The Role of a Long-Pulse, High-Heat-Flux, Hot-Walls Confinement Experiment in the Study of Plasma-Wall Interactions for CTF and Demo

Rob Goldston, PPPL

Introduction

It is clear that the step to Demo from ITER is very large in the area of Plasma-Wall Interactions. Most current fusion experiments use inertially-cooled carbon plasma facing components. ITER will use a combination of water-cooled beryllium, tungsten and (in its first phase) carbon plasma facing components. Most researchers in the area of plasma facing components project that Demo (and by implication CTF) will need to operate with He-cooled tungsten as the plasma-facing material, and that this material will need to operate at very much higher temperatures than ITER or present devices ~ 700C. Alternatively, liquid metal surfaces offer attractive opportunities to sidestep some of the most difficult issues, although they introduce their own set of challenges. Thus the experience that has been gained to date with plasma-wall interactions, and even some of the information gained from ITER, may have little relevance for CTF and Demo.

In this brief paper we examine how a long-pulse, high-heat-flux, hot-walls confinement experiment could contribute to the study of PWI issues for CTF and Demo. Clearly such a device would be only one element in a broad, integrated program. This program would need to include very substantially increased efforts on theory and modeling, on new and upgraded test stands, and on existing and upgraded confinement experiments, including the development of new PWI/PMI diagnostics. Some aspects of these programs are described in Reference 1[1], along with an "existence-proof" concept for a new confinement facility with long pulses, high power and hot walls. There would also need to be very close coordination with research on ITER, and testing on IFMIF (or equivalent).

Contributions to Each PWI Issue

The Plasma Wall Interactions Panel has divided PWI issues into five categories; we address potential contributions to each of these here:

SOL and Divertor Plasma

The time constants for plasma physics evolution in the SOL and divertor plasma are short compared to the pulse lengths even of existing experiments, but the time evolution of the surface that the plasma faces can have many time scales, associated for example with surface accumulation of gas, diffusion of the gas into the first wall, and co-deposition. It will also be the case that as the most active regions for some of these processes become saturated, others will begin to dominate. All are strongly dependent on the material composition of the wall, and on its temperature. Certainly the processes in the SOL and divertor plasmas are also highly dependent on the power flux being carried by them. Thus it will be very valuable to have a Demo-relevant long-pulse, high-power, high-wall-temperature experimental facility in which to measure the complex physics of the SOL and divertor plasmas: turbulent heat and particle transport, particle flows, impurity transport, radiation transport and He pumping. To make the extensive measurements needed to challenge theory and identify missing physics will require excellent diagnostic access, and a commitment to addressing PMI physics and technology as the central

[1] Goldston, R.J., et al., http://www-pub.iaea.org/MTCD/Meetings/FEC2008/ft_p3-12.pdf

mission of such a device. A machine capable of long-pulse DD operation is likely most appropriate to address these issues in support of rapid, successful operation of CTF and Demo.

Erosion & Redeposition

The physical interactions between a confined plasma and its boundary are many. They will be significantly affected by the very different properties of the plasma facing components planned for CTF and Demo, compared with current experiments and ITER, and it is not credible that this would first be encountered on CTF or Demo itself. A long-pulse, high-heat-flux, hot-walls DD confinement experiment with excellent diagnostic access and the flexibility to test a range of different solid- and liquid-surface plasma facing components and geometries would provide a key test-bed to understand the relevant physical phenomena at the plasma-material surface. Key issues that will require advanced diagnostics include: impurity generation, RF sheaths, dust production, surface morphology changes, erosion rates that determine component lifetimes, and energetic alpha effects. (These last could be simulated with RF heating near the edge of a non-DT plasma.)

It is worth noting that the plasma-material interface is under such intense plasma bombardment that neutron effects, while present, are likely to be secondary. Redeposited layers will be highly amorphous, so neutron-induced displacements are not anticipated to represent first-order effects on their material properties. Neutron effects on the thermal conductivity and brittleness of the substrate material should be tested off-line[2], and taken into consideration, *e.g.,* in the thickness of the plasma-facing components to be tested or in scaling the impact of off-normal events. Coupons of materials irradiated in IFMIF or other facilities can be tested in a high-power non-DT machine for alterations in PMI effects.

It will also be necessary to develop techniques to monitor and remove the dust that evolves from the solid surfaces during continuous plasma operation. Developing this full technology for the first time in a non-DT environment is likely much more practical than doing so in a highly activated and contaminated DT system. The total activation and contamination in a CTF will be 30 – 50 thousand times greater than in an appropriate DD PMI machine.

Clearly there will be much theoretical and test-stand work to be done in this area, as well as testing on existing experiments, such as the high-temperature W divertor planned for C-Mod and the liquid-lithium experiments planned on NSTX. This work needs to be coordinated with the activities of the new DD confinement device. Long-pulse, high-power, high-temperature qualification of new surface materials will provide confidence in employing them on a multi-$B DT machine for which the study of plasma-materials interactions is not the primary mission.

ELMs & Disruptions

The impact of transient events and the development of robust avoidance techniques are issues that need to be studied in a high-power, long-pulse, high-performance toroidal confinement devices, including ITER. While it would not be possible to simulate Demo-level disruption impacts in a practical smaller device, one could establish repetitive ELMs at a much higher fractional energy loss level than acceptable in Demo, and so for example at Demo-relevant energy loss per unit surface area, and study their effects on plasma-material interactions with Demo-relevant plasma facing components. This would complement the work on ITER. Long pulses and high duty factor at high performance would allow validation of the reliability of

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[2] See Whitepaper by Tang, X. *et al.*

disruption precursor detection at high β and of ELM prevention techniques, as well as techniques to avoid impurity accumulation and uncontrolled density growth in the absence of ELMs.

Tritium Retention
A long-pulse, high-temperature, high-power, largely DD device can address some of the key issues associated with tritium. One can use such a device to study hydrogenic retention and permeation with Demo-relevant materials, at Demo-relevant temperatures. Trace tritium can be used to track permeation and retention as necessary. It may be desirable to place irradiated coupons from IFMIF or its equivalent into such a device, in order to test tritium permeation and retention in such samples, complementing test-stand studies. This device would also provide information on the expected CTF and Demo plasma-material interface, which could then be simulated off-line, if an appropriate plasma simulator test stand can be developed – and perhaps co-located with IFMIF. A powerful DD facility will require remote handling, although one anticipates activation and contamination levels much less than in a CTF, as noted above. Thus one could gain experience for the first time with RAMI for the exotic plasma-facing-components that will be required for CTF and Demo, such as brittle He-jet-cooled tungsten or liquid metal jets, in a more forgiving environment, where such technological issues constituted a major element of the basic device mission.

Innovations
A number of innovative approaches have been proposed for heat-flux mitigation in Demo, which cannot be tested in ITER. These include very high radiation fraction, extreme flux expansion, stellarator-like edges, new materials, liquid surfaces and active coating techniques. It is clear that a high-heat-flux, long-pulse, hot-first-wall device, with high heating power compared to the L-H threshold, extreme flexibility in poloidal field configuration and relative ease to change out internal components for entirely new configurations, will be needed to qualify these approaches so that CTF and Demo can be assured of success in their missions.

The requirement to test new liquid surface PFC concepts in a long-pulse, hot-walls, high-heat-flux plasma environment is particularly obvious. After theoretical modeling, technology development and test stand qualification, it will be critical to determine the plasma response to the liquid PFC's. This is especially true in the case of lithium, where plasma recycling is likely to be strongly affected, and where the impact of evaporation on plasma performance will need to be assessed. It will also be critical to qualify techniques to remove all injected liquids. It is interesting that the role of neutron effects for liquid-surface PFC's is limited to the structures that control the liquid flows, which are not directly exposed to the plasma, so this issue is separable from PWI considerations and can be tested straightforwardly, e.g., in IFMIF.

Conclusion

In sum, it appears that a high-heat-flux, long-pulse, hot-walls confinement device with excellent access and flexibility can make decisive contributions to the study of plasma-wall interactions, speeding the programs on CTF and Demo. The PWI/PMI issues constitute a sufficiently grand challenge that a major coordinated program is required in this area, including enhanced theory and modeling, test-stand work, work on existing facilities, and also a new device whose primary mission is to develop the PWI/PMI physics and technology for CTF and Demo.