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# Innovative tokamak DEMO first wall and divertor material concepts

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ABSTRACT

ITER has selected Be as the first wall and C and W as the divertor surface materials. When extrapolated to the DEMO design, C and Be layers will not be suitable due to radiation damage. The remaining material, W, could also suffer radiation damage from helium ion implantation and experience blistering at the first wall and form submicron fine structure at the divertor. In this paper we introduce a new concept called the boron W-mesh (BW-mesh) in which B is infiltrated into a W-mesh. The goal is to use a thin coating of B to protect the W-mesh from helium ion damage and to maintain a sufficient amount of B to protect the W from transient events like edge localized modes (ELMs) and disruptions. Critical issues and corresponding development of this BW-mesh concept have been identified, including the need for real time boronization.

## 1. Introduction

Carbon (C), beryllium (Be), tungsten (W) and molybdenum (Mo) are commonly used surface materials in operating tokamak experiments. Tokamak devices can be divided into five classes. Class 1 represents the current operating machines, class 2 represents superconducting long discharge devices, class 3 represents ITER with a limited total neutron fluence of 0.3 MW a/m$^2$, class 4 comprises long burn DT fuel testing devices and class 5 is the long-term goal: steady state DEMO and power reactors. First wall material issues are increasingly complex with increasing class number. For the ITER design, the guidance is to apply a Be layer onto the plasma facing chamber surface, and C and W are used at the divertor [1]. For long burn DT fuel testing devices and DEMO, when the selection of chamber wall material is considered, the additional requirements of steady state operation and tolerance to radiation damage from neutrons and charged particles will have to be taken into account. A Be layer will not be suitable due to radiation damage (dimensional instability, gas production and excessive increase of T inventory due to transmutation) [2,3]. Similarly, a carbon divertor surface will not be suitable due to high physical and chemical sputtering rates, radiation damage (dimensional instability and reduction of thermal conductivity) of the material and the potential for large retention of tritium [3]. Unfortunately, the commonly accepted material W for DEMO application could also suffer significant radiation damage from high He ion fluence of >10$^{26}$/m$^2$ [4–7]. Section 2 of this paper describes the potential damage of W surface material from helium ions. Section 3 reviews innovative Li surface concepts. Section 4 summarizes the common practice of wall conditioning and the work on real time boronization and siliconization. Section 5 describes the BW-mesh concept. Section 6 presents the critical issues of the BW-mesh concept, Section 7 presents the conclusions.

## 2. Damage to the W at the first wall and at the divertor

Tungsten, W, has commonly been recognized as the most suitable surface material for DEMO and power reactors. Unfortunately, W and Mo could suffer radiation damage from He$^+$ ion implantation. In both laboratory and toroidal experiments, internal damage on different types of W material (powder metal, single crystal and coating) from He ion irradiation leads to the formation of blisters from room temperature to 873 K for He$^+$ fluence range of $10^{21}$ to $4 \times 10^{22}$ m$^{-2}$ at energy range of 200 eV to 8 keV [4–5], which corresponds to DEMO first wall conditions. At higher temperatures of ~1200 K and with ion energy range of 10–80 eV and at the fluence of $\sim 3.5 \times 10^{27}$ m$^{-2}$, He plasma exposures showed blackening of the W-surface with the formation of submicron fine structure [6,7]. This would correspond to DEMO divertor conditions. Correspondingly, for the ITER design, the He$^+$ flux obtained by B2–EIRENE modeling for the first wall and divertor are $\sim 10^{17}$ m$^{-2}$ s$^{-1}$ and $\sim 10^{21}$ m$^{-2}$ s$^{-1}$, respectively [8]. These results are not encouraging indicators for the application of W to DEMO. Blistering at the first wall and submicron fine structure at the divertor could result in W (or Mo) transport to the plasma core, severely limiting the core performance. However, further experiments from PISCES did indicate the possibility of W surface morphology change inhibition with a mixture of D$_2$–He plasma and with C background. Similar inhibition was obtained with Be background and could even be projected to a boron background [9].

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## 3. Innovative Li wall concept

With the goal of resolving some of the fundamental problems on the selection of chamber surface material, unconventional surface material design approaches were evaluated by the fusion community, including a liquid metal surface for the chamber wall and divertor. Different innovative options were evaluated, such as the lithium infiltrated Mo-fabric limiter tested in T-11 M, T-10 and the FTU divertor [10], and a lithium coated chamber surface and divertor tested in CDX-U [11]. New Li experiments are planned for LTX and NSTX [12]. Key results from the FTU limiter [11], which is a lithium filled metal fiber based capillary pore system, showed that the design withstood $\sim$60 discharges with power fluxes up to 5 MW/m$^2$, as well as plasma disruptions, with no damage to the capillary pore system and the limiter structure. The potential drawback of this approach is the low melting point of Li (180 °C) and the relatively high vapor pressure. It is difficult to achieve high thermal conversion efficiency for a Li-based divertor design in DEMO.

## 4. Boron as a plasma facing material

While considering the above issues, we noticed that for most of the operating toroidal experimental devices, boronization or siliconization has often been applied in order to minimize the amount of oxygen and high-Z impurities getting into the plasma core. Boron is a material very familiar to tokamak operation, since it is one of the most commonly used materials for chamber wall conditioning and has been used in DIII-D, NSTX, TEXTOR, JT-60U, C-Mod, ASDEX-Upgrade, JFT-2 M, LHD, and HT-7 (references are too numerous to cite; selected ones are Refs. [13,14]).

In addition to the beneficial effect of impurity reduction, boron also can be expected to have lower tritium uptake compared to carbon. We found that absorbed tritium can mostly be released at a relatively low temperature of 300–400 °C [15]. Comparing, the corresponding temperature for hydrogen release from C would be $\sim$1000 °C.

Because of these beneficial properties, the use of boron has previously been proposed as a protective plasma facing layer for future devices [16]. Making use of the stopping and range of ions in matter (SRIM) modeling code [17], results show that the ranges of He ion in the boron layer are $\sim$100 nm and 2 nm for He$^+$ energy of $\sim$10 keV and 100 eV, respectively. This indicates that a thin layer of boron could be used to protect the metallic substrate from He$^+$ damage.

We found that the layer of fresh B coating in different tokamaks is around 100 nm thick. Even though a fast deposition rate of $\sim$10 nm/s for B-containing films has been demonstrated on the PISCES-B linear plasma device [18], thicker and more robust B coatings would be difficult to achieve due to internal stresses induced in the process of coating [19]. Even with these potentially favorable properties of boron coatings, we will still have to maintain a constant protective layer of B during steady state operation. This implies the need for real time boronization in order to maintain the thickness of the boron surface. Many attempts at real time boronization have been tried in various devices including DIII-D, PBX-M, NSTX, TEXTOR and LHD [20–23].

## 5. The boron loaded W-mesh (BW-mesh) concept

Even with the successful development of real time boronization, the thin B-coating will not protect the component surface under type-I ELMs and disruption. At high power deposition, the metallic substrate will melt. In order to accommodate the rapid discharge of energy during transient events and learning from the liquid metal infiltrated metal fiber approach, we propose the use of a thin layer of BW-mesh to withstand ELMs and disruptions while retaining the capability of transmitting high grade heat for power conversion.

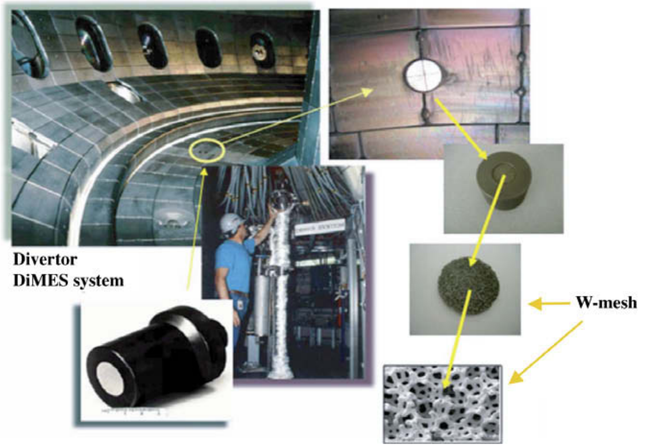

**Fig. 1.** BW-mesh concept can be tested with the DiMES system in DIII-D.

The concept of the BW-mesh can be summarized in the following: a $\sim$50% void W-mesh as shown in Fig. 1 can be infiltrated with boron, with the goal of filling in all the open pores and maintaining a coating of B covering the W surface facing the plasma. Methods of loading/infiltration are being evaluated, which can include methods like high temperature diffusion, physical infiltration at low temperature, chemical vapor infiltration or plasma spray. The W-mesh is to trap enough B to withstand the energy deposited from occasional ELMs and disruptions. This may be credible since the melting point for B and W are 2076 °C and 3927 °C, and corresponding boiling points are 3380 °C and 5900 °C, respectively. Based on the large difference of these temperatures, one can project that the infiltrated boron would be vaporized before significant damage to the W-mesh would occur. From the energy balance between energy dump and B vaporization, the estimated B layer removed per disruption, including the vapor shielding effect, would be about 60 μm thick. Therefore, a net B thickness of 1 mm could take a few disruptions without excessive damage to the W-mesh. This disruption tolerant characteristic could be demonstrated in existing tokamaks and plasma simulators. The BW-mesh thickness of 2 mm is also selected for the maintenance of adequate heat transfer through the layer. Relying on the high thermal conductivity of W-metal, an equivalent thermal conductivity of $\sim$20 W/m-K through the BW-mesh is treated as the design goal. As illustrated in Fig. 1, a test piece of BW-mesh can be fitted into the DiMES module and tested at the lower divertor of DIII-D [24]. If successfully developed, this mixed material surface could be used to cover the areas where ELMs and disruption strike would occur. Since the goal for this BW-mesh concept is for steady state operation, a means of real time boronization during the plasma discharge is needed. This BW-mesh is at a very early stage and many critical issues have been identified and are presented in the next section.

## 6. Critical issues

The BW-mesh is a new mixed material surface materials concept. It is engineered to address many of the surface material issues, but a few critical issues have been discovered and will need to be addressed. Since B is used as a neutron absorber for the fission reactor shield design, a question that is commonly asked is the use of B surface for DT fusion application. Neutronic calculations show that indeed with the natural B, containing 20% of B$^{10}$, the B depletion can be high at about 20.24% after an operating neutron fluence of 19 MW a/m$^2$. But the depletion can be drastically reduced to 0.43% after the same neutron fluence by tailoring the B to contain 100% B$^{11}$ [25]. It was also noted that due to the use of a thin layer of boron in front of the first wall, it will not have much impact on the tritium breeder performance of the surrounding blanket modules.

The BW-mesh concept is at an early stage of development; the concept will have to be demonstrated and tested. Some of the key issues that will need to be addressed are:

- *Fabrication and testing of BW-mesh samples* – Suitable high purity W-mesh has to be identified and infiltrated with high purity B. The sample can be tested with the DiMES facility in DIII-D [24] to demonstrate the tolerance to transient events like ELMs and disruption. The property of tritium uptake can also be quantified. The thermal and mechanical properties of the BW-mesh will need to be tested in high heat flux test stands.
- *Real time boronization* – The approach of real time boronization in a tokamak can be demonstrated in operating tokamaks with minimum impacts to their physics missions. Suitable B-carrying gas or particles will need to be selected and applied. Impacts from the location of the gas injector or B-particle release location will need to be studied in detail and in conjunction with the operating mode of the plasma discharge.
- *FW and divertor component development* – With favorable results from the BW-mesh concept development, suitable BW-mesh components for the FW and divertor surface will have to be developed. This includes the economical fabrication of the components including the joining of BW-mesh to the heat sink material, which most likely will be a ferritic steel based material.
- *Ancillary technologies* – Since B will become a consumable material for steady state tokamak devices, corresponding supporting technologies in boron-loaded vacuum systems and tritium extraction systems in the plasma fueling stream will have to be developed.

## 7. Conclusions

For the selection of chamber wall material for DEMO, commonly used materials like C, Be and W would likely not be suitable due to high physical erosion rates and/or radiation damage from neutrons and/or helium ions. Learning from other innovative approaches, the proposed BW-mesh concept has the potential of alleviating many of the concerns, but at the same time introduces new issues that will need to be resolved. The key one is on the replenishment of the B surface, which will require real time boronization during the steady state DEMO operation and the addition of boron as another consumable material for the steady state DEMO operation. Other critical issues are identified and will also need to be addressed. This BW-mesh concept is at a very early stage of development, but the initial step has been taken in the fabrication of the BW-mesh sample to be tested in DIII-D.

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