ReNew White Paper, submitted to Theme II (relevant to all panels).

Contributions of a sustained high heat flux facility to "Creating predictable, high performance steady state plasmas"

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Introduction

It is widely recognized that plasma-boundary challenges are among the greatest, and least understood, aspects of fusion energy research, and represent huge 'gaps' in our readiness for DEMO. Many believe that, as part of a research program to address these issues, a new integrated confinement facility with extremely long pulses, high heat flux and flexible, high temperature PFCs is required, and missing in the world program. We strongly agree, and have submitted White Papers outlining in general an "Energy Sustainment Mission" to Themes II, III and IV[1], and particular contributions to the PWI Issue[2]. However, the community must also recognize that significant new facilities in the ITER construction and commissioning period – which is the time frame of ReNeW - will be extremely limited in number. Any new device should be designed to contribute strongly in multiple areas, addressing gaps which have been identified for DEMO by the 2007 FESAC panel and others. Its size and cost should be the smallest which still meets scientific requirements.

ReNeW Theme II addresses the core plasma physics and tools needed to "create predictable, high performance, steady state plasmas". To be relevant to DEMO, a new facility should be as close as possible in magnetic configuration, auxiliary tools, and parameters to that expected in the first DEMO. Steady state and high heat flux are interlinked necessary components for the Energy Sustainment Mission, which is crucial for "Taming the Plasma Material Interface" (Theme III). We propose that a D-D tokamak device, with aspect ratio of about 4 as in ARIES-RS or -AT to allow for core shielding, and with superconducting magnets, and heating and current drive tools applicable to DEMO, would contribute most strongly to Theme II.

Preliminary scoping studies for such a facility indicate that the mission can be met with a compact device, R~1 m. Key constraints for the 'Vulcan' scoping study were that the surface averaged heat flux should match that of DEMO (~1 MW/m^2), and the normalized edge collisionality and divertor response should also be in the relevant range, yet allow arbitrary pulse length with non-inductive current sustainment. Operating density is the key adjustable parameter in finding a *simultaneous* solution to power handling and current sustainment needs since these have opposite dependencies with density. While the design is by no means fixed, some approximate parameters are given in Table 1 below. A range

[1] Theme II-5. D. Whyte et al "**An Energy Sustainment Science Mission**" (overview).
[2] Theme III- 41. D. Whyte et al, "**Taming the Plasma-Material Interface and an Energy Sustainment Mission.**

of operating regimes is envisaged. To ensure success of the PMI mission, a relatively high field and conservative beta could provide steady-state heat fluxes, as well as significant neutron fluence. At lower field, higher beta would provide a greater challenge in the areas of Control, Integration and Off-normal events. Further details of the proposal, and anticipated contributions to key Issues in this Theme, are summarized below. For each Issue, experiments using such a facility could form a natural *part* of a Research Thrust, in conjunction with other needed research activities such as modeling and experimental tests, to answer key scientific questions in the fusion program.

Table 1: Key physics parameters of 'Vulcan' scoping study.

Parameter		
R , a , plasma surface S	1.0 m , 0.25 m, 14.5 m^2	
R/a, elongation	4 , 1.8	
P_{heat} (MW), $\mathbf{P_{heat}/S}$ (MW/m2)	14.5, **1.0** (design criterion)	
	Full field	Half field
B_T (T)	7.0	3.5
Ip (MA), q^*	1.55, *3*	0.77, *3*
P_{CD} (MW)	7.7	2.2
f_p / f_{ece}	0.79	1.6
$<n_e>$ (10^{20} m^{-3})	3.0	3.1
<T> (keV)	3.4	1.6
β_N , β_t	1.93, *1.7*	3.7, *3.3*
Bootstrap fraction	0.46	0.9
D-D Neutron flux (10^{14}/s/m^2)	4	0.3
Upstream $q_{//}$ (GW/m^2)	4.6	4.6
Divertor similarity f.o.m. ~ $n_{20}^{7/2}$ R	3	3.1

Parameters used for calculations: H_{89}=2, CD from 4.6 GHz LH, targeted range of similarities for boundary from ARIES-AT and RS: Upstream $q_{//}$ ~ 4-5 GW/m2, divertor target plasma n_{20} $R^{2/7}$ ~ 2.7-3.5

Integration of high performance, steady-state burning plasmas

A crucial element here is that of integrating high performance steady-state plasmas – by definition non-inductively driven and having substantial bootstrap fraction, hence high confinement – with the challenge of divertor and PFC power handling. Development of better materials and divertors is not sufficient. For instance, we already know how to reduce peak heat loads via copious radiation. However, due to profile stiffness, the plasma confinement is reduced due to edge cooling. Similarly, divertor detachment is currently the best power dissipation strategy for ITER. But, this requires high density and therefore increases the external current drive needed to maintain some fraction of the non-inductive current; the degree of this constraint varies with current drive technique (LHCD, beams etc). Due to the highly non-linear response of the boundary plasma, particularly to core/upstream density, we can expect that the critical edge plasma parameters of parallel heat flux and divertor T response can match DEMO-like values, while still being compatible with CD requirements in a R=1 m device. (Table 1). The Vulcan device may require power dissipation techniques beyond even detachment such as expanded volume divertors. These are more feasible / economical to test in a small device. Setting the dual constraints of power exhaust and plasma sustainment properly frames the boundary – core coupling; a solution to only one of these is not allowable. Beyond basic survival of the PFC power handling strategy there is also the effect of PFC erosion (in terms of impurity influx) on core performance; we currently have no capability to predict the level of core impurities for a given impurity source. Although not completely understood, it is well established empirically that the "boundary condition" of the walls has enormous impact on plasma performance. Stepping up to CTF/DEMO energy throughput and high ambient wall temperatures signifies many orders-of-magnitude changes to the plasma-wall coupling (fueling, impurity control, etc.); a step up which was not required for ITER due to its water cooling. It seems naïve to think that we would not expect large differences in overall plasma operation and optimization on entering this unexplored new PWI regime.

Beyond the lack of demonstrated compatibility of high power, driven core plasmas with a divertor power dissipation strategy there are many strong, non-linear interactions between edge/SOL/pedestal physics, core transport, heating and current drive etc. These are far beyond current or anticipated predictive capability and can only be assessed in an integrated experiment. A power handling solution in a magnetic configuration or under conditions very different from that expected on DEMO would not necessarily give confidence that the issue has been resolved; this integration experiment would provide the needed bridge to a tokamak CTF or DEMO.

In the lower field, higher beta mode of operation, all of the above challenges would be integrated with operation closer to stability limits, for many times current relaxation and other core plasma time scales. Bootstrap current would be dominant. This would place added emphasis on the need for stable, well controlled kinetic and current profiles. Simultaneous integration of multiple control loops, and avoidance and mitigation of off-normal events, discussed further below, would be a key part of the research program.

The additional complexity of self-heating would of course not be directly addressed in a D-D device; it is anticipated that ITER will provide much of this physics and experience. A D-T facility would of course need to be much larger and be many times more expensive. However, simulation of alpha heating effects using strong ECH would be an interesting upgrade to the mission and capabilities.

Control

The challenge of producing plasmas which are sustained for indefinite pulse lengths – perhaps days to weeks – with high duty cycle, will enable a significant advance in control capabilities. All needed diagnostic sensors and actuators will need to operate reliably without drifts, and have in-vessel components which tolerate high temperatures and heat fluxes. There will be a new emphasis on fault-tolerant control schemes and redundancy. This should benefit from, and ultimately extend, the experience anticipated on KSTAR and EAST. In particular, the divertor/boundary control challenge will be seriously addressed for the first time. As the edge evolves to equilibrium, even away from MHD stability limits, local temperature excursions of PFCs and associated impurity influx have the potential to perturb the core equilibrium and would need corrective action.

In the lower field mode of operation, at higher beta and bootstrap fraction, the margin for excursions would be reduced, and need for active control of MHD instabilities increased. In particular, operation with β_N above the no-wall limit, requiring RWM stabilization techniques, would be be explored. As external current drive is reduced, profile control will become even more challenging.

Off-Normal events

The energy sustainment science mission requires arbitrary long plasma pulses and control of the plasma-wall interaction, particularly exposure temperature. Disruptions will be highly perturbing, particularly in a high field compact tokamak where the poloidal magnetic energy leads to substantial wall heating (e.g. Alcator C-Mod). This means that for the first time in a tokamak the capability to operation "truly" disruption free will be absolutely necessary in order to meet its science goals. At the same time, while the disruptions will be perturbing, as in present devices the plasma energy density will not be so large as to ensure large PFC surface damage with each disruption, as is the case for unmitigated disruptions in large devices like ITER. Therefore this device can be seen to provide a parallel disruption mission to the pulsed ITER, where disruptions may affect operational availability but do not affect its Q=10 burning plasma science. We need to have the knowledge of how to operate disruption-free (Vulcan) combined with understanding the level of PFC damage associated with reactor-level disruptions (ITER).

A second consideration to off-normal events is that the high ambient temperature of the PFC may have a strong effect on the response of the surfaces to transient heating from ELMs and disruptions. It is after all these surface responses, and the consequential response of the surface to quiescent plasma exposure, which actually set the energy density limit for off-normal events. For example one may imagine that the high T wall may both provide bigger challenges, such as reduced T window for PFC operation, but at the same time provide opportunities for material "healing". Vulcan would provide the first insights into the integrated PFC material responses at high ambient temperatures and transient plasma heating.

Auxiliary Systems

Auxiliary heating and current drive is crucial to provide the high power flux, to enable the high density and temperature gradients for substantial bootstrap fraction, and to sustain the remaining current while controlling its profile. The type and mix of heating will clearly be important. In an initial assessment we have looked at primarily ion cyclotron range of frequency (ICRF) power for central heating, and lower hybrid range of frequency (LHRF) power for off-axis current drive. These have the advantages that sources are readily available. In the ICRF regime it will be possible to use sources at about 100-110 MHz for fundamental minority hydrogen heating at 7.0 T, or alternatively one could employ fundamental ^{3}He cyclotron damping with 70 MHz sources. In either case we would rely on second harmonic heating at the plasma core in the reduced field scenario (3.5 T).

Development of launchers capable of coupling high power density, steady state and extremely high reliability, and of tolerating high heat loads, at high temperature, will be needed, and will contribute strongly to key issues in this panel. Generation of impurities must be minimized. This will require the development and implementation of successful techniques for mitigating impurity production from nonlinear antenna effects such as ICRF sheaths.

While the core wave physics is fairly well understood, experiments would explore regimes of field and density beyond those in ITER and closer to a CTF/DEMO. It will be necessary to demonstrate that LH waves can be successfully coupled at DEMO relevant densities, avoiding parasitic absorption via parametric decay instability (PDI). LHRF sources at 5.5 GHz may be needed in order to accomplish this. Linear wave propagation of both the ICRF and LHRF waves in the scrape off layer (SOL) will have to be carefully studied in order to avoid coupling of these waves to surface modes. Further investigation with advanced models and in current experiments should be carried out as part of the H&CD selection.

Use of ECH and/or NBI could also be considered for part of the heating and current drive mix, though CD efficiency appears lower with ECCD. In each case, physics is fairly well understood but development of sources would likely be required – higher frequency, high power gyrotrons, steady-state neutral beams. A major advantage of making the configuration and absolute parameters of an integrated high heat flux experiment as close as feasible to those expected for DEMO is that the needed research and development, both scientific and technological, will directly address gaps for DEMO and inform its eventual design.

<u>Validated Predictive Capability</u>

The proposed facility would play a key role in developing predictive capability for plasma-wall interactions and integrated core-edge physics. We note that there is a significant extrapolation in power loading and pulse length in going from current devices to ITER and from ITER to Demo. And while current codes can describe qualitatively some observed phenomena, they generally fail to predict many features observed in today's experiments and cannot quantitatively, from first principles, describe any of the measured profiles or dynamics. This new device, operating uniquely in steady-state at high power and particle flux with high-temperature PFCs, would be in a particularly strong position to test models in a number of critical areas including steady-state plasma wall interactions; erosion and redeposition and other modifications of the first wall chemistry or morphology; fuel retention, recycling, pumping and fueling; dust generation and migration. The measurement capability detailed below will be a key component in this validation process. We note that this will be much more readily obtained in a non-burning experiment.

<u>Measurements in a steady state device</u>

Making accurate measurements with reliable, robust diagnostics on a steady-state, burning plasma is a major challenge that has not been sufficiently addressed by experiments to date. The steps to both a burning plasma and a *steady state* burning plasma represent significant increases in our measurement/diagnostic capabilities. A steady-state, high-heat-flux environment is of great value for providing some of the necessary experience in these areas. Not only will steady-state measurement issues (like long time reliability and calibration) be addressed, but necessary diagnostic development will be facilitated by such a device. To carry out the program described here, new and improved diagnostics will be essential. These include:

- Measurements for profiles and fluctuations including better geometric coverage (2D, 3D, including private flux region)
- Reliable sensors for control actuators, e.g. j(r) for current profile control
- Heat flux measurements, IR (surface temp), calorimetry (bulk temp), extensive 3D coverage
- Dust generation and transport
- n_e, ϕ, T_e, T_i, B fluctuations
- Measurement of perpendicular and parallel flows
- Measurements of RF sheaths
- Measurement of impurity generation rates
- In-situ measurements of PFC condition (chemistry, morphology), erosion, redeposition
- Measurements of Ly_α etc. (radiation transfer/opacity) and other diagnostics of neutrals in divertor and SOL

Furthermore, since one of the goals of gaining a validated predictive capability (previous section) is to reduce the measurement requirements under burning plasma conditions, this will reduce the pressure on a future burning plasma's diagnostic set in some areas, e.g. RF sheaths and neutrals. However, because of their importance, some measurements will still be required under burning plasma conditions. Some of the "indispensable" measurements will require significant development, e.g. for control-sensors, dust, and profiles, and, as such, address urgent diagnostic development needs for burning plasmas. Thus, it is crucial that the diagnostics developed for this device to make the "indispensable" measurements also be designed to operate robustly in a steady state burning plasma environment.

Magnets

Robust, steady state, high field magnets will be a critical component of the device, which would be the first U.S. tokamak to use superconducting coils. Although there have been several superconducting tokamaks built outside the US, the US still leads in understanding of high current cables (Cable in Conduit Conductor, invented in the US) and their applications to toroidal and poloidal magnets. The present device, although without the use of tritium, will produce heavy fluences in the magnet. The magnet insulation is particularly sensitive to radiation damage. To be constructed in the near term, as we propose would be optimum for timely PMI information, the magnet technology for Vulcan needs to be at or near state-of-the-art. The use of Nb^3Sn superconductor is needed in order to provide the fields required for the full field (high performance) operation. Table 2 presents a self-consistent set of parameters, although not yet optimized, particularly with respect to shielding requirements. A parametric study indicates that the minimum major radius of the machine is around 1m. We note that although the cost monotonically increases with major radius, it is not a strong function of R.

Table 2: Key engineering parameters for 'Vulcan' (at full field)

Magnetic field	(T)	7
Major radius	(m)	1
Effective shielding	(m)	0.08
Peak field	(T)	12.29
Power in neutrons	kW	2.5
Shielding factor		2.5
Nuclear power to refrigerator	kW	0.8

Development for Vulcan would explore technologies that could result in lower cost, more reliable, maintainable magnets than in any present or planned device, as well as improvements in magnet insulation. Improved insulation systems compared with those used in ITER could be utilized. This would result in increased lifetime of the device, an important goal. The program can thus benefit from a short but substantial effort in the development of better magnet insulation. Novel techniques for detecting quench and for magnet protection in the case of quench can be tested that will result in increased current density and decreased cost of the conductor, by decreasing the amount of copper in the conductor. The very long pulses may help alleviate the fast ramp rate limitation of superconducting magnets.

With more R&D effort, the project could assess and potentially exploit further magnet technology developments potentially including high temperature superconductors and/or demountable resistive-SC joints for ease of modification and maintenance to internal components. This is important since flexibility to modify and test the wal configuration is integral to the PMI mission. Successful demonstration in a device of this scale and pulse length would give confidence that they could be exploited in DEMO, potentially making a more attractive, cost effective, reactor design and positioning the US in a leading role. They would also be of great advantage to a future Component Test Facility such as FDF, potentially radically improving its design and reducing its power needs. Finally, we note that although it might be possible to achieve the physics objectives of Vulcan using resistive magnets, the power requirements would be severe and result in large operation costs. This option would clearly not contribute to the chief gaps highlighted by the Greenwald FESAC report.