Plasma Surface Interactions SciDAC: Dynamic plasma material surface interactions at the edge of a magnetically confined fusion reactor

Abstract
The PSI SciDAC is developing coupled models for the dynamic interaction between plasma and material surfaces at the edge of a magnetically confined fusion energy reactor. Our goals are to determine the importance of intermittent transient events such as edge localized modes (ELMs) on impurity production and material erosion and to understand how plasma impacts impurities in both the plasma and material surfaces. Hence, we are developing a model of ELM heat pulse using the 4D guiding center COGENT kinetic code and a model of divertor plasma turbulence using the 3D BOUT++ framework. Ultimately, we will couple these models with microscopic models of the walls and study the physics of the coupled system.

Motivation
ITER will be the first tokamak to achieve Q>10 and produce 500 MW of fusion power. An important goal of the PSI SciDAC is to develop models that predict the performance of divertor plasma facing components (PFCs) with respect to impurity production and material migration, because these surfaces are exposed to extreme particle and heat loads. However, such predictions are challenging because they require multiphysics models that span many orders of magnitude in spatial and temporal scales.

Moreover, the plasma fluxes are dominated by intermittent and turbulent events, such as ELMs, which are intense filamentary structures that are ejected from the core to the edge. Fundamental research questions are: Do plasma-wall interactions cause intermittent oscillations & instabilities? Will plasma-wall interactions change the character of plasma near material surfaces?

Approach
In order to develop predictive capability, high-fidelity models for both the edge plasma and material PFCs must be coupled together. We plan to study the physics as well as the dependence of simulation performance on the choice of numerical coupling algorithm. Our main focus will be on simplified slab and cylindrical geometries which nonetheless can handle the most important effects of toroidal geometry: magnetic field line pitch and field line curvature χ.

Results: ELM Heat Pulse
COGENT solves the guiding center kinetic equation in slab geometry
\[ \frac{\partial}{\partial t} \left( \frac{1}{2} N \right) + \nabla \cdot \left( N \mathbf{v} \right) = 0 \]

JET-like SOL
\[ B_e = 3 \: T \: B_i = 0.3 \: T \]

\[ N_{exp} = 5 \times 10^{19} \: m^{-3}, T_e = 1.5 \: keV \]

The ELM heat pulse benchmark [7-8] is specified by imposing Maxwellian source with \( T=1.5 \: keV \) and \( S=9.1 \times 10^{17} \: m^{2} \cdot s^{-1} \); initial conditions chosen to match Ref. [8]. Simulations here use kinetic ions and adiabatic electrons:
\[ v_{e} = \frac{e}{m_{e}} \cdot T_{e} \cdot \nabla \cdot \left( \frac{1}{2} m_{e} \mathbf{v} \right) \]

Results for 0.4 MW ELM pulse lasting 200μs:
\[ Q_{pump} \approx 5.5 \: GW/m^{2} \]

Peak heat flux saturates as a function of ELM duration

Distribution function becomes significantly non-Maxwellian for collisionless simulation

Arison temperature \( T_{ar} \approx 1.5 \: keV \)

Sonic outflow near target plates → transition to 1/3 Maxwellian

Conformal mapping can be used to simulate divertor geometry

ITER tokamak
divertor cassette
ELM filaments induce D\(_{e}\) emission near walls and cause target plate erosion

Dynamic Plasma-Wall Coupling
Our first goal is to test the explicit coupling strategy using simplified models: the 2D UEDGE [9] edge plasma transport code and the 1D FACE wall model [5].

Example of a dynamic simulation of an initially pure tungsten wall that absorbs hydrogen until the recycling coefficient becomes nearly unity. The evolution of the ion and neutral densities and temperatures and the predicted recycling coefficient \( \Gamma \) are shown for an explicitly coupled simulation using the UEDGE and FACE codes.

Coupling is performed via explicit data exchange on each coupling time step. Each code subsamples its own time step using backward Euler implicit integration. Coupling time step increases exponentially as simulation proceeds (x1.024/step).

Conclusions
The PSI SciDAC is developing dynamically coupled plasma-wall models.

- Ultimate goal is to predict the dynamic recycling of main ions and impurity ions between plasma and plasma facing components as well as the erosion of material surfaces that are impacted by large transient events such as a major ELM.

- ELM heat pulse benchmark has been simulated using an adiabatic Boltzmann electron transport code.

- Results compare well to previous fluid and kinetic studies.

- Future work will extend to two kinetic species: both ions and electrons

- Divertor-relevant turbulence model is being developed within BOUT++ framework.

- PFCs are observed to load with H particles until a slowly evolving quasi-equilibrium state is achieved.

- Future work will focus on coupling more complex plasma and wall models.

References

This work was performed under the auspices of the U.S. DOE by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and is supported by the U.S. DOE Office of Science, Office of Fusion Energy Sciences, and Office of Advanced Scientific Computing Research. The Xolotl Plasma-Surface Interactions (SciDAC) project on Plasma-Surface Interactions.

I. Joseph\(^1\), M. R. Dorr\(^1\), M. A. Dorf\(^1\), J. Guterj\(^2\), S. I. Krasheninnikov\(^3\), R. D. Smirnov\(^4\), M. V. Umansky\(^1\)
\(^1\)Lawrence Livermore National Laboratory, Livermore, CA
\(^2\)General Atomics, La Jolla, CA
\(^3\)University of California, San Diego, CA

LLN-POST-754943
SciDAC-4 Principal Investigator (PI) Meeting, Rockville, MD, July 23-24, 2018