Establishing the surface science and engineering of plasma-facing liquid-metal PFCs

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Near-surface interactions between the energetic particles from fusion plasma and its interface with the wall have been known to be important for decades (e.g. wall conditioning effects on plasma performance). Lack of fundamental understanding of the dynamic coupling of plasma and the plasma-facing material surface has hindered extrapolation of current fusion PFC materials performance to future burning fusion plasma reactor conditions. On the other hand, key uncertainties exist for PFC liquid materials in future burning-plasma reactor scenarios (some unique to only liquids) including: hydrogen/helium particle-surface interactions and materials migration, plasma-induced erosion and re-deposition, materials mixing, high-temperature operation, and liquid-metal surface/interface stability. The fundamental question is: Can liquids provide a viable pathway for a robust PFC that can be confidently expected to meet the performance requirements of a next-step burning-plasma device, e.g.. FNSF?

This proposal is an integral element of a broader liquid metal PFC initiative (see FESAC abstracts by R. Maingi and by M. Jaworski). We propose to establish the surface science and engineering of plasma-facing liquid-based PFCs addressing four major knowledge gaps: 1) understanding the free-surface flowing liquid stability in fusion reactor environments, 2) elucidating fuel and particle control in plasma-facing liquid surfaces, 3) deciphering the temperature limits of plasma-facing liquid surfaces, and 4) establishing computational materials science of plasma-exposed liquid surfaces.

We will address the four major knowledge gaps by combining surface science and in-situ irradiation studies in ex-vessel test stand laboratory experiments, high heat flux linear plasma devices and confinement devices. In particular we will conduct fundamental single-effect surface science studies with multi-effect in-situ irradiation studies of a collection of candidate liquid-metal materials coupled to multi-scale computational materials science codes. Surface science test-stand facilities will be tailored to: carry out fundamental, single particle/single energy, controlled environment, controlled temperature, and known substrate structure and composition studies for candidate liquid-metal materials. In-situ irradiation test stands will combine measurements of liquid-metal surface properties (e.g. sputtering, hydrogen recycling and retention, helium pumping, surface chemistry and morphology) under realistic fusion conditions of particle energy, incident angle, flux and temperature. Connection of fundamental experiments in ex-vessel test stands will be systematically connected to more complex fusion-like environments with in-situ PMI diagnostics on linear plasma devices and ultimately in toroidal-relevant confinement devices. Computational materials science will be systematically validated in ex-vessel test stands providing for predictive boundary conditions to plasma edge codes used in conjunction with PMI diagnostics in confinement devices.