# Coupled Kinetic-MHD Simulations of ELM Effects on Divertor Heat Loads

Julian C. Cummings, Caltech

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Co-authors: CS Chang, PPPL
Gunyoung Park, NFRI Korea
Linda Sugiyama, MIT

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# Abstract

The behavior of divertor plate heat load profiles during discharges with Type I ELMs is under investigation in present-day tokamak experiments such as DIII-D and NSTX. These studies have key implications for the ability of the ITER divertor to withstand peak energy fluxes driven by large individual ELMs and the accumulated heat load and surface ablation. We present here simulations of ELM activity and associated divertor heat loads in which we couple the discrete guiding-center neoclassical transport code XGC0 with the nonlinear extended MHD code M3D using the End-to-end Framework for Fusion Integrated Simulations, or EFFIS. In these simulations, the kinetic code and the MHD code run concurrently on the same massively parallel platform. Periodic data exchanges are performed using a memory-to-memory coupling technology provided by EFFIS. XGC0 starts from the equilibrium reconstruction of a specific discharge, just before the onset of a Type I ELM. M3D models the fast ELM event and sends updates of the magnetic field perturbations to XGC0, which in turn tracks ion and electron dynamics within these perturbed fields and collects divertor particle and energy flux statistics over several time intervals before and during the nonlinear ELM. Magnetic field updates are performed on the Alfvén time scale, allowing us to track ELM effects on the time history of divertor heat loads. We report here how EFFIS technologies facilitate these coupled simulations and discuss results for a selection of discharges from the 2010 JRT studies.

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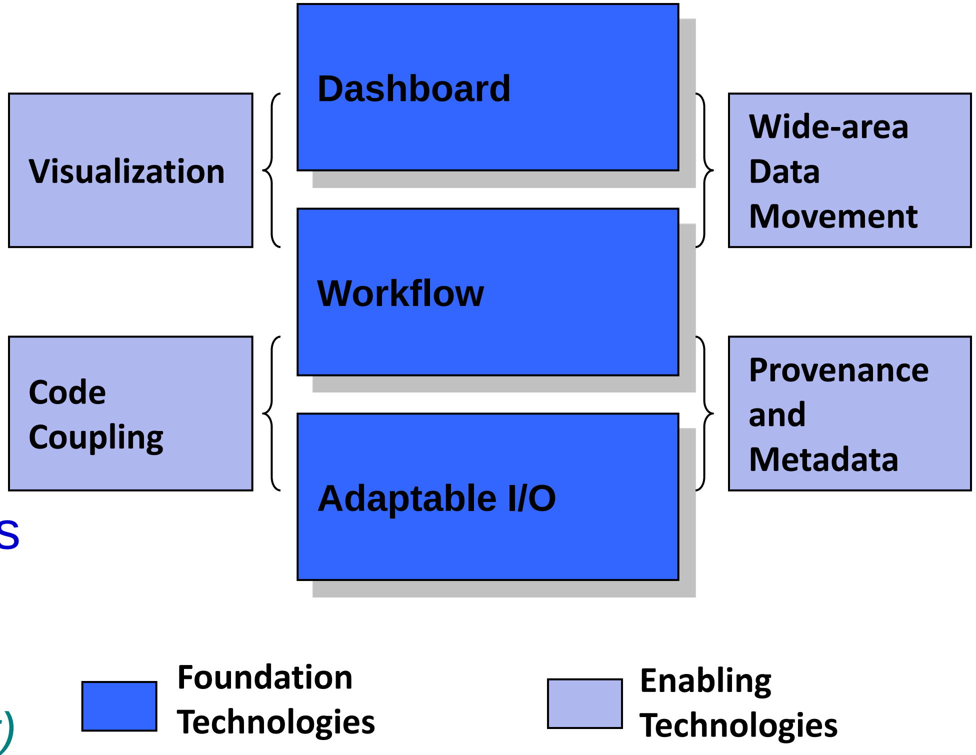
# Kinetic-MHD Code Coupling Simulations

- Basic purpose is to model edge pedestal buildup (kinetic model) followed by ELM crash (MHD model)
- As kinetic code proceeds, we determine when pedestal pressure profile is linearly MHD unstable
- Then launch extended MHD simulation for nonlinear evolution of ELM and "healing" of MHD equilibrium
- In principle, one can rerun kinetic code based upon the new equilibrium and start the next ELM cycle
- <u>Code coupling scenario</u>: run the kinetic code during MHD nonlinear ELM evolution, with periodic updates of perturbed B-field, and monitor divertor heat loads

# EFFIS Technologies

- From SDM center*
  - *Workflow engine – Kepler*
  - *Provenance support*
  - *Wide-area data movement*
- From universities
  - *Code coupling (Rutgers)*
  - *Visualization (Rutgers)*
- Newly developed technologies
  - *Adaptable I/O (ADIOS) (with Georgia Tech)*
  - *Dashboard (with SDM center)*




* Institutions involved: LBNL, NCSU, ORNL, SDSC, UC Davis, U. Utah

**Approach**: place highly annotated, fast, easy-to-use I/O methods in the code, which can be monitored and controlled, have a workflow engine record all of the information, visualize this on a dashboard, move desired data to user's site, and have everything reported to a database

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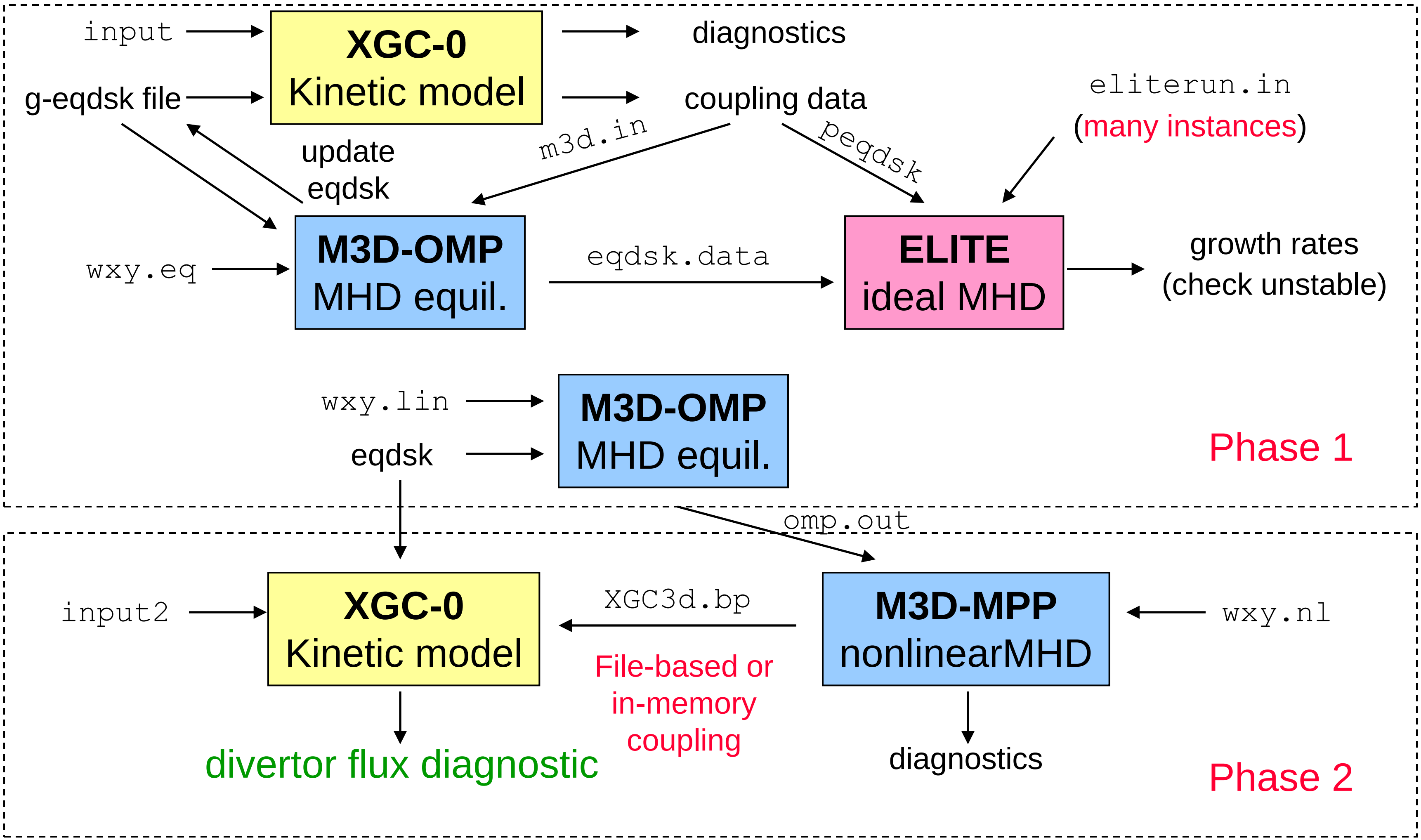
# Basic Code Coupling Scenario

- Four different simulation codes in use
  - *XGC0: kinetic simulation of edge plasma, including neoclassical and anomalous transport with ion-electron-neutral dynamics*
  - *M3D_omp: MHD analysis code, produces equilibrium & mesh*
  - *ELITE: ideal MHD linear stability analysis code*
  - *M3D_mpp: fully parallelized extended MHD initial value code*
- MHD codes accept plasma profile data (n,T,j) from XGC0 and *eqdsk* data file (from EFIT) for magnetic equilibrium
- M3D_omp code is run in "equilibrium only" mode to generate new *eqdsk* equilibrium for XGC0 and mesh for M3D_mpp code
- M3D_omp code also creates high-resolution *eqdsk* for ELITE
- ELITE checks linear stability of several intermediate-n modes
- When ELM is unstable, launch coupled XGC0/M3D_mpp run
- XGC0 reads 3d perturbed fields and samples divertor heat load

# Kinetic-MHD Code Coupling Schematic



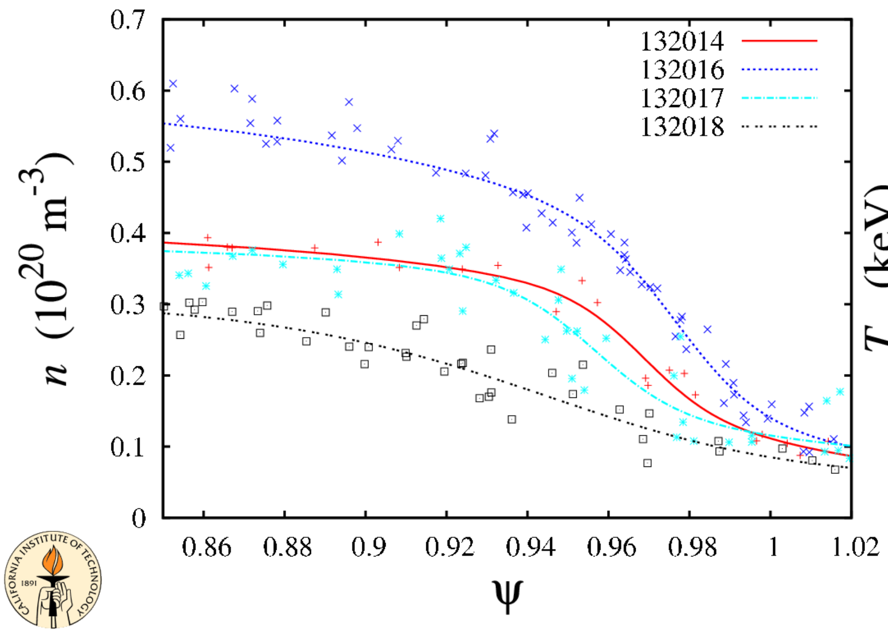
# In-memory Coupling of XGC0 and M3D_mpp

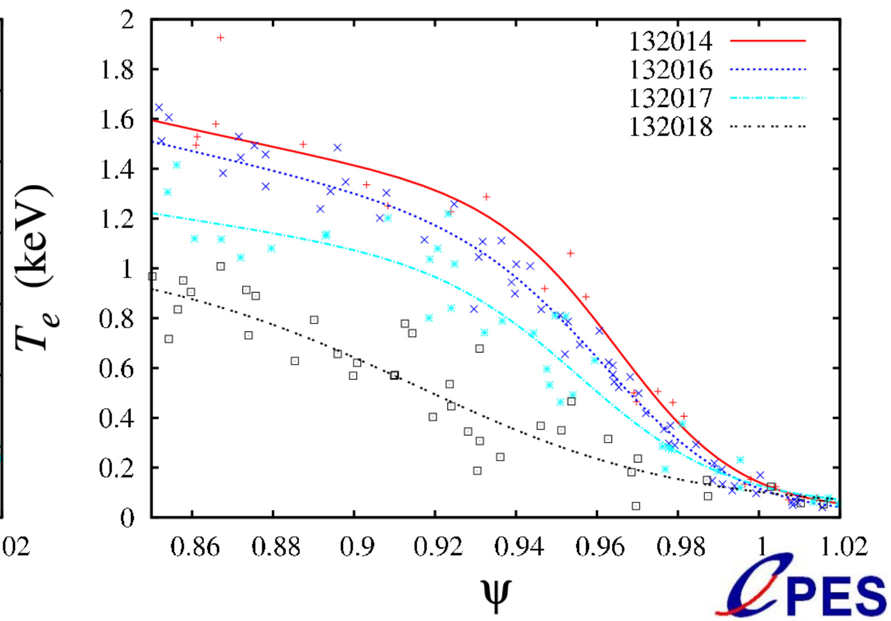
- For file-based transfer of 3d field data sets
  - *Use ADIOS with "MPI" method for parallel output from M3D_mpp*
  - *Call `adios_read()` in XGC0; all processes read all field data*
  - *Both codes run on same platform to avoid file transfers*
- To switch to in-memory coupling
  - *Change to "DART" method in external XML configuration file*
  - *Workflow updates setting in XGC0 input file automatically*
  - *No changes to XGC0 or M3D_mpp source code!*
  - *Both codes typically must run on the same platform*
- Coupled code simulations now routinely performed with either file-based or in-memory coupling method
  - *DART memory-to-memory coupling is preferred for more frequent data transfers used during ELM event modeling*

# Study of Plasma Current Scan DIII-D Discharges

- **Four DIII-D discharges that represent a plasma current scan are analyzed [Snyder *et al*., PoP 16 (2008) 056118; Groebner *et al*., NF 49 (2009) 085037]**
- **The discharges have about the same**
  - **toroidal magnetic field (2.1 T)**
  - **plasma shape (average triangularity 0.55)**
  - **normalized toroidal beta ($\beta_n$ ~ 2.1-2.4)**
- **The plasma current varied in the range 0.5-1.5 MA**

| Discharge | 132016 | 132014 | 132017 | 132018 |
|---|---|---|---|---|
| Time, msec | 3023 | 3023 | 2998 | 1948 |
| $I_p$, MA | 1.50 | 1.17 | 0.85 | 0.51 |

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# Coupled Code Simulation of Divertor Heat Load (1)

- Phase 1: XGC0 simulation of edge pedestal buildup
- Input data drawn largely from DIII-D shot analysis
  - *Sample equilibrium from EFIT analysis of shot 132014 at time 3000 ms, just before observation of large Type 1 ELMs*
  - *Use fitted experimental density and temperature profile data*
- XGC0 run input parameters
  - *256,000 ion particles run on 128 cores of Cray XT4*
  - *Set to run for 100 ion toroidal transit periods in 50,000 steps*
  - *Simple neutrals physics model with 0.99 recycling rate*
  - *Turbulent transport model with radially varying D coefficients*
    - *Diffusivities tuned to maintain observed plasma profiles*
  - *One dump of plasma profiles and eqdsk update in each ion toroidal transit time*
- XGC0 run with ideal MHD stability tests in <90 minutes

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# Coupled Code Simulation of Divertor Heat Load (2)

- Phase 2: XGC0/M3D_mpp coupled run starts from final plasma profiles and magnetic equilibrium of Phase 1
- XGC0 run parameters
  - *8M ion and electron particles on 1024 Cray XT4 cores*
  - *Set to run for just 2 ion toroidal transit periods in 10,000 steps*
  - *Read 3d B field data from M3D periodically using ADIOS*
  - *Sample inner/outer divertor electron and ion heat loads*
- M3D_mpp run parameters
  - *72 poloidal planes, 19,441 nodes per plane, run on 1152 cores*
  - *Write 3d B field data periodically using ADIOS*
  - *Run ~120 Alfvén periods in 12 hours wallclock (job queue limit)*
  - *Many restarts needed to get through nonlinear ELM evolution*

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# Coupled Code Simulation of Divertor Heat Load (3)

- Study presents challenges in terms of disparate time scales and proper synchronization of simulation codes
  - *XGC0 heat load diagnostic period is ion transit time (≈80 μsec)*
    - *Comparable to experimental diagnostic time resolution of 6 kHz*
  - *ELM evolves on Alfvén time ($\tau_A$≈0.5 μsec) → many timesteps*
  - *Complete nonlinear ELM study limited by scaling of MHD code*
  - *Must carefully manage performance of both codes, avoid idling*
- One approach is to collect ELM perturbation data from successive M3D runs in files, then read into XGC0
  - *ELM perturbation studied for 385 $\tau_A$ using M3D checkpoint files*
  - *XGC0 runs 2 divertor heat load diagnostic periods of 1 ion transit time each, reading in the 3D perturbed field data during period 2*
    - *First period: formation of self-consistent radial E field*
    - *Second period: study effect of including perturbed magnetic field components from M3D on divertor heat loads*

# Sample Divertor Heat Load without ELM Fields

## Inner

Inner heat load is narrow, localized near strike point.

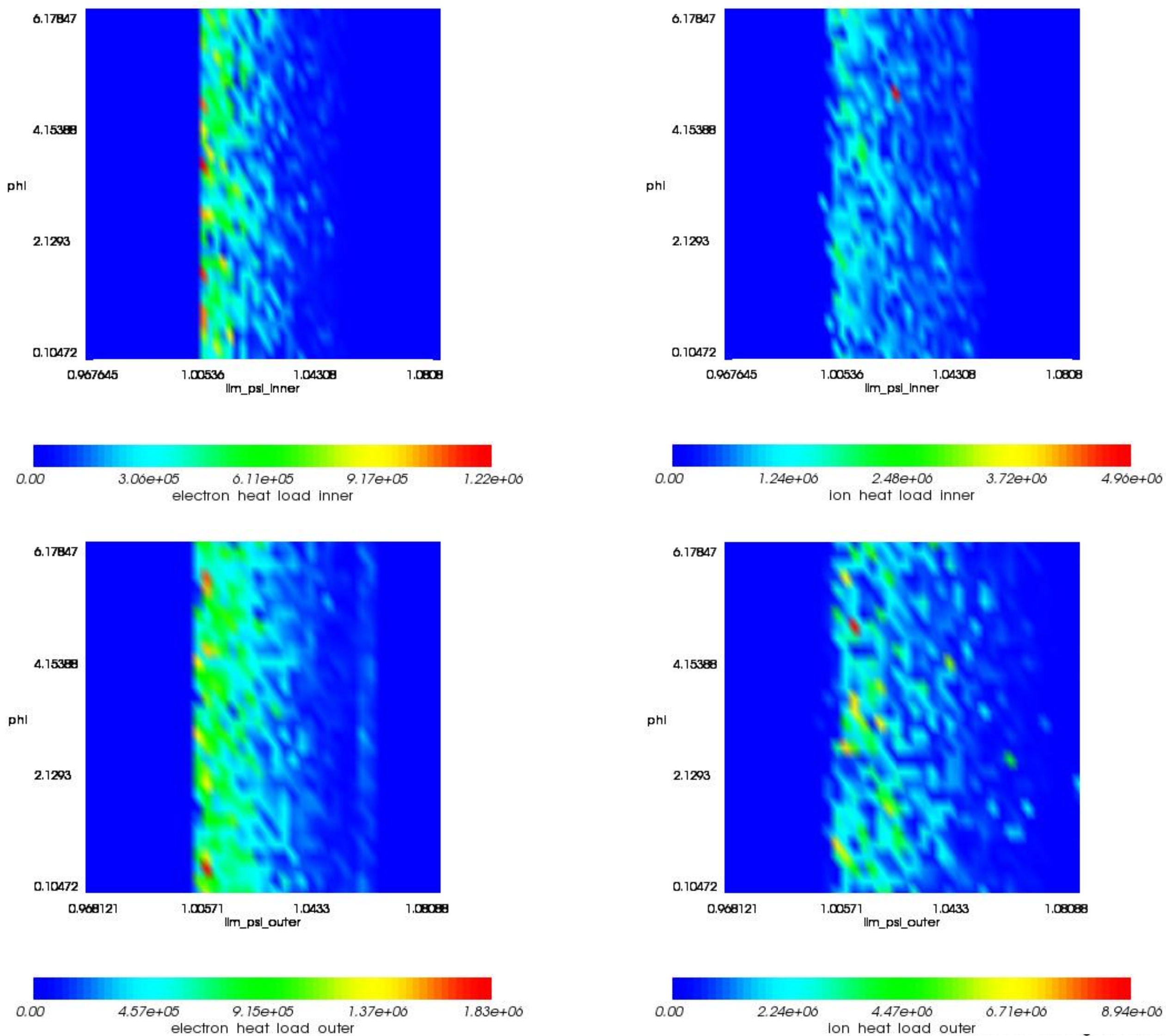
NB: No radiation model included! Detached plasma is not considered.

## Outer

Outer heat load is much broader, no structure in toroidal direction

Maximal hot spot ~9 MW/m$^2$

Electron | Ion



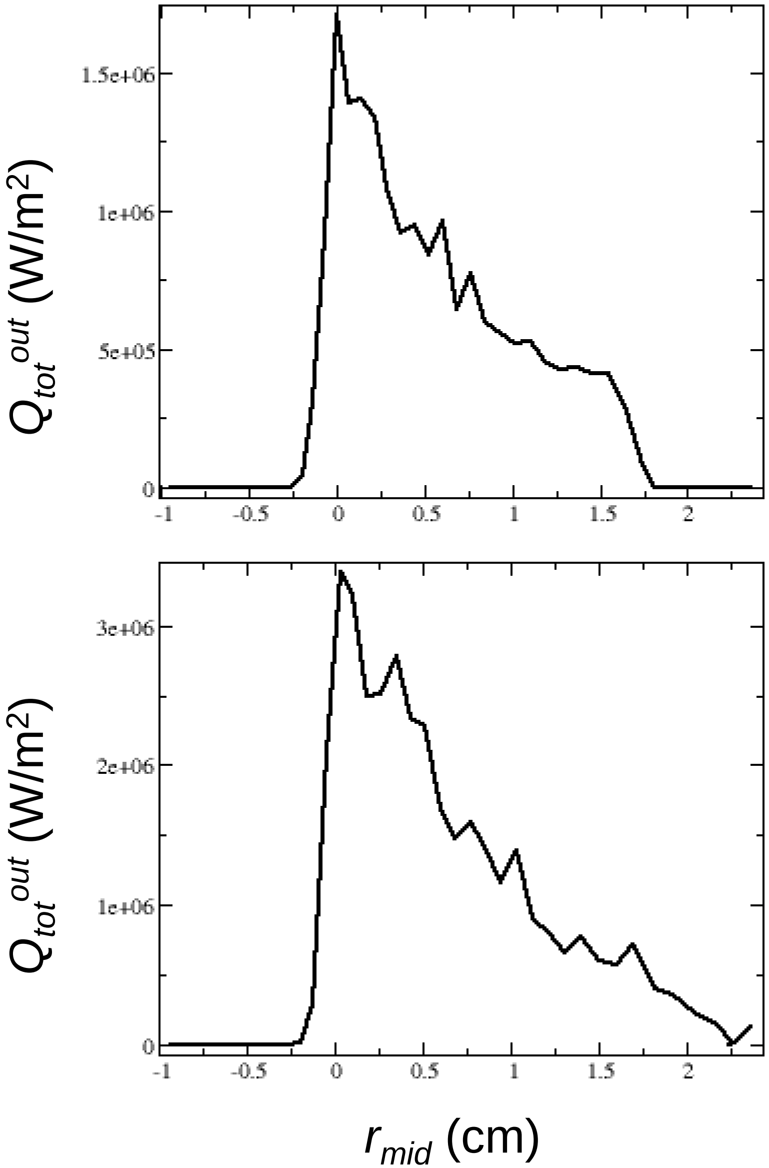
# Divertor Heat Load Profiles without ELM Fields

## Inner

Inner heat load
peak ~1.7 MW/m$^2$
**Heat load profile width ~0.6 cm**

## Outer

Outer heat load
peak ~3.4 MW/m$^2$
**Scrapeoff layer width $\lambda_q$~0.9 cm**

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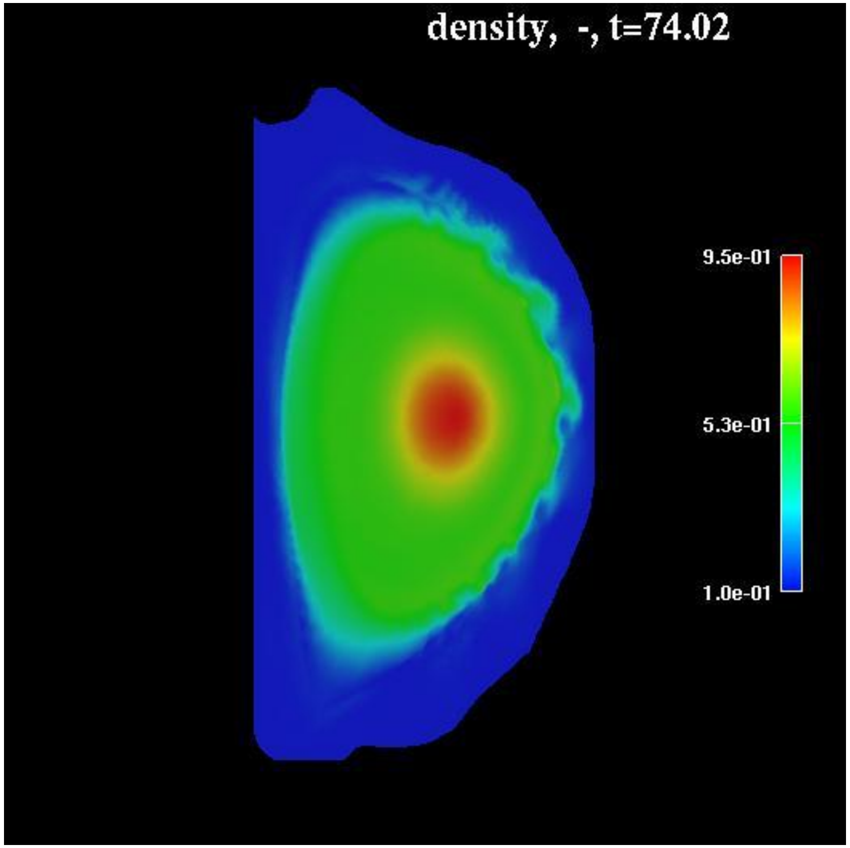
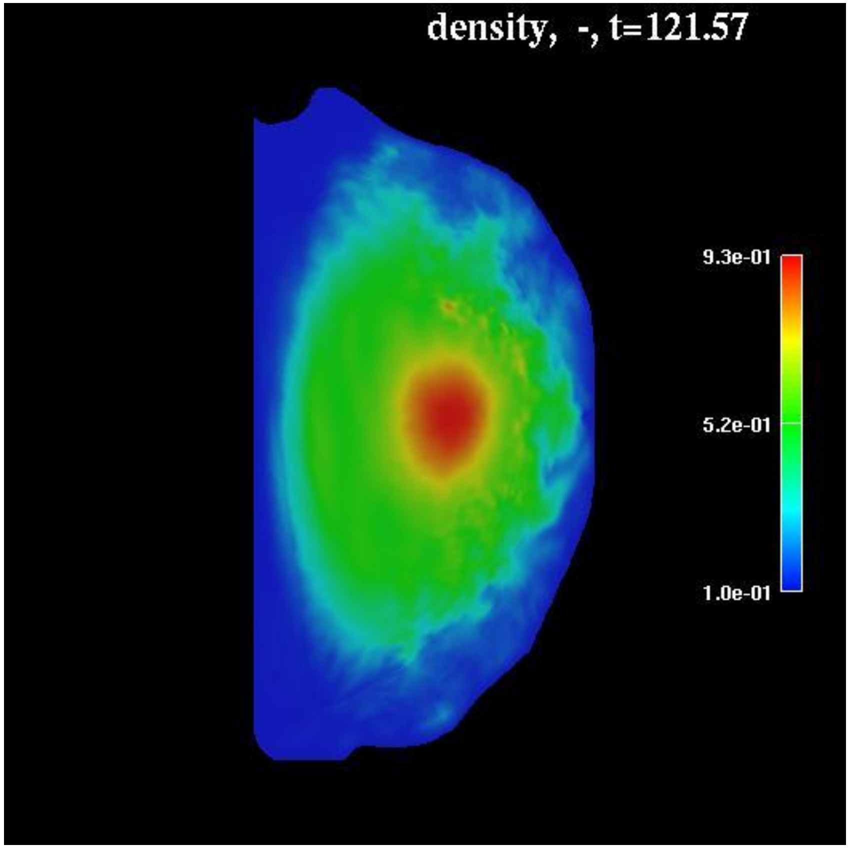
# ELMs from M3D




T= 74 $\tau_A$
(strong ELM structures)

T= 122 $\tau_A$
(nonlinear ELM evolution)

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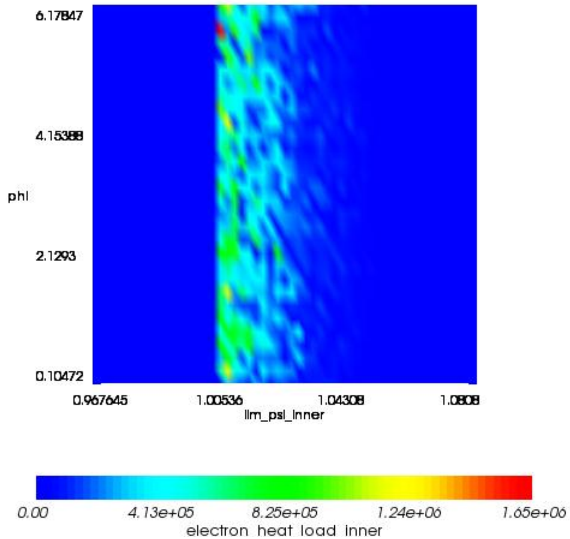
# Sample Divertor Heat Load with ELM δB Field

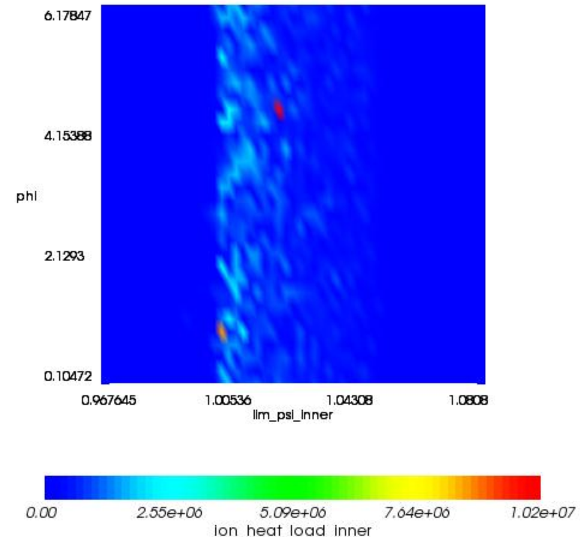
Electron | Ion

## Inner

Inner heat load is narrow, localized near strike point.

Heat flux slightly broader with ELM perturbations

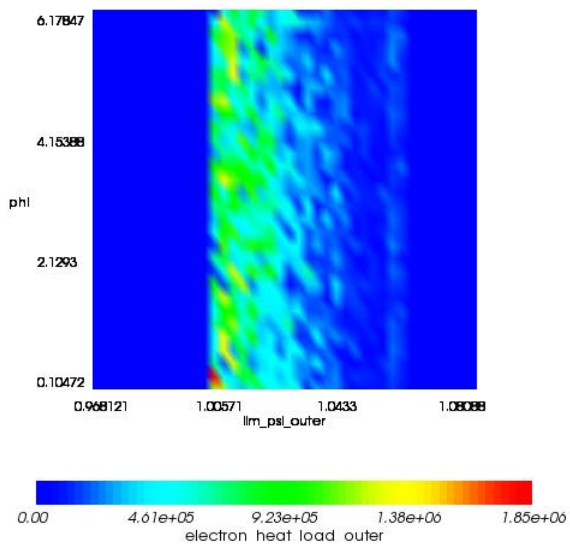


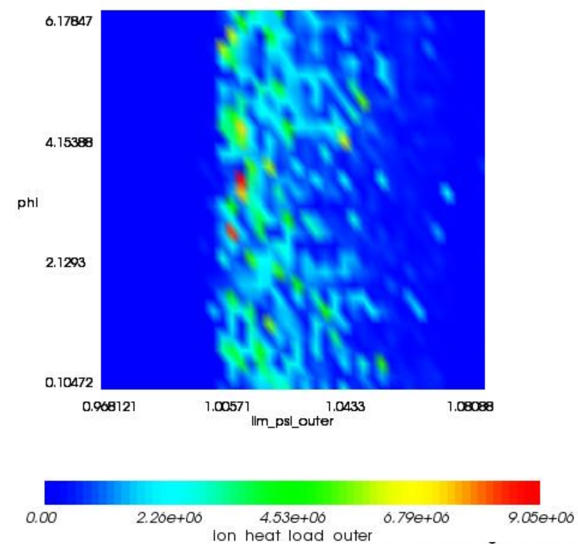




## Outer

Outer heat load is much broader, more structure in radial direction

Maximal hot spot ~10 MW/m$^2$



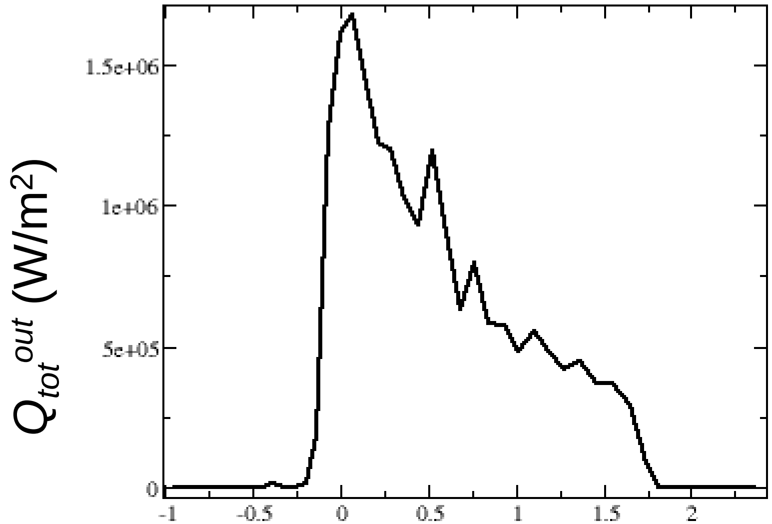



# Divertor Heat Load Profiles with ELM δB Field

## Inner

Inner heat load peak ~1.7 MW/m$^2$

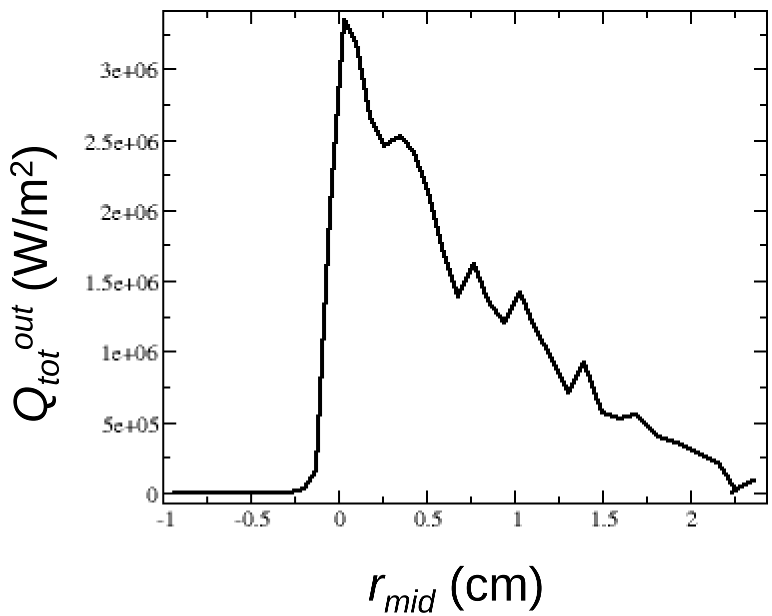
**Heat load profile width ~0.6 cm**




## Outer

Outer heat load peak ~3.4 MW/m$^2$

**Scrapeoff layer width $\lambda_q$~0.9 cm**

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# Conclusions

- Coupled kinetic-MHD studies of divertor heat load in DIII-D discharges with large Type I ELMs are presented
  - *Procedure involves coupling 4 independent codes using EFFIS*
    - *Kepler scientific workflow to orchestrate action and data flow*
    - *ADIOS for optimized data transfer either to disk or in memory*
    - *ESimMon dashboard for simulation monitoring and data analysis*
  - *If unstable ELM is detected, M3D evolves field perturbations*
  - *XGC0 imports perturbed fields and simulates kinetic response*
- Initial results indicate several challenges to address
  - *Sufficient sampling period for divertor heat load diagnostic requires a very long time history of ELM field data*
  - *Disparity in processing speed between XGC0 and M3D for a given period of simulated time make direct coupling difficult*

# Future Work

- Study limits of particle and temporal resolution
  - *What number of particles and length of sampling period is required for consistent divertor heat load diagnostics?*
- Two-way coupling: XGC0 sends pressure data to M3D
  - *Kinetic code can provide info on perturbed ion and electron pressure tensor to MHD code*
  - *Potentially more consistent picture of plasma response to ELM*
- Investigate XGC0 particle load balance for longer runs
- XGC0 code restart to retain plasma profile changes
  - *Long coupled simulation is needed to track full ELM history*
  - *Both codes must checkpoint/restart in consistent fashion*