High-Level Fusion Physics and Materials Interface Challenges

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The long range strategic vision of the U.S. Fusion Energy Science Program is to support the design and operation of a burning plasma experiment (ITER), to develop a program that might include a Fusion Nuclear Science Facility (FNSF), to test materials under severe and fusion relevant conditions at high neutron fluence, and to proceed with DEMO. This development path for fusion energy provides appropriate guidance for near term priorities in the Fusion Energy Science Program. It is important that the U.S. fusion program complete the near term critical research and development (R&D) activities over the next 8-10 years required to be in a position to move forward with the design and construction of FNSF, in expectation that funding might be made available perhaps from the decreasing funding required for ITER. Based on the design of ITER and recent U.S. program review reports [1-4], we can identify a number of high priority research areas that address material and material-plasma interface challenges. These research areas can be addressed with focused task groups using existing hardware and with necessary close collaboration between the physics, technology and materials communities.

Recommendation

We propose five high-level research areas to prepare for FNSF that can be addressed with appropriate funding and focused task groups using facilities available in the U.S. and internationally.

1. Tritium

It is clear that tritium supply, inventory, breeding, recovery, safety and leakage are critical for the development of a DT magnetic fusion program. Correspondingly, a key parameter for all of these areas that must be fully understood and predictable is the plasma burn-up fraction. This parameter is a function of plasma fueling, tritium burn-up, wall-recycling, fuel pumping, fuel cycle and plasma operation and choice of PFC materials and design details. As an example, improvement on the technology to immediately recycle the plasma exhaust would greatly reduce the tritium inventory to be processed by the reactor's tritium plant.

2. Heat Flux Distribution

Due mainly to parallel heat flux, there is a disconnect between the ITER-specified chamber heat flux of 1-5 MW/m^2 and the ARIES-type power reactor having a specified chamber surface heat flux of ~0.5 MW/m^2. There is another disconnect between the ITER-specified divertor maximum heat flux ~10 MW/m^2 and the much higher heat flux projected for FNSF and DEMO with maximum heat flux of >>10 MW/m^2, which can easily exceed available materials design limits. The chamber wall heat flux must be addressed by the control of ELMs and radial transport, and the divertor heat flux distribution will have to be derived from scrape off layer (SOL) physics and the divertor plasma operation and divertor geometric configuration. The potential solution approaches to these coupled physics and technology issues will have to be understood and fully assessed before an acceptable solution can be found.

3. Plasma Facing Material (PFM)

Tungsten (W) is the only surface material being considered for DT machines, but there are problems with the formation of W-fuzz and blisters formation under high temperature and fluence. The transport of W into the plasma can also limit the performance of the tokamak. Possible solution approaches will have to be investigated and selected. Such approaches could include a real-time conditioning of the W-surface with a low-Z material such as, B, Si and C. This solution can only be obtained by close collaboration between experts on plasma operation and SOL physics, and experts on material transport and surface material behavior. Consideration also has to be given to external systems design, especially when tritium extraction, inventory, control, fueling and safety are involved. Techniques for dust and co-deposited layer minimization or removal inside of the vacuum vessel are needed even for FNSF.

4. Plasma Transient Events

Transient type-I ELMs, disruptions, and runaway electrons will damage chamber wall and divertor surface materials in reactor-grade devices**.** The present approach includes reliable plasma control to minimize the incidence of transient events and mitigation of damaging effects when machine faults produce such events. A more comprehensive integrated assessment of FNSF/DEMO control and operation, and machine availability requirements, and the corresponding maintenance approach will have to be performed self-consistently in order to make credible FNSF/DEMO recommendations. This will include the choice and use of heating and current drive systems, normal versus superconducting coils, the possible use of de-mountable superconducting coils and steady state versus day-long pulsed operation scenarios.

5. Materials Radiation Damage

There is inadequate data for material damage from 14 MeV neutrons, particularly and at high enough fluence for PFC and in-vessel components. Plasma operation and the understanding of SOL and chamber component design, including the choice of PFM, will have an impact on PFC design. Plasma material interaction physicists will have to work with PFM experts and neutronics and irradiation damage material experts to propose recommendations to address this challenge. PFM and PFC themselves will have major impacts on the selection of structural material and corresponding functional materials, such as joining and welding materials. It becomes essential for the physics and material communities to understand each other in order to recommend neutron source devices that can provide the correct high dpa, gaseous (helium, hydrogen) generation and metallic transmutations and helium/dpa ratios in order to project radiation damage caused by DT fusion neutrons. Bootstrap development of the suitable structural material will have major impacts on the necessary fusion power core change-out approaches. This will bring the communities together in order to seriously address this challenge.

References

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