# Plasma Facing Material Selection: A Critical Issue for Magnetic Fusion Power Development

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**Abstract.** This paper proposes a possible development approach that may satisfy the requirements for plasma facing materials (PFM) in a fusion power plant. Five fundamental physics and engineering performance requirements will have to be satisfied for the selection of suitable PFM for the next advanced DT device beyond ITER; they are: (a) heat flux removal, (b) acceptable lifetime, (c) acceptable contamination to the plasma core, (d) radiation resistance, and (e) the ability to withstand occasional rapid transient events like edge localized modes (ELMs) and disruptions. If the materials selected for ITER were to be used in an advanced DT device, C tiles and Be coatings would suffer radiation damage, and W could also suffer damage from neutrons and helium ions. Li has been proposed as a possible PFM option. However, due to vaporization and subsequent transport into the plasma core, modeling indicates that Li will have a maximum allowable surface temperature of <400°C. Because of the required minimum allowed structural material temperature of >350°C for the ferritic steel substrate, the allowable surface heat flux removal capability of Li would be too low to make Li a credible chamber surface material. Another innovative approach based on the use of low-Z loaded W surface is proposed with the loading of Si into an array of small indentations or toroidal grooves in the W to over 10 micron equivalent thickness, such that the thin W-surface can withstand an occasional disruption without melting. At the same time it is necessary to control and mitigate rapid transient events like disruptions, type-I ELMs and runaway charged particles in order to reduce the frequency of thermal dump to the chamber wall. Additional efforts will be needed to assure the uniformity of heat and particle flux distributions to the chamber wall and to maintain in real time replenishment of low-Z material onto the chamber surface for steady state operation.

## 1. Introduction

For the development of advanced solid surface materials, it is difficult to foresee any low activation metallic alloy that can outperform W-alloy in high temperature performance, low physical sputtering rate and high thermal conductivity. Ceramic surface materials such as SiC and $B_4C$ could have high temperature capability, but they tend to be brittle, possess low thermal conductivity at high temperature and high neutron fluence, and they have relatively high physical sputtering rates and high generation of helium under high fusion spectrum neutron fluence, making them unacceptable for this application. In considering the choice for plasma facing materials, ITER has selected Be as the plasma facing material (PFM) and C and W as the divertor region surface materials [1]. When extrapolated to an advanced DT device, C tiles and Be coating will not be suitable due to radiation damage [2]. The remaining material, W, could also suffer neutron radiation damage and damage from helium ion implantation, which could cause the generation of tungsten “fuzz” at the divertor [3–6] and surface morphology changes with the generation of blisters at the chamber wall [3]. Both the tungsten “fuzz” and the tungsten blisters could result in contamination of the plasma core.

## 2. 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-11M, T10 and the FTU divertor [7], and a lithium-coated chamber surface and divertor tested in CDX-U [8]. New Li experiments are planned for LTX and NSTX [9]. Key results from the FTU limiter [7], which is a lithium-filled metal fiber-based capillary pore system, showed that the design withstood ~60 discharges with power flux 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 for the use of Li is the low melting point of Li (180°C) and the relatively high vapor pressure. To limit this power degradation due to fuel dilution to less than 20% of the plasma power, modeling results show that the maximum allowable Li surface temperature is <400°C [10]. Furthermore, in order to maintain an acceptable increase in the ductile-brittle transition temperature (DBTT) of the ferritic steel structural material under neutron radiation, its temperature needs to be >350°C. To work within these temperature limits, heat transfer calculations have been performed to show that the corresponding allowable steady state surface heat flux removal capability for Li will be <0.2 MW/m$^2$, implying a neutron wall loading of <1 MW/m$^2$, which is too low for an economical fusion power reactor.

## 3. Boron and Silicon as Plasma Facing Materials

While considering the above issues, we noticed that for most of the operating toroidal experimental devices, boronization or siliconization has often been used in order to minimize the amount of oxygen and high-Z impurities getting into the plasma core. Boron is a material commonly used for tokamak operation, since it is often used for chamber wall conditioning and has been used in DIII-D, NSTX, TEXTOR, JT-60U, C-Mod, ASDEX-Upgrade, JFT-2M, LHD, and HT-7. References are too numerous to cite; selected ones are Refs. [11] and [12]. Machines like HT-7 and EAST [13,14] also use siliconization for wall conditioning.

In addition to the beneficial effect of impurity reduction, boron can be expected to have reduced tritium uptake compared to carbon. We found that absorbed tritium can mostly be released at a relatively low temperature of 300°–400°C [15]. A similar assumption could be made for Si, but this still needs to be demonstrated. 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 range of ions in the material modeling code (SRIM) [17], results show that the ranges of He ion in the boron layer are ~100 nm and 2 nm for He ion energy of ~10 keV and 100 eV, respectively. This indicates that a thin layer of boron could be used to protect the W or other metallic substrate from He ion damage.

From routine boronization we have found that the coating of B in DIII-D is typically less than 1 μm thick. As shown later the required thickness of B to withstand the thermal load of a disruption is ~10 μm. Therefore we will have to find a way to put enough B or Si onto the W surface for it to be a viable advanced PFM candidate. Furthermore, after a disruption, we will also have to find a way to replenish the evaporated B or Si. This implies the need for suitable application of real-time boronization or siliconization in order to maintain the amount of the boron or Si on the W surface, especially at the target locations. It should be noted that many attempts at real time boronization have been tried without negative impacts in various devices including DIII-D, PBX-M, NSTX, TEXTOR, and LHD [18–21].

## 4. The Choice Between B and Si

Initially, we initiated the development with filling of B into the indentations of the W-surface. In order to closely match the coefficient of thermal expansion with that of pure W, we have decided to focus on Si since it has a better match. Furthermore, when B is used for DT fusion application, we will have to use isotope tailoring to reduce the content of $^{10}B$ in order to minimize the absorption from thermal neutrons [22].

## 5. The Si-filled W-surface Concept

For the development of advanced solid surface materials, it is difficult to foresee any low activation metallic alloy that can outperform W-alloy. However, in addition to potential surface damage from helium ions, W or any metallic surface is sure to melt to some extent under the thermal dump of transient events such as edge localized modes (ELMs), or disruptions [23]. Therefore, in order to develop an acceptable robust PFM, an innovative approach for maintaining adequate material for vaporization to handle a limited number of transient events is needed. A proposal for holding an adequate low-Z material on the W-surface is to fill the indentations or toroidal grooves on a W surface with Si. Our initial trial with indentation is shown in Fig. 1. The indentations on the W-surface are designed with a diameter of 1 mm and a depth of 1 mm, on a W surface thickness of 2 mm. With a sufficiently large fraction of surface area filled with Si in the indentations, this material would allow for the possibility of protecting the W-substrate from the thermal dump of a disruption or high power ELMs via the vapor shielding effect. The W-surface was selected to have a thickness of ~2 mm to retain the capability of high heat transmission for power conversion. Button samples of this concept were fabricated as shown on the upper left side of Fig. 1. Si coatings can be seen on the two unexposed Si-filled W-buttons shown in the upper middle of Fig. 1.

## 6. Exposure and Results in DIII-D

Figure 1 also shows a photo of the Divertor Materials Evaluation System (DiMES) module located at the lower divertor of DIII-D [24] loaded with seven material button samples. As shown two Si-filled W-surface buttons are located on the left side, three graphite buttons are in the middle and two pure W-buttons are on the right side. The diameter of the DiMES module is 4.8 cm. DiMES module was exposed in piggyback mode in five plasma discharges. The outer strikepoints were about 4 cm inboard of the DiMES surface. Photos of the two Si-filled W-surface buttons exposed to four high power lower single-null high-beta, steady-state hybrid discharges of $B_T$ = 1.88 T and $I_p$ = 1.08 MA, are shown on the bottom left of Fig. 1. The same buttons exposed further to a disruption discharge at $B_T$ = 1.7 T and $I_p$ = 1.2 MA are shown on the bottom right. More details of these buttons are shown in Fig. 2.

For the disruption discharge we found that it had not positioned the thermal dump onto the DiMES surface, and it failed to demonstrate the beneficial effect of a vapor shield. We will attempt to perform similar experiments in the future with better positioning of the thermal dump from a disruption. However, encouraging results can be reported from these discharges. As shown in Figs. 1 and 2, after high power discharges nearly all the surface Si has been removed from the W-button, yet there is still a good amount of Si remaining in the W-indentations, which would be ready to provide a vapor shielding effect when a thermal dump reaches the Si-filled W-surface.

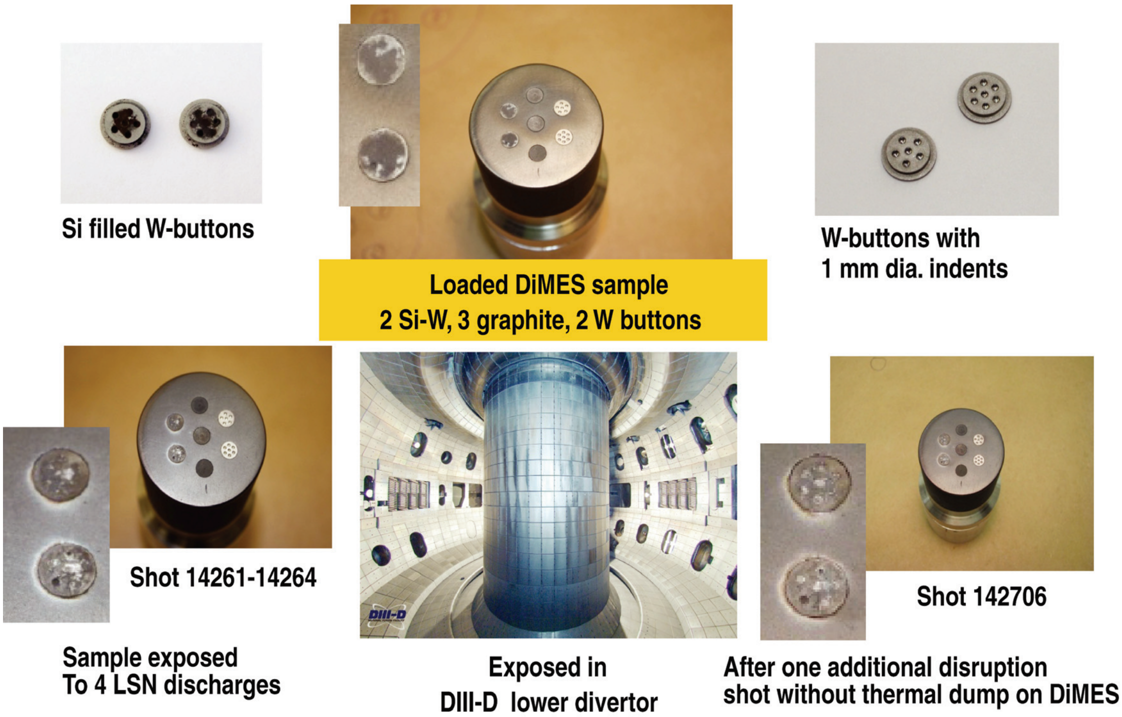


*FIG. 1. Initial results of transient tolerant Si-filled W-buttons exposed in DIII-D.*

Figure 2 shows some higher magnification views of the exposed Si-filled W-buttons from Energy Dispersive X-Ray (EDX) diagnostics. On the upper left side of the figure, we can see the melted Si surface material. On the right we can see the relatively clear surface of the W and graphite buttons, indicating the lack of Si transport during the discharges. During the disruption discharge, line radiation from 176–512 nm was monitored using an optical chord viewing the DiMES sample face directly with an Ocean Optics USB2000 spectrometer ($T_{int}$ = 100 ms, 0.164 nm/pixel dispersion, 1.07 nm optical resolution). Within the sensitivity limit of the instrument, we found that essentially all the radiation lines were from carbon; no verifiable Si or W lines were found during the disruption discharge.

We will continue to examine the results from this experiment and to determine the maximum heat flux and surface temperature during the four high power plasma discharges.

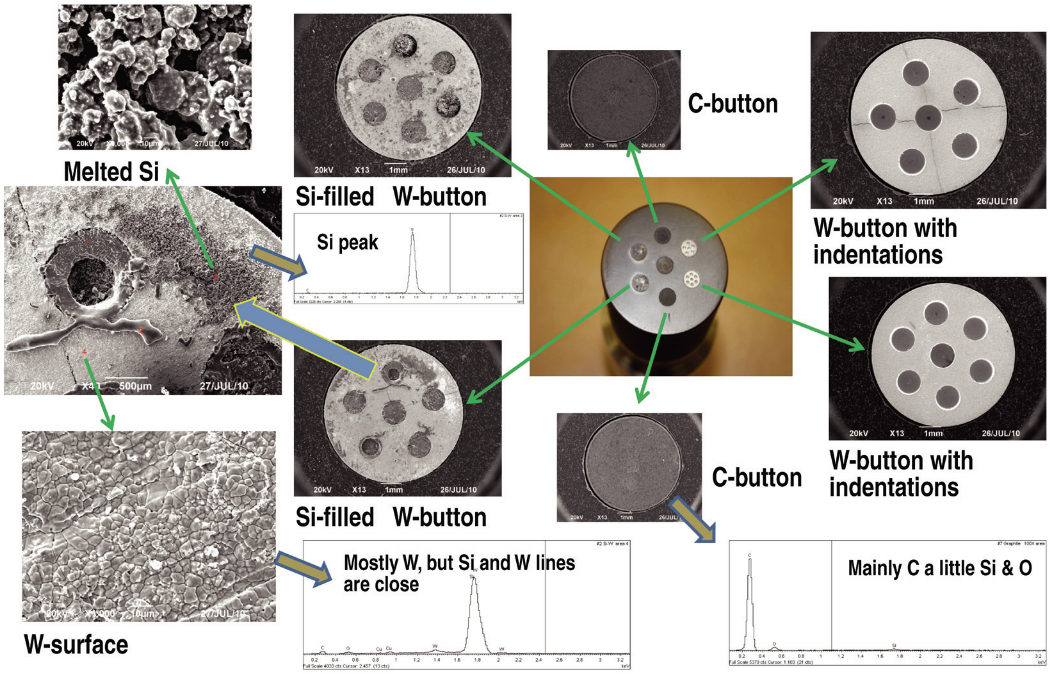


*FIG. 2. Details showing melted Si but minimal transport.*

## 7. Vapor Shielding Effects

One key necessity for the protection of the W substrate is the vapor shielding effect [25]. This observation is based on modeling results which show that for an ITER-like disruption, the thermal energy will be absorbed by vaporizing B and be radiated away from the bulk material. We used HEIGHTS comprehensive simulation package to study the effect of disruptions on plasma facing materials [26]. The preliminary analysis showed that a thin layer of B or Si will quickly evaporate and form a shielding layer to protect the W underneath it. This is credible since the melting point for B, Si and W are 2027°C, 1412°C and 3380°C, and corresponding boiling points are 3802°C, 2480°C and 5727°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-surface would occur. From the energy balance between energy dump and B vaporization, the estimated B layer removed per disruption with an energy density of 25 MJ/m$^2$ and impact duration of 0.1 ms, including the vapor shield effect, would be about <10 μm thick. Therefore, an equivalent B thickness of 1 mm could take a few disruptions without excessive damage to the W-surface. Similar results can be projected for Si but will need to be demonstrated by modeling and experiments. Si could be even more effective in protecting W due to its radiation properties. However, melt layer losses and splashing from hydrodynamic instabilities and overheating could result in significant erosion of the coating layer and expose more W surface to plasma streams [27]. We would like to demonstrate this disruption-tolerant characteristic in a tokamak in DIII-D in the near future.

## 8. First Wall and Divertor Design

In order to make use of the Si-filled W-surface concept, we have to consider its possible application to first wall chamber and divertor design. Taking into account the fact that we have to remove surface heat flux in the range of 0.5–1.0 MW/m$^2$ at the chamber wall and the maximum heat flux of around 10 MW/m$^2$ at the divertor, while fulfilling all the operation temperature limits of selected structural materials [28], the use of multi-layer material design is suggested. A four-layer design would consist of Si and W materials with the Si-filled W-surface on top of an oxide-dispersion ferritic steel layer, which is on top of the ferritic steel substrate structure material. These four materials/layers could be maintained with the necessary operating temperature range for the W-layer of 700° to 1300°C. This temperature range will also help in the release of tritium from Si. At the same time, the Si in background plasma or coated Si could protect against charged particle damage to the metallic substrate and mitigate the formation of W-fuzz. This high temperature operation will also be necessary to maintain a high chamber wall helium coolant temperature to satisfy the requirement of high thermal efficiency for a power reactor. Below the W surface, the oxide-dispersion ferritic steel layer would be operating within its temperature range of 500° to 700°C, thus allowing the structural material ferritic steel to operate below its maximum allowed temperature of 550°C. Details of this layered surface will have to be developed, but it points the direction on how future PFM and chamber wall components could be designed.

## 9. Critical Issues

The Si-filled W-surface concept is at an early stage of development; we started with the geometry of indentations and the concept will have to be further demonstrated and tested. Some of the key issues that need to be addressed are:

- Fabrication and testing of the Si-filled W-surface sample – A second set of suitable high purity W-surface buttons with indentations or toroidal grooves will be identified and filled with high purity Si. The use of toroidal grooves can reduce the number of W-surface edges intersecting the parallel heat flux. Transient events can be tested in tokamak and high heat flux test stands.

- Real time siliconization – The approach of real time siliconization can be demonstrated in operating tokamaks with minimal impact to their physics missions. In order to demonstrate the replenishment of vaporized Si, suitable Si-carrying gas, particles or pellets for real time siliconizaton will need to be selected and applied. Impacts from the location of the gas injector or Si-solid release will need to be studied in detail for various operating modes of the plasma discharge.

- First wall (FW) and divertor component development – With favorable results from the Si-filled W-surface concept, suitable Si-filled W-surface components for the FW and divertor surface will have to be designed, fabricated and tested in tokamaks and test stands. This includes the economical fabrication of the components including the joining of Si-filled W-surface to the multi-layer heat sink materials.

## 7. Conclusions

The concept of the Si-filled W-surface can be summarized as follows: A ~50% void W-surface can be filled with Si, with the goal of filling in all the open indentations or toroidal grooves. The first Si-filled W-surface buttons with indentations have been fabricated and exposed to high power discharges in DIII-D. Impacts from the high power thermal dump from disruptions still have to be demonstrated, but initial results support the retention of Si in the indentations of the W-surface, thus allowing the possible demonstration of vapor shielding effects during the thermal dump from disruptions. This early experiment demonstrates the possibility of developing a robust PFM design. Efforts will continue on the selection of suitable W material, indentations or groove geometry, and fabrication of the Si-filled W-surface. Key critical issues have been identified and the development of the Si-filled W-surface concept will continue. At the same time it is necessary to control and mitigate rapid transient events like disruptions, type-I ELMs and runaway charged particles in order to reduce the frequency of thermal dump to the chamber wall and divertor surfaces [29]. Additional efforts will also be needed to achieve uniformity of heat and particle flux distributions at the chamber wall, to minimize peak heat flux at the divertor and to learn how to maintain in real time the replenishment of Si in the indentations or toroidal grooves for steady state operation.

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