Vertical Forces during VDEs in an ITER plasma and the Role of Halo Currents

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Motivation

- Vertical Displacement Events (VDEs) are major disruption events, produced when the vertical stability control is lost.
- These events cause large currents to flow in the vessel and other adjacent metallic structures.
- These currents are due to both magnetic induction and poloidal halo current flow between the plasma and the vessel.
- The forces produced by these currents can potentially damage vessel structures and other adjacent metallic structures.

- **Halo currents and their associated forces are expected to play an important role in ITER.**

- **Therefore, a better understanding of these halo currents and their associated forces is needed.**

In this work…

- We used the M3D-C^1 code to simulate VDEs in an ITER plasma with special attention to the role of halo currents and the forces produced by them.

- We covered a wide range of cases, from small to large halo currents to look for the worst case scenario that could plausibly occur.

- We will show that both inductive and halo forces are related and, for similar conditions, **changing the halo currents does not change the total vertical force** since it is offset by the toroidal contribution.

- We have used the 2D version of the code (axisymmetric). A 2D benchmark was recently done. 3D simulations are underway.

* Carl Sovinec's talk. I. Krebs et al, submitted to Nuclear Fusion (2019).

2D non-linear VDEs in an ITER plasma

- Based on standard 5.3 T – 15 MA ITER scenario.
- **Used realistic parameters for wall resistivity**. It was adjusted to give the correct $\tau = L/R$ time (235 ms).
- **Started from equilibrium** and perturbated it to produce the VDE instability.
- When $q_{\mathrm{sep}} \approx 2$ the thermal quench is initiated by increasing the plasma thermal conductivity $\kappa_{\perp}$:

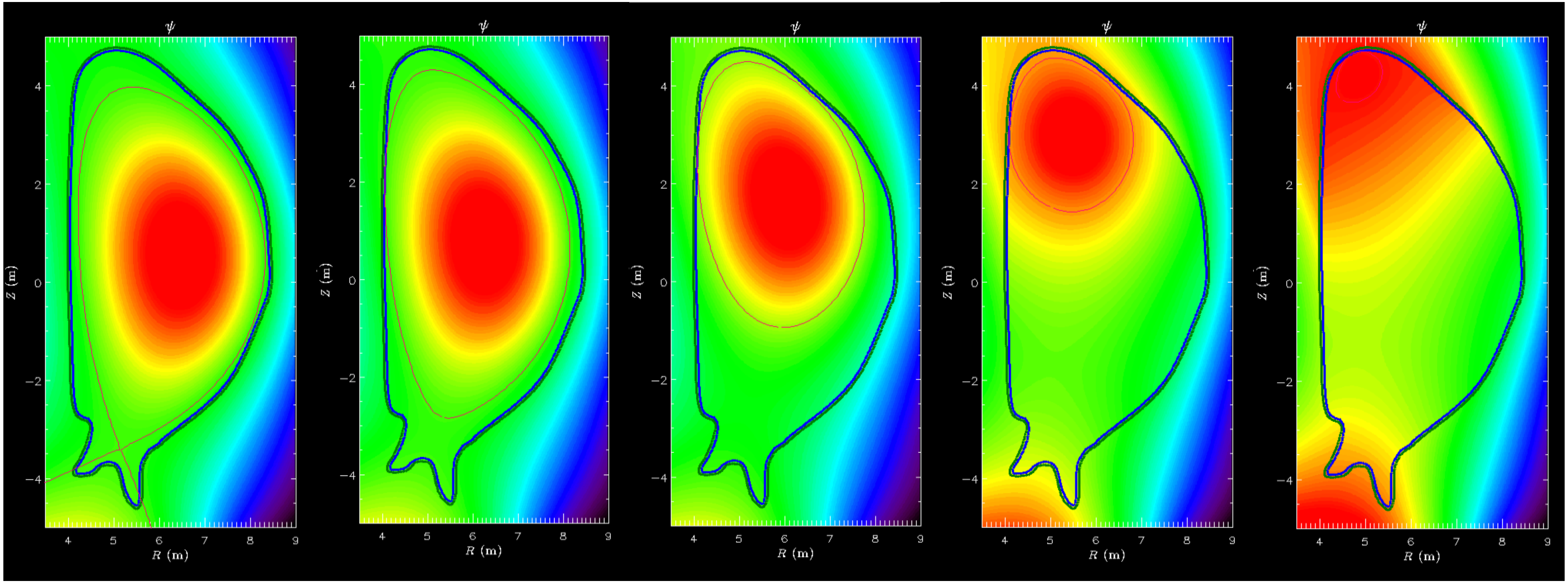
$$\frac{3}{2} n \frac{\partial T}{\partial t} = -\nabla \cdot \boldsymbol{q} + \eta \mathbf{J}^2 + (\ldots)$$

$$\boldsymbol{q} = \kappa_{\perp} \nabla_{\perp} T + \kappa_{\parallel} \nabla_{\parallel} T$$

A general picture…

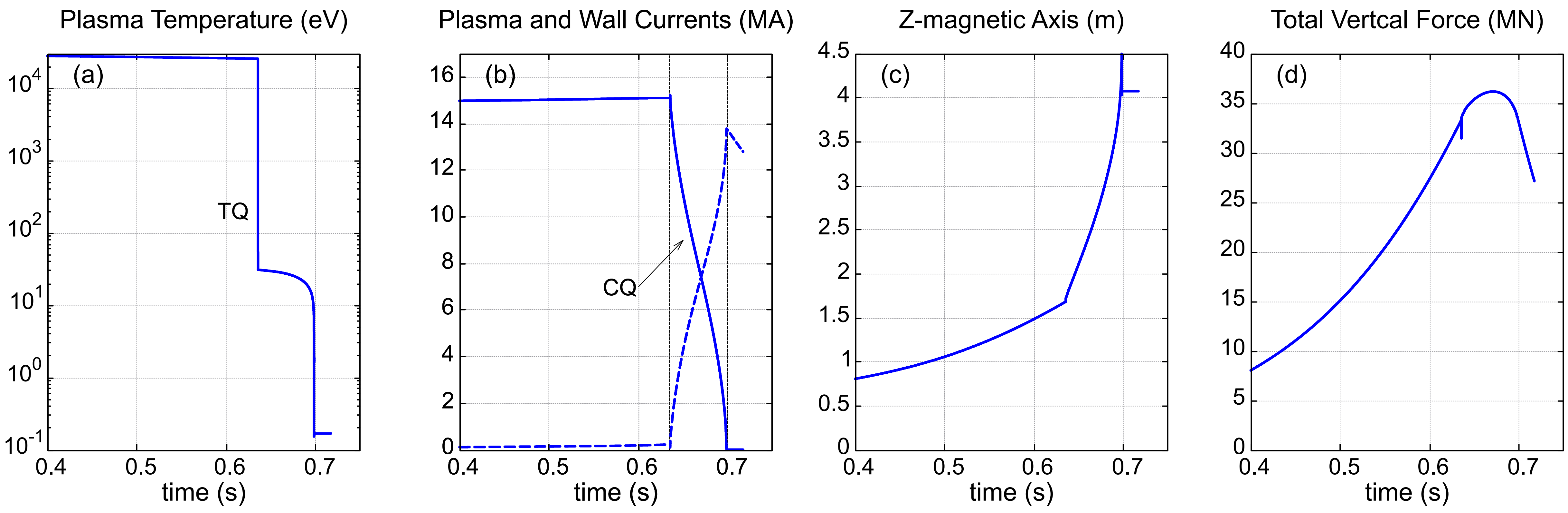
Screenshots of a VDE

Initial equilibrium	375 ms Wall Contact	635 ms Thermal Quench	678 ms Max Vertical Force	700 ms LCFS disappears



A general picture…

Some global quantities vs. time



Vertical force and halo currents

$$\hat{z} \cdot \mathbf{F}_V = \hat{z} \cdot \int_{vessel} \mathbf{J} \times \mathbf{B} \, \mathrm{d}V \quad = \int_{vessel} \left(-J_\varphi B_R + J_R B_\varphi \right) \mathrm{d}V$$

The $J_\varphi B_R$ → due to toroidal induction.
The $J_R B_\varphi$ → due to halo currents.

Can we increase the halo current in order to increase the total vertical force?

In 2D simulation we initiate the TQ by increasing the thermal conductivity $\kappa_\perp$. We can do it in different ways:

- Varying the thermal conductivity magnitude and profile.
- Varying the temperature at the boundary.

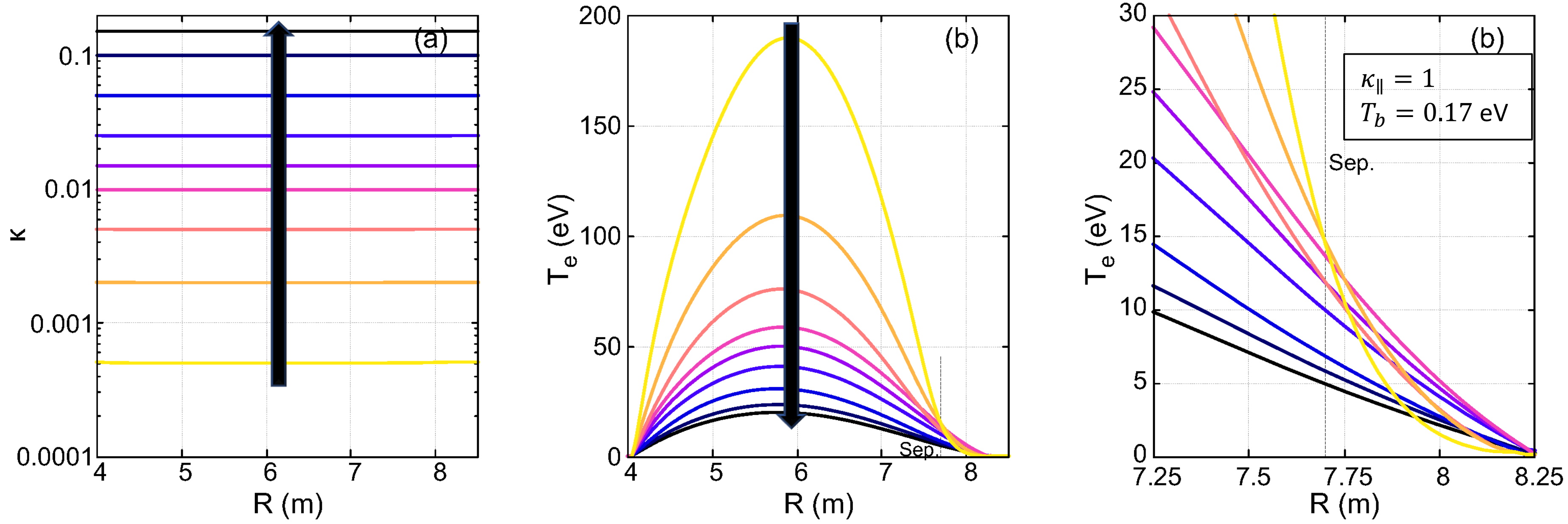
We generated a series of cases with different halo currents to analyze their effects.

Basically, in the open field line (halo) region:

higher temperature → lower plasma resistivity → higher currents.

I. Uniform post-TQ $\kappa_\perp$

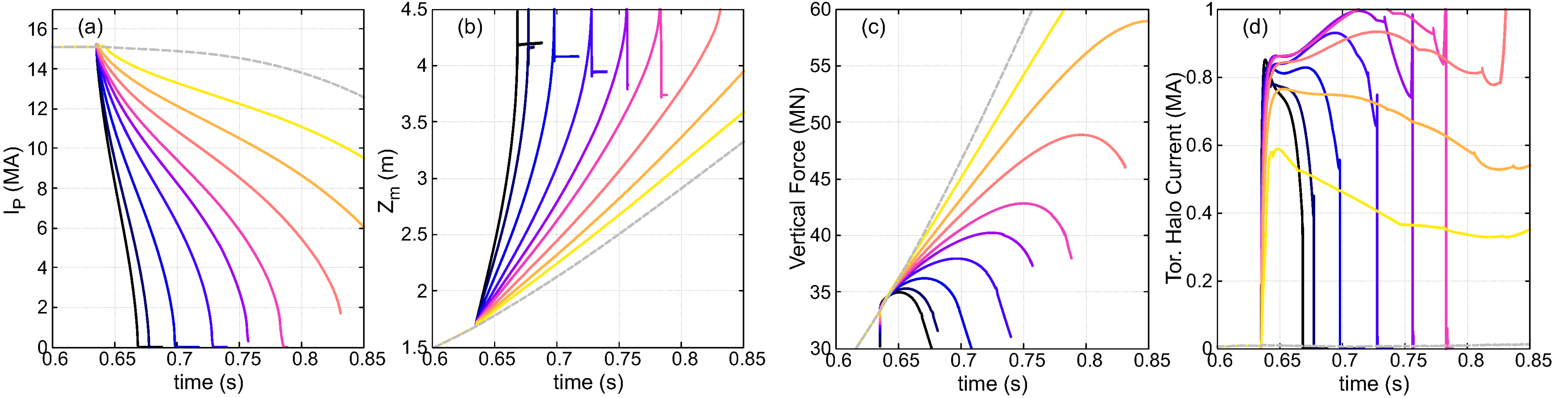
Dependance of post-TQ temperature on $\kappa_\perp$ values



- Smaller $\kappa_\perp$ values → higher post-TQ T_e.
- Halo region is naturally formed after the TQ.
- Changing κ in this way has only small effect on open-field-line temperature.

I. Uniform post-TQ $\kappa_\perp$

Effect of varying κ on global plasma parameters



- Smaller $\kappa_\perp$ values → higher post-TQ T_e → slower CQ.
- Slower CQ → slower upward motion.
- Larger vertical forces for high T_e.
- **Only small dependence of maximum halo current magnitude on κ (< 1 MA)**

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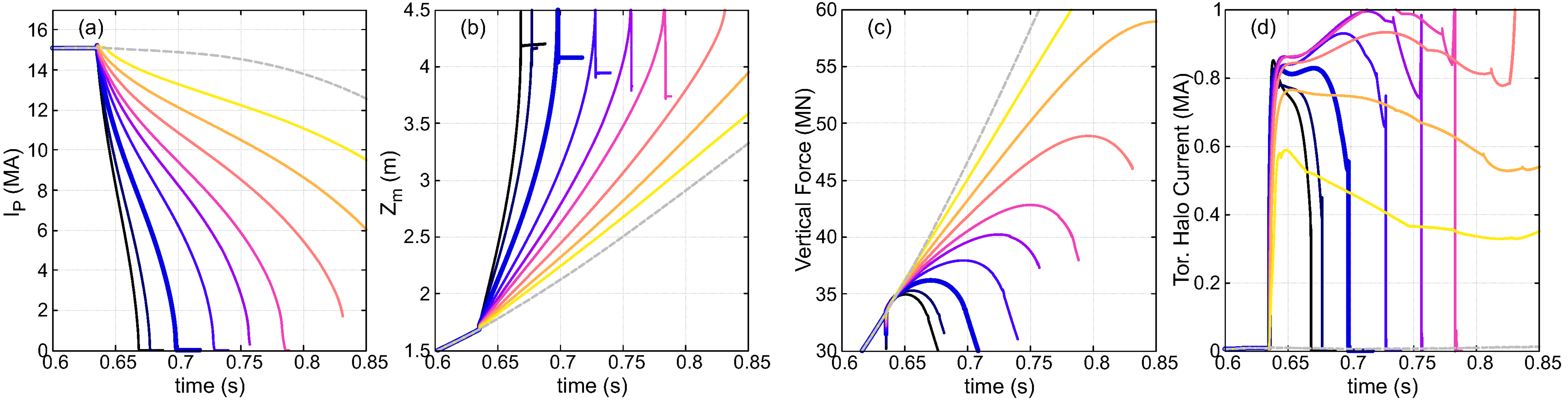
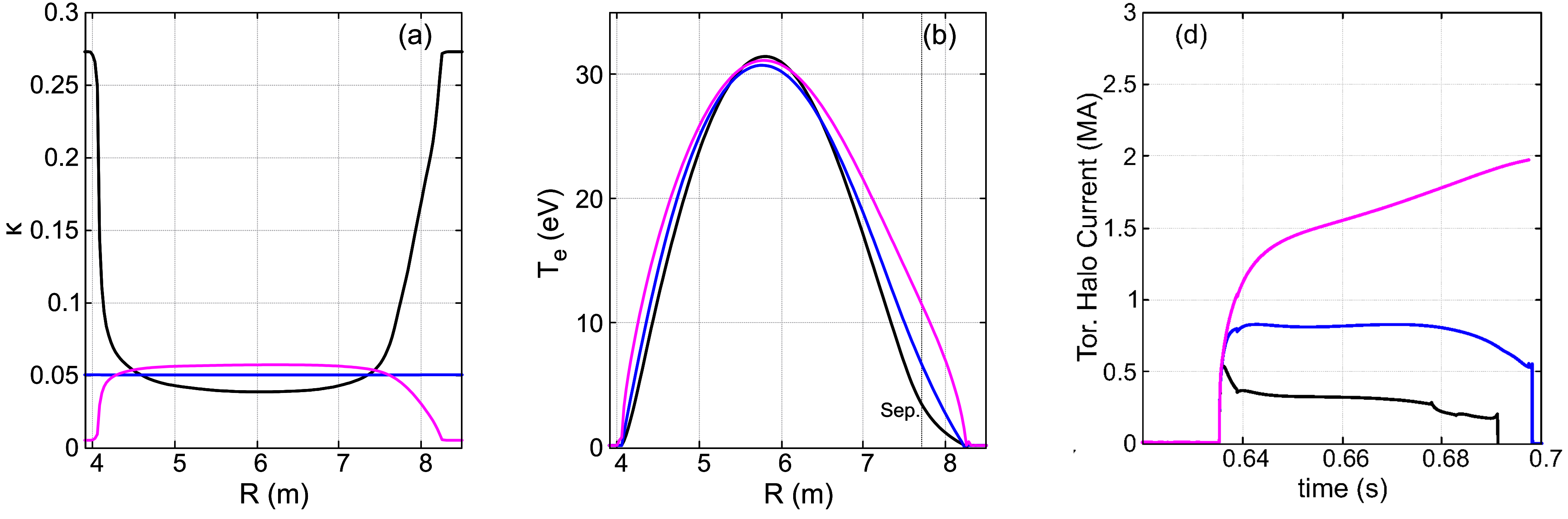


- Smaller $\kappa_\perp$ values → higher post-TQ T_e → slower CQ.
- Slower CQ → slower upward motion.
- Larger vertical forces for high T_e.
- **Only small dependence of maximum halo current magnitude on κ (< 1 MA)**
- **We select the case $T_e \sim 30$ eV as a reference**

II. Different post-TQ $\kappa_{\perp}$ profiles

Effect of varying κ profiles on post-TQ T_e and halo current.



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

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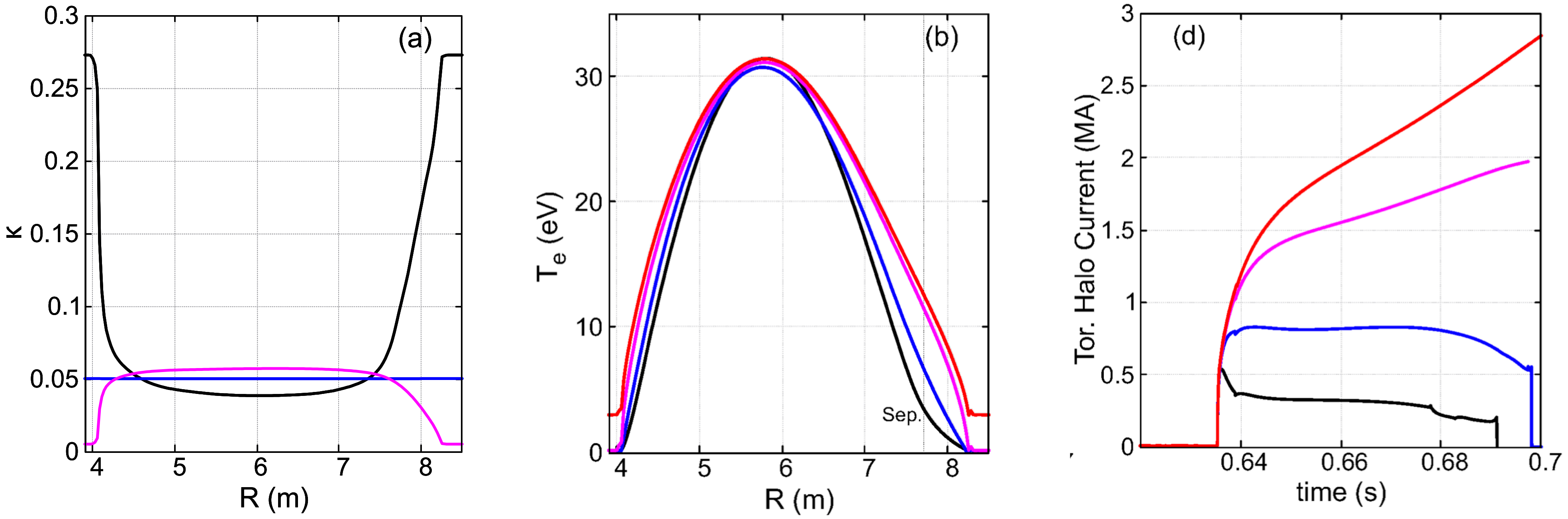
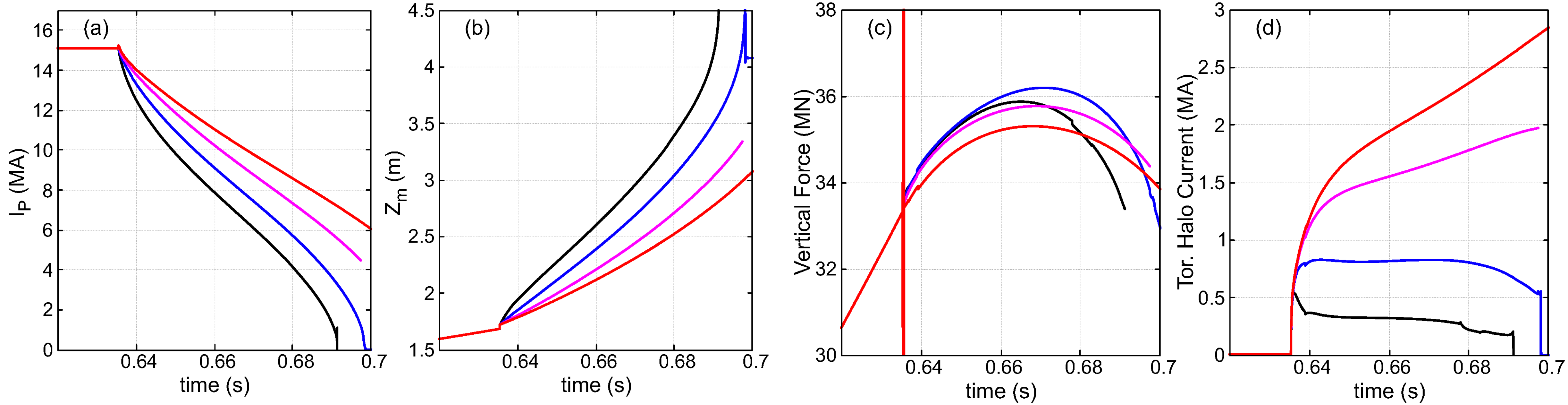


- Compare κ **constant**, **increasing**, or **decreasing** in radius
- κ **decreasing** in radius leads to largest T_e on open field lines ➔ halo current
- To increase even more the halo current, we increased the boundary temperature from **0.17 eV** to **3 eV**.

II. Different post-TQ $\kappa_\perp$ profiles

Effect of varying κ profiles on global plasma parameters



- κ **decreasing** with radius leads to slower CQ and larger halo current.
- **Increasing** boundary T_e strength these effects.
- **Total vertical force largely unaffected.**

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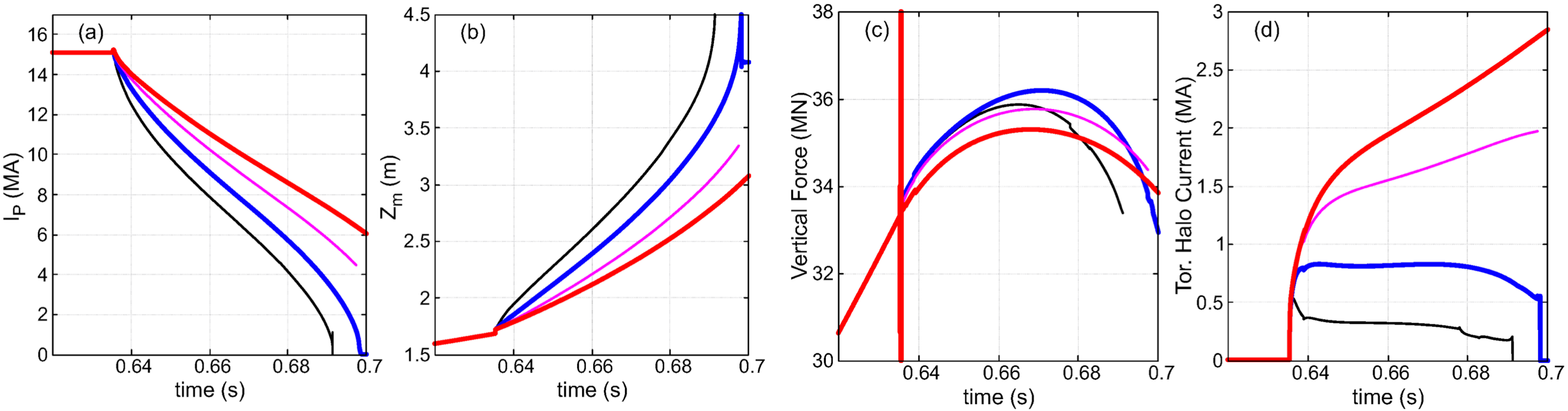

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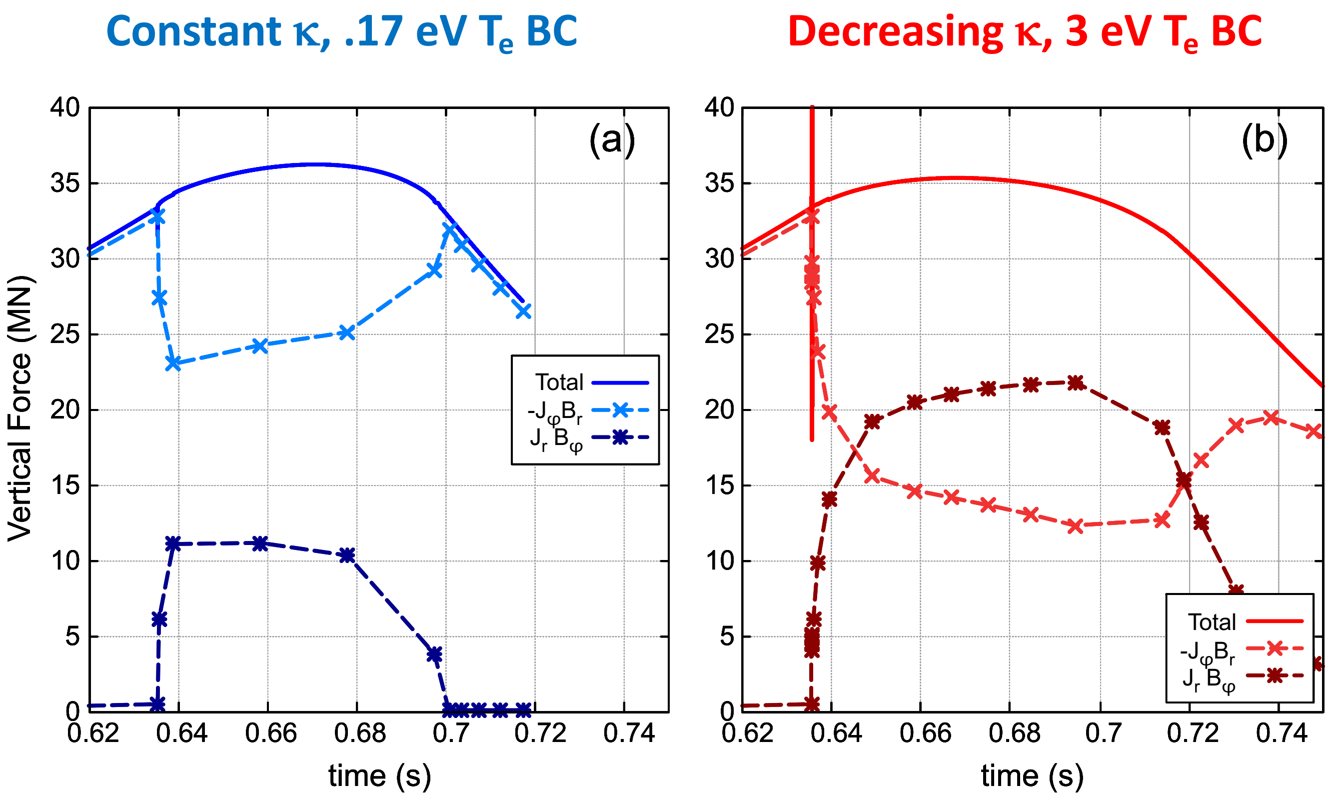
Comparison and breakdown of forces



- Larger halo current had larger $J_r B_\varphi$ term, as expected,
- but, it is offset by a stronger reduction in the $J_\varphi B_r$ contribution.
- **Total vertical force is almost unaffected by magnitude of halo current.**

Comparison and breakdown of forces

Relationship between inductive toroidal and poloidal halo wall forces

It is possible to write the total force on the vessel as (*)

$$F_v = F_v^{tor} + F_v^{pol} = -F_c$$

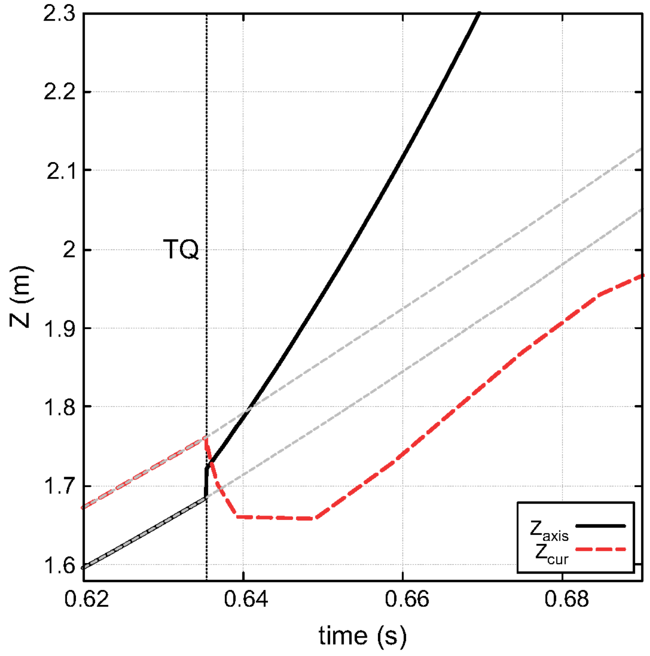
The halo formation after the TQ occurs in a timescale ($\tau \lesssim 10$ ms) much shorter than the dissipation time of wall currents ($L/R = 235$ ms). Thus, the vessel "acts" as an almost perfect conductor during this process.

Therefore, the poloidal flux outside the vessel does not change implying that F_c and, as a consequence F_v, remains constant.

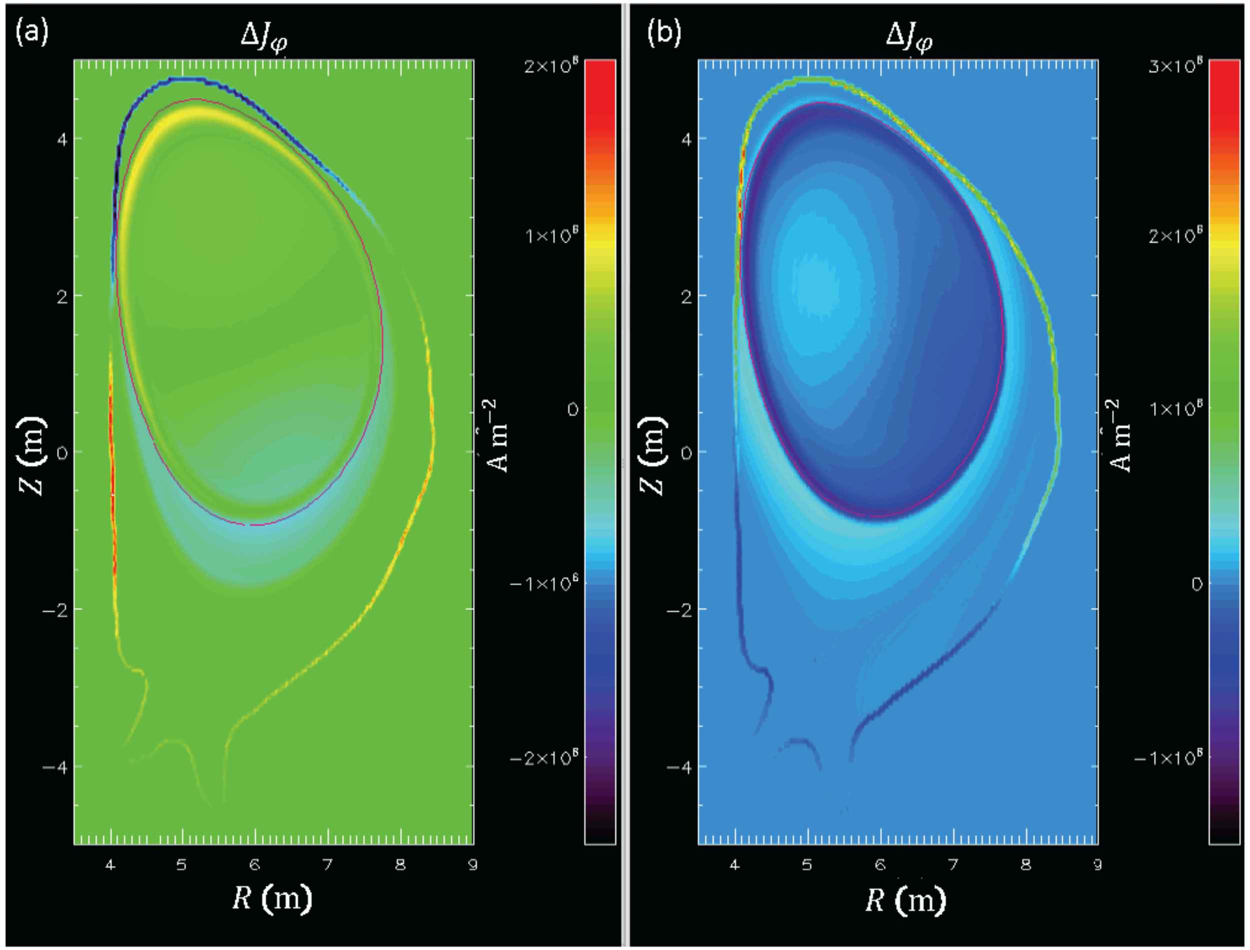
(*) Wesson, Tokamaks (Oxford Press, 2011).

Comparison and breakdown of forces

How toroidal contribution offsets the poloidal halo force?



The halo region formation produces a current density centroid displacement



Summary

We performed a series of 2D-VDE simulations varying

- the post-TQ thermal conductivity and
- the post-TQ temperature boundary condition

in order to cover a wide range of cases.

- We found that vertical wall force shows a dependence on post-TQ temperature.
- Slower CQ generally lead to larger vertical forces:
    - for CQ times short compared to vessel L/R time.
    - However, the presence of halo currents can modify this scaling.

- We showed that vertical wall force shows a very weak dependence on halo current magnitude.
    - Toroidal contribution to the total force compensates the halo contribution.

Moving forward…

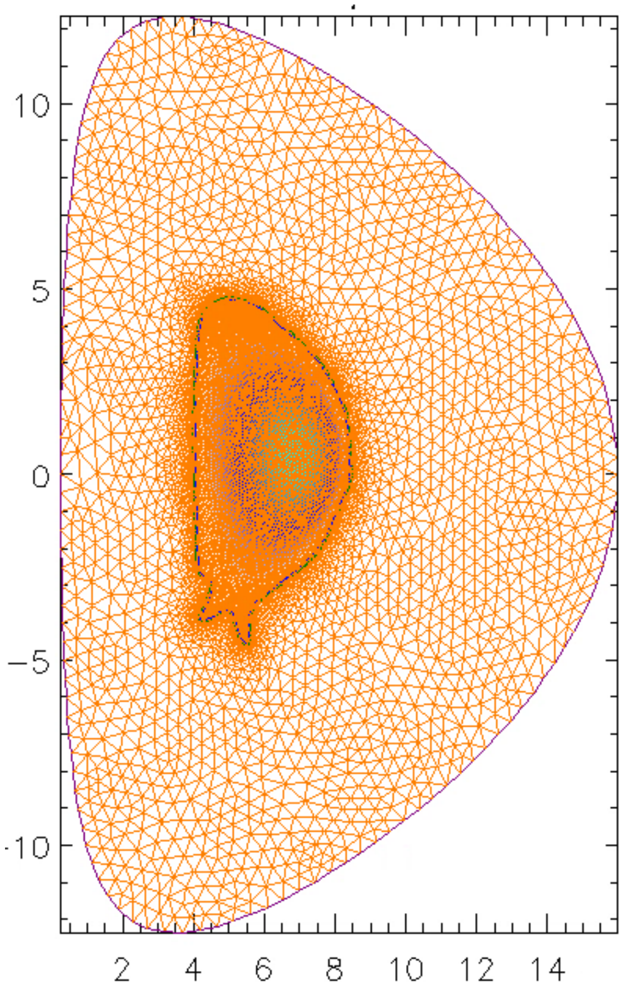
- We have already started 3D non-linear simulations.
  - kink instabilities and sideways force.

- Implementing a more realistic wall with anisotropic wall resistivity.

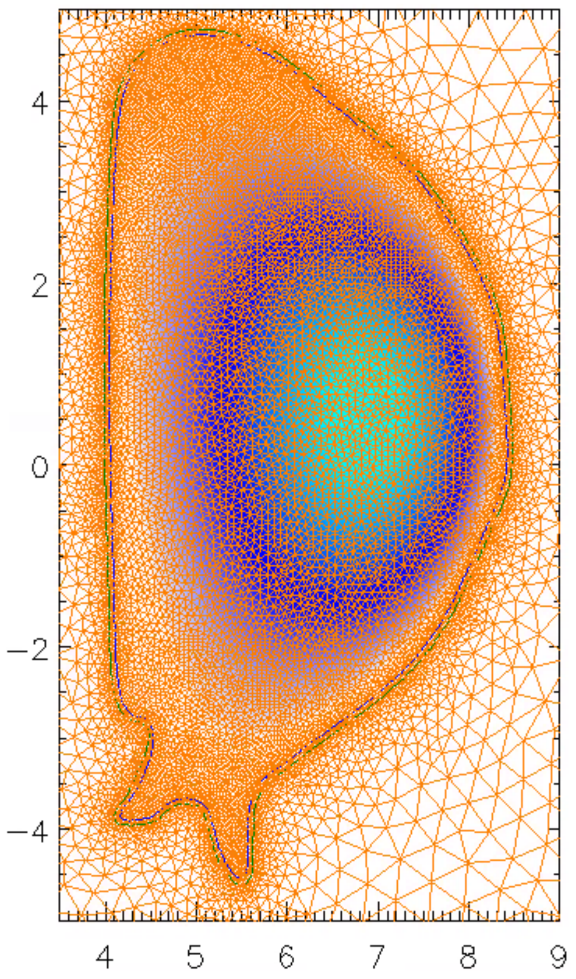
- Working in coupling M3D-C^1 results with the CARRIDI engineering code (actual vessel).

Extra slides…

Poloidal unstructured mesh



Full Mesh

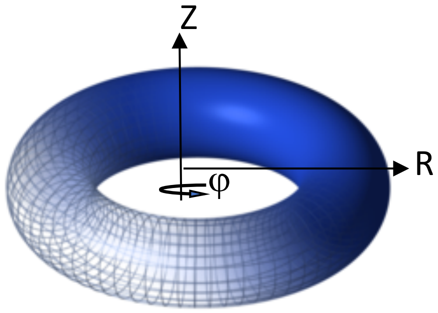


Close-up of Plasma Region

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

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

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



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

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

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

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

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

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

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

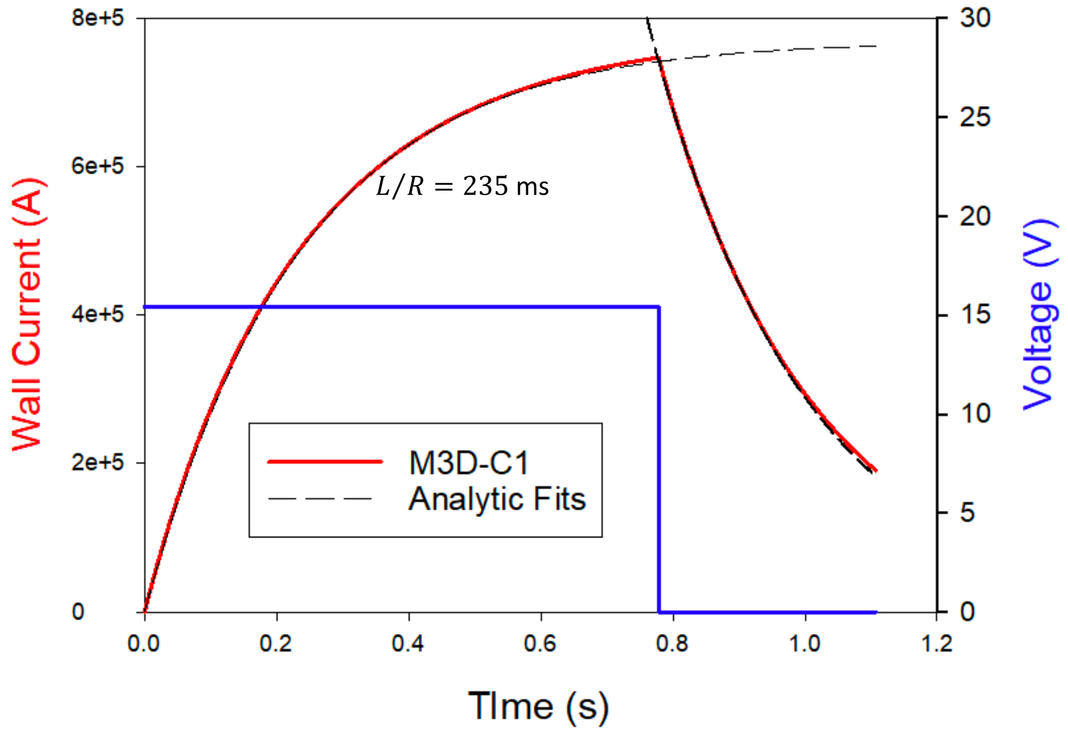
$$\mathbf{\Pi}_e = (\mathbf{B}/B^2)\nabla \bullet \left[\lambda_h \nabla\left(\mathbf{J} \bullet \mathbf{B}/B^2\right)\right], \qquad Q_\Delta = 3m_e(p_i - p_e)/(M_i \tau_e)$$

Blue terms are 2-fluid terms. **NOT reduced MHD.**

Using the appropriate L/R time

- Applied a constant loop voltage at the domain boundary.
- Without any plasma, the system behaves as a basic LR-circuit.

$$I(t) = \begin{cases} I_0\left(1 - e^{-t/\tau}\right) \\ I_c e^{-(t-t_c)/\tau} \end{cases}$$

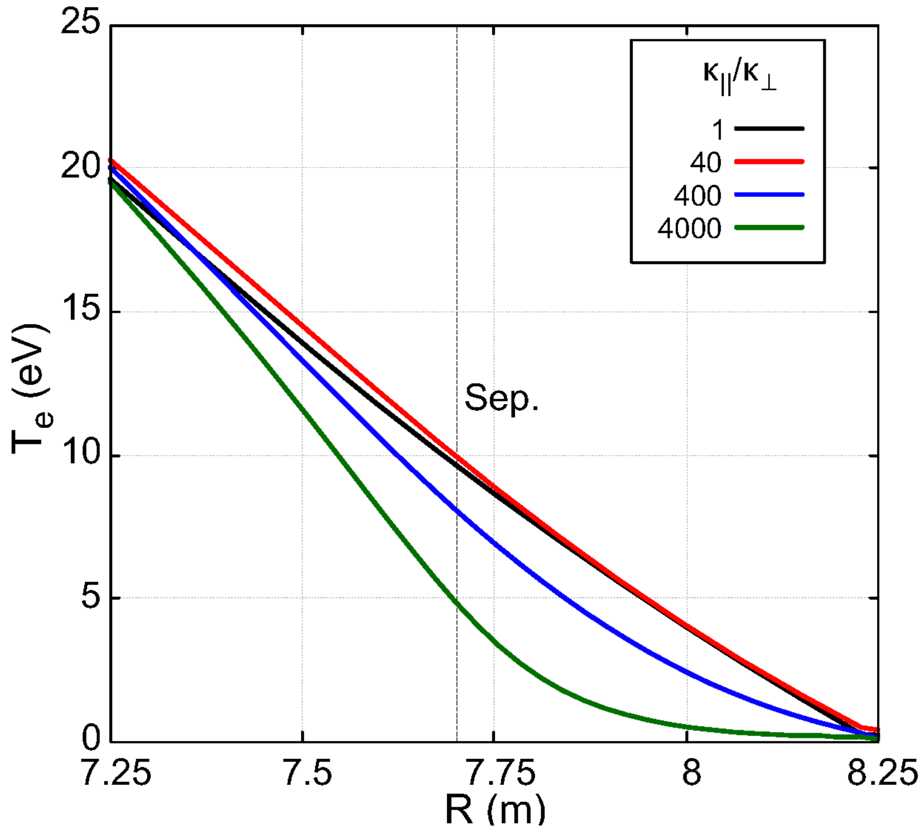


$\kappa_{\parallel}/\kappa_{\perp}$ effect on the open field line T_e

- **Inside the plasma:** the post-TQ temperature profile is mostly determined by $\kappa_{\perp}$

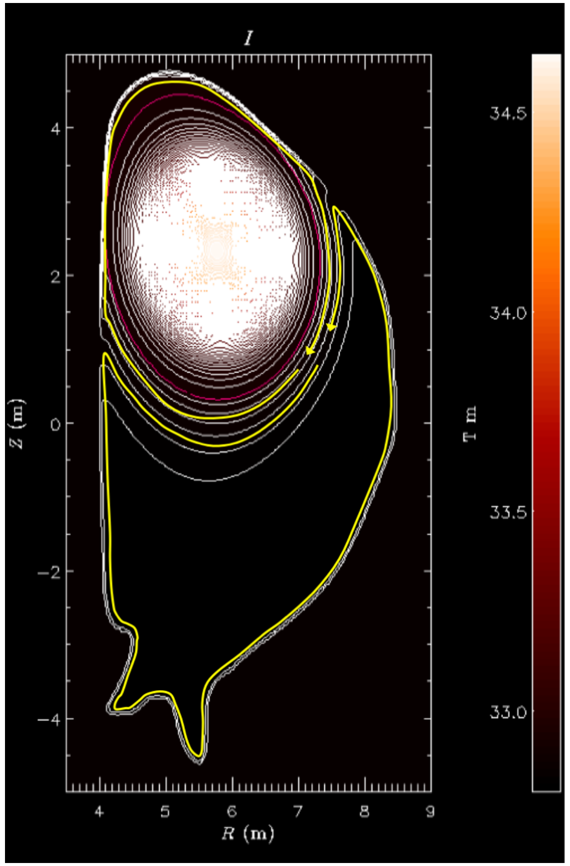
$$T_{TQ} \approx \kappa_{\perp TQ}^{-2/5}$$

- **Outside the plasma:** $\kappa_{\parallel}$ links the plasma temperature with the boundary condition. Assuming $T_{SOL} \sim e^{-\alpha x}$, very simplified $\alpha \sim \alpha\left(\sqrt{\kappa_{\parallel}/\kappa_{\perp}}\right)$ dependence can be derived.

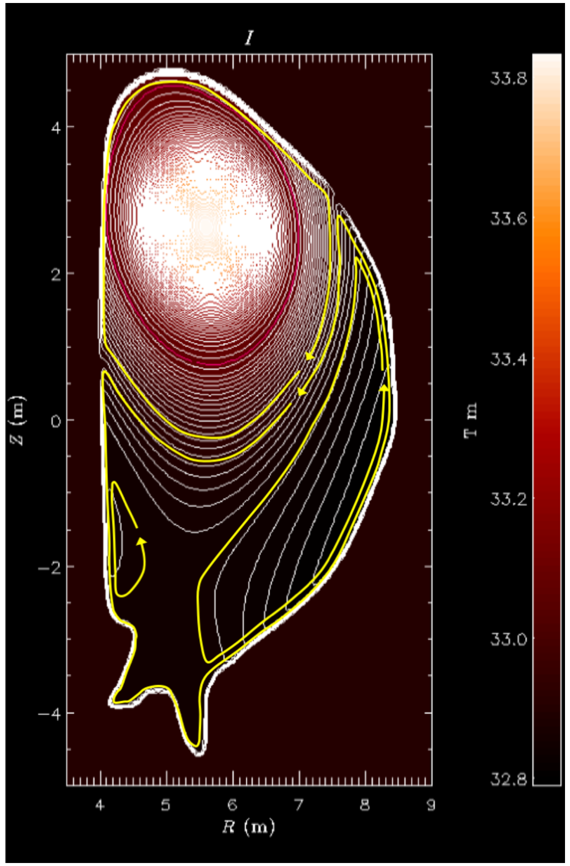


Poloidal halo currents patterns for both cases

Constant κ, .17 eV T_e BC



Decreasing κ, 3 eV T_e BC



Poloidal halo currents can follow different paths and generate a complex pattern.

Current breakdown

Constant κ, .17 eV T_e BC | **Decreasing κ, 3 eV T_e BC**