Max-Planck-Institut für Plasmaphysik

Complete 3D MHD simulations of ITER post-Themal Quench plasmas with realistic Lundquist numbers

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Disclaimer ITER: *ITER is the Nuclear Facility INB No. 174. This work physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.*

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Context

- **3D MHD simulations of disruptions are required to predict and understand**
  - Plasma density assimilation and radiation profiles after Massive Material Injection
  - Thermal load mitigation
  - **Electromagnetic load mitigation (this talk)**
  - **Runaway electron confinement in 3D fields (this talk)**
  - Others (RE beam termination, optimization of SPI parameters, etc)

- **Simulations are computationally challenging**
  - System of equations with many degrees of freedom (~10 million)
  - Large temporal time scales (~100 ms for ITER) with Alfven time dynamics (~ micro-seconds)
  - Non-existent for full ITER disruptions with realistic time-scales

This talk

JOREK-STARWALL* 3D simulations for full ITER current quenches with realistic Lundquist numbers (~50 ms CQ and ~ 2 million cpu.h)

- **Are the 3D wall forces reduced for mitigated disruptions in ITER?**
- **What is the level of magnetic field stochasticity during the current quench?**
- **Will runaway electrons be lost before avalanching in such fields?**

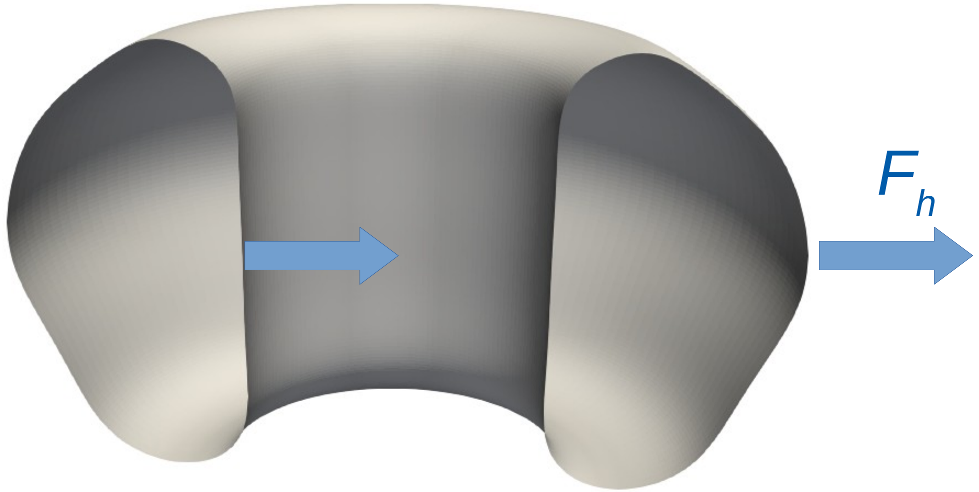
*[Hoelzl, *NF* **61**, p. 065001]
*[Merkel, arXiv:1508.04911]

Motivation: Uncertain wall force extrapolations from JET

- **3D disruptions lead to sideways wall forces in JET ~4 MN** [Gerasimov, *NF* **55**, p. 113006]
- **Extrapolations to ITER** (based on $\mathrm{F}_{wall} \sim I_p B_\phi R$) give unacceptable forces (~40 MN)
- If **Wall time constant > Current Quench time** → **Large force reduction** [Pustovitov, *NF* **57**, p. 126038]
- **How large will be the forces for ITER mitigated disruptions?**

  Previous 3D MHD simulations showed maximum sideways forces much smaller than 40 MN

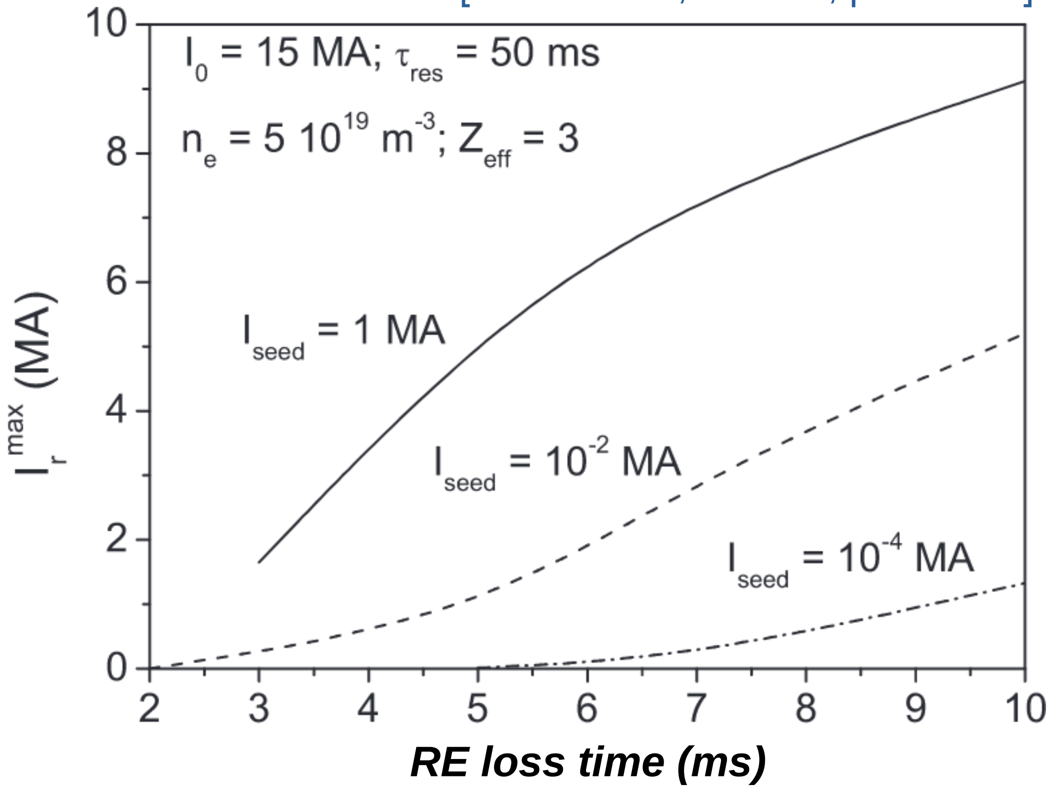
  - **M3D:** F_h ~ 5.0 MN [Strauss, *PoP* **25**, p. 020702]
  - **M3D-C¹:** F_h ~ 0.5 MN [Jardin, IAEA-FEC 2020 poster]
  - **JOREK:** F_h < 1 MN **(this talk)**



Motivation: Runaway electron (RE) confinement during the CQ

- If DMS is not successful, large RE beams (~10 MA) may form [Martin-Solis, *NF* **57**, p. 066025]
- **Strong RE de-confinement by 3D MHD fields could prevent runaway formation**
- **Lack of 3D disruption simulations during the CQ**

[Martin-Solis, *PoP* **28**, p. 032505]



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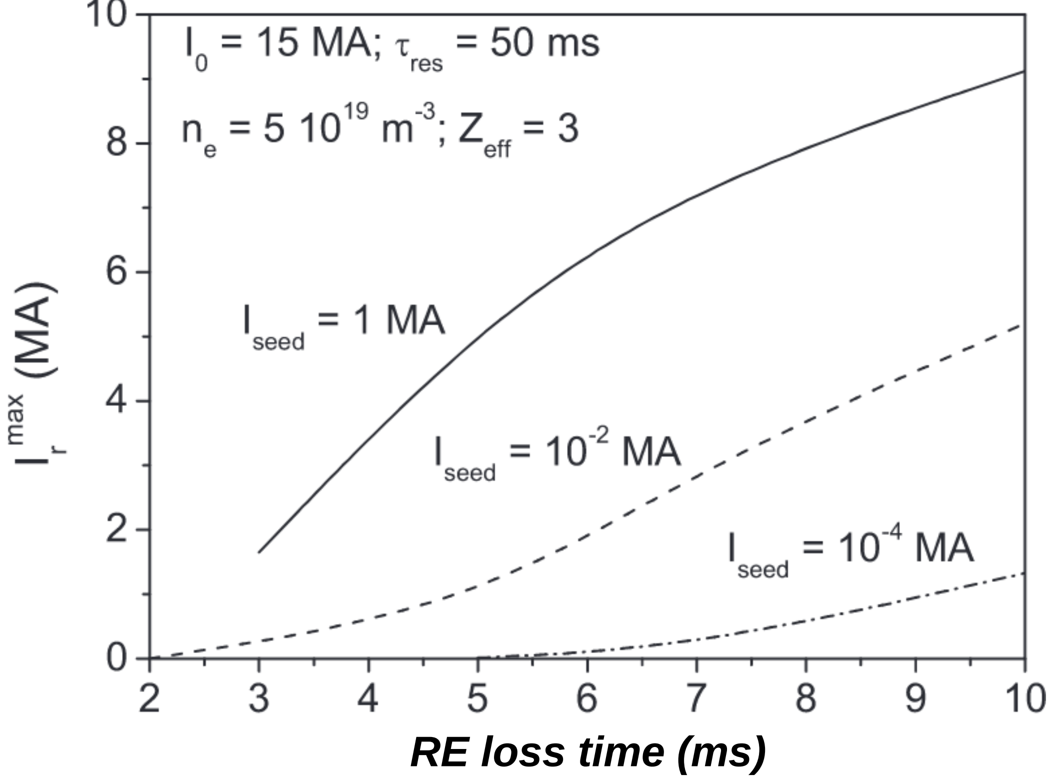
RE loss time in ITER is presently unknown

3D MHD simulations + RE tracking will give estimates

[Martin-Solis, *PoP* **28**, p. 032505]



JOREK – A visco-resistive 3D MHD code

Numerics

- Fourier harmonics for the toroidal direction - Bezier finite elements in the poloidal plane including the SOL
- Fully implicit time-stepping

Models and extensions

- Reduced MHD (used here) / Full MHD [Pamela, *PoP* **27**, p. 102510]
- Impurity SPI w/o coronal equilibrium assumption [Hu, *submitted*]
- Self-consistent RE fluid model [Bandaru, *PRE* **99**, p. 063317]
- Kinetic particle effects [D van Vugt, *PhD thesis*]
- Resistive walls [Hoelzl, *JoP* **401**, p. 012010] (coupling to CARIDDI volumetric wall code ongoing)
- Sheath boundary conditions

Recent key results on disruptions

- Simulated RE beam termination in JET [Bandaru, *PPCF* **63**, p. 035024]
- 3D simulations of JET's I_p-spike [Nardon, *submitted to PPCF*]
- 3D VDE benchmark with NIMROD and M3D-C[1] [Artola, Sovinec, Jardin et al., *PoP* **28**, p. 052511] **(see C. Sovinec talk)**

PF coils and passive conductors for ITER

Included with the STARWALL code with realistic time constants

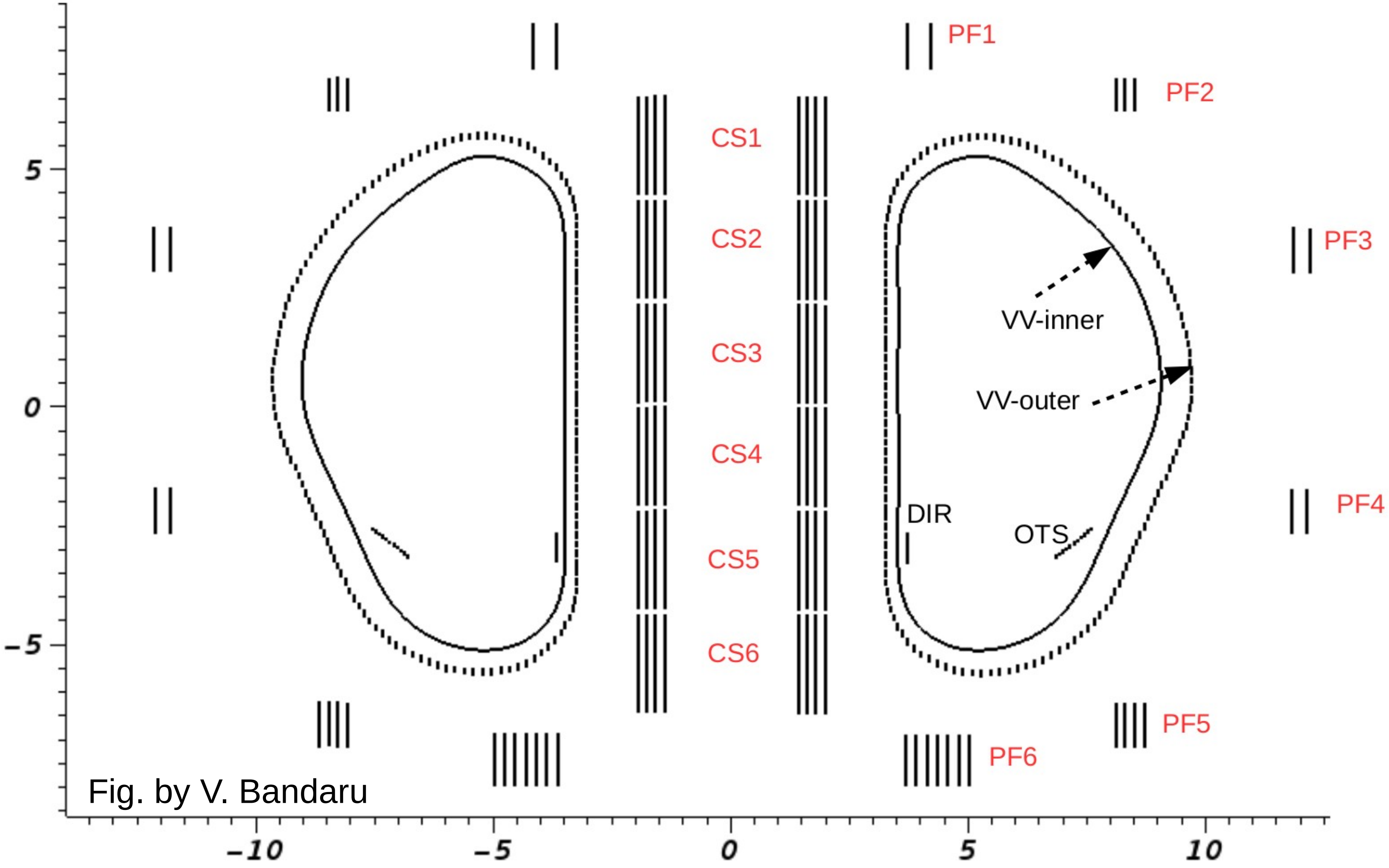
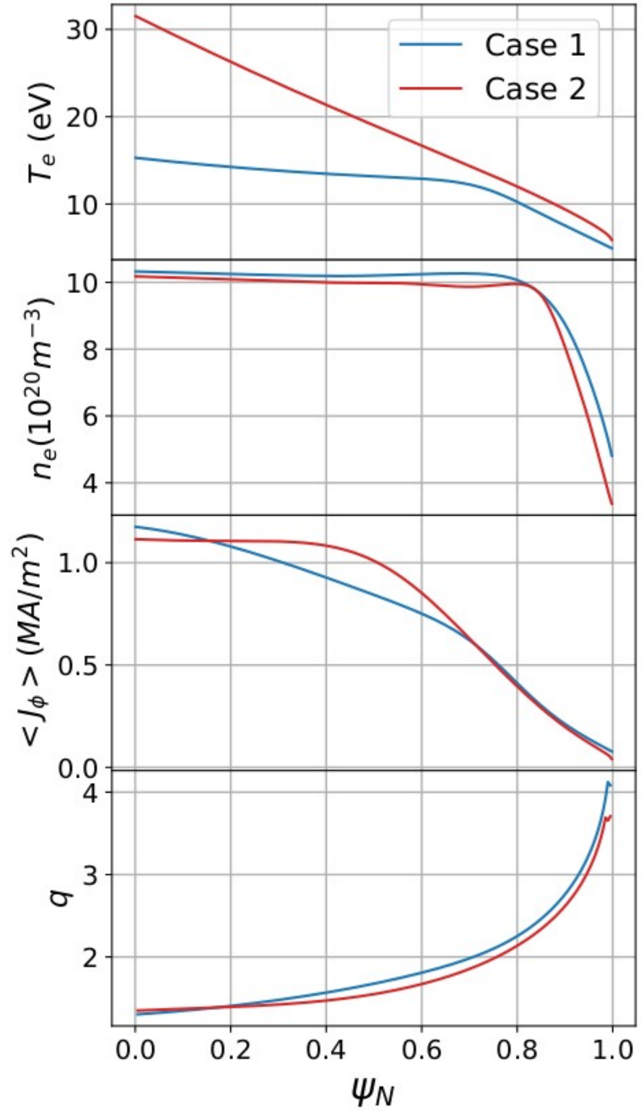


Fig. by V. Bandaru

Simulated cases with JOREK-STARWALL

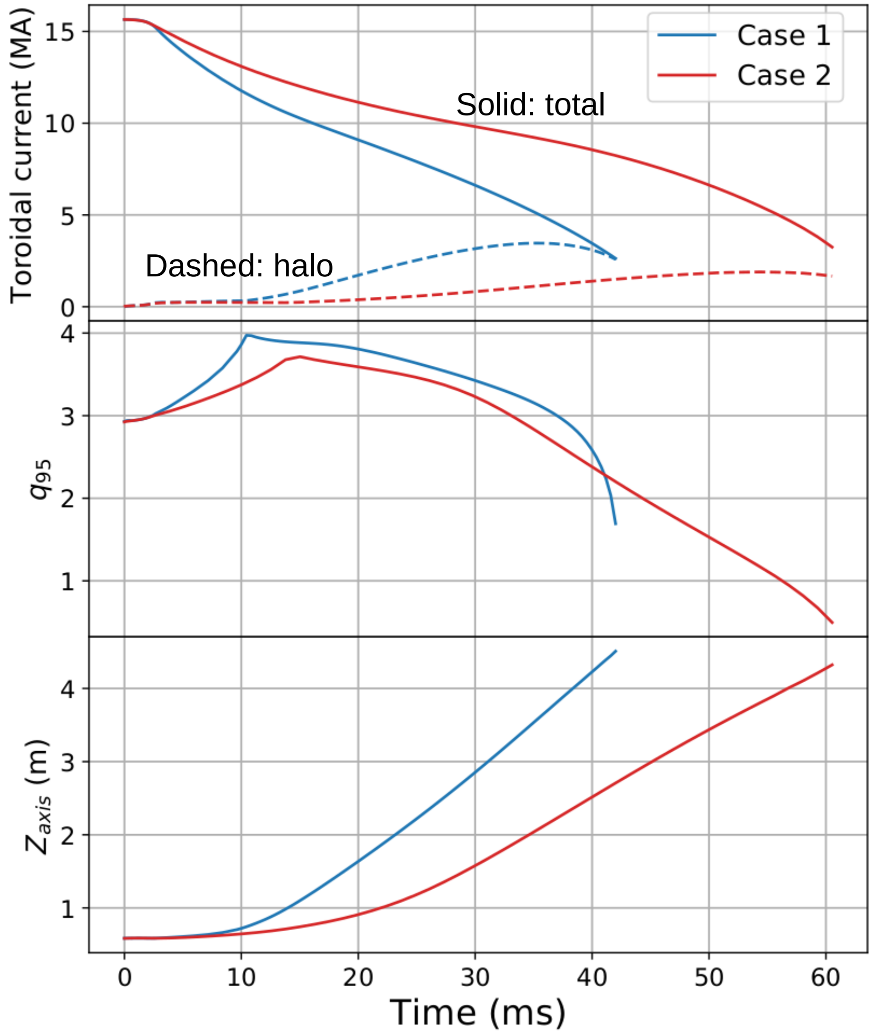
- **ITER 15 MA Post-Thermal Quench plasmas** (after DMS application)
- **Low temperature / High density**: T_e~10-30 eV and n_e= 1e21 m^{-3}
- **Realistic resistivity and parallel conductivity** (T_e dependent)
- **Dirichlet boundary conditions at first wall** (T_e=1 eV and n_e= 0.5e20 m^{-3})
- **2 cases with different initial profiles**
    1) Flat Te-profile (completed)
    2) Peaked Te-profile (still running)
- Simplified model: **Single fluid / No-impurities / No neutrals**
- **Main assumption → 100% radiated magnetic energy**

  (no Ohmic heating term in pressure equation)



Axisymmetric runs (case 1 .vs. case 2)

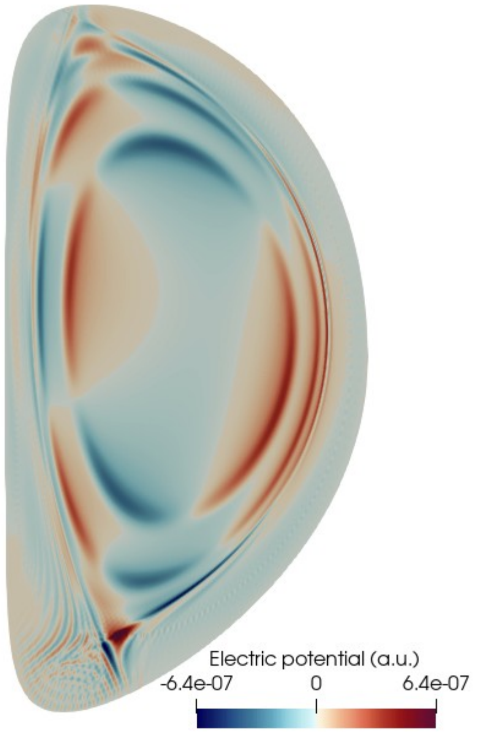
- **Both cases show upward vertical motion in 2D**
- **Case 1: Initially flat T_e**
  - $q_{95} > 3$ if $I_p > 5$ MA
- **Case 2: Initially peaked T_e**
  - Slower I_p decay
  - Smaller halo currents (due to larger T_{core}/ T_{halo})
    - ➔ $q_{95} < 2$ when $I_p < 8$ MA
    - ➔ **(potentially more MHD unstable)**



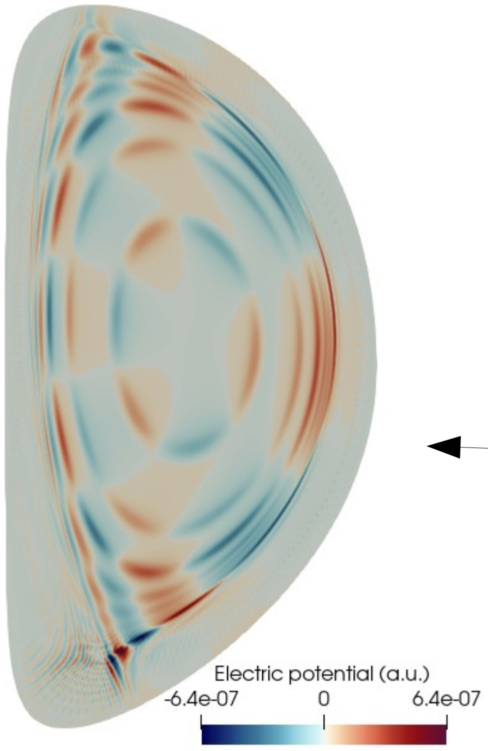
3D run for case 1 (initially flat T_e)

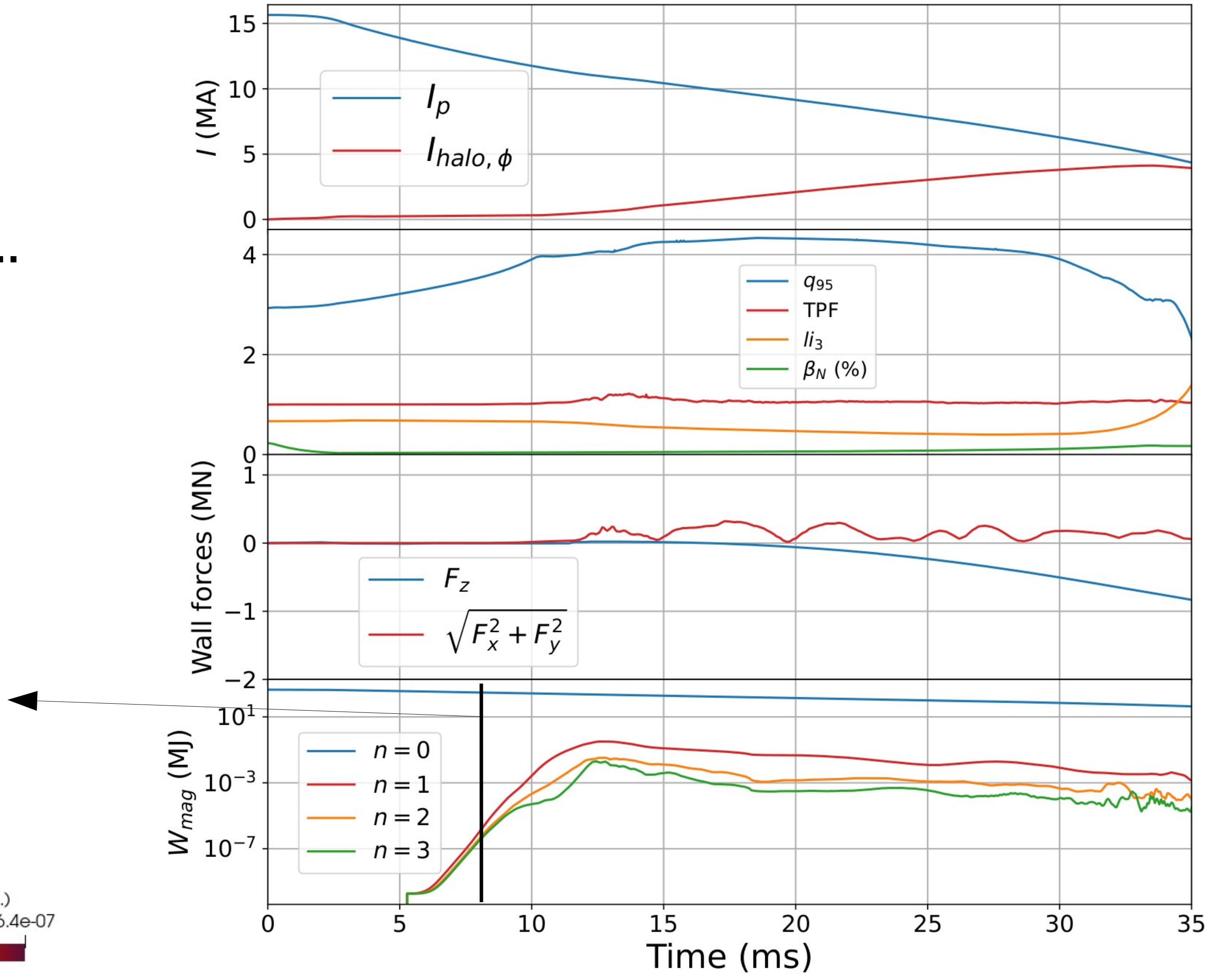
- Run with 11 toroidal Fourier harmonics (0-10)
- Case unstable to a variety of tearing modes

m/n= 2/1, 3/1 ...



m/n= 3/2, 4/2, 6/2 …





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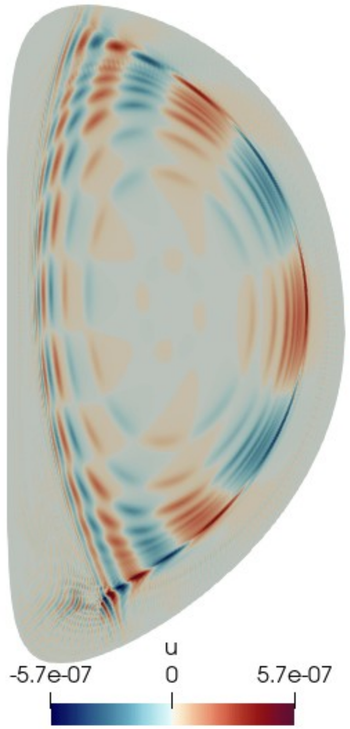
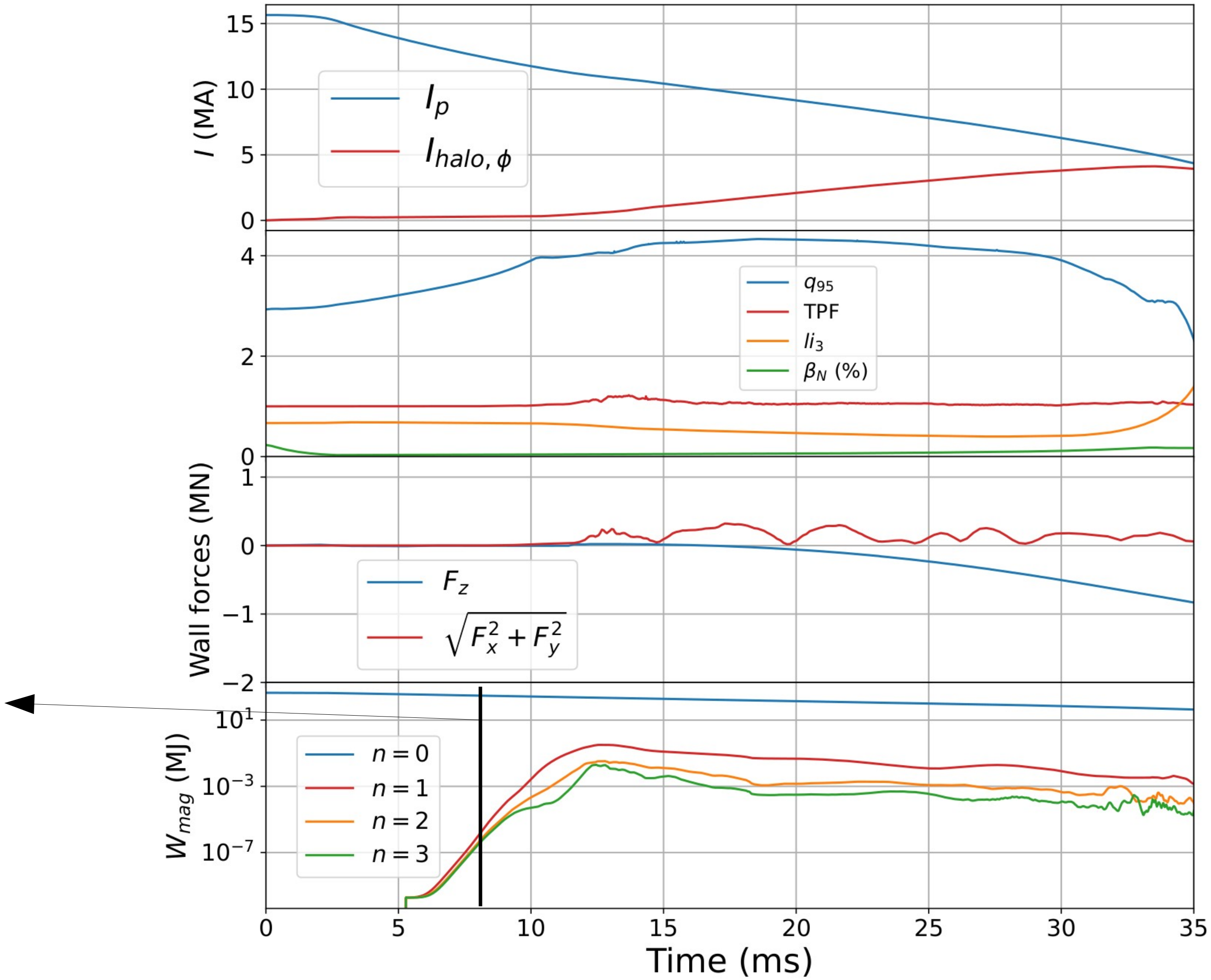
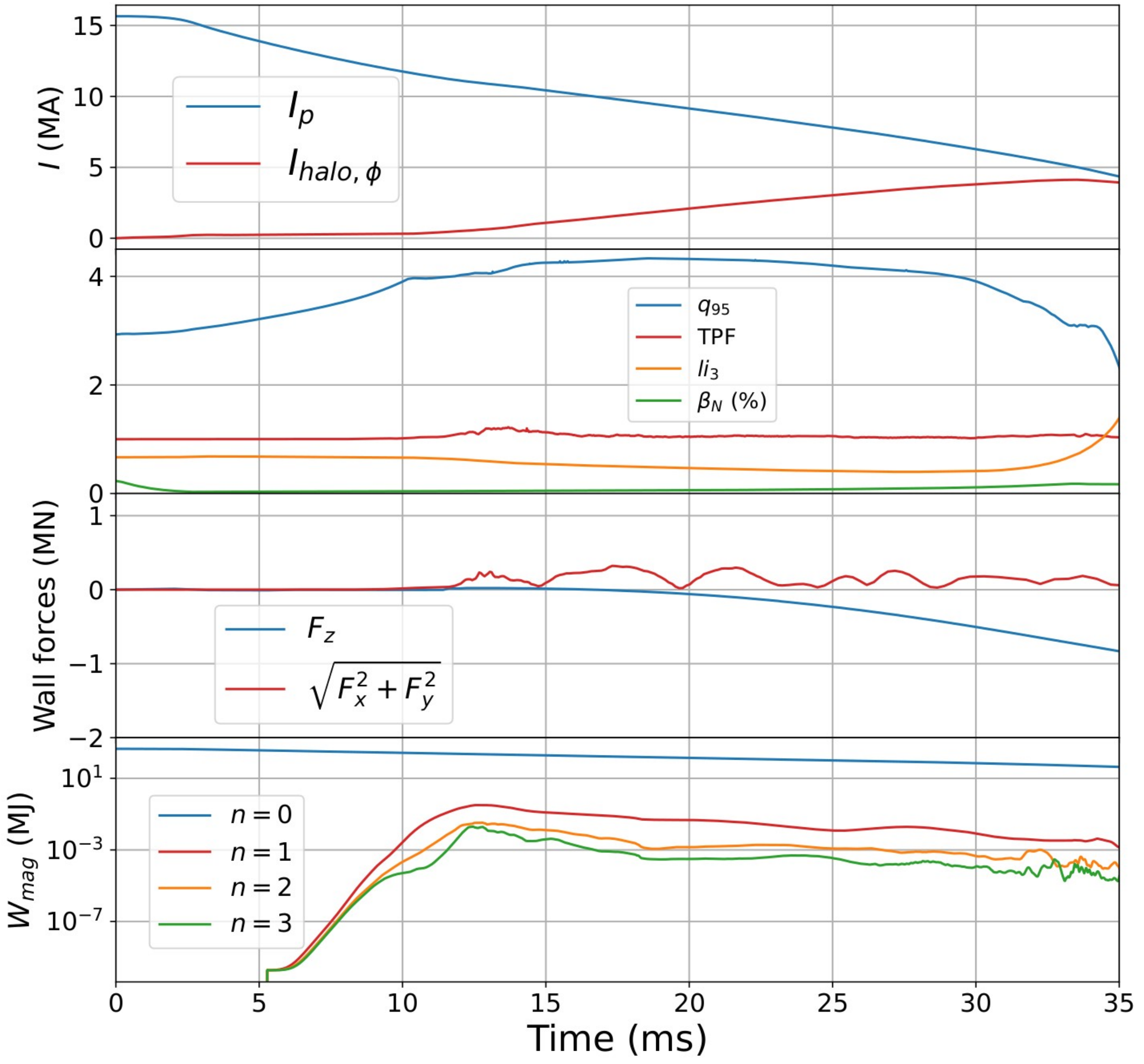
m/n= 4/3, 6/3, ...





3D run for case 1 (initially flat T_e)

- **q_{95} > 2 all the evolution** (no strong kink modes)
  - ➔ **Horizontal force < 1 MN** !
  - ➔ (residual compared to the 40 MN extrapolated from JET worst cases)
- Maximum ITER vertical wall forces for slow VDEs ~80 MN [Sugihara, *NF* **47**, p. 337]
- **Vertical force is small ~1 MN during the CQ** (in agreement with the ideal wall limit)



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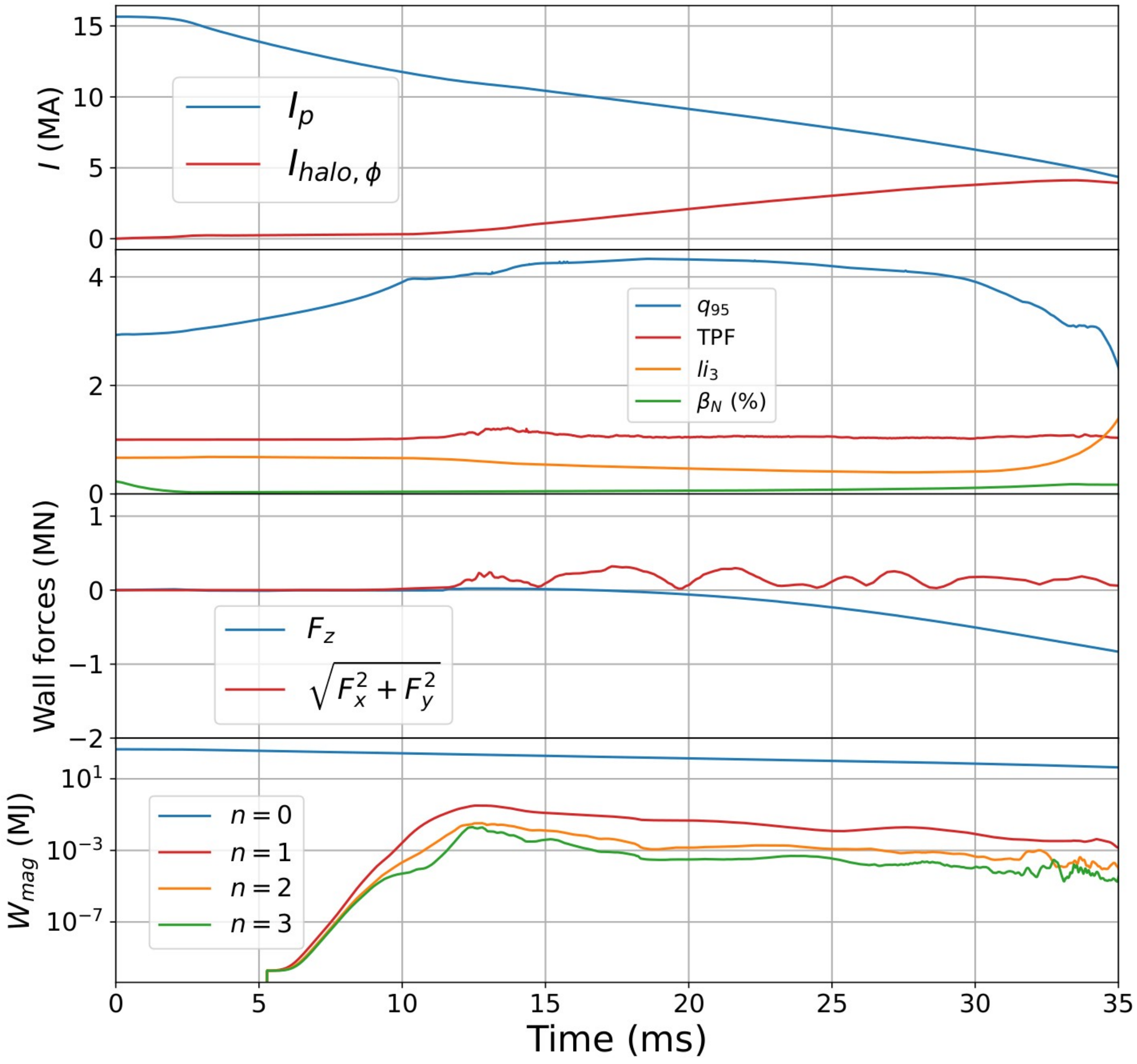
What happens after the CQ?

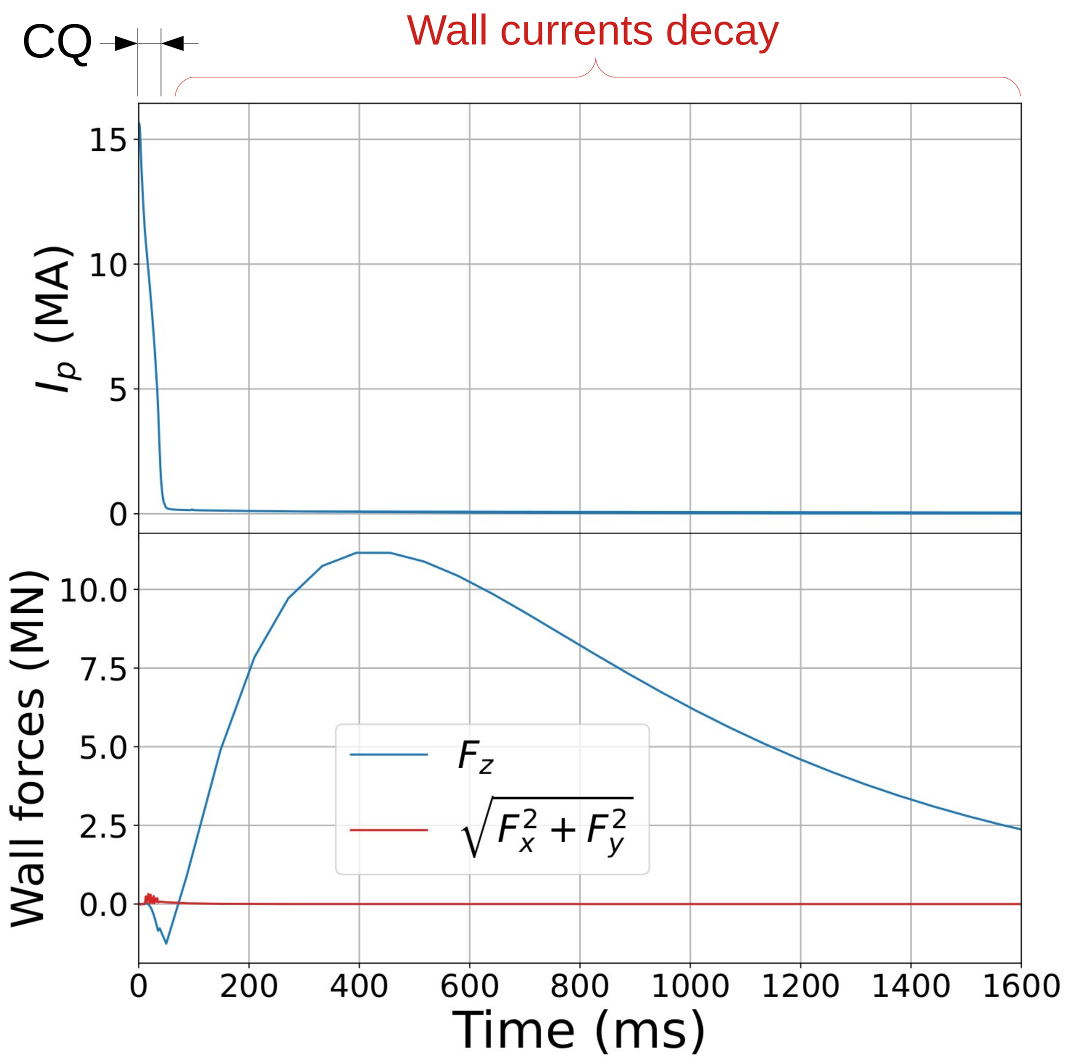
Can the forces increase during the wall's L/R time (~500 ms)?

observed in V. Yanovskiy CQ simulations (in preparation)



3D run for case 1 (initially flat T_e)

- Horizontal force remains residual
- **Vertical force increases from -1 MN to 11 MN after the plasma is gone!**
- **It is imperative to run no-plasma simulations after the CQ in 3D MHD codes !**
- **A fast CQ avoids issues related with force amplification due to rotation.**



3D run for case 1 (initially flat T_e)

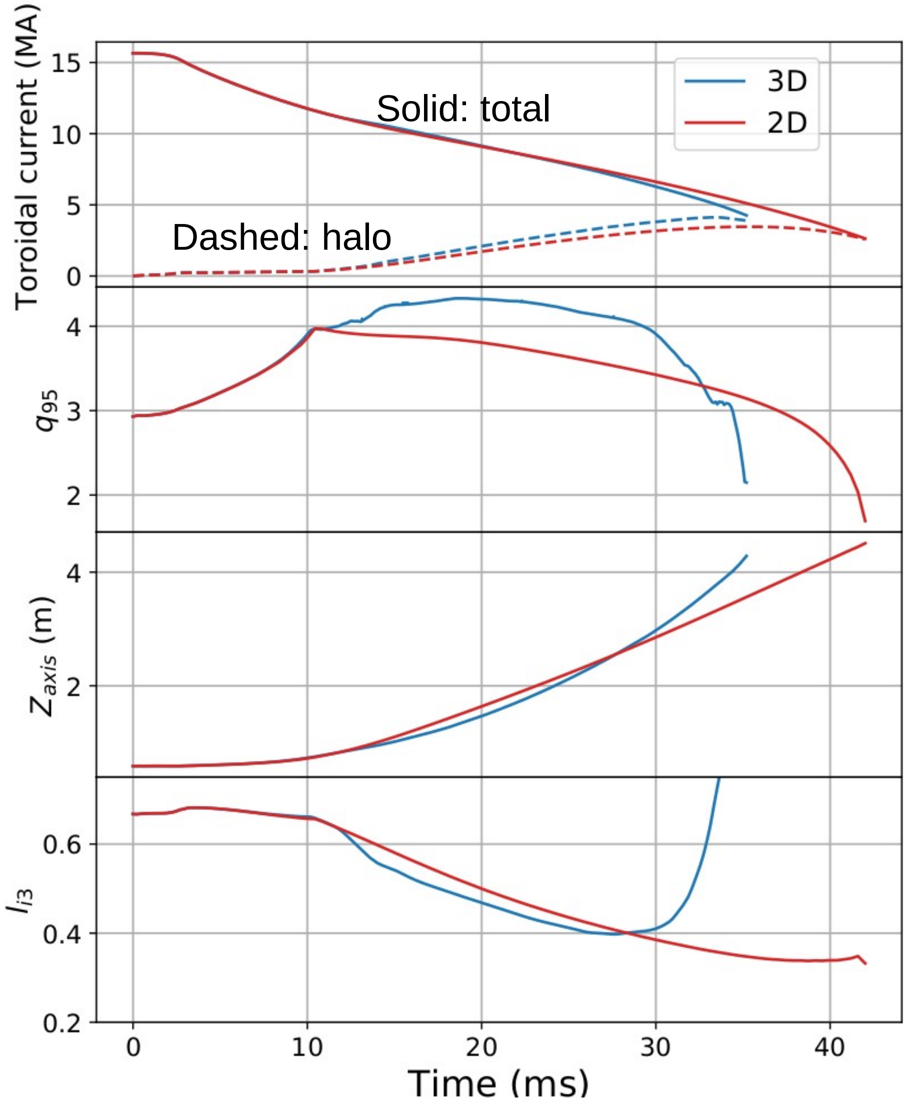
Why do we need to wait to the wall's L/R time?

Wall force = - (Plasma + wall forces on the coils) [Wesson, *Tokamaks*, 2011]

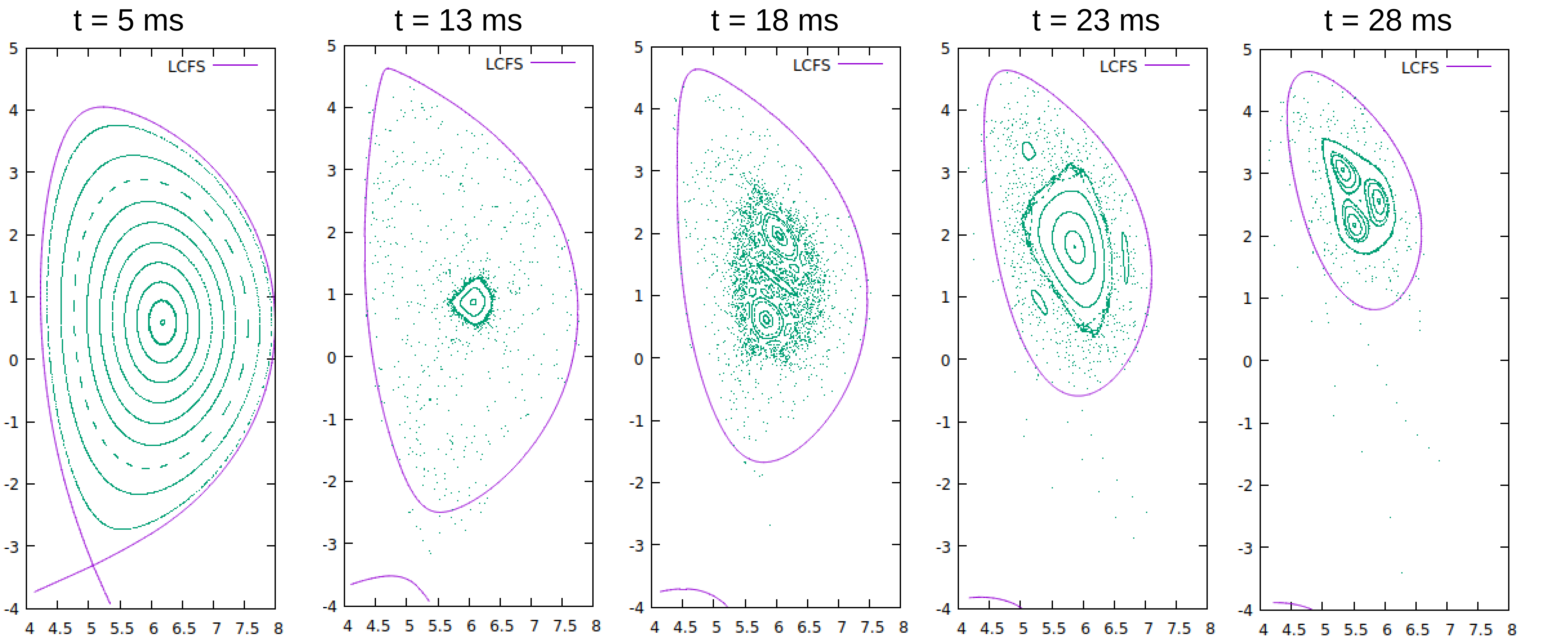
The coils only see plasma/wall field changes in the wall's L/R time (due to wall shielding)

2D / 3D comparison run for case 1

- Similar current evolution
- q_{95} larger for 3D case



3D run for case 1 (Poincare plots)



3D run for case 1 (RE confinement)

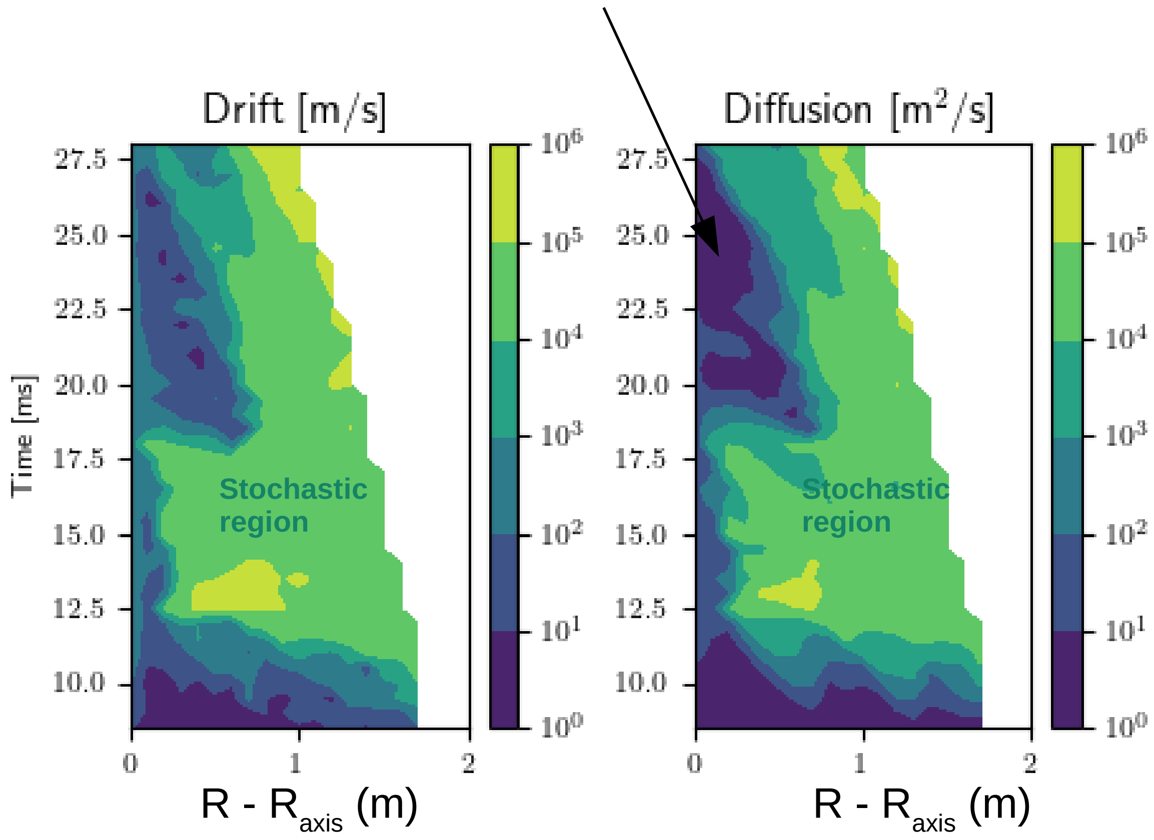
Work performed by **K. Särkimäki**

- RE particles initialized at different locations on the midplane with

$$p = 10^{0.5} mc, \ v_{\|}/v = -0.9$$

- RE particles are tracked for 0.04 ms or until they are lost to the wall .
- Stochastic regions deconfine REs in very short time-scales (< 1 ms) and **REs depletion is expected**
- **REs may survive in the small confined regions in the core** where the avalanche mechanism dominates

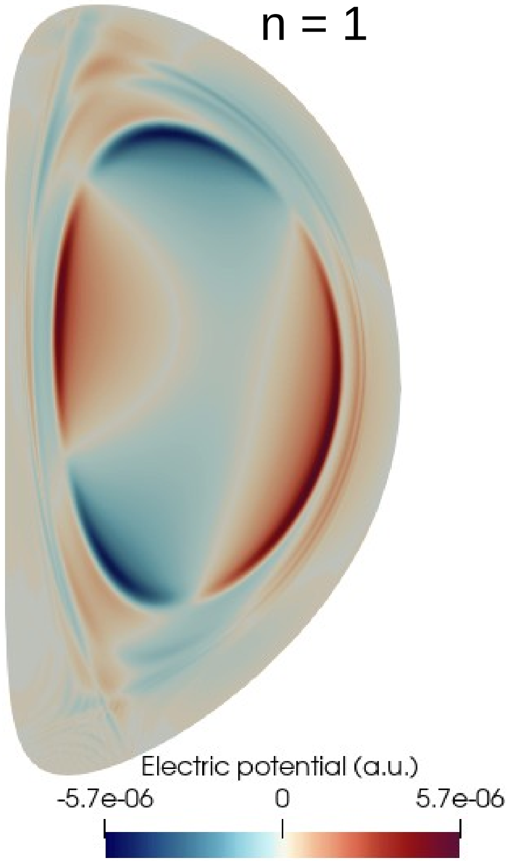
Confined regions re-appear at the core

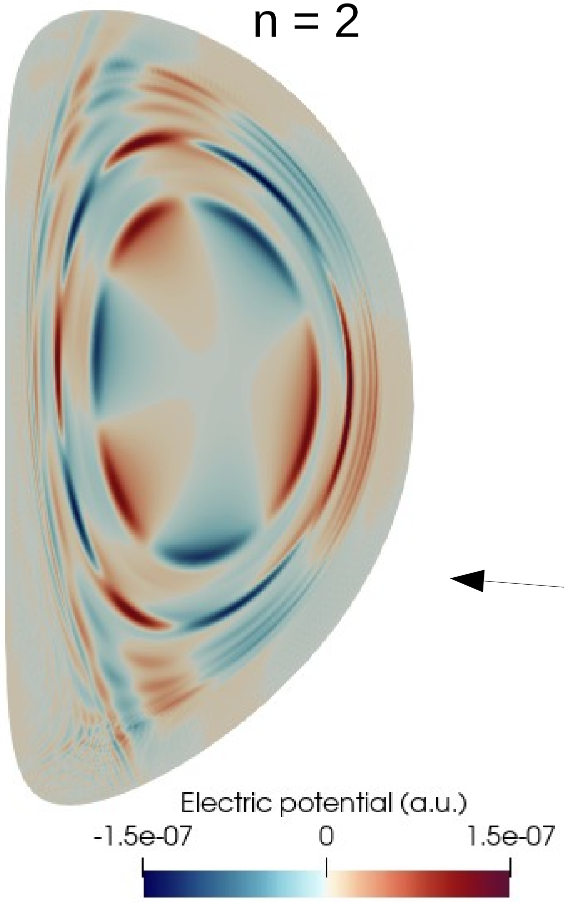


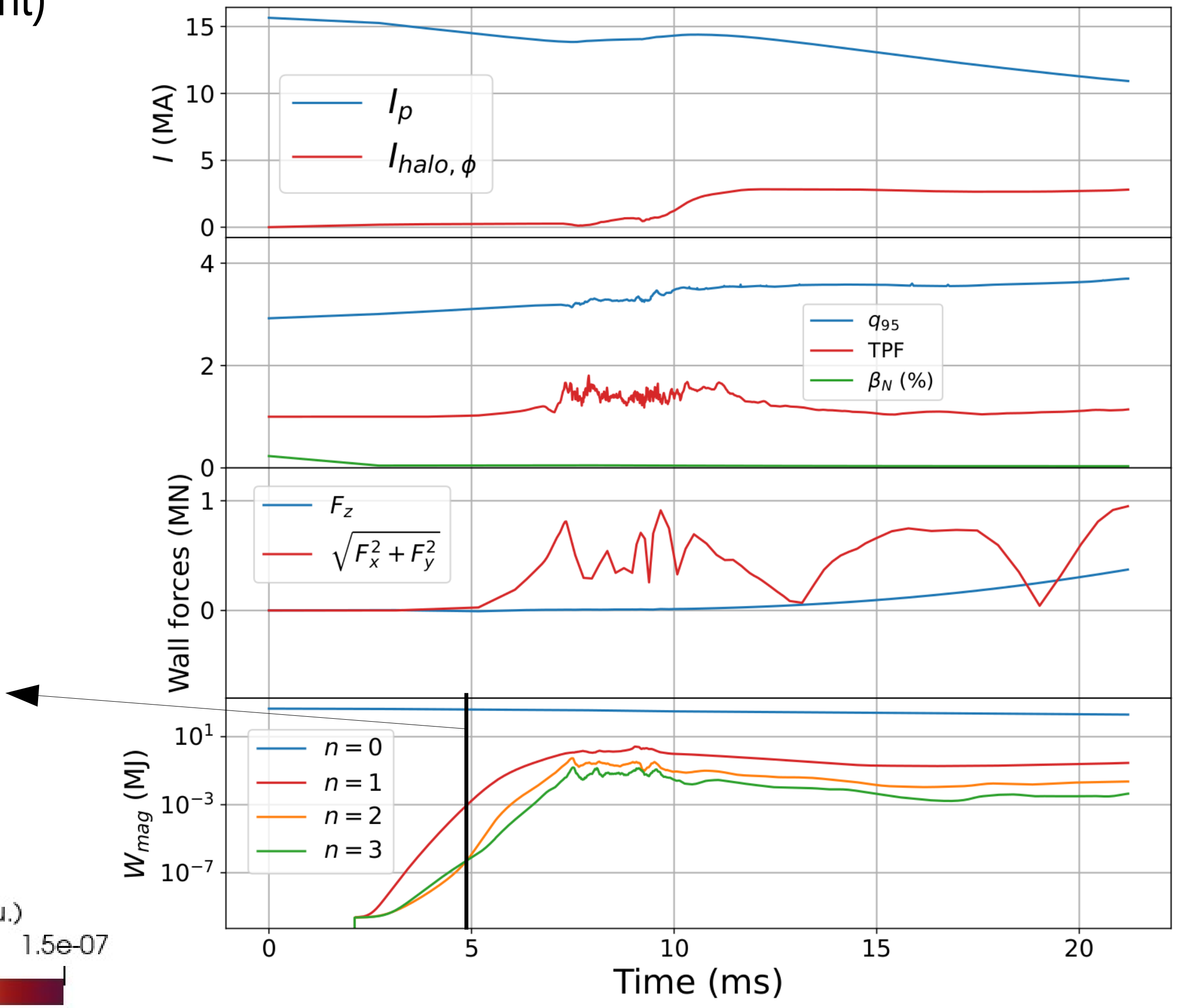
Evaluation of effective RE radial transport coefficients from [Särkimäki, *NF* ***58***, p. 125017]

3D run for case 2 (peaked T_e, still running...)

- **Dominant 2/1 mode** (other tearing modes are also present)

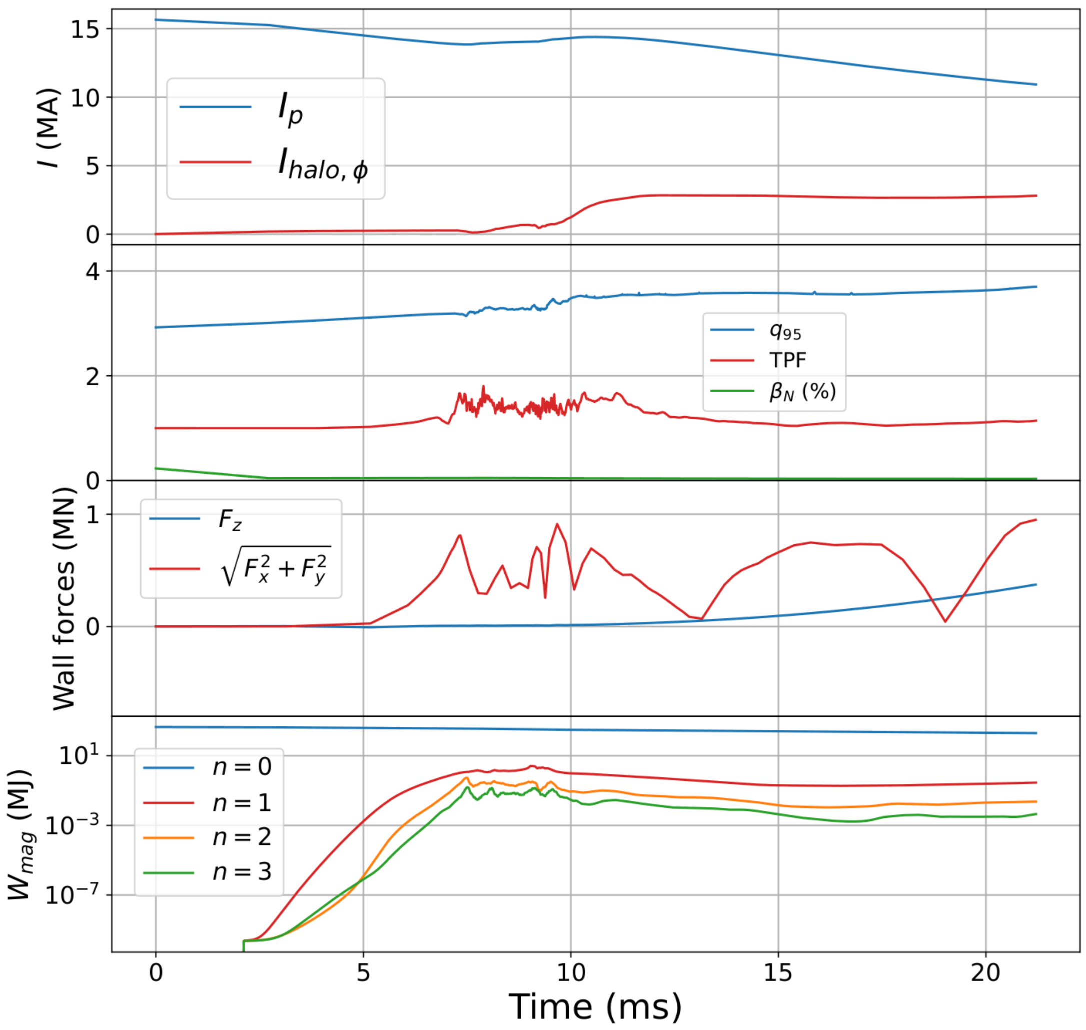






3D run for case 2 (still running...)

- **Dominant 2/1 mode** (other tearing modes are also present)
- Sideways forces are larger (but still < 1 MN)

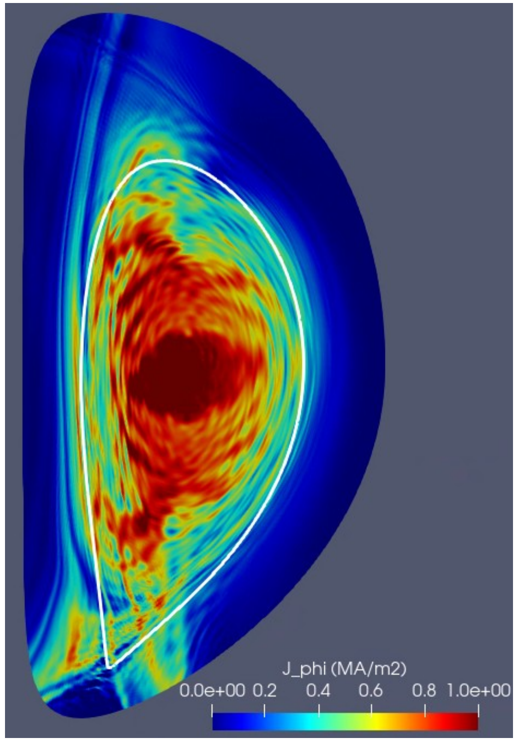


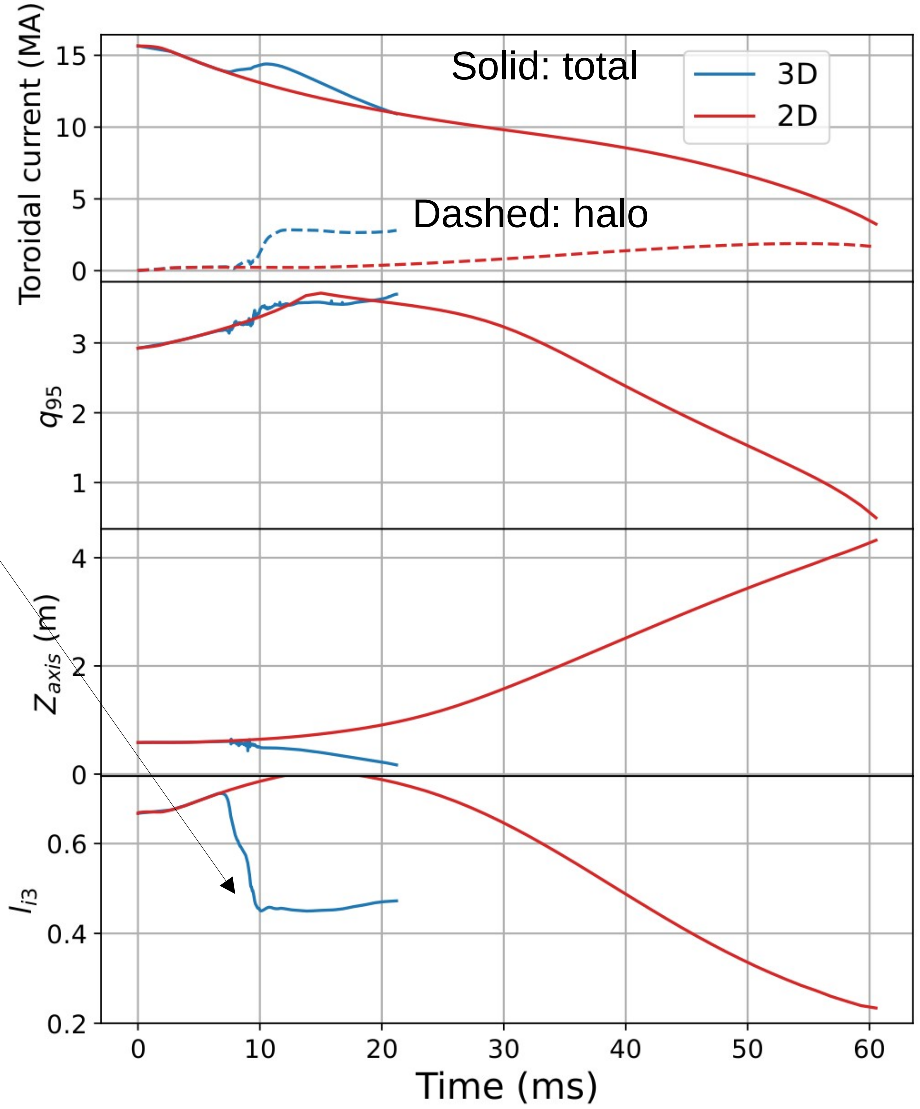
3D/2D comparison for case 2 (still running...)

- **Dominant 2/1 mode** (other tearing modes are also present)
- Sideways forces are larger (but still < 1 MN)
- Stronger MHD activity (large current profile flattening)
  - Re-distribution of current into the halo
  - **Plasma moves downwards**

    (direction sensitive to l_i changes)

    [Lukash, *PPCF 47*, p. 2077]





Conclusions

- **A full 3D CQ simulation was performed with JOREK-STARWALL**
- Post-TQ ITER 15 MA (mitigated) disruption (Current quench time ~50 ms)
- Unstable to several tearing modes (2/1, 3/1, 3/2, 6/2 ...)
- $q_{95} > 2$ during the evolution (no strong kink modes)
  - → **Small horizontal forces (<1 MN)** compared to JET extrapolations (~40 MN)
  - → **Maximum vertical forces of 11 MN**
- Forces can increase when the plasma is gone: **Runs are required after the CQ!**
- **A fast CQ in ITER avoids force amplification due to rotation**
- **Significant field stochasticity observed but confined regions reform**
  - → **REs quickly deconfined in stochastic regions, but could survive in small core regions**
  - → **Effective RE radial transport coefficients computed** (K. Särkimäki)

Future work

- Complete and analyze case 2 (downward VDE)
- Use RE transport coefficients to predict RE beam current (V. Bandaru, K. Särkimäki)
- Repeat simulations with more advanced models (including Ohmic heating, impurity radiation, sheath BCs)
- Study influence of wall asymmetries