Development and qualification of innovative advanced refractory alloys for steady-state burning plasma-wall interface materials

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Overview and Motivation

Of the various materials options at the plasma-material interface (i.e., graphite, liquid metals, etc...) refractories are an attractive option for steady-state, high-temperature (700-1000 C) operation with heat fluxes between 10-20 MW/m^2. However, Mo and W have serious materials issues regarding radiation tolerance (brittle fracture, hardening, swelling, transmutation, etc...even at high temperatures [1]) and hydrogen retention/permeation that must be addressed to make them a viable option for steady-state burning plasma operation in fusion reactors (e.g. DEMO).

The approach presented here is the coupling of a low-Z component alloyed with an ultra-fine grain (UFG) refractory material. The low-Z component should have a lower surface tension than the refractory matrix such that when operated at high temperature and under intense particle irradiation, the low-Z component is “driven” to the plasma-material interface by means of both thermodynamic segregation and radiation-induced diffusion mechanisms. One particularly attractive low-Z component is lithium (although others such as Be or B may work). Focus on lithium alloyed with tungsten, for example, is based on recent progress in understanding its surface properties [2,3] and progress in radiation-resistant UFG (ultra-fine grain) refractory materials including UFG metal alloys (e.g. W) dispersed with metal-carbides [4]. In particular in this white paper the combination of both a low-Z radiation-driven component (Li or other compatible low-Z material) with an UFG refractory (UFG-W in this case) is proposed as an optimal PWI material. This design would allow for the low-Z component to conform to the radiation-resistant high-performance structural material (e.g. W or other refractory) to allow operation under hot (T>700C) reactor conditions.

Low-Z radiation-driven refractory alloys along with other low-Z coating concepts must be investigated rigorously in a comprehensive and coordinated experimental plan that links particle-beam, plasma devices and novel *in-situ* PMI diagnostics in existing and future tokamaks together with erosion/re-deposition computational modeling. In particular, testing of such ideas should be done in proposed long-pulse, high heat-flux, hot-wall devices such as NHTX (Goldston) or Vulcan (Whyte). More importantly, such materials must also be designed in line with advanced divertor geometries such as super-X (Kotschenreuther et al.) and others to broaden the scope of PWI materials qualification.

Linking erosion/re-deposition models validated with off-line experimental facilities to the complex plasma edge environment has found some successes, however predicting overall surface evolution and behavior under complex synergistic particle irradiation effects remains elusive. *We must couple well-diagnosed in-situ off-line experiments that qualify candidate materials using single-effect science to elucidate on dynamic surface response compatible with future fusion reactor environments.*

In coordination with off-line experiments there needs to be a direct coupling with *in-situ* PMI tokamak diagnostics used with computational modeling to enhance our qualification of materials options. This approach deviates from the common paradigm to treat the plasma-wall interface as a “black box” while we condition it and watch for effects on the confined plasma. *Materials options are scarce and thus we must design a plasma-material interface that is as “simple as* *possible" while remaining "as robust as possible" in future reactor environments. Taming the plasma-material interface may mean designing a material compatible with the notion it will erode under the violent reactor edge plasma environment it interacts with.* For example, off-line *in-situ* experiments that test hydrogen retention during multi-particle bombardment of the proposed advanced refractory alloys can be coordinated with *in-situ* tokamak PMI probes under well-diagnosed (i.e. divertor diagnostics) conditions.

Objective

The objective of this white paper is to introduce a small thrust or part of a larger thrust to achieve three goals:

- Establish new *in-situ* PWI materials science facilities to identify and qualify new materials
- Design and test new innovative advanced refractory alloys for the PWI
- Couple investigation in single-effect science to robust tokamak PMI in-situ diagnostics

Innovative PWI Materials

The PWI material must be compatible with the fuel and plasma environment. The PFC material must be compatible with the thermal and neutron load, particularly during transients. To commensurate the two, a low Z-refractory alloy may work provided it maintains a nearly 100% plasma-facing surface of the low-Z component.

Radiation-driven UFG refractory alloys

As stated earlier the approach presented here is the combination in solid solution of a low-Z radiation-driven component designed for the PWI with an UFG refractory material (which can also be dispersed with carbides or other precipitates) designed for the sub-surface and bulk regions compatible with operation under hot (T>700C) reactor conditions. Surface free energy in combination with ion-induced effects and temps ~ 500-1000 C can drive large amounts of a low-Z component (e.g. Li or B) to the surface while still keeping many of the major component properties of the alloy unchanged (e.g. H retention, low vapor pressure, etc...). Since erosion and recombination at surfaces for the incident particle energy distributions occur predominantly in the first 10's nm from the surface, this region could be dominated (in principle > 99%) by segregated low Z species. In addition, the overall erosion levels from this region would be in principle reduced to the segregated low Z component.

The plasma wall interface (PWI) contains a surface dynamically modified by the edge plasma and thus the plasma-facing surface must be compatible. Therefore the surface material should: 1) have if possible the most simple metal, 2) easily mobile in the condensed state (for self-healing), 3) minimal plasma intrusion (low radiative plasma losses), 4) least erosive (high redeposition fractions), 5) most adaptable to plasma environment (easily ionizable, ELM suppression, particle control) and lastly should be compatible with radiation-resistant bulk material that can operate at temperature near 700-1000 C.

Lithium-based refractory alloys would likely be compatible with both atomistic erosion during steady-state operation and transient events. Why lithium? Lithium is the simplest metal having a nearly spherical Fermi surface and thus having predictable condensed matter properties. Lithium coatings and dopants also can enhance use of graphite in a steady-state burning plasma environments. Lithium is likely the most adaptable metal to a plasma environment having a large second ionization potential and known for large (>99%) re-deposition fraction with almost zero net erosion during "normal" operation. During "off-normal" transient events, lithium can provide vapor shielding of the underlying structural material with minimal radiation power losses. Lithium as an alloy has 4 orders of magnitude lower vapor pressure compared to pure lithium surfaces [5]. Lithium in a refractory matrix has low cohesive energy allowing it to self-recover under particle irradiation during generation of Frenkel and subsequent temporal evolution of freely migrating defects in the collision cascade zone.

New facilities or upgraded facilities for identifying and qualifying innovative materials designs

Off-line test stand for PMI materials science

Off-line facilities should be designed to provide *in-situ surface dynamic measurement* of innovative materials to quickly test fundamental properties that can be accelerated for further testing in more complex environments or phased environments: linear plasma device and fusion device. These can be well-diagnosed particle-beam facilities with tunable and versatile parameter space. One should avoid simulated experimental environments that may be end up being *"neither fish nor fowl"*, rather these new facilities can work closely with upgraded existing linear devices (e.g. PISCES-B) and use them in conjunction with robust PMI probe diagnostics and advanced computational modeling to speed up design of novel PWI materials.

There also exists a gap between materials modeling and experimental techniques that can elucidate on not only the fundamental damage mechanisms in the complex plasma edge environment but also on the particle-induced material evolution during steady state and transient plasma events. *In particular how the PWI at length scales less than a micron couple to structural effects of depths of a few microns or more.* Therefore, these facilities can also introduce appropriate energetic particle-beams to study the bulk/surface interface to elucidate effects on retention, diffusion, segregation, permeation and phase transformation (among other mechanisms).

In-situ Tokamak PMI diagnostics

Addition of both on-line and off-line *in-situ* diagnostics that can directly elucidate on dynamic mechanisms (e.g. synergistic effects of D and He on surface retention and recombination, etc...) are critical to the qualification of reactor-compatible PWI materials. In this regard as stated before, probing must cover a wide spectrum of depth scales from the first few 100's nm (where sputtering and recombination are dominant) to regions about 1 micron and then 10's of microns into the bulk. These probes must be coupled to study dynamic materials effects at the PWI.

Facilities: *Off-line particle-beam test stand $2M, In-situ tokamak PMI diagnostics $2.5M + labor per annum*

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