Plasma Surface Interactions SciDAC:

Dynamic plasma material interactions at the tokamak edge

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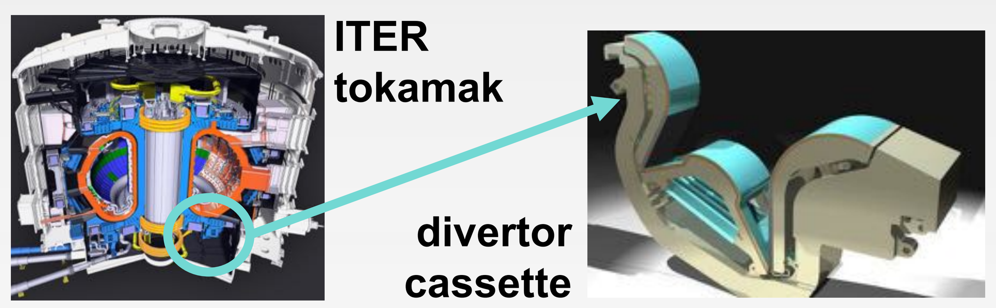
Abstract

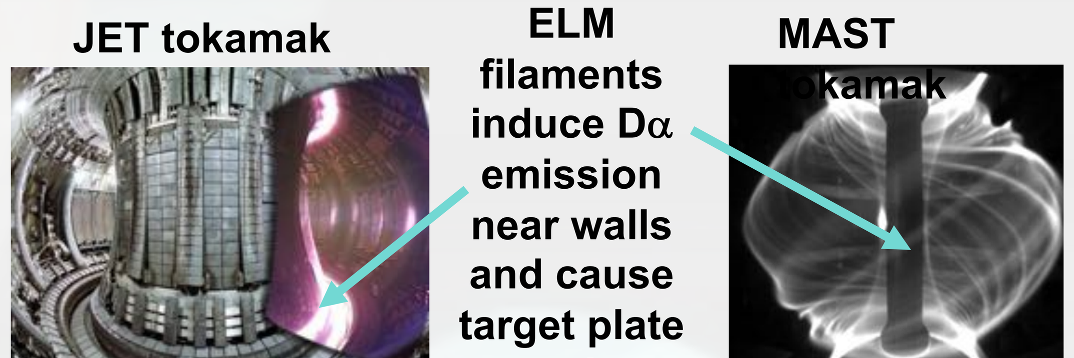
The PSI SciDAC is developing coupled models for the dynamic interaction between plasma and material surfaces at the edge of a magnetically confined fusion energy reactor. Our goals are to determine the importance of intermittent transient events such as edge localized modes (ELMs) on impurity production and material erosion and to understand how plasma turbulence impacts the dynamic recycling of main ions and impurities between 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 together with microscopic models of the walls and study the physics of the coupled system.



Motivation

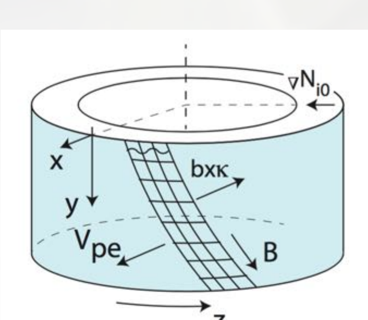
ITER will be the first tokamak to achieve Q>10 and produce 500 MW of fusion power. An important goal of the PSI SciDAC is to develop models that predict the performance of divertor plasma facing components (PFC) with respect to impurity production and material migration, because these surfaces are exposed 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 new types of coupled oscillations & instabilities? Will plasma-wall interactions change the character of turbulence near material surfaces?*

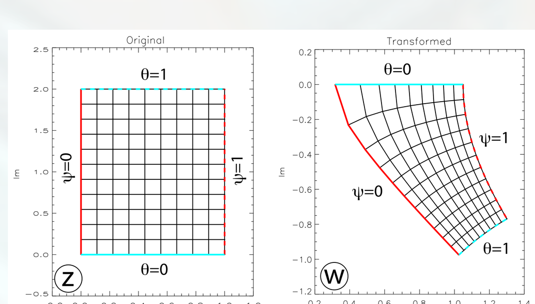


Approach

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 geometry, which nonetheless can handle the most important effects of toroidal geometry: magnetic field line pitch and field line curvature **κ**.



Conformal mapping can be used to simulate divertor geometry



Goal: Determine the erosion rate of material surfaces that are impacted by large transient events such as ELMS.
Approach: Simulate heat pulse propagation using the 4D guiding center kinetic COGENT code [1]. Determine under what conditions energetic particle tails are found to form and whether kinetic effects impact quantitative results. Eventually, couple to sheath model (hPIC [2]) and erosion model (Fractal-TriDYN [3]).

Goal: Determine the impact of turbulence on the dynamic recycling of main ions and the impact of coupled plasma-wall models on plasma turbulence.
Approach: Study the coupling between wall codes and plasma codes in 2D and 3D. Develop a divertor-relevant model of plasma turbulence within the BOUT++ framework [4] to couple to wall codes (FACE [5], Xolotl [6]).

Results: ELM Heat Pulse

In our study [7] COGENT solves the guiding center kinetic equations:

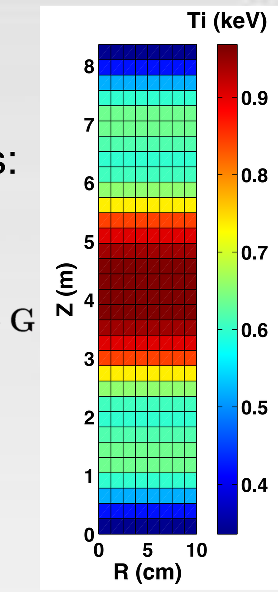
$$\frac{\partial}{\partial t}B_\parallel^* f + \nabla_{\mathbf{R}}(\dot{\mathbf{R}}B_\parallel^* f) + \partial_{v_\parallel}(\dot{v}_\parallel B_\parallel^* f) = 0 \qquad \mathbf{u} \equiv (\dot{\mathbf{R}}, \dot{v}_\parallel)$$

$$\dot{\mathbf{R}} \equiv \frac{v_\parallel}{B_\parallel^*}\mathbf{B}^* + \frac{La}{ZB_\parallel^*}\mathbf{b}\times\mathbf{G} \qquad \dot{v}_\parallel \equiv -\frac{1}{mB_\parallel^*}\mathbf{B}^*\cdot\mathbf{G}$$

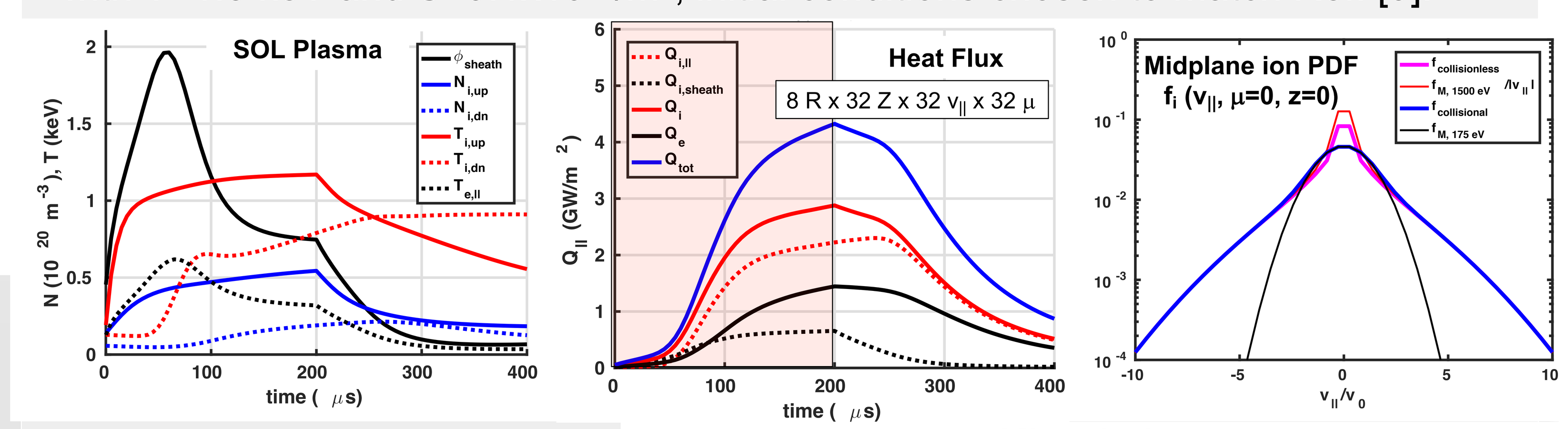
$$\mathbf{B}^* \equiv \mathbf{B} + La\frac{mv_\parallel}{Z}\nabla_R\times\mathbf{b} \qquad B_\parallel^* = \mathbf{b}\cdot\mathbf{B}^*$$

$$\mathbf{G} \equiv Z\nabla_R\Phi + \frac{\mu}{2}\nabla_R|\mathbf{B}| \qquad \mathbf{b} \equiv \mathbf{B}/|\mathbf{B}|$$

JET-like SOL
$B_t = 3$ T, $B_p = 0.3$ T
$R = 3$ m, $2L_\parallel = 80$ m
$N_{ped} = 5\times10^{19}$ m^{-3}, $T_{ped} = 1.5$ keV



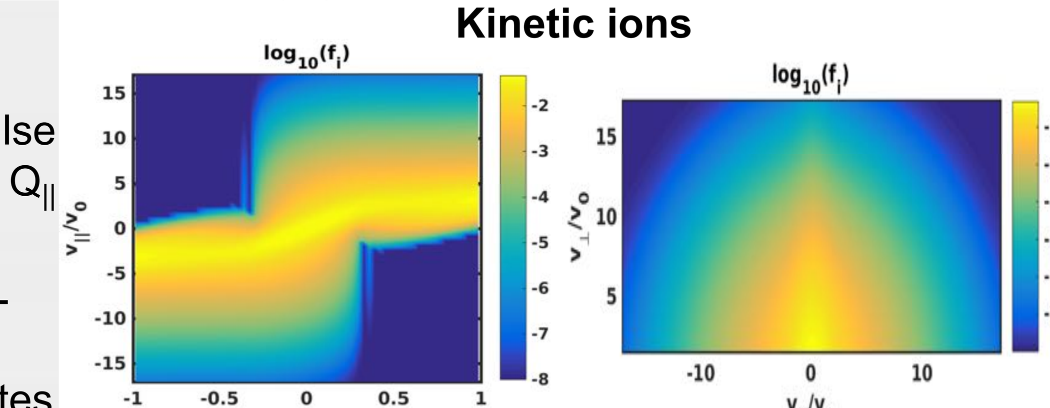
The ELM heat pulse benchmark [8-9] is specified by imposing Maxwellian source with T=1.5 keV and S=9.1x10²³/m³; initial conditions chosen to match Ref. [9].



Kinetic ions & Boltzmann electron benchmark case:
Results for 0.4 MW ELM pulse lasting 200μs yield a peak $Q_\parallel$ ~4.3 GW/m² at 200μs

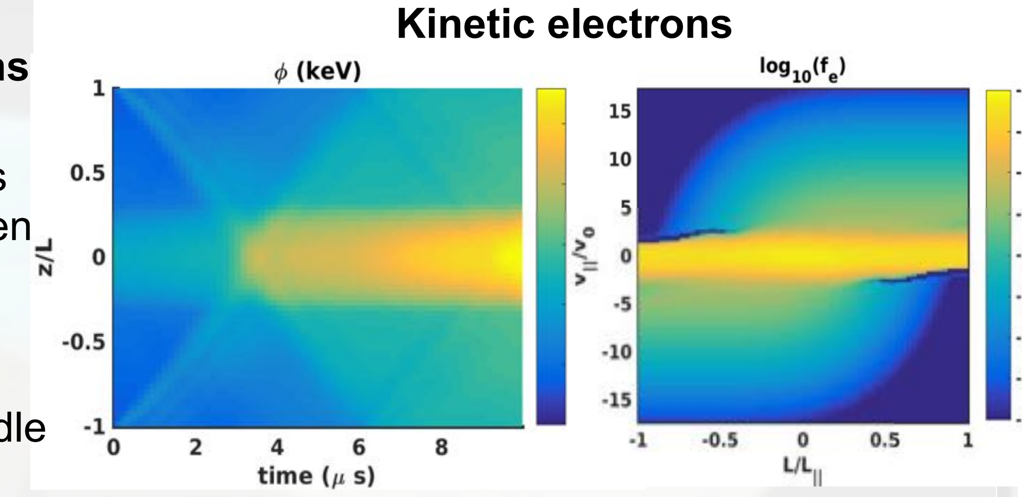
-Distribution function has non-Maxwellian tail ~ $f_{Max}/v_\parallel$
-Sonic outflow near target plates → transition to ½ Maxwellian

Kinetic ions



Kinetic ions & kinetic electrons
This is extremely challenging: explicit time integration requires ~10⁵ time steps due to the Alfven wave. We are developing a general ARK explicit-implicit (Jacobian-free Newton Krylov) time integration scheme to handle these issues.

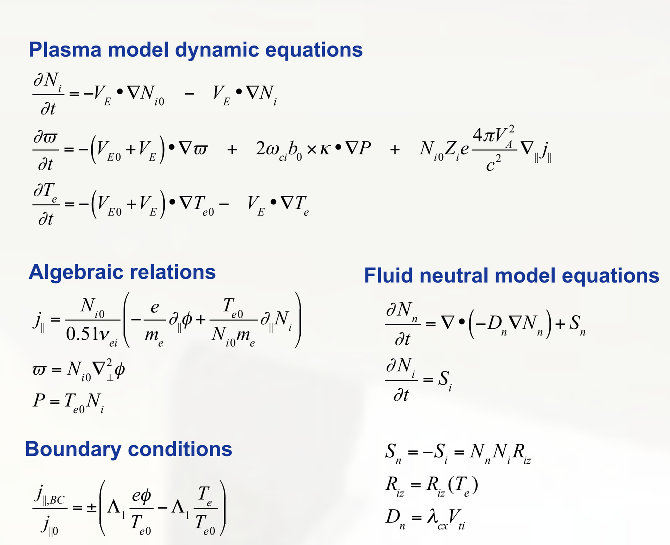
Kinetic electrons

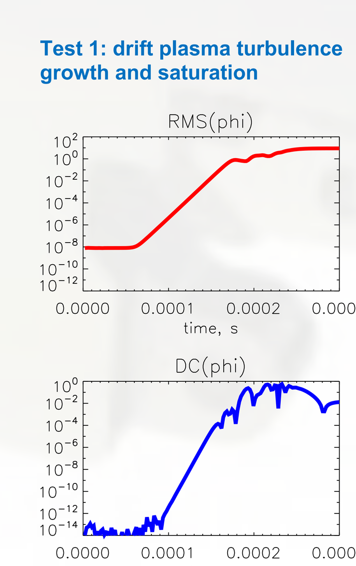


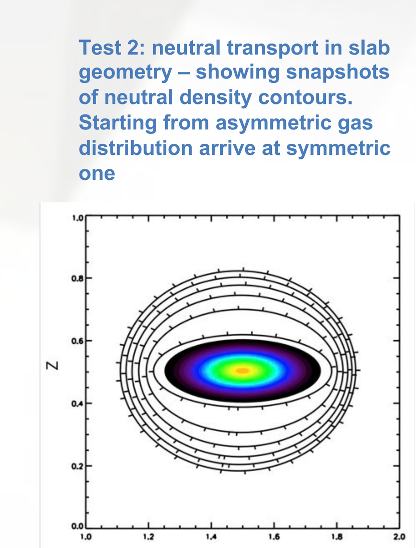
Divertor Turbulence

BOUT++ Divertor Turbulence Model

Divertor turbulence has characteristics of curvature-driven drift-resistive ballooning modes (DRBM) at the midplane and electron temperature (T_e) gradient driven conducting wall modes (CWM) in the pre-sheath region near the divertor target.



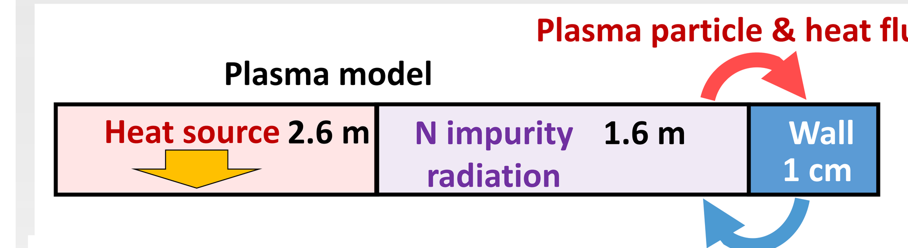




Linear tests have been performed verifying accuracy of the growth rates and real frequency of the DRBM and CWM modes.

Dynamic Plasma-Wall Coupling

We are exploring the physics of coupled plasma and wall models. Here, we show results for dynamic ELM and steady-state simulations using simplified models: the 2D UEDGE [10] edge plasma transport code and the 1D FACE wall model [5].

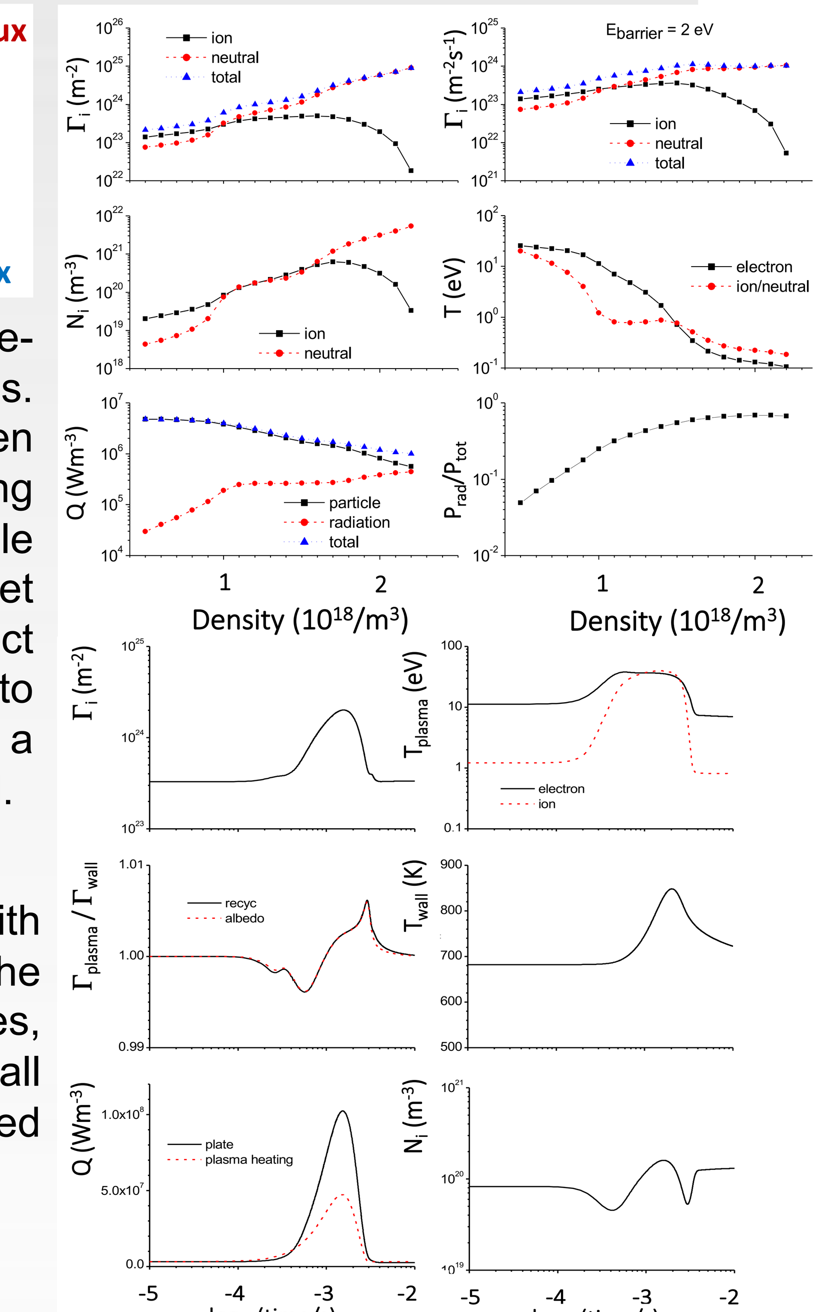


Steady State Simulation

Steady state is achieved via explicit time-dependent coupling of plasma & wall codes. Plasma model has fixed fraction of Nitrogen impurities that help to radiate the input heating power of Q=6 MW/m². Wall model has single type of H traps (E_{dt}=0.9eV) and Dirichlet temperature BC (500 K). BCs have perfect recycling, but particles require 2eV of energy to penetrate the wall. Detachment is observed as a rollover in flux as upstream density is increased.

Dynamic ELM Simulation

ELM is simulated as dynamic heat source with peak Q=90MW/m² and N_i=10¹⁸/m³. During the ELM, the target plates initially absorb particles, but, as the PFCs absorbs heat and the wall temperature rises, strong outgassing is produced and the steady-state conditions are recovered.



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 ELMs

Kinetic ELM heat pulse benchmarks have been reproduced
- 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
- Model passes linear tests for growth rate and real frequency of fastest growing eigenmodes including both curvature and sheath driving terms
- Model is being pushed into the nonlinear regime in order to predict the interaction between turbulence and wall recycling

Coupled plasma and wall codes illustrate the dynamics of particle recycling and detachment during transient ELM events and steady state conditions
- Both steady-state & complete ELM cycle were simulated for small transient events
- Future work will focus on coupling more complex plasma and wall models

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