The Challenge in Compatibility of Main-chamber Materials with Next-Step Fusion Devices
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Background: A key part to the fusion materials challenge is the integration of the plasma/wall interface with the core plasma. The transport in the SOL/pedestal region will ultimately dictate how this plasma/wall interaction (PWI) will effect the fusion performance of reactors. In a typical high performance toroidal device with a divertor, e.g. an H-mode tokamak, the fluxes to the wall can be characterized for two regions: 1) the divertor region itself where particle fluxes need to be significant for pumping and heat fluxes are expected to be regulated by detachment. Here the erosion of the plasma facing material (PFM) is minimized by prompt local (re)deposition mechanisms in play for both low and high Z materials making net erosion much less than gross erosion; and 2) the main-chamber region, particle and heat fluxes are dominated by either charge-exchange or ions including ELMs. In this region, the prompt local (re)deposition is less than in the divertor making net erosion nearly equal to gross erosion. In addition to net erosion, which is a concern for PFM lifetime, a more important process, because of its impact on the fusion core/pedestal, is that this main-chamber eroded material has a high probability for penetration into the core. This is due to a combined effect of the longer ionization mean free paths and SOL flux compression away from the divertor in most confinement geometries. Here, shaping of the main-chamber wall components could help to reduce the impurity source.

Due in part to the different plasma/wall physics as discussed above, ITER will use a mixed-material PFM solution – high-Z in the divertor (W) and low-Z in the main chamber (Be). For devices beyond ITER, however, it is widely expected that an all high-Z PFM will be used. This raises the serious issue of core contamination in operating regimes needed for optimal fusion performance, but to-date other options have not been experimentally investigated that could be appropriate in a fusion reactor.

Additionally, in contrast with our understanding of PWI in the divertor region, understanding of PWI in the main-chamber is not only more challenging (since the main-chamber is seldom toroidally symmetric and therefore diagnosis is complex) but it has also been much less pursued. Illustrating this point: since the 2009 ReNEW workshop and even before, this area has been effectively dropped in worldwide fusion efforts. A basic summary of this topic was given by Roth et al. [1] around the time of the ReNEW workshop, which still describes the state of the physics understanding/validation of main-chamber PWI:

“In contrast to the divertor, the present understanding of particle and energy fluxes, at the first wall of ITER is more uncertain. Present experimental and modeling results indicate that the flux of neutrals, produced by charge-exchange processes between the incoming cold recycling D/T neutrals and hot edge plasma ions, is in the range of $10^{19}$-$10^{21}$ m$^{-2}$s$^{-1}$ with typical energies ~ 8 – 300 eV, but extending into the keV range. In addition to neutral particles, ion fluxes can also reach the first wall, in particular due to plasma turbulence which results in transport perpendicular to the field lines.”

Taken together, the above concerns highlight a serious worldwide gap in our understanding and capability to move forward with confidence to ITER and beyond, and therefore this whitepaper is calling for a focused effort on this specific topic such as described in the following section.

Proposed Approach: The guiding philosophy proposed here is that of ‘separation of functionality’, a phrase introduced by Stoneham et al [2] in 2004 although it describes an ubiquitous engineering science principle: “There are three main avenues proposed in this work for designing materials for fusion power plant: new carbon-based materials as coatings, tailored alloys, and innovative composites designed to separate functionality through its components” [2]. In the context of fusion materials, examples of function separation would include properties such as: mechanical strength; erosion/ablation resistance;
thermal conduction; neutron damage resistance; and tritium retention, to name a few.

Within the specific context of this whitepaper and given the different divertor and main-chamber PWI processes, separate solutions for each region are envisaged. Specifically, a process that: (i) for the main wall incorporates in-situ refurbishable low-Z refractory coatings such as C, B and/or Si be used on a structural substrate which is resistant to neutron damage; and (ii) strong divertor detachment be used, which results in deposition of low-Z wall material on the targets eliminating target erosion [3]. This concept is similar to the already established and widely accepted wall conditioning techniques of carbonization, boronization, and/or siliconization. The most important difference for long-pulse/high-duty cycle devices is that the low-Z PFC slag accumulating in the divertor elsewhere will have to be managed so as not to disrupt plasma operation [4]. New/novel coatings or materials, developed through, for example, new manufacturing techniques, that reduce or minimize these main-chamber erosion processes should also be fully explored; such materials and techniques are still in their infancy but are being vigorously pursued for a wide range of practical applications outside fusion.

Success in the development of such a main-chamber PFM solution will require detailed characterization and understanding of main-chamber PWI. The outstanding main-chamber PWI issues were highlighted over a decade ago by Philipps et al [5], and the lack of adequate understanding of these issues remains the situation today. The principal issues needing to be addressed are:

- Identify and characterize the locations and strengths of main chamber impurity sources (including components needed for sustained operation, such as RF antennas) on the core plasma performance,
- Identify and characterize the contribution of ion- and neutral-induced erosion, including the fast-ion loss component, and also from fusion products born on prompt loss orbits,
- Identify the fraction of erosion due to transients (e.g. ELMs and/or disruptions),
- Characterize the dependence of ELM-induced erosion on the ELM type and parameters.

The challenge of these tasks can scarcely be understated and has contributed to the lack of viable solutions in this area. A coordinated effort involving multiple devices and disciplines is needed. This coordination should include the materials science, the PMI science, and the plasma physics communities. Such close collaboration is needed for understanding and to develop potential solutions (e.g. additive manufacturing, and/or nano-composite materials), which will then be taken through the development and evaluation process in plasma devices with the necessary and complimentary measurements. Such an evaluation process should be pursued through a reinvigorated measurement capability/focus [6] and/or with the in-situ testing of solutions in tokamaks [4]. The plasma device testing should include both linear and toroidal plasma devices, both short and long pulse. Such an approach will provide understanding and innovation opportunities coupled with sufficient evaluation capability to mitigate risk and will thereby increase the readiness of potential solutions for application in any future next-step device.

The US fusion community is well placed to enact the above approach to address this main-chamber-materials challenge. With a world-class fusion materials community, a portfolio of short-pulse toroidal devices that are positioned to address a wide-range of main-chamber PWI issues (covering low-Z (DIII-D), high-Z (CMOD), and liquid metal (NSTX-U) solutions), and community-driving advisory panels emphasizing this general topic for many years, especially with respect to the coming “ITER era”, the urgency for this type of initiative has been well articulated and stressed. Given this confluence, the elements are in place for the US to take a world-leading role in this specific area of main-chamber PFM solutions. Missing from the US mix is, of course, a long-pulse toroidal device and therefore international collaboration with the number of new long-pulse devices is called for as well.

**Anticipated Result/Impact:** The challenge to find a solution for main-chamber plasma facing components that are viable in next-step devices beyond ITER is clear. Solutions with either all low-Z or all high-Z PFM have serious shortcomings. It is proposed here that solutions involving separation of function be investigated for low-Z refractory coatings on structural substrates that are resistant to neutron damage in a focused, coordinated effort with a multi-discipline and multi-device emphasis.
References:
[4] PC Stangeby et al., Flow-through solid PFCs using carbon or other low-Z refractory coatings, OFES PMI Workshop Whitepaper, see this conference.
[6] D Buchenauer et al., Neutral H sensor for C-X H flux on wall and divertor, OFES PMI Workshop Whitepaper, see this conference.