VDE simulations with M3D-C^1

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ITPA Project: JA on disruption forces

Key person (first name, family name)	Collaborators	e-mail address	Brief description of a possible contribution		
			Before the Daejeon meeting in April 2019	Before the FEC-2020 and ITPA meeting in October 2020	
Stephen Jardin	Nate Ferraro, Isabel Krebs, Cesar Clauser Also, in collaboration with CREATE-F4E	jardin@pppl.gov nferraro@pppl.gov cclauser@pppl.gov ikrebs@pppl.gov	1. 2D Hot and Cold ITER VDE simulations with M3D-C1 with different halo assumptions 2. Continue benchmark of M3D-C1, NIMROD, JOREK (2D nonlinear)	1. 3D Hot and Cold ITER VDE simulations with M3D-C1 with different halo assumptions 2. Continue benchmark of M3D-C1, NIMROD, JOREK (3D nonlinear)	
Fabio Villone	Guglielmo Rubinacci	fabio.villone@unina.it rubinacci@unina.it	1. Comparison of CarMa0NL halo simulations with experimental data 2. Dependence of disruption force on CQ time and growth rate	1. Simplified modelling of AVDEs 2. Coupling of 3D plasma with 3D wall during disruptions (collaboration with PPPL & F4E)	

Outline

- **Benchmark Studies with NIMROD, JOREK**
- **ITER 2D VDE Studies with halo region**
- **ITER 3D VDE Studies (preliminary)**

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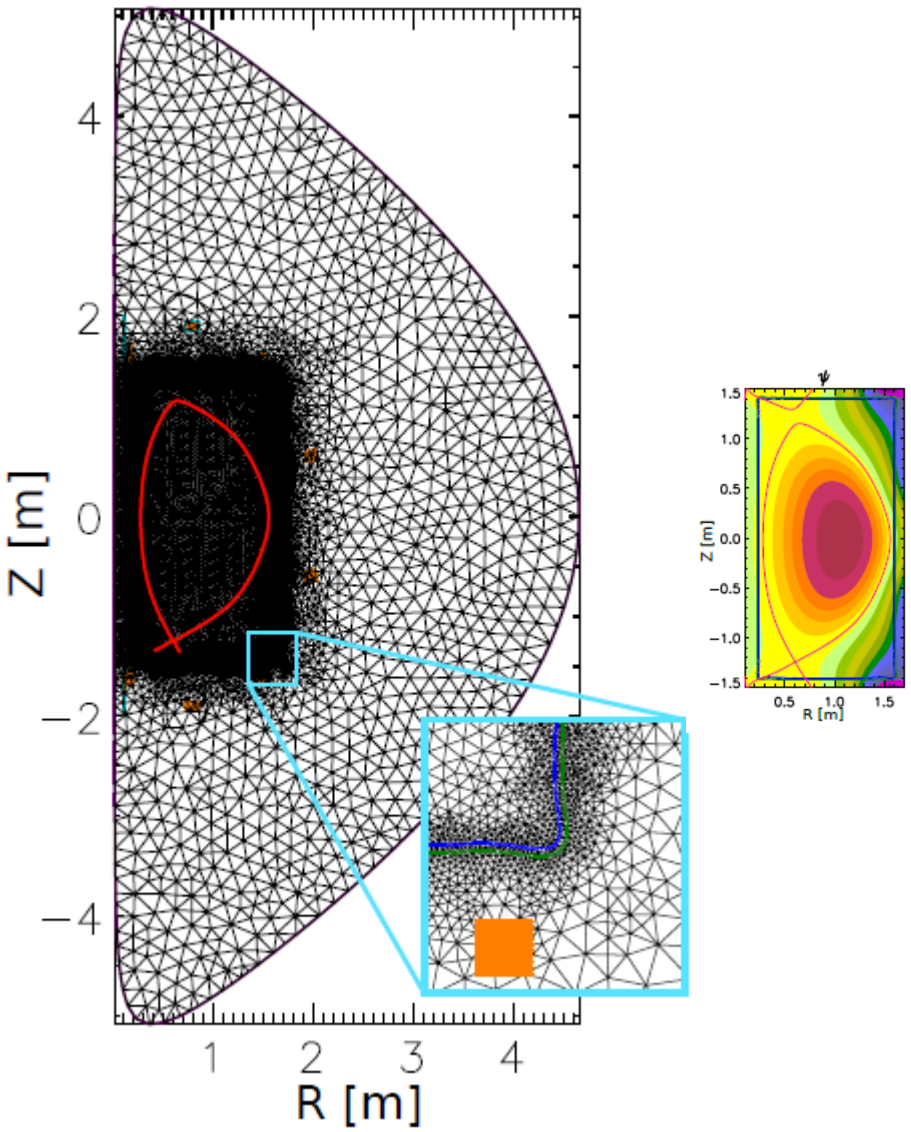
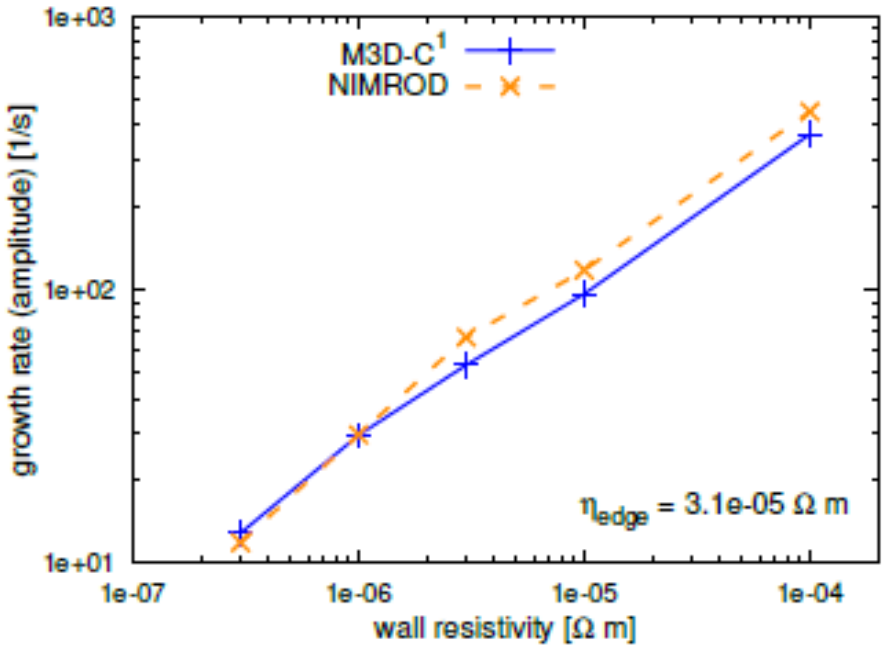
Benchmark Geometry

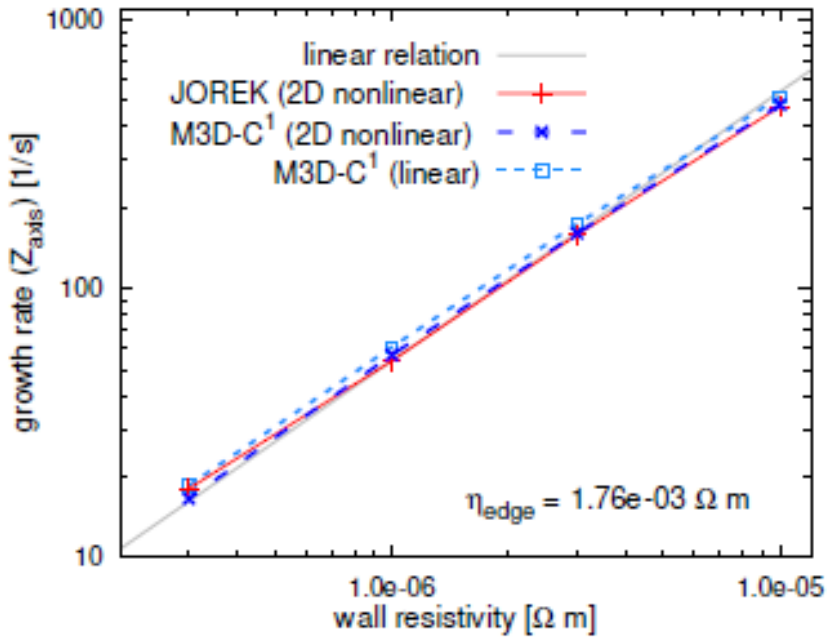


- Start with NSTX equilibrium plasma from a geqdsk
- Replace NSTX vacuum vessel with rectangular vessel that all codes can handle
- Shown on the left is unstructured mesh used in M3D-C1
- M3D-C1 has 3-regions in which different equations are solved:
  - Plasma Region (MHD)
  - Wall Region ($E = \eta J$)
  - Vacuum Region ($J=0$)

Linear 2D Benchmark M3D-C[1], NIMROD & JOREK

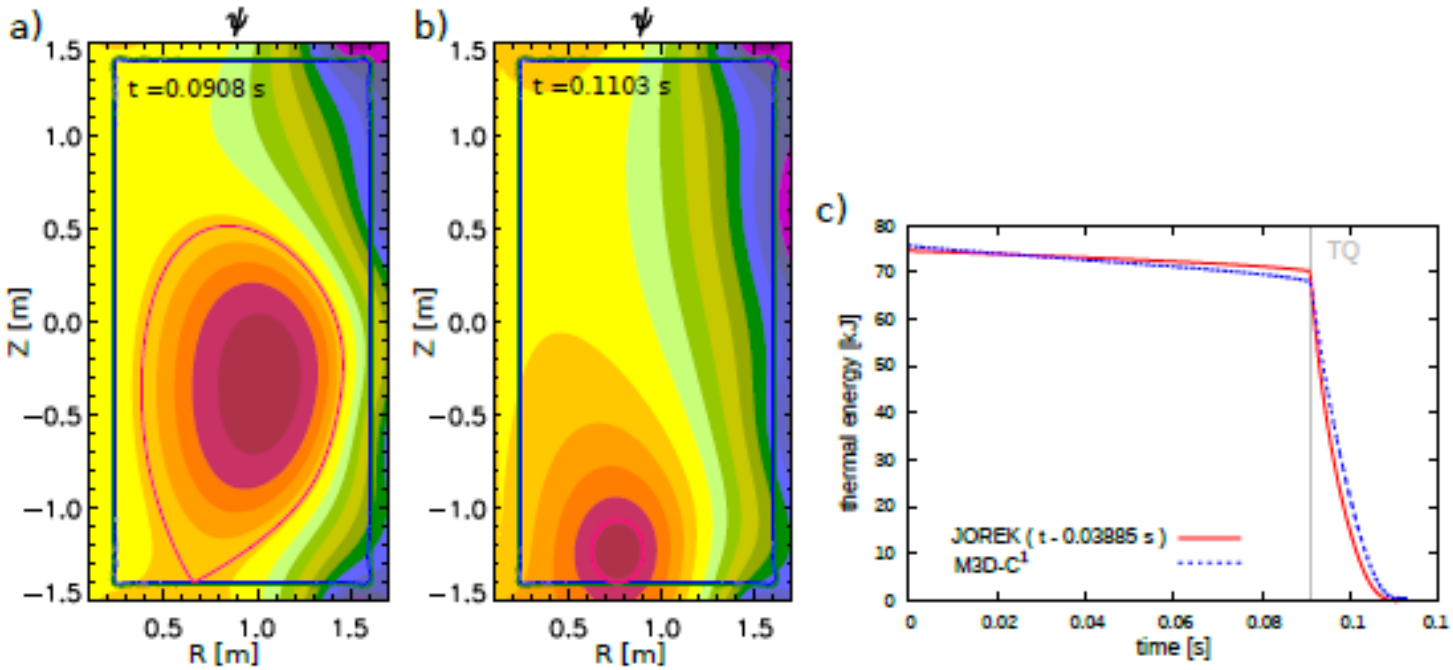


Growth rate as a function of wall resistivity for M3D-C1 and NIMROD. Results agree to 11%. (better at low wall resistivity)



Growth rate as a function of wall resistivity for M3D-C1 and JOREK-starwall

Nonlinear 2D Benchmark M3D-C[1] & JOREK (1)

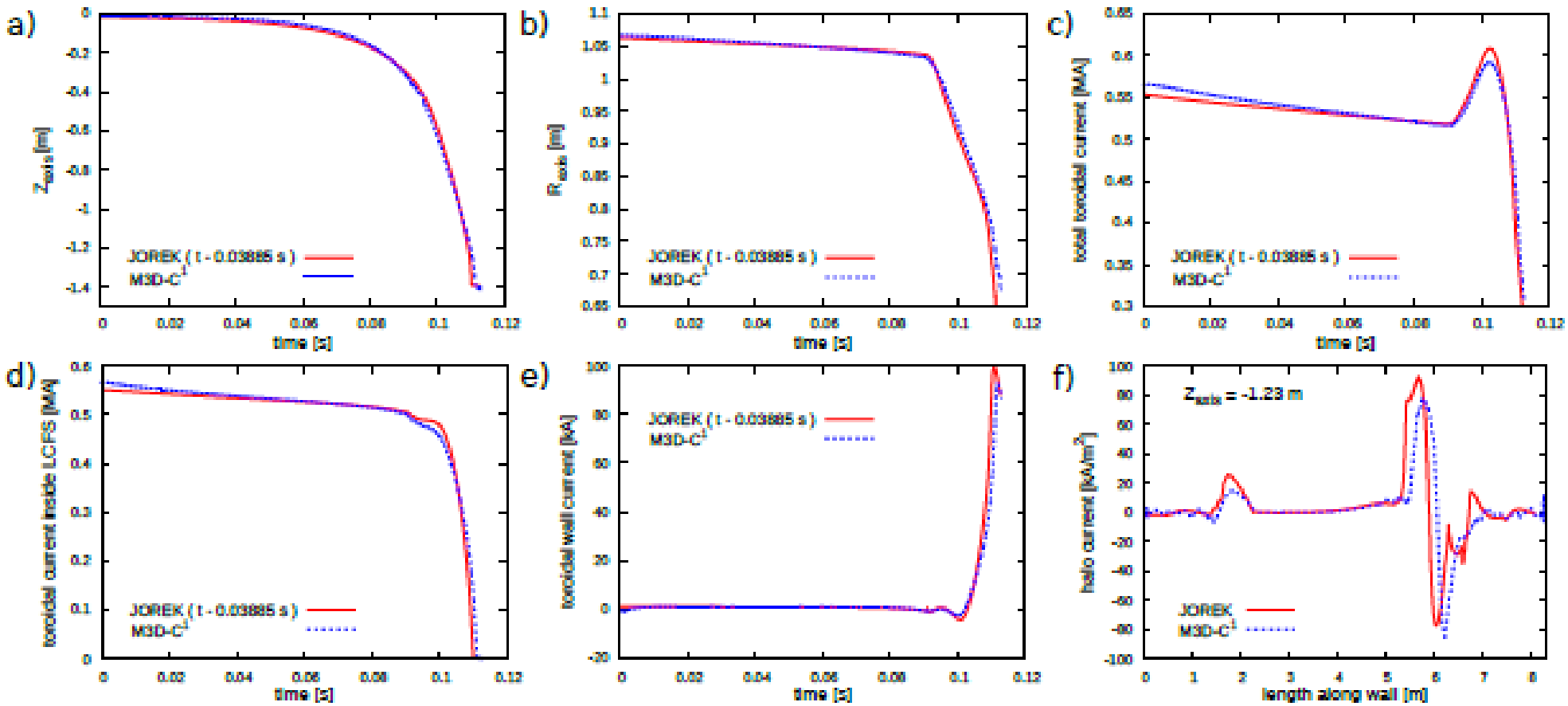


(a) Flux contours when plasma first touches wall (M3D-C1)

(b) Flux contours near end of M3D-C1 VDE simulation.

(c) Time traces of Thermal Energy in both M3D-C1 and JOREK
(note TQ is induced by sudden increase in thermal conductivity ($\kappa_\perp$)

Nonlinear Benchmark M3D-C[1] & JOREK (2)



(a) Z-position of magnetic axis

(b) R-position of magnetic axis

(c) Toroidal current within vessel

(d) Toroidal current within LCFS

(e) Net toroidal wall current

(f) Halo current density vs wall position when Zaxis=-1.23 m

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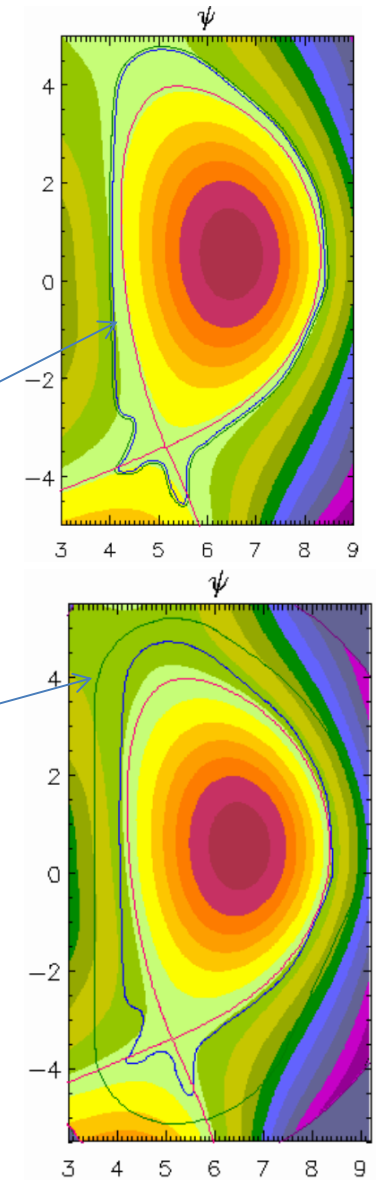
- Benchmark Studies with NIMROD, JOREK

- **ITER 2D VDE Studies with halo region**

- ITER 3D VDE Studies (preliminary)

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: 250,000 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 (in progress)
  - 3D M3D-C^1 simulations (planned)



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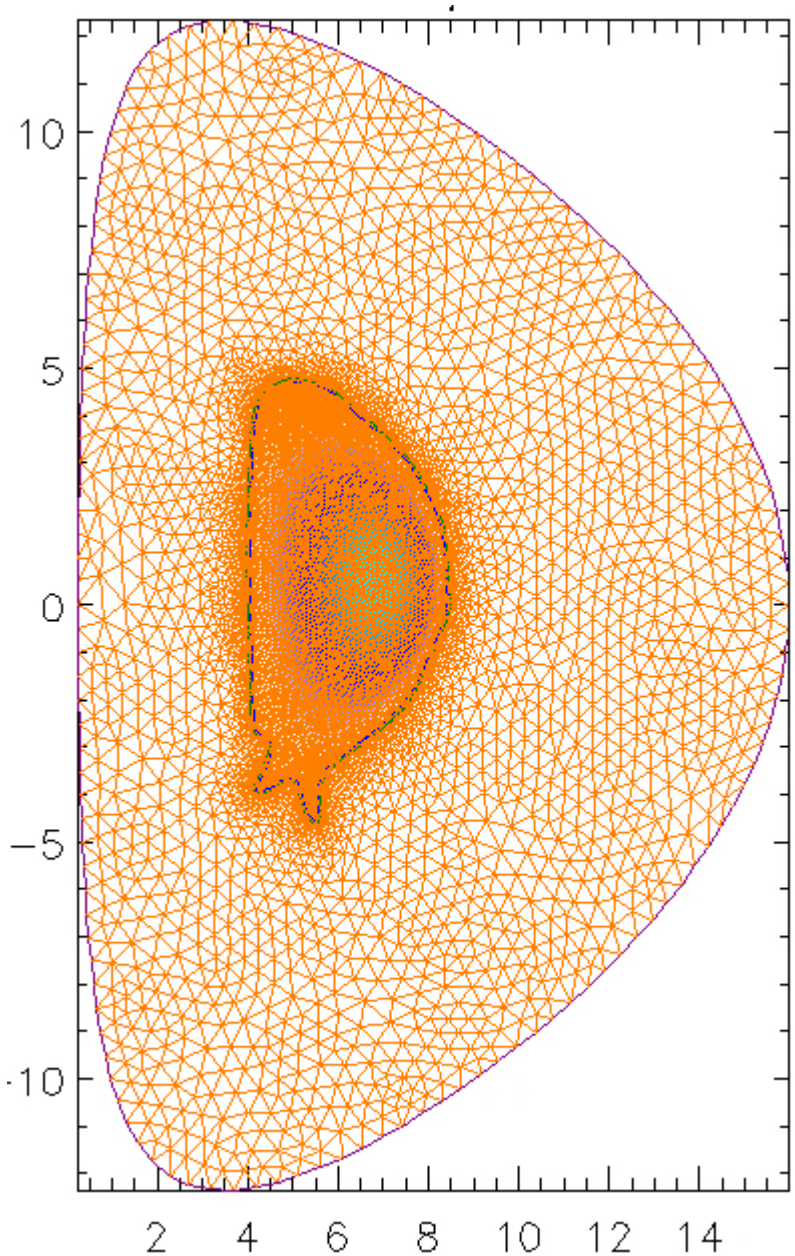
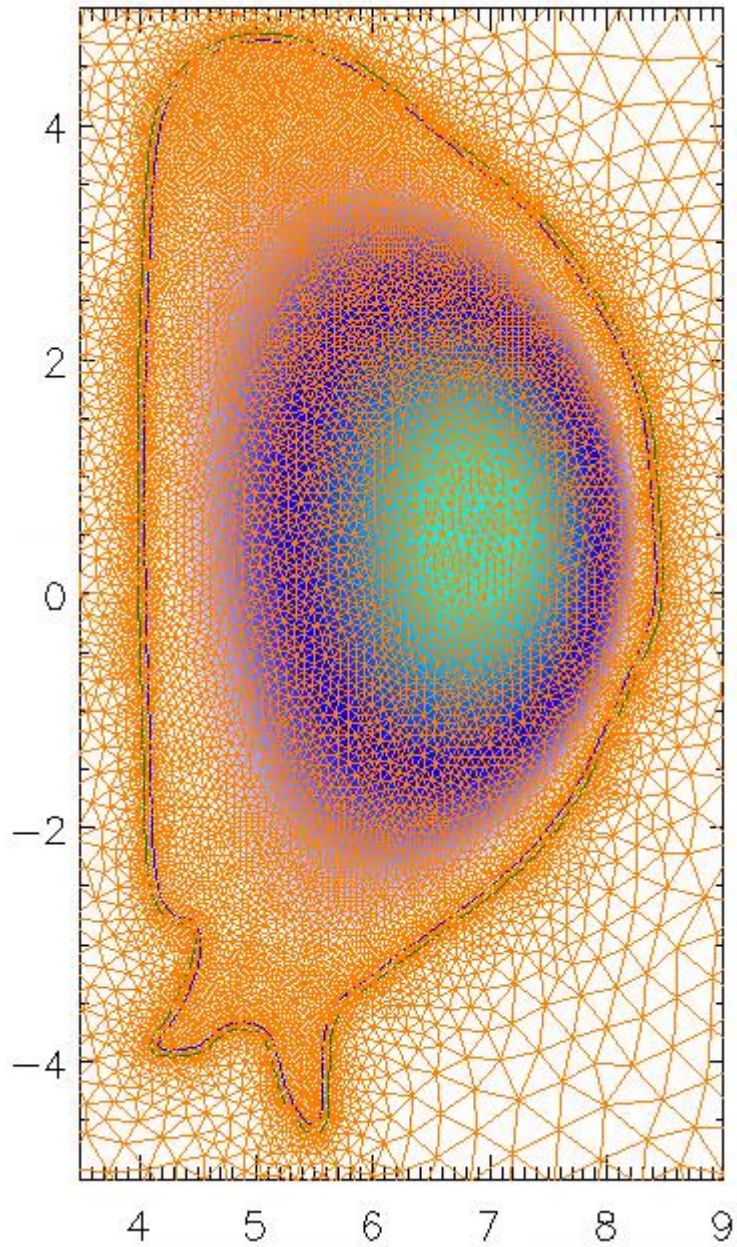
/p/m3dc1/nferraro/data/test/mesh/iter_mesh

Poloidal unstructured mesh used in ITER calculation

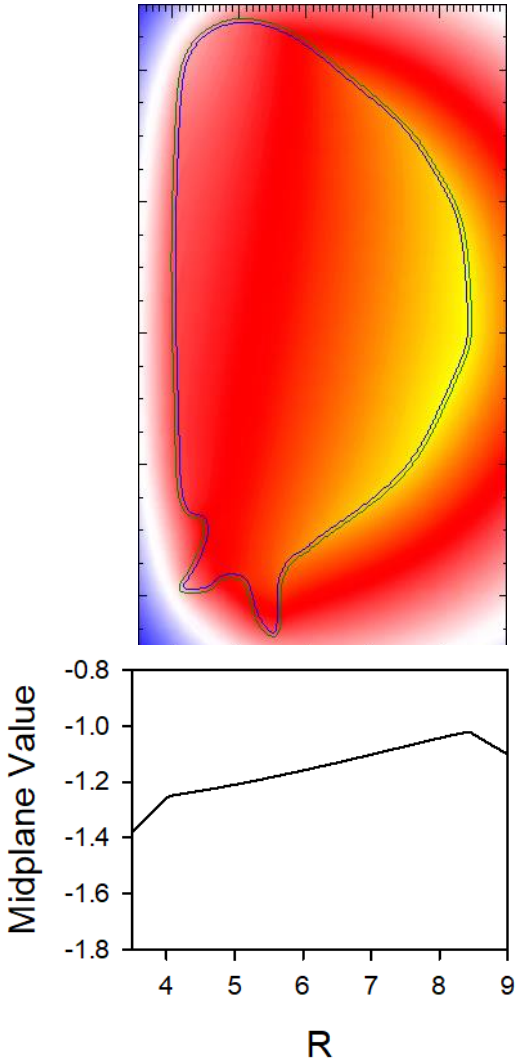


Full Mesh

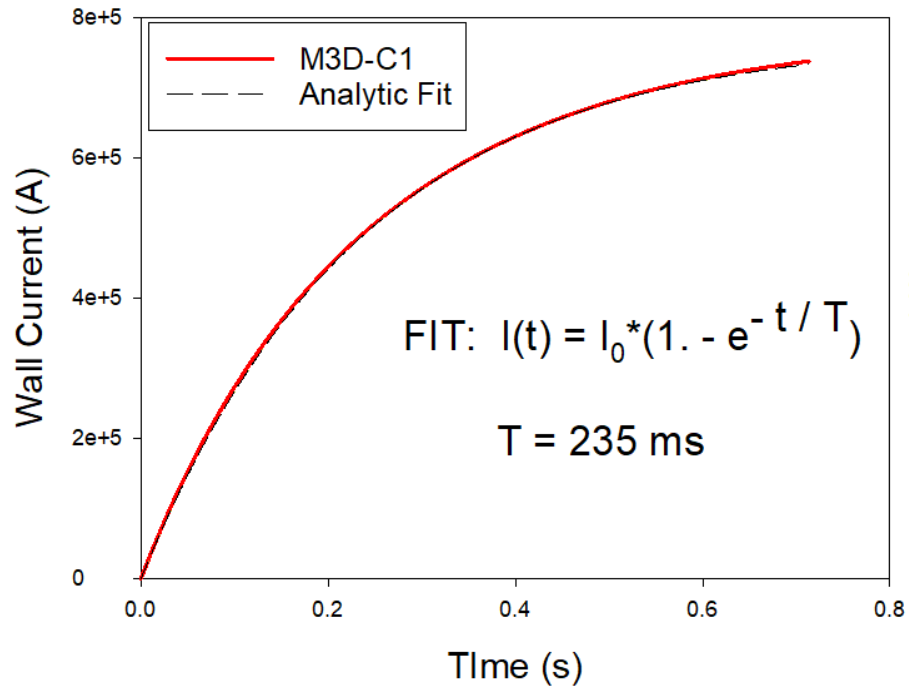


Close-up of Plasma Region

L/R time from simulation without plasma



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

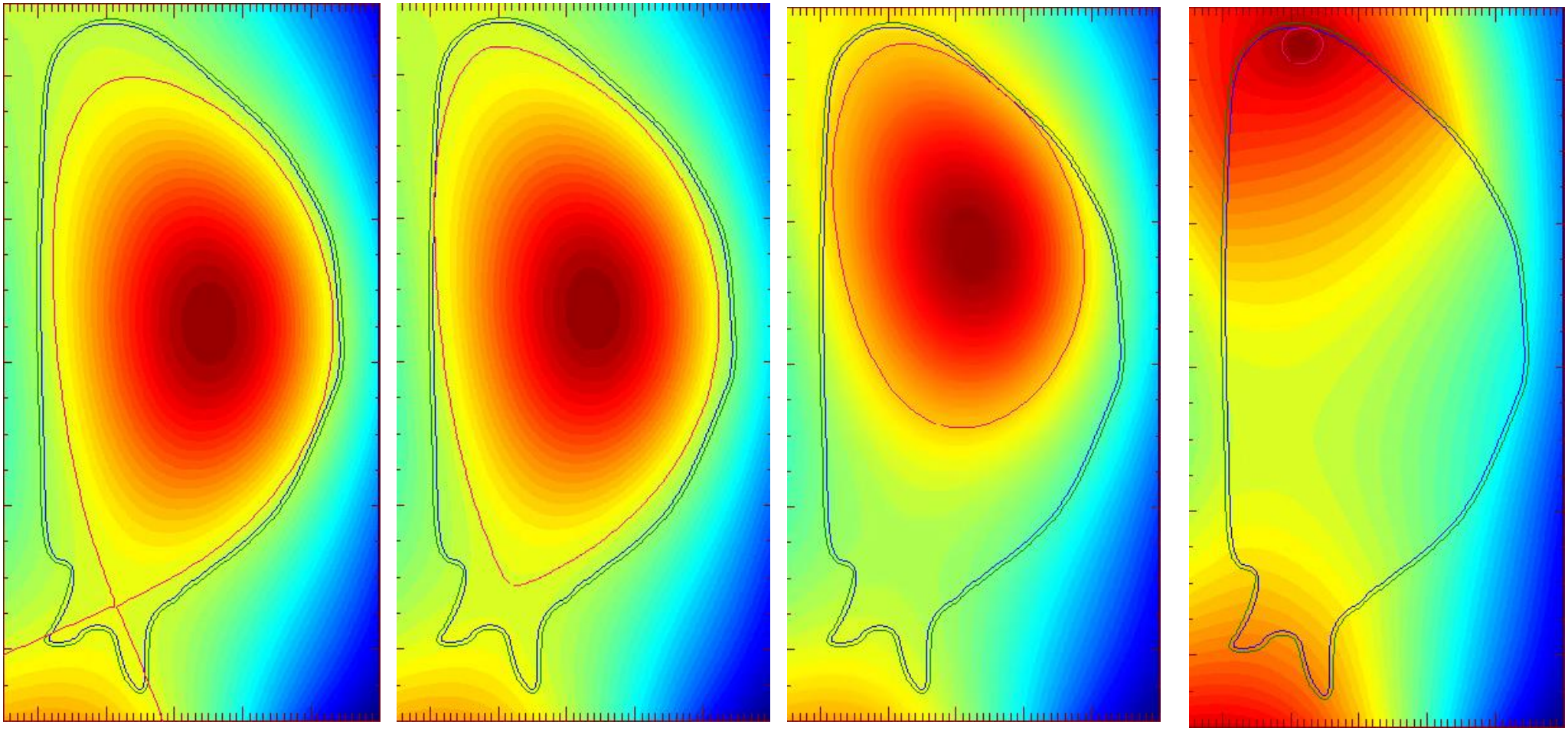


Simulation time: 1,100,000 τ_A

2D nonlinear ITER VDE simulation with single wall

"Standard Baseline Case"

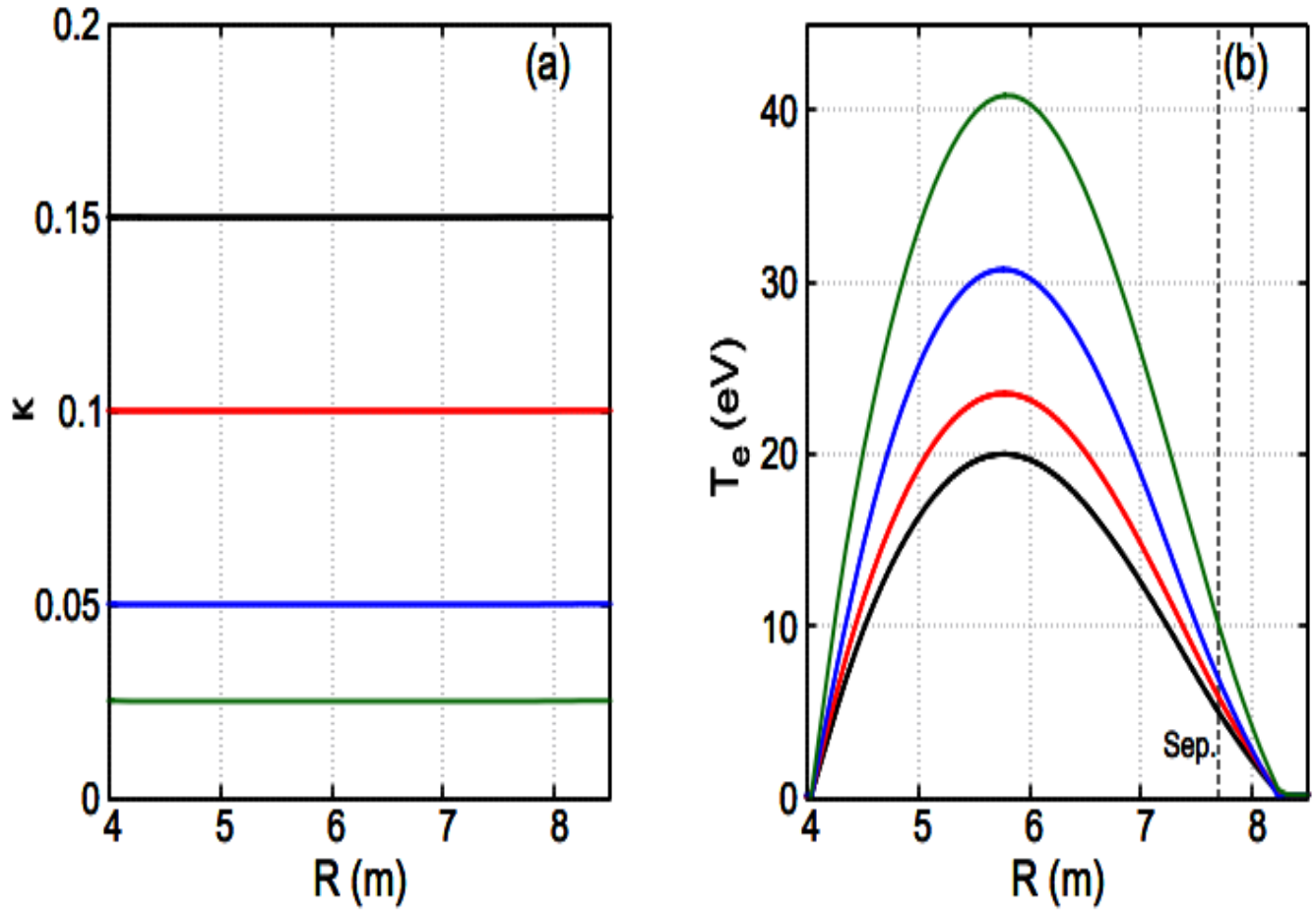
Equilibrium (t=0ms) | Wall contact (t=37 ms) | TQ (t=63 ms) | Max Force (t=65 ms)



Poloidal Magnetic Flux

Run03: slice 0,10,13,16)

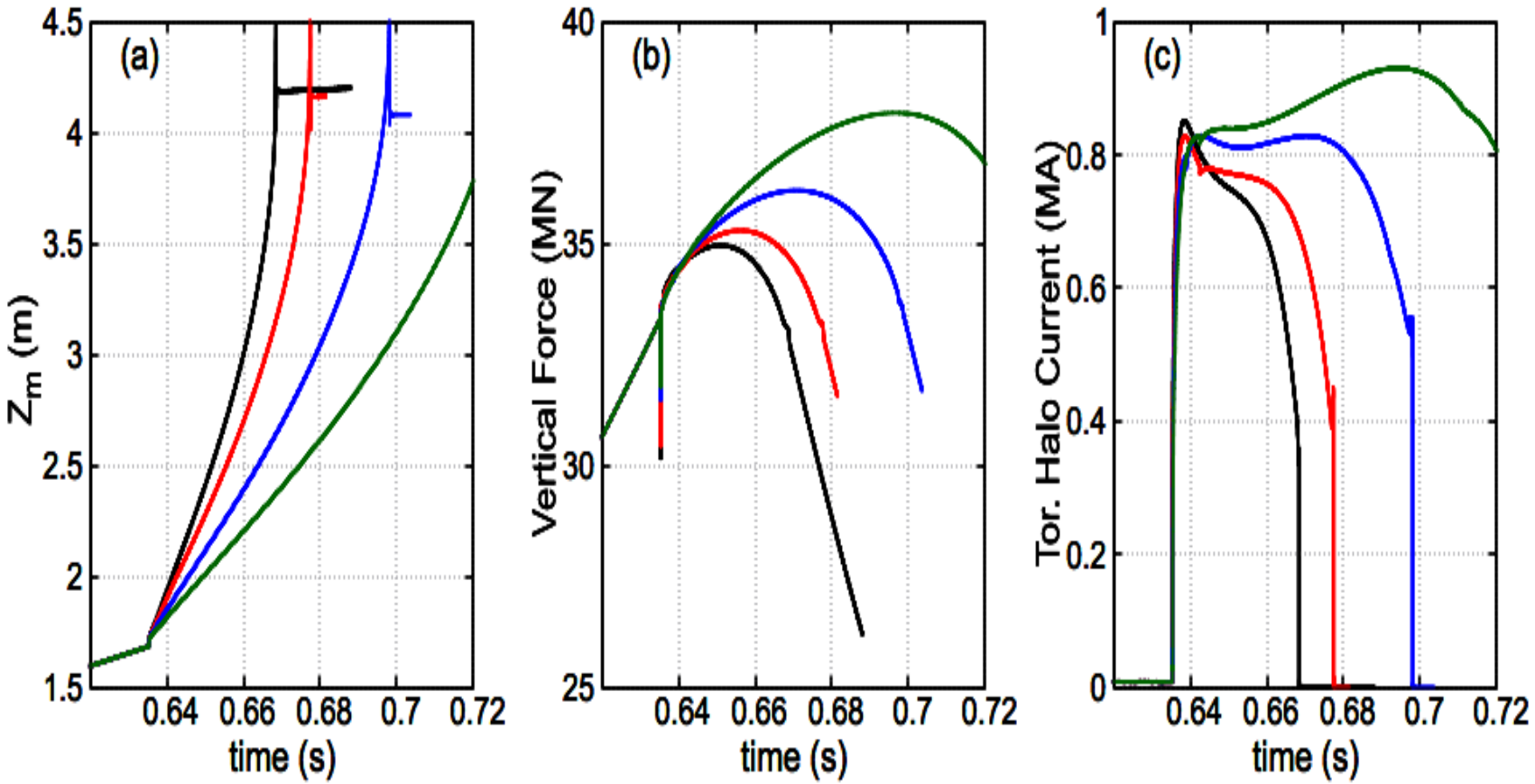
Dependence of post-TQ T_e on Thermal Conductivity (κ)



To initiate Thermal Quench (TQ) we suddenly increase $\kappa_\perp$ to a large value

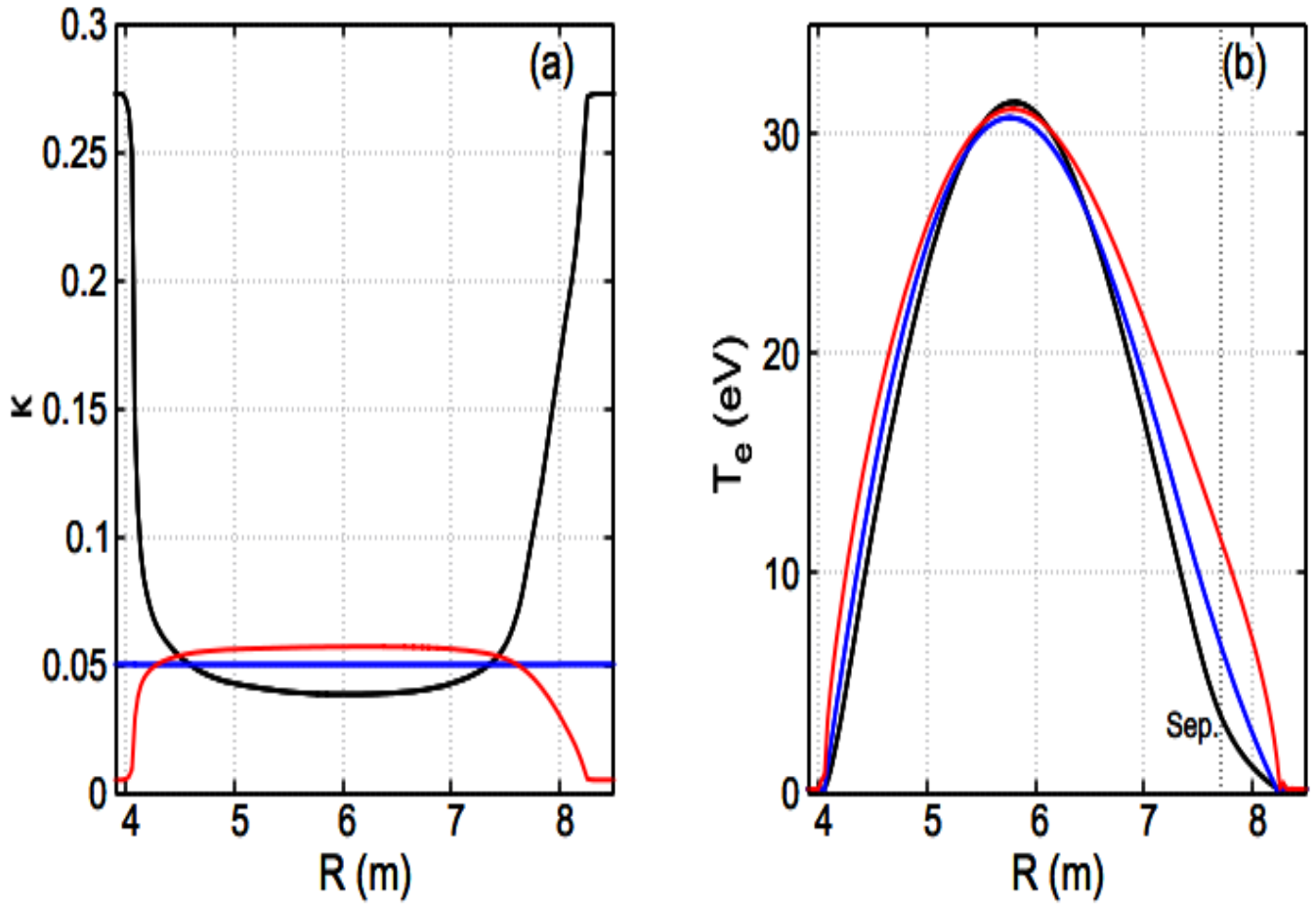
- **.025**, **.05**, **0.1**, **0.15** (dimensionless internal units)
- Larger values lead to lower post-TQ temperatures ➔ faster CQ
- Changing κ in this way has only small effect on open-field-line temperature

Effect of varying κ on plasma motion & forces



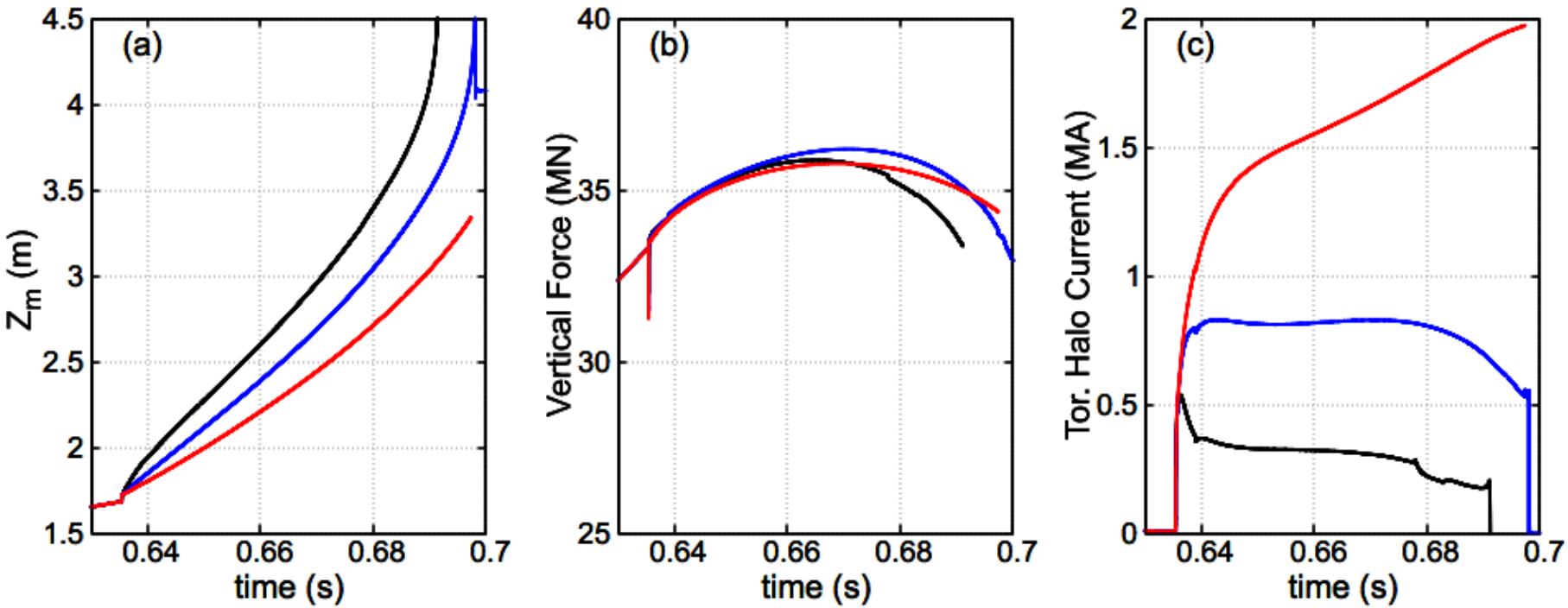
- Slower upward motion and larger vertical forces for small κ (High Te)
- Only small dependence of maximum halo current magnitude on κ

Dependence of post-TQ T_e on κ profile



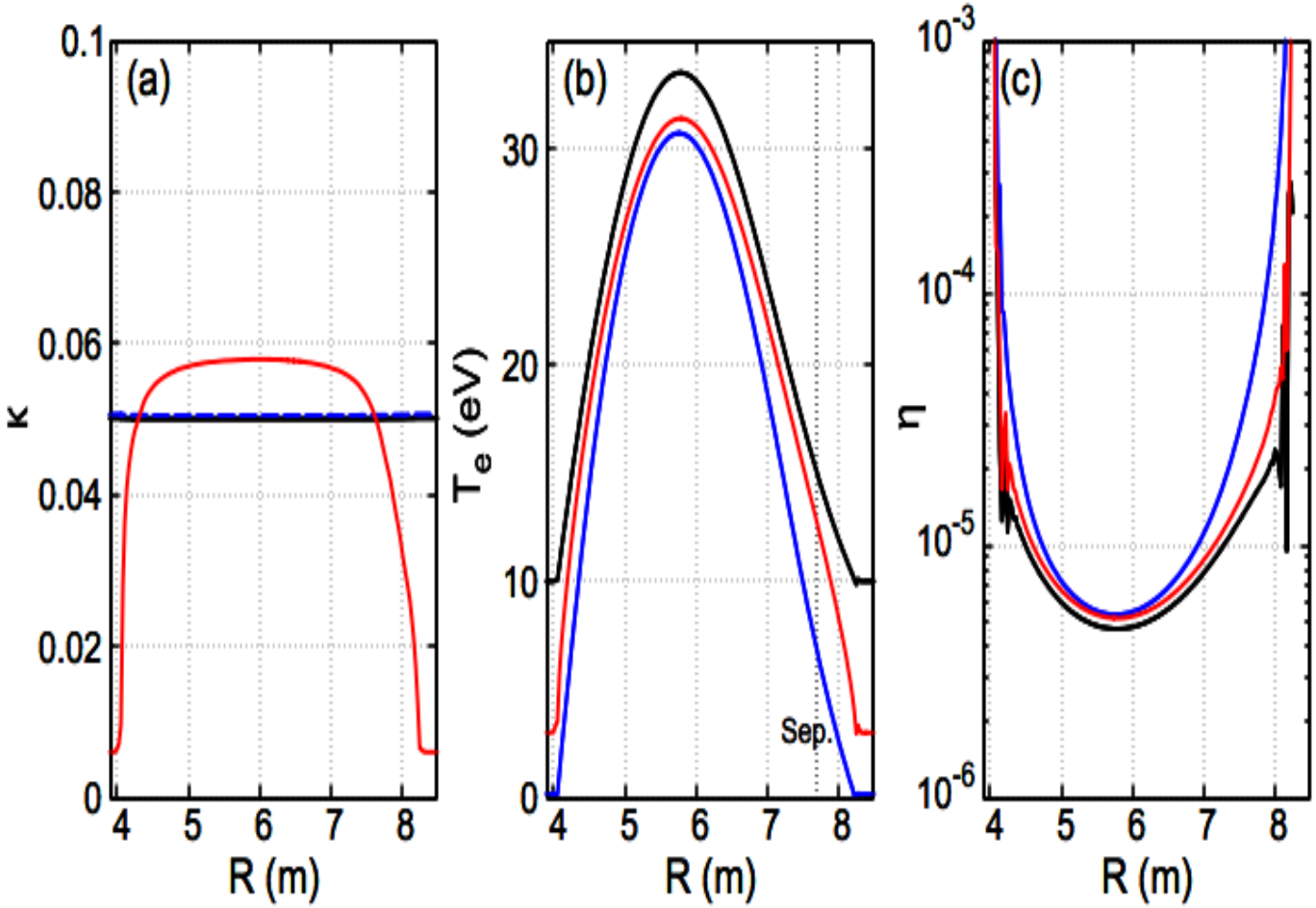
- Compare κ **constant**, **increasing**, or **decreasing** in radius
- κ **decreasing** in radius leads to largest T_e on open field lines ➔ halo current

Effect of κ profile on plasma motion & forces



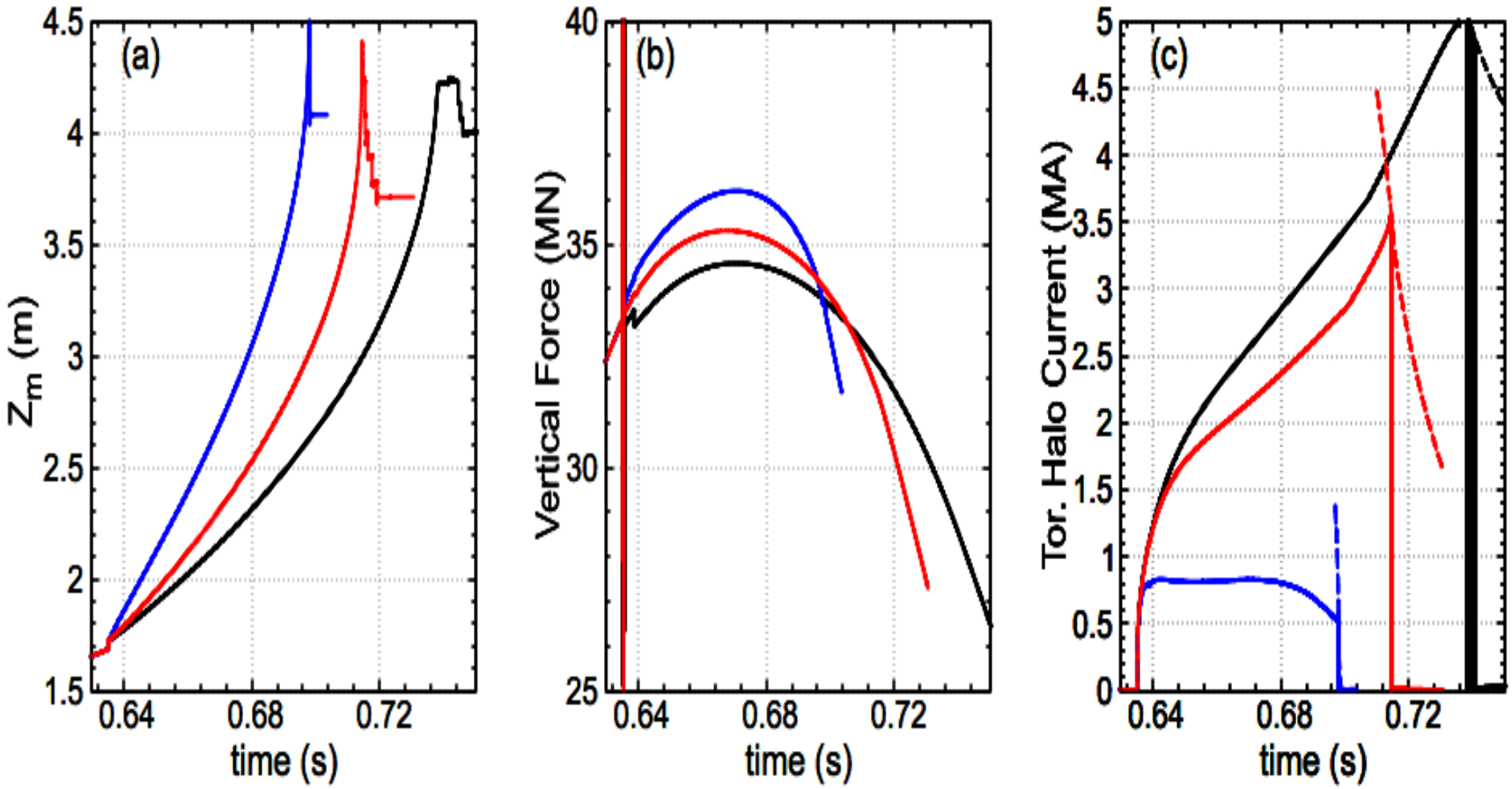
- κ **decreasing** with radius leads to slower drift, larger halo current
- Total vertical force largely unaffected

Dependence of post-TQ T_e on T_e boundary value



- Compared boundary values of **.1 eV**, **3 eV**, and **10 eV**
- Note: **3 eV** case also had κ **decreasing** with radius

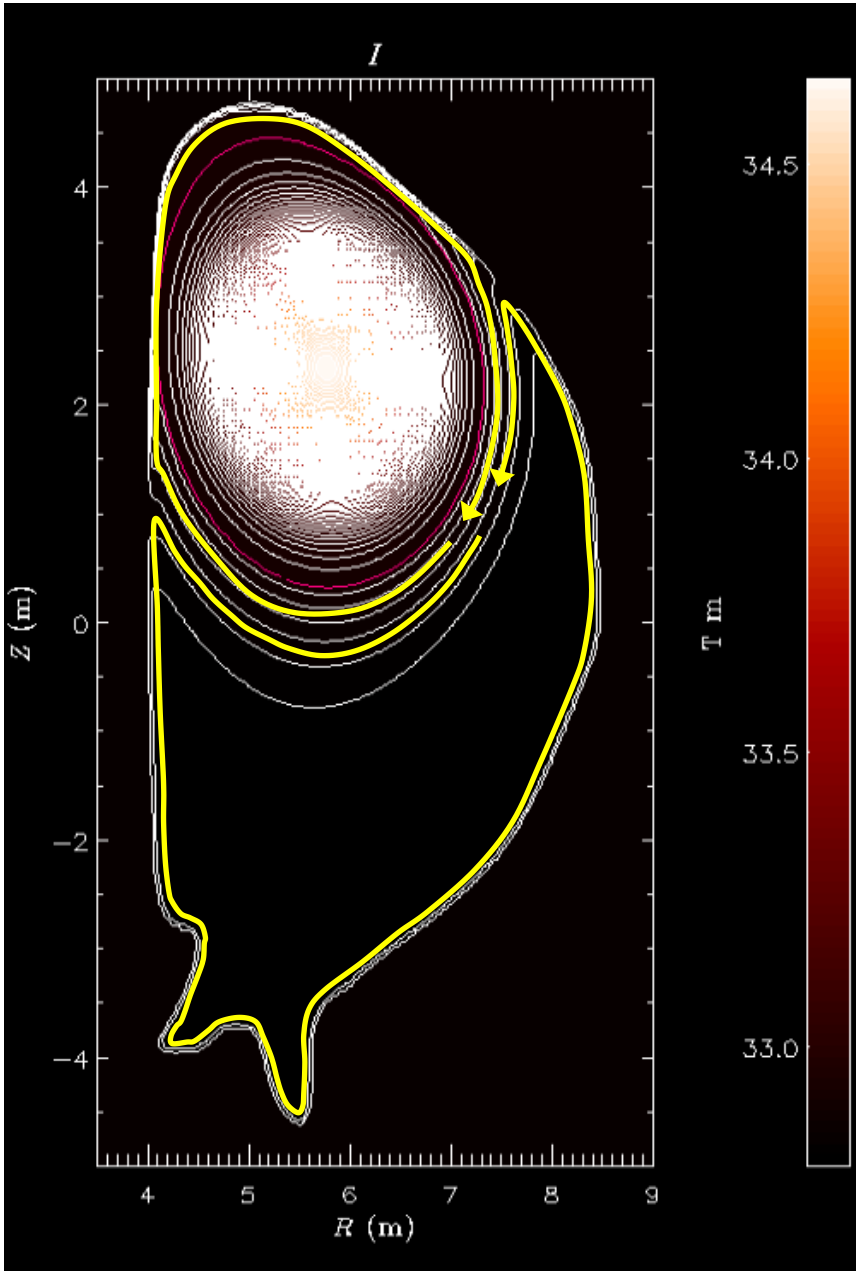
Effect of T_e BC on plasma motion & forces



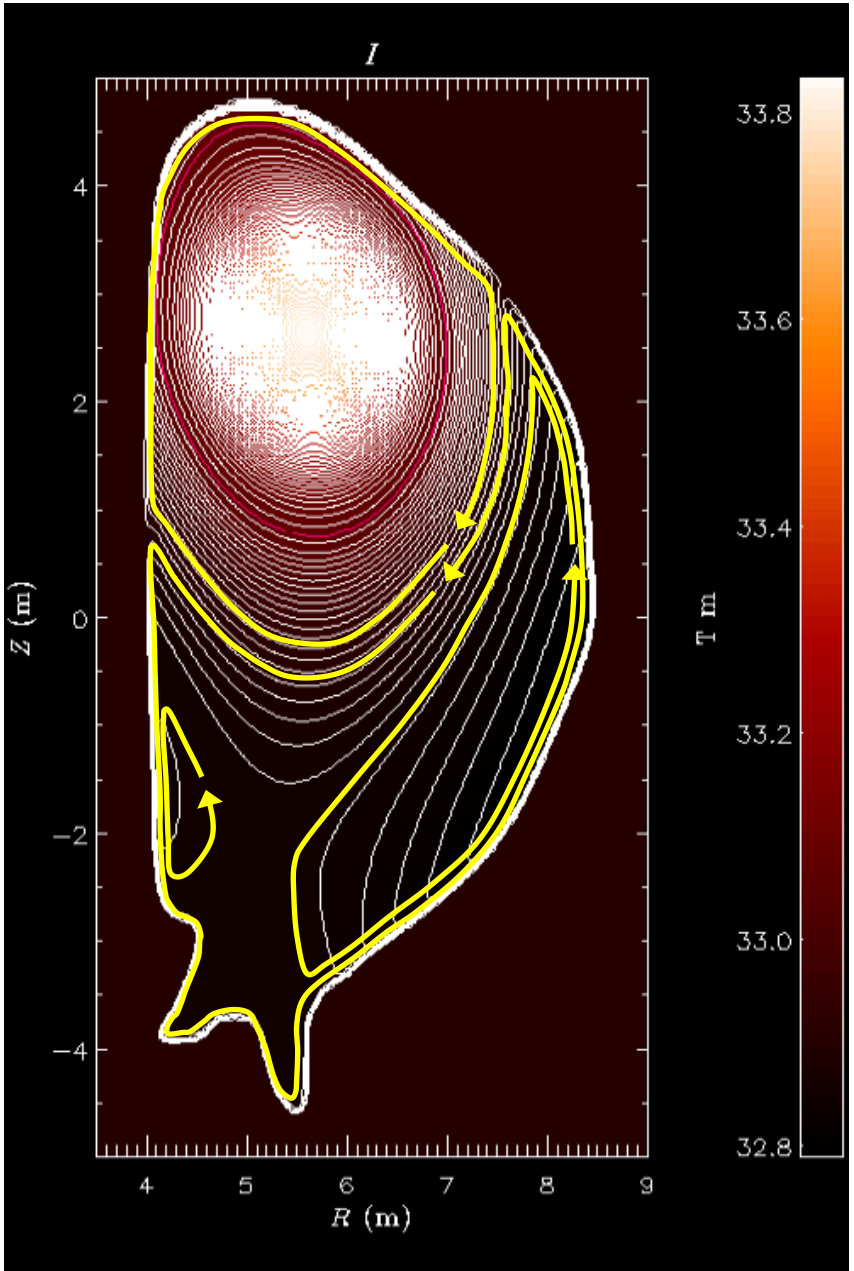
- Case with **10 eV BC and flat κ** also leads to slower growth and more halo current
- **Raising edge T_e BC** and has similar effect as **κ decreasing with radius**
- T_e BC has little effect on net vertical force

Halo Current patterns for two cases.

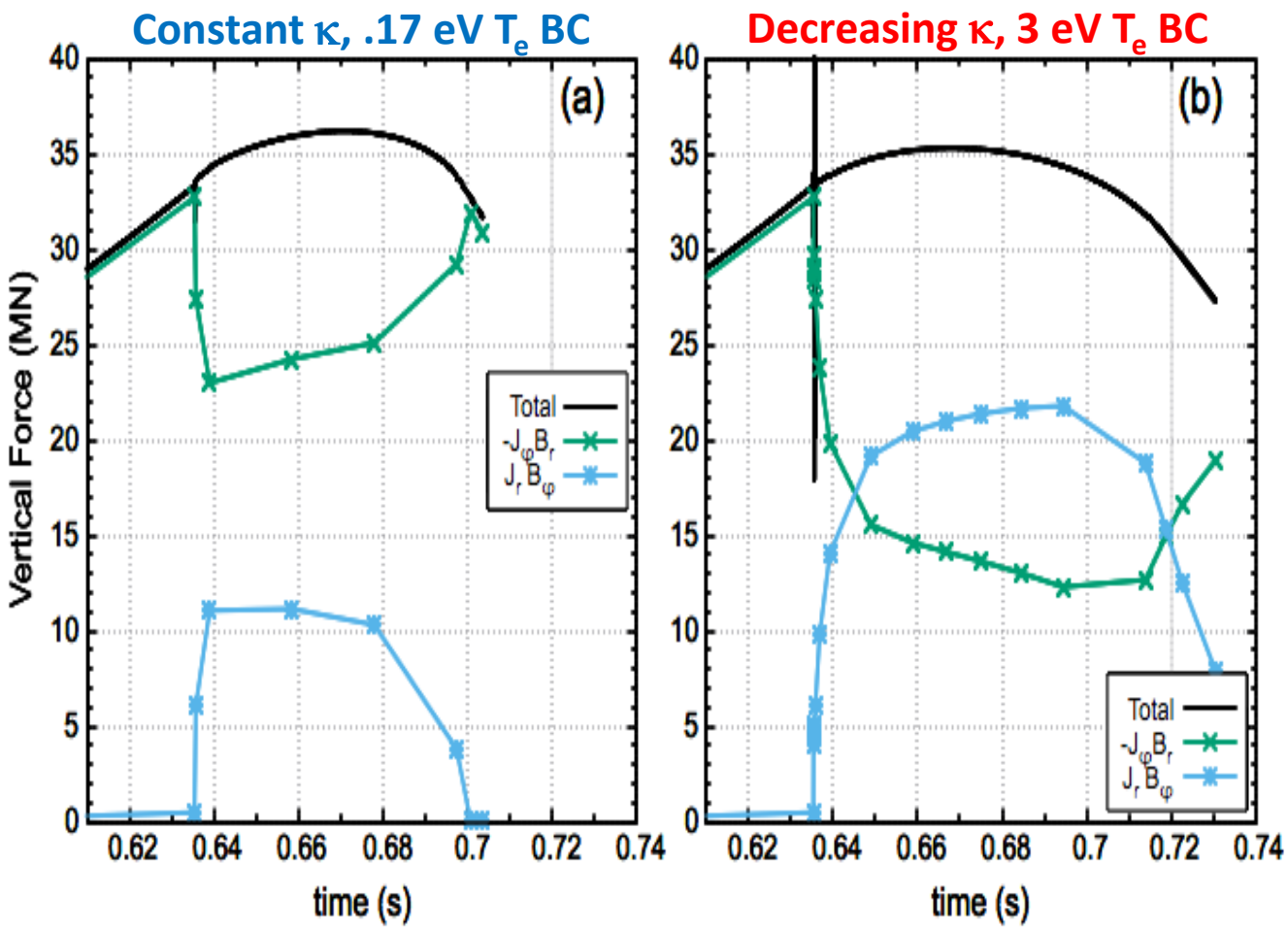
Constant κ, .17 eV T_e BC t = 658 ms



Decreasing κ, 3 eV T_e BC t = 684 ms



Comparison and breakdown of forces



- Case (b) with larger halo current had larger vertical force due to J_r x B_φ but smaller vertical force due to J_φ x B_r
- **Total vertical force almost unaffected by magnitude of halo current !!**
- **It can be shown that $F_W = F_{wc} + F_{pc}$ (notation of Pustovitov)**

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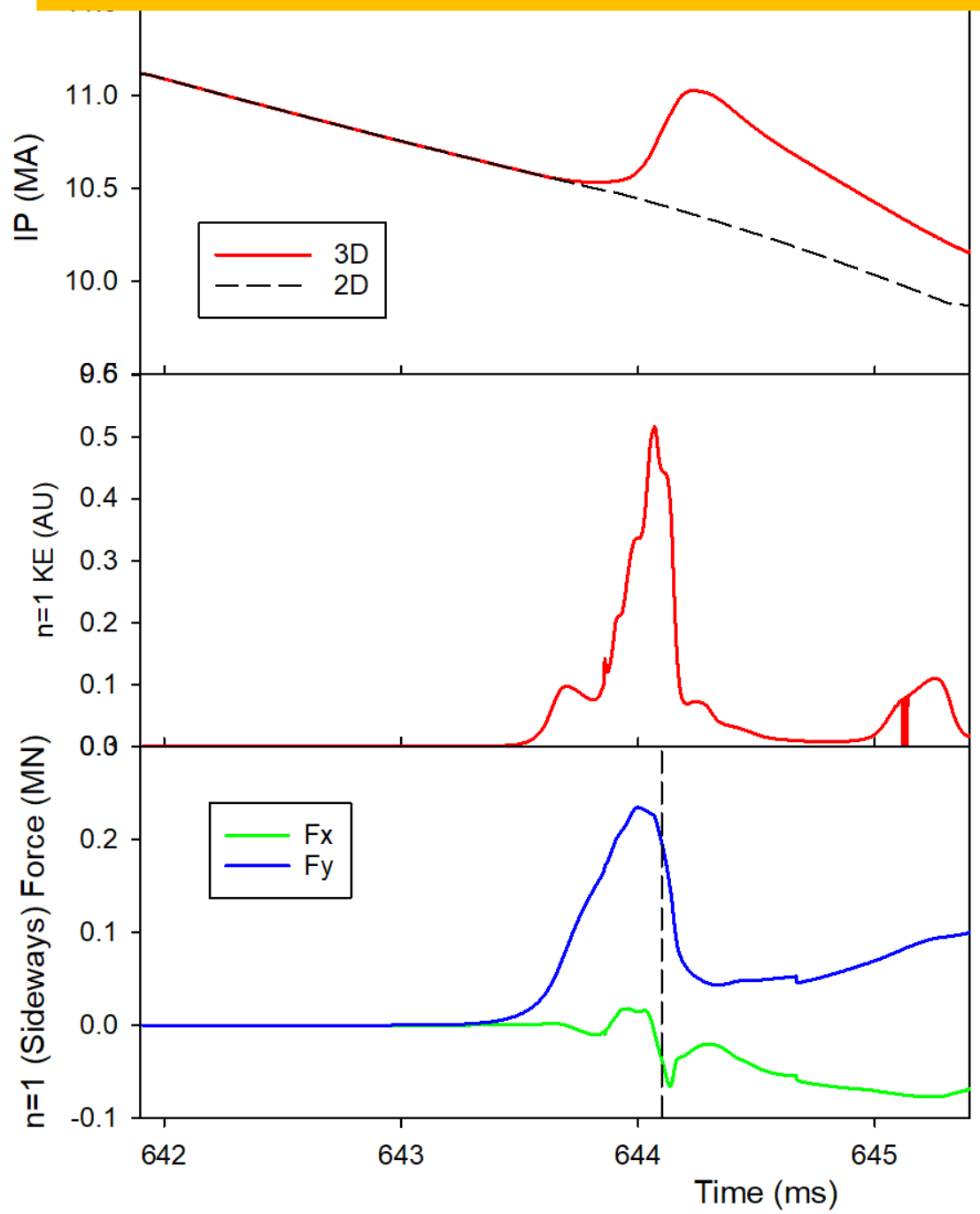
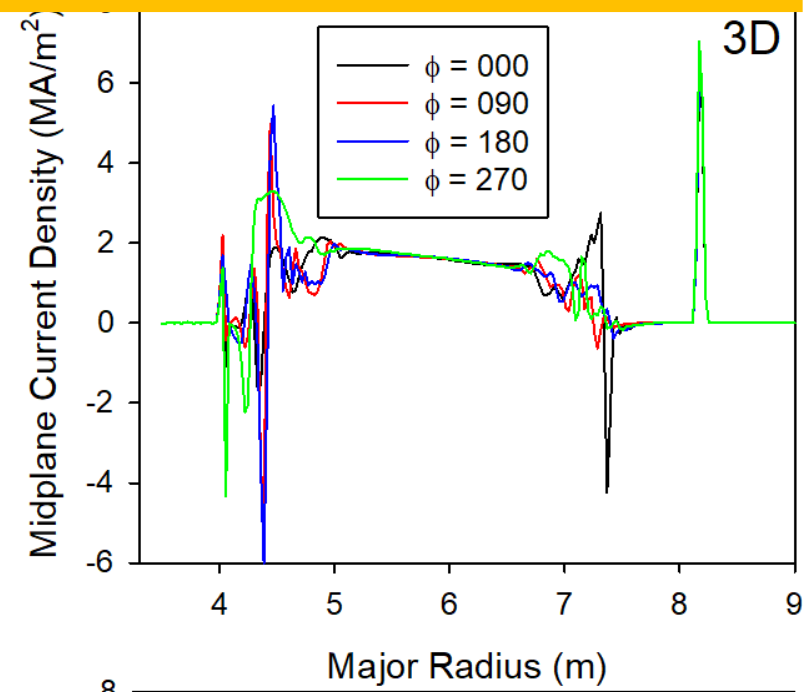
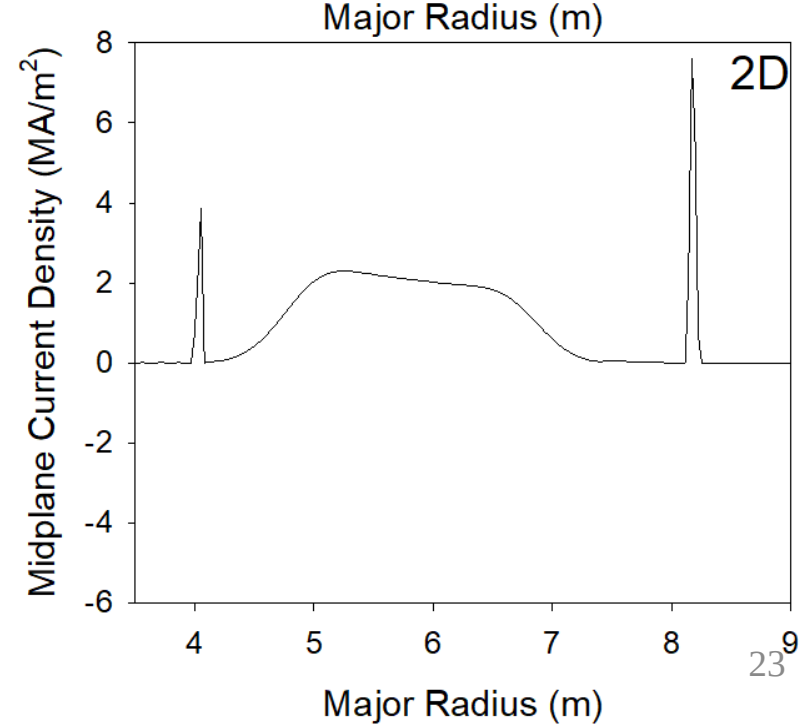
- **ITER 3D VDE Studies (preliminary)**

3D VDE…Preliminary results (TQ also initiated by $\kappa_{\perp}$)





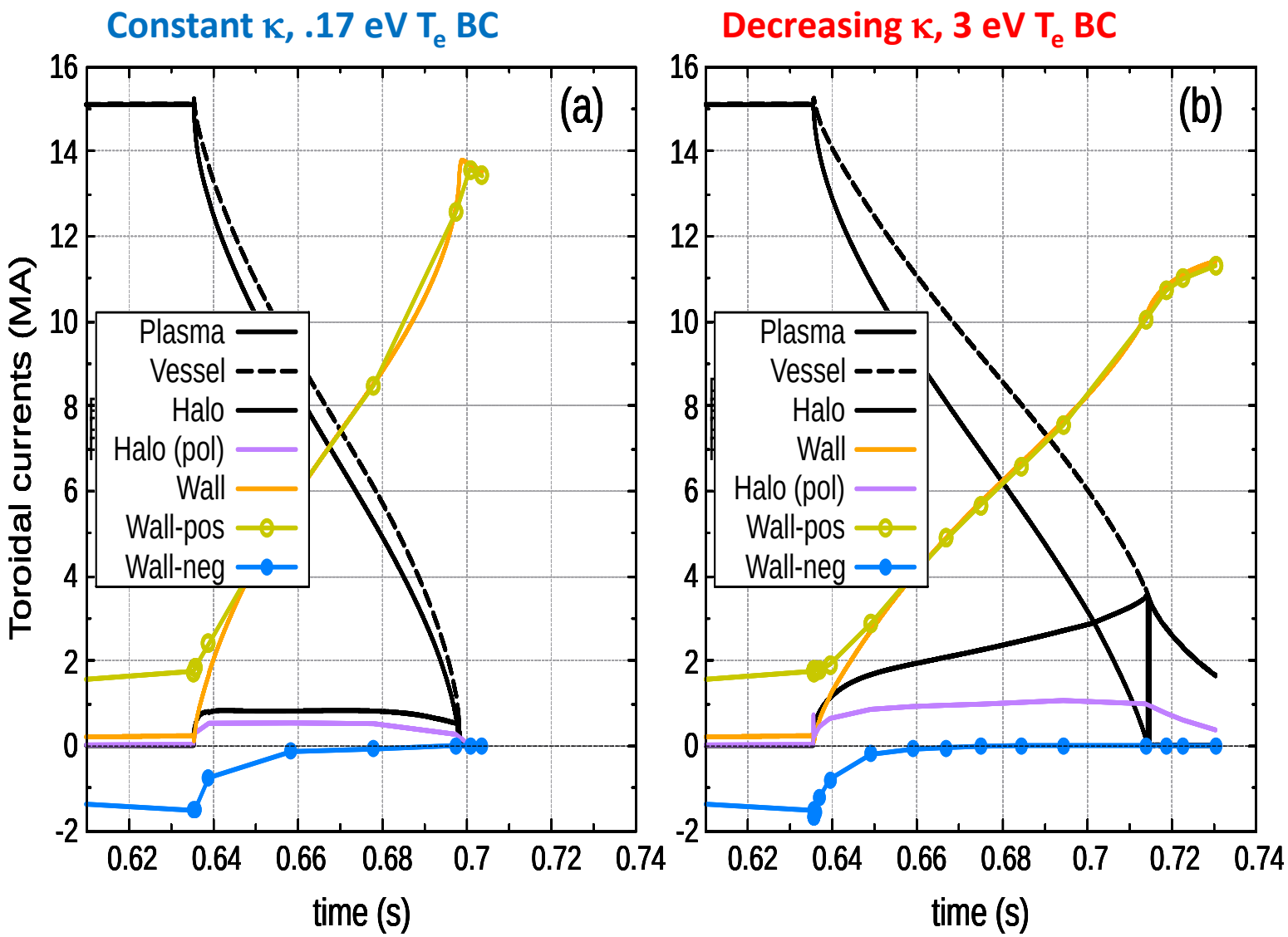


Summary

- **Benchmark Studies with NIMROD, JOREK**
  - M3D-C1, NIMROD, JOREK agree on 2D linear growth rates to about 10% over wide range
  - Good agreement between M3D-C1, JOREK on nonlinear induced currents and halo currents
  - Now being extended to include NIMROD (2D) and all codes 3D
- **ITER 2D VDE Studies with halo region**
  - Vertical wall force increases with larger post TQ plasma temperature (up to a point)
  - Vertical wall force has very weak dependence on halo current magnitude
- **ITER 3D VDE Studies (preliminary)**
  - Current spike appears in 3D but not in 2D
  - Sideways force much smaller than vertical force

Extra Slides

Comparison of induced currents



- Case (b) with large halo current has reduced wall current

$\mathbf{F}_{pc}$ is the force on the plasma due to the poloidal field coils

$\mathbf{G}_{pc}$ is the force on the plasma due to the toroidal field coils

$\mathbf{F}_{wc}$ is the force on the wall due to the poloidal field coils

$\mathbf{G}_{wc}$ is the force on the wall due to the toroidal field coils

$\mathbf{F}_{pw}$ is the force on the plasma due to the wall toroidal currents

$\mathbf{G}_{pw}$ is the force on the plasma due to the wall poloidal currents

$\mathbf{F}_{wp}$ is the force on the wall due to the plasma toroidal currents

$\mathbf{G}_{wp}$ is the force on the wall due to the plasma poloidal currents

The total force on the plasma due to the coil currents and wall currents must be zero:

$$\mathbf{F}_{pc} + \mathbf{F}_{pw} + \mathbf{G}_{pc} + \mathbf{G}_{pw} = 0 \tag{1}$$

The total force on the wall is due to poloidal and toroidal currents in coils and plasma:

$$\mathbf{F}_{W} = \mathbf{F}_{wc} + \mathbf{F}_{wp} + \mathbf{G}_{wc} + \mathbf{G}_{wp} \tag{2}$$

Because the poloidal currents in the plasma and the wall do not contribute to the toroidal field outside the vessel, their net force on the toroidal field coils must be zero:

$$\mathbf{G}_{wc} + \mathbf{G}_{pc} = 0 \tag{3}$$

Since $\mathbf{F}_{pw} = -\mathbf{F}_{wp}$ and $\mathbf{G}_{pw} = -\mathbf{G}_{wp}$ we can use (1) to rewrite (2) as:

$$\mathbf{F}_{W} = \mathbf{F}_{wc} + \mathbf{F}_{pc} + \mathbf{G}_{wc} + \mathbf{G}_{pc} \tag{4}$$

Now, use (3) to write (4) simply as:

$$\mathbf{F}_{W} = \mathbf{F}_{wc} + \mathbf{F}_{pc}$$

Therefore, the total force on the wall can be expressed as that due to the interaction of the toroidal currents in the plasma and the wall with the fields from the poloidal field coils.