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TAMING THE PLASMA INTERFACE: BW-SURFACE FOR CTF AND DEMO

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GENERAL ATOMICS

For the development of CTF and DEMO fusion devices, next to the requirement of robust performance of the plasma is the performance of the plasma facing components. Beyond ITER, due to radiation damage from high energy neutrons and helium ions none of the conventional surface materials like C, Be and W will be acceptable for the steady state D-T fuel cycle operation. To resolve this problem, the goal oriented innovative concept of BW-surface is being explored to withstand steady state plasma burn, and reduce damages from occasional ELMs and disruptions while retaining the capability of transmitting high grade heat for power conversion. With the recommended use of boron (B), judicious real-time boronization will be required to maintain a suitable boronized layer on the chamber wall for steady state operation.

BACKGROUND

The importance of this subject of Plasma Facing Components and Materials (PFC) is echoed in the identification as Tier 1 issue from the 2007 Greenwald “Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy”.

ITER has initially proposed Be, W and C as its plasma facing materials, and the final decision could still be evolving to just the use of Be and W. But it is well known that in addition to high erosion rate from physical sputtering, under high fusion neutron fluence both Be and C will generate a large amount of helium and suffer atomic displacements leading to volumetric swelling and unacceptable material properties for the design. Among these three materials, W has the lowest physical and chemical erosion rate and has been the favored plasma facing material for CTF and DEMO.

It was unexpected that recent results from Japan showed that at high He ion fluence of $2x10^{26}$ #/m^2 (after about a few hundreds of ITER’s 400s discharges) and at high surface temperature of > 600° C, nano-hair of W would be formed at the divertor and blistering will occur on the W surface at the chamber wall [1,2]. These results were confirmed in the PISCES experiments at UCSD [3]. The damage to these surfaces could mean higher erosion rate of the W-surface from the first wall and divertor, leading to possible contamination of the plasma or limited lifetime of the W-surface components.

After surveying options like C-tiles, Be-tiles, B-tiles, free surface Li, W-wall with C divertor tiles and -wall with Li divertor, as an alternative proposal, a possible innovative solution can be inferred from the fact that boron or silicon has been used successfully to condition the walls in all high performance tokamaks. However, if boron is to be used, real-time boronization will be required to maintain a thin boronized layer on the chamber wall for steady state operation. This boronized layer could also protect the W substrate in order to retain low-Z wall characteristics. To support this idea, the concept of using a thin layer of B loaded W-surface was proposed [4], which is described in the following.

THE BW-SURFACE CONCEPT

The proposal is to fill high purity B into a W-surface that has 50% voids. All the open volume and surfaces of the W surface are to be filled and covered with B. The B coating would protect the W-material due to the small mean free path of charged particles, which is estimated to be at ~10s of nm, while the coating thickness would be around 100 nm thick. Since all the W surfaces are to be coated with B, therefore low Z_{eff} in the plasma can be maintained. An initial design example of the BW-surface layer can be about 1 mm thick and 50% of the W material is with open voids, which are filled with B. Its function is to provide the source of B to be sublimated while handling part of the high energy dump from occasional ELMs and disruption, whereas the high thermal conductivity of the W is to provide the thermal conducting path from the plasma surface to the metallic substrate like ODFS and RAF/M steel. Rough estimates have shown that under a vertical displacement disruption, the vaporized B layer, including vapor shielding effects would be < 50 μm/disruption. This could allow the BW-surface to withstand a few disruptions. This estimate will have to be verified by more detailed modeling and experiment.

A key concern for the use of carbon in ITER is the trapping of tritium. A similar trapping mechanism would occur in boron. Interestingly, experimental results have shown that the trapped tritium in B will all be released at a temperature of 400°C–500°C [5]. This range of operation temperature would be lower than the expected minimum operating temperature of a CTF or DEMO chamber surfaces.

Since B is a well known neutron absorber, there are potential concerns for negative impact on tritium breeder and corresponding high level of radiation damage on itself. Neutronics calculation results have shown that the neutron absorption effect of B is mainly from B^{10}. With isotopic tailoring of B and with the extraction of B^{10}, the radiation effects from neutrons will be reduced by a factor of 50. The amount of B present will not have significant impact on the production of tritium [6]

To maintain a B coated surface for steady state operation, real-time boronization is required. Fortunately, real-time boronization has been tried in many tokamak and stellerator machines [7–10]. All attempts have shown positive results on plasma performance. But surface coating uniformity has not been fully demonstrated, most likely due to the lack of experimental demonstration time, the gas injection ports were also not designed for uniform coating of B from real time boronization, and the fact is also that real-time boronization is not necessary in pulsed or short burn operation machines.

THE VALUE

The value for the development of this BW-surface concept is that it provides a new approach for reducing the impact from occasional ELMs and disruption, while maintaining a low-Z surface for steady state DEMO and protecting the W substrate from charged particles damage. This assumes that high power ELMs and disruptions are either suppressed or avoided. The occasional ELMs and disruption events are low probability events and with the BW-wall approach, not every occurrence will need a reactor shutdown to repair the damage, due to very high power loads to the PFC surface. Successful development of real-time boronization approach will also be directly beneficial and applicable to the ITER all metal wall operation by limiting the possible transport of the metallic wall material into the plasma core.

NECESSARY STEPS FOR DEVELOPMENT

The BW-surface is an innovative surface material concept and it needs the resolution of a few critical technical issues. For the development of this goal oriented concept we propose to begin with the demonstration with a few proof-of-principal experiments. The following research items have been identified and a few of them can be performed in operating tokamaks and test stands in the near future.

1. Demonstrate the filling of high purity boron into a high purity W-surface. This area can be supported by vendors and universities.
2. Quantify the B coating thickness from the boronization of DIII-D by using the Divertor Material Evaluation System (DiMES).
3. Model disruption and high power ELMs impact on the BW-surface.

4. Test of the thermal performance of the BW-infiltrated W sample in high heat flux test stands, e.g. at SNL in Albuquerque, New Mexico and other disruption simulation devices.
5. Test of BW-surface including transient tolerance, ELMs and disruptions in a tokamak, e.g. using DiMES and Mid-plane Material Evaluation Sample (MiMES) facilities in DIII-D and other operating tokamaks.
6. Study the migration and accountability of boron in present tokamaks.
7. Perform real time boronization for the study of deposition rate and coating distribution and thickness uniformity in DIII-D and other tokamaks.
8. Perform accountability of tritium (D) distribution, absorption, release and distribution in tokamaks with boronized wall and linear plasma experiments like PISCES.
9. Initiate technology development of BW-surface, like the attachment of the BW-surface onto a ferritic steel substrate and the fabrication of larger surface/area BW-surface. This should only be initiated with the acceptable demonstration of items 1 to 5.

Successful results from items 6 to 8 can possibly lead to the recommendation of applying real-time boronization in ITER.

MAKING PROGRESS

Presently we are working on items 1 to 3. Holes are being drilled on W discs that would fit the DiMES sample holder and we are in the process of learning how to fill boron in the drilled W-plate. Disruption impact modeling is being performed at Purdue University.

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