VDE simulations with M3D-C^1

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Outline

- **Features of the M3D-C^1 code**
- **Benchmark Studies with NIMROD, JOREK, CarMa0NL**
- **ITER VDE Studies**

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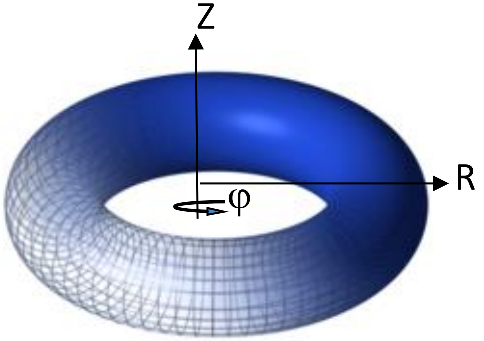
- ITER VDE Studies

3D Extended MHD Equations in M3D-C[1]

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

$$\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E} - \nabla\Phi, \quad \mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{J} = \nabla \times \mathbf{B}, \quad \nabla_\perp \bullet \frac{1}{R^2}\nabla\Phi = -\nabla_\perp \bullet \frac{1}{R^2}\mathbf{E}$$



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

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{ne}\left(\mathbf{R_c} + \mathbf{J} \times \mathbf{B} - \nabla p_e - \nabla \bullet \mathbf{\Pi}_e\right) - \frac{m_e}{e}\left(\frac{\partial \mathbf{V}_e}{\partial t} + \mathbf{V}_e \bullet \nabla \mathbf{V}_e\right) + \mathbf{S}_{CD}$$

$$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla \bullet \left(p_e \mathbf{V}\right)\right] = -p_e \nabla \bullet \mathbf{V} + \frac{\mathbf{J}}{ne} \bullet \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n + \mathbf{R}_c\right] + \nabla\left(\frac{\mathbf{J}}{ne}\right) : \mathbf{\Pi}_e - \nabla \bullet \mathbf{q}_e + Q_\Delta + S_{eE}$$

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

$$\mathbf{V}_e = \mathbf{V}_i - \mathbf{J} / ne$$

$$\mathbf{R}_c = \eta ne\mathbf{J}, \qquad \mathbf{\Pi}_i = -\mu\left[\nabla \mathbf{V} + \nabla \mathbf{V}^\dagger\right] - 2(\mu_c - \mu)(\nabla \bullet \mathbf{V})\mathbf{I} + \mathbf{\Pi}_i^{GV}$$

$$\mathbf{q}_{e,i} = -\kappa_{e,i}\nabla T_{e,i} - \kappa_\parallel \nabla_\parallel T_{e,i}$$

$$\mathbf{\Pi}_e = (\mathbf{B}/B^2)\nabla \bullet \left[\lambda_h \nabla\left(\mathbf{J} \bullet \mathbf{B}/B^2\right)\right], \qquad Q_\Delta = 3m_e(p_i - p_e)/\left(M_i \tau_e\right)$$

Blue terms are 2-fluid terms. Also, now have impurity and pellet models for disruption mitigation. **NOT reduced MHD.**

M3D-C^1 uses unique 3D high-order finite elements

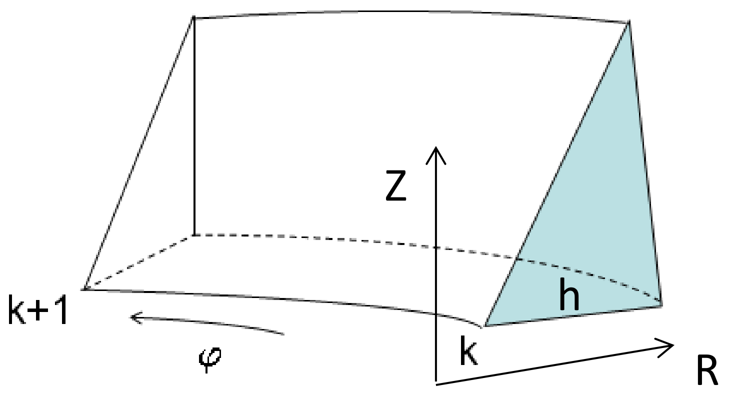
- M3D-C^1 uses high-order curved triangular prism elements

- Within each triangular prism, there is a polynomial in (R,φ,Z) with 72 coefficients

- The solution *and 1st derivatives* are constrained to be continuous from one element to the next.

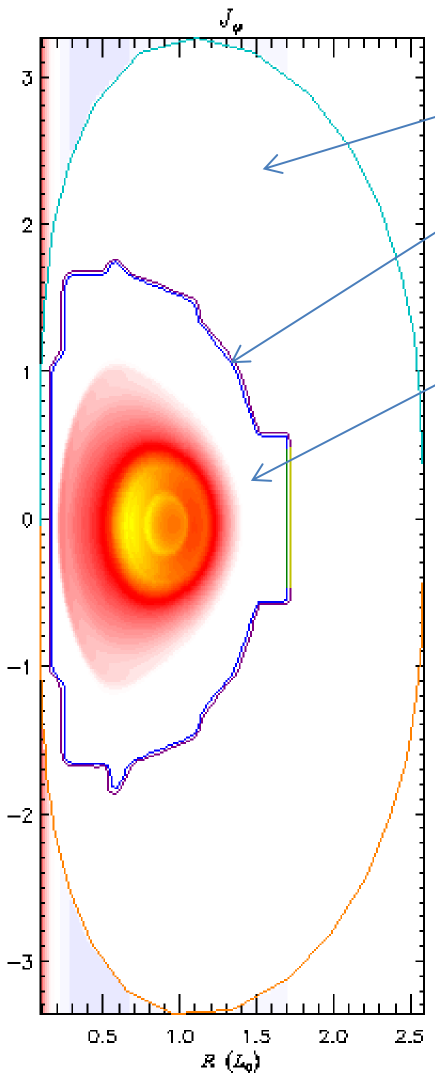
- Thus, there is much more resolution than for the same number of linear elements

- Error ~ h^5



Also, implicit time-stepping allows for very long time simulations

*M3D-C¹ has been extended to 3 regions for RW**



Vacuum (**J**=0)

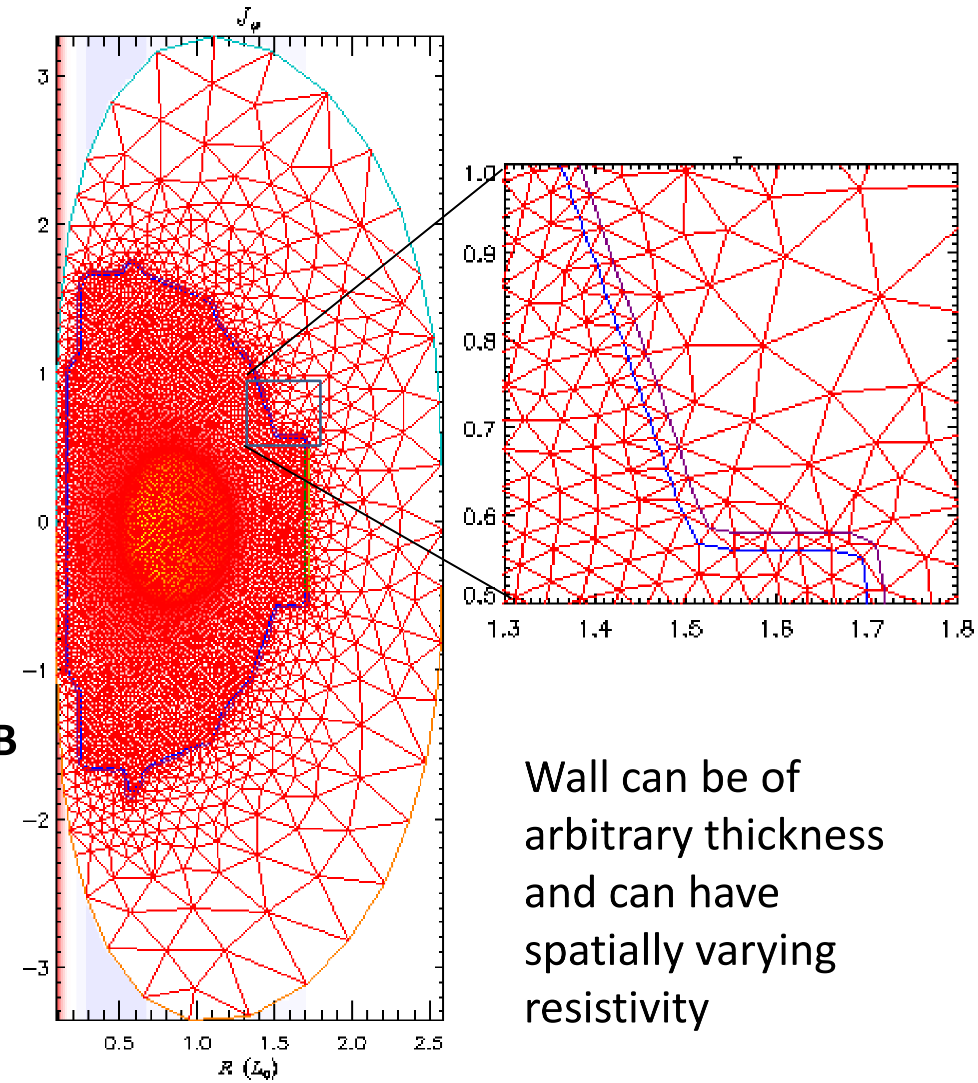
RW (**E** = η_W **J**)

Plasma (X-MHD)

BC:

- **v**, p, n set at inner wall
- **B** set at outer (ideal) wall

- No boundary conditions on **B** or **J** at the resistive wall
- (halo) Current can flow into and out of the wall



Wall can be of arbitrary thickness and can have spatially varying resistivity

*Ferraro, et al. ,Phys Plasma **23** 056114 (2015)

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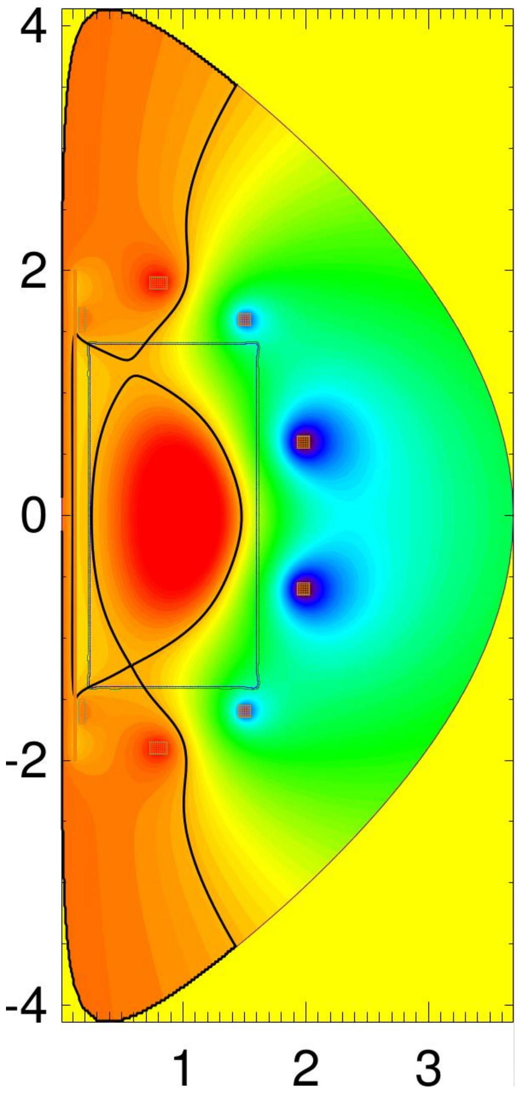
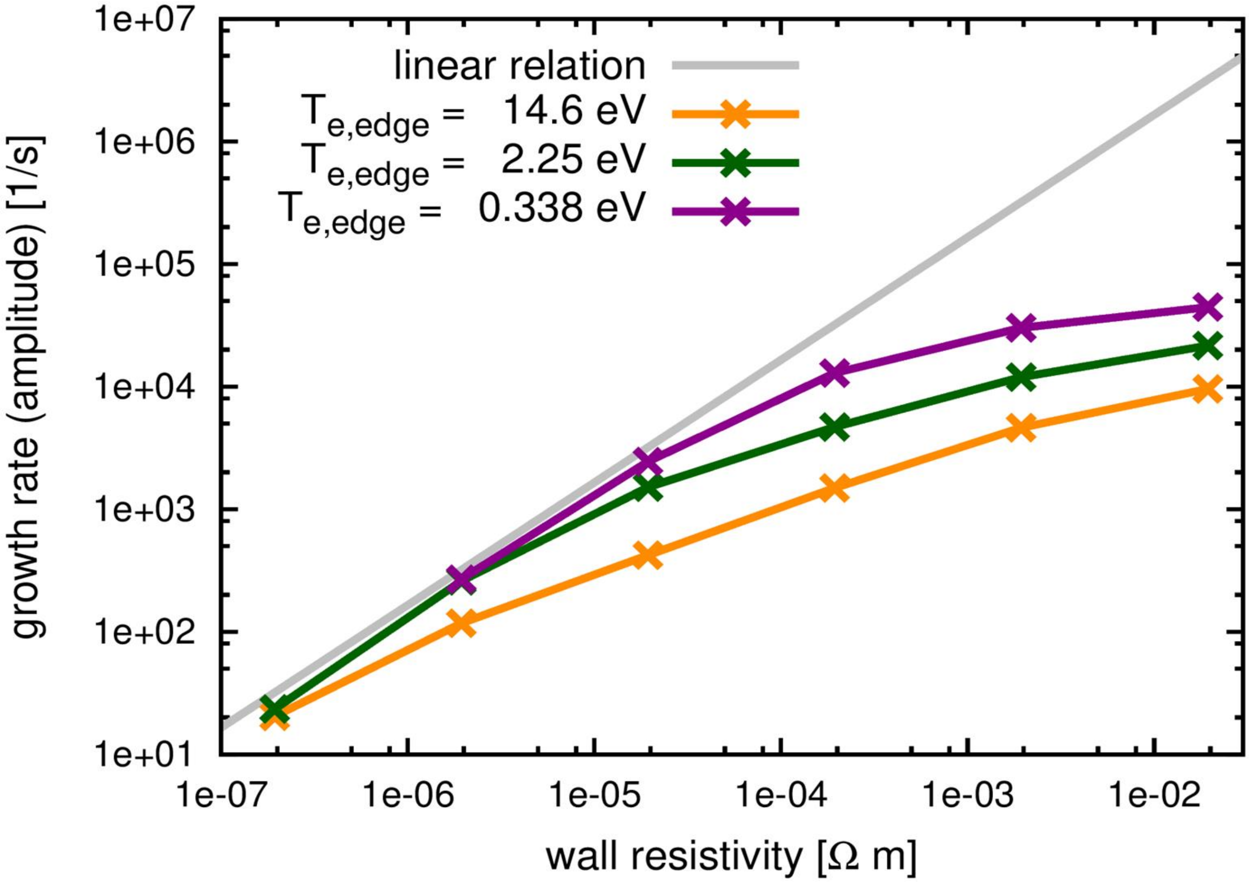
Benchmark M3D-C^1, NIMROD & JOREK

- 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

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

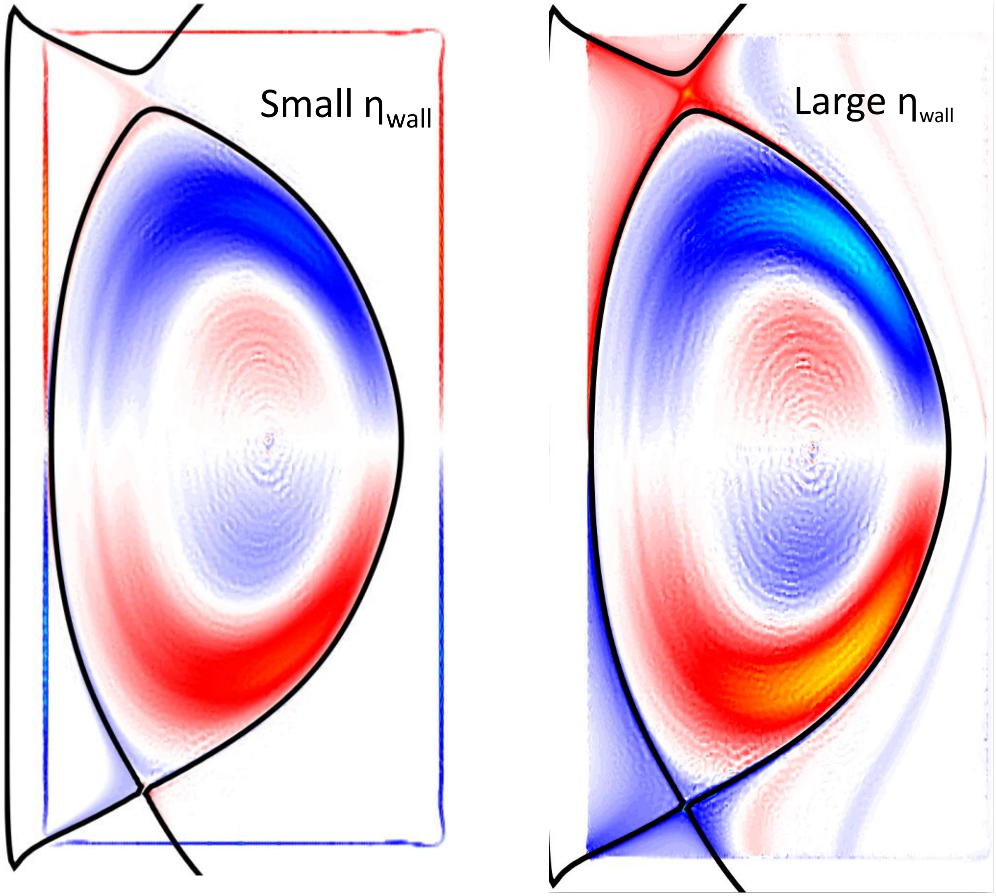


Linear VDE growth vs. η_{wall} depends on T_{edge}



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

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

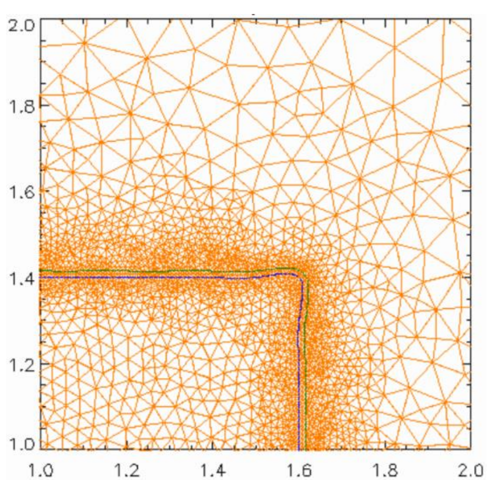


Toroidal current density eigenfunctions

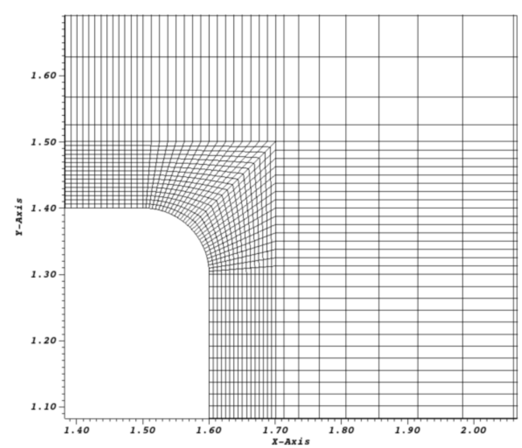
- Small η_{wall} , small T_{edge}: VDE growth rate ~ η_{wall}
- Large η_{wall}:, large T_{edge}: VDE slowed down by response currents in open field line region

Linear benchmark with NIMROD

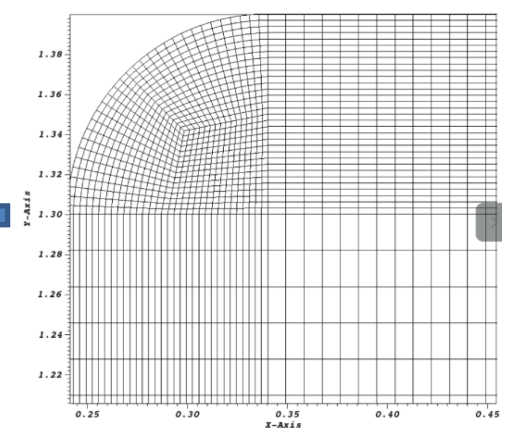
	M3D-C^1	NIMROD
Poloidal Direction	Tri. C^1 Reduced Quintic FE	High. Order quad C^0 FE
Toroidal Direction	Hermite Cubic C^1 FE	Spectral
Magnetic Field	$\mathbf{B} = \nabla\psi \times \nabla\varphi - \nabla_\perp f' + F\nabla\varphi$	$\mathbf{B} = B_r\widehat{R} + B_z\hat{Z} + B_\varphi\widehat{\varphi}$
Velocity Field	$\mathbf{V} = R^2\nabla U \times \nabla\varphi + \omega R^2\nabla\varphi + R^{-2}\nabla_\perp\chi$	$\mathbf{V} = V_r\widehat{R} + V_z\hat{Z} + V_\varphi\widehat{\varphi}$
Coupling to Conductors	same matrix	Separate matrices w interface



M3D-C^1 3 regions, thick wall

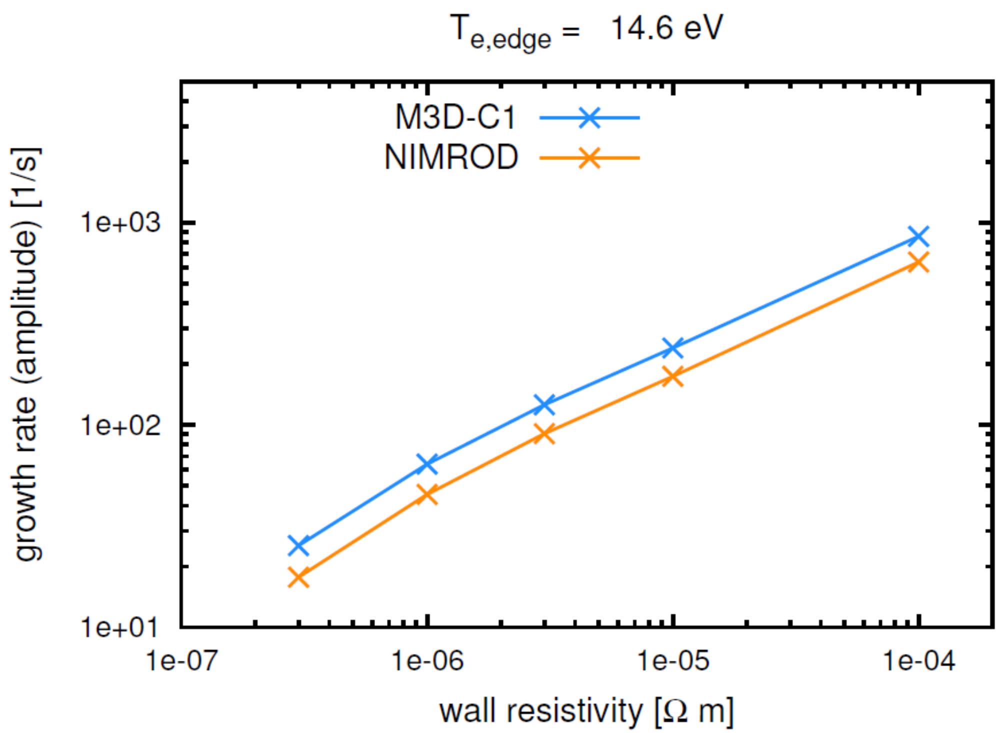


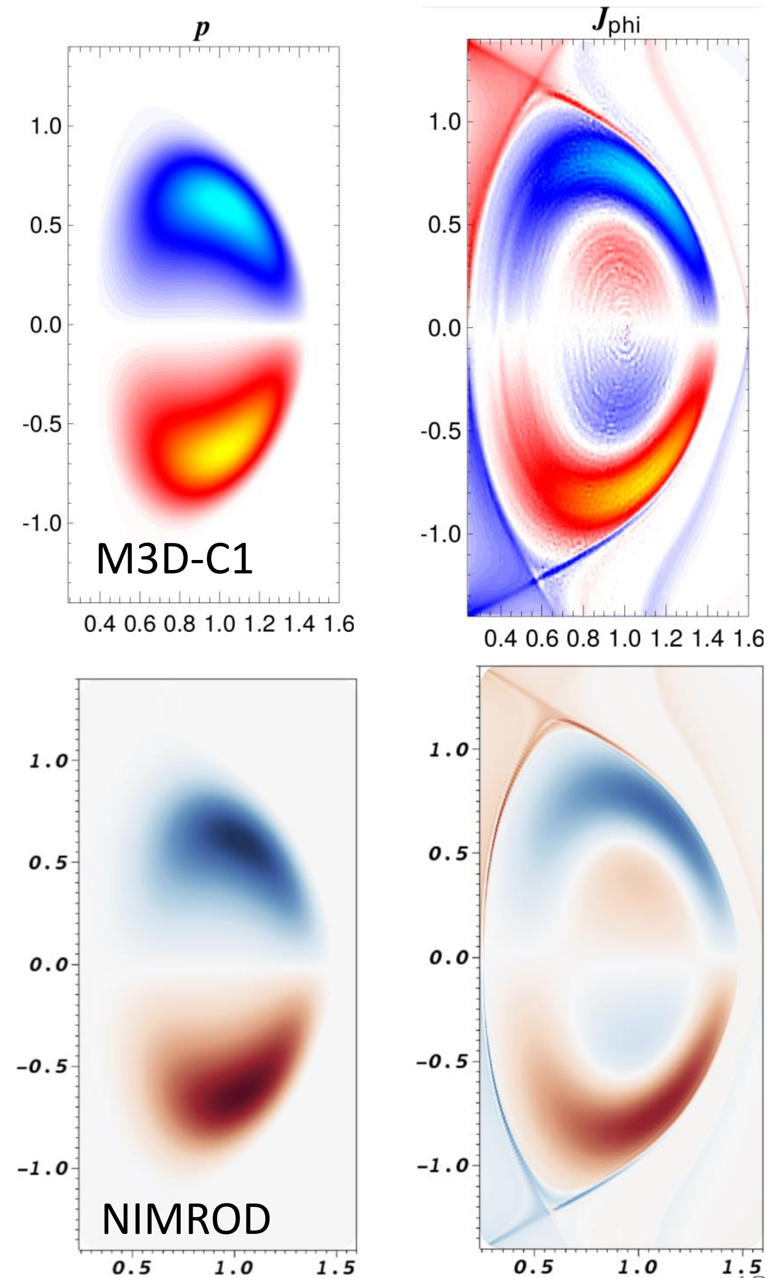
NIMROD vacuum region



NIMROD plasma region

Linear benchmark with NIMROD (preliminary)





- Growth rates differ by ~ 30%
- Slight differences in diffusion parameters

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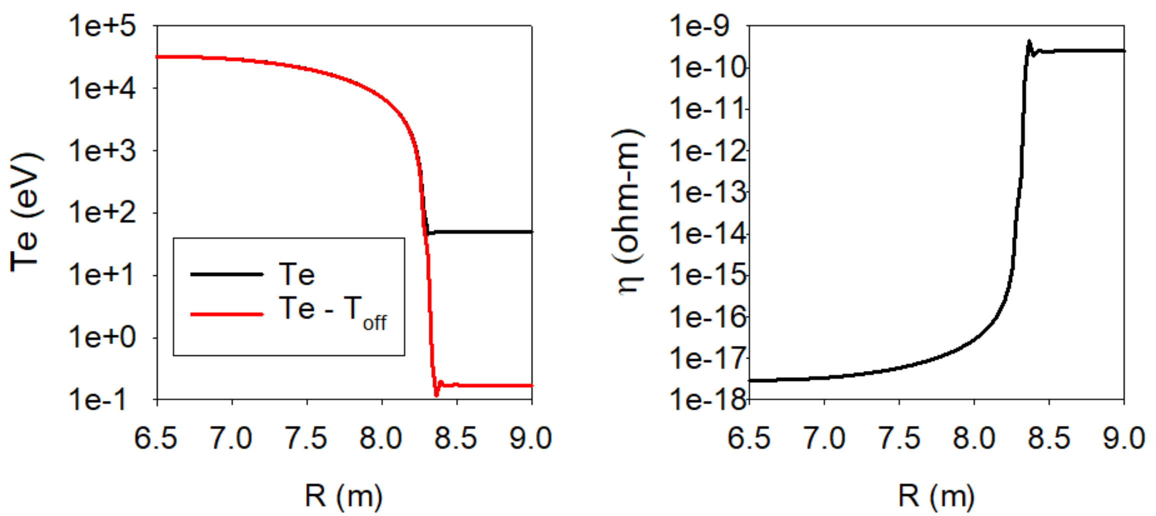
Linear benchmark with JOREK-STARWALL

- Comparison of linear phase of 2D nonlinear simulations
  - To avoid negative temperatures from developing, we use an offset in resistivity calculation so open-field-line resistivity is not constrained by T_{edge}: $\eta = \eta_{spitzer}(T_e - T_{off})$



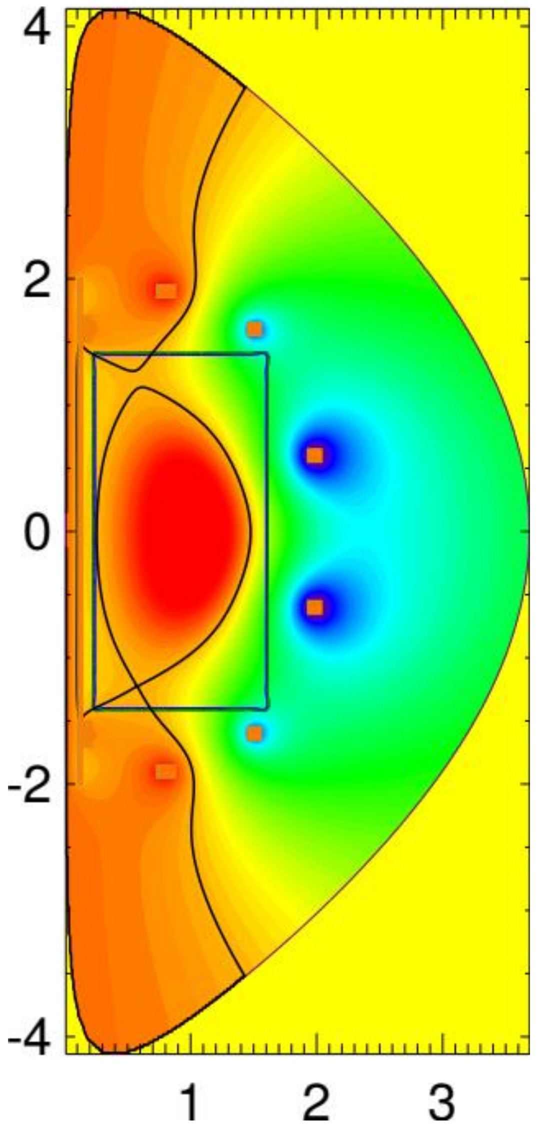
8 orders variation in resistivity from center to wall !!!

- 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

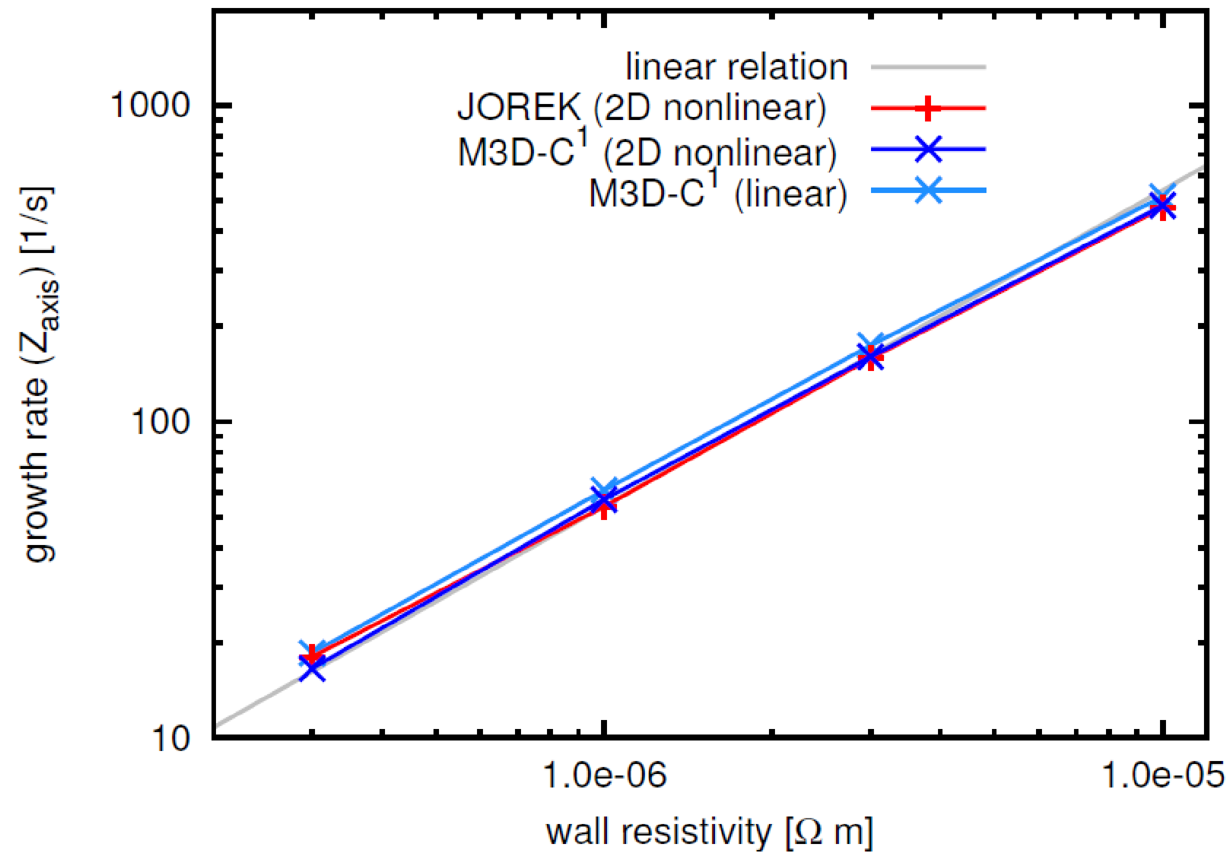
Progress on VDE benchmark between M3D-C1 & JOREK

– linear phase of 2D nonlinear simulations

Equilibrium Ψ



Z_{axis} = -1.64cm to -3.04cm, effective $T_{e,edge}$ = 1eV



- Based on simplified NSTX VDE case
- Difference between linear growth rates ≤ 9%

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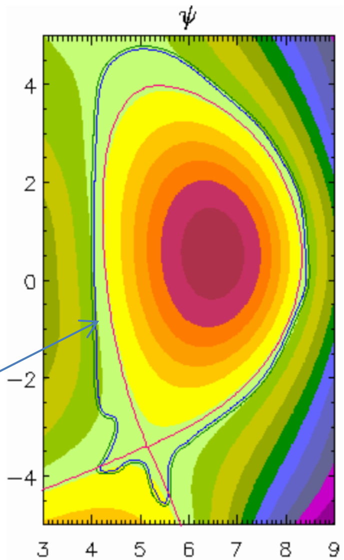
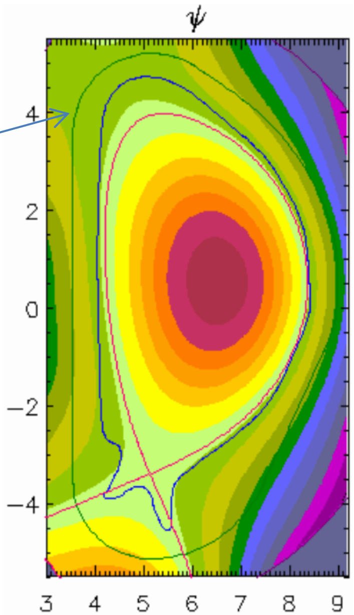
2D nonlinear ITER VDE simulation

- Based on standard 5.3 T / 15 MA ITER scenario
- Used <u>realistic parameters</u> for *wall resistivity, plasma resistivity, plasma mass* (no scaling: 1,150,000 τ_A!!)
- 2D benchmark with CarMaONL in progress
  - 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





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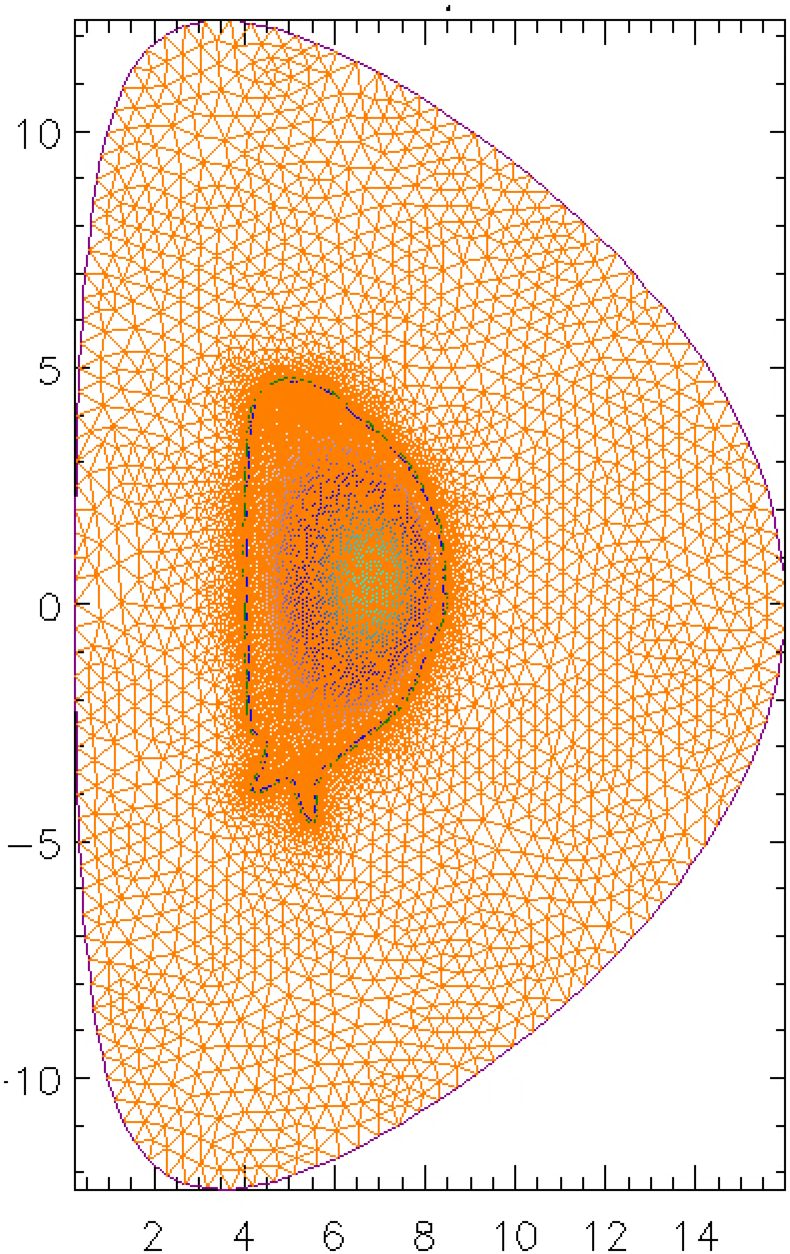
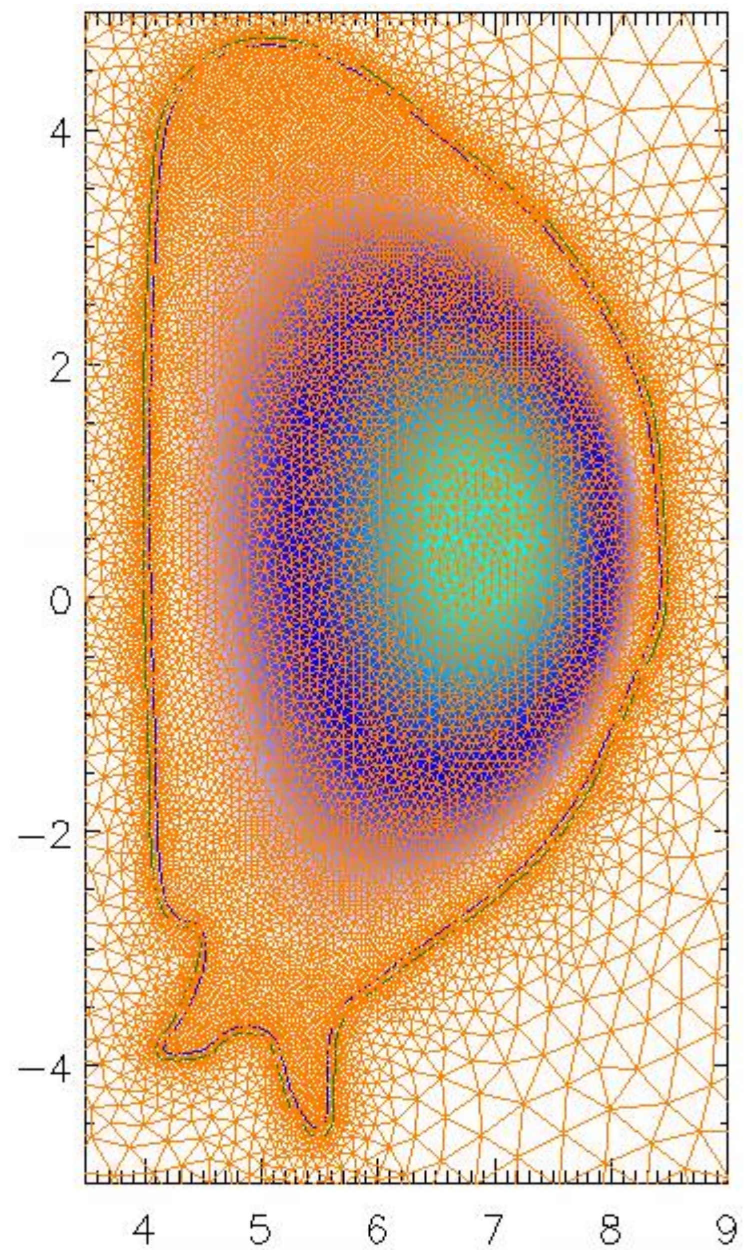
/p/m3dc1/nferraro/data/test/mesh/iter_mesh

Poloidal unstructured mesh used in ITER calculation



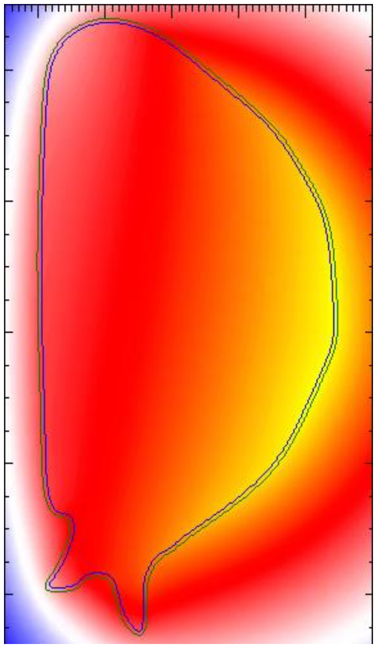
Full Mesh

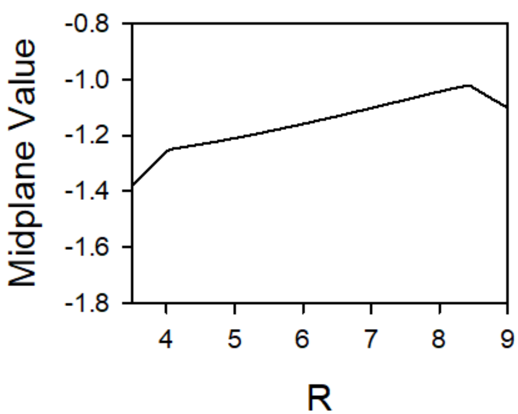


Close-up of Plasma Region

L/R time from simulation without plasma

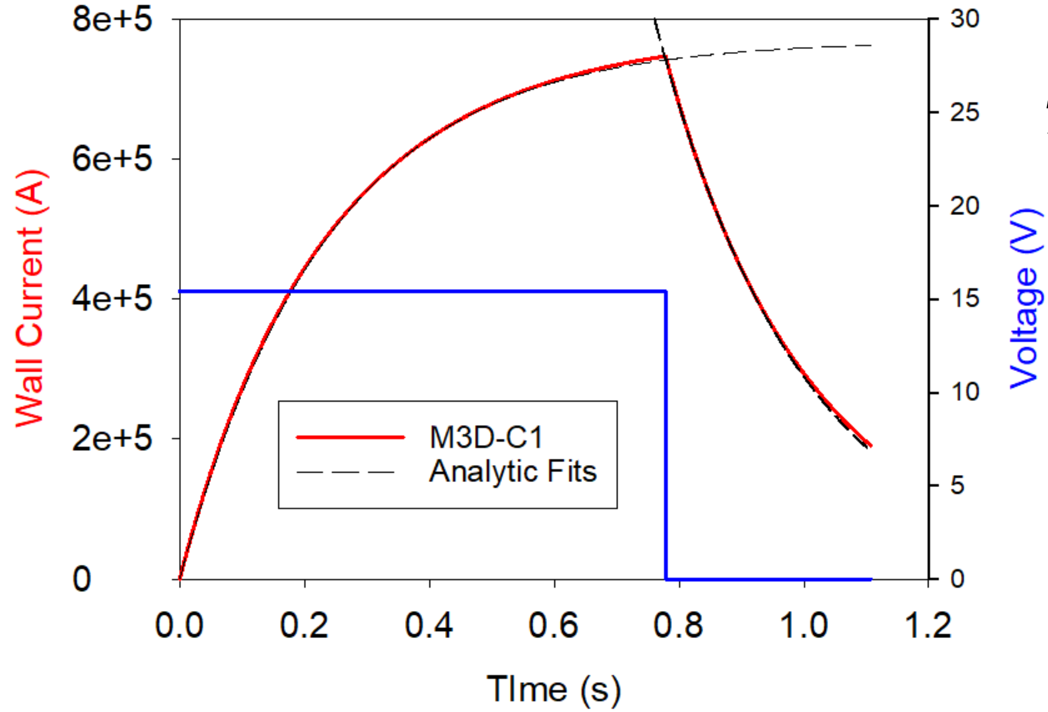
Ψ





- Simulation with constant loop voltage applied at t=0 & no plasma
- Wall resistivity adjusted to give correct L/R time

$$I(t) = \begin{cases} I_0\left(1 - e^{-t/T}\right) : & t < t_M \\ I_M e^{-(t-t_M)/T} : & t \geq t_M \end{cases}$$

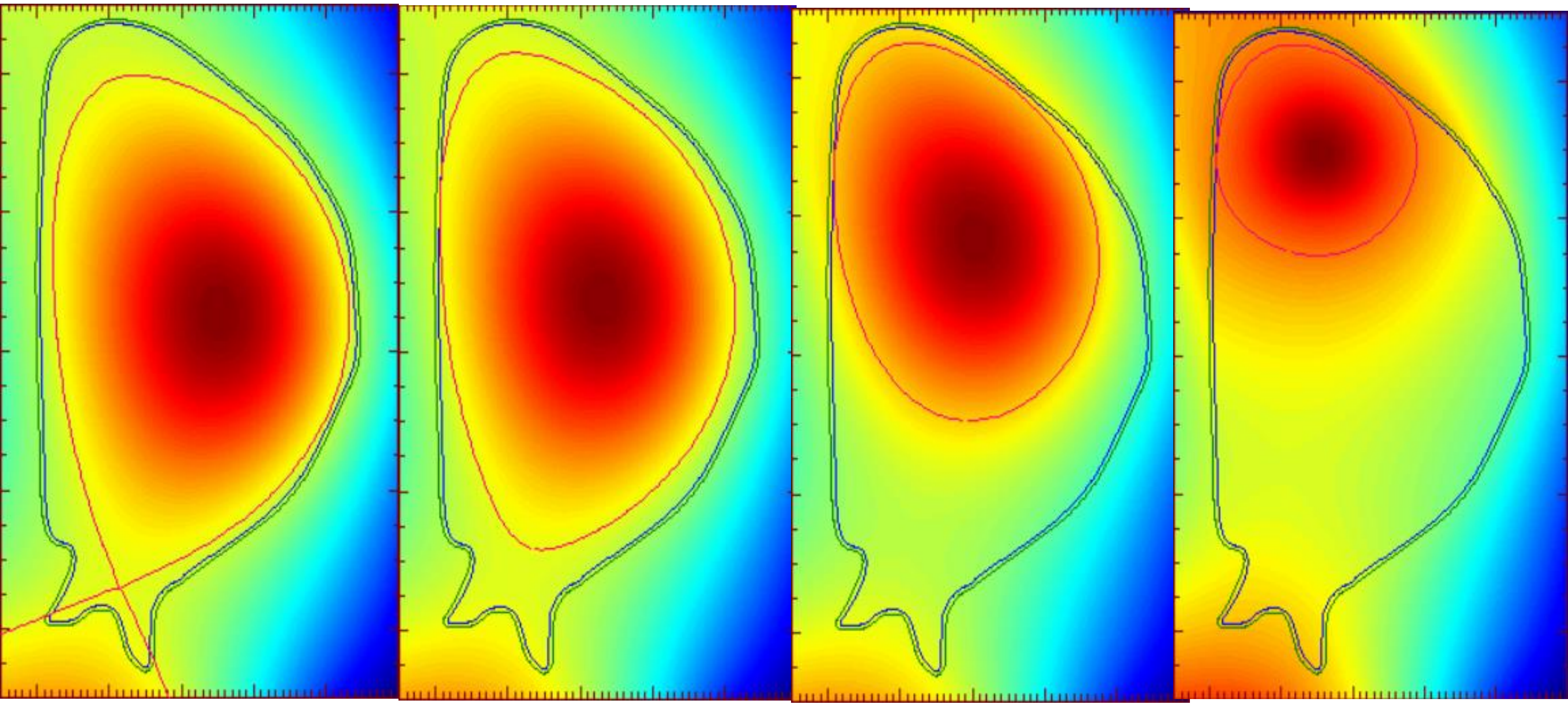


$T = 235\ ms$

Simulation time: 1,800,000 τ_A

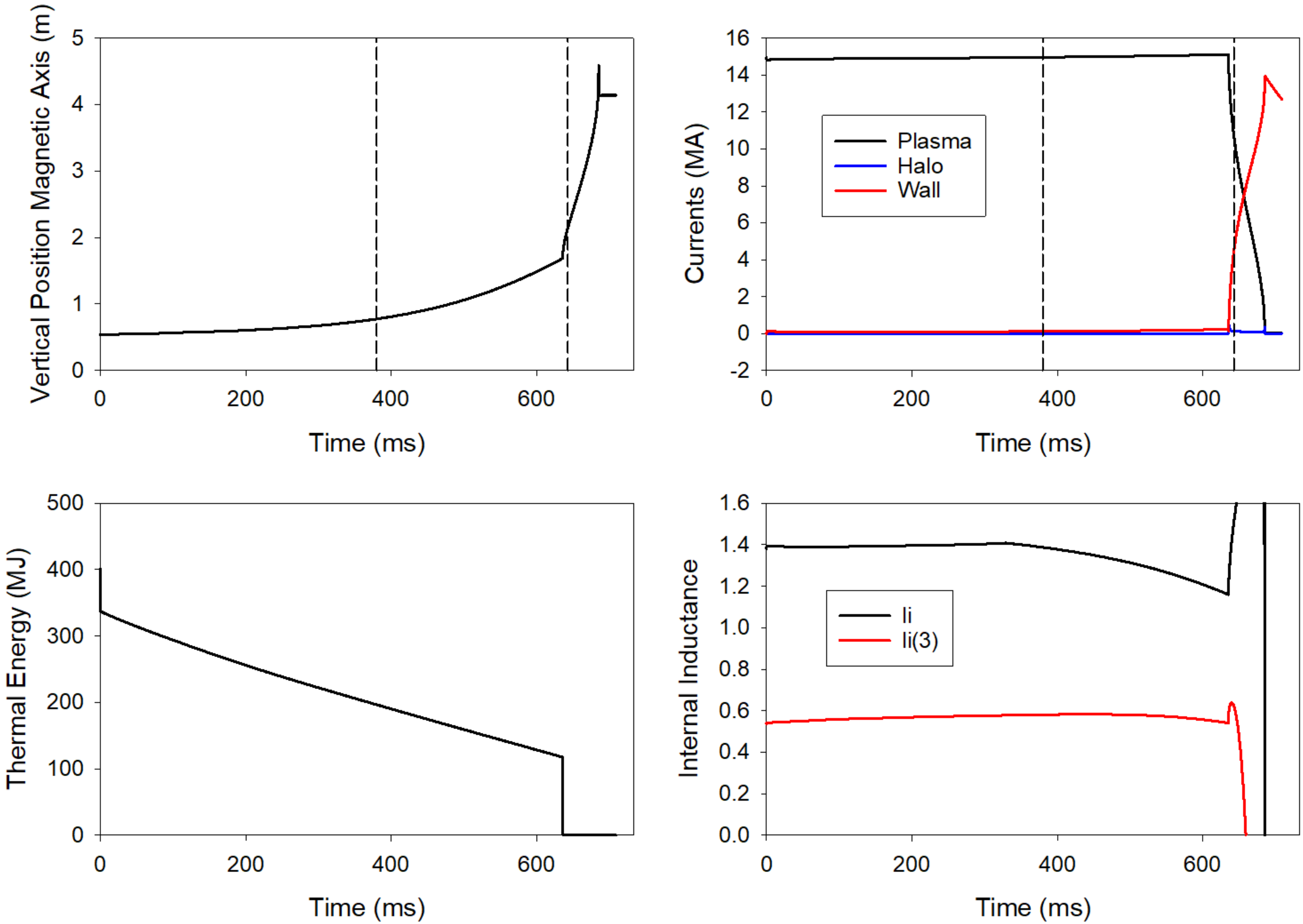
2D nonlinear Hot ITER VDE simulation with single wall

Equilibrium (t=0ms) | Wall contact (t=380 ms) | TQ (t=643 ms) | Max Force (t=673 ms)



Poloidal Magnetic Flux

2D nonlinear ITER Hot VDE simulation

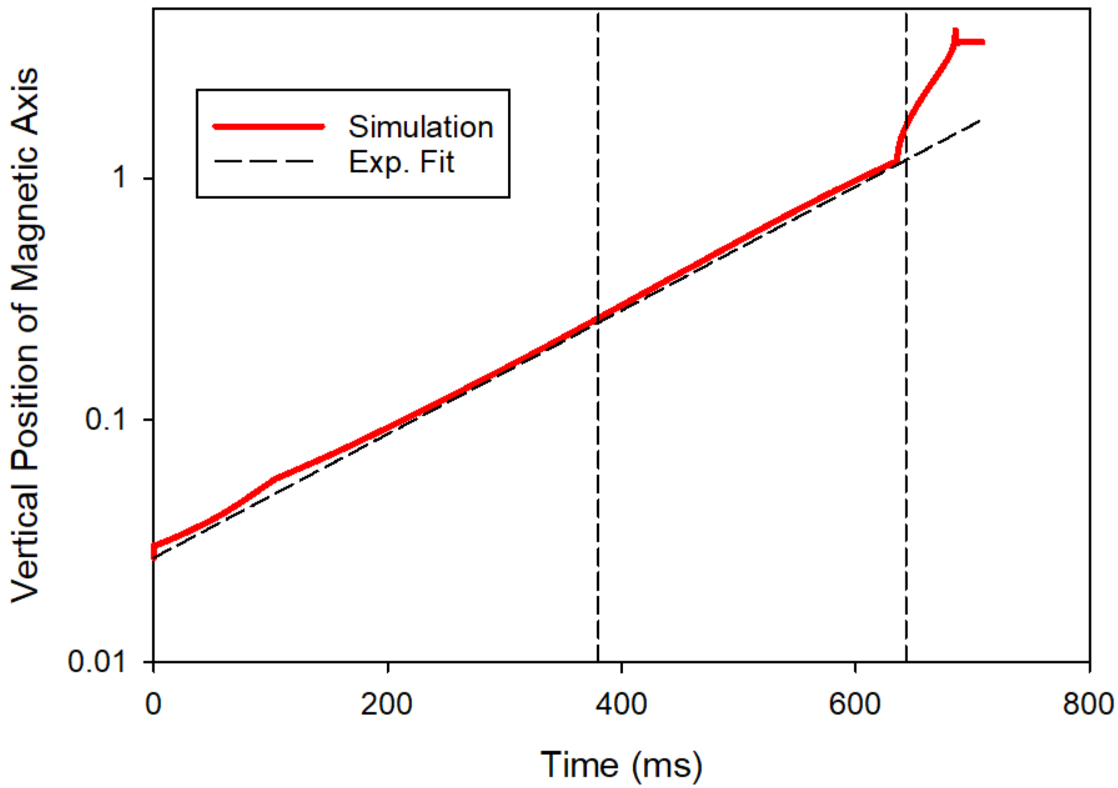


2D nonlinear ITER Hot VDE simulation

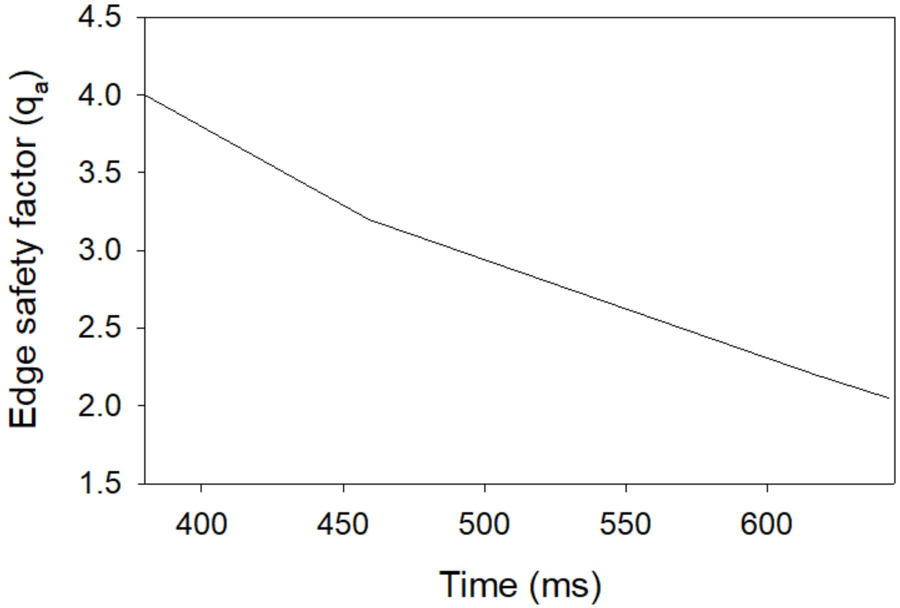
Z-position of magnetic axis well fit by linear growth rate until start of the thermal quench

$$Z_{mag} - Z_0 = .027 \exp\left(\frac{t(ms)}{170}\right)$$

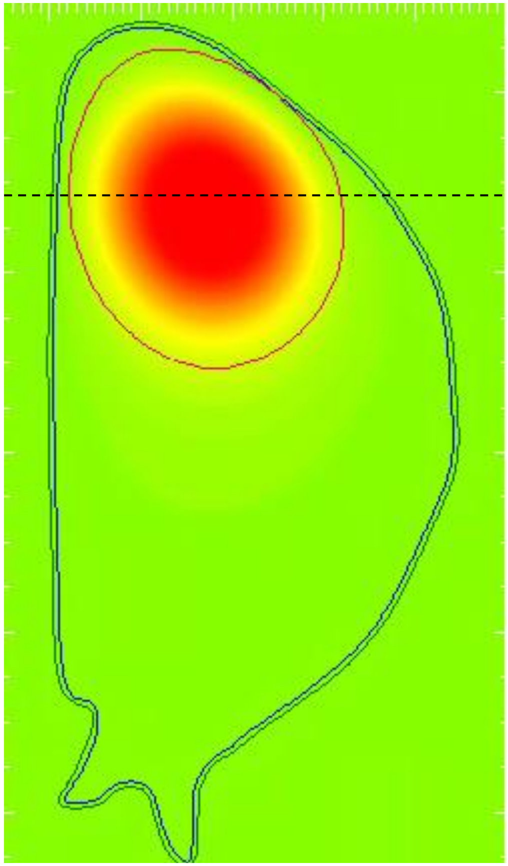
Touches wall TQ

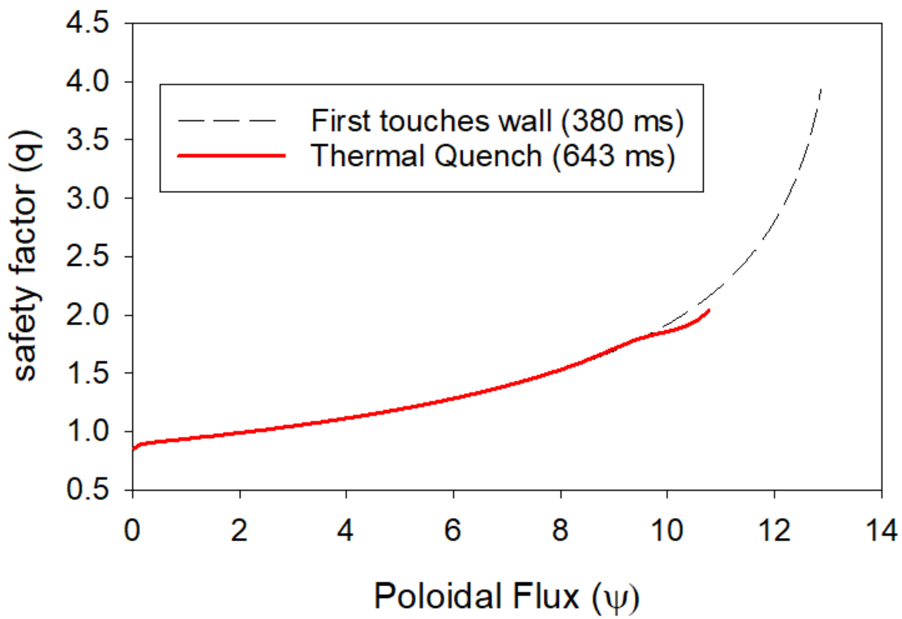


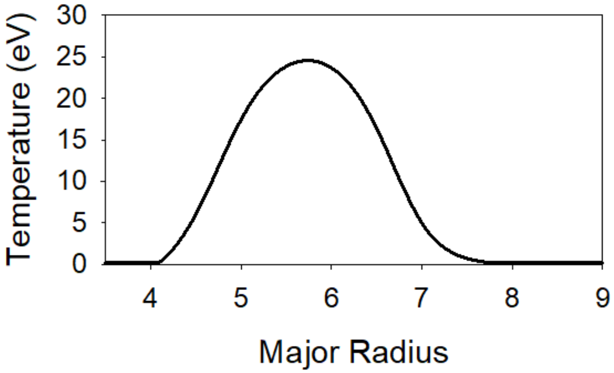
Thermal Quench at t = 643 ms (q_a = 2)



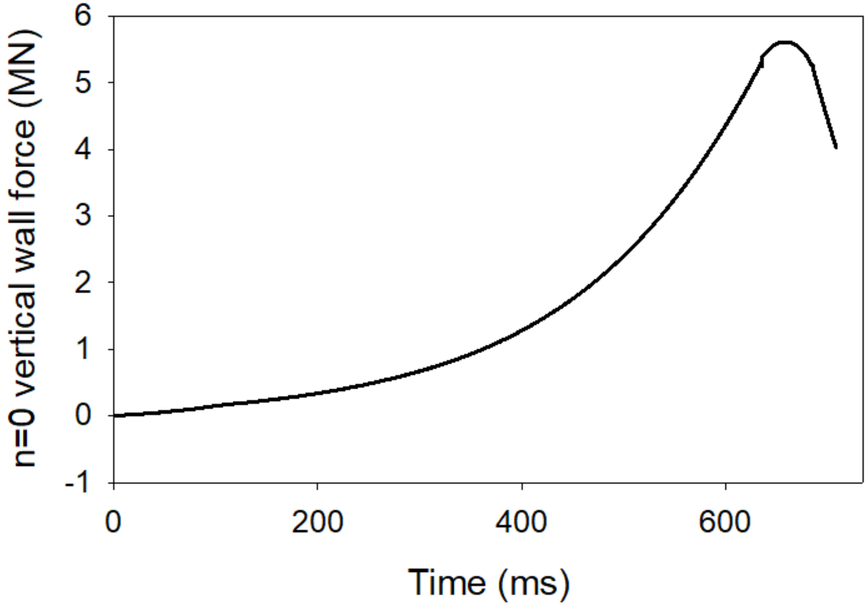
Thermal quench:
➔ $\kappa_\perp$ increased to 10^6 m^2/s so that $T_e(0)$ ~ 25 eV in the presence of Ohmic heating

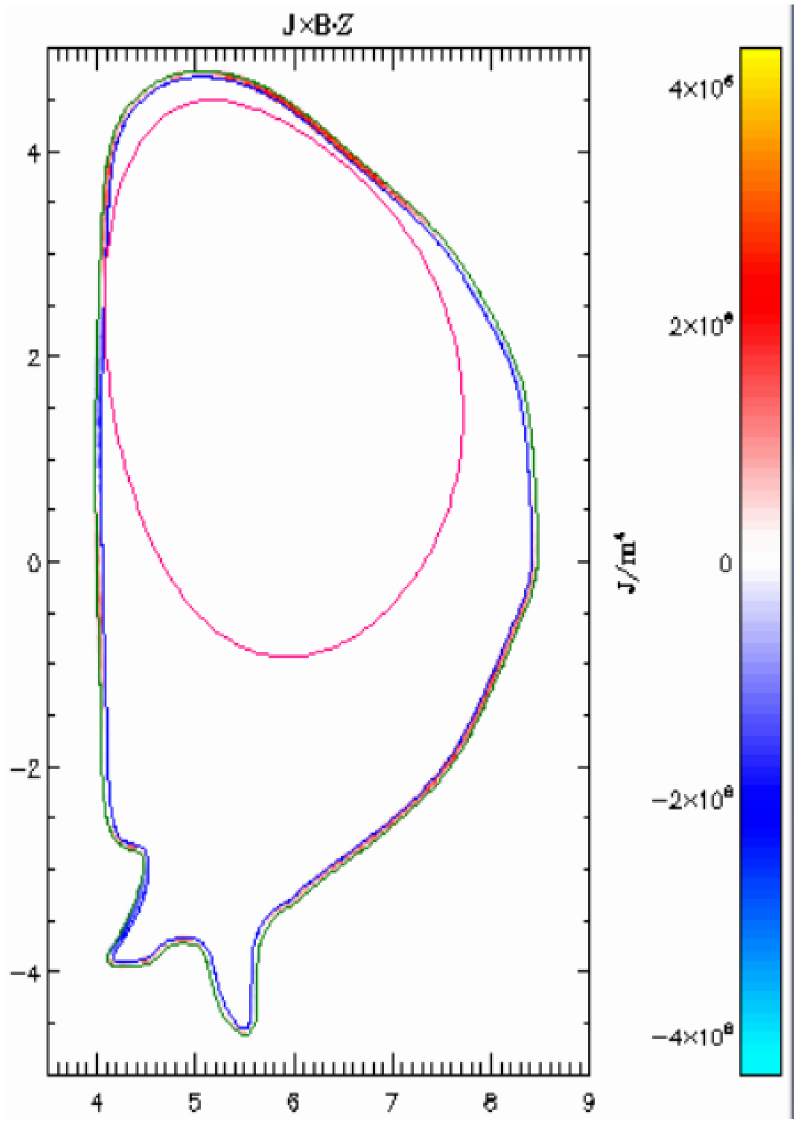






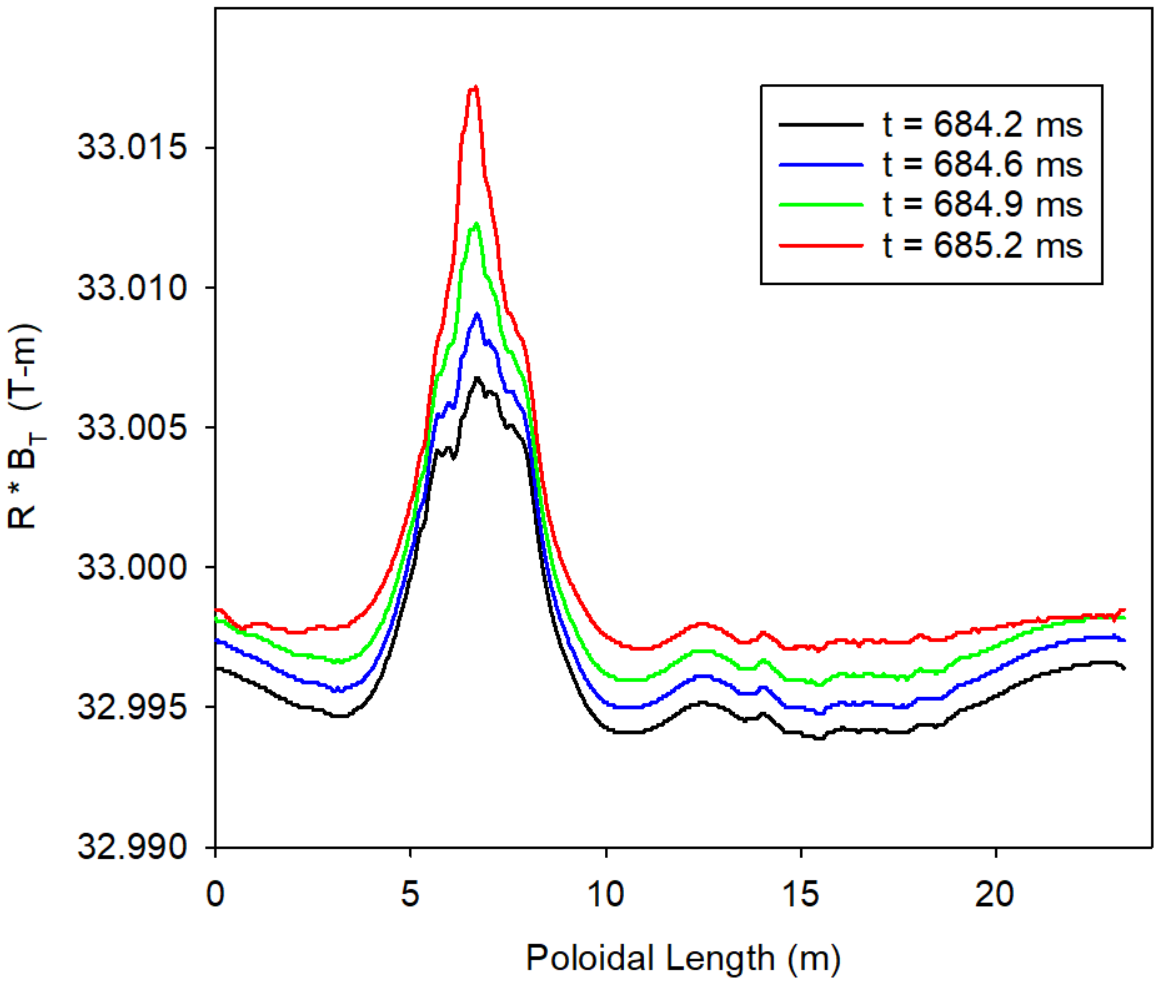
Vertical Force on Wall

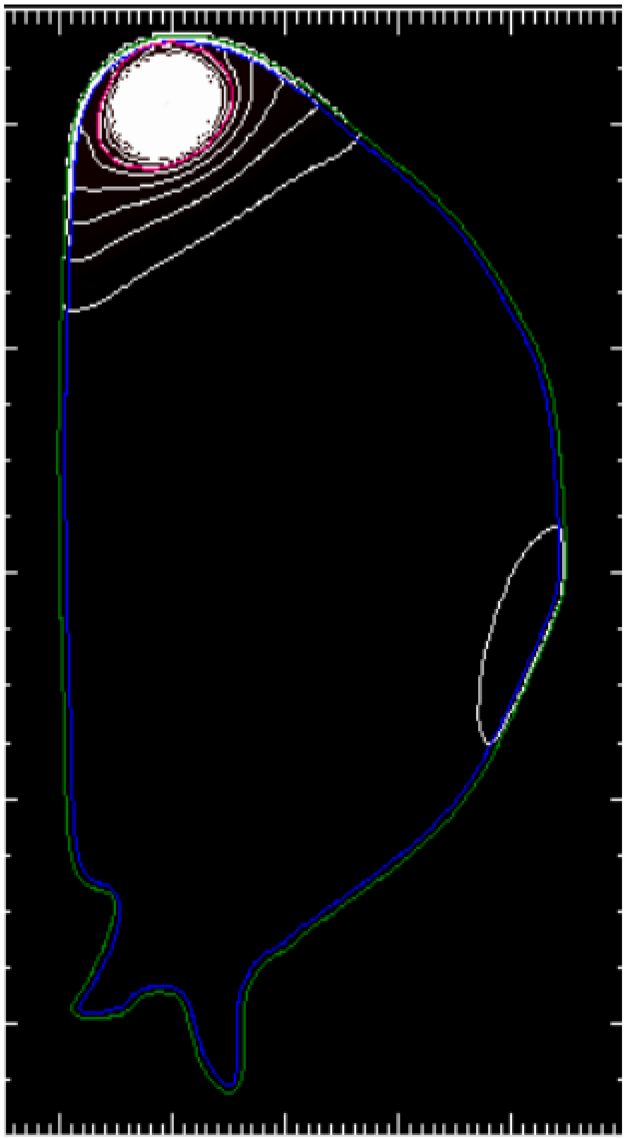




Vertical wall force @ t=646 ms

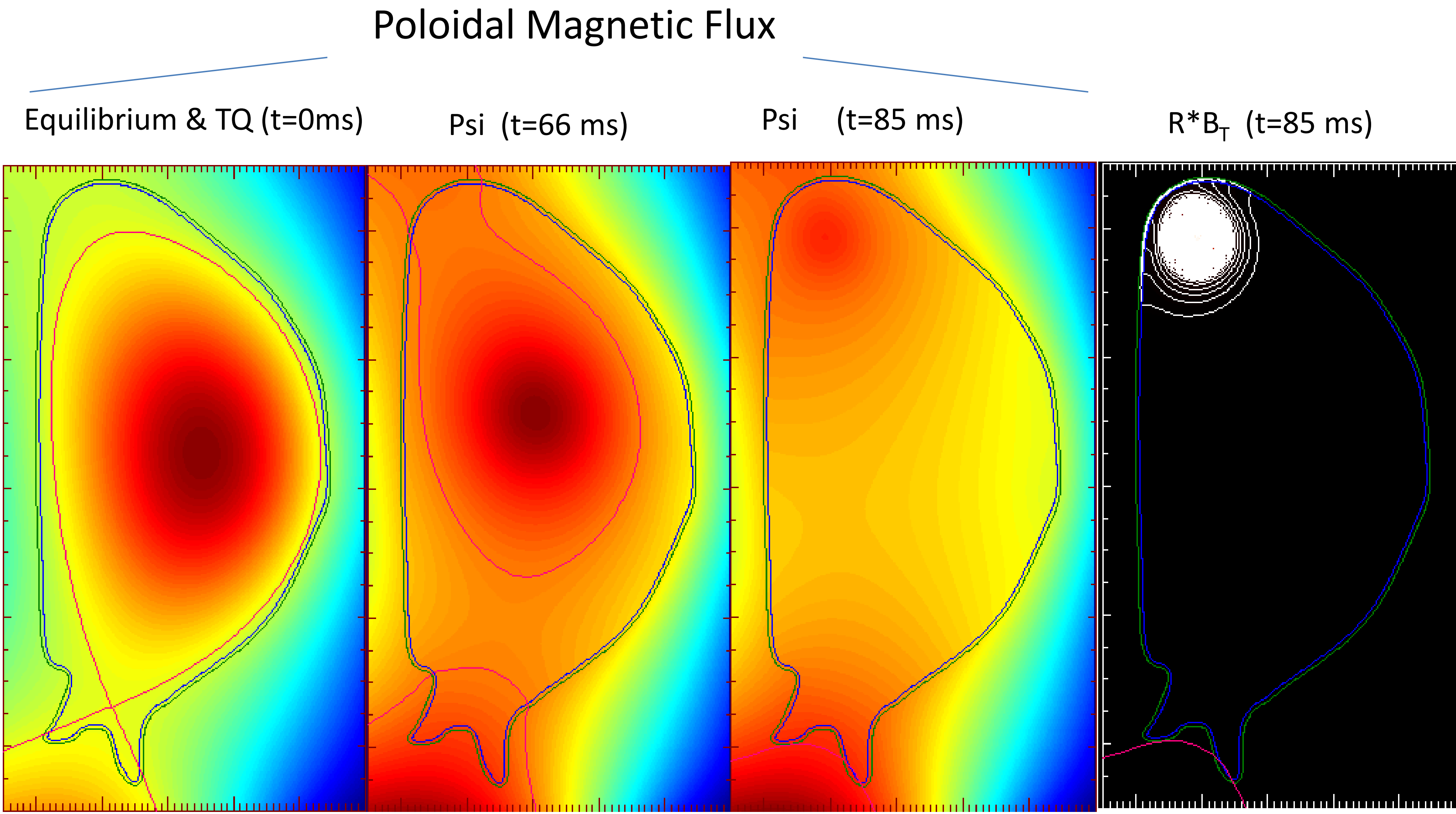
Halo current at time of maximum force





R * B_T at t=684.6 ms

2D nonlinear Cold ITER VDE simulation with single wall



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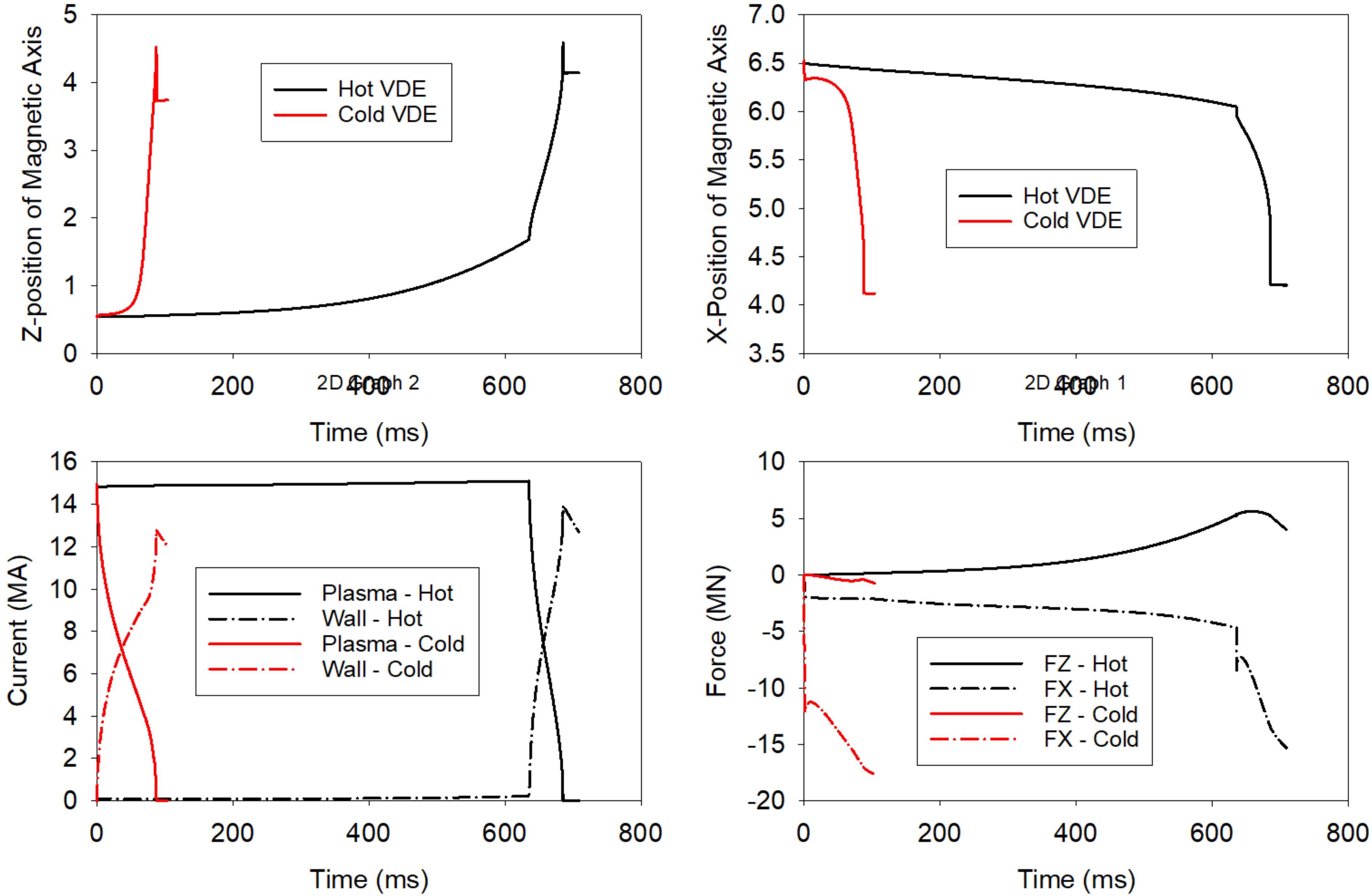
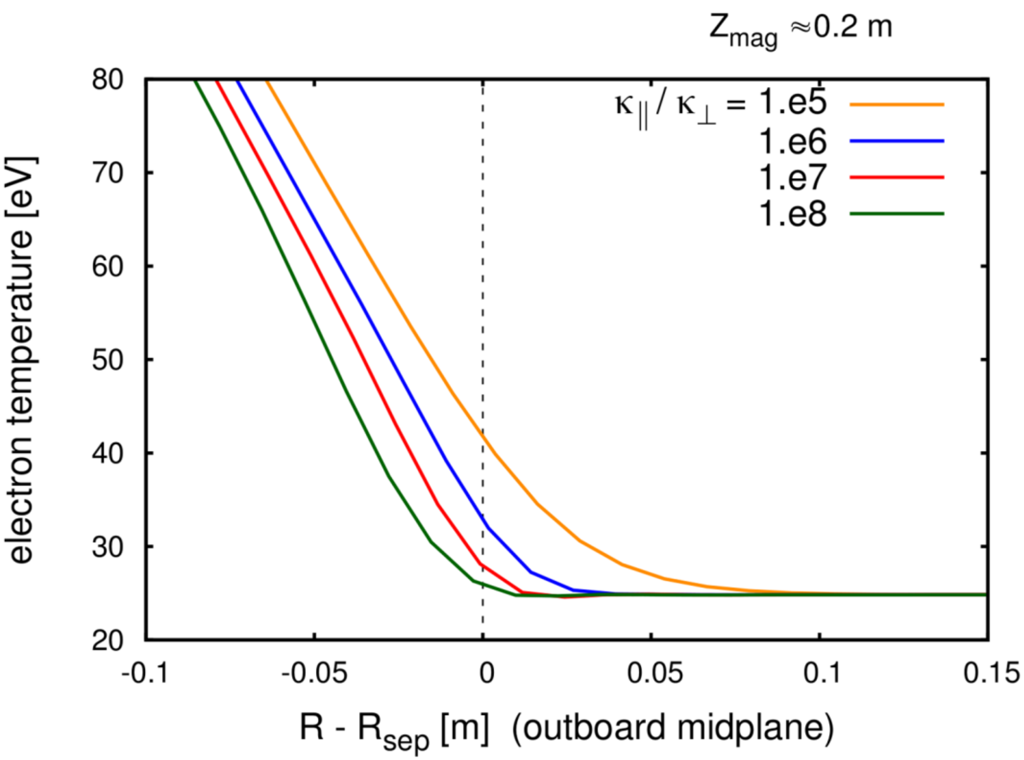
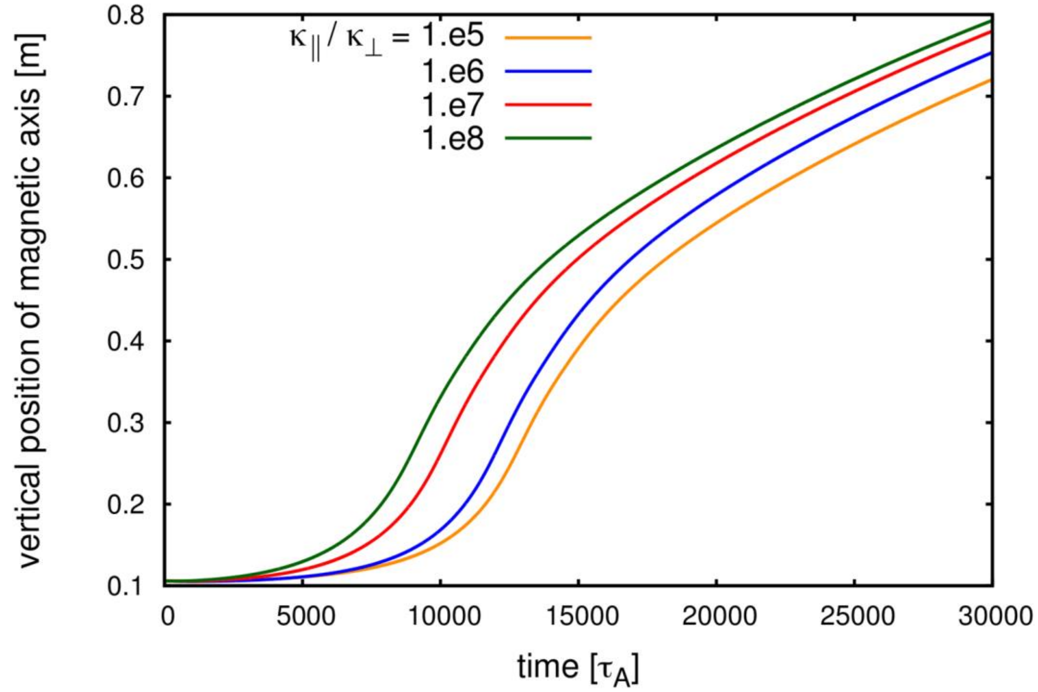
Comparison of 2D nonlinear Hot and Cold ITER VDE



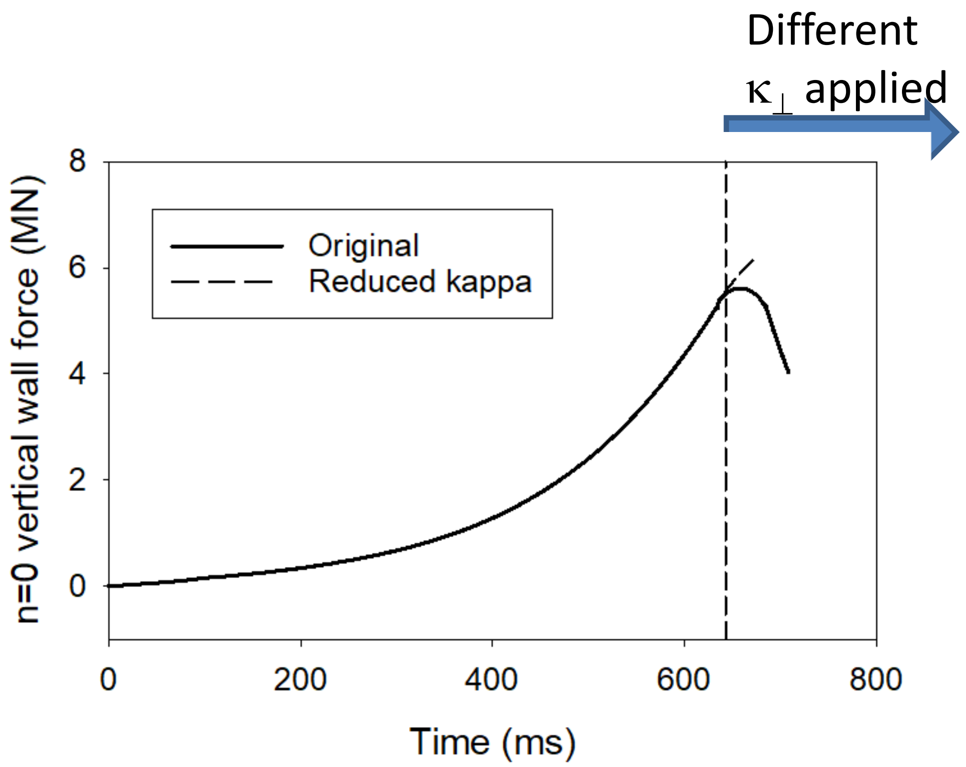
Halo width self-consistently determined by $\kappa_{\parallel}/\kappa_{\perp}$





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

Dependence of Maximum Vessel Force on Post-TQ Te



Higher post-TQ electron temperature led to slower current decay and larger vertical force on vessel.

Ongoing and Future Work

- **Benchmark Studies with NIMROD, JOREK, CarMa0NL**
  - Continue these to 2D NL and 3D NL

- **ITER VDE Studies**
  - 2D parameter studies on $\kappa_{\parallel}/\kappa_{\perp}$, TQ time
  - Thick Vessel with varying resistivity
  - Couple to Cariddi (3D conducting structures)
  - Fully 3D calculations (with SPI)