ReNeW White Paper: Thrust for Enhancing Modeling and Simulation of Plasma Instabilities/Surface Interactions with innovative mitigation techniques

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Motivation

Plasma/material interactions (PMI) during four types of plasma transient/instabilities is a critical issue for magnetic fusion. Key concerns are: 1) Plasma Facing Component (PFC) erosion lifetime, structural integrity, and plasma contamination. The major events for surface and structural response to plasma transients are Edge Localized Modes (ELM's), disruptions, Vertical Displacement Events (VDE's), and runaway electrons.

The US is the world leader in PMI transient/surface-interaction modeling with a 20+ year history in the US fusion program incorporating theory/modeling, computer code development, and experimental validation. Analysis has been made for numerous devices such as DIII-D ITER, and plasma guns, laser and z-pinch machines, and powerful electron beams.

In spite of this effort, there are very serious gaps in modeling, analysis, and understanding the PFC transient response in existing machines, ITER, and future DEMO machines. Such understanding is critically needed for ITER and DEMO; for example it is not clear whether future machines will survive the projected ELMs frequency, one major disruption, one VDE, or one runaway electron event. This thrust proposes an integrated effort to comprehensively answer these questions and predict/analyze all possible mitigation methods and innovative plasma facing component designs.

Existing US PMI Modeling Capability

The major PMI transient response analysis tool in use in the US is the HEIGHTS Computer Code Package. HEIGHTS package is considered the world's premier capability to study full 3D transient material/structure response due to sudden and intense energy deposition. This package consists of coupled codes for computing plasma transient deposition on surfaces [1-5], vapor formation [6], radiation transport [7, 8], atomic data [9], MHD [10, 11], and surface thermal conduction and hydraulics [12,13]. The package computes the surface/structure and plasma response to the above-mentioned ELMs, disruptions, VDEs, and runaway electrons [1, 13, 14].

The main theme of HEIGHTS modeling is fully integrated simulation analysis of various plasma transient events in 3D geometry. There have been many successful efforts at code validation, e.g. HEIGHTS comparisons for eroded material, plasma shield formation, and cloud expansion after plasma gun and fusion device surface irradiation. The models used in the integrated HEIGHTS code were recently benchmarked against VDE simulation experiments using powerful electron beam and have an excellent agreement with the data [13, 14].

What is lacking:
There are extensive gaps in existing PMI surface/plasma-transient interaction theory, modeling/code efforts and experimental validation, including:

1. Model development and coupling of energy transport from core to SOL & turbulent transport to PFCs (divertor, walls).
3. Mixed materials effects (Be, C, and W) on plasma vapor formation/shield induced formation and response.
4. Melt layer formation and splashing
5. Liquid metal surface (Li, Sn, Ga) response to plasma transients and effect on SOL/core plasma,
6. PFC structural changes due to impact of instabilities.
7. Droplet and dust formation and transport.
8. Transient effects on resulting core-plasma operating limitations in ITER and DEMO, and solutions to same.
9. Dynamic coupling between Core, SOL, and PFC surface during instabilities
10. Detailed analysis of various mitigation methods in full 3D tokamak geometry, for example, liquid metal (flow, splashing, contamination, etc), pellet injection (dynamic behavior of plasma during injection, radiation losses, radiation deposition on nearby components, etc).

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. Output of this thrust would be improved predictions of plasma facing component transient performance and required plasma operating limits for ITER and beyond, and understanding of needed plasma/material interaction R&D. Most importantly is to find innovative mitigation techniques and design options for tolerating transient events through integrated simulations and PMI experiments. This thrust would interact with other PMI modeling and experimental efforts, e.g., a general PMI modeling enhancement thrust [15], and new facility, facility upgrade projects generally.

Tasks
- Plasma Material Interaction (PMI) model and code development upgrade for plasma transient/plasma-material response.
- 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. plasma electron, ion guns, and z-pinch devices.).

- Validation-on new devices of laser produced plasma and z-pinch devices at the newly established CMUXE laboratory at Purdue and also devices at UIUC.

Funding

- Request: 7.5 M$ (1.5 M$/yr for 5 yrs)

The cost includes augmented support for operating the experimental capabilities at the newly established CMUXE laboratory, e.g., Laser and discharge produced plasma devices, diagnostics, etc.

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