Halo current studies with self-consistent MHD simulations for ITER 15 MA plasmas

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Outline

- The JOREK-STARWALL code for halo current modelling
- 2D VDE benchmark with M3D-C1 and NIMROD
- Understanding the 2D halo currents at ITER (15 MA/5.3T)
- Prediction of the halo properties and B.C.s
- Conclusions and future work

The JOREK-STARWALL code for halo current modelling

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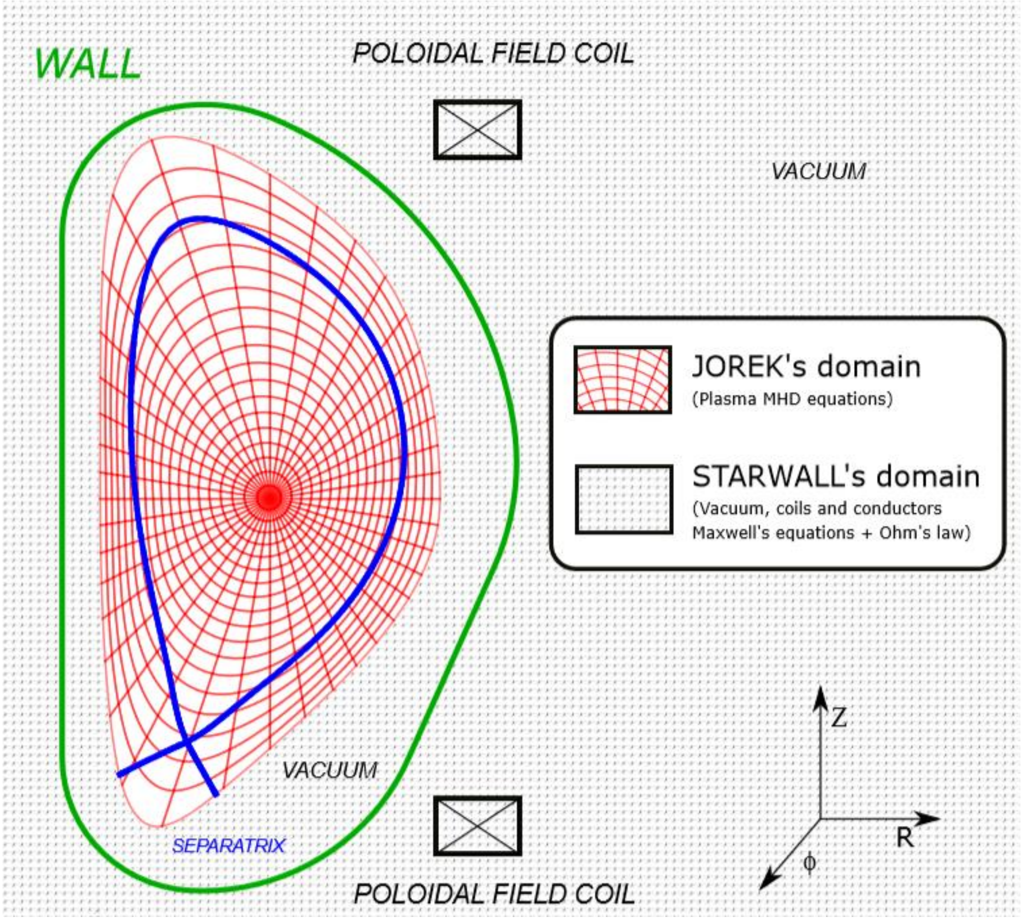

JOREK *[Huysmans, NF2007]*

- 3D non-linear MHD equations
- Toroidal geometry
- C1 Finite elements in poloidal plane
- Fourier harmonics for ϕ direction
- Fully implicit time evolution

STARWALL *[P. Merkel, 2015]*

- Solves Maxwell's equations and Ohm's law
- Green's function method
- Thin wall approximation

Implicit coupling through B.C.s for $\vec{B}$

[Hoelzl, 2012]

$$\vec{B}_{\tan} = \vec{f}(B_n, \boldsymbol{Y})$$

Tangential field — Normal field — Wall currents

The JOREK-STARWALL code for halo current modelling

EM boundary conditions

Reduced MHD, the E-field is

$$\mathrm{E} = -\partial_t \psi \nabla \phi - F_0 \nabla_{\mathrm{pol}} u$$

- $\partial_t \psi$ has resistive wall free-boundary conditions
- Ideal wall BCs for poloidal E-field $(u = 0)$
- Poloidal currents calculated from

force balance $\mathbf{J} \times \mathbf{B} = \nabla p$

Strong assumption. Poloidal currents do not decay in the wall (**infinite conductivity in the poloidal direction**)

2D VDE benchmark with M3D-C1 and NIMROD

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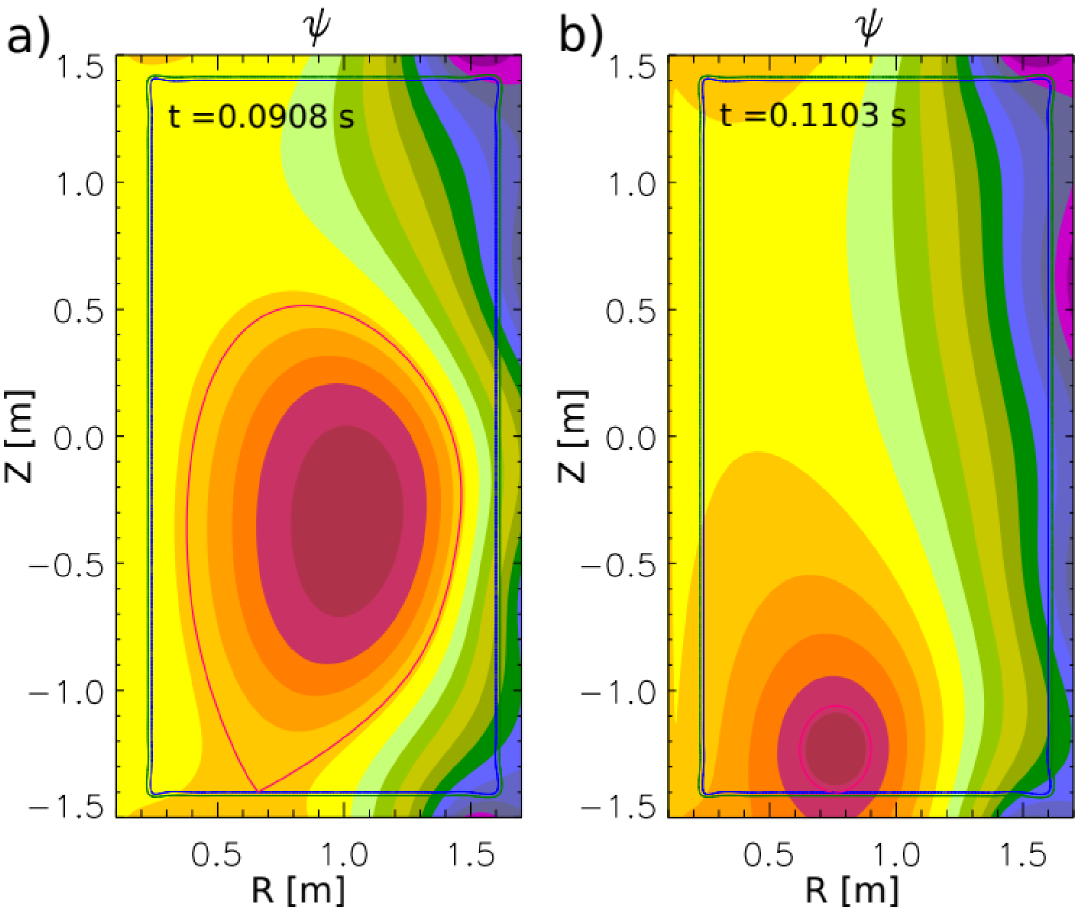
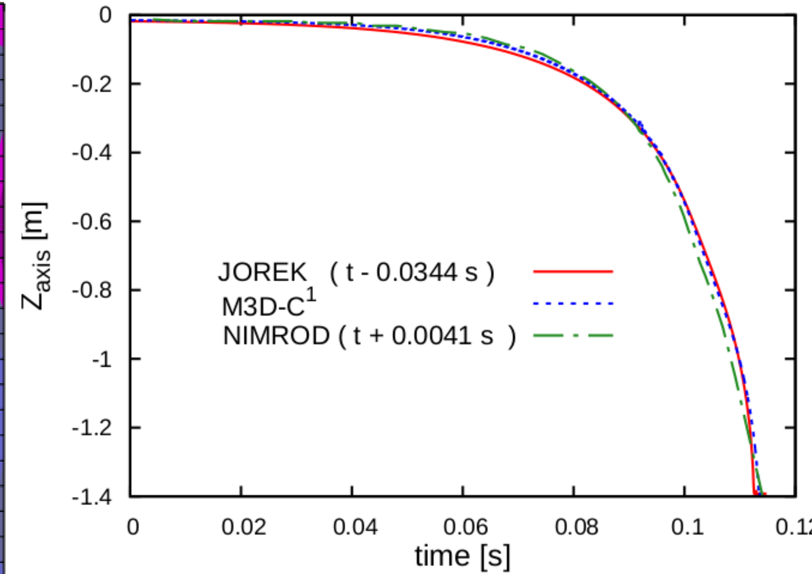
VDE based on the NSTX #139536 discharge





Phase 1: Hot VDE until wall contact
Phase 2: Artificially triggered TQ when the plasma becomes limited (increasing $\kappa_\perp$)

*[**I. Krebs**, F.J. Artola, C. Sovinec 2019]*

2D VDE benchmark with M3D-C1 and NIMROD

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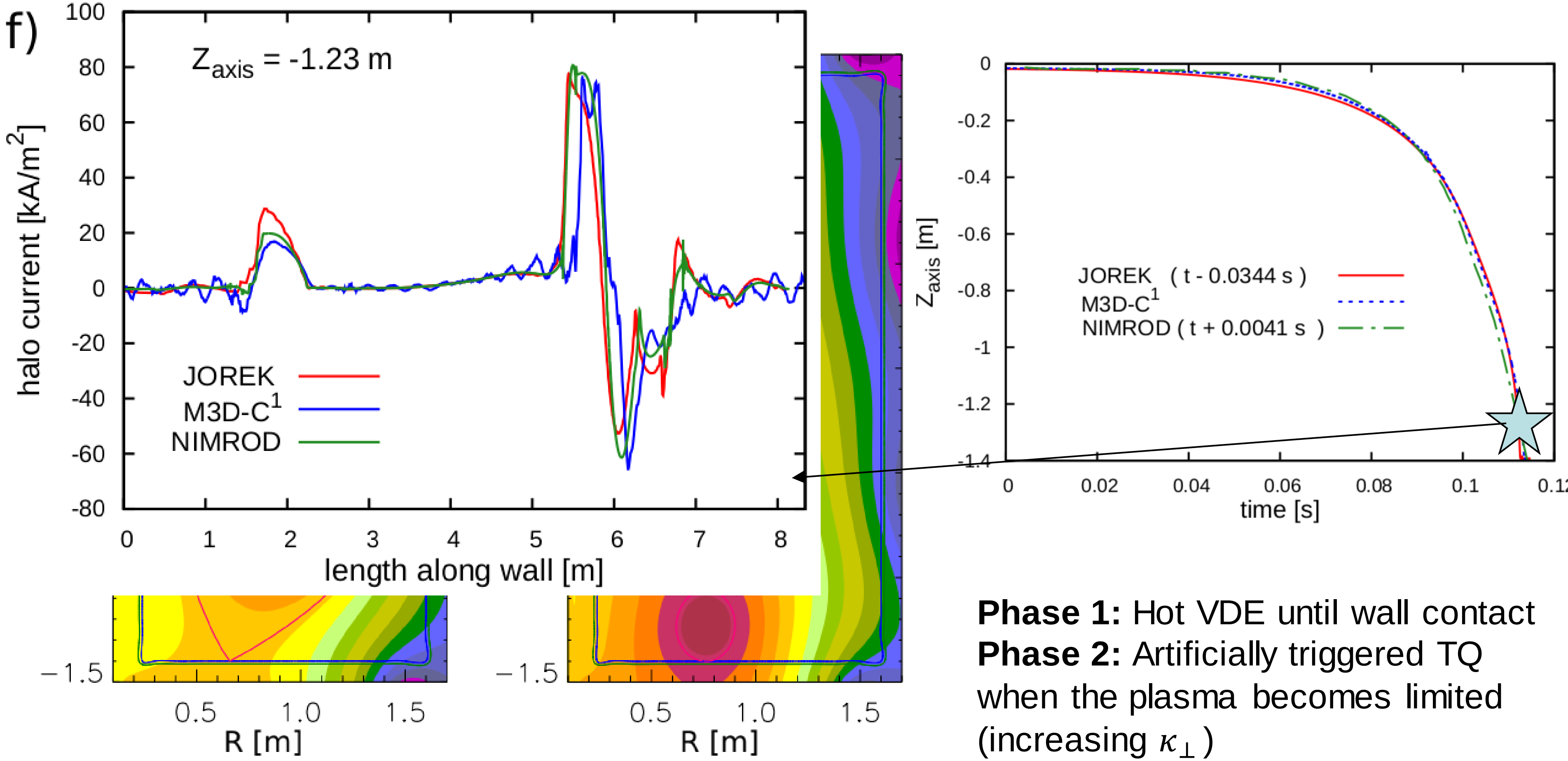

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Understanding 2D halo currents at ITER (15 MA / 5.3T)

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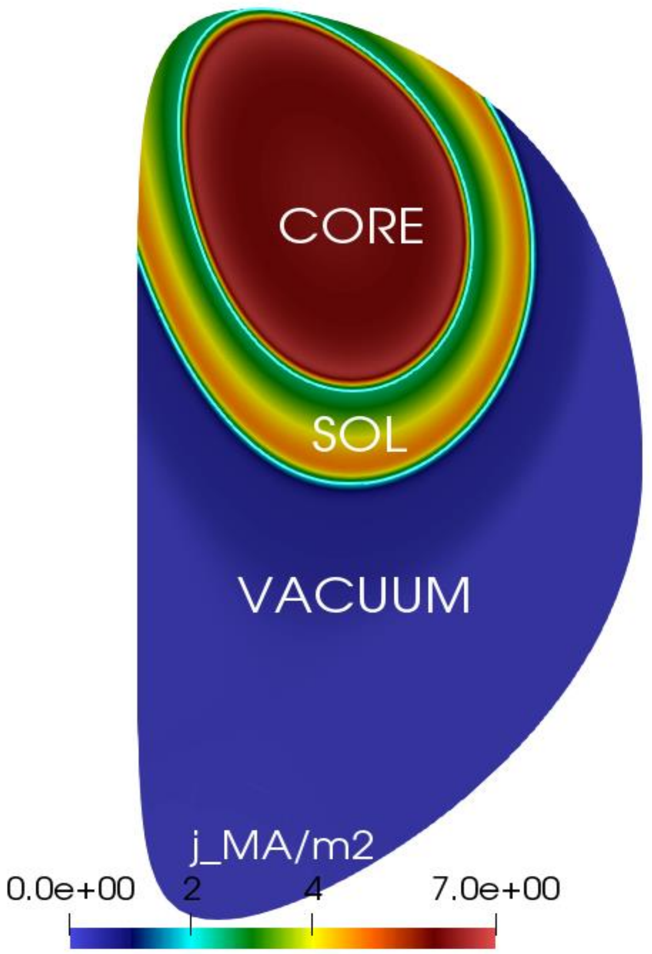
Halo current different regimes

- Hot VDE regime $(\tau_w \ll \tau_p)$

  I_p ~ cte during VDE

- Ideal wall regime $(\tau_p \ll \tau_w)$

  $Z_{axis} = f(I_p)$ *[D. Kiramov 2017 PoP]*

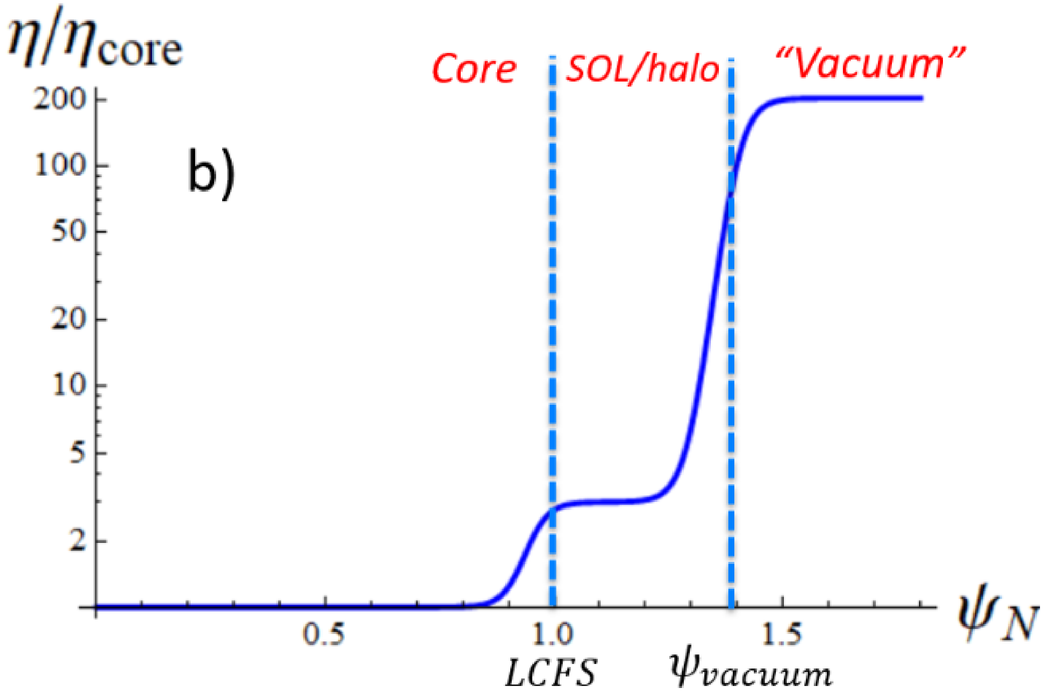


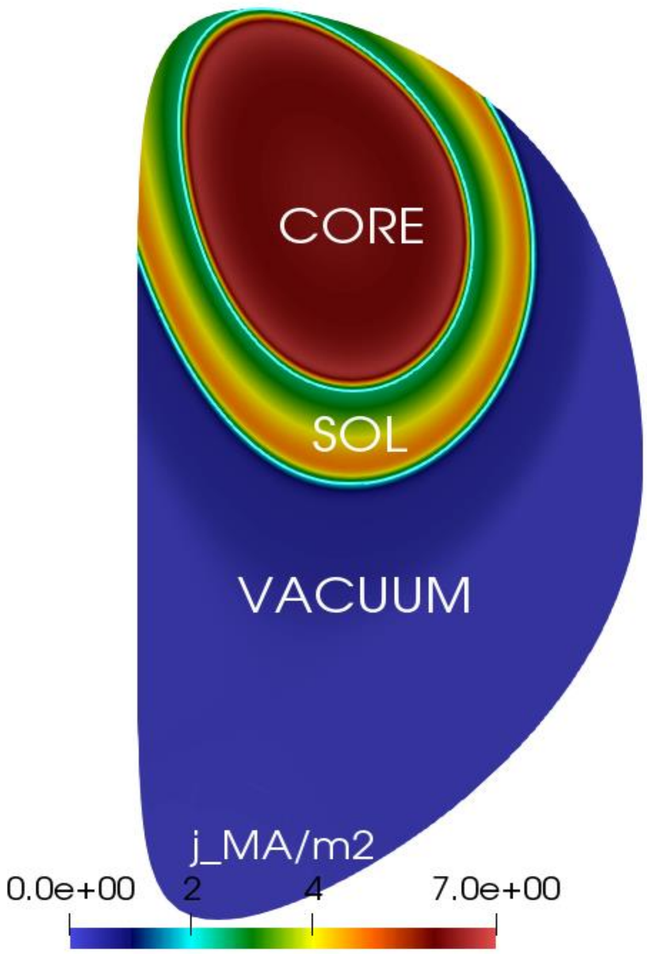
$\tau \equiv \text{Current resistive decay time}$

Understanding 2D halo currents at ITER (15 MA / 5.3T)

Parametric scan in CQ time

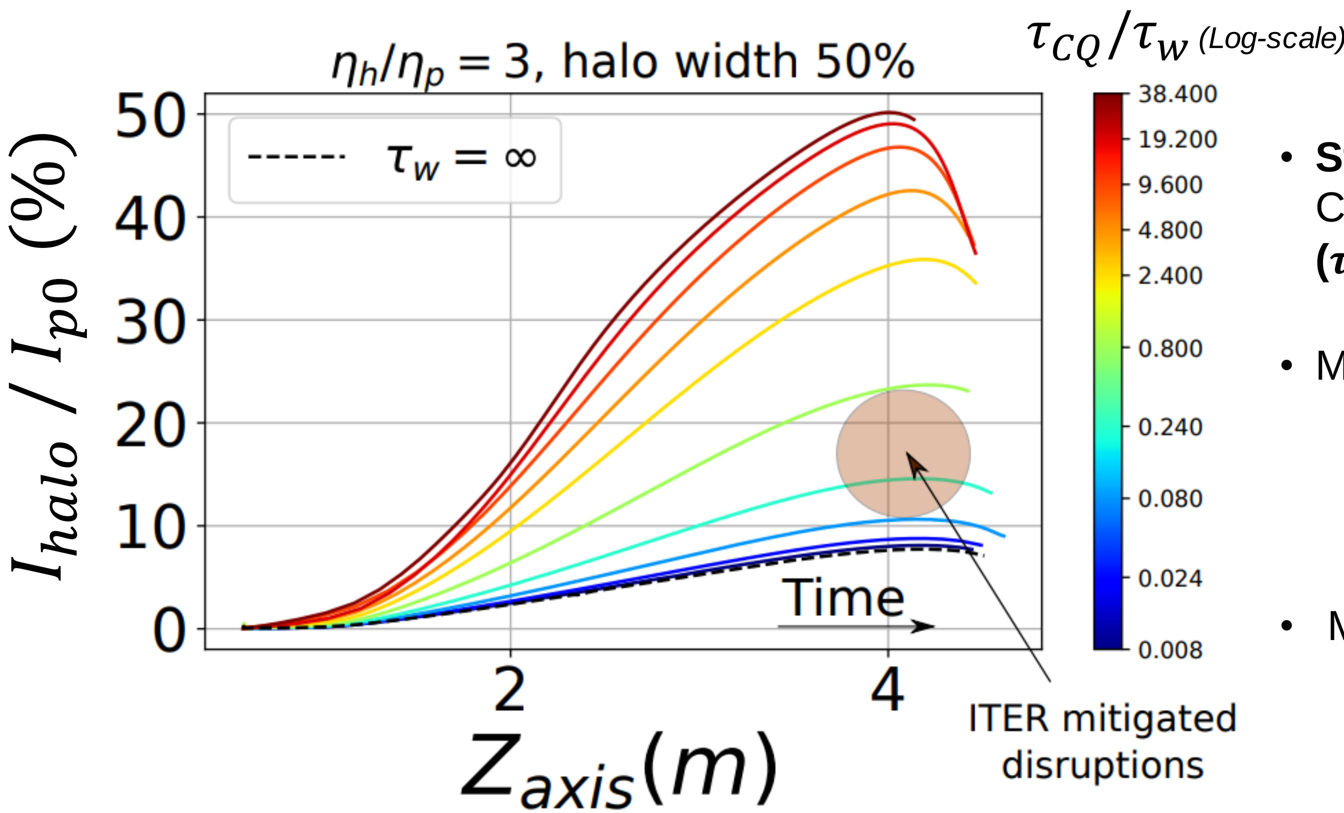
Plasma resistivity is prescribed as a flux function





Understanding 2D halo currents at ITER (15 MA / 5.3T)

Scan in CQ time (scaling plasma resistivity profile)



- **Strong dependence** on CQ time to wall time ratio (τ_{CQ}/τ_w)
- Maximum at $\tau_{CQ}/\tau_w \rightarrow \infty$

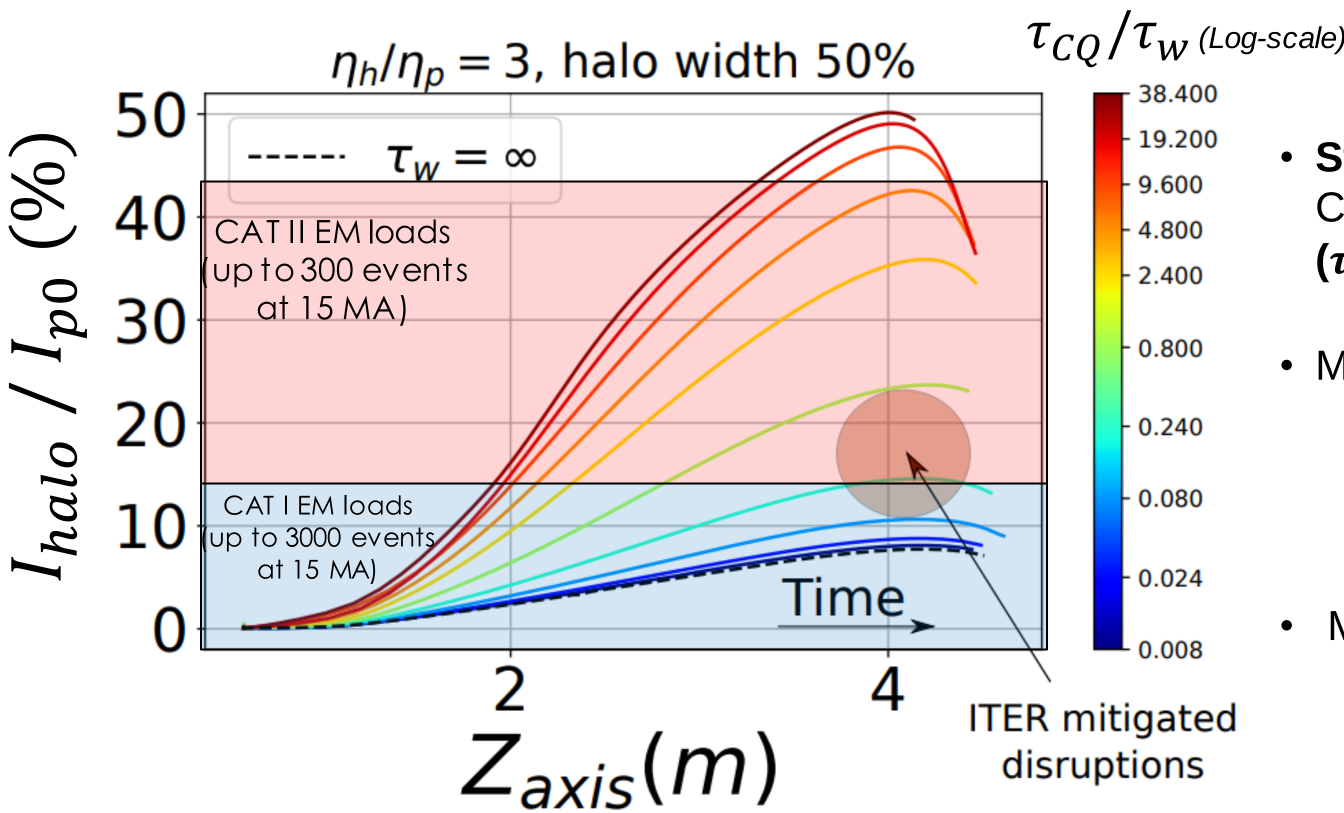
Halo currents stabilize VDE

- Minimum at $\tau_{CQ}/\tau_w \rightarrow 0$

Eddy currents stabilize VDE

Understanding 2D halo currents at ITER (15 MA / 5.3T)

Scan in CQ time (scaling plasma resistivity profile)



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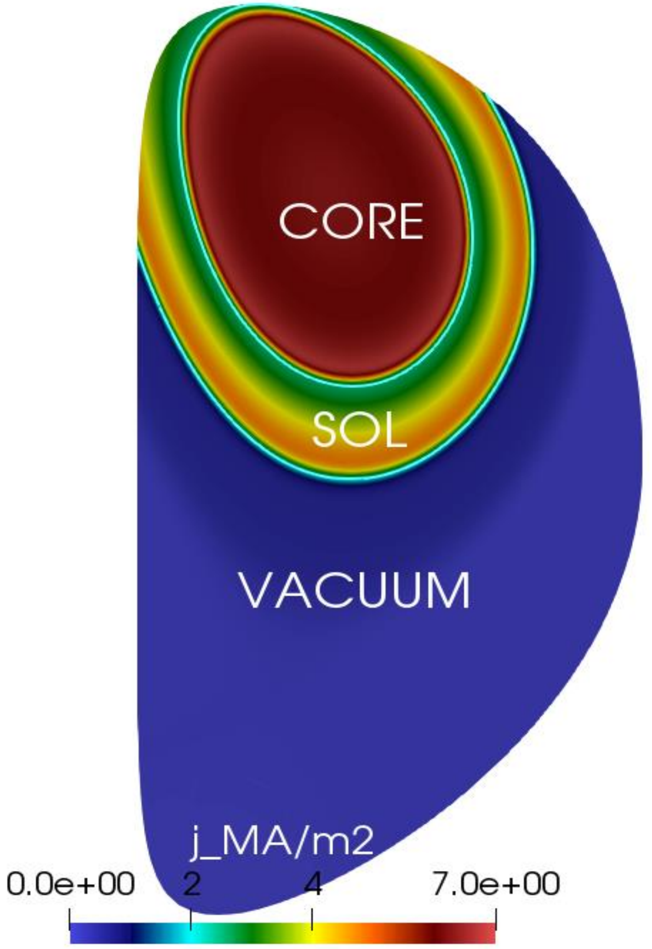
Understanding 2D halo currents at ITER (15 MA / 5.3T)

Halo current different regimes

- Hot VDE regime $(\tau_w \ll \tau_p)$
  - Cold halo $(\tau_h \ll \tau_w)$
  - Hot halo $(\tau_w \ll \tau_h)$
- Ideal wall regime $(\tau_p \ll \tau_w)$
  - Cold halo $(\tau_h \ll \tau_p)$
  - Hot halo $(\tau_p \ll \tau_h)$

also discussed in [Boozer PoP 2013]

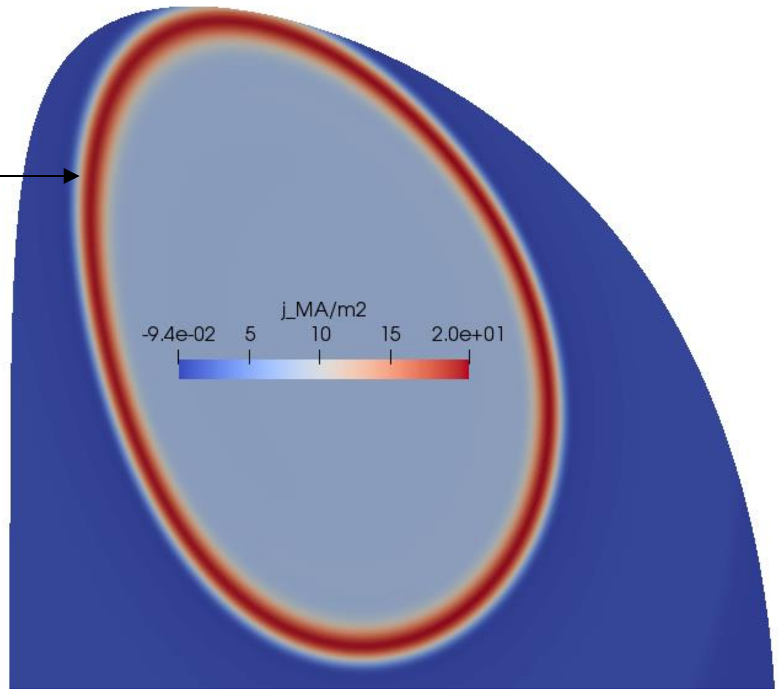
$\tau \equiv$ Current resistive decay time



Understanding 2D halo currents at ITER (15 MA / 5.3T)

Hot VDE + cold halo $(\tau_h \ll \tau_w \ll \tau_p)$

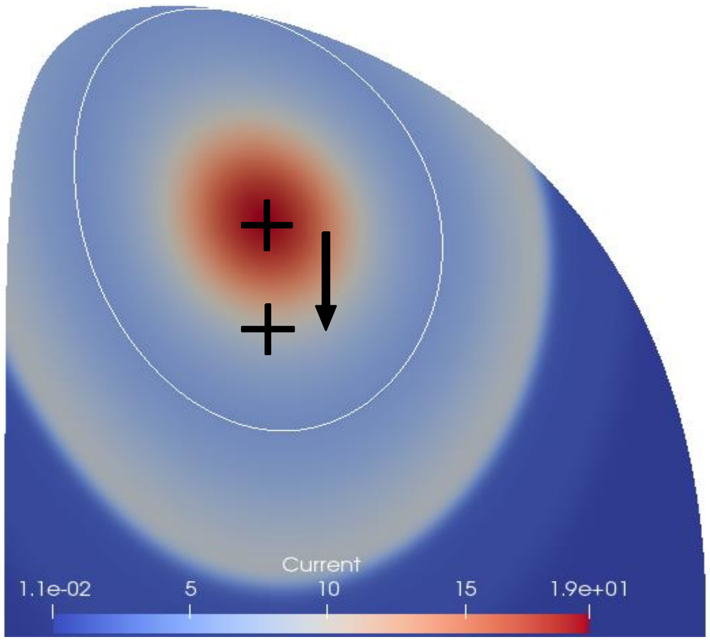
- Currents are lost in wall and halo faster than in plasma core
- Currents are re-induced in plasma edge (large current densities)
- **Big drop of edge safety factor** I_p is largely conserved ($q_a \propto a^2$)
- Potential destabilization of external kink modes



Understanding 2D halo currents at ITER (15 MA / 5.3T)

Hot VDE + hot halo $(\tau_w \ll \tau_h \sim \tau_p)$

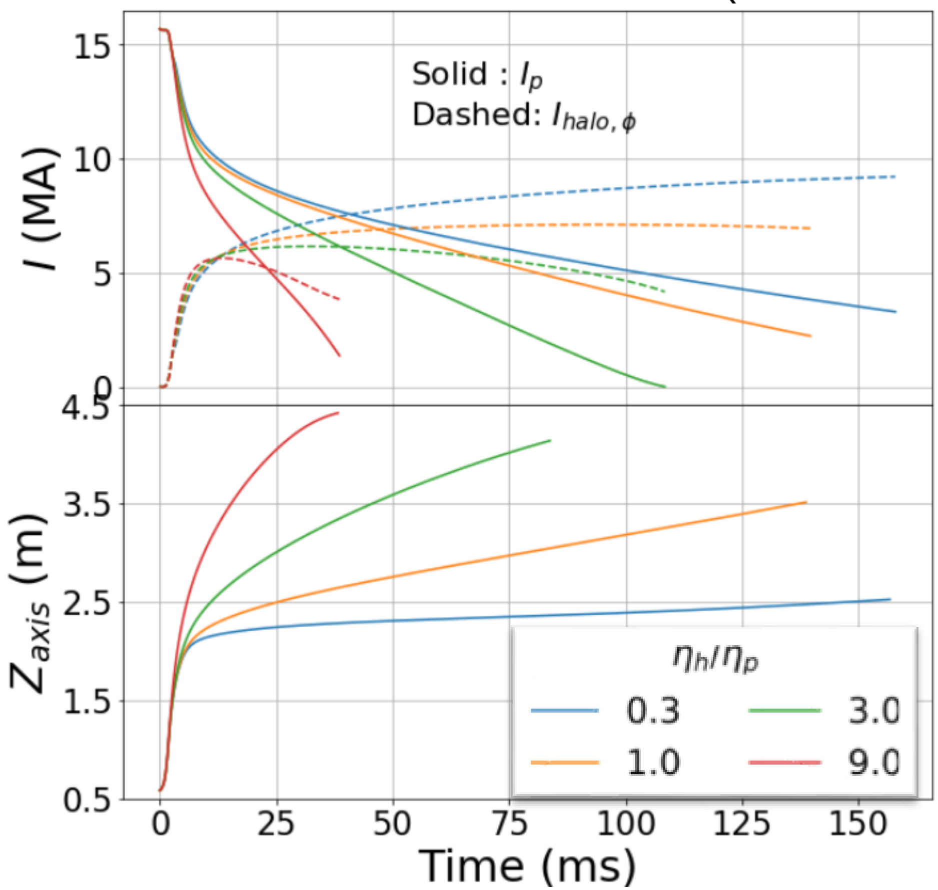
- Toroidal current is transferred into the halo region as the plasma moves vertically
- Halo currents stabilize vertical motion
- After stabilization, motion is given by resistive decay of core + halos



Hot VDE + hot halo $(\tau_w \ll \tau_h \sim \tau_p)$

Halo resistivity scan

$\tau_{CQ}/\tau_w = 64$



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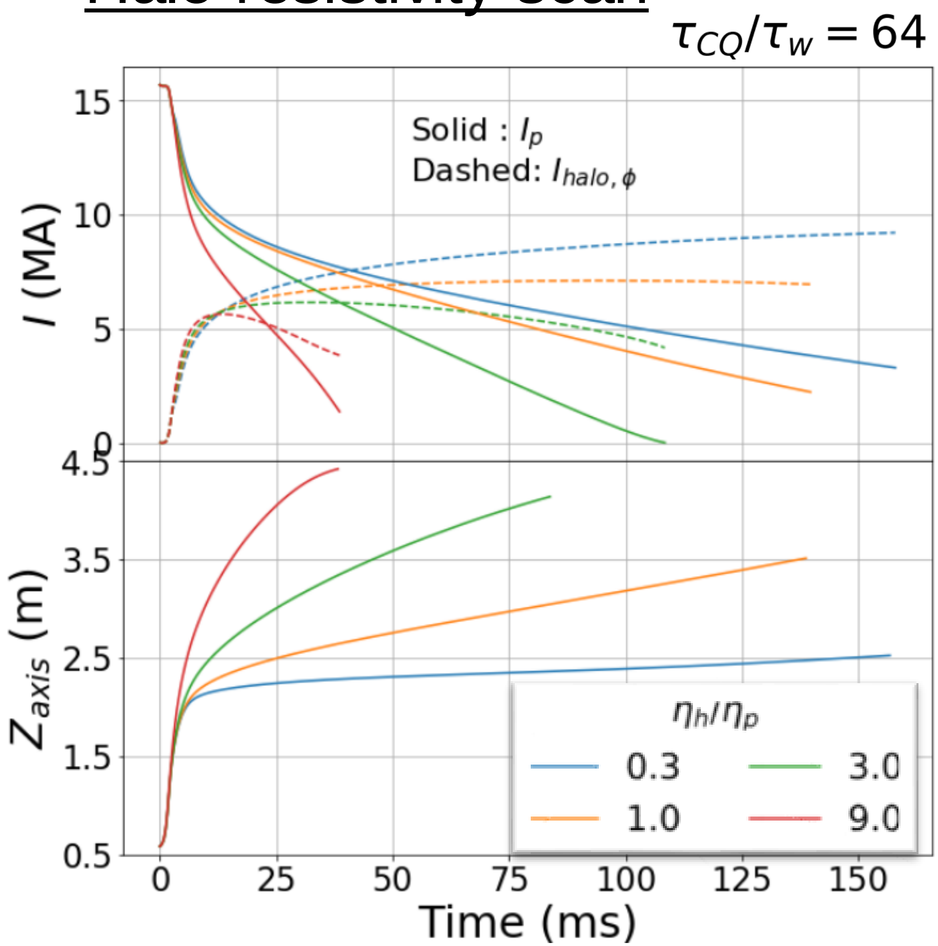
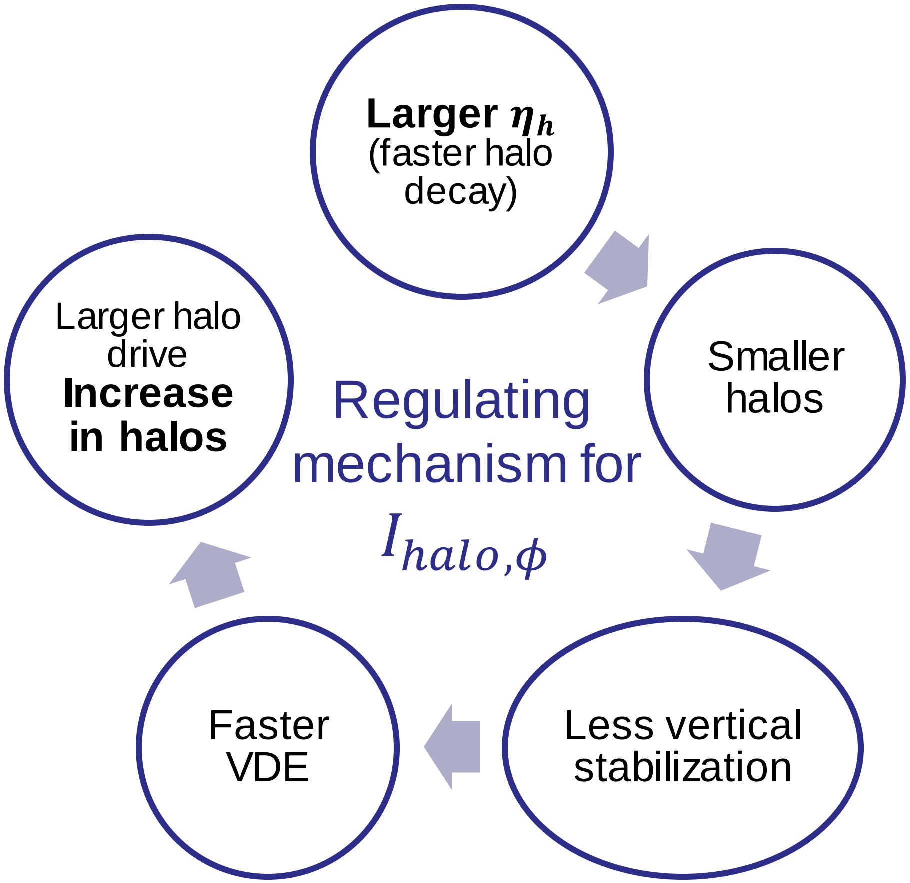


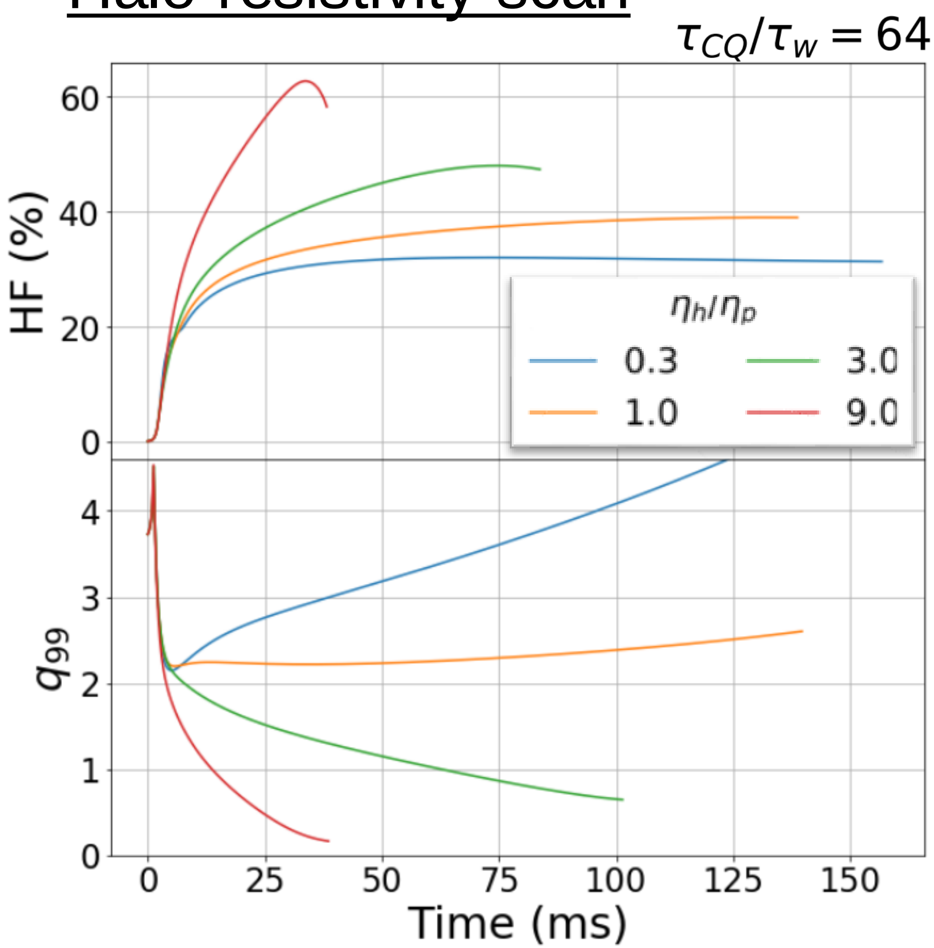


$I_{halo,\phi}$ depends weakly on η_h

Understanding 2D halo currents at ITER (15 MA / 5.3T)

Hot VDE + hot halo $\left(\tau_w \ll \tau_h \sim \tau_p\right)$

Halo resistivity scan



But $I_{halo,pol}$ depends strongly on η_h through q_a

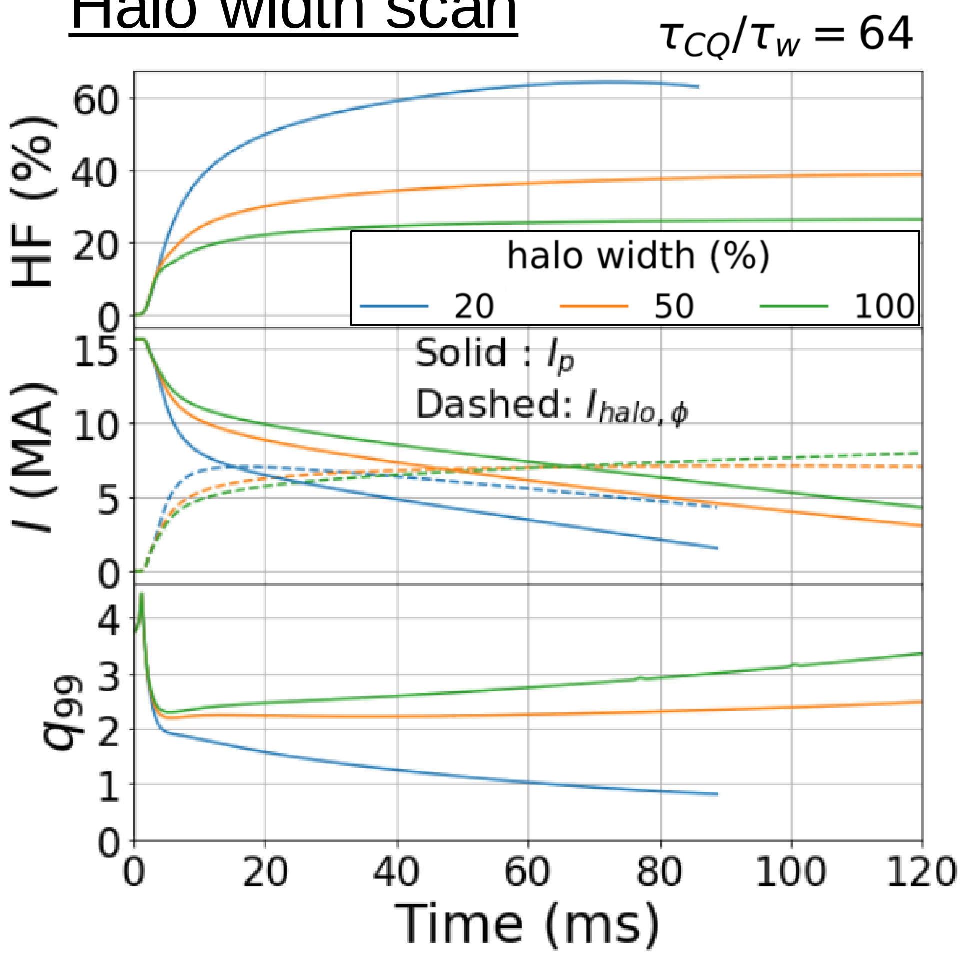
$$I_{halo,pol} \sim \frac{I_{halo,\phi}}{q_a}$$

Finally increasing the halo resistivity gives larger poloidal halo currents

Understanding 2D halo currents at ITER (15 MA / 5.3T)

Hot VDE + hot halo $\left(\tau_w \ll \tau_h \sim \tau_p\right)$

Halo width scan



$I_{halo,\phi}$ also has a weak dependence on the halo width

Weak dependence through

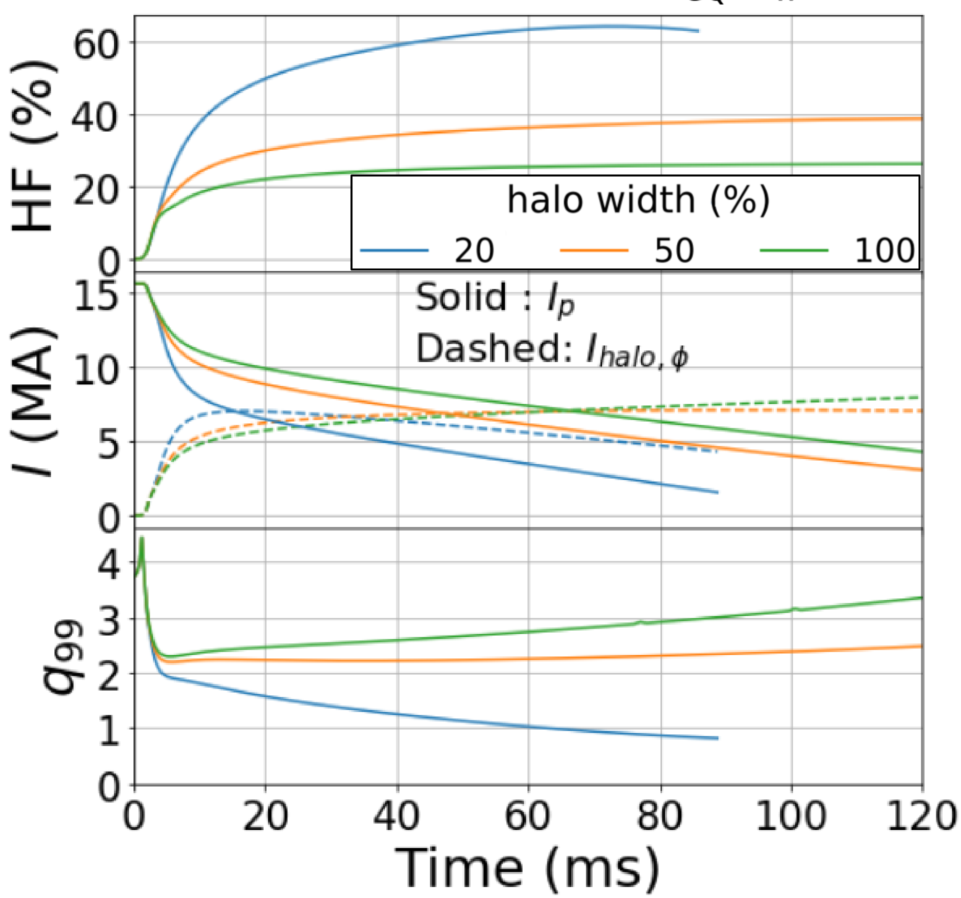
$$\tau_h \propto w_h/\eta_h$$

Understanding 2D halo currents at ITER (15 MA / 5.3T)

Hot VDE + hot halo $(\tau_w \ll \tau_h \sim \tau_p)$

Halo width scan

$\tau_{CQ}/\tau_w = 64$



$I_{halo,\phi}$ also has a weak dependence on the halo width

Weak dependence through

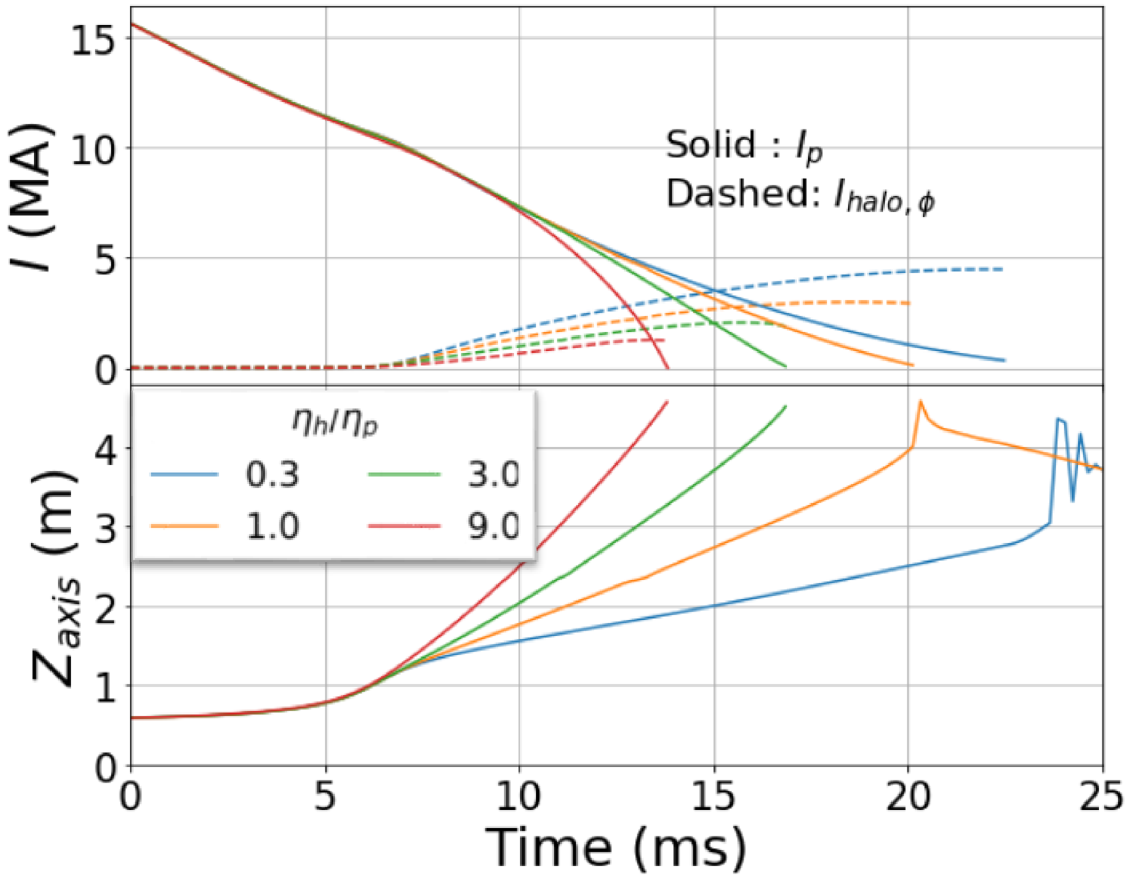
$$\tau_h \propto w_h/\eta_h$$

But $I_{halo,pol}$ has a much stronger dependence through q_a. **More effective at narrow halos**.

Understanding 2D halo currents at ITER (15 MA / 5.3T)

Ideal wall regime $(\tau_p \ll \tau_w)$

<u>Halo resistivity scan</u> $\tau_{CQ}/\tau_w = 0,\ \eta_h/\eta_p = 1$



Halo currents also slow down vertical motion

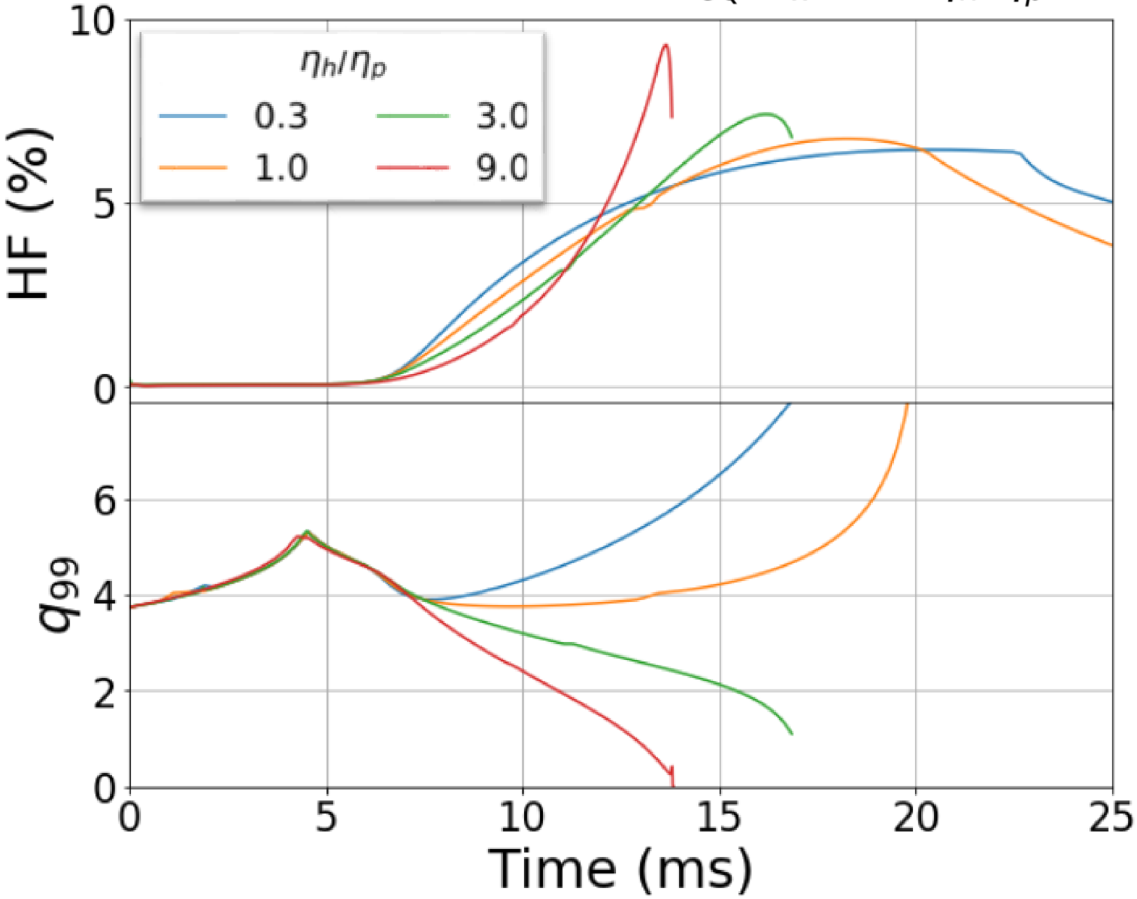
$I_{halo,\phi}$ is also not linear in η_h

(self-regulating mechanism)

Understanding 2D halo currents at ITER (15 MA / 5.3T)

Ideal wall regime $(\tau_p \ll \tau_w)$

Halo resistivity scan $\tau_{CQ}/\tau_w = 0,\ \eta_h/\eta_p = 1$



q_a and $I_{halo,pol}$ depend strongly on η_h

The poloidal halo fraction (HF) is a factor 5-10 smaller than in the hot VDE regime

Prediction of the halo properties and B.C.s

Prediction of the halo properties and B.C.s

Currently working VDE model

- Temperature dependence for resistivity and parallel conductivity

$$\eta = \eta_0 \left(\frac{T}{T_0}\right)^{-3/2} \qquad \kappa_{||} = \kappa_{||,0} \left(\frac{T}{T_0}\right)^{5/2}$$

- Ohmic heating term in energy equation
- Bohm's boundary condition $(\mathrm{v}_{||} = c_s)$
- Sheath heat flux B.C.

$$-\left(\kappa_\perp \nabla_\perp T + \kappa_{||} \nabla_{||} T\right) \cdot \mathbf{n} + nT\mathbf{v} \cdot \mathbf{n} = \gamma_{sh} n T c_s \frac{|\mathbf{B}\cdot\mathbf{n}|}{|B|}$$

Prediction of the halo properties and B.C.s

Missing ingredients of VDE model

- Neutrals, recycling and atomic processes (key for density evolution, now $\boldsymbol{n_e(\psi)}$)
- Impurity evolution and radiation
- Limit on ion saturation current ($J \leq J_{sat}$), (in progress)

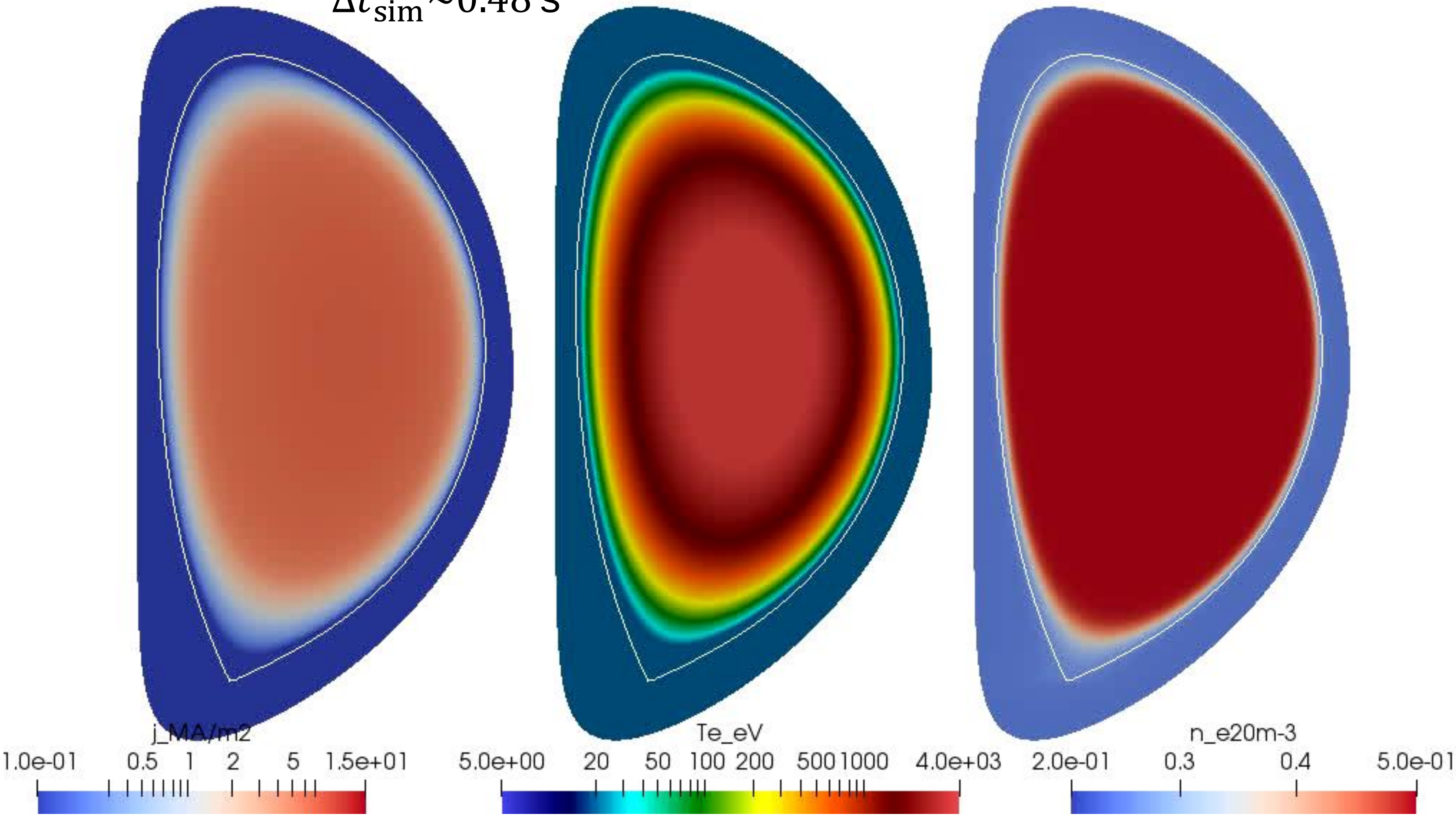
Prediction of the halo properties and B.C.s

Simulation setup

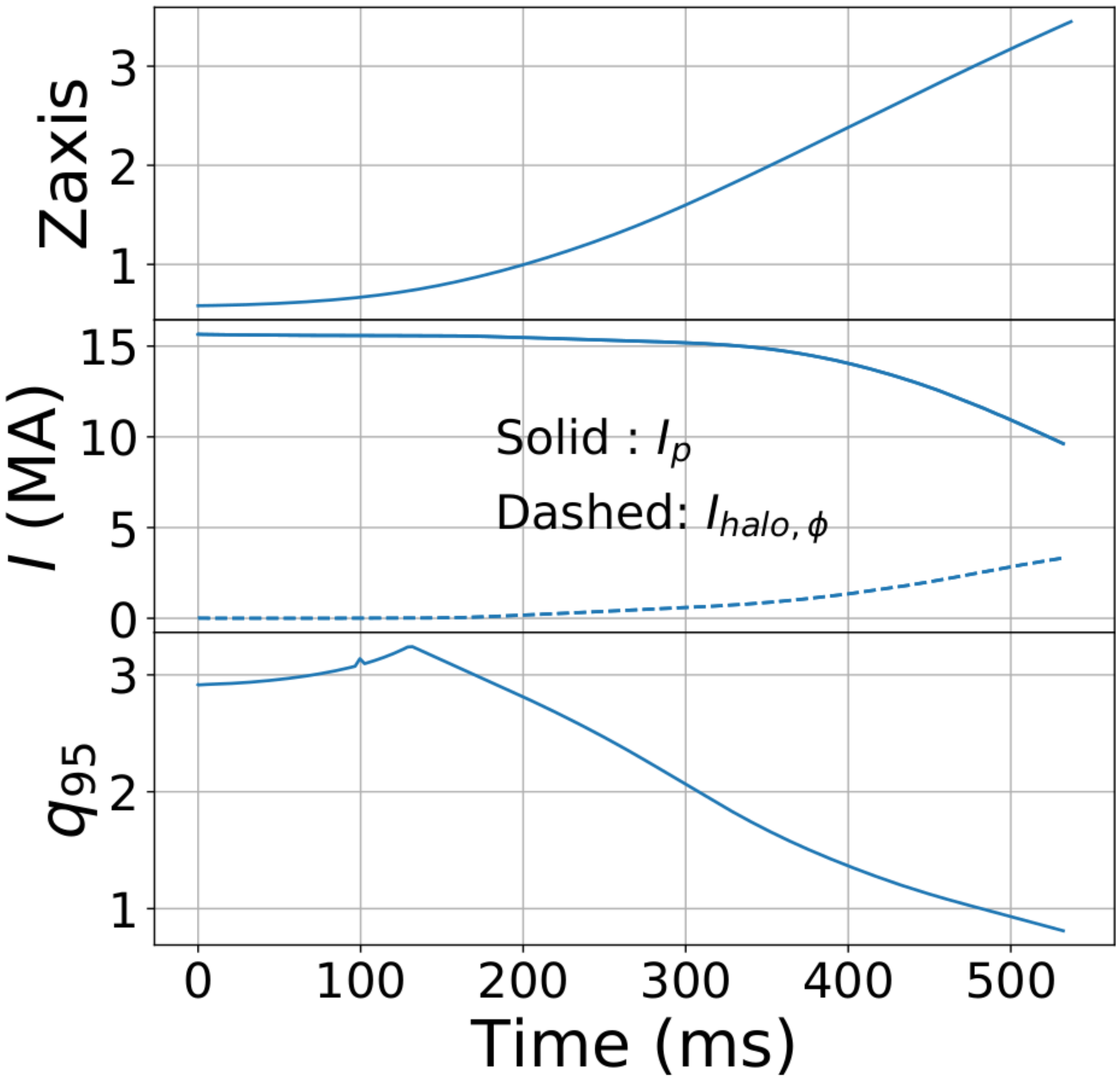
- Upward ITER VDE, 15 MA / 5.3 T
- Post-disruption equilibrium ($\beta_p = 0.05$)
- Flat J-profile after helicity mixing (from DINA)
- No radiation (ohmic heating re-heats the plasma)
- Realistic Spitzer and Braginskii values for η_0 and $\kappa_{\parallel 0}$
- $\kappa_\perp = 4\ \mathrm{m}^2/\mathrm{s},\ \gamma_{sheath} = 8,\ T_e = T_i,\ \tau_w = 0.5\ \mathrm{s}$

Prediction of the halo width and B.C.s

$\Delta t_{sim} \sim 0.48$ s

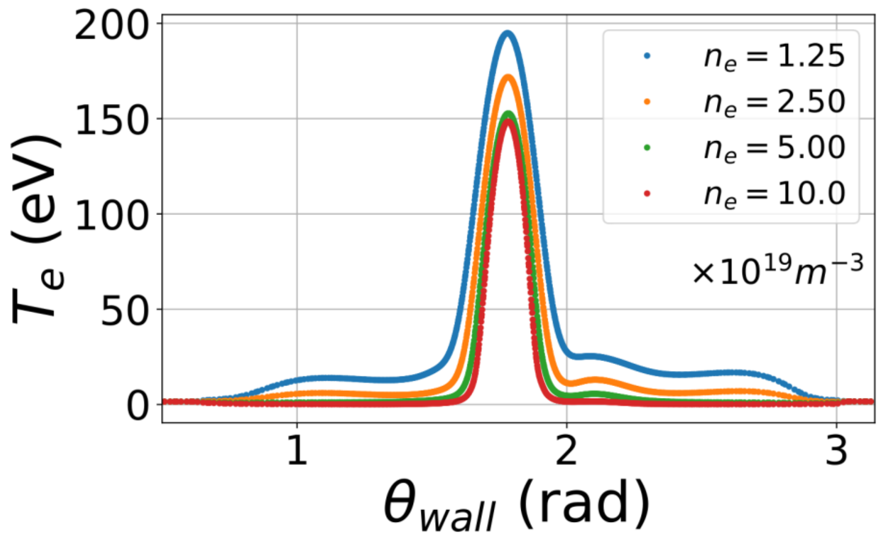


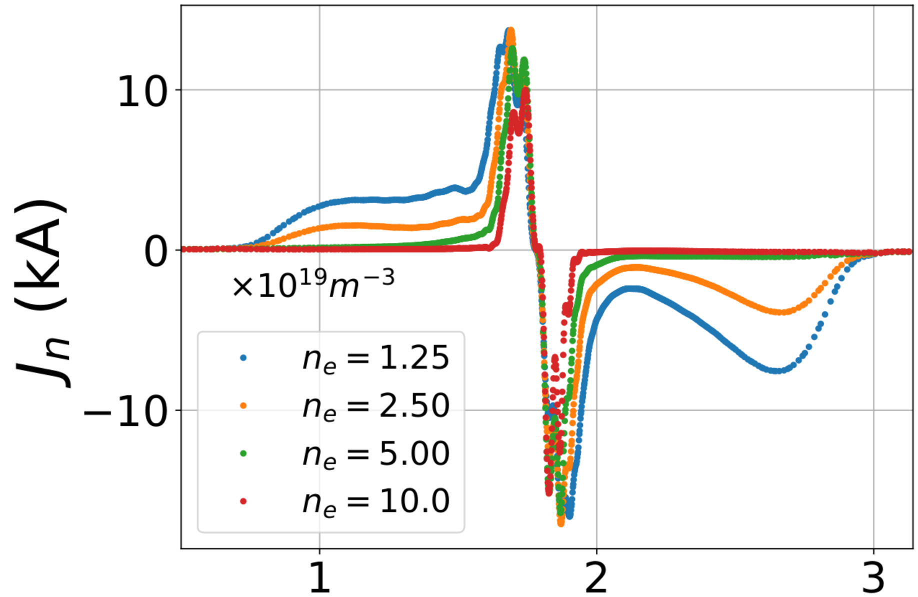
Prediction of the halo width and B.C.s



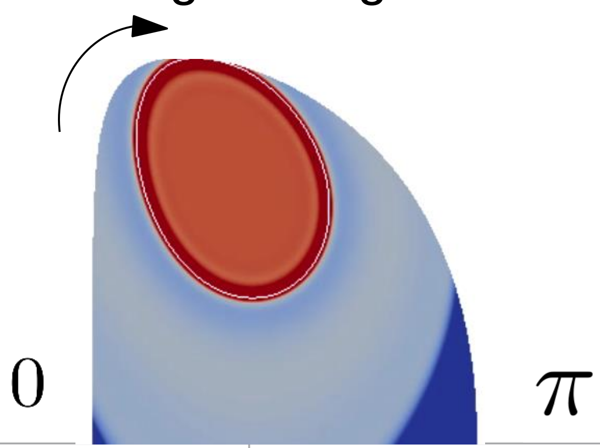
Prediction of the halo width and B.C.s

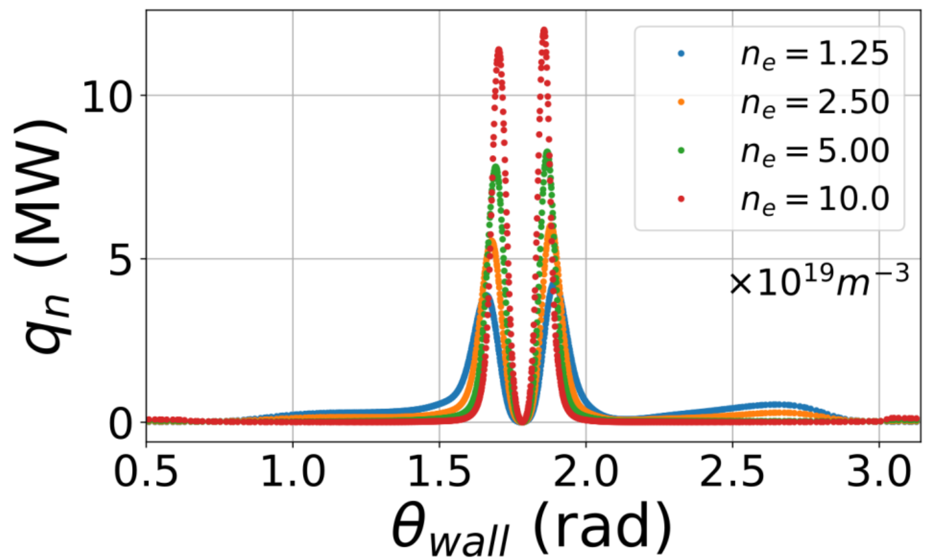
Density scan (Zaxis=2.0 m)





Poloidal angle along the wall





Conclusions and future work

JOREK / M3D-C1/ NIMROD benchmark: good agreement for 2D halo currents

<u>2D VDEs ITER studies</u>

- Hot VDE limit ($\tau_w \ll \tau_p$) **largest halo fractions** ($\mathrm{HF_{max}}$~50 %)
- Ideal wall limit ($\tau_p \ll \tau_w$) **smallest halo fractions** ($\mathrm{HF_{max}} < 10$ %)
- **ITER mitigated disruptions** ($\mathrm{HF_{max}} \sim 10 - 25$ %)
- Self-regulating mechanism for $I_{\mathrm{halo},\phi}$, weak dependence on $\tau_h \propto w_h/\eta_h$
- Poloidal halo currents depend strongly on q_a ($I_{\mathrm{halo,pol}} = I_{\mathrm{halo},\phi}/q_a$), which decreases at shorter τ_h
- Maximum HF at ($\tau_w \ll \tau_h < \tau_p$) with small halo widths
- **Influence of initial l_i and core resistivity profile?**

Conclusions and future work

Prediction of halo width and temperature

- **Current VDE model including**
  - Realistic resistivities and conductivities
  - Energy balance in the halo: sheath losses and ohmic heating
  - Sheath B.C.s
  - Imposed density $n(\psi)$

- **Still missing**
  - Density evolution with neutrals and atomic physics
  - Impurity radiation
  - Limit on current density (ion saturation current)

- **Results for hot VDEs show**
  - Large halo widths (for Jphi) at low temperature