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

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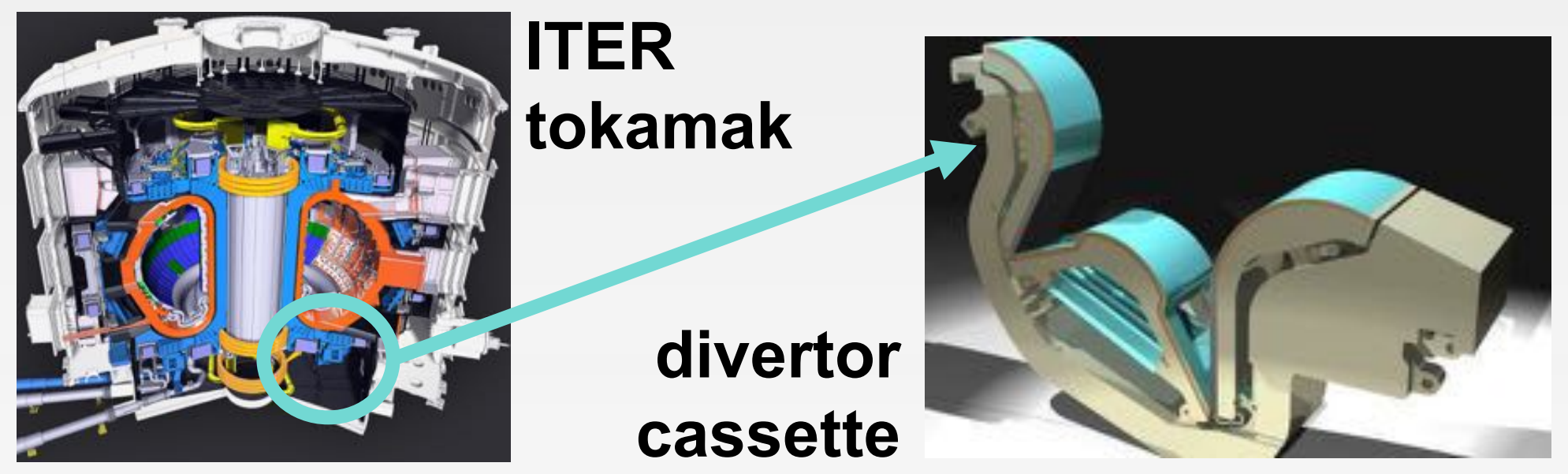
## Abstract

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

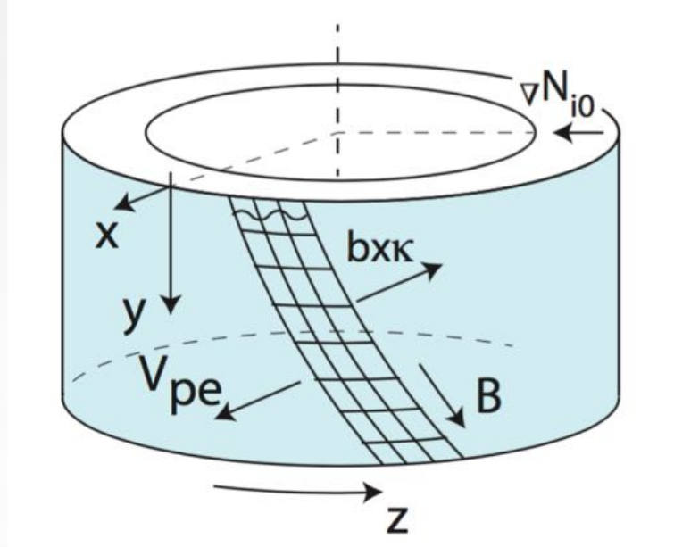
ITER will be the first tokamak to achieve Q>10 and produce 500 MW of fusion power. An important goal of the PSI SciDAC is to develop models that predict the performance of divertor plasma facing components (PFC) with respect to impurity production and material migration, because these surfaces are exposed 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?*

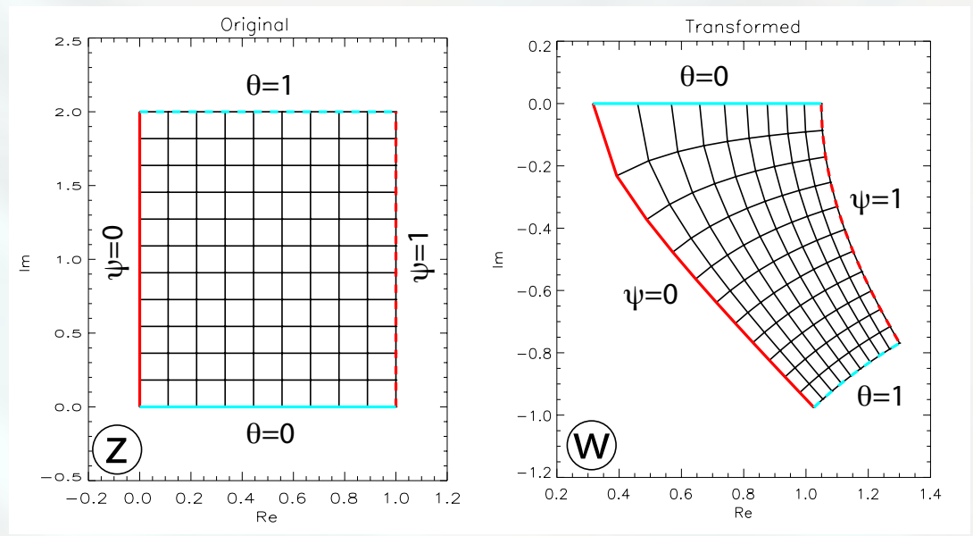
**ELM filaments induce Dα emission near walls and cause target plate erosion**

## 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 $\kappa$.



**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

COGENT solves the guiding center kinetic equation in slab geometry

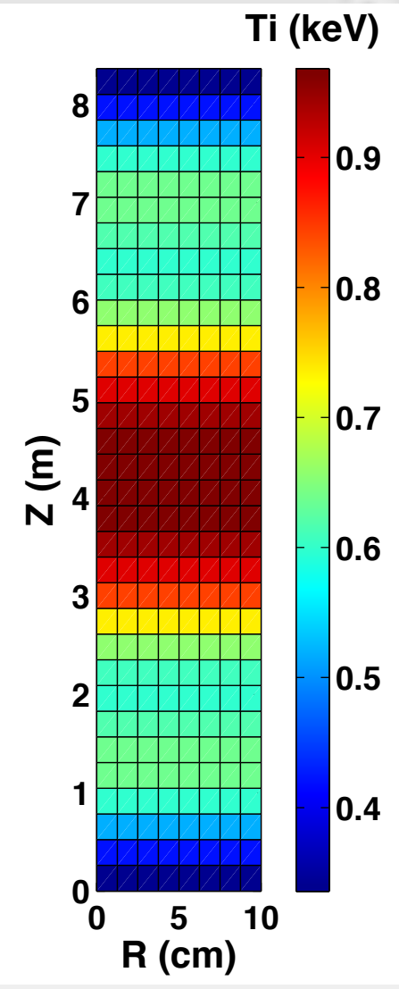
$$\frac{\partial}{\partial t}B_\parallel^* f + \nabla_{\mathbf{R}}(\dot{\mathbf{R}}B_\parallel^* f) + \partial_{v_\parallel}(\dot{v}_\parallel B_\parallel^* f) = 0 \qquad \mathbf{u} \equiv (\dot{\mathbf{R}}, \dot{v}_\parallel)$$

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

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

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

**JET-like SOL**
$B_t = 3\ \mathrm{T}, B_p = 0.3\ \mathrm{T}$
$R = 3\ \mathrm{m}, 2\ L_\parallel = 80\ \mathrm{m}$
$N_{ped} = 5\mathrm{x}10^{19}\ \mathrm{m}^{-3}, T_{ped} = 1.5\ \mathrm{keV}$

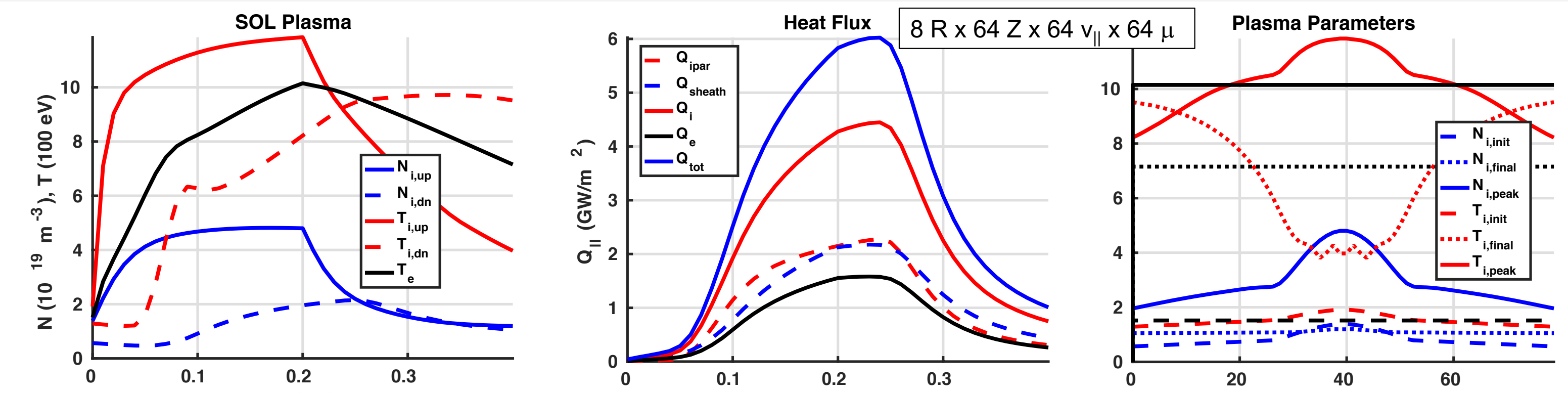


The ELM heat pulse benchmark [7-8] is specified by imposing Maxwellian source with T=1.5 keV and S=9.1x10²³/m³; initial conditions chosen to match Ref. [8].

Simulations here use kinetic ions and adiabatic electrons:

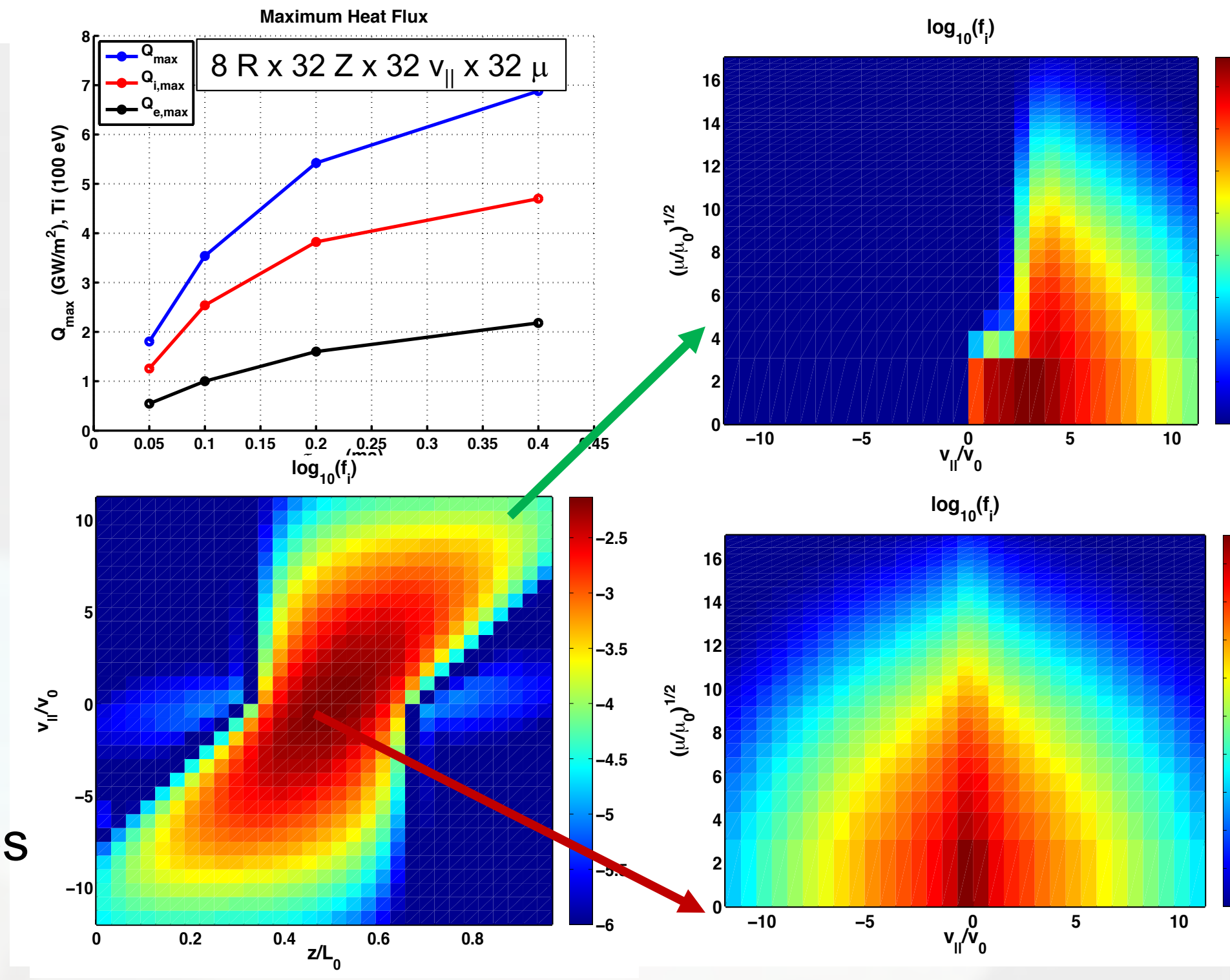
$$e\phi = e\phi_s + T_e \ln(n_i/n_0) \qquad Q_{tot} = Q_i + Q_e \qquad Q_e = 2\,T_e\,\Gamma_i \qquad Q_{i,sheath} = Ze\phi_s\,\Gamma_i$$

$$e\phi_s = (T_e/2)\ln(2\pi m_e v_i^2/T_e) \qquad Q_i = Q_{i,par} + Q_{i,sheath} \qquad Q_{i,par} = (3T_i + mv_i^2)\,\Gamma_i/2 + Q_{i,cond}$$



Results for 0.4 MW ELM pulse lasting 200μs
- $Q_\parallel$ peaks at ~5.5 GW/m² after ~60μs
- Peak heat flux saturates as a function of ELM duration

Distribution function becomes significantly non-Maxwellian for collisionless simulation
- Anisotropic temperature $T_\parallel << T_{perp} = 1.5$ keV
- Sonic outflow near target plates → transition to ½ Maxwellian



## 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. **Plasma model equations:**

$$\frac{\partial N_i}{\partial t} = -V_E \bullet \nabla N_{i0} + \nabla_\parallel (j_\parallel / e) \qquad \frac{\partial T_e}{\partial t} = -V_E \bullet \nabla T_{e0}$$

$$\frac{\partial \varpi}{\partial t} = 2\omega_{ci} b_0 \times \kappa \bullet \nabla P + N_{i0} Z_i e \frac{4\pi V_A^2}{c^2}\nabla_\parallel j_\parallel$$

$$j_\parallel = \frac{eN_{i0}}{0.51\nu_{ei}}\left(-\frac{e}{m_e}\partial_\parallel\phi + \frac{T_{e0}}{N_{i0}m_e}\partial_\parallel N_i\right)$$

$$\varpi = N_{i0}\nabla_\perp^2\phi$$

$$P = T_{e0}N_i$$

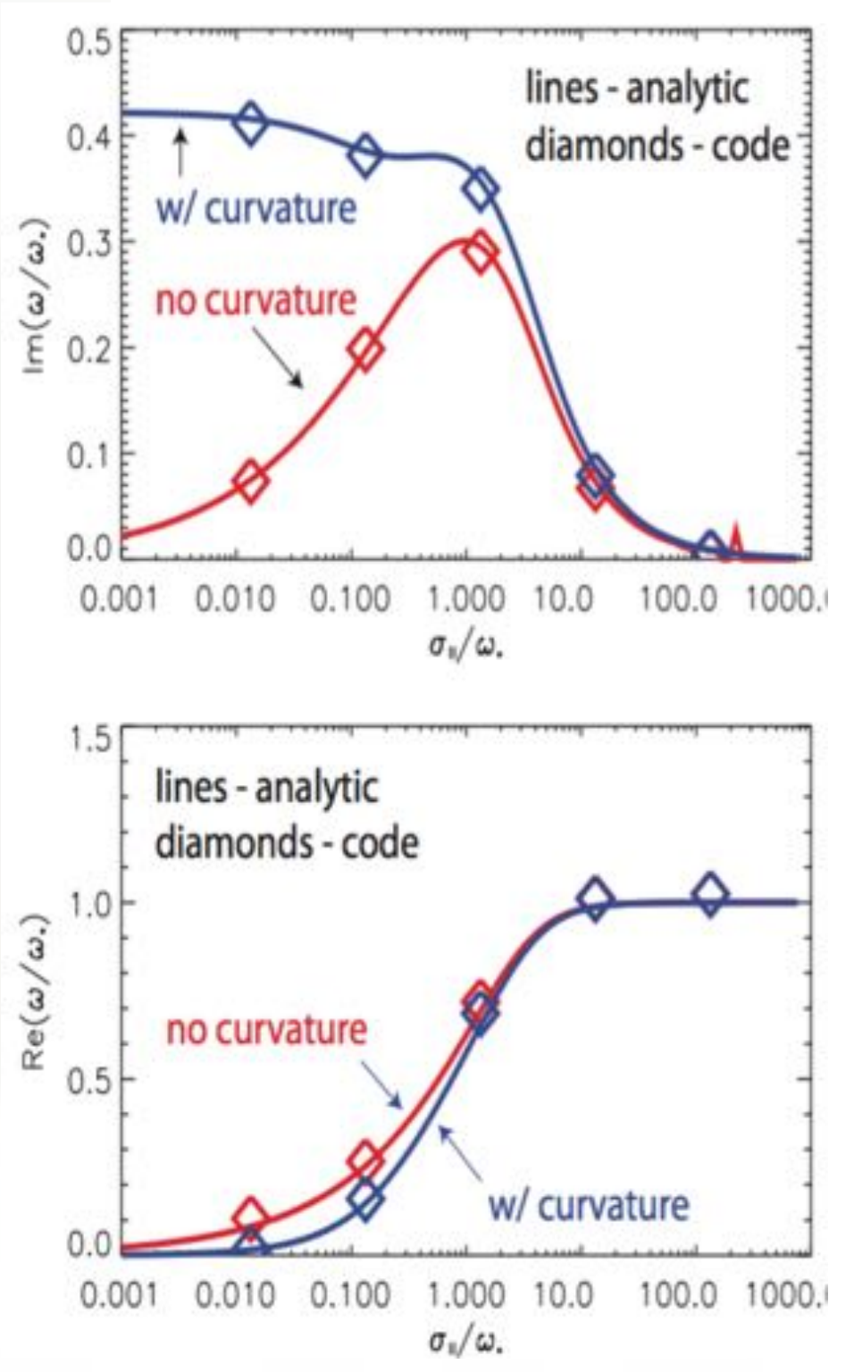
**Sheath BCs**

$$D\nabla_\parallel\phi = \pm(\Lambda_1\phi - \Lambda_1 T_e)$$

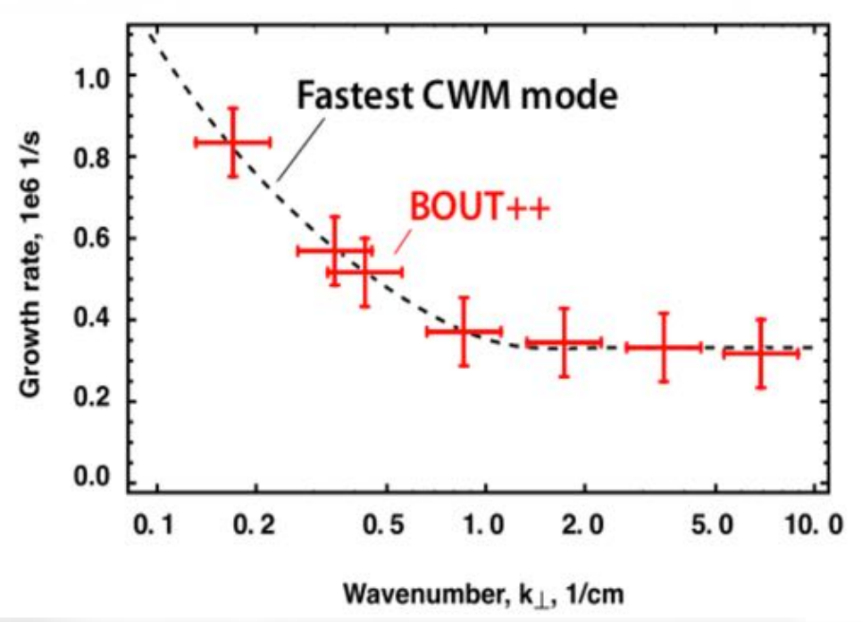
$$D = \sigma \parallel T_0^2 / N_0$$

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

**Drift-Resistive Ballooning Mode**

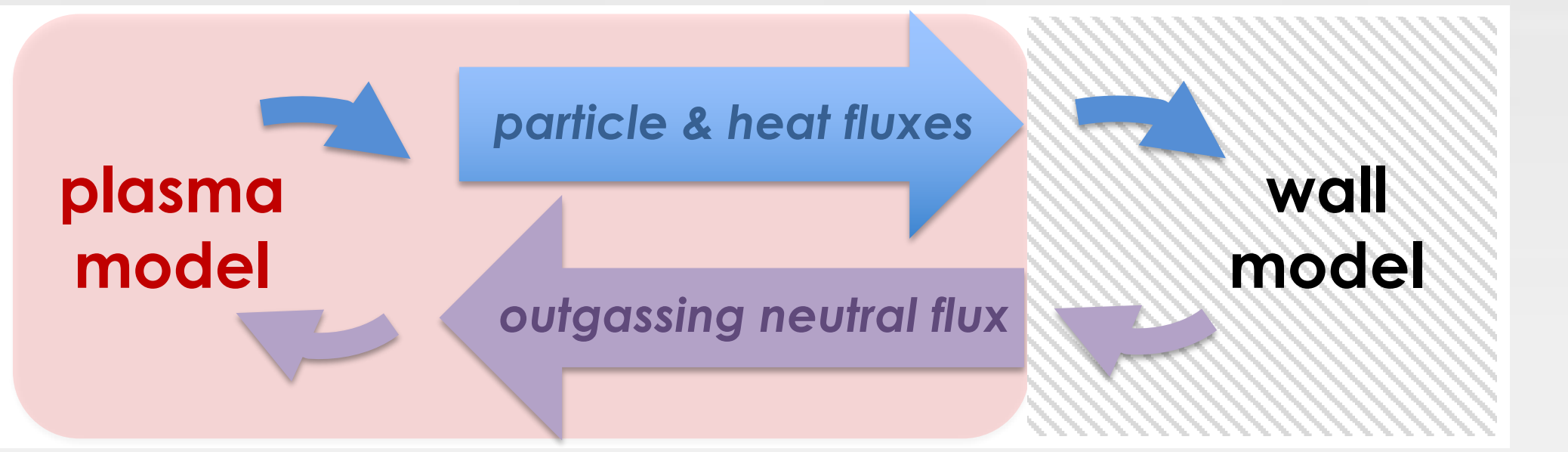


**Conducting Wall Mode**



## 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].



plasma model

particle & heat fluxes

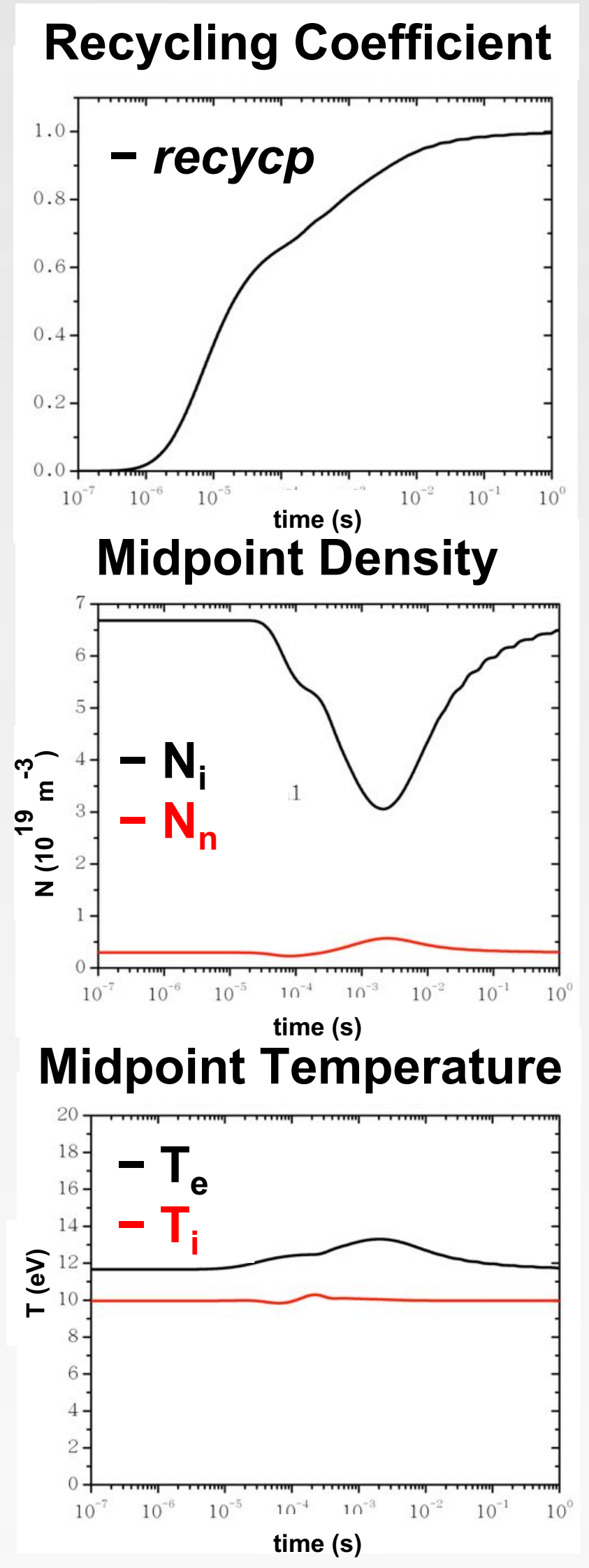
outgassing neutral flux

wall model

**Recycling Coefficient**

**Midpoint Density**

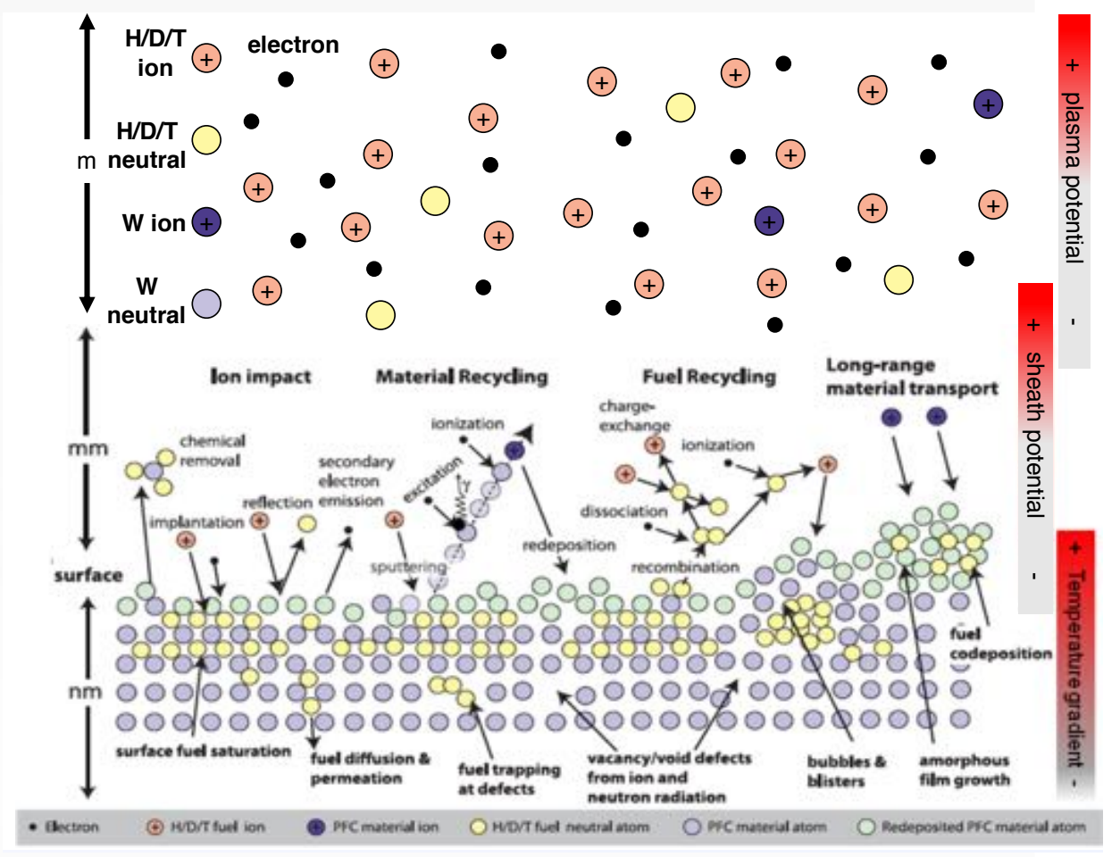
**Midpoint Temperature**



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 neural densities and temperatures and the predicted recycling coefficient *recycp*=$-\Gamma_n/\Gamma_i$ 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 subcycles 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 ELMs

**ELM heat pulse benchmark has been simulated using an adiabatic Boltzmann electron model**
- 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 verification tests for growth rate and real frequency of fastest growing eigenmodes including both curvature and sheath driving terms
- Future work will extend to include neutral dynamics

**Initial tests of dynamic recycling between coupled plasma and wall codes have been performed**
- 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

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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 through the Scientific Discovery through Advanced Computing (SciDAC) project on Plasma-Surface Interactions.

LLNL-POST-754949

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