VDE simulations with M3D-C^1

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J. Artola, C.R. Sovinec, M. Hoelzl, F. Villone

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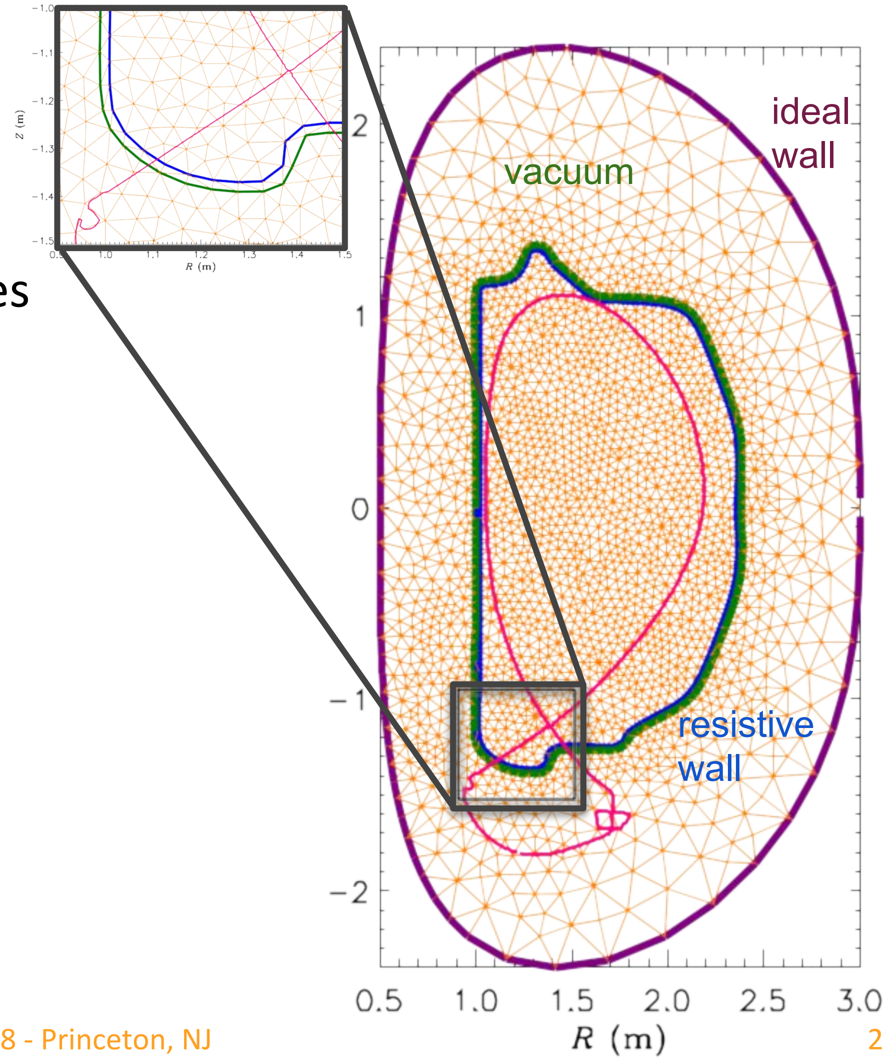
PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

Modeling VDEs with M3D-C[1]

- 3D nonlinear extended MHD equations
- Implicit time stepping allows simulations over transport time scales



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  - Allows for halo currents (no boundary condition on **B** at resistive wall)
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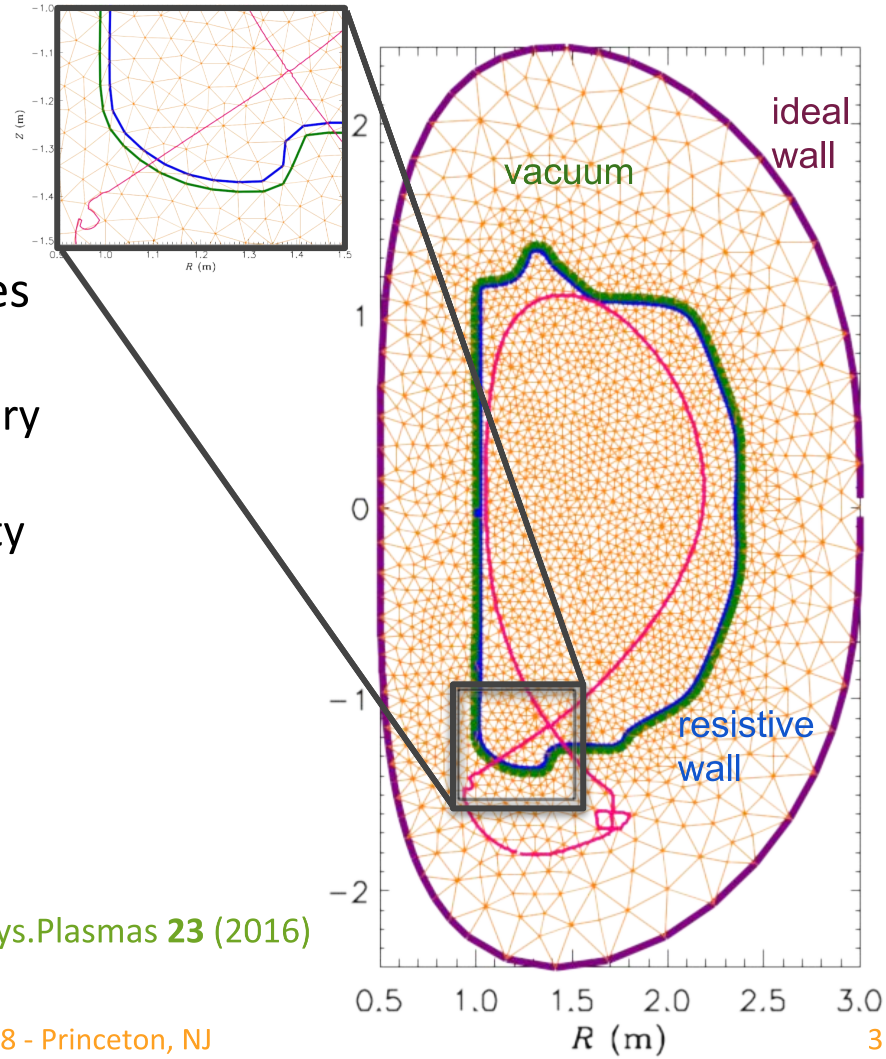

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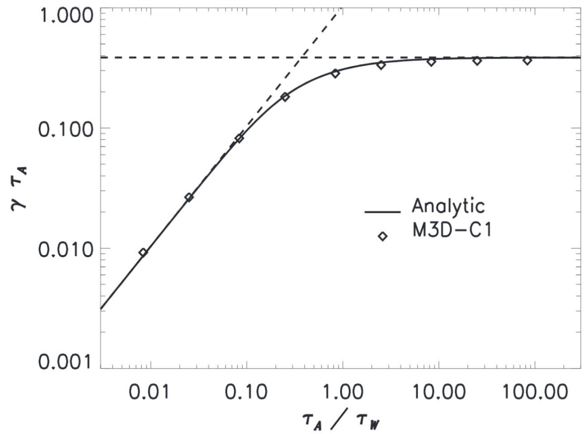
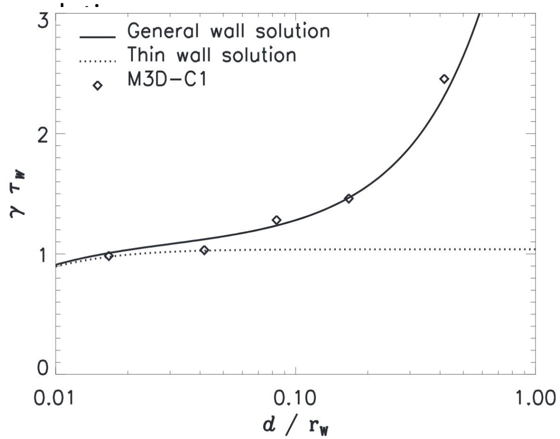


RWM growth rate vs. resistive diffusion time of the wall, solid line: thin-wall



RWM growth rate vs. wall thickness
solid line: general analytic solution
dotted line: thin-wall solution

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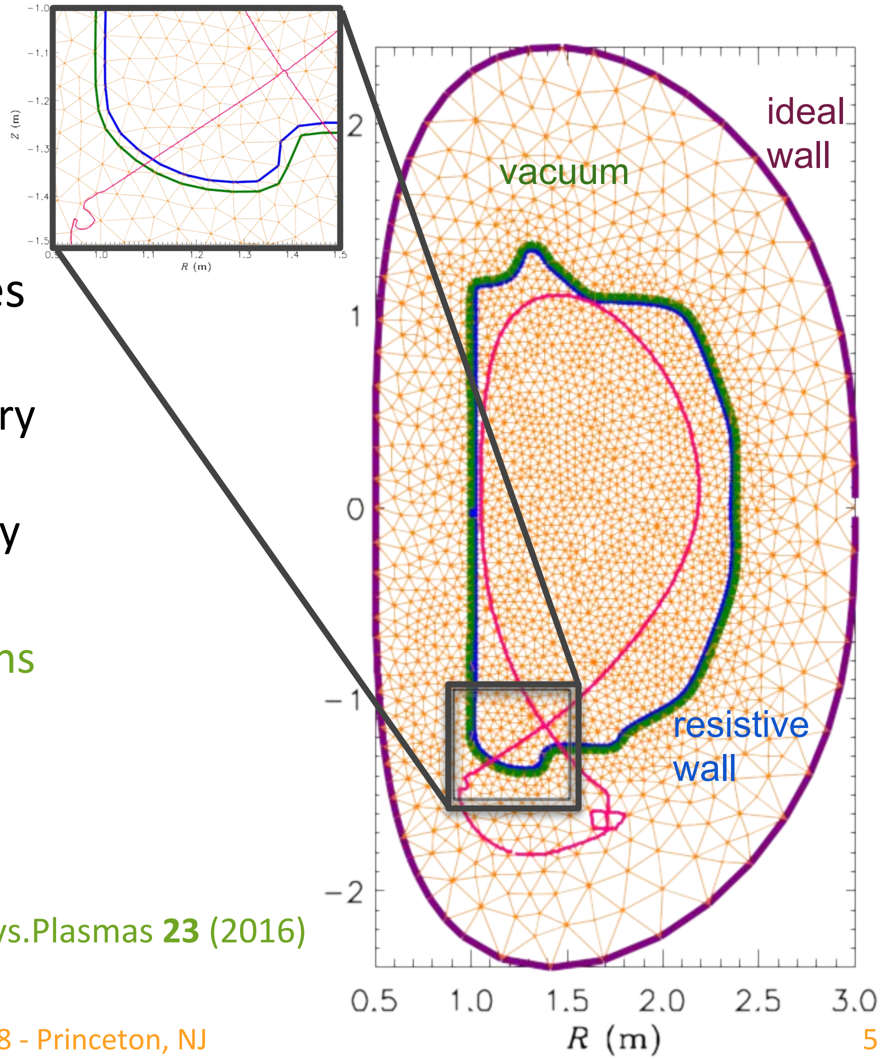

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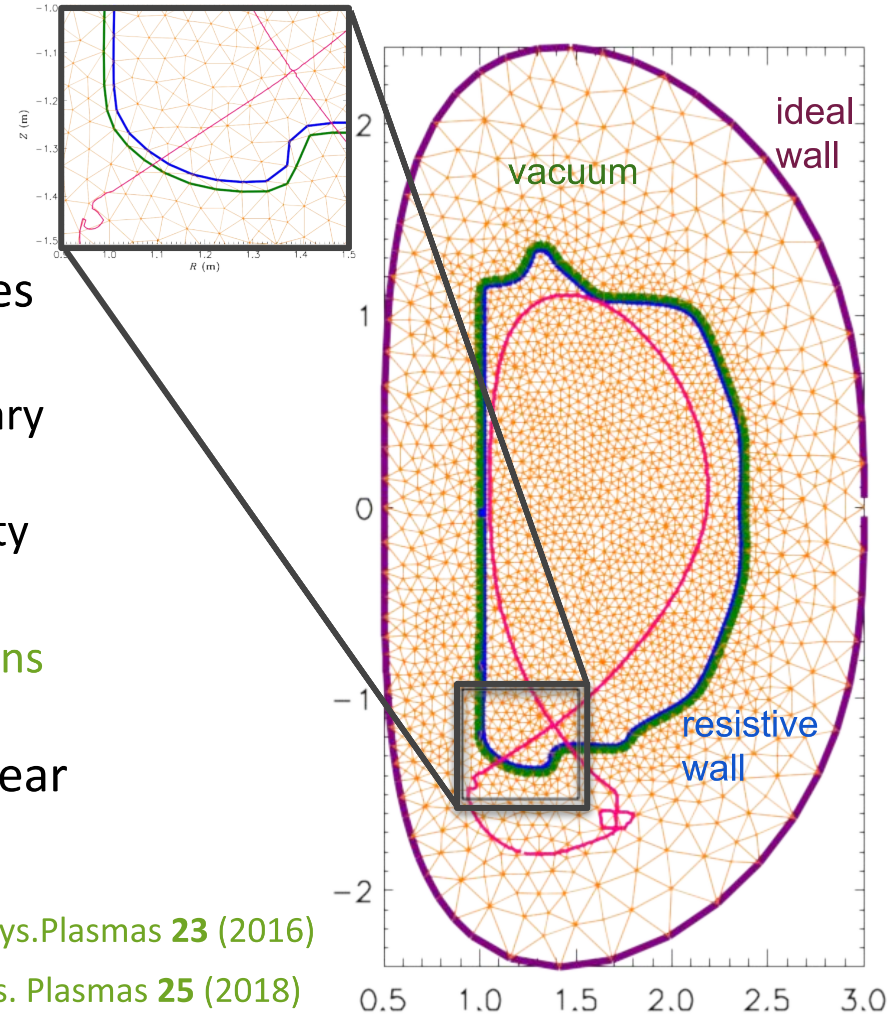
→ Example of self-consistent 3D nonlinear simulations of VDE in NSTX**



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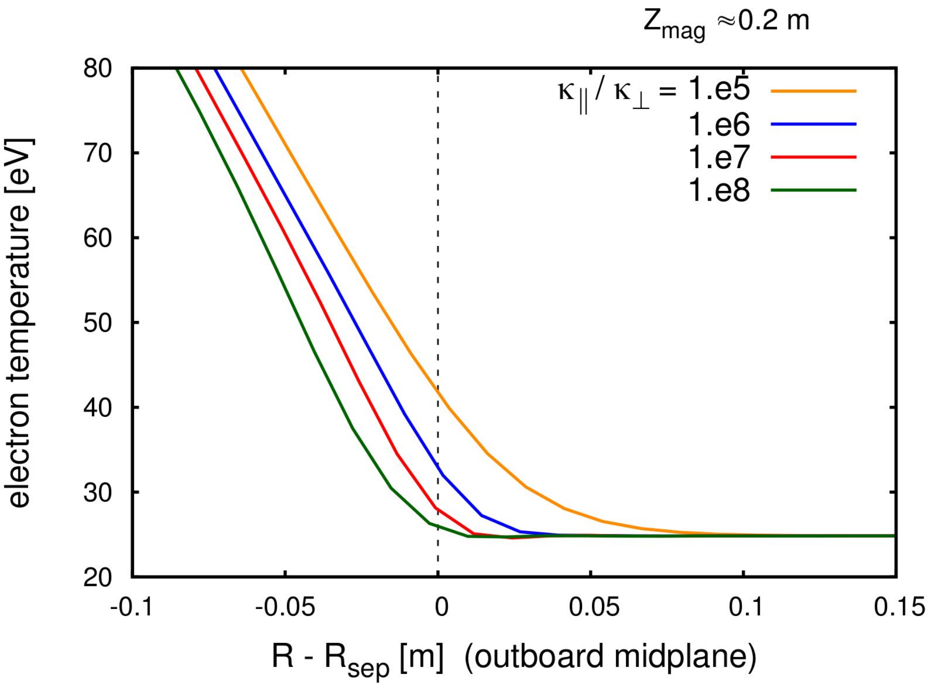
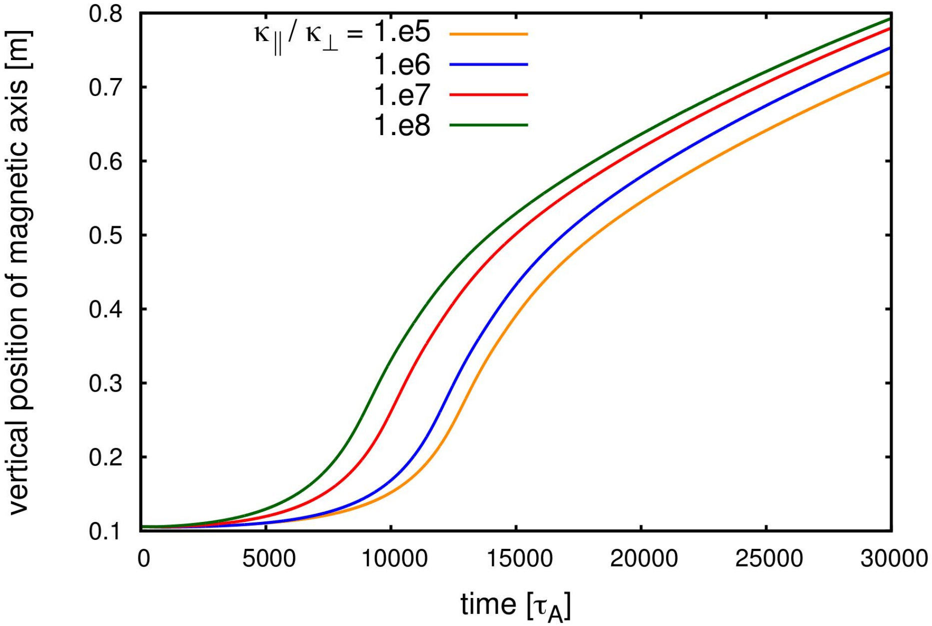
D. Pfefferle, et al.: Phys. Plasmas **25 (2018)

Halo width self-consistently determined by $\kappa_{//}/\kappa_{\perp}$





→ Halo width & temperature at LCFS determined by T_{edge} & $\kappa_{//}/\kappa_{\perp}$

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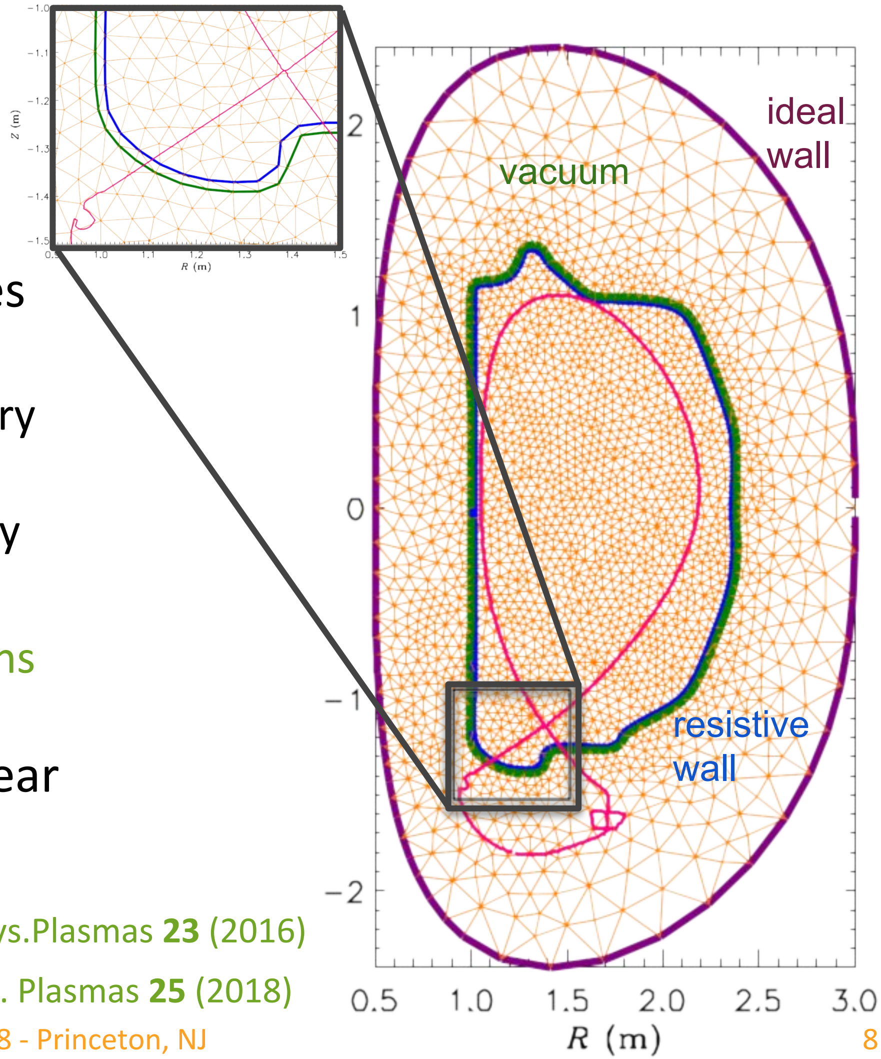

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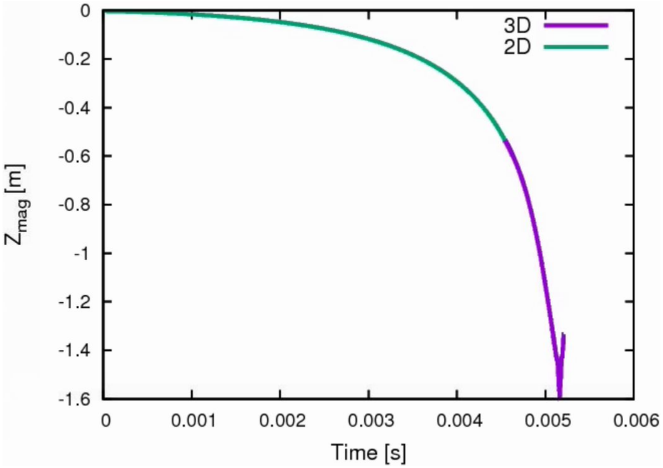
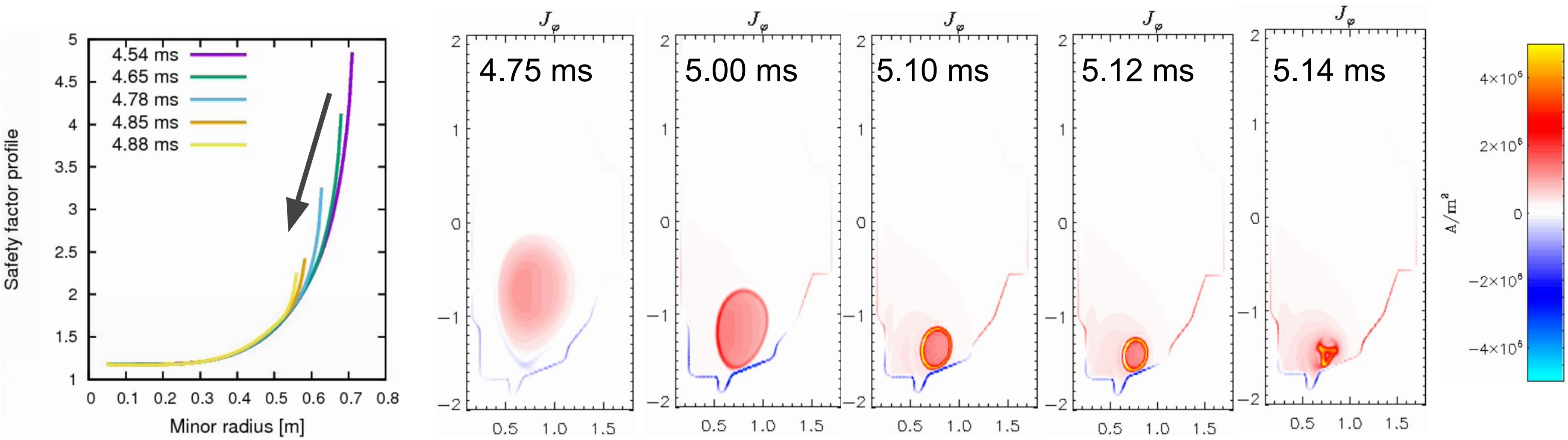
Evolution of hot VDE in M3D-C^1 simulation



- Equilibrium is vertically unstable, plasma drifts towards wall, stays axisymmetric

[D. Pfefferle, et al.: Phys. Plasmas **25** (2018)]

Evolution of hot VDE in M3D-C1 simulation



- Equilibrium is vertically unstable, plasma drifts towards wall, stays axisymmetric
- Plasma becomes limited by wall, edge safety factor drops, edge current sheet forms, 3D instabilities develop at edge

[D. Pfefferle, et al.: Phys. Plasmas **25** (2018)]

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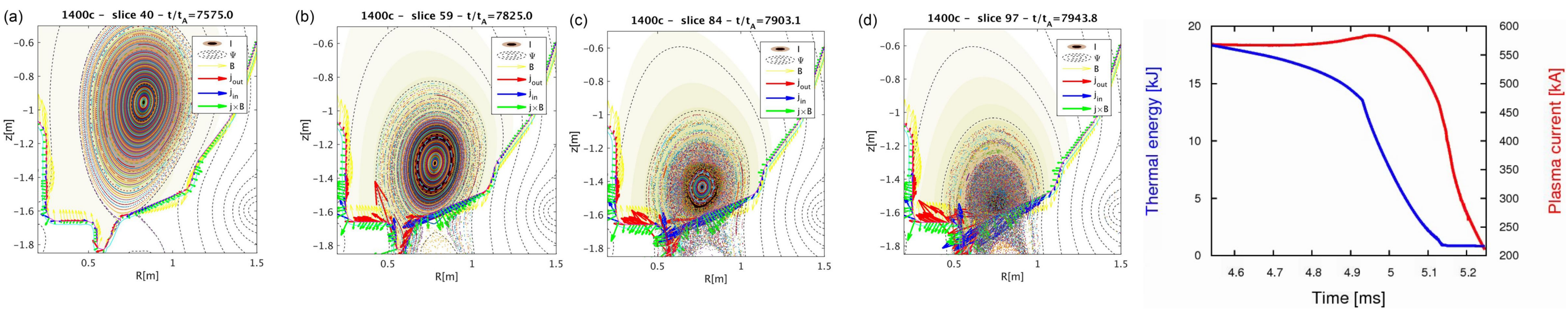

- Equilibrium is vertically unstable, plasma drifts towards wall, stays axisymmetric
- Plasma becomes limited by wall, edge safety factor drops, edge current sheet forms, 3D instabilities develop at edge
- Breaking of flux surfaces causes thermal quench leading to current quench

[D. Pfefferle, et al.: Phys. Plasmas **25** (2018)]

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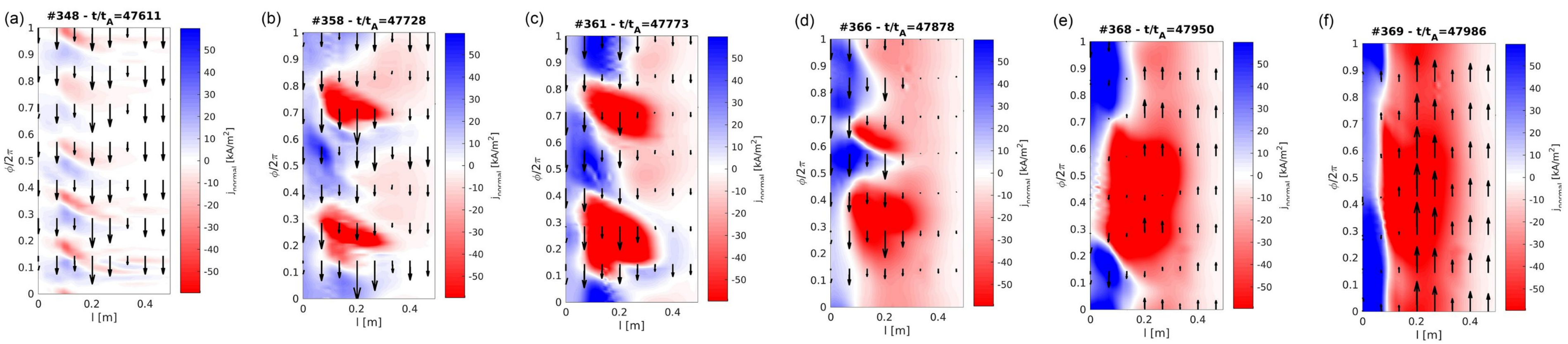

- Equilibrium is vertically unstable, plasma drifts towards wall, stays axisymmetric
- Plasma becomes limited by wall, edge safety factor drops, edge current sheet forms, 3D instabilities develop at edge
- Breaking of flux surfaces causes thermal quench leading to current quench
- Non-axisymmetric halo currents

[D. Pfefferle, et al.: Phys. Plasmas **25** (2018)]

Benchmarking M3D-C^1 simulations of VDEs

- VDE benchmark with 3D nonlinear MHD codes NIMROD & JOREK
- VDE simulations based on ITER scenario for benchmark with CarMaONL
  - CarMaONL = evolution of 2D equilibria + 3D model of conducting wall structures (CARIDDI)

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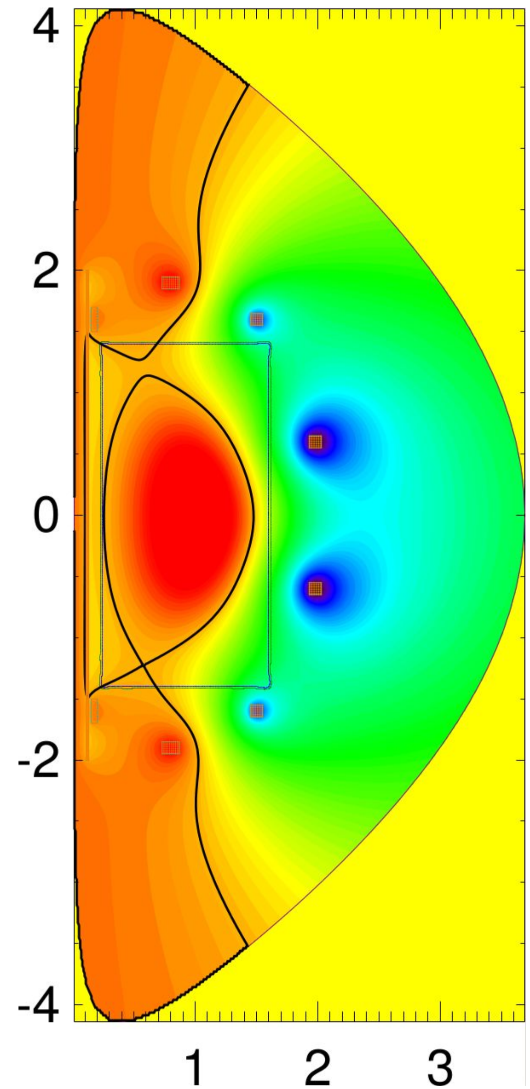
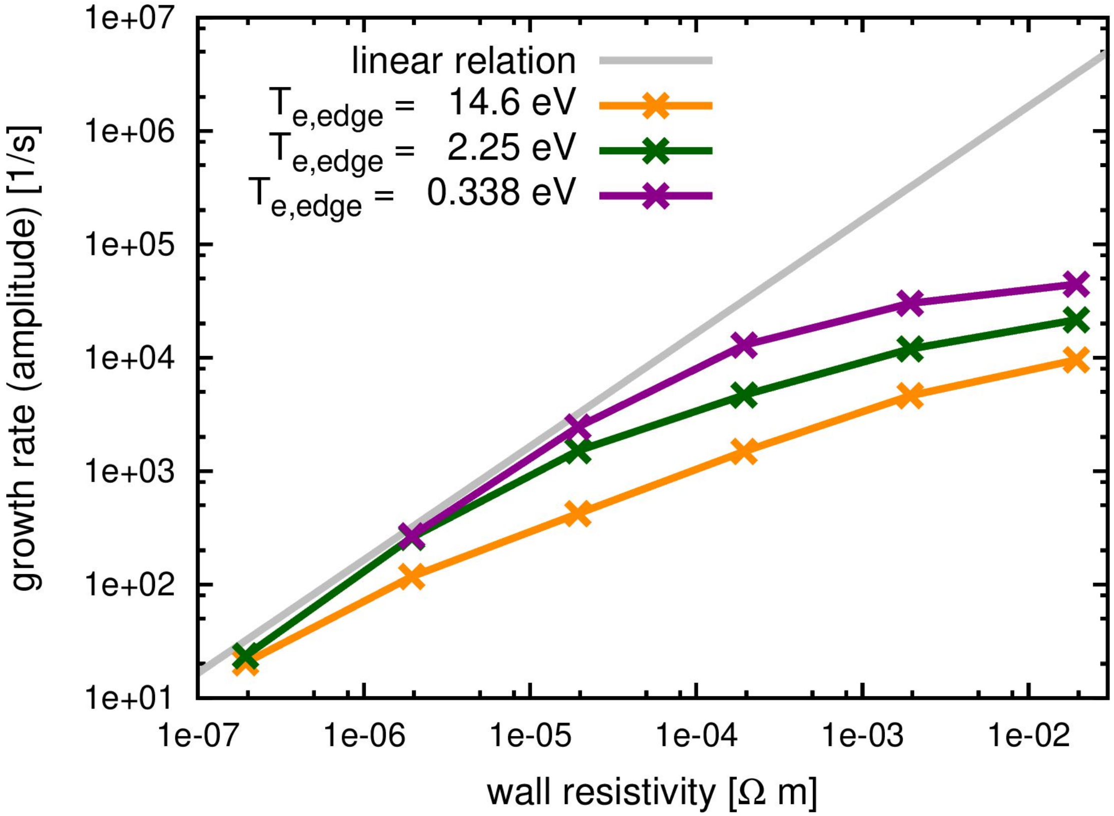
Benchmark M3D-C1, NIMROD & JOREK

- Compare results of all three codes for the same VDE case
  - Based on NSTX VDE discharge #139536
  - Axisymmetric rectangular resistive wall that all codes can handle
- Linear, 2D axisymmetric nonlinear & 3D nonlinear simulations
  - Compare evolution, wall currents & forces



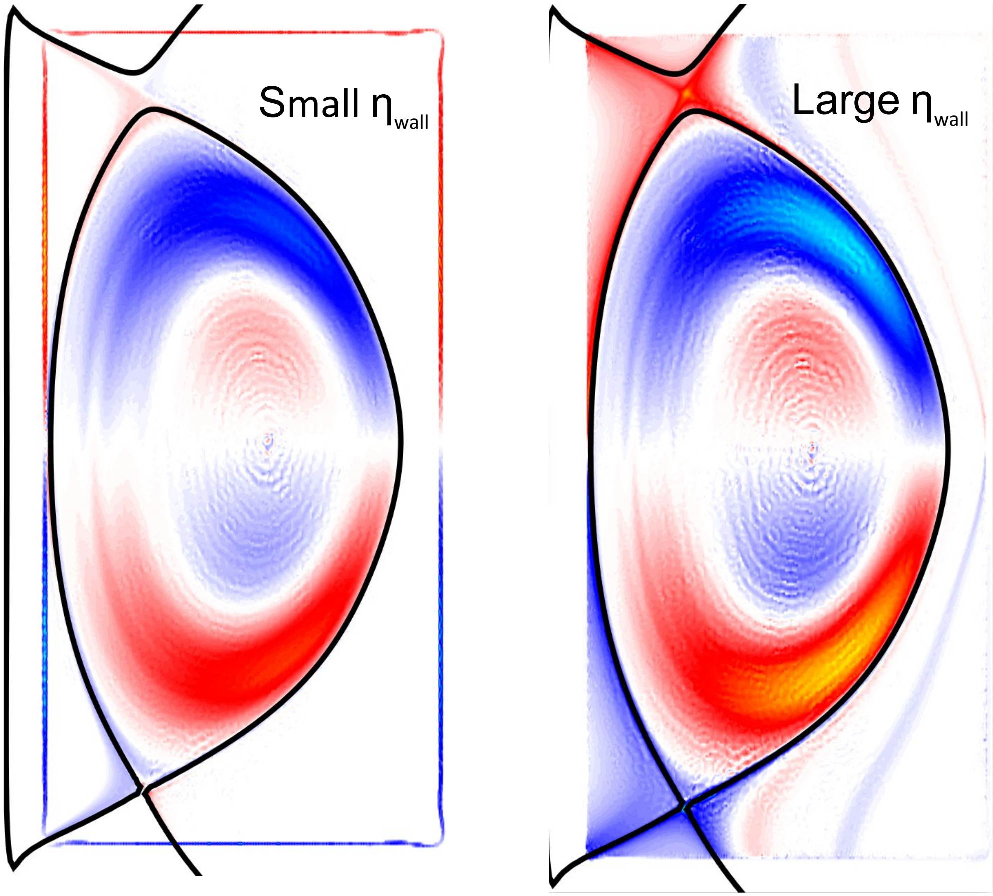
Linear VDE growth vs. η_{wall} depends on T_{edge}



- Small η_{wall}:
  VDE growth rate ~ η_{wall}

- Large η_{wall}:
  VDE slowed down by response currents in open field line region

Linear VDE growth vs. η_{wall} depends on T_{edge}



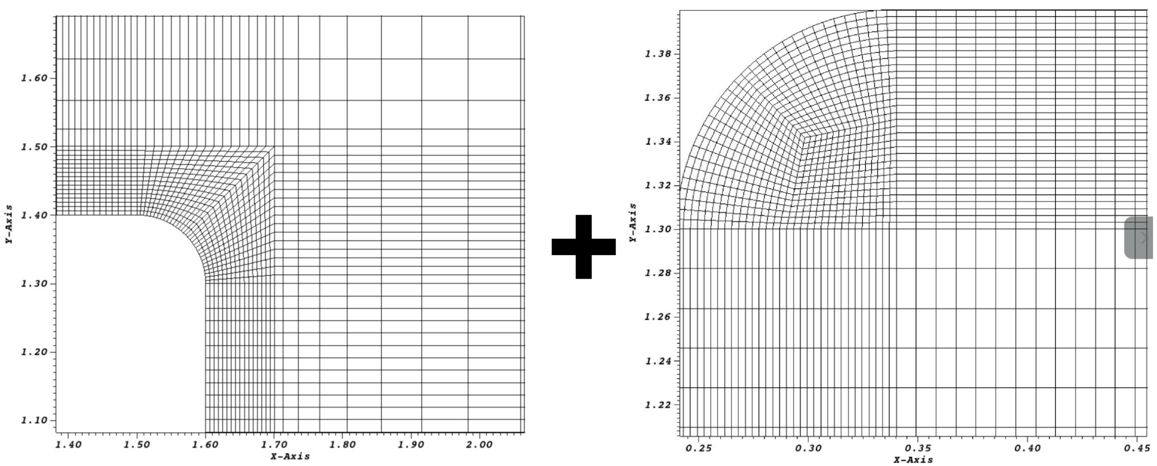
Toroidal current density eigenfunctions

- Small η_{wall}:
  VDE growth rate ~ η_{wall}
- Large η_{wall}:
  VDE slowed down by response currents in open field line region

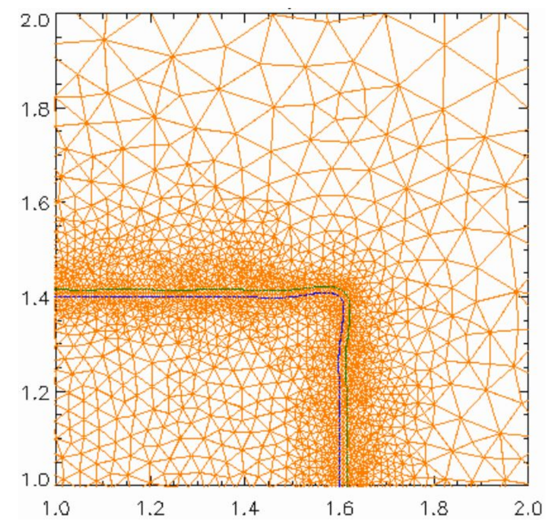
Linear benchmark with NIMROD

- Differences between NIMROD & M3D-C^1
  - Discretization toroidal direction: spectral & C^1 finite elements
  - Resistive wall model: thin & thick

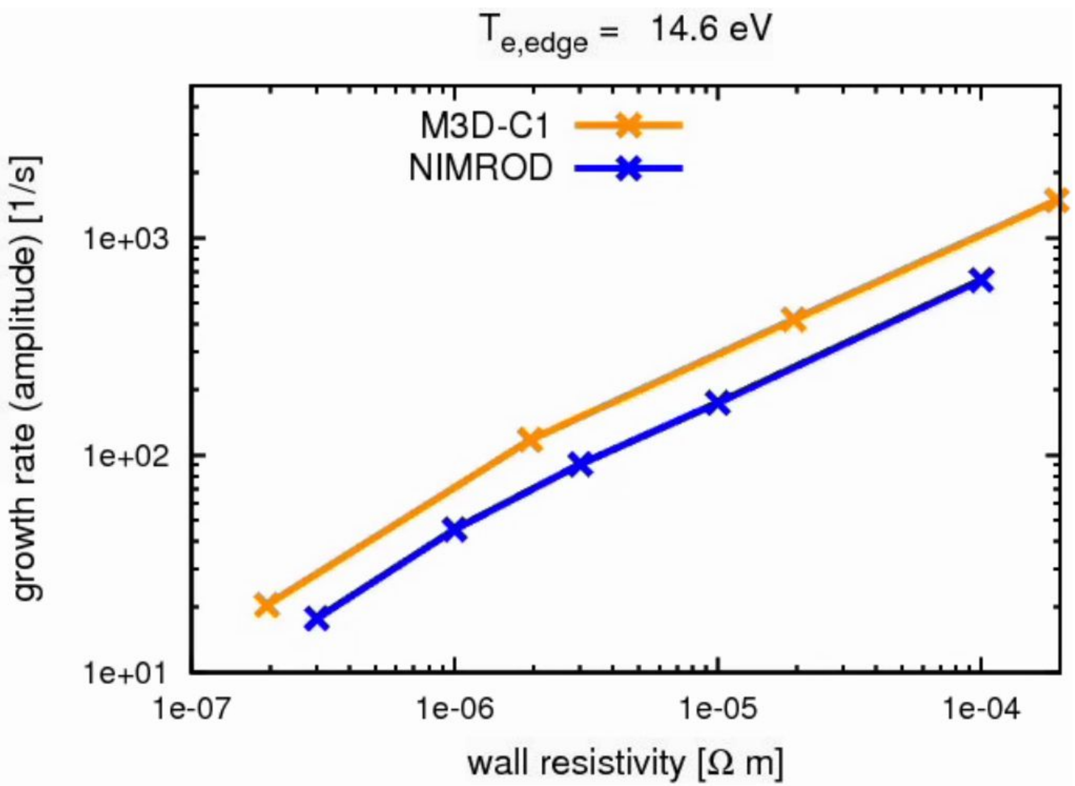
NIMROD



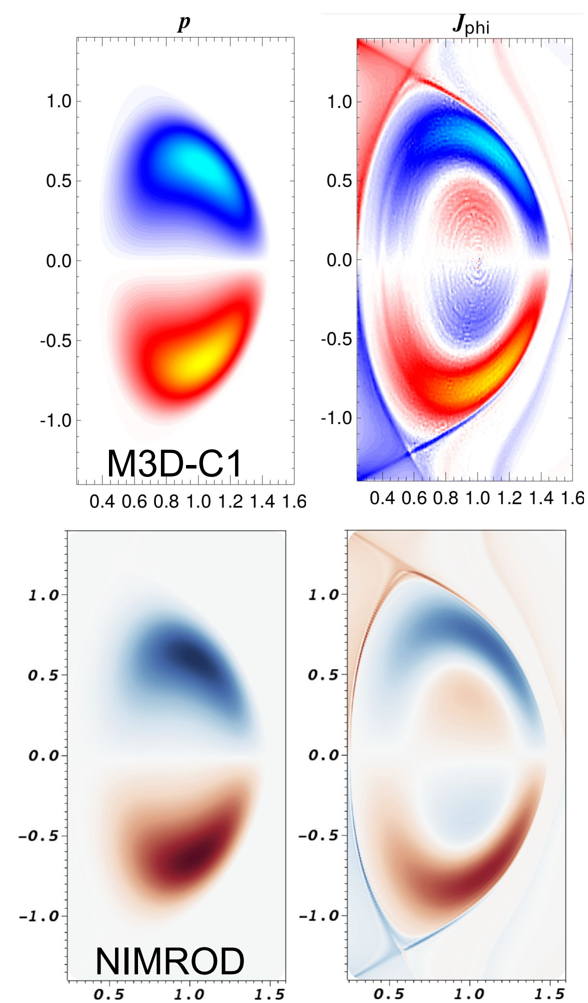
M3D-C^1



Linear benchmark with NIMROD (preliminary)



Pressure & toroidal current density eigenfunctions



- Growth rates differ by ~40%
- Slight differences in diffusion parameters

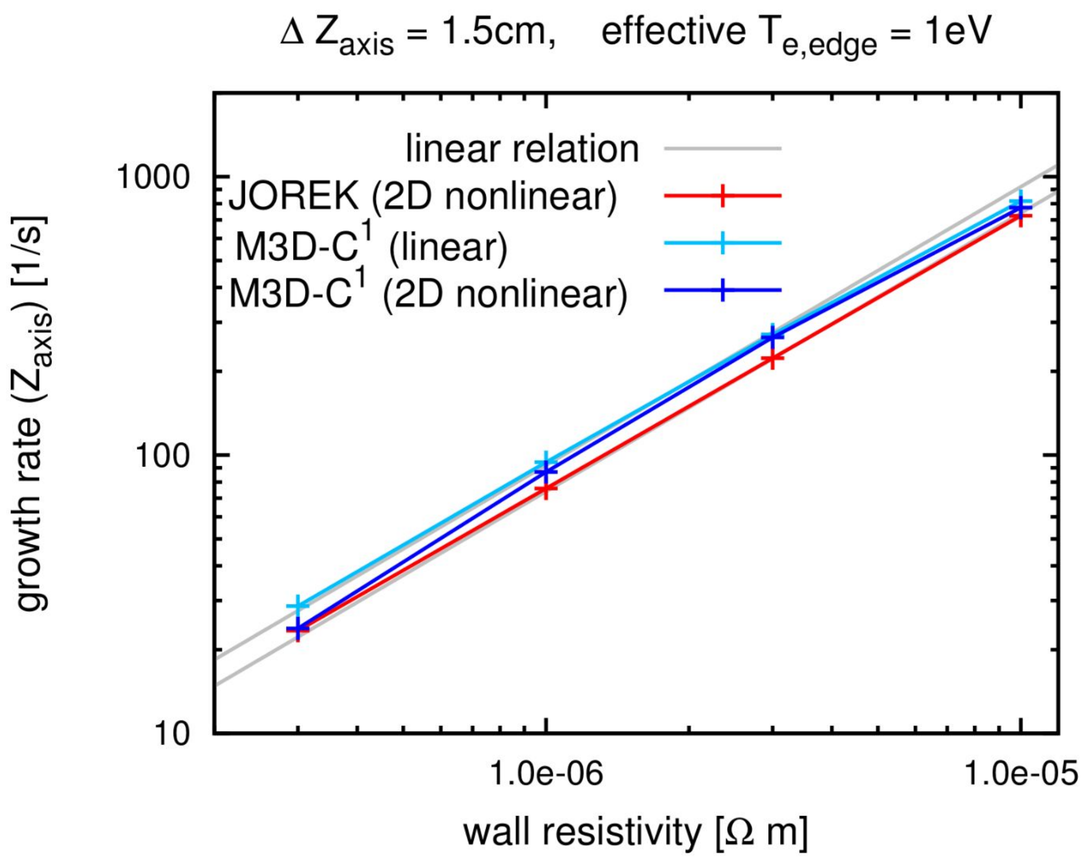
Linear benchmark with JOREK-STARWALL

- Comparison of linear phase of 2D nonlinear simulations
  - negative temperature offset in resistivity calculation to avoid influence of currents in open field line region:

    $$\eta = \eta_{spitzer}(T_e - T_{off})$$

- Differences between JOREK & M3D-C^1/NIMROD models:
  - JOREK has full MHD model, but uses reduced MHD for VDEs
  - No ideal wall BCs at domain boundary
  - Only normal velocity component vanishes at resistive wall

Linear benchmark with JOREK-STARWALL



→ growth rate ~ η_{wall}, deviation of growth rates ≤ 20%

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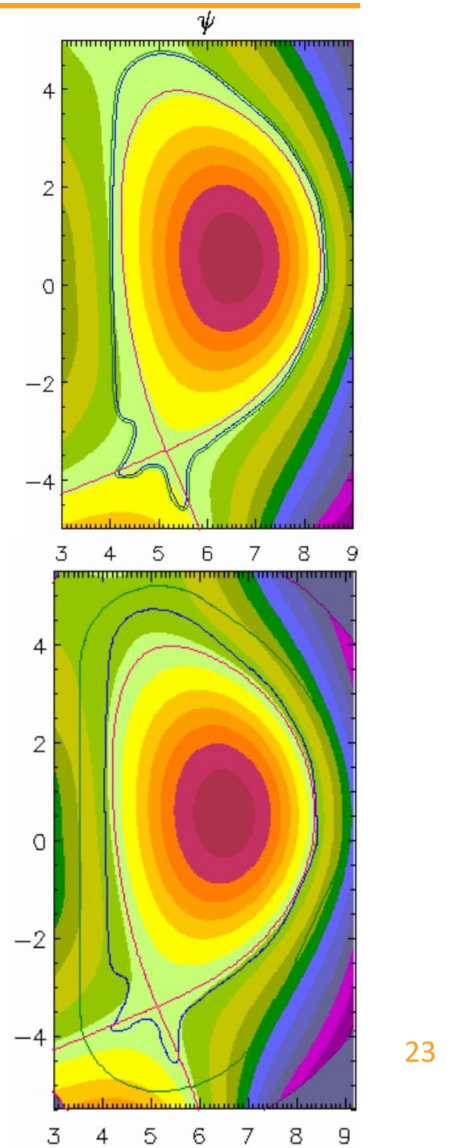
2D nonlinear ITER VDE simulation

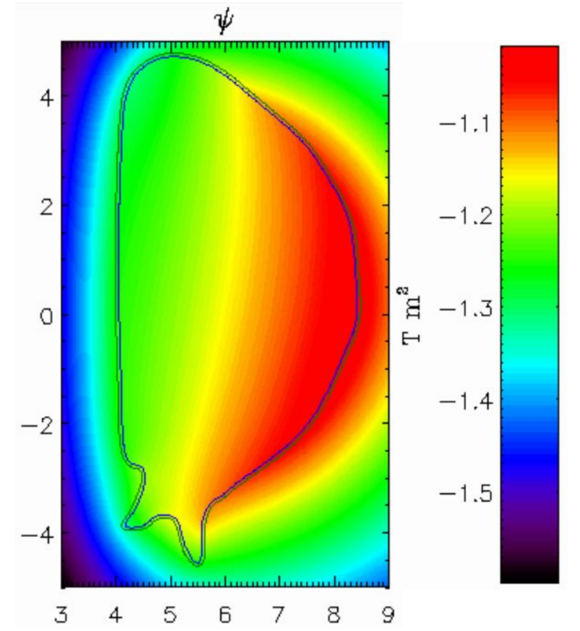
- Based on standard 5.3 T / 15 MA ITER scenario

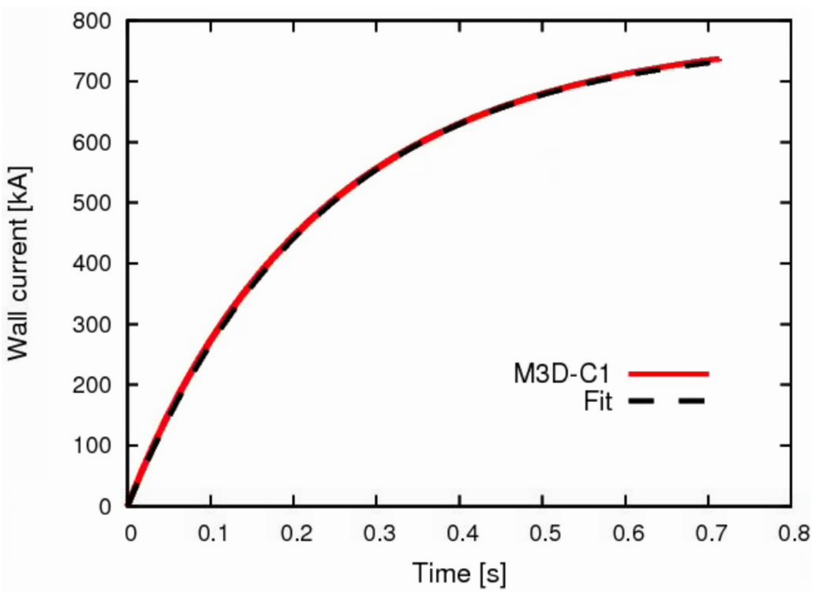
- Goals of benchmark with CarMaONL
  - Comparison of 2D evolution & wall currents/forces
    - with ITER first wall as resistive wall
    - with first wall as boundary & vessel wall as resistive wall
  - Coupling M3D-C^1 & CARIDDI (3D conducting structures)
    - 2D M3D-C^1 simulations
    - 3D M3D-C^1 simulations

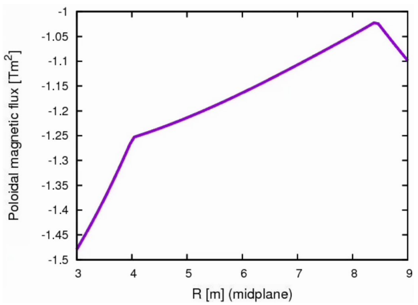


L/R time from simulation without plasma

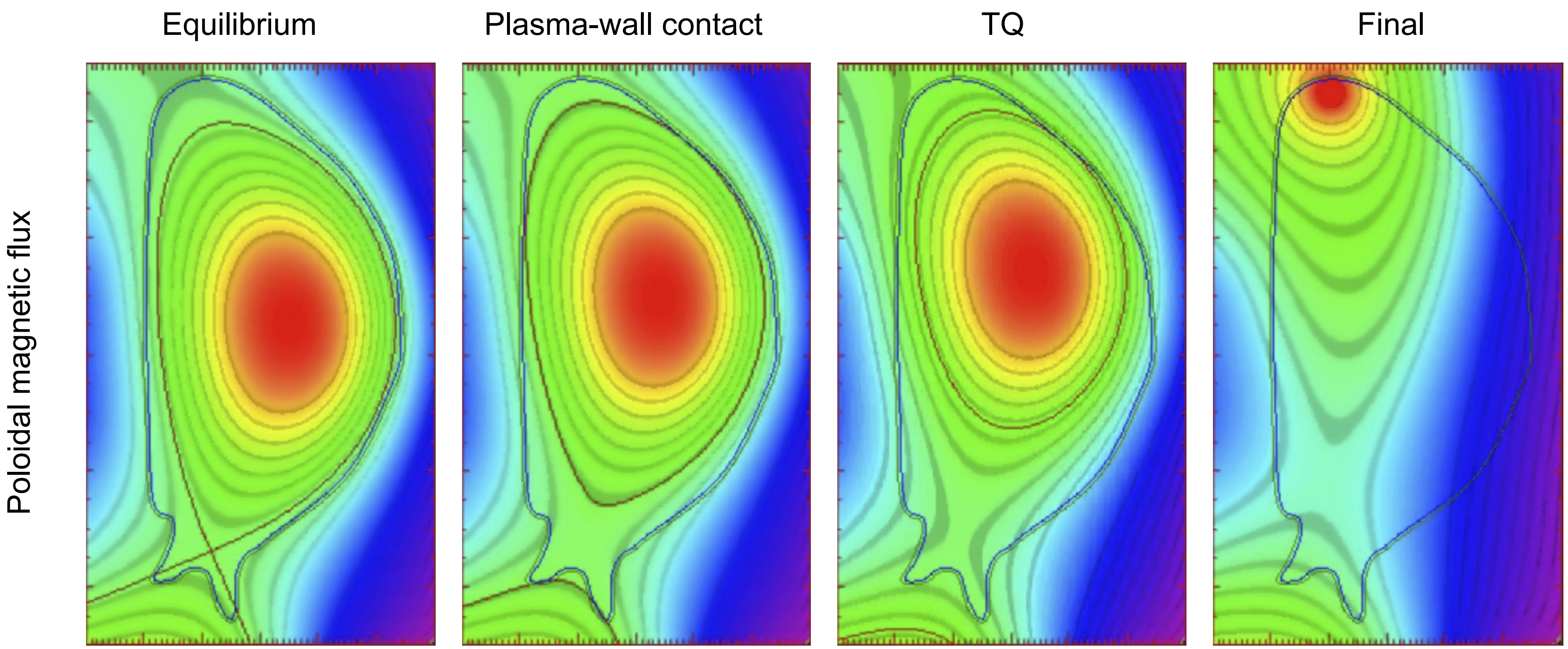
- Simulation with constant loop voltage applied at t=0 & no plasma
- $I(t) = I_0 * (1 - \exp(- t / \tau))$
  - τ = 235 ms





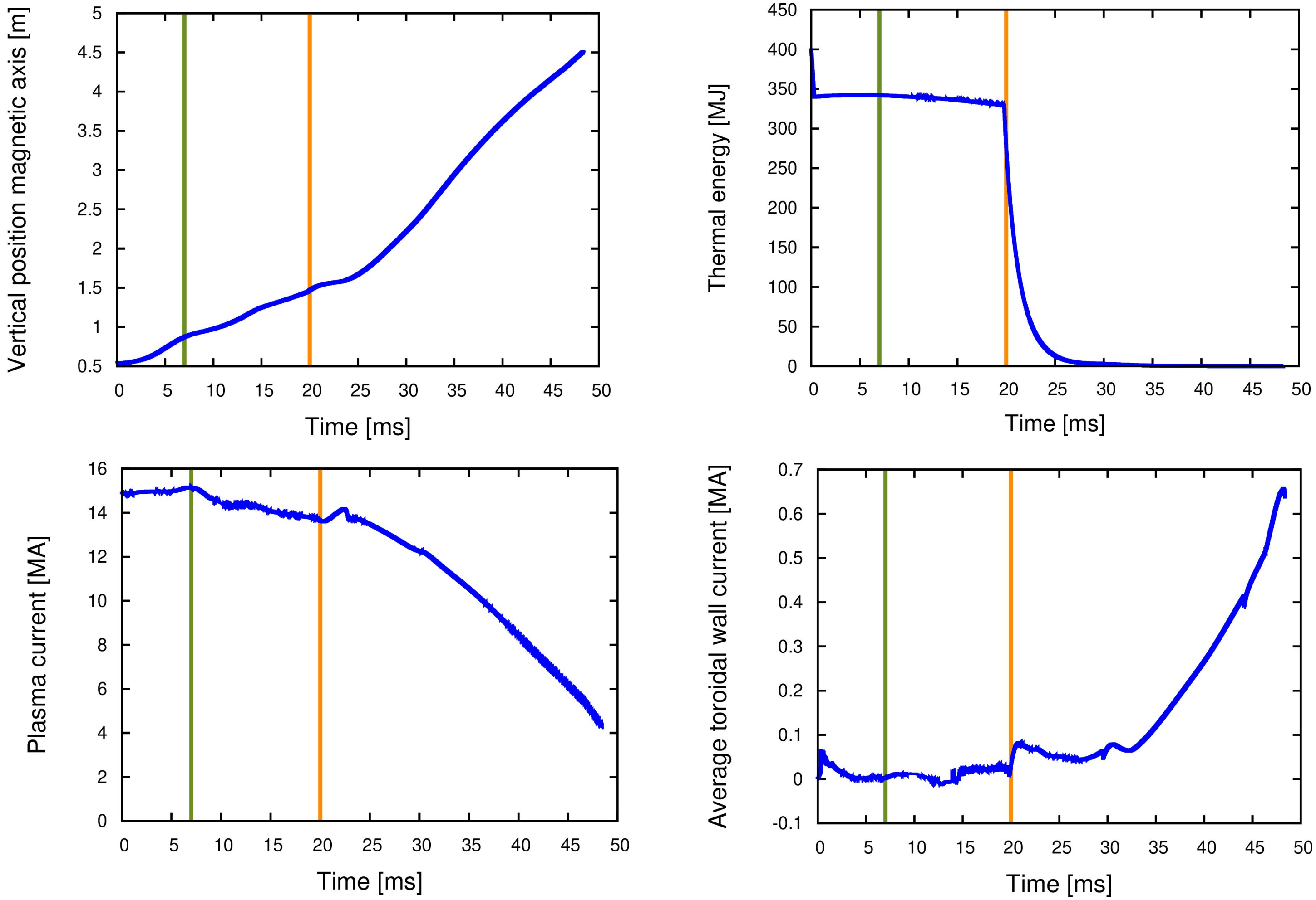


2D nonlinear ITER VDE simulation



→ Artificial TQ: increase of $\kappa_\perp$ by factor 1000 when $q_{edge} = 2$

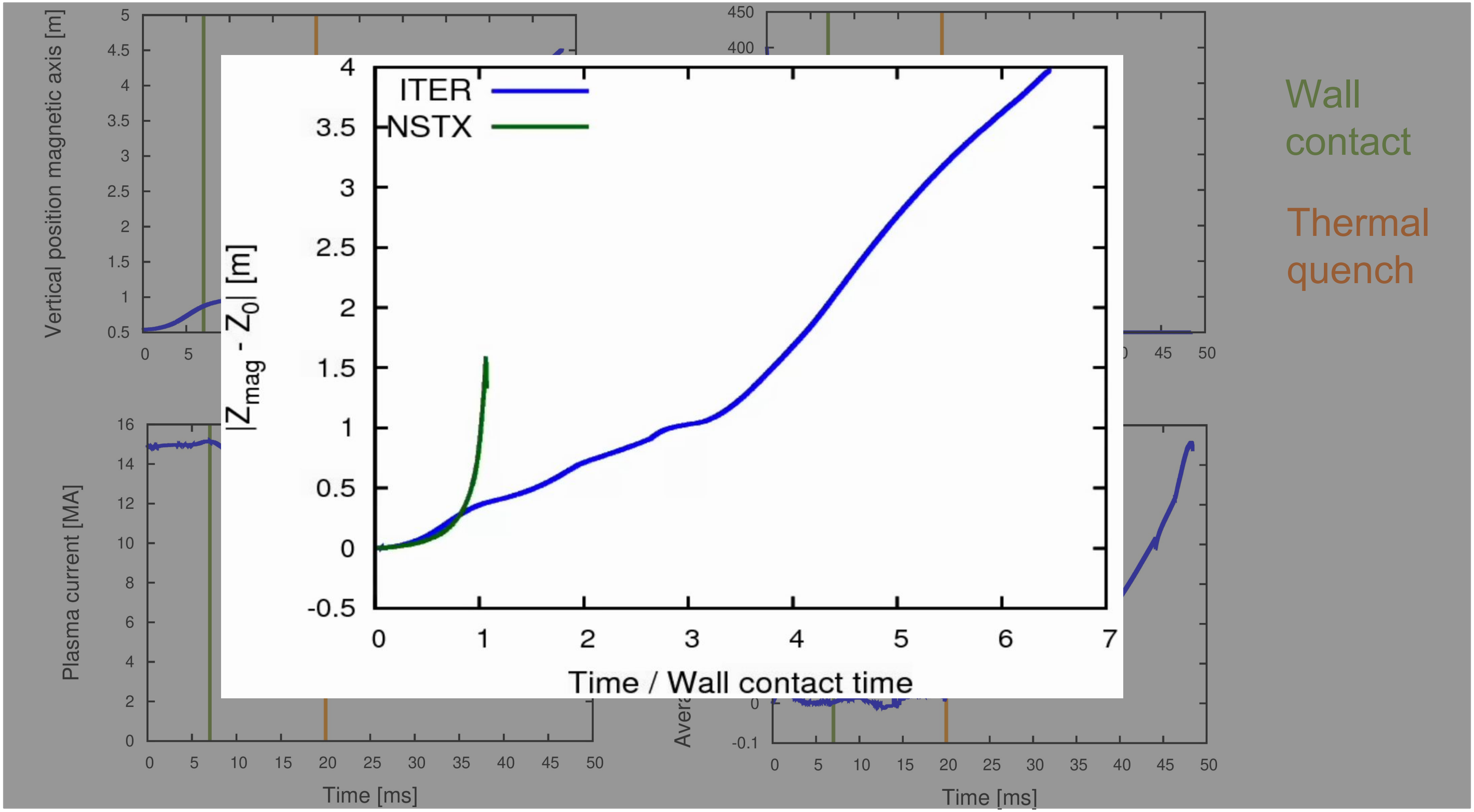
2D nonlinear ITER VDE simulation



Wall contact

Thermal quench

2D nonlinear ITER VDE simulation



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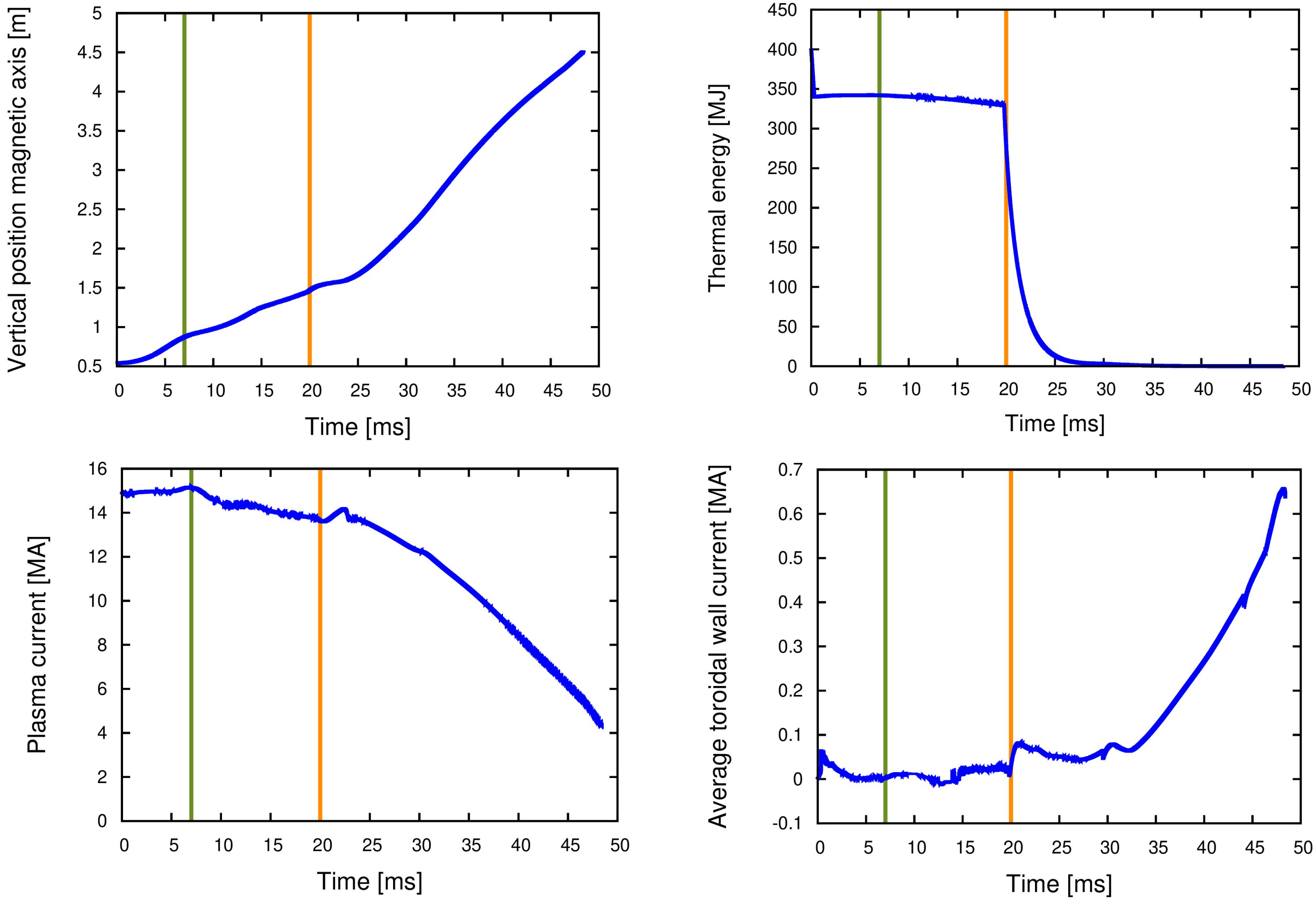
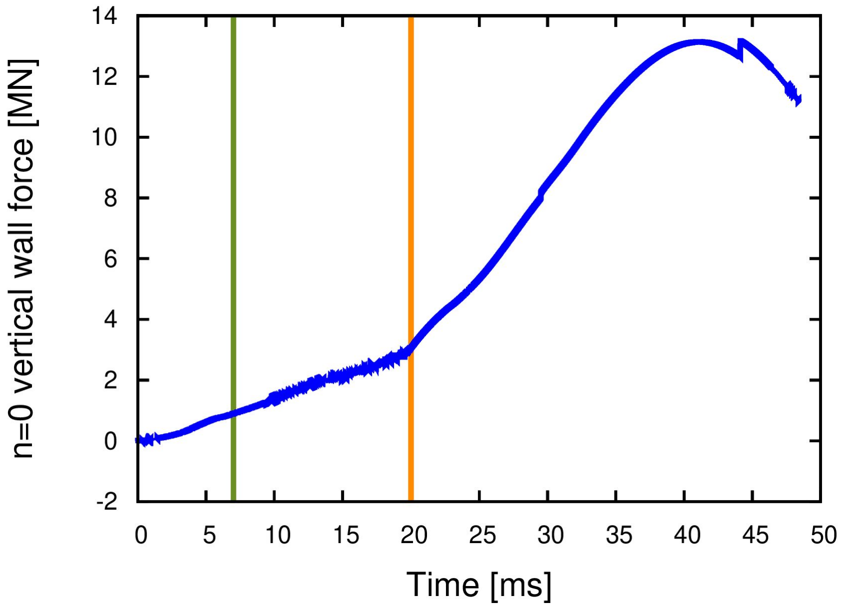


Wall contact

Thermal quench

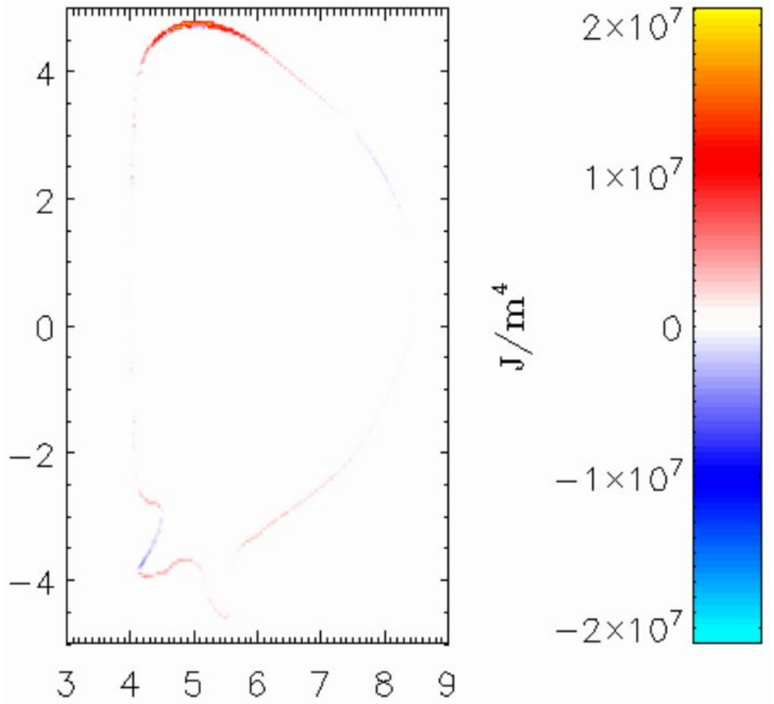
Vertical force on wall



Wall contact

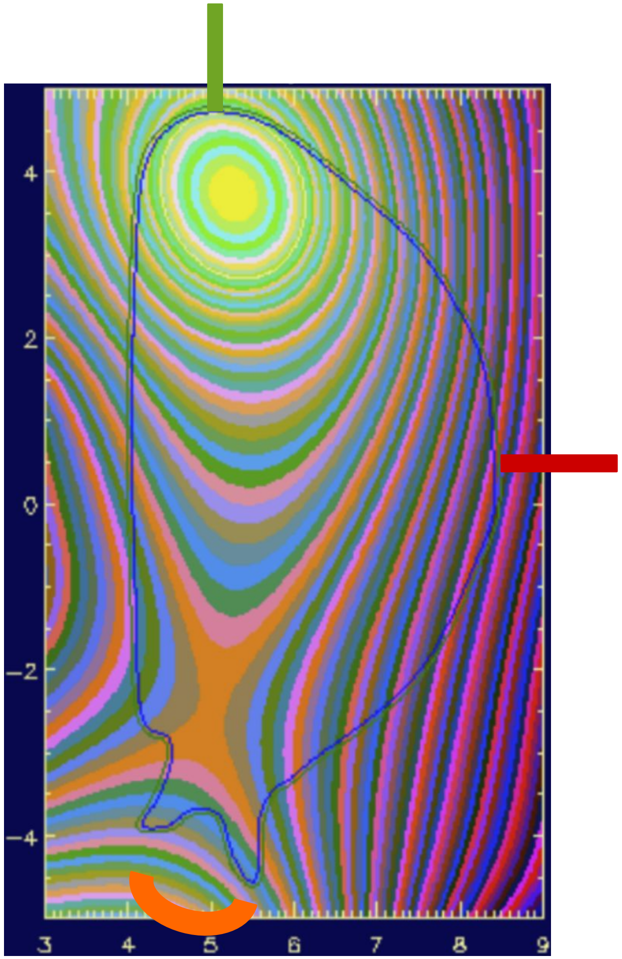
Thermal quench

Vertical force density

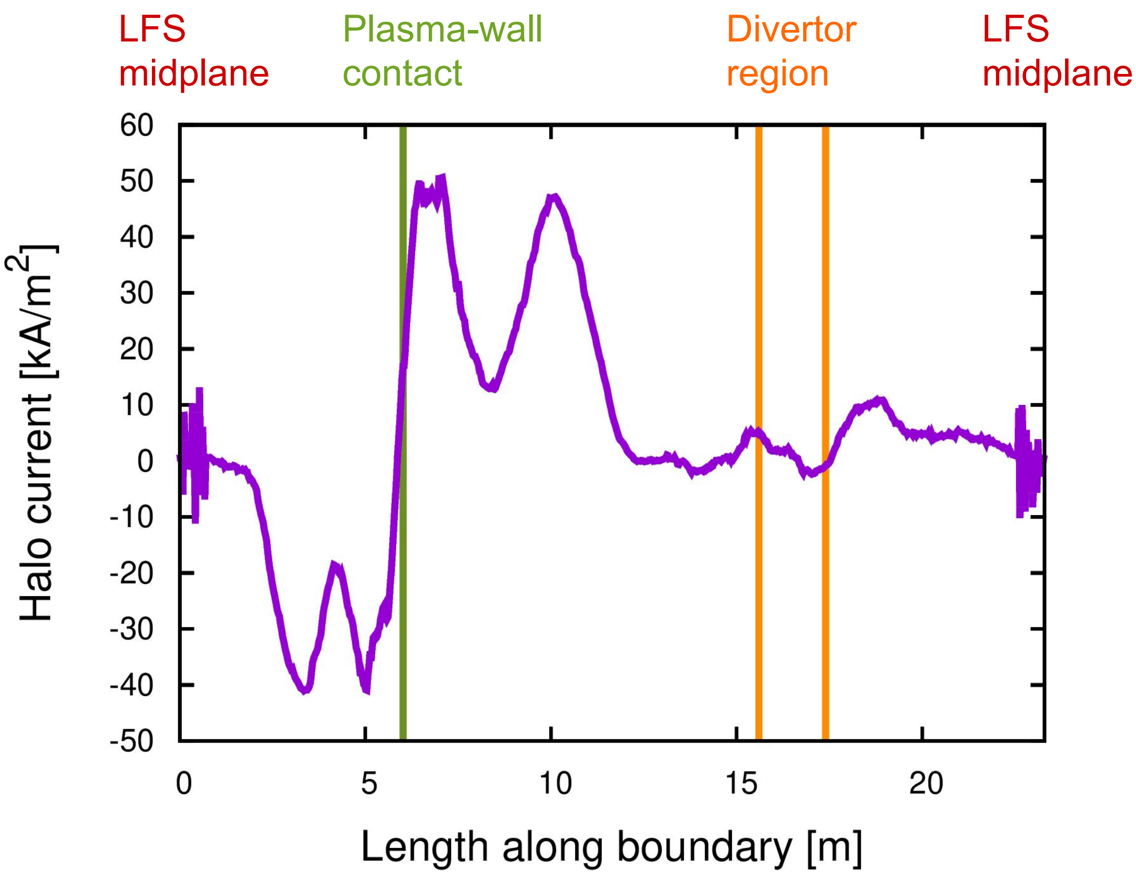


t = 0.04 s

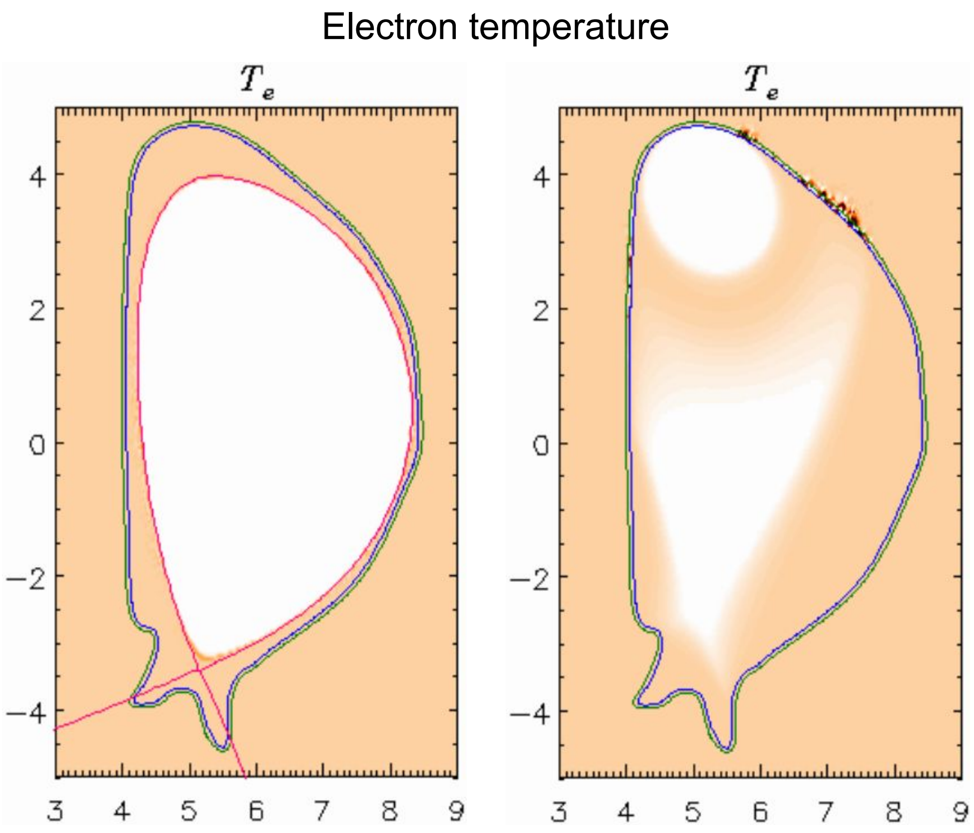
Halo current



Poloidal magnetic flux (t = 0.04 s)

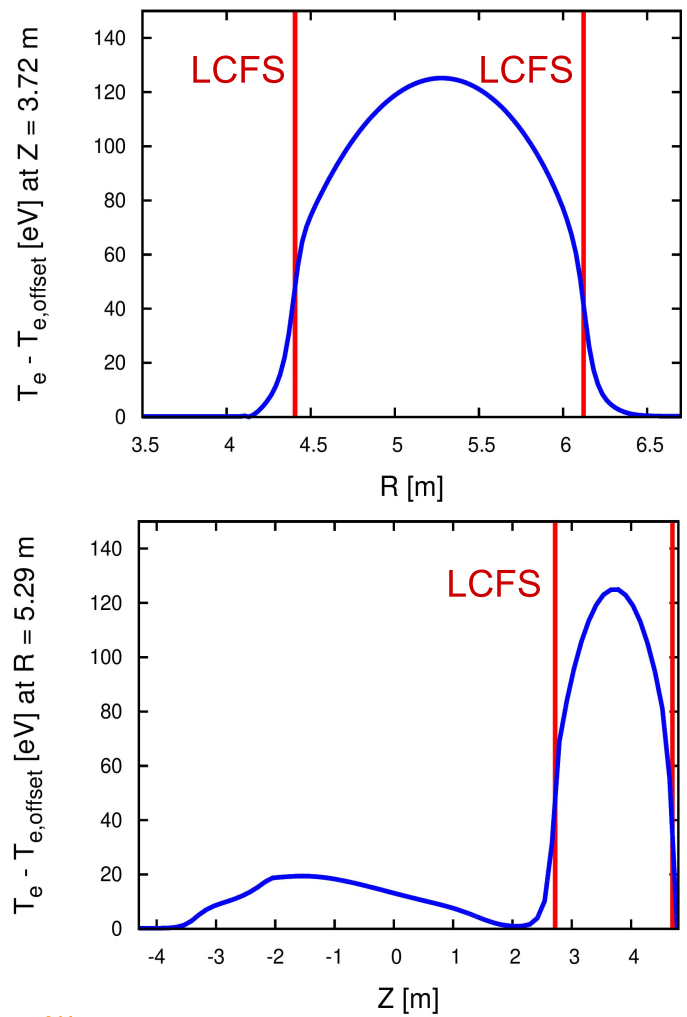


Residual temperature outside LCFS



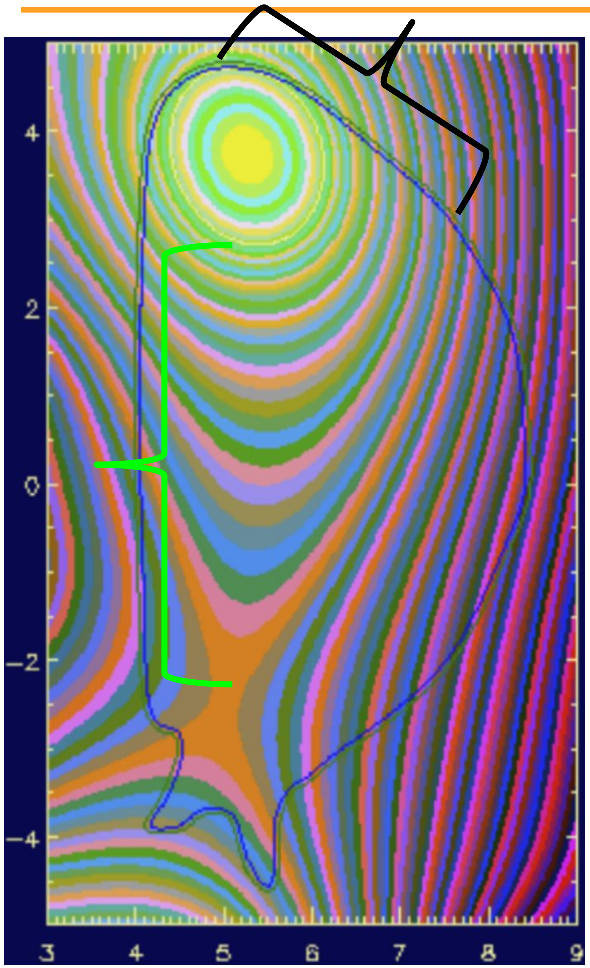
t = 0

t = 0.04 s



t = 0.04 s

Residual temperature near X-Point causes second spike in halo current



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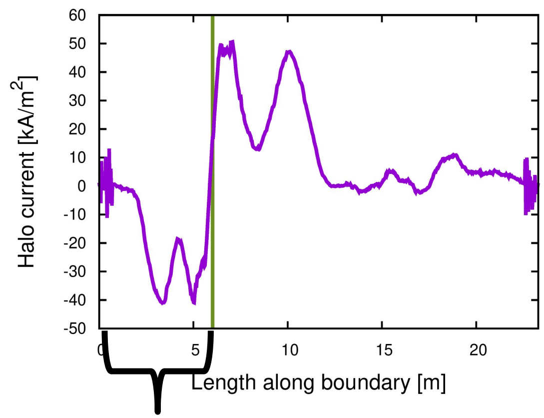
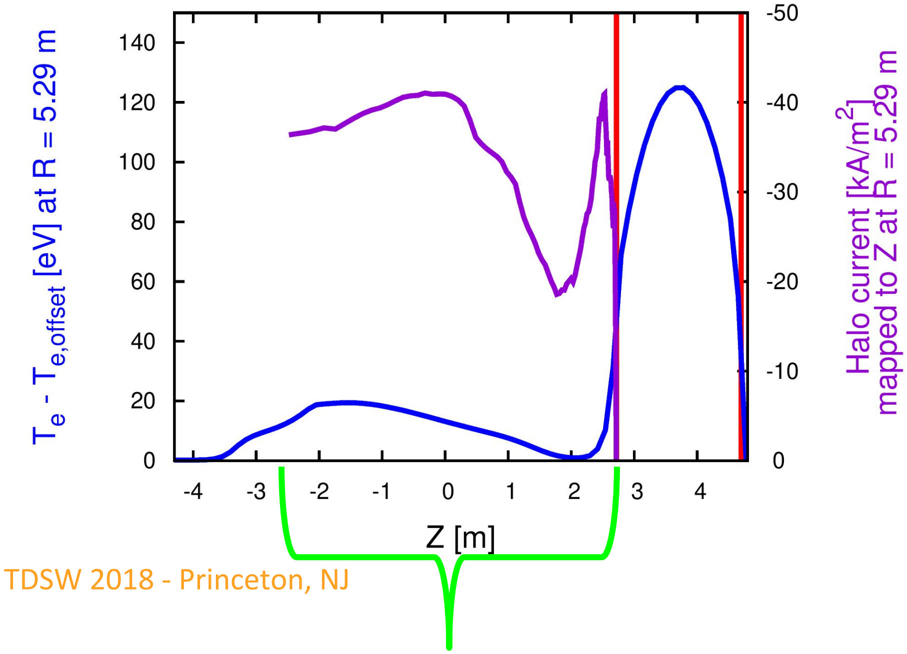
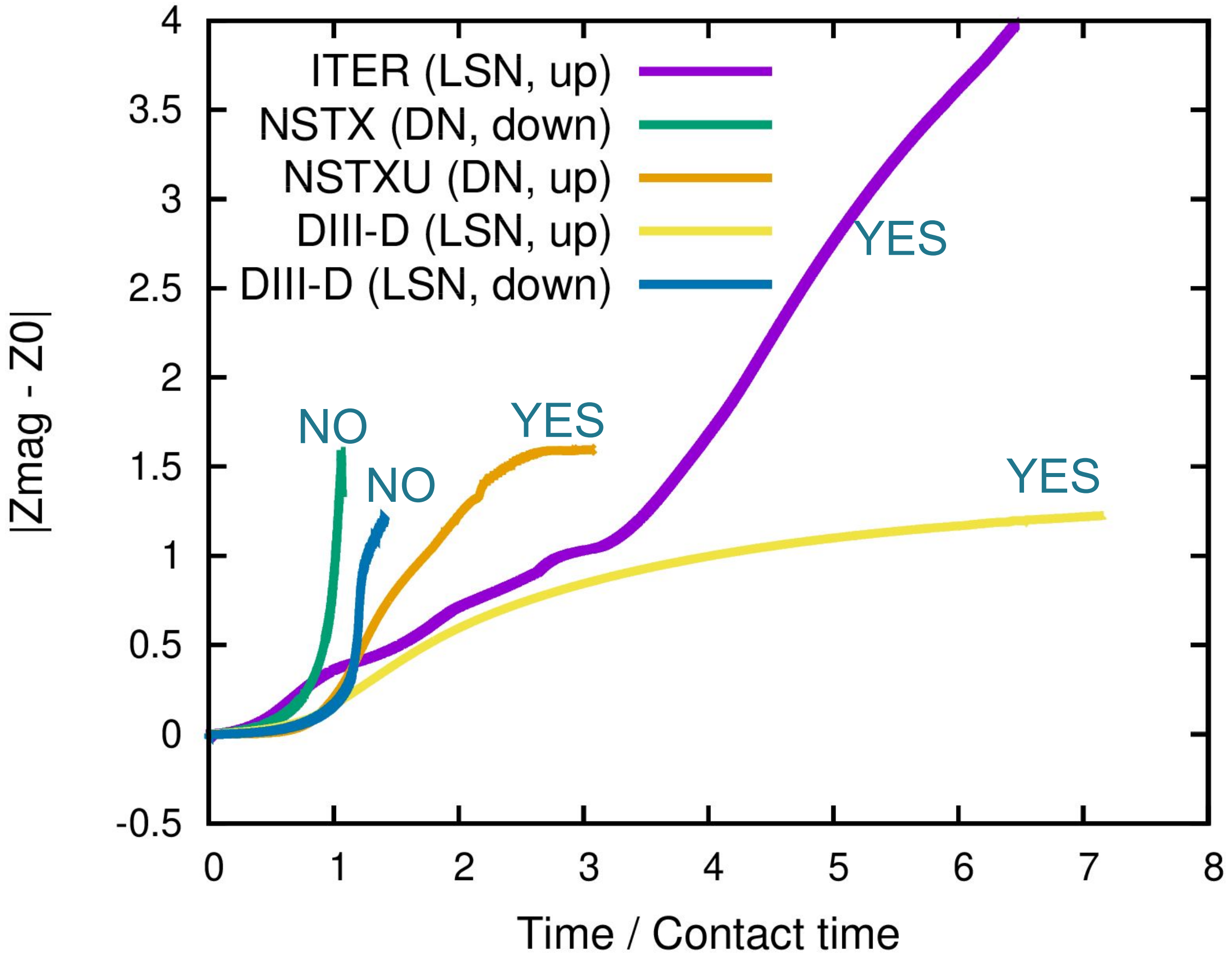




Does residual temperature cause slow-down?

Residual temperature?



Summary

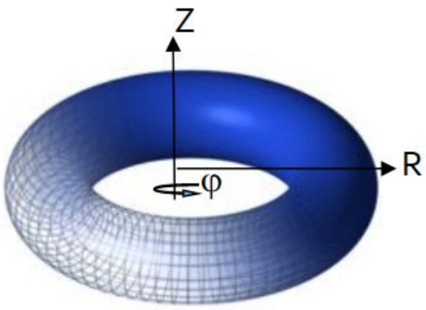
- M3D-C^1 provides model options & diagnostics necessary for self-consistent VDE simulations
- 3D nonlinear VDE simulations qualitatively reproduce many features of experimental observations
- Focus on benchmark activity with several different codes
  - Linear ✓
  - 2D nonlinear
  - 3D nonlinear
- Future work:
  - More experimental validation
  - Coupling M3D-C^1 & CARIDDI

Backup slides

M3D-C[1] & NIMROD equations

$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = \nabla \bullet D_n \nabla n + S_n$$

$$\left.\begin{aligned} \frac{\partial \mathbf{A}}{\partial t} &= -\mathbf{E} - \nabla\Phi \\ \nabla_\perp \bullet \frac{1}{R^2}\nabla\Phi &= -\nabla_\perp \bullet \frac{1}{R^2}\mathbf{E} \\ \mathbf{B} &= \nabla \times \mathbf{A} \end{aligned}\right\} \text{M3D-C1} \qquad \left.\begin{aligned} \frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \\ \nabla \bullet \mathbf{B} &= 0 \end{aligned}\right\} \text{NIMROD}$$



$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla\mathbf{V}\right) + \nabla p = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_i + \mathbf{S}_m, \qquad \mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta\mathbf{J} + \mathbf{S}_{CD}$$

$$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla \bullet (p_e\mathbf{V})\right] = -p_e\nabla \bullet \mathbf{V} + \mathbf{J} \bullet \mathbf{E} - \nabla \bullet \mathbf{q}_e + Q_\Delta + S_{eE} \qquad \mathbf{q}_{e,i} = -\kappa_{e,i}\nabla T_{e,i} - \kappa_{\parallel e,i}\nabla_\parallel T_{e,i}$$

$$\frac{3}{2}\left[\frac{\partial p_i}{\partial t} + \nabla \bullet (p_i\mathbf{V})\right] = -p_i\nabla \bullet \mathbf{V} - \mathbf{\Pi}_i : \nabla\mathbf{V} - \nabla \bullet \mathbf{q}_i - Q_\Delta + S_{iE}$$

M3D-C^1 model

- Boundary conditions
  - Velocity: all components vanish at RW
  - Pressure & density: constant at RW
  - Magnetic field: normal component constant at ideal wall

- Resistive wall
  - Evolution magnetic field

$$\delta_t \mathbf{B} = -\nabla \times (\eta_{\mathrm{wall}} \mathbf{j}) \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$

- Vacuum
  - $\mathbf{j} = 0$