Disruption Impact Reduction

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Brief comment on FSP Goals

- Most difficult part of FSP is in simultaneously satisfying the requirements of:
  1. Being something new:
     different from the base/SciDAC program
  2. Being something important:
     address critical issues to ITER
  3. Being relevant to exascale computing
- Satisfying 1 & 2 has generally meant that if it involves integration with different sub-communities it is FSP, if not it is out
  - It is a process that is ongoing
  - Patience is required

Multiple causes of disruptions exist

- Long-wavelength instabilities
  - Ideal MHD modes
  - Resistive Wall Modes (RWM)
  - VDEs (n=0 RWM)
  - Tearing modes (but usually when locked)
  - …
- Transport
  - Hardware/software faults Most common
  - Density limits
  - …
- External events
  - Pellet injections
  - Shutdown scenarios
  - Impurity gas jets
    - AKA, Mitigated disruptions
  - …

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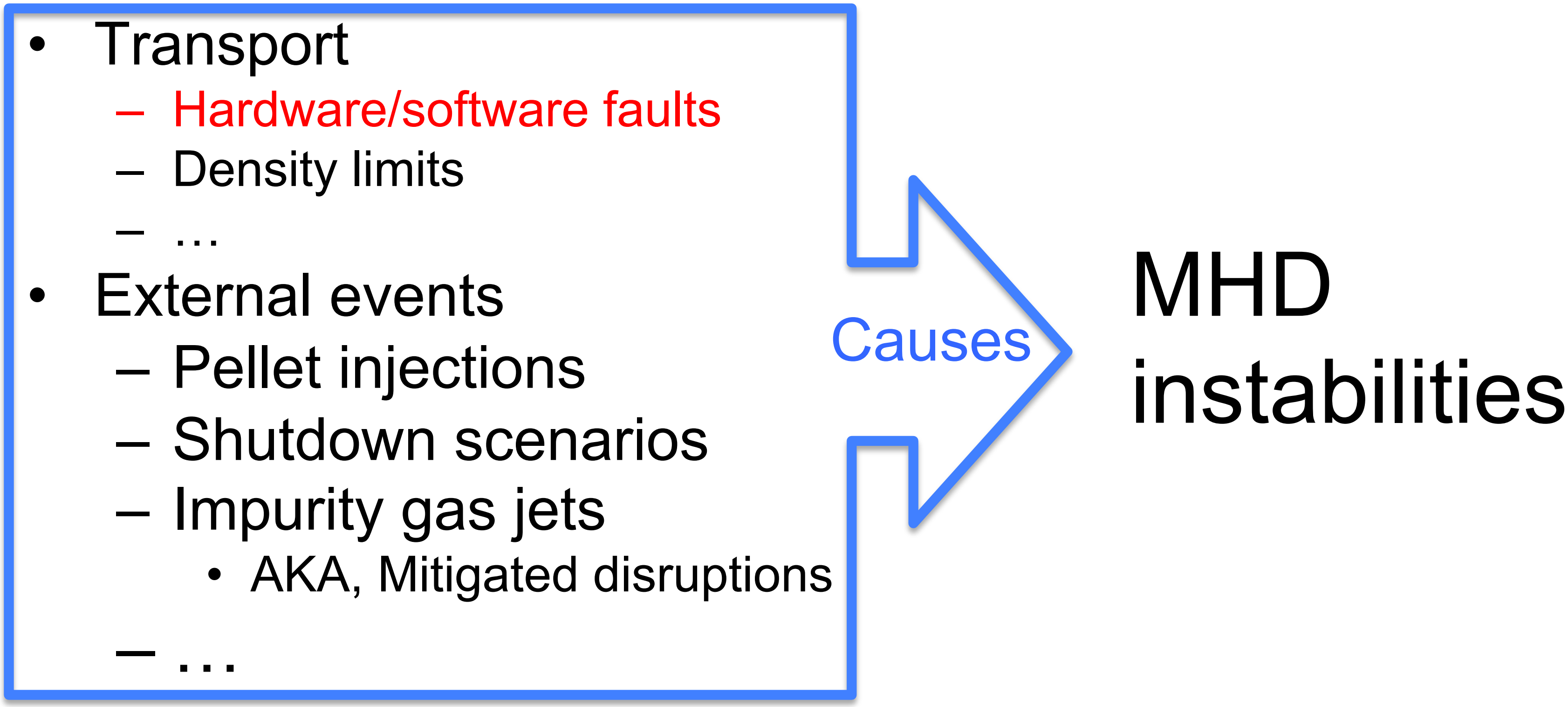

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Causes

MHD instabilities

Preventing/mitigating disruptions requires a broad approach

- Two needs of modeling:
  - Avoid disruptions entirely
    - Use transport modeling to optimize plasmas that avoid MHD stability or density limits
    - Modeling of feedback stabilization of MHD modes
  - Use modeling to understand what happens during a disruption, and:
    - Understand which operational regimes are most dangerous
    - Provide insight for and quantitative evaluation of mitigation techniques
    - Understand machine designs that can withstand disruptions

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Whole device modeling
Validation
Kinetic/MHD coupling

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Edge physics, …

FSP Disruption Science Driver

- How well can we predict the onset of a disruption and what strategies are available to avoid their development?
- What are the effects of runaway electrons and what is the impact of operating regimes on their generation?
- How does impurity transport affect disruption dynamics, and how do we use this information to mitigate the effects?
- What is the impact of disruptions on the material wall, and how can we better design the first wall to handle the thermal loads?
- What are the forces on the vacuum vessel and support forces during a disruption, and how do we improve their design?
- How can we better design disruption mitigation systems?
- What are the best plasma models for simulating plasma disruptions?

Issues have been raised about MHD boundary conditions during disruptions

Issues:

- How do model the “vacuum” region?
- Do we allow currents through the wall?
- Do we have a plasma inflows/outflows from the wall?

External kink: demonstration of “vacuum” simulations

- The ‘vacuum bubble’ paper [Rosenbluth, Monticello, Strauss, and White, PF 19, 1987 (1976)] considers external kink with 2D incompressible MHD in long cylinders.
  - Lagrangian methods are used to track plasma-vacuum interfaces (uniform-*J* cases) and flux surfaces (parabolic-*J*).
  - The violent cases show plasma swallowing bubbles.
  - A drag term is used for finding minimal energy states.

Minimal energy states presented in the RMSW reference with *q*(*a*) varied and uniform-*J* (left) and parabolic-*J* (right).

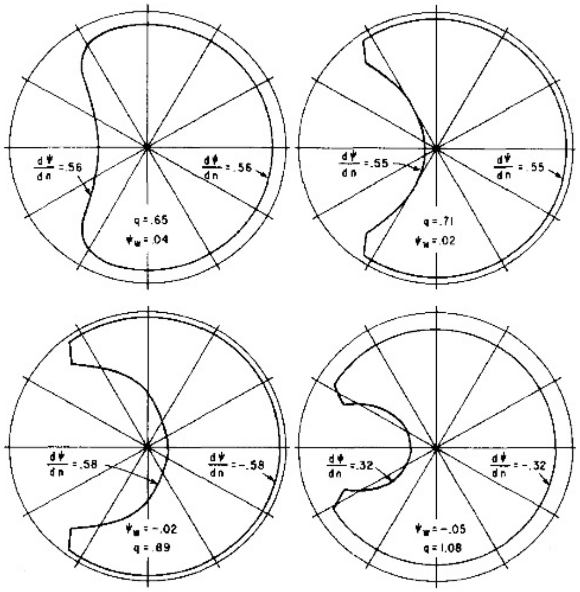


FIG. 5. Minimal energy states, $a = 0.8$. Note that $\partial\psi/\partial n$ is discontinuous for $\psi_w < 0$.

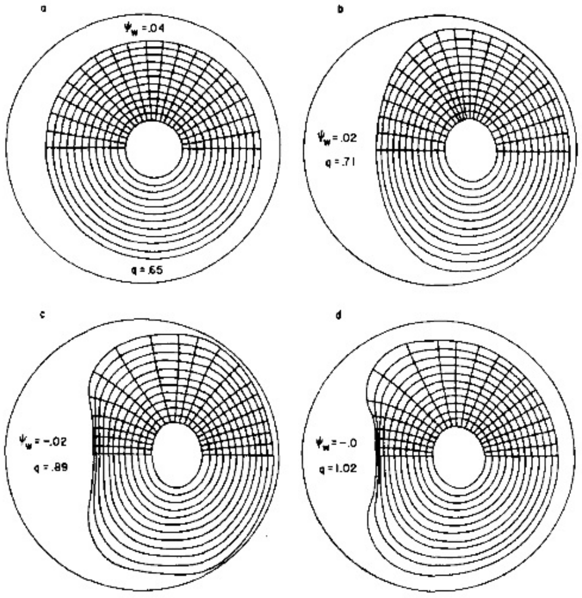
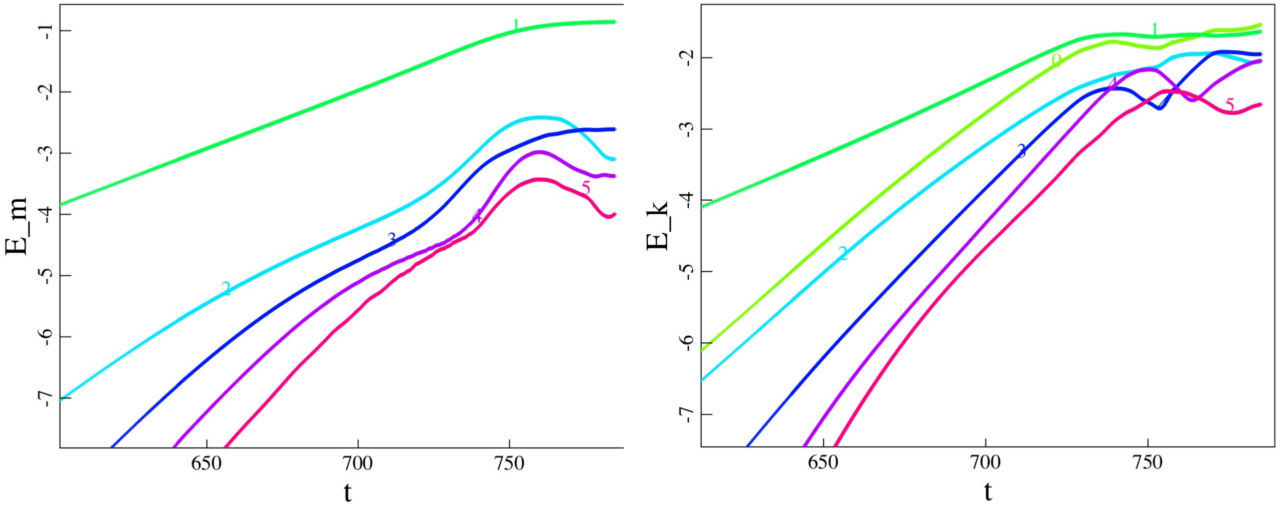


FIG. 10. Minimal energy states for $m = 1$ in the case of a parabolic current profile. Compare with Fig. 5.

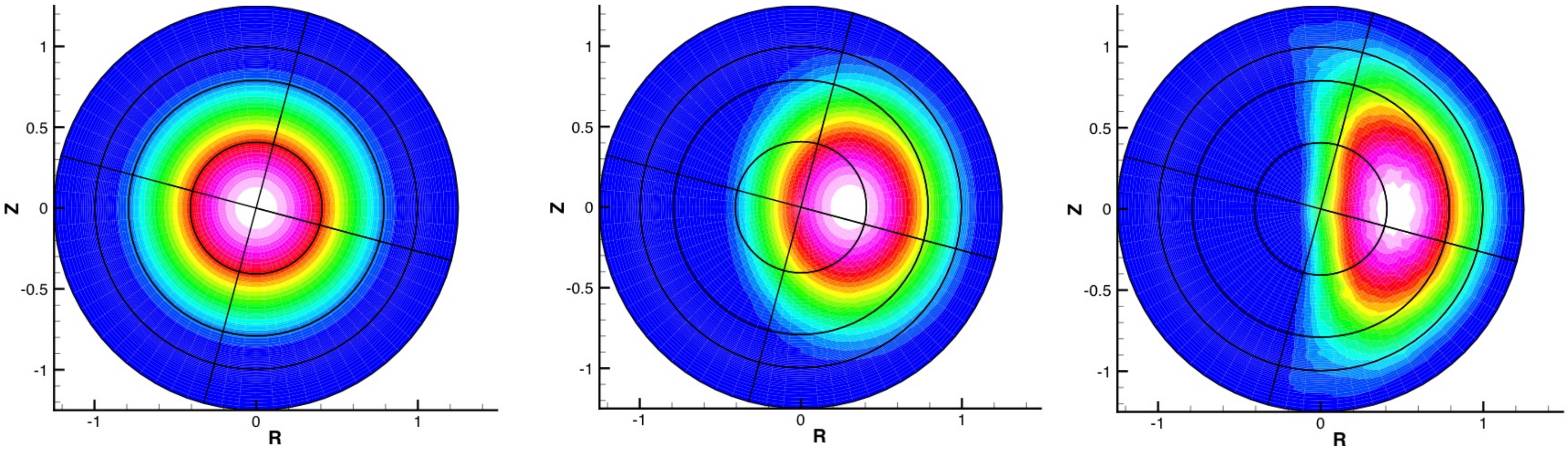
Minor modifications were made to apply NIMROD to the parabolic-*J*, $q(a)$=0.89 case.

- For preprocessing, the equilibrium requires no numerical integration (B_z is uniform), and a hyperbolic-tangent profile for n is specified.
- In NIMROD, the modifications make η a 3D function of n, $\eta(n) \sim n^{-n_\eta}$, and n_η=4 is used in the nonlinear computations.
- The cylindrical code was used to check that $B_z/B_\theta(a)$=10 with L_z=141a produces a mode that is close to the incompressible limit (γ is within 2%).
- A series of linear NIMROD computations check sensitivities to n_η, background density, the width of the transition, and resolution.
- The nonlinear computation presented here has $\eta(0)=4\times10^{-5}$, η_{edge}=6.4, n_{edge}=0.05, some hyper-dissipation, upwinding dissipation, and toroidal components $0 \le n \le 5$.



Logarithm of perturbed magnetic (left) and kinetic (right) energy from the nonlinear computation.

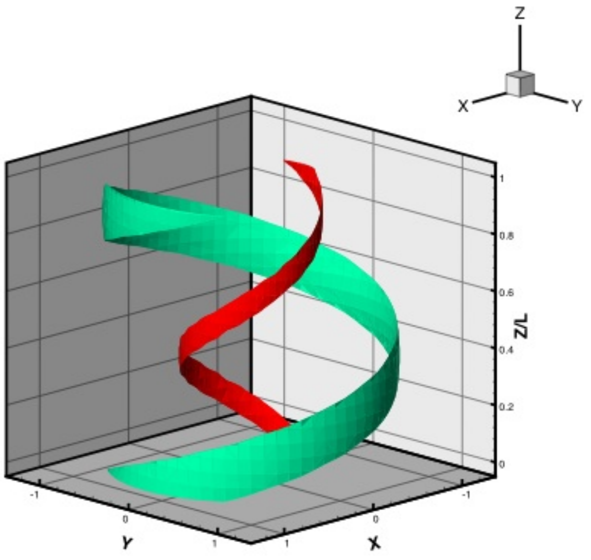
The drag term has not been used in the NIMROD computation; the plasma column distorts into the wall.



Contours of constant pressure at t=0, 3 τ_A from maximum displacement, and 1 τ_A from maximum displacement.

- Computationally, this case ‘exercises’ NIMROD’s ability to advect sharp fronts in *n* and to solve linear systems with very strong variation in coefficients over the periodic coordinate.

Helical surface currents flow parallel to J_0 along the phase of the column that moves inward and anti-parallel along the phase that moves outward



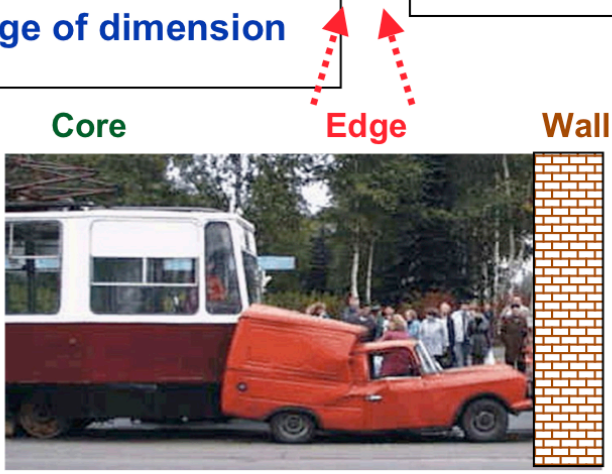
Modeling of edge plasmas does not use true vacuum region

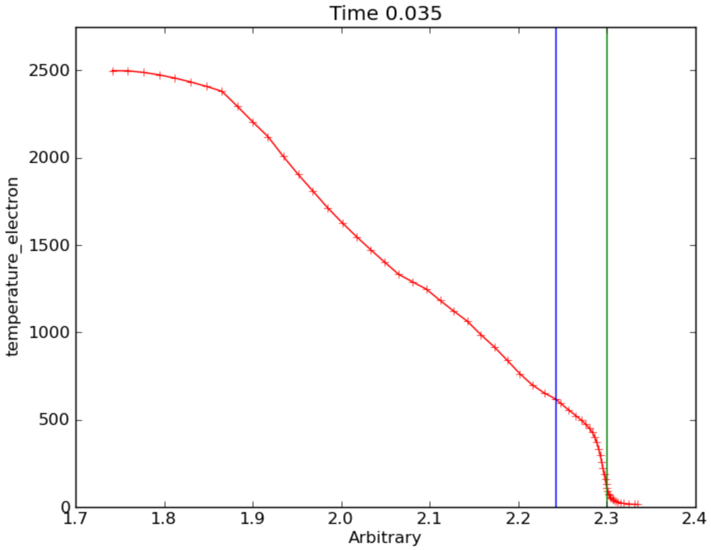
“Soft” interface to core

- Continuous physics
- Overlap region, no fixed location
- Couple at a radial point; plasma uniform poloidally
- Likely change of dimension

“Hard” interface to wall

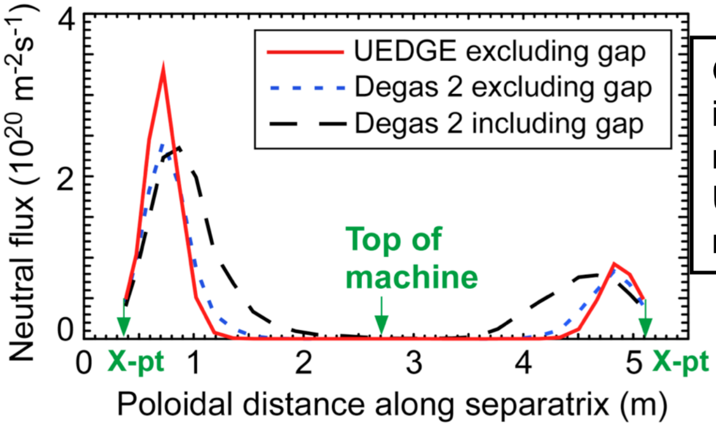
- Discontinuous physics
- Fixed coupling location
- Couple along 1D boundary
- Likely change of dimension



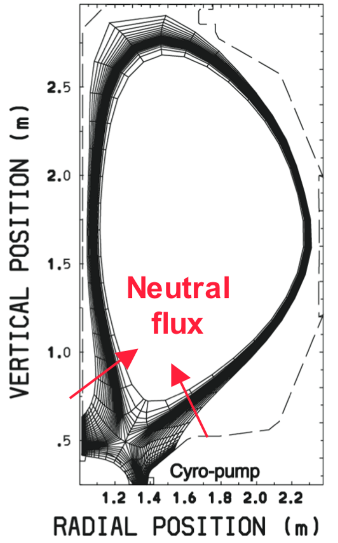


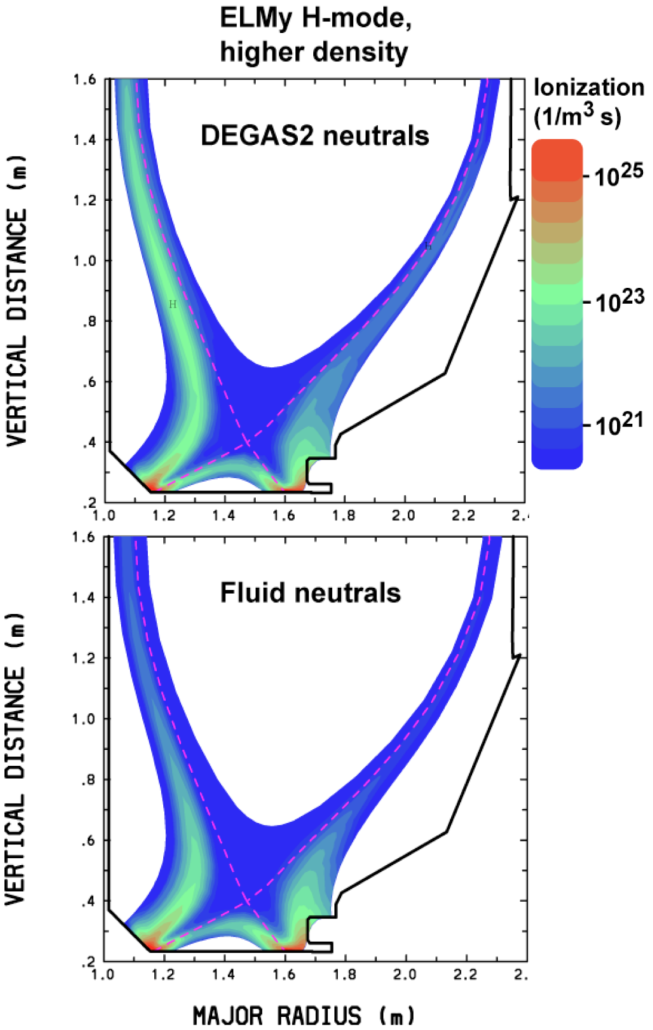
Edge modeling has traditionally focused on steady states

Radial neutral fueling-flux across separatrix in DIII-D



Gap region is beyond normal UEDGE mesh





Traditional focus: divertor widths, wall heat flux, neutral fueling

Fluid modeling of steady-state plasmas give information on key physics

Boundary conditions:

- Sheath boundary conditions
  See: Fundamenski, PPCF 2005 (Review article)
- Recycling coefficients (as input parameter) for neutrals

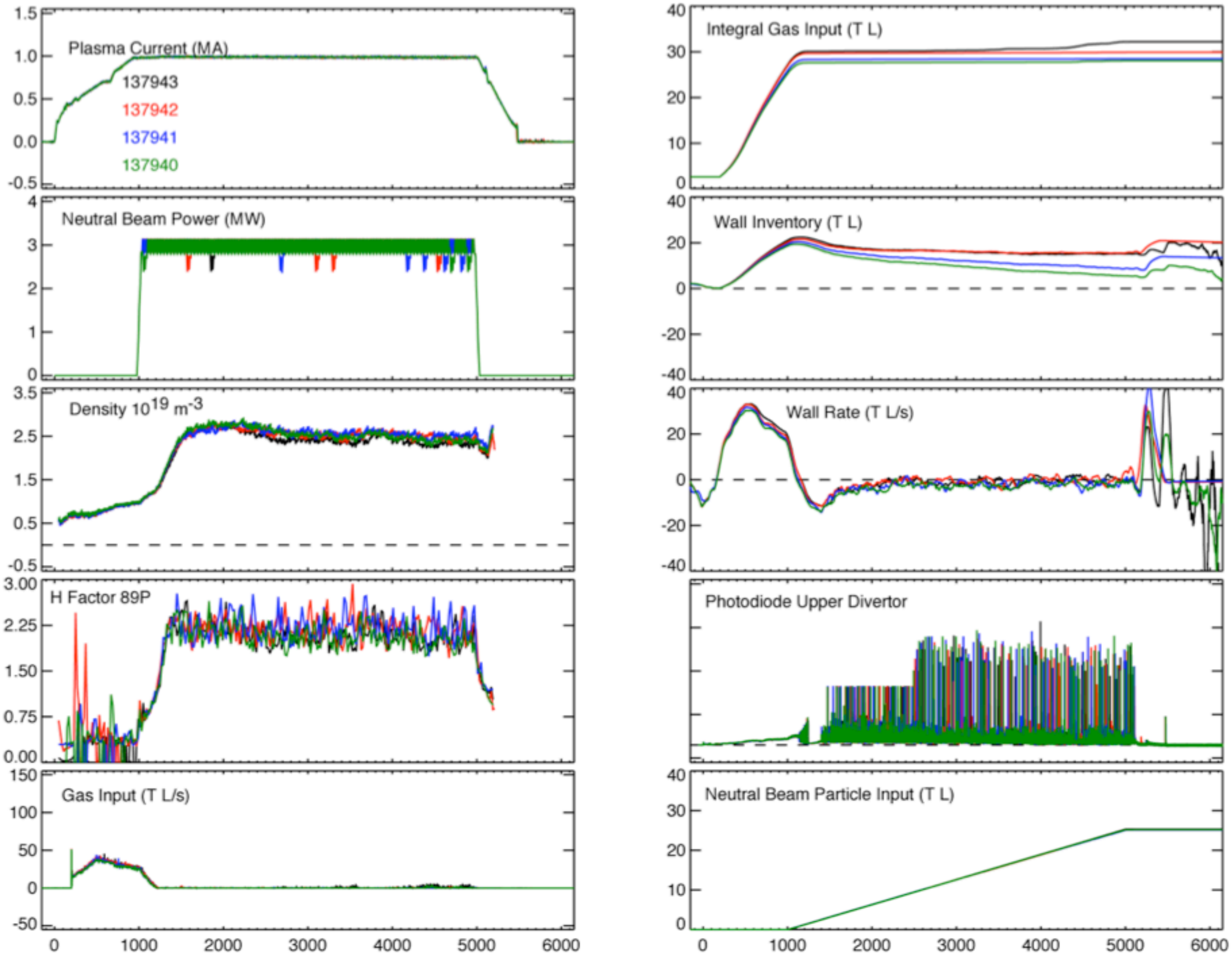
- Work is ongoing for improving current status by coupling to wall.

As CEMM codes include more physics, do longer time scale simulations, including this physics increases in importance.

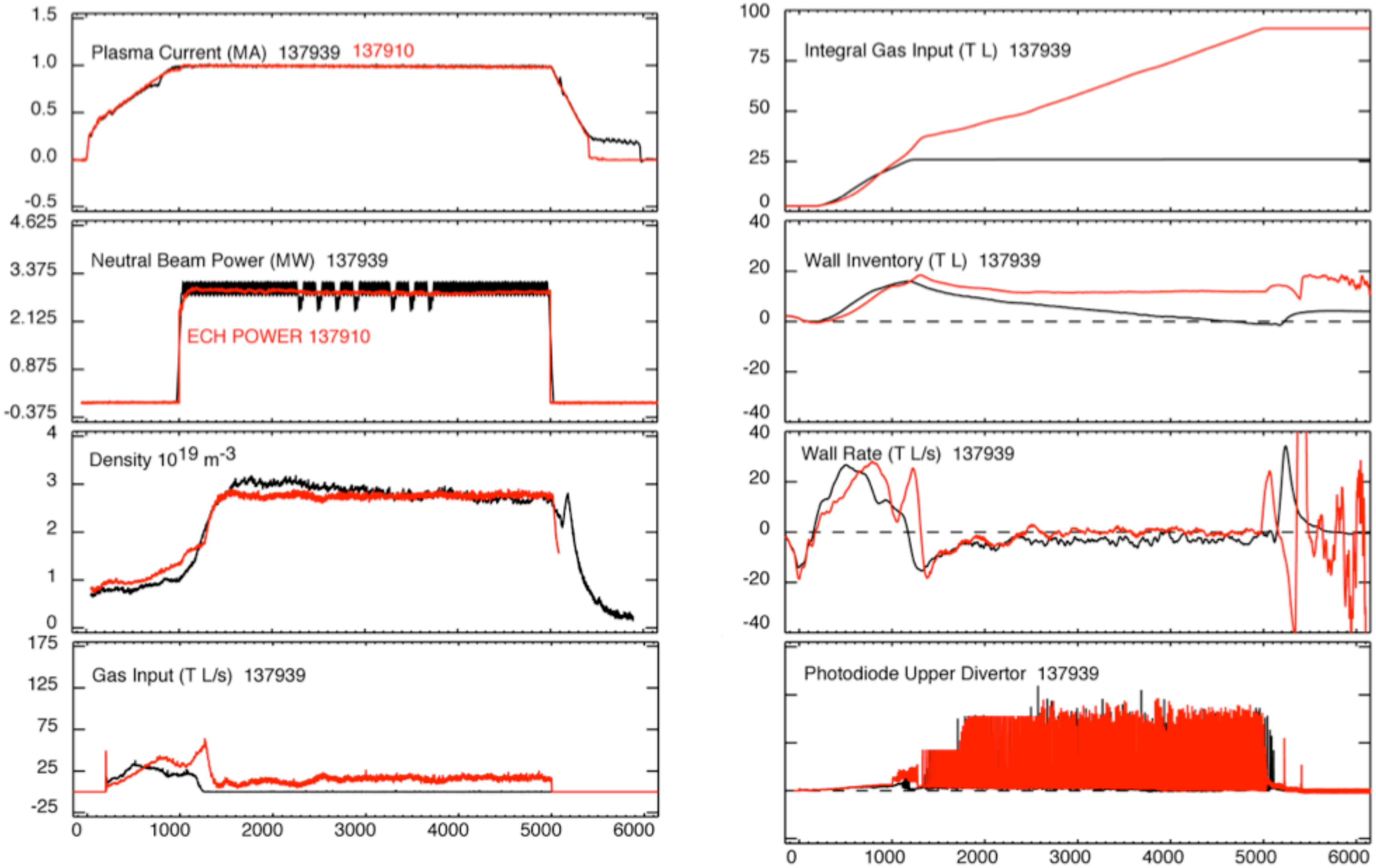
Change in balance of wall retention occurs during startup/shutdown

C-MOD:
Moly Walls

2009 FS



DIII-D sees similar behavior despite different materials



Disruptions affect particle balance dramatically

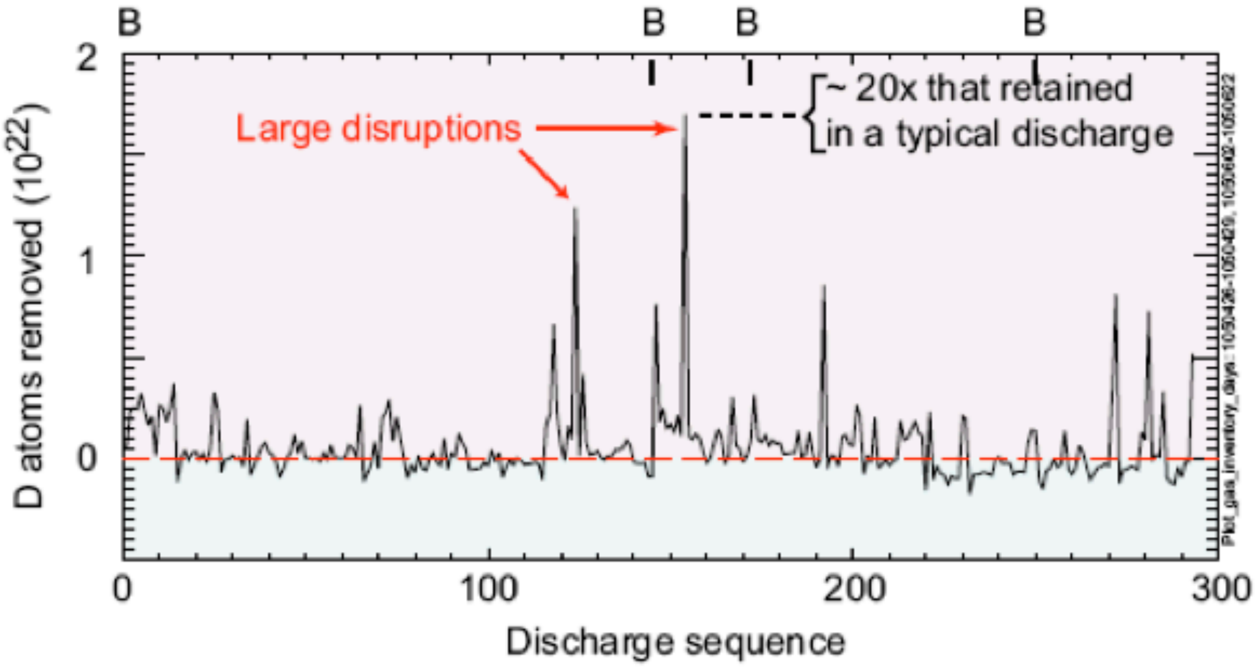


Fig. 11 Shot-to-shot particle balance in C-Mod. B marks times of boronizations [1].

Modeling of wall retention due to disruption models temperature

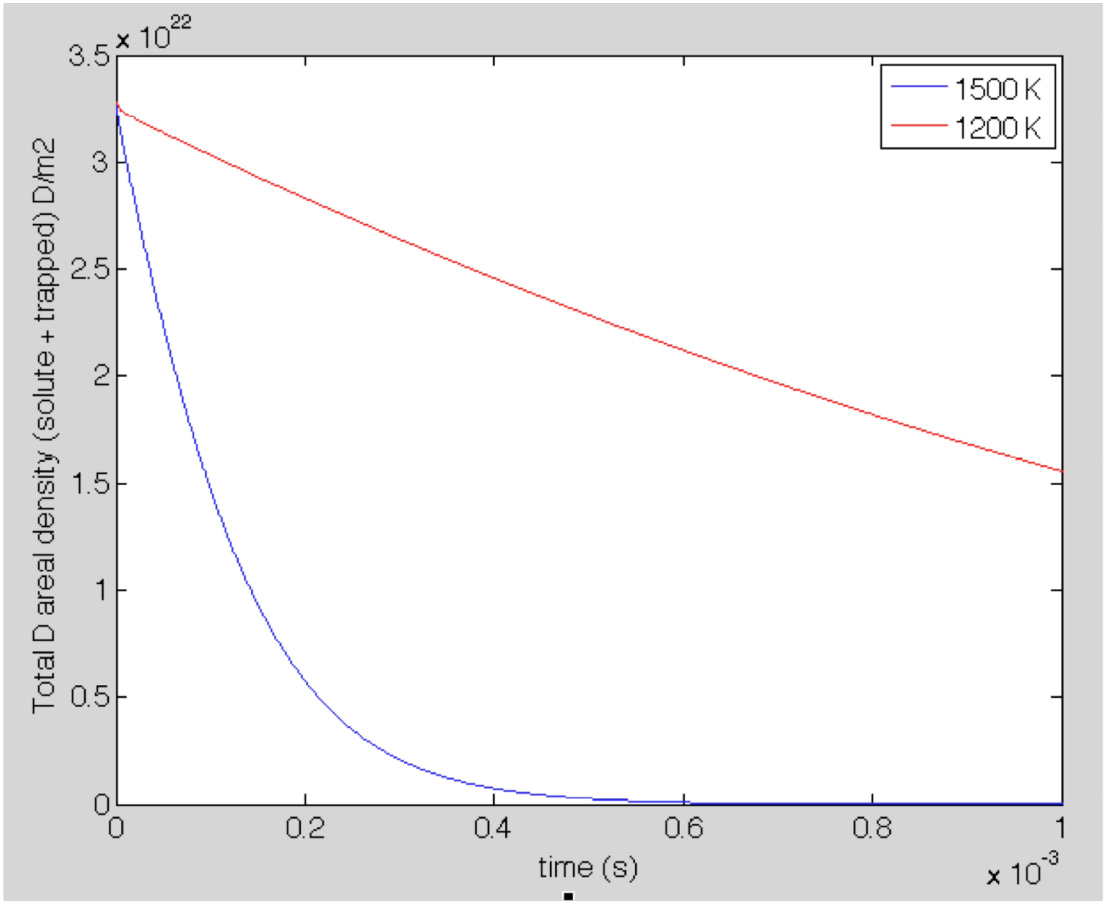


Fig. 21 Numerical simulation of disruption-heating induced reduction of retained D in Mo for two different assumptions of surface temperature.

Hydrogenic and impurity inflows can affect disruptions

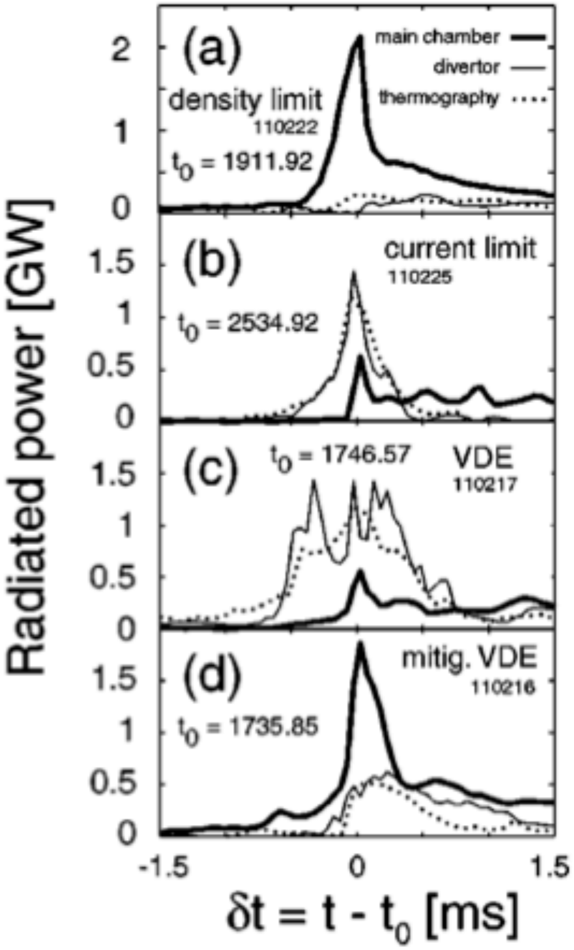


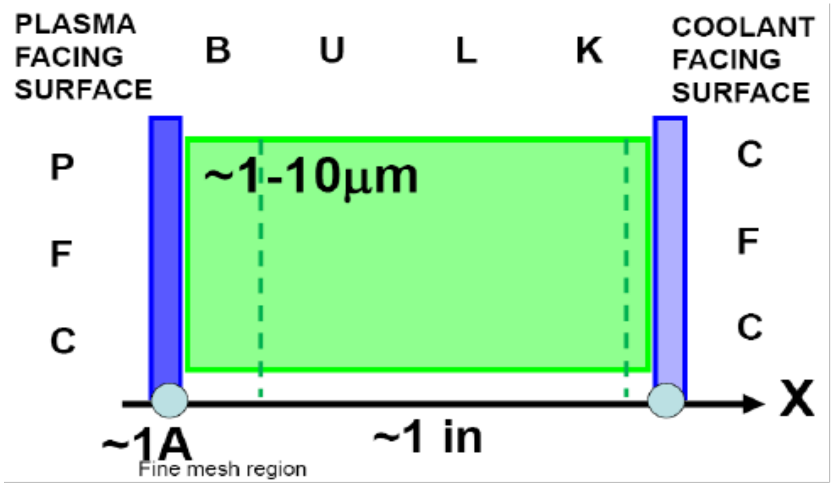
FIG. 3. XUV power radiated from the main chamber and divertor as a function of time for different types of disruptions. Also shown for comparison is divertor thermography data. Time t_0 corresponds to the peak in total radiated power.

Hollmann 2003:

- “Self-mitigated” density limit disruption
- Dominant energy loss is radiation losses to main chamber
- Radiation is primarily from impurity generation and neutral outgassing
- Believed to play some role in all disruptions

WallPSI is a continuum code to simulate time-dependent 1-D transport of plasma particles and heat in the wall

- Modeling of wall segment includes:
  - 1-D bulk and 0-D plasma facing surface (PFS) & coolant facing surface (CFS)
  - Mobile, adsorbed and trapped hydrogen modeling
  - Wall segment covered with non-uniform mesh w/ 1A Δx near surfaces
  - Incorporates collisional and thermally activated reactions
  - Diffusive and non-diffusive particle species transport
  - Modeling of reflection coefficients, sputtering yields, hydrogen implantation profile, profile of recoils,and profile of penetrating flux
- **Multiscale**
  - **shortest time <1ns (treated as collisions)**
  - **largest time >1year (bulk diffusion, permeation)**



More detailed models can be found in HEIGHTS package

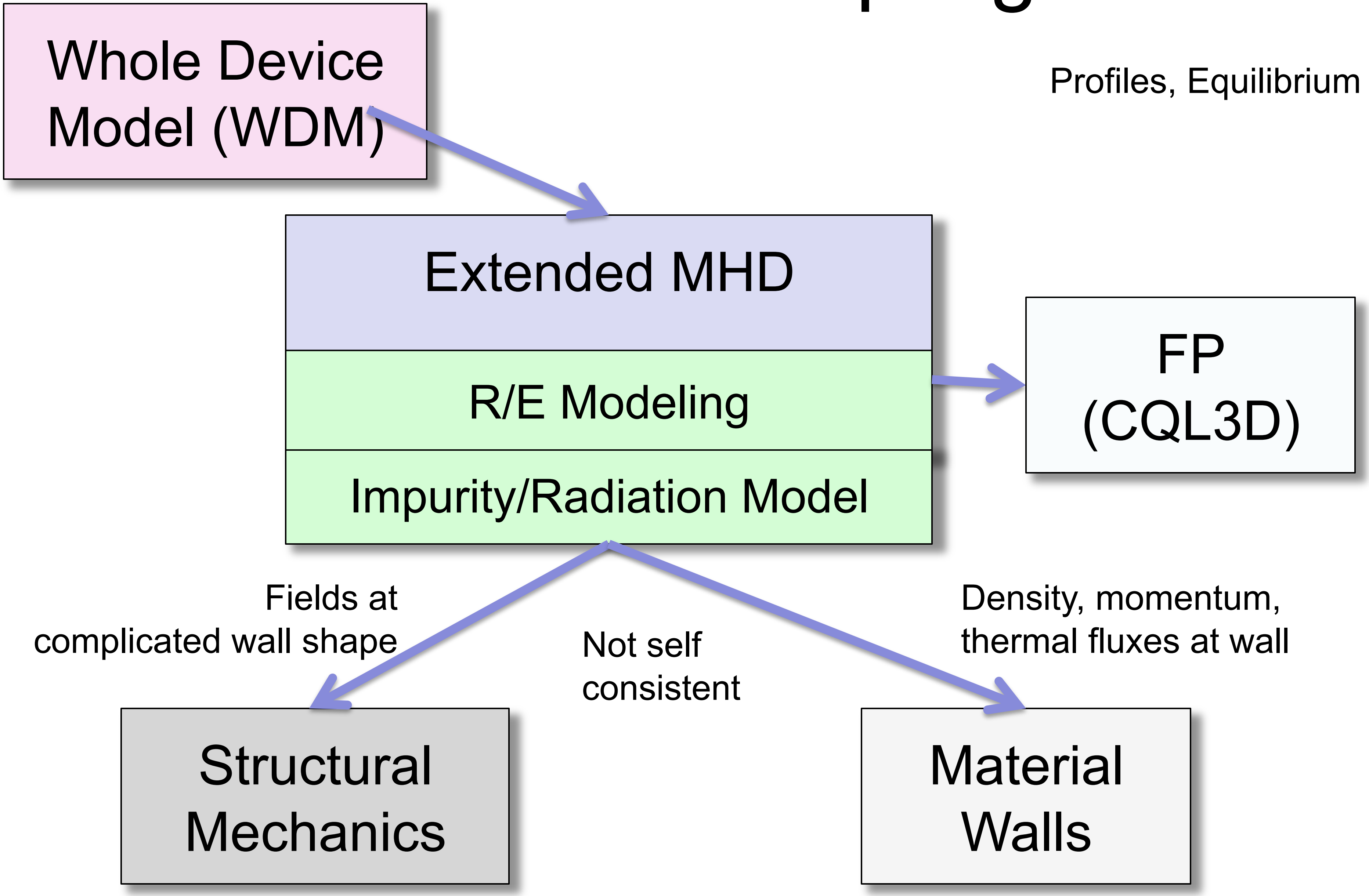
Implications of edge modeling on CEMM codes

- Near-steady-state conditions are reasonably well-described by sheath boundary conditions, recycling coefficients

- Non-steady-state conditions (ELMs, disruptions) is more difficult
  - No easy model exists – physics is inherently complicated
  - WallPSI offers a reasonable model that might be usable in a nearer time scale
  - HEIGHTS package has many detailed models, but significant caveats exist for this as well
  - Coupling to these packages offers not only the ability to improve the modeling of MHD behavior, but also the ability to study wall retention

Adding this physics is a natural FSP goal

Near term coupling



Whole Device Model (WDM)

Profiles, Equilibrium

Extended MHD

R/E Modeling

Impurity/Radiation Model

FP (CQL3D)

Fields at complicated wall shape

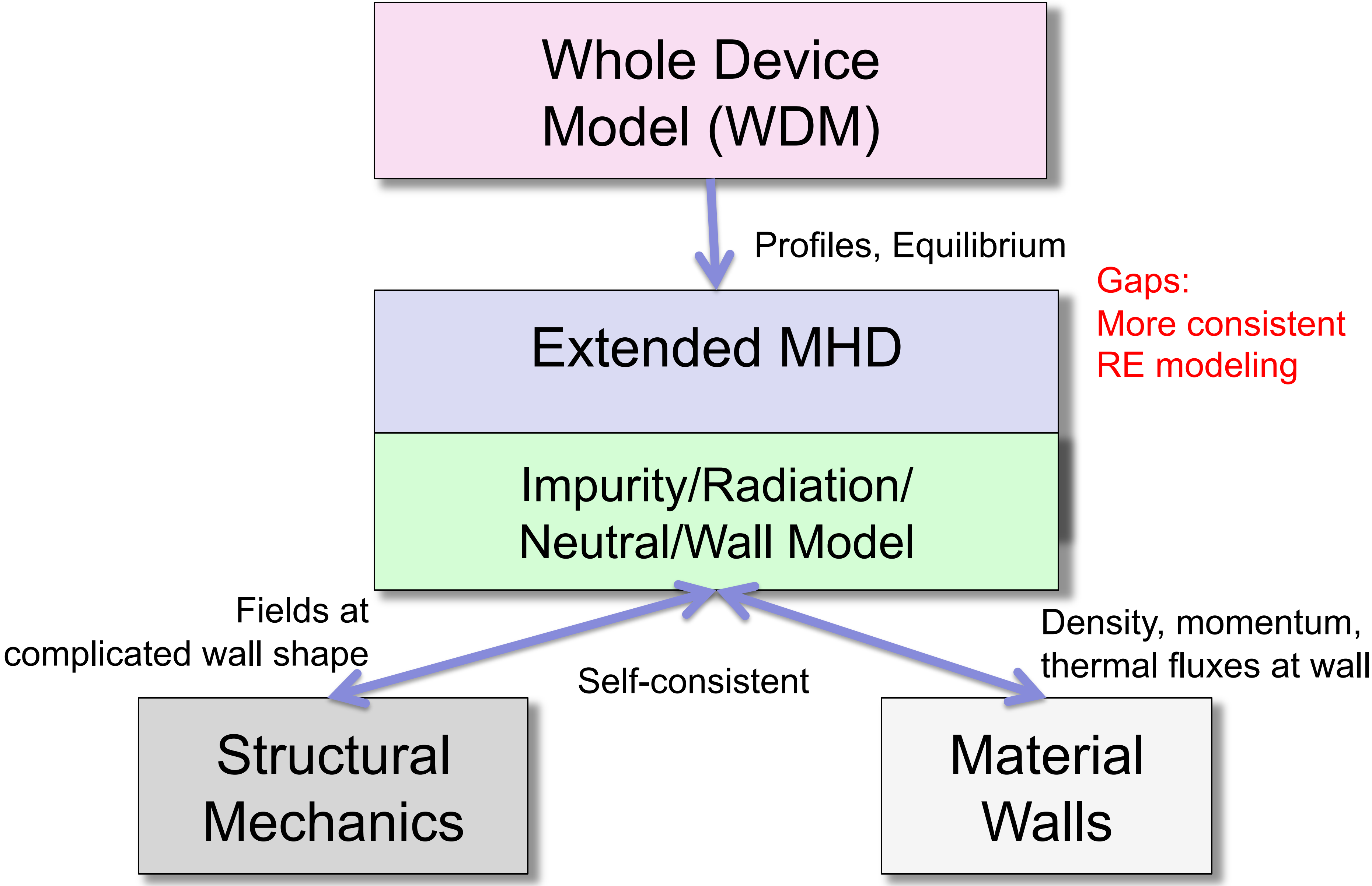
Not self consistent

Density, momentum, thermal fluxes at wall

Structural Mechanics

Material Walls

Mid-term coupling



Whole Device Model (WDM)

Profiles, Equilibrium

Gaps:
More consistent
RE modeling

Extended MHD

Impurity/Radiation/
Neutral/Wall Model

Fields at
complicated wall shape

Self-consistent

Density, momentum,
thermal fluxes at wall

Structural Mechanics

Material Walls

Comparison with Zakharov’s Proposal

Concrete actions proposed:

- Use kinetic models for energy loss
  - Ramos-Held DKE will allow 2nd –order accurate electron losses
  - Ions are more problematic – longer term project for discussion
- Use kinetic electrons for RE modeling
  - Started by Izzo. More work needed as indicated in roadmap
- Coupling of codes to gas injections modeling
  - Begun by Izzo. More work needed as indicated in roadmap
- Plasma edge and plasma-wall interactions
- Coupling to vessel conducting structures
- Theory developments
  - Adaptive grid
  - Development of kinetic-MHD hybrids
  - Models for plasma/wall interactions
- Validation