ReNeW White Paper: Plasma Material Interactions (PMI)-Thrust for Enhancing Modeling & Predictive Computations

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Motivation

Plasma/material interactions (PMI) is one of the most critical issues for magnetic fusion. Key PMI issues are: 1) Plasma Facing Component (PFC) sputtering erosion/redeposition including erosion lifetime, plasma contamination, and tritium codeposition, 2) surface response to plasma transients including Edge Localized Modes (ELM's), disruptions, Vertical Displacement Events (VDE's), and runaway electrons, 3) effect of PMI on plasma SOL, edge, and core parameters, and 4) other plasma induced surface changes/properties including He and D-T driven nano-structure ("fuzz") formation in tungsten, and dust formation/transport.

The US is generally considered the world leader in PMI modeling with a 20+ year history in the US fusion program for computational modeling of PMI, incorporating theory/modeling, computer code development, and experimental validation. Analysis has been made for essentially every major US and world tokamak (TFTR, JET, DIII-D, NSTX, CMOD, TEXOR, etc.), future devices (ITER, DEMO), and numerous other devices (e.g. plasma arc-discharge simulators, plasma guns, mirror-machines).

In spite of this effort, there are major gaps in modeling, analysis, and understanding the PFC response in existing machines, ITER, and certainly post-ITER devices. Such understanding is critically needed for ITER and DEMO; for example it is not clear whether future machines will survive the projected steady-state heat load, let alone even one major disruption or sustained ELM activity. It is likewise highly unclear what limits the PFC response will impose on the core plasma. This thrust proposes a coordinated, increased effort to remedy this situation, whereby a reasonable funding increment in this area, will be highly cost effective in advancing our predictive analysis capability and identification of the best material choices, plasma operating modes, and plasma facing component designs.

Existing US PMI Modeling Capability

Two major PMI code packages in use in the US are: 1) OMEGA Collaboration, 2) HEIGHTS Code Package. OMEGA consists of US codes and code-packages, for plasma parameter computation in the plasma edge/scrape-off-layer (SOL) (UEDGE plasma and DEGAS neutrals codes, and kinetic plasma add-on packages to same), erosion/redeposition analysis (REDEP/WBC), and related codes for sputter yield computation (e.g. TRIM-SP, MD codes), tokamak type sheath computation, material sputtering/D-T and He recycle, mixed-material evolution, and so on. OMEGA is not coupled real-time, but rather uses coupling via individual efforts and coordination.

The HEIGHTS code package consists of coupled codes for computing plasma transient deposition on surfaces, vapor formation, radiation transport, atomic data, MHD, and surface thermal conduction and hydraulics. The package computes the surface and plasma response to the above mentioned ELMs, disruptions, and other plasma transients.

There are additionally US models/codes for such areas as dust formation/transport, atomic and molecular processes, liquid metal surface properties, and the like.

There have been successful efforts at code validation, e.g. with REDEP package showing good code/data comparisons with PISCES-B and DIII-D results for physically sputtered carbon and tungsten, and HEIGHTS comparisons for eroded material after plasma gun and fusion device surface irradiation.

Gaps

As summarized in e.g. [1], these are extensive gaps in existing PMI theory, modeling/code efforts and experimental validation, including:

1. Analyzing/explaining many existing results, e.g. CMOD Mo divertor tile erosion results, chemically sputtered carbon in DIII-D (and liquid lithium and solid vanadium DIII-D DiMES probe results), enhanced plasma performance in NSTX lithium shots, as well as for numerous international machines where the US could make a substantial contribution.
2. Model development and analysis of scaling and intermittent character of SOL turbulent transport determining heat-flux and particle-flux profiles on PFCs (divertor, walls), and subsequent impurity transport back to core.
3. Mixed materials (e.g. Be/W, C/W): plasma induced formation and response.
4. Sheath: wall near-tangential sheath parameters, this being critically important in ion acceleration and heat transmission; ICRF induced sheath and effects for ITER and future devices.
5. Liquid metal surface (Li, Sn, Ga) response including He and D-T pumping/reflection and effect of same on edge/core plasma, temperature-dependent sputter yields, sputtered/evaporated material in-plasma transport.
6. Tungsten nanostructure changes due to He, N, etc.
7. Dust formation and transport.
8. Plasma transient effects and resulting core-plasma operating limitations in ITER and DEMO, and solutions to same.
9. Atomic and molecular data-gaps in database.
10. Hydrogen isotope retention in He and D-T irradiated materials.
11. Supercomputing-There is a general major need to develop/improve stand-alone PMI supercomputer capability (in particular via implementing OMEGA real-time coupling) as well as to incorporate PMI code packages into integrated (SCIDAC, FSP etc.) projects.

Funding

We propose an initial 5 year thrust for the US PMI program, to help remedy the existing gap situation. This would be used for a coordinated program to augment theory, model and code development, and validation with existing machines. We would also interact strongly with our world fusion program colleagues. A follow on program continuing this effort as well using new facilities would also be defined. An output of this thrust would be improved predictions of plasma facing component performance and required plasma operating limits for ITER and beyond, and understanding of needed plasma/material interaction R&D.

Tasks

- Plasma Material Interaction (PMI) model and code development upgrade.
- Theory, as needed to support above.
- Validation efforts-experiments, modeling, and code/data comparison on existing US and world-fusion program devices and off-line test stands (e.g. beam accelerators, linear plasma devices etc.).
- Validation-on new devices if/when available.

Funding

- Modest effort (Option 1) 7 M$ (1.4 M$/yr for 5 yrs)
- Moderate effort (Option 2) 15 M$ (3 M$/yr for 5 yrs)

We are on a steep portion of the “learning curve”. Option 1 would permit significant enhancement to the existing highly-underfunded modeling/computation capability, but still leaving significant gaps. Option 2 would permit faster remediation. Cost of both options includes modest increases in experimental capability, e.g., addition of low-cost diagnostics, but does not include major facility construction or major upgrades-these will be the subject of other ReNeW panel thrust areas.

Also, efforts for this research thrust would interact with thrusts to increase operating time and/or add major diagnostics on existing devices, new device construction, supercomputer applications (e.g., Fusion Simulation Project), transient plasma control, core plasma theory/modeling, and similar relevant areas.

Reference

1. R. Goldston and the ReNeW PMI Panel, “PWI Gaps vs. Tools to Develop Understanding and Control”