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DTT Consortium

JOREK simulations of runaway electron beam generation in DTT

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Outline

- Introduction: DTT and motivation
- JOREK code and RE treatment
- Scenarios and equilibriums
- ATQ simulations
- 2D CQ simulations for the Day-0 scenario
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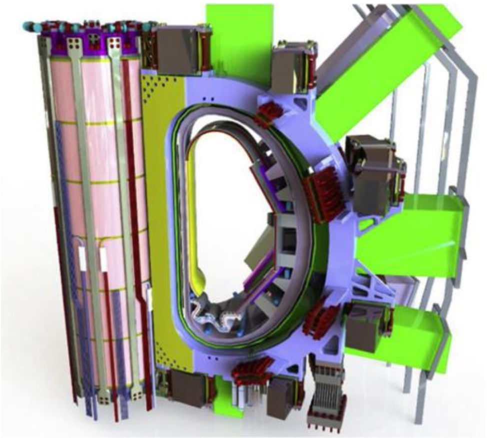
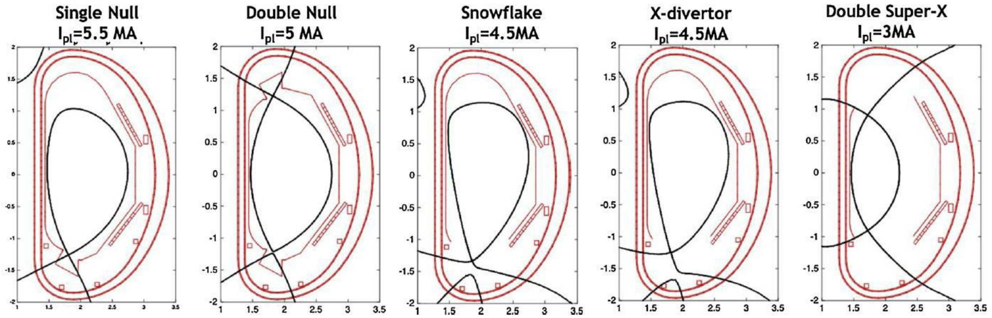
Divertor Tokamak Test (DTT) facility

The DTT facility that will be built in Frascati, Italy, will serve as a test bed for the EU-DEMO regarding **advanced magnetic** and **divertor configurations**.



[1]



[1]

While its size is much smaller compared to ITER or DEMO, DTT **preserves** the value of the **ratio** of the **power flowing to the divertor** to the **major radius** (P_{sep}/R) thanks to substantial external heating power.

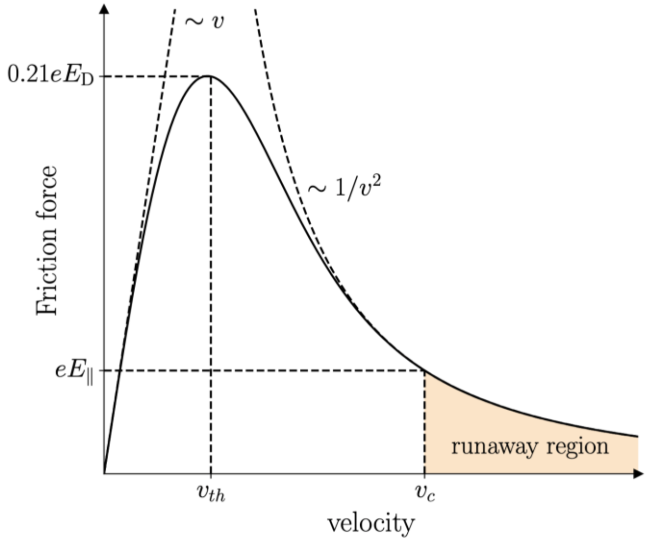
	DTT	ITER	DEMO
R (m)	**2.19**	6.2	9.1
a (m)	**0.7**	2	2.93
A	**3.1**	3.1	3.1
I_p (MA)	**5.5**	15	19.6
B (T)	**6**	5.3	5.7
Heating P_{tot} (MW)	**45**	120	460
P_{sep}/R (MW/m)	**15**	14	17
Pulse length (s)	**95**	400	7600

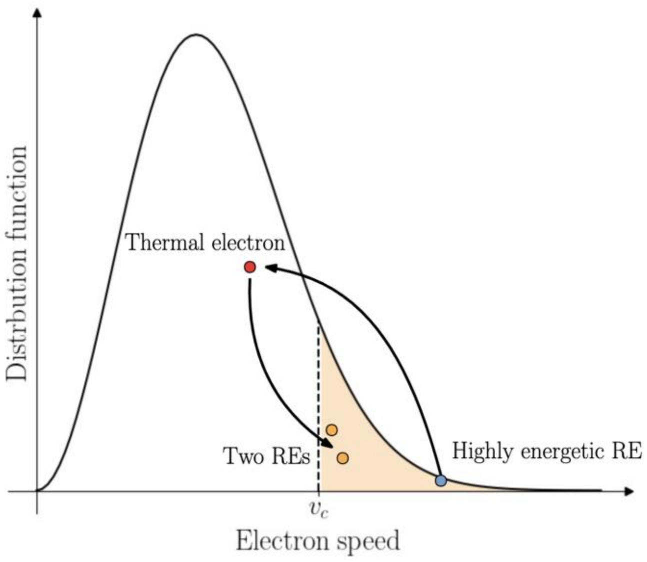
[2]

[1] Ambrosino R. 2024 *Fusion Engineering and Design* **167**, 112330
[2] DTT website, https://www.dtt-project.it

Disruptions and runaway electrons

- Failures, accidents, or unforeseen MHD instabilities in tokamaks can trigger **disruptions**.
- The loss of plasma confinement results in **temperature decrease**, which **increases** the electrical **resistivity**, inducing a current preserving $E_{\parallel}$.
- Electrons with a sufficient velocity ($v > v_c$) can be accelerated towards the **speed of light**. In turn, they can make other electrons enter in the runaway regime, **avalanching**.



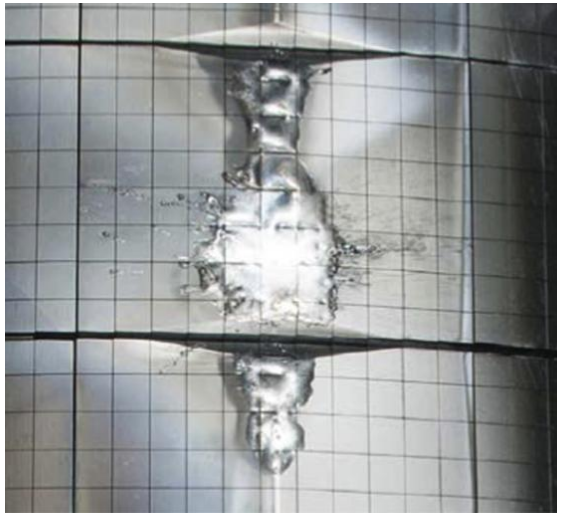


Illustrations taken from: P. Halldestam and H. Bergstroem *2022 MSc thesis*

Motivation

- Runaway electrons (REs) avalanche depends **exponentially** on the pre-disruption I_p and they can form beams reaching energies up to several **tens of MeV**.

- Uncontrolled loss of such beams in larger devices would lead to **deep melting of PFCs** and possible damage to cooling pipes.



Matthews G. F. *et al 2016 Physica Scripta* **2016**, 014070

- Notwithstanding the smaller size of DTT if compared to ITER or DEMO, **disruptions** and **runaway electrons** (RE) formation pose a **considerable concern** to its operation.

- The aim of this work is to contribute to the **design** of effective **avoidance and mitigation strategies** by studying the extent of REs generation in different DTT scenarios and their impact on PFCs.

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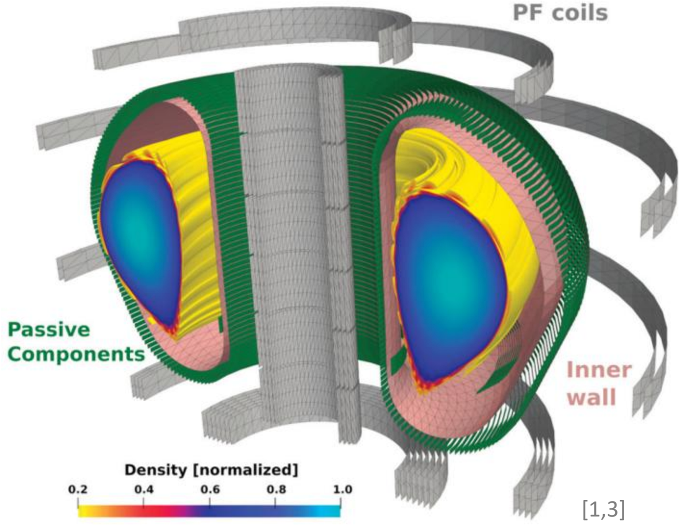
The JOREK code

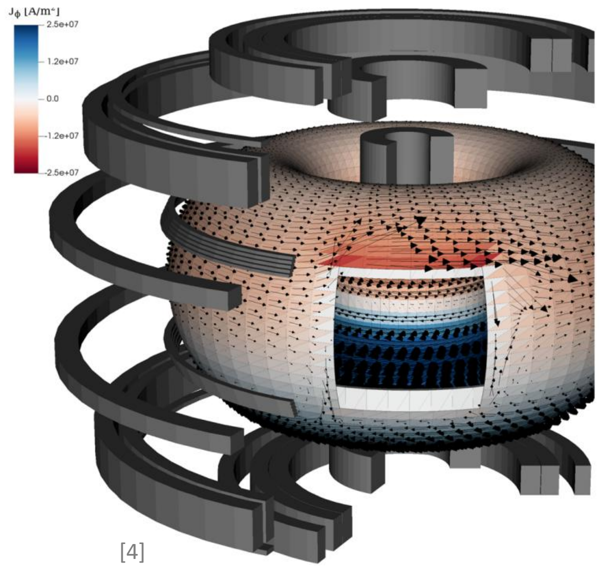
- JOREK [1,2] is a **3D non-linear** magneto-hydrodynamic (**MHD**) code that can resolve realistic toroidal tokamak X-point geometries.

- It uses **finite elements** in the poloidal plane and Fourier expansions in the toroidal direction.

- While the main fields of applications are **ELMs** and **disruptions**, many other are present, including (but not limiting to):
  - Turbulence studies
  - Energetic particles
  - Stellarator applications



[1,3]



[4]

[1] Hoelzl M. *et al* 2021 *Nuclear Fusion* **61**, 065001
[2] Hoelzl M. *et al* 2024 *Nuclear Fusion* **64**, 112016
[3] Artola F. J. *et al* 2018 *Nuclear Fusion* **58**, 096018
[4] Isernia N. *et al* 2023 *Physics of Plasmas* **30**, 113901

REs models in JOREK

1. **"Post-processing" Kinetic REs** by tracing macroscopic marker particles in the fields computed via JOREK:
   - Accurate transport and phase space information
   - May be computationally expensive
   - No effect of REs on the bulk plasma

2. **RE fluid model coupled with MHD equations**, treating REs as a separate species from the background plasma, allowing for feedback and, thus, a more complete modelling:
   - MHD-RE interactions are captured
   - Less expensive computationally
   - No accurate transport

3. **Kinetic RE model coupled with MHD** equations, allowing to capture the transport of REs more accurately (**recent development** [Bergström H. *et al* 2025 *Plasma Phys. Control. Fusion* **67**, 035004]):
   - MHD-RE interactions are captured
   - Accurate transport and phase space information
   - More computationally expensive

REs fluid model in JOREK

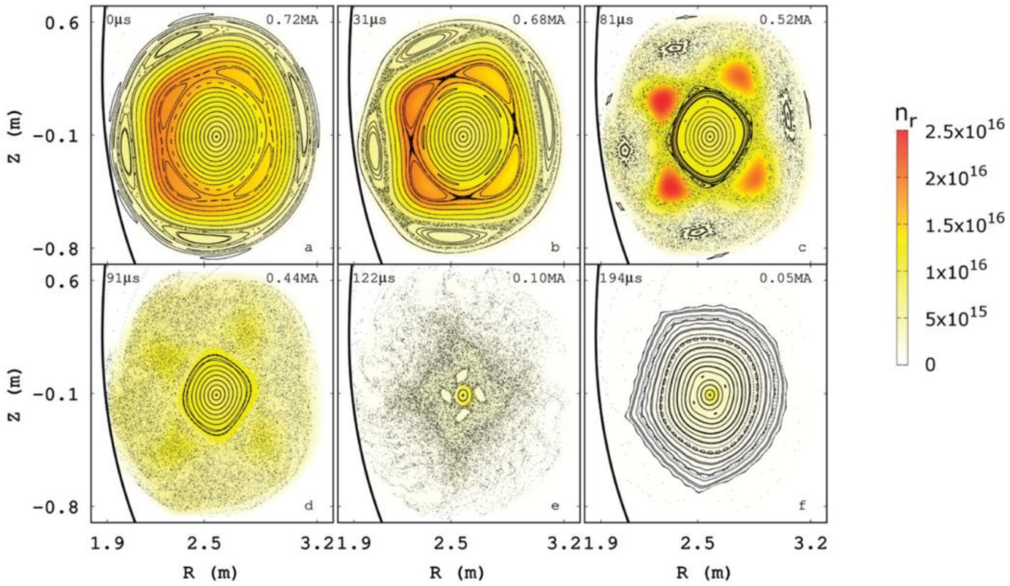
- REs are treated as a **separate fluid species** from the background plasma.

- Only **RE number density** n_{RE} is evolved, coupled electromagnetically with the reduced MHD equations via **current-coupling**.

- n_{RE} is subjected to transport via $E \times B$ drift and parallel advection at the speed of light. A **large parallel diffusivity** $D_{\parallel,RE}$ mimics the latter.

- RE volumetric sources include generation of RE seed via Compton scattering and tritium decay, together with the avalanche source.

- More details in:
  - Bandaru V. *et al* 2019 *Physical Review E* **99**, 063317
  - Bandaru V. *et al* 2024 *Physics of Plasmas* **31**, 082503



Bandaru V. *et al* 2021 Plasma Physics and Controlled Fusion **63**, 035024

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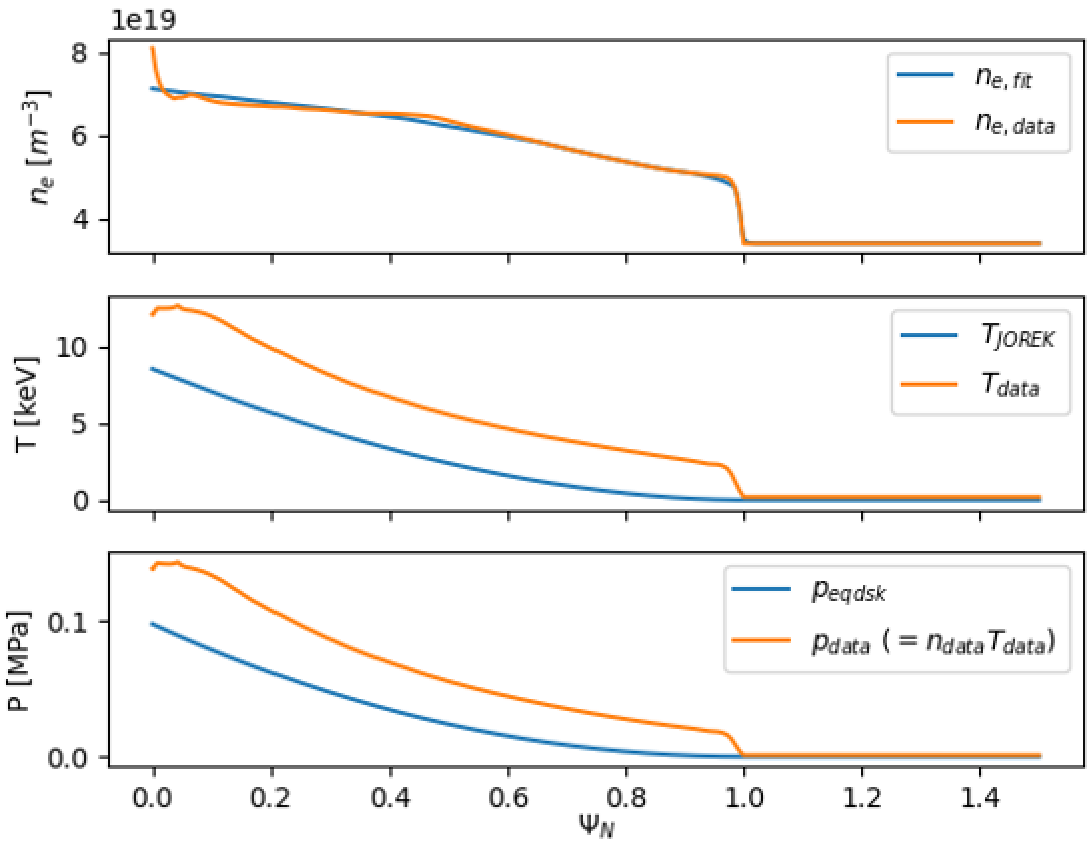
Day-0 (I_p = 2MA) scenario

- Eqdsk file from "SN scenario A (**Day-0**)" at flat-top (#07549) started from the version **v15** of CREATE-NL equilibria.

- JOREK needs **temperature** and **density** to recompute the equilibrium. A fit of the density is used together with the pressure provided by the eqdsk to retrieve the temperature to be used in JOREK (blue curve).

- The data for the density and the temperature (orange curves) are the most updated ones, while this eqdsk version is assuming hypothetical **bell-shaped plasma profiles** (contrary to the older version v13).



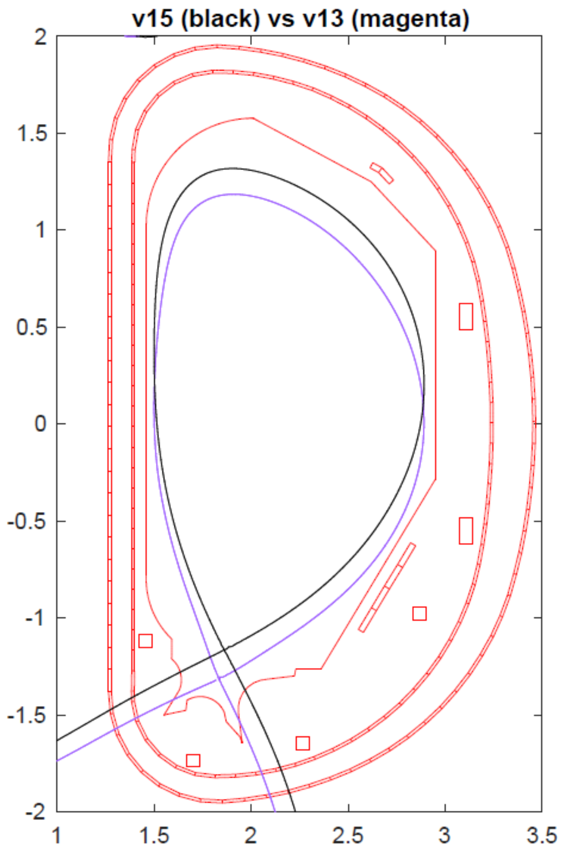
Day-0 (I_p = 2MA) scenario

- The choice of v15 with respect to v13 has been motivated by:

  1. The **higher importance** of **updated geometries** and magnetic configuration **over accuracy of plasma shapes** for the study I am performing (ATQ, see next): the version v15 (black line) considers an updated version of the configuration with respect to the older v13 (magenta line);

  2. MHD stability needs (**q>1 in all core region**) in JOREK: the eqdsk of v13 has more realistic pressure profiles, but it has a q<1 up to Ψ_N = 0.4.

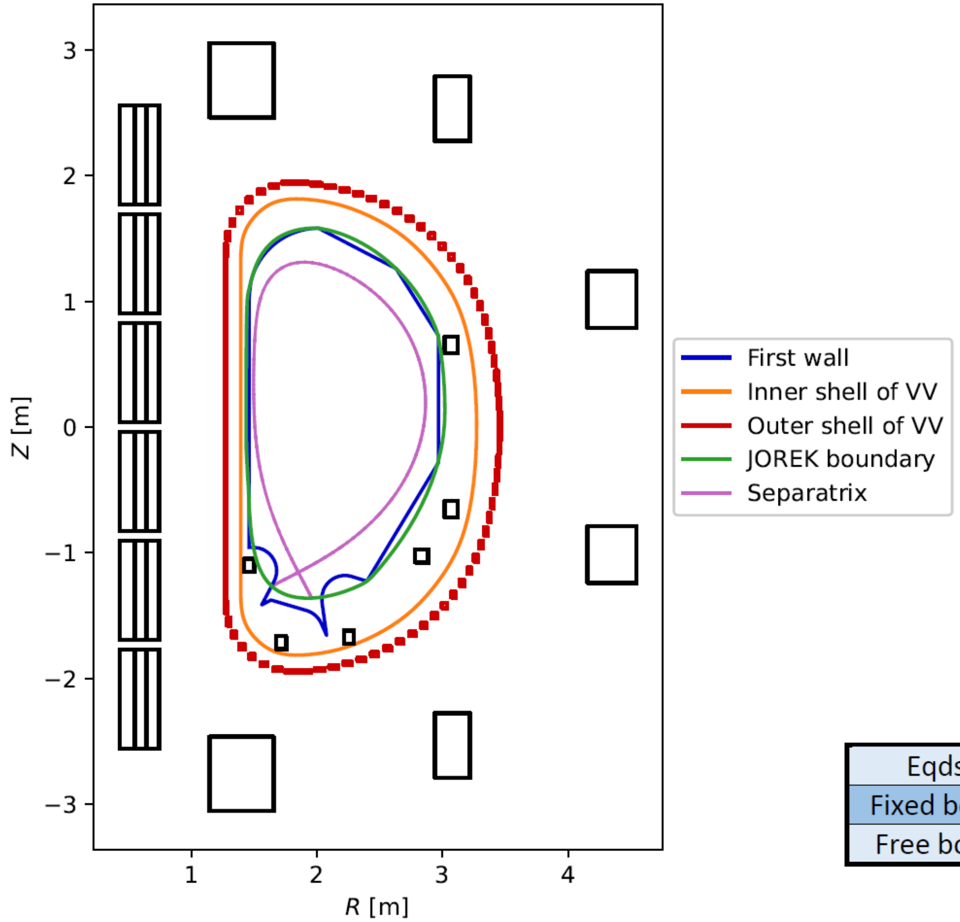
- There is ongoing work to obtain the newest version v15 with realistic pressure profiles.

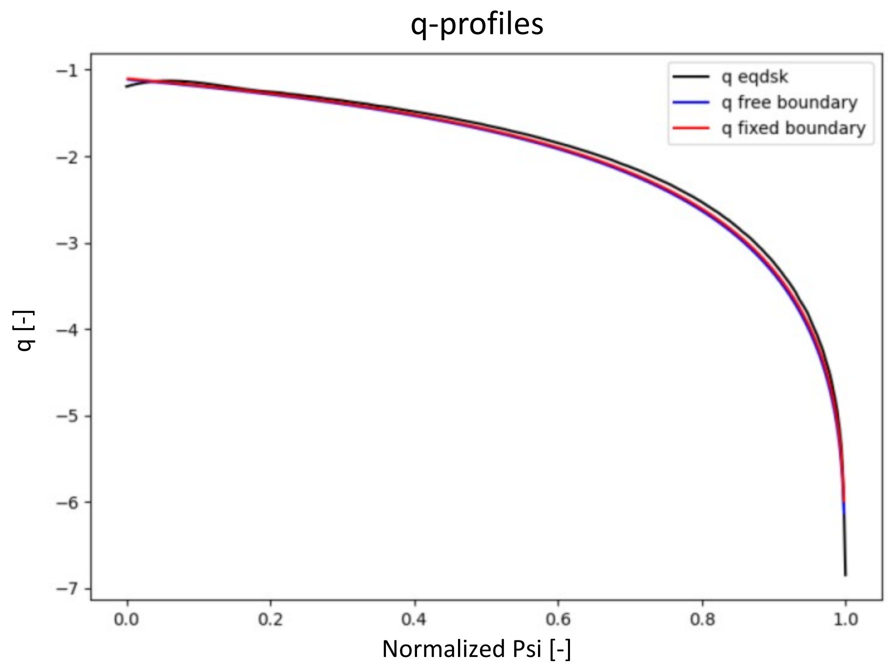


Courtesy of R. Ambrosino

Day-0 (I_p = 2MA) equilibrium in JOREK

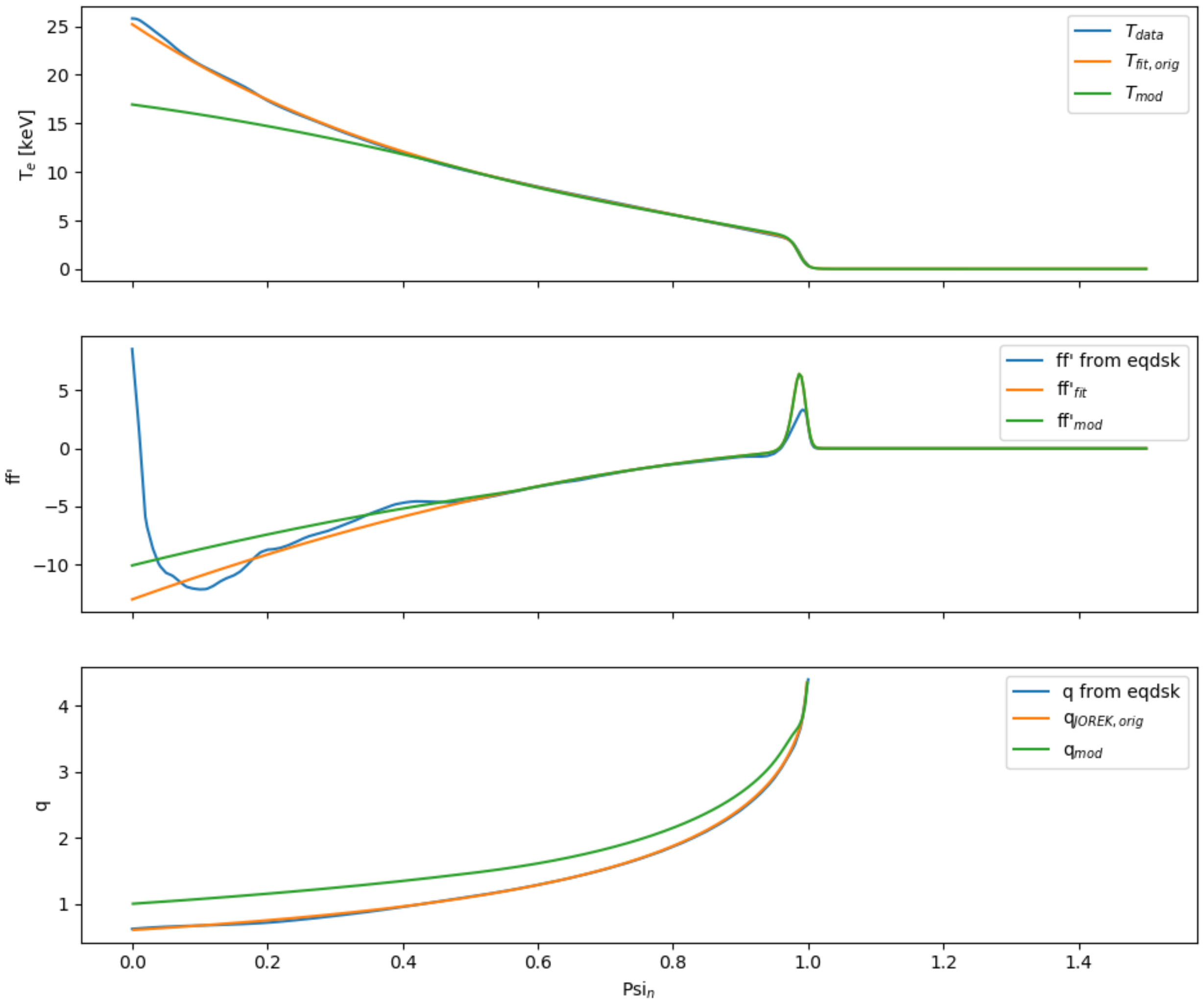
The conducting structures are included via **JOREK-STARWALL coupling**. The re-calculated equilibrium is consistent with the initial input, representing a **reliable starting point** for the work.

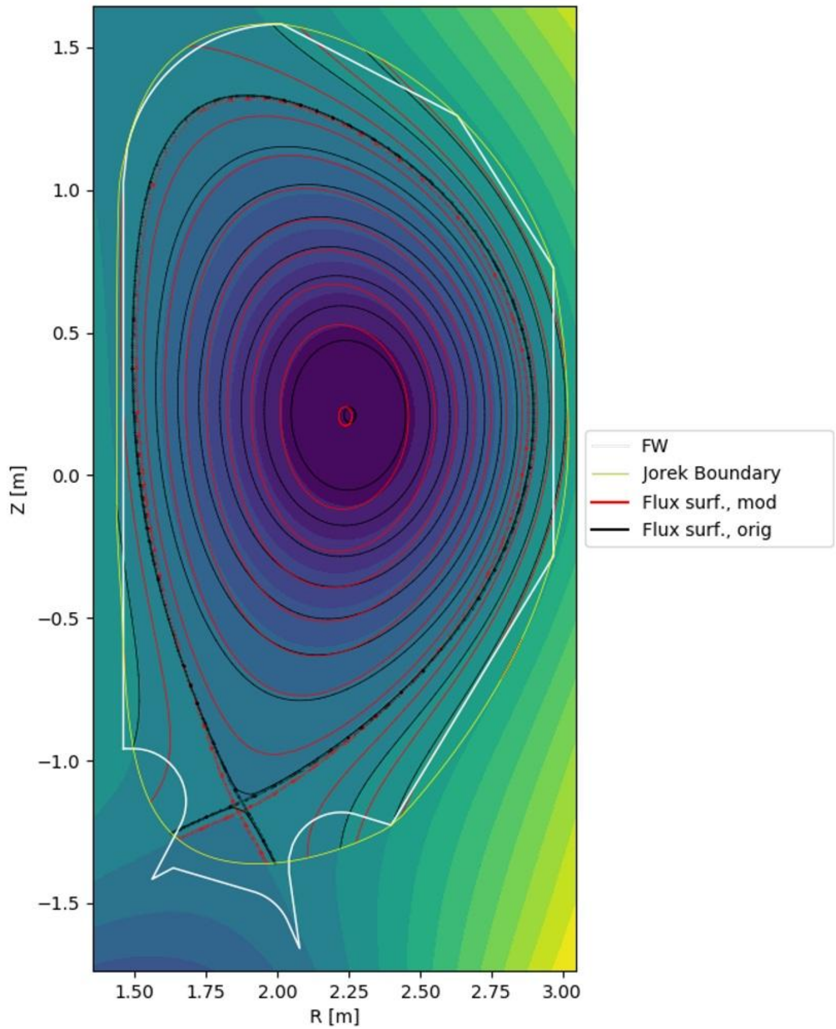




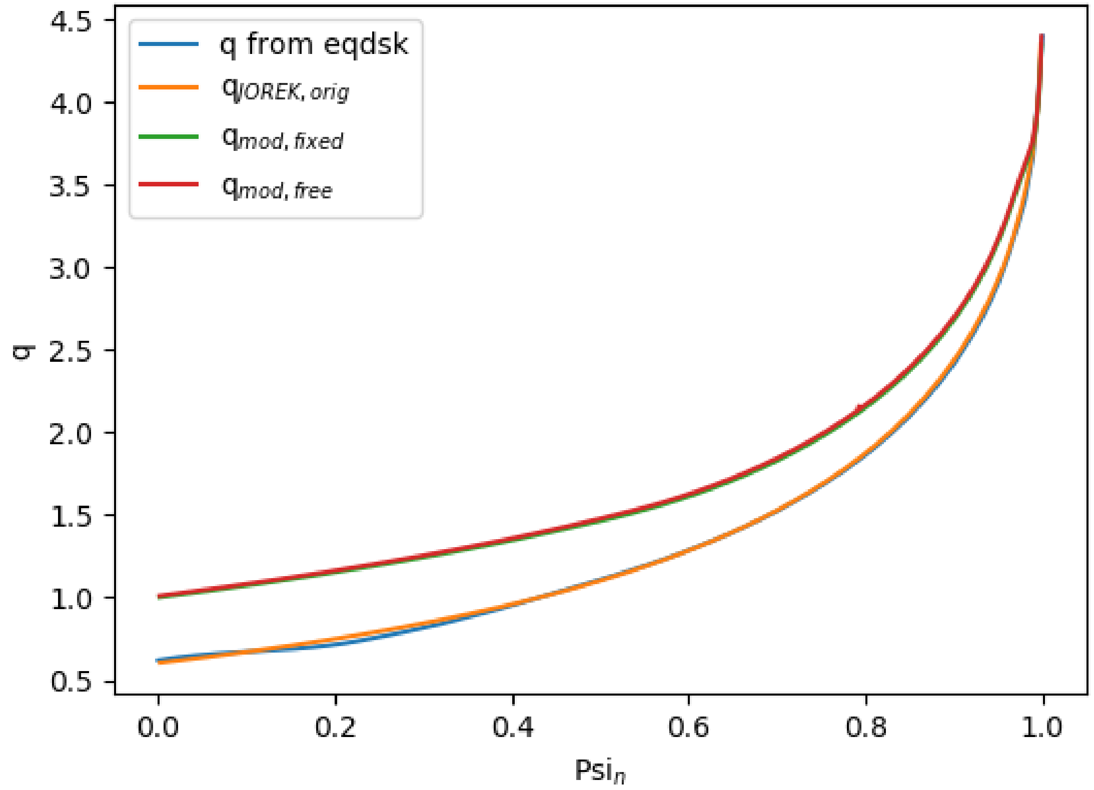
	Current	R x-point	Z x-point	R B-axis	Z B-axis
Eqdsk file	-2 MA	1.85544 m	-1.16542 m	2.24373 m	0.18796 m
Fixed boundary	-1.9969 MA	1.85855 m	-1.16388 m	2.24057 m	0.18613 m
Free boundary	-1.9845 MA	1.85274 m	-1.15680 m	2.23100 m	0.18699 m

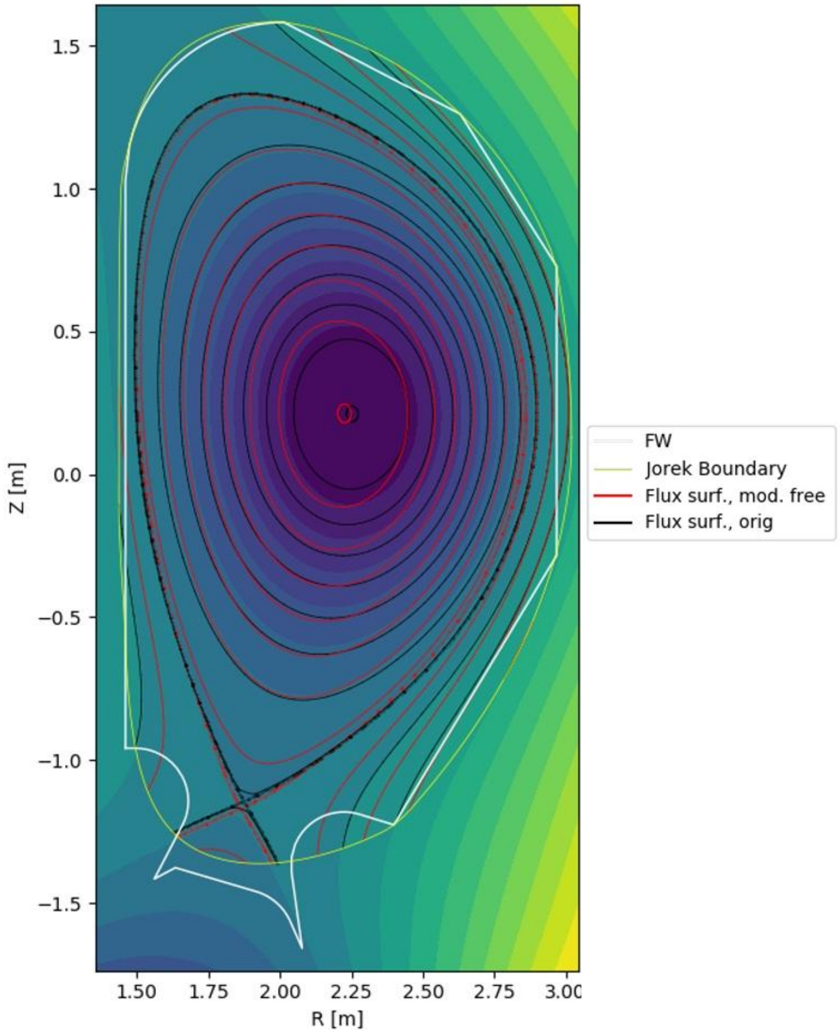
Full Power Scenario (I_p = 5.5MA) – Fixed boundary





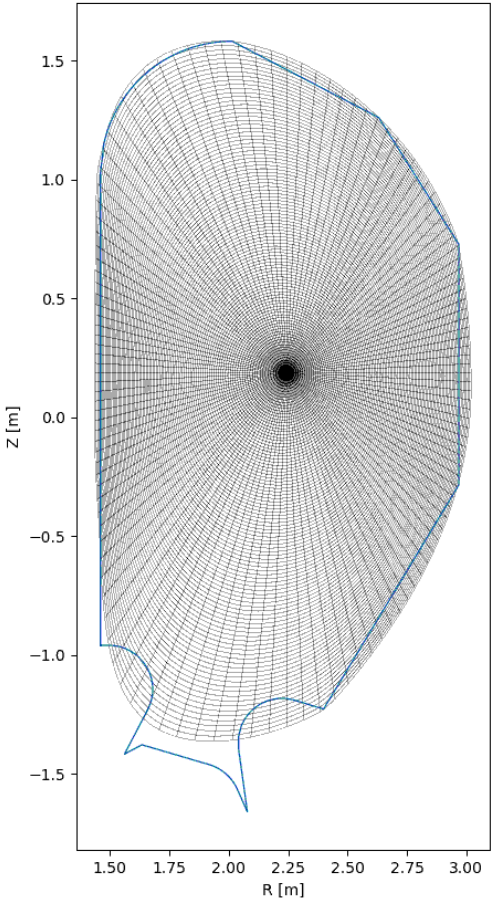
Full Power Scenario (I_p = 5.5MA) – Free boundary





- The current in the coils was adjusted to comply with the modified configuration
- **q>1** in the whole domain, both for free and fixed boundary

Simulation setup

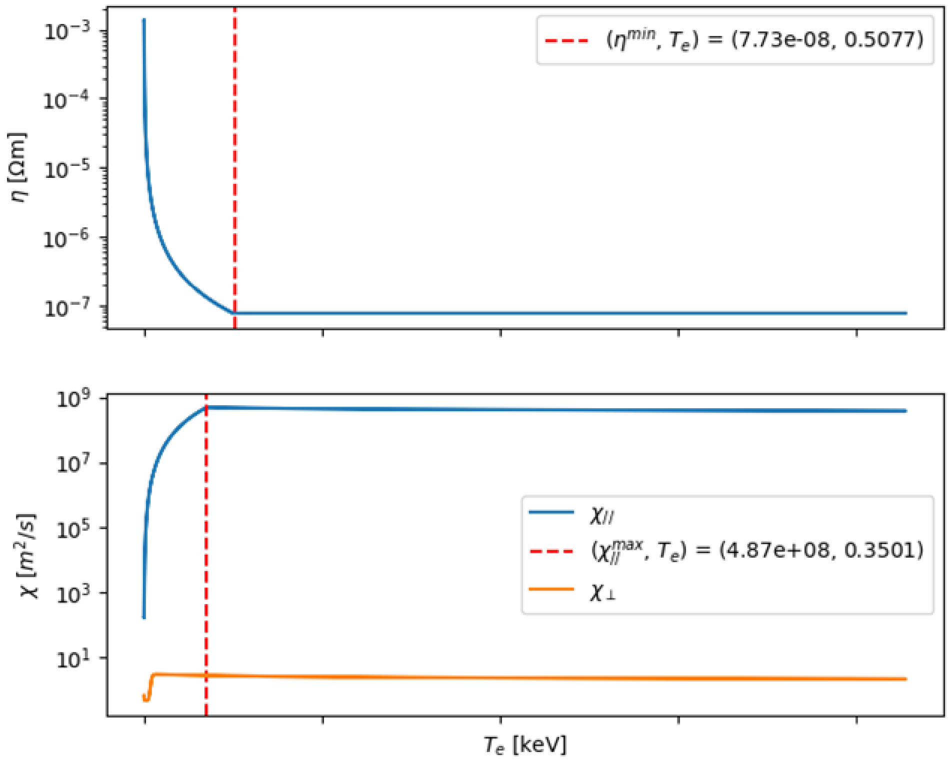


$n_R \times n_\theta = 101 \times 128$

Reduced MHD model with RE fluid with:

- $v_{||} = 0$
- single temperature
- no neutrals

Parameter	Values
$\boldsymbol{\eta}\ (\Omega\, m)$	*Spitzer*, with: $\boldsymbol{\eta^{min}} = \eta(T_e = 500\ eV)$
$\boldsymbol{\chi}_{\parallel}\ (m^2 s^{-1})$	*Spitzer-Haerm*, with: $\boldsymbol{\chi_{\parallel}^{max}} = \chi(T_e = 350\ eV)$
$\boldsymbol{D}\ (m^2 s^{-1})$	1.23
$\boldsymbol{\eta_w / d_w}\ (\mu\Omega)$	$50\ \left(= \frac{0.75\ \mu\Omega m}{15\ mm}\right)$



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Artificial thermal quench (ATQ)

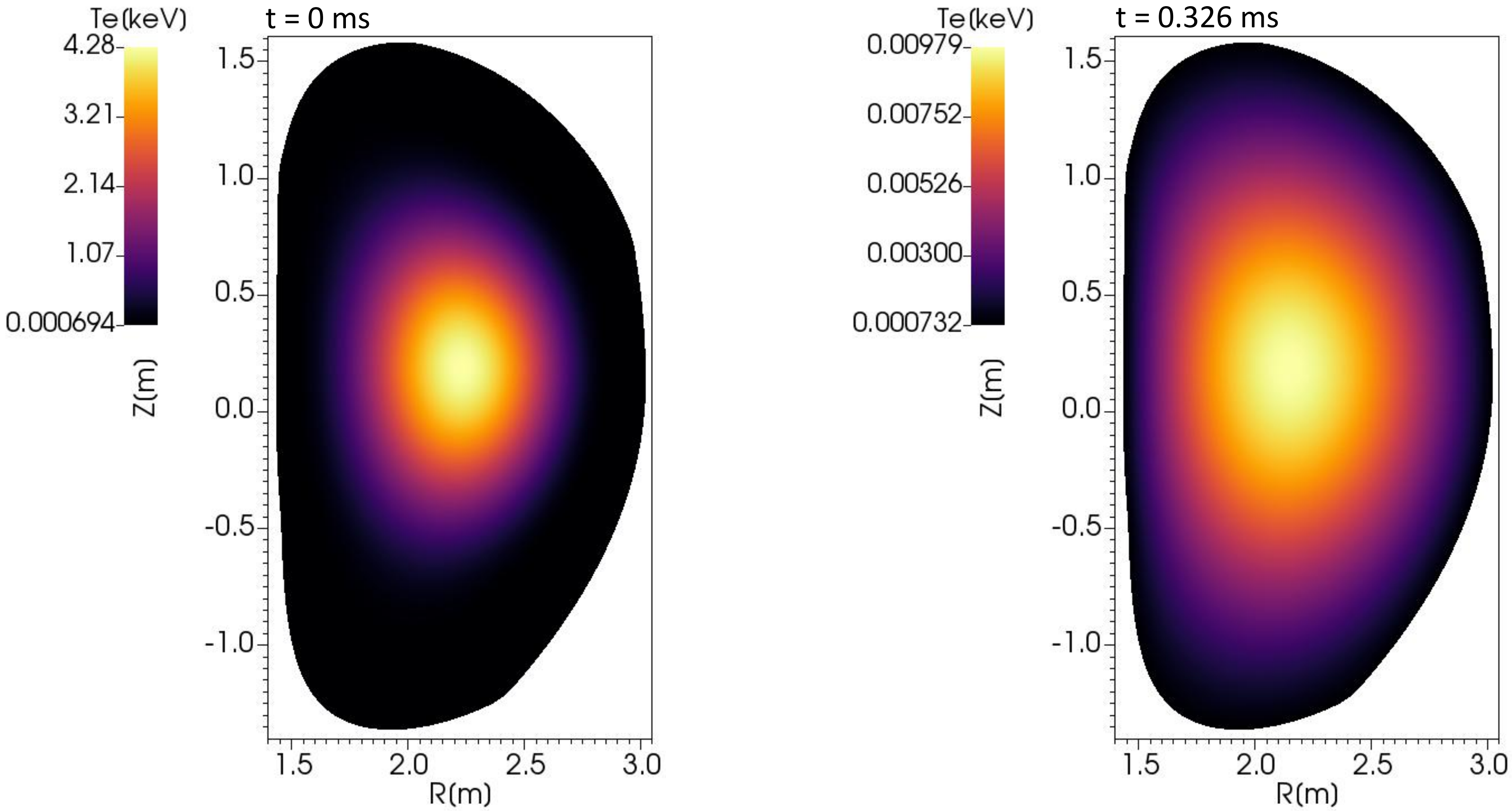
- The **artificial thermal quench** (ATQ) is used to arrive in a simplified way to a post-disruption phase, mimicking the physics that actually occurs during a disruption.

- It is a procedure already adopted to replicate experiments or make predictions in:
  - JET [Schwarz N. *et al* 2023 *Nuclear Fusion* **63**, 126016]
  - ASDEX Upgrade [Schwarz N. *et al* 2023 *Plasma Physics and Controlled Fusion* **65**, 054003]
  - ITER [Bandaru V. *et al* 2024 *Nuclear Fusion* **64**, 076053]
  - EU-DEMO [Vannini F. *et al* 2025 *Nuclear Fusion* **65**, 046006]

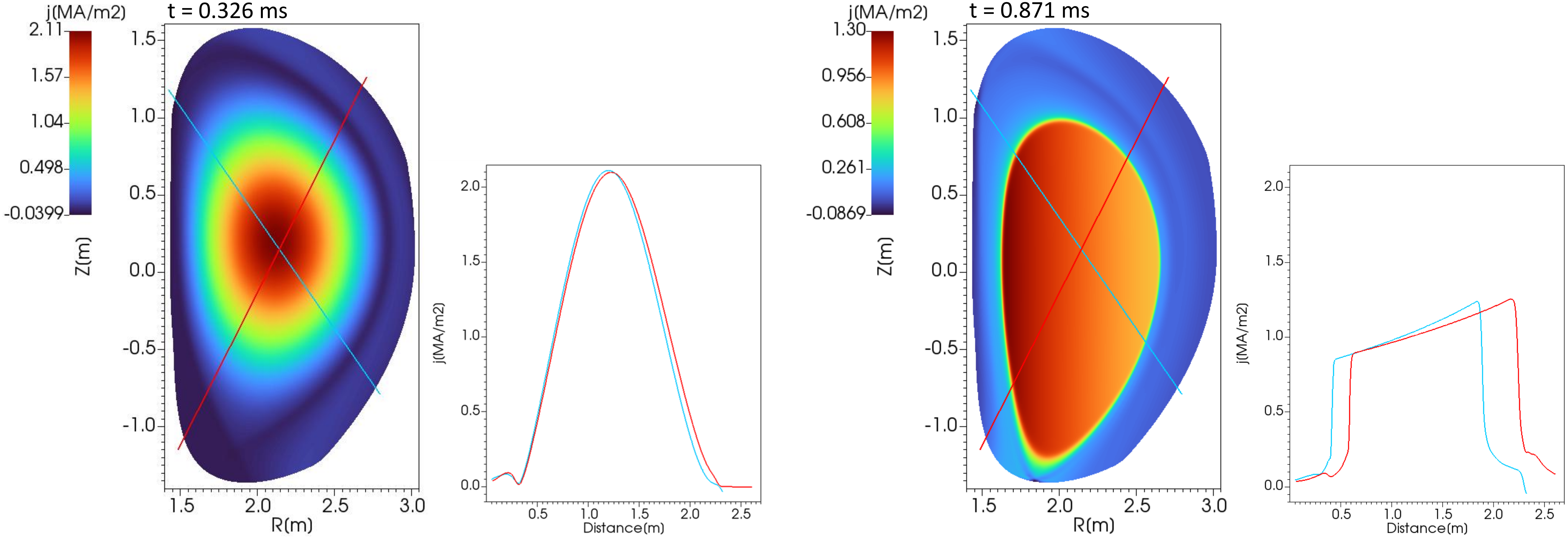
- This phase is run in **2D** (toroidally symmetric, n=0) and its steps are:
  1. **Perpendicular thermal diffusivity** is **increased** to have a quick thermal collapse
  2. The **current profile** is **flattened** via large electrical hyper-resistivity
  3. **Impurities** are **injected** into the domain in a uniform fashion

Thermal quench phase

Perpendicular thermal diffusivity is **increased** to have a quick thermal collapse. Ohmic heating is switched off. Temperature drops to $T_e \sim 10$ eV (from $4.3\ keV$) after $\sim 0.3\ ms$



Current flattening phase and impurity injection



- The current profile is flattened inside the core by increasing hyper resistivity, which also implies a **flattening** of the profile of the **safety factor q**.
- **Neon impurities** are **injected** into the domain with a uniform distribution. CQ is then simulated.

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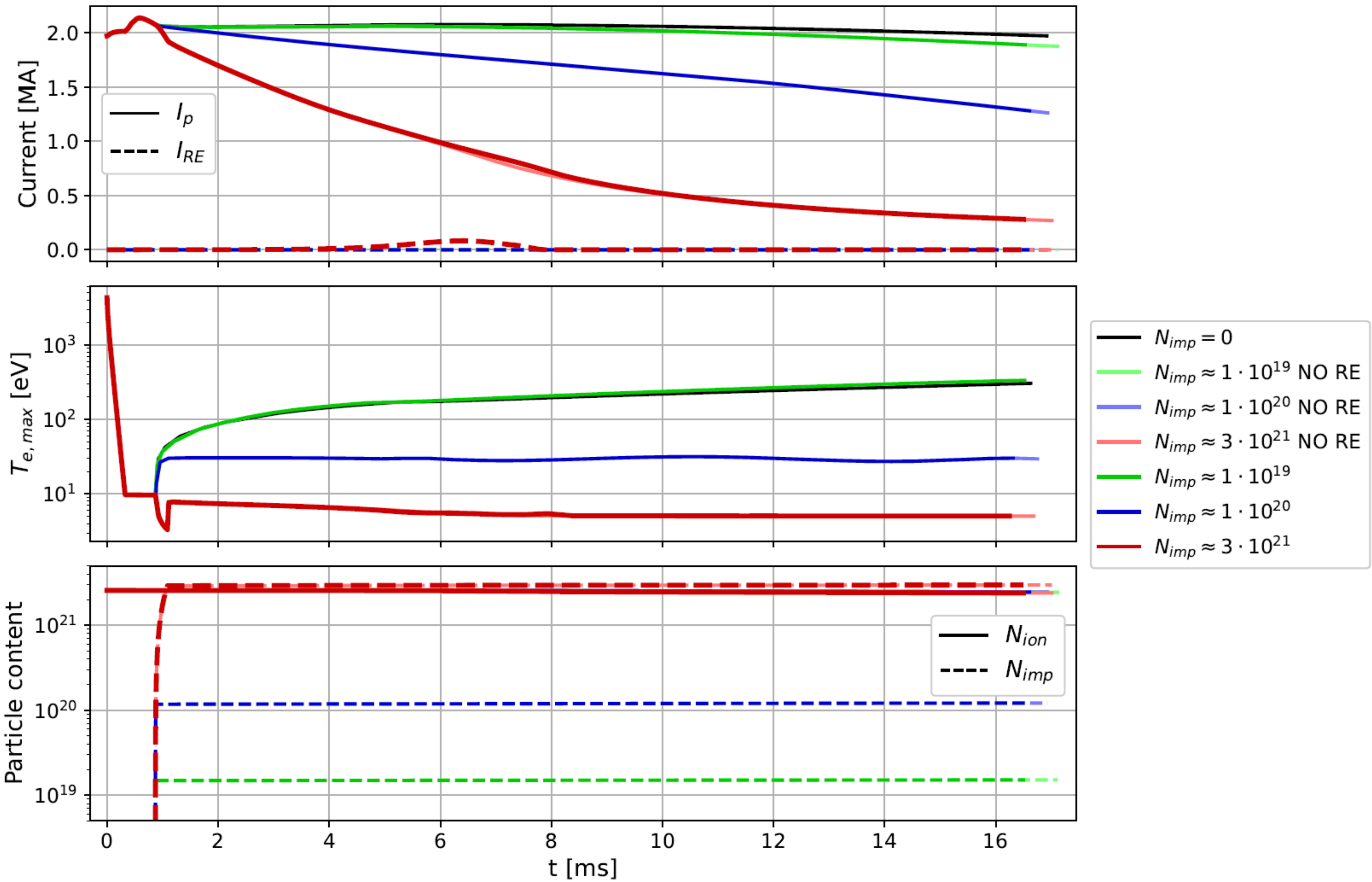
Current quench phase

We explored various current quench scenarios to evaluate the impact of **impurities** and **initial RE seed** currents:

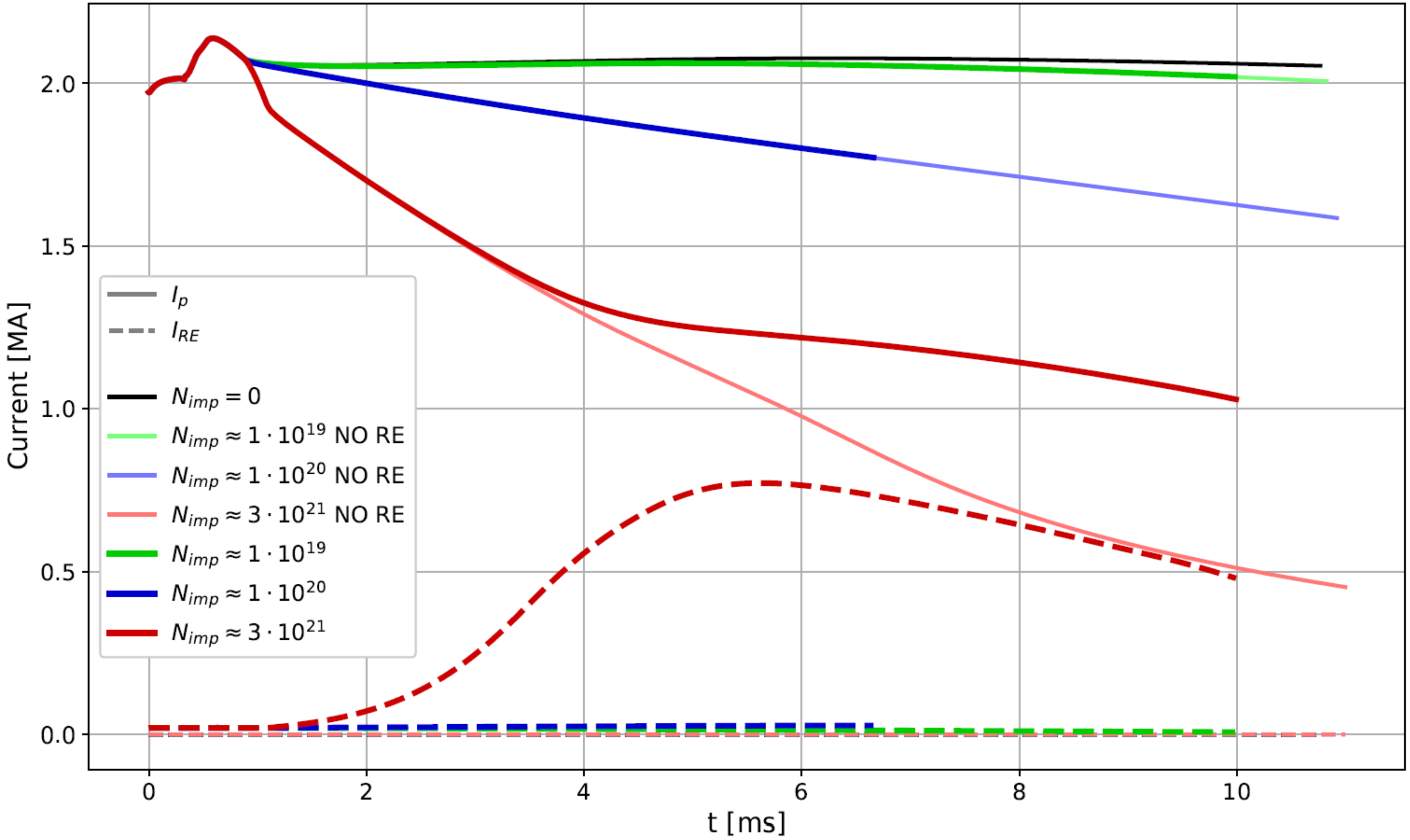
- a **benchmark** simulation without impurities nor REs is used as reference;
- the impurity content varied from $\mathbf{10^{19}}$ to $\mathbf{3 \cdot 10^{21}}$ number of particles;
- the RE seed currents ranged from $\mathbf{2}$ **A** to $\mathbf{20}$ **kA**.

For each impurity level, the CQ is run **with and without REs**.

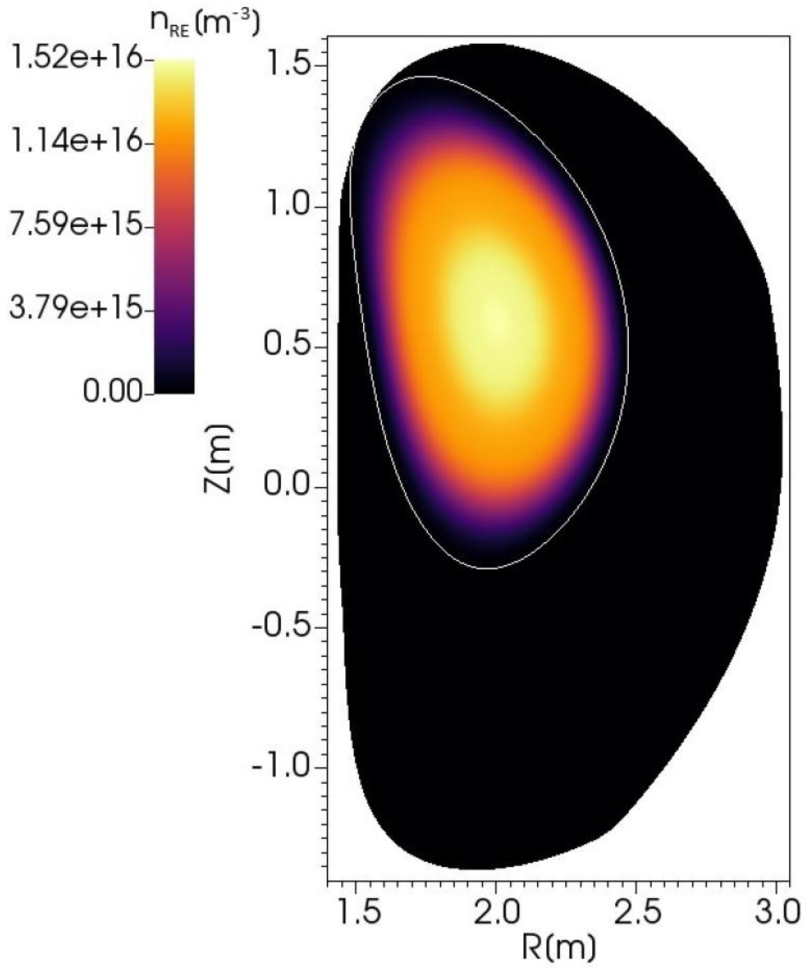
RE seed current = 200 A



RE seed current = 20 kA



RE seed current = 20 kA



- Similar post-TQ temperature in the confined and open field line region and the relatively high SOL temperatures cause **substantial currents** to be induced in the **open field line region**, where electrons cannot be converted to REs.
- Instead, almost the entire current inside the **confined region** is converted into **REs**.
- The growth of REs is stopped by the **scraping-off** of the plasma against the first wall, due to its **vertical motion velocity exceeding that of RE avalanche**.

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- Non-negligible RE currents are only observed in a scenario that combines the highest initial RE seed current and impurity content considered here, reaching a peak of about 0.8 MA.

- These conditions should be easily **avoidable** in practical Day-0 operation of DTT. The highest number of impurities was valuable for exploring RE risks, but it does not reflect realistic operational conditions. **Managing the impurities** injected is a straightforward and effective approach to **minimize or avoid RE formation**.

- Thus, the **Day-0 scenario** can be **considered safe** regarding the risks associated with RE beams, removing the immediate need for complex RE mitigation strategies.

- The work is ongoing for the **full power scenario** of DTT ($\boldsymbol{I_p \approx 5.5}$ **MA**), where similar impurity levels and RE seeds currents are expected to result in much more substantial RE generation, because of the exponential dependence of the RE avalanche on the pre-disruption current. **3D** studies of **beam termination** on PFCs will follow.