

ReNeW White Paper: An Energy Sustainment Science Mission

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An exciting intellectual opportunity and challenge exists for the US fusion community in studying a *truly* sustained, steady-state, high performance tokamak. The *scientific* goal of this device is to obtain states of real “global” equilibrium between the core/edge plasma, fuel cycle, plasma-wall interactions and material evolution, at reactor-relevant power fluxes. The equilibrium would serve two critical purposes:

- 1) Identify the controlling parameters and necessary timescales for actually obtaining the equilibrium.
- 2) Exploit the equilibrium state to vastly improve our measurement and understanding of the underlying physical mechanisms of this complex and coupled system.

The essential *demonstration* goal of such a device would allow us to bridge the enormous knowledge gap required to sustain energy throughput; this throughput is in the end the required “product” of a fusion device as either a Component Test Facility (CTF) or a DEMO reactor. The US has a unique opportunity to grab this issue now since it is presently neglected in the international spectrum of present or planned fusion experiments, including ITER. An energy sustainment science mission would simultaneously push the knowledge frontiers of integrated high performance plasmas, plasma-wall interactions and fusion materials.

In present tokamak research “steady-state” refers to obtaining stationary core plasmas, i.e. timescales longer than the current relaxation time. However the global system, and in particular the plasma-facing components (PFC), are far from equilibration on such timescales due to evolving temperature, fuel content, and erosion/mechanical viability. Strong coupling of the plasma and materials informs us that these evolving PFC properties will result in a non-stationary plasma. Simultaneously the requisite for a CTF or DEMO is the production and safe exhaust of fusion, exhaust and electrical energy - period (not ‘interesting’ plasma physics). Economic D-T reactors are typically designed to $\sim 4 \text{ MW/m}^2$ wall neutron loading, so that the plasma exhaust requirement is $P/S \sim 1 \text{ MW/m}^2$ continuously for a duration of $30 \times 10^6 \text{ s} = 1 \text{ year}$; i.e. an energy exhaust requirement $\sim 30 \text{ TJ/m}^2$. ITER and presently planned devices fall ~ 100 to 1000 times short of the energy exhaust requirement, due to low P/S and small duty cycle. Just as important, the blanket and PFC must operate at ambient temperatures in excess of 700 C for thermal efficiency, or over 1000C for non-metallics such as SiC, which dictates that a CTF must also have such temperatures for component testing. While this might appear to be a modest change from present near-room-temperature 300K devices, in fact this jump in temperature translates to effectively an astronomical change in the wall-plasma behavior. This is because the physical chemistry rates for the important reactions in materials follow Arrhenius relationship $\sim \exp(-E/kT)$ with activation energies $E \sim 0.5-1$

eV; this translates into 10-15 order of magnitude changes in rates when stepping from ITER and other water-cooled devices to CTF/DEMO!

These two quantitative “step-ups” comprise the energy sustainment “chasm” -- and the issues are linked to each other through plasma-wall interactions (PWI) and their effects on core plasma performance. The energy throughput and temperature can be seen as the main driver of evolution in the plasma performance and wall properties. A good example is fuel retention and recycling. Through processes like net erosion or material damage (e.g. displacement, swelling), the thermal equilibrium of the surfaces evolve at several time-scales, leading to dramatically different plasma fuelling from the wall due to the exponential dependence of H reactions in the materials with temperature (which dominates external fueling). The high performance plasma will respond to these fueling changes, which affects the heating profiles and erosion patterns at the PFC, thus closing the circle and clearly affecting the plasma performance. The energy throughput, high temperature and high performance core issues cannot really be separated from one another and must be addressed in an *integrated* experiment. The empirical lesson of all present confinement devices is that small changes in the material boundary, such as depositing sub-micron films, will have dramatic influence on core plasma performance (e.g. lithium, boronization, etc.). Can we be so naïve as to believe that orders of magnitude change in the wall physical chemistry will be trivial?

Bridging the energy sustainment chasm to CTF/DEMO motivates a D-D confinement facility that meets the following requirements: arbitrarily long pulse length with high-performance plasma, $P/S \sim 1 \text{ MW/m}^2$ and high ambient temperature walls. Arbitrary pulse length is required to ensure that one can actually reach states of near-equilibrium of interest; the estimated timescales for reaching these states are highly varied, and depend on the phenomena of interest. For example thermal equilibration to the local plasma heating occurs in seconds, but the thermal equilibration of the surface evolving due to net erosion or neutron damage could take days to months, effects due to swelling and displacement will take times dictated by temperature and rate of radiation damage. Critically, these equilibration times are hypersensitive to the ambient temperature through Arrhenius dependences and the plasma response is non-linear to the wall boundary conditions. All this must be compatible with material thermal limits for heat loading and core plasma performance. In short, to assure equilibrium, go find it! Once established, the equilibrium state would be a critical new analytic tool at our disposal to understand this complex system; indeed without achieving equilibrium it seems that we can not hope to understand these states sufficiently for predictions for CTF/DEMO.

Ongoing design and engineering feasibility studies have identified that such a mission could be carried out in a relatively small $R \sim 1 - 1.25 \text{ m}$ superconducting D-D tokamak operated fully non-inductively. This facility would be complementary to ITER, which will primarily address burning plasma issues. A Research Thrust to enable such a mission, which should also include off-line development and testing and modeling, would

contribute strongly to issues being studied by several ReNeW Themes. Some examples are given below. We will present more detailed White Papers and Workshop presentations on the expected contributions to the following Themes and Panels:

Theme III: Taming the Plasma-Material Interface

Plasma-Wall Interactions: How to best scale, using physics figures of merit, the edge plasma properties and heat exhaust issues? The goal is to both match the conditions expected in CTF/DEMO, and at the same time, assure a reasonable chance of exploring options that will solve the PWI problem such as peak heat loading being too large. This is critical since in order to tackle the energy sustainment issue at relevant P/S the device must first design and find solutions to the problem that instantaneous heat loads may be too large compared to material limits; which could cause PFC failure in several seconds. The mission would rely on a broader research program to exploit existing facilities to better understand the heat exhaust science challenge, and to assure that technology can achieve sufficient steady heat loading ($\sim 10 \text{ MW/m}^2$). In this way the device would integrate both the exploration *and* solving of the power-exhaust gap on the path to the energy sustainment mission, in a manner which by definition is compatible with the high performance non-inductive core plasma. By exploiting arbitrary long pulse lengths the mission would push the frontiers of the PSI field by attaining and quantifying equilibrium (or stationary) conditions between the wall and plasma.

Plasma-Facing Components: The mission would comprise a large motivation for engineering suitable gas-cooled PFCs; after off-line testing these would of course be put to test in an integrated manner in the confinement facility.

In-vessel components: Similar comments as to PFCs but with particular focus to the cooling/heating manifold design and to RF launchers, which will be crucial to provide much of the external heating and current drive for sustainment.

Theme II: Creating predictable, high performance steady state plasmas

Integration of high-performance steady state plasmas: Simultaneously achieving high performance, non-inductively driven plasmas and high power fluxes is a crucial integration challenge, since the requirements for external current drive, high bootstrap fraction and divertor power handling are quite different. It is not enough simply to test materials at high heat fluxes. Since the plasma sustainment issues vary substantially with magnetic configuration and with current drive tools, we argue that to convincingly resolve this issue, it must be demonstrated in a configuration, and with tools, similar to those expected for DEMO.

Measurements and Control: The new challenge of truly steady state operation will spur the development of robust diagnostics, actuators and control techniques, including boundary control, to maintain a high performance plasma for arbitrarily long periods.

Off-normal events: Avoiding disruptions and large unexpected transient events is critical to the *science* mission of the device since these by definition would unacceptably perturb

the desired equilibrium. This would require for the first time in tokamak a truly integrated disruption avoidance for arbitrary pulse lengths in an evolving plasma-wall setting. This would certainly challenge and address this critical aspect of off-normal events, i.e. avoiding them. At the same time, while perturbing to the science mission, because of the smaller size and energy content, such events would not be catastrophic to the wall as they would be in a reactor. This essentially gives one more chances to design a truly non-disrupting tokamak; one cannot experiment with avoidance and mitigation techniques if no errors are tolerable. Timely construction would help prepare for ITER operation, particularly the steady state phase.

Plasma Modification by Auxiliary Systems: Auxiliary systems to heat the plasma and drive current are integral to the mission. These would need to be developed and tested for steady state operation, with high power density and in the presence of reactor-level heat fluxes. While we presently envisage a primarily RF-driven device, this could spur research into steady state neutral beams.

Magnets: Robust, steady state, high field magnets will be a critical component of the tokamak, which would be the first U.S. tokamak to use superconducting coils. The device would allow the US to explore technologies that could result in lower cost, more reliable, maintainable magnets. Several innovations in magnet technology will be demonstrated, of work that is being investigated at the present time at a low level or work that has yet to be investigated. We anticipate exploiting technology developments potentially including high temperature superconductors and/or demountable resistive-SC joints for ease of modification and maintenance to internal components. It is expected that development efforts will have to take place before being capable of implementing these technologies in fusion devices.

Theme V: Harnessing fusion energy:

The initial design studies have shown that with high magnetic field (> 6 T) it will be possible to explore an “intermediate” nuclear mission with the R~1 m device using volumetric D-D neutrons in the high performance plasma. While of course the D-D reactivity is much smaller, in fact the arbitrary pulse length would allow one to examine the onset of nuclear damage effects, although with limited helium accumulation due to the lower energy neutron spectrum. The effect of displacement damage in PFCs should reach equilibrium, for example. Effects such as reduced thermal conductivity due to displacement occur at low displacements per atom ($\sim 10^{-3} - 10^2$ dpa) which could be achieved in ~2 weeks of operations. The device would also require / test integrated tests of neutron shielding with a high temperature wall/blanket which is required for efficient harnessing of fusion energy for electricity production. Multiple material choices could be investigated for the PFCs and cooling structures. Steels (bare and or covered with refractory materials), and well as non-metallic PFCs (such as SiC), could be tried in different sections of the device’s wall. In particular, the use of small sections of high-temperature SiC could bring early data about its potential for DEMO and for commercial reactors, data that is presently lacking.