrounding material surfaces is urgently required [1,2]. HDTX would be a new research facility designed to address the science underlying three critical issues for plasma-material interactions (PMI) under reactor-equivalent conditions:

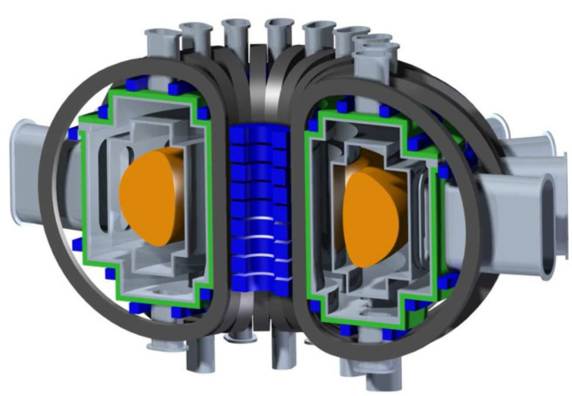
a) Material Control: Develop understanding and control of plasma-facing component (PFC) material erosion, transport and redeposition consistent with PFC lifetime. Understand the role of waste (e.g. dust, 'slag', evaporated liquids) in affecting operation and performance.

b) Fuel Control: Develop understanding and control of retention of hydrogenic fuel ions in PFCs, and exhaust of helium ash to project that acceptable tritium inventories can be achieved.

c) Heat Control: Develop understanding and control of the very high heat flux emerging from a reactor-class fusion plasma, to allow dissipation of the reactor plasma heat effluent consistent with high performance of the core plasma.

High power and particle fluxes, fluences and duty factors, far beyond those to be provided in any existing facility, are required to address these issues. Physics solutions aimed at each of the above issues have been proposed and some are being tested separately, at reduced parameters. This research is very important, but HDTX will be the only facility, worldwide, capable of addressing all of these issues, in an **integrated** fashion, at reactor-equivalent plasma and first-wall conditions. *Such a program of research would leapfrog the US beyond our international partners in providing answers to essential reactor feasibility questions. We note that all of the science understanding gained by the research on HDTX would be applicable to the ST and most would be applicable to the stellarator fusion concept.*

II. Facility Description: Recent multi-machine studies of the SOL parallel heat flux width [3], λ_q, show that high magnetic field and small size optimize the achievement of reactor-level parallel power and particle fluxes towards PFC surfaces, providing the appropriate test environment needed to address the PMI issues cited above. The Vulcan design [4] (see figure) (a = 0.3m, R = 1.2m, B = 7T) provides an appropriate geometry and field, but further optimization will occur in the Conceptual Design phase of the project. Very high power will be required to achieve reactor-relevant power and particle fluxes. The facility will have steady-state coils, likely superconducting, with a combination of external current drive and internal bootstrap current to allow long pulses and high duty factor. A reactor-temperature first wall, ≥ 800K and deuterium fuel, are needed to address the mission issue of fuel control.



More detailed characteristics of the facility are derived in the following from the three mission issues enumerated in Section I:

a) Material Control: Campaign-averaged measurements in existing experiments of the net erosion at tungsten divertor strike points are ~ 0.1 nm/sec [5,6], corresponding to 3mm/burn year or 60 kg/m^2. Given reactor divertor PFC thicknesses of 3-5 mm, we require a net erosion rate of < 0.01 nm/sec to project to ~2 years of reactor operation. Of equal concern is the predicted erosion of the thin ferritic steel inserts covering blanket modules of ~4 mm/burn year [7]. Where will eroded material accumulate? What is the effect on the properties of a surface dominated by re-deposited material? Conversely, will dust form and constitute a safety and/or operational concern? There are analogous issues for liquid-metal PFCs.

   To study and measure the net erosion as well as material migration we estimate that, at best, in-situ diagnostics will be able to assess surface evolution with a resolution of 100 nm [8]. Then a single successful discharge at 0.01nm/sec erosion rate will require at least 10,000 seconds to measure the peak erosion or re-deposition, and 10^5s, perhaps in repeated pulses, for sufficient resolution of the profile shape. Operation at 20% duty factor would allow 600 10^4 second discharges per year, enough for a diverse, well planned, research program.

   It would seem that total net erosion and deposition would only depend on the total integrated operational time allowing 'chained' short discharges. However, cyclic thermal stress could lead to changes in material properties including flaking, suggesting discharges of order 10^4 s.

b) Fuel control: Studies of hydrogenic retention will require reactor-relevant hot walls ≥ 800K and deuterium operation (allows retention analysis). HDTX research should explore the physics of fuel retention to demonstrate in-vessel inventory (reactor-equivalent) of < 1 kg. Long pulses are ideal to assure that the initial surface retention is small compared to during the pulse, and to minimize fuel loss from PFCs between pulses. A second concern, which requires further analysis, is that repeated pulses, and accompanying thermal cycling, affect diffusion of hydrogen within high-Z components, and on the chemistry of liquid metals.

c) Heat Control: There are many possible ways to compare the heat load difficulty of HDTX with that of a reactor. A simple one is P/S, the surface power density averaged over the first wall. Another is P/R, the power that must be dissipated per unit length along the divertor. Recent results [3] show that the radial width of the heat flux footprint scales about as $(a/R)/B_p$. If this is combined with the standard formula for the parallel heat flux, $q_{//} = PB/(4\pi R\lambda_q B_p)$ we find $q_{//} \propto PB/a$. We find that for a device of the size of Vulcan, powers up to ~ 40 MW may be required to match reactor parameters closely enough (see Table).

Tokamak operation is replete with examples showing that lowering [9] (raising [10]) recycling at PFCs enhances (degrades) core confinement. It is essential to understand whether changes in recycling, corresponding to reactor temperatures and/or liquid metals, significantly affects the core performance.

It is clear that extensive core and divertor plasma diagnostics will need to be fielded on this device, with special emphasis on the scrape-off layer and divertor plasmas. Equally important, very extensive in-situ and, as far as possible, real-time surface-analysis diagnostics will be required, with wide coverage.

Considerable flexibility will be required in the magnetic and divertor configuration to allow the study of different divertor configurations (e.g. super-x vs. vertical plate) as well as PFC material (tungsten vs. liquid metal), unless near-term experiments make that down-selection for us.

Integrated control of the plasma will be critical as well. Dependable and efficient current drive, consistent with clean, high performance plasmas and optimal divertor dissipation, is necessary to achieve the high duty factor required for high fluences. Avoidance of disruptions and mitigation of other transients will be needed as well.

HDTX will provide an incentive to develop engineering capabilities that will ultimately be required for fusion power reactors: Launchers for heating and current drive, PFCs (plasma-facing materials, mounting techniques, liquid metal technology), high effective current density superconductor configurations, remote handling and advanced cooling for high temperature operation. Experience in these areas would enhance our capability to build any next step device.

III. Facility impact beyond FES mission - Technologies for handling of high heat flux are important in areas as diverse as radio-frequency generators and rocket nozzles. New approaches developed in the context of HDTX could have wide applicability.

The applicability of fusion for neutron production and commercial fusion energy would be advanced by HDTX's critical contributions.

IV. Scientific Community Considerations - The need for a PMI-focused facility has been emphasized in multiple community studies over the past 5 years. The FESAC Priorities, Gaps, & Opportunities report [1] highlighted the fact that PMI contained substantial gaps in the step from ITER to DEMO. This was re-iterated in the ReNeW strategic planning; specifically the need and concepts for a PMI-based facility were highlighted in Thrust 12 [2], which set as an action:

"Develop design options for a new facility with a demo-relevant boundary, to assess core-edge interaction issues and solutions. Key desired features include high-power density, sufficient pulse length and duty cycle, elevated wall temperature, as well as steady-state control of an optimized core plasma…Develop an accurate cost and schedule for this facility, and construct it"

Several of the grand challenges and recommendations in the PMI area were specified in the Zinkle report [11], including the need for a facility with the main mission elements proposed here. Finally the Rosner priorities panel ranked PMI control amongst the highest priority scientific elements in the ReNeW thrust portfolio [12], and advocated a facility with these mission elements in the Charge 3 response [13]. The European fusion roadmap [14] assessed the solution of the PMI challenge in very strong terms, "A reliable solution to the problem of heat exhaust is probably the main challenge towards the realisation of magnetic confinement fusion."

V. Context of the facility in the world effort: HDTX is clearly distinguished from the Asian superconducting divertor tokamak facilities (see Table) in terms of power density, pulse length and duty factor. HDTX will also have the unique features of a hot vacuum vessel and PFCs, necessary for material and fuel control studies, and shielding for extensive DD operation, necessary for high performance plasmas and fuel control.

Device Capabilities based on ReNeW [2] and FESAC International Collaboration Report [15]

	HDTX	EAST	KSTAR	JT-60SA	ITER	ARIES-AT
P_{HEAT}/A [MW/m^2]	1-2	0.55	0.38	0.21	0.21	0.85
P_{HEAT}/R [MW/m]	20-40	13	12	14	28	75
$P_{HEAT}B/a$ [MWT/m]	500 – 1000	270	200	80	340	1400
Pulse-length [s]	10,000	1000	300	100	2500	10,000,000
Duty factor	20%	0.65%	0.32%	0.46%	3.2%	75%

Linear plasma devices, such as Magnum-PSI, will provide important information on PMI physics, particularly in fuel control at normal incidence where the fluxes may approach those of HDTX. However, the lack of reactor-level parallel heat flux and tokamak geometry (field line angle and SOL) undercut the contributions to erosion and redeposition studies, not to mention effect on core impurity levels and transport. The very different parallel heat flux mechanism (convection vs. conduction) makes such a device inappropriate for development of divertor configurations (e.g. compare Super-X to vertical plate geometry).

Research on HDTX would lower the risk of any pre-Demo facility and could potentially allow the next step to be a Pilot plant or Demo consistent with the recent EU Roadmap [14] where it is stated that a "dedicated test on specifically upgraded existing facilities or on a dedicated Divertor Tokamak Test (DTT) facility will be necessary" (before Demo).

HDTX has strong advantages in terms of overall cost, risk and speed of acquiring solutions compared to doing these studies in the first phase of an FSNF. To meet its eventual nuclear mission, the first-phase PMI FNSF would have to be significantly larger affecting costs and heating requirements. Like HDTX, it would need the flexibility to handle multiple materials and divertor and magnetic configurations. Each PMI solution or actuator change would be much more expensive and take longer to implement than on HDTX. *Achieving the fuel control goals of HDTX would greatly strengthen the case for obtaining the tritium site permit for any next step device*. Proceeding directly to the first-stage non-nuclear FNSF probably means acquiring the site and building the first phase without such a permit. **We deem that highly risky**.

VI. Construction cost estimate: Using the scaling developed for the FIRE device [16] a 1.2m machine yields a capital cost estimate of ~$600M in current dollars ($20B for ITER).

There is potential for cost sharing with international collaborators by, for example, leveraging the EU interest in a DTT facility. We should welcome such collaboration, but the U.S. should seize this opportunity to take world leadership in this scientifically rich and technologically challenging area, that is recognized internationally as central for the success of fusion energy.

Operation costs should be similar to current leading tokamak experiments, with the exception of the electricity cost for high duty factor operation of high-power systems. We estimate that the yearly operating cost could be in the range of $100M.

VII. Readiness of the facility concepts (Based on existing design studies – between grades A and B) - Two pre-conceptual studies, Vulcan [4] and NHTX [17], have been previously completed for devices with the mission elements discussed here, one at higher aspect ratio with superconducting coils, and another at lower aspect ratio with water-cooled copper coils. Given the recent results on scaling of SOL heat flux width, the HDTX design will benefit from both of these studies, likely heading to the higher aspect ratio of the Vulcan design, but with higher power.

We judge that the requirements for CD-0 for this device have long ago been met (c.f. the statement in the ReNeW report quoted above: "Develop an accurate cost and schedule for this facility, and construct it." During the Conceptual Design phase leading to CD-1, it will be important to weigh the range of options for heating and current drive. Options that are not chosen for initial installation can later be tested in the extreme PMI environment of HDTX. It will also be important to consider the options of actively cooled copper coils vs. various materials and geometries for superconducting coils. The impacts of aspect ratio of access should be assessed as well. Because of the strong background of work already accomplished, we judge that an adequately funded conceptual design activity could be ready for CD-1 within ~ one year. We estimate that scientific research could begin within the specified 10-year period.

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