

The Role of a Long-Pulse, High-Heat-Flux, Hot-Walls Confinement Experiment in the Development of Plasma Facing Components for CTF and Demo

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Introduction

It is clear that the step to Demo from ITER is very large in the area of Plasma Facing Components. Indeed the recent FESAC Priorities, Gaps and Opportunities Report placed Plasma Facing Components at the top of its Tier 1 Priority issues: *solution not in hand, major extrapolation from current state of knowledge, need for qualitative improvements and substantial development for both short and long term*. The FESAC Panel also placed Plasma Facing Components at the top of list of “Areas where the U.S. has opportunities to gain leadership through significant investment.”

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, $\sim 700\text{C}$. 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-facing components, and even some of the information gained from ITER, may have limited relevance for CTF or 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 1¹, 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 PFC Issue

The Plasma Facing Components Panel has divided the Plasma Facing Components issues into seven categories; we address each of these here:

Physics

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 studied in CTF or Demo itself. A long-pulse, high-heat-flux,

¹ Goldston, R.J., et al., http://www-pub.iaea.org/MTCD/Meetings/FEC2008/ft_p3-12.pdf pages 6 – 7.

hot-walls confinement experiment, focused on PWI/PMI issues, 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. The impact of transient events and the development of robust avoidance techniques are also issues that can only be studied in a high-power toroidal confinement geometry. It would seem prudent to investigate these issues first in a machine with excellent diagnostic access, flexibility and relative ease of repair. It is worth noting that the plasma-material interface is under such intense plasma bombardment that neutron effects 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.

Solid Surface and Design

Evidently a large fraction of this task is to be undertaken in engineering development and on test stands. However the practical experience of testing components such as He-jet-cooled tungsten divertor targets in the environment of a long-pulse, high-temperature, high-heat-flux plasma is likely to be highly salutary. 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 DD environment is likely much more practical than doing so in a highly activated and contaminated, and expensive, DT system, which absolutely depends on the success of the technology development. It will be critical, however, to expose the relevant materials, joints and permeation barriers in IFMIF or its equivalent to determine the effects of energetic neutrons on material properties such as thermal conductivity and DBTT. Neutron effects on the thermal conductivity and brittleness of the substrate material should be tested off-line², and taken into consideration, e.g., in the thickness of the plasma-facing component or in scaling the impact of off-normal events. Coupons of materials irradiated in IFMIF or equivalent can be tested in the high-power DD machine for alterations in PMI effects. This will be needed to qualify such components for a CTF or Demo. It is not practical to build these components using materials that have not been tested in such a manner, and then to install them in a powerful DT machine. Results from a long-pulse, high-heat-flux, long-pulse DD device focused on PMI issues, and from IFMIF, will speed the implementation of the programs on CTF and Demo.

Liquid Surface and Design

The requirement to test new liquid surface PFC concepts in a long-pulse, high-temperature, high-heat-flux plasma environment is self-evident. 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 particularly 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. From a technological point of view, one can anticipate that over long pulses there will be significant distribution of liquid metals in the vacuum vessel, so techniques to remove the liquid metals during continuous plasma operation will need to be developed. 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. Tests in IFMIF or its equivalent should be adequate to assure that the necessary material properties of such structures are preserved in CTF or Demo.

² See Whitepaper by Tang, X. et al.

Surface Heat Transfer and Components Testing and Analysis

While one is inclined to conclude that there is little role for a plasma confinement experiment in this area, the experience on Tore Supra contradicts this perspective. The need for high numbers of high quality defect-free components for Tore Supra was very challenging, and the development of the needed quality-control technology only occurred when strongly driven by this need.

Tritium, Safety, and RAMI

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 will 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. This device will 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 total activation and contamination levels 30 – 50 thousand times less than in a CTF. 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 much more forgiving environment.

Surface Materials

This issue is tightly coupled with the plasma-surface interactions described under *Physics*. 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. However long-pulse, high-power, high-temperature qualification of new surface materials will be needed to have confidence in employing them on a major DT machine for which the study of plasma-materials interactions is not the primary mission.

Maintenance and Development Program

As discussed under RAMI, the PFC's anticipated for use in CTF and Demo are dramatically different from those in use today or even those planned for ITER. Thus the maintenance of these systems will present unique problems. These can be uncovered and addressed in a flexible machine with excellent access, optimized for addressing such issues.

Conclusion

In sum, it appears that a high-heat-flux, long-pulse, hot walls confinement device with excellent access and flexibility can make major and even decisive contributions to the development of plasma facing components to speed 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