DE LA RECHERCHE À L'INDUSTRIE

3D non-linear MHD modelling of Massive Gas Injection (MGI) -triggered disruptions in JET

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7th Theory and Simulation of Disruptions Workshop,
Princeton, 5-7 July 2019 (presented remotely)

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Outline

- The model
- Description of a typical simulation
- Mechanisms leading to the Thermal Quench (TQ)
- Physics of the TQ and I_p spike

The model

The JOREK model for MMI (i.e. MGI or SPI) simulations

- Reduced MHD, no diamagnetic effects

- <u>8 variables</u>:
  - Poloidal magnetic flux ψ ($\mathbf{B} = F_0 \nabla\phi + \nabla\psi \times \nabla\phi$)
  - Toroidal current density $j = \Delta^* \psi$
  - Electric/flow potential u
  - Parallel velocity $v_{||}$

$$\mathbf{v} = v_{||}\mathbf{B} - R^2 \nabla u \times \nabla\phi$$

(assumed common for all species)

  - Vorticity $\omega = \frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial u}{\partial R}\right) + \frac{\partial^2 u}{\partial Z^2}$
  - Impurity mass density ρ_{imp} (summed over all charge states)
  - Total mass density (main ions + impurities) ρ
  - Temperature T, assumed common to all species

- Coronal equilibrium (CE) assumption provides charge state distribution, radiation losses, ionization energy (ADAS data)
  - Benchmark with M3D-C1 and NIMROD suggests that CE assumption slows down the radiative collapse

Ohm's law $$\frac{\partial \psi}{\partial t} = \eta(T_e)\Delta^*\psi - R\{u,\psi\} - F_0\frac{\partial u}{\partial \phi}$$ (+ hyper-resistivity)

Vorticity $$R\nabla\cdot\left[R^2\left(\rho\nabla_{pol}\frac{\partial u}{\partial t} + \nabla_{pol}u\frac{\partial \rho}{\partial t}\right)\right] = \frac{1}{2}\left\{R^2\left|\nabla_{pol}u\right|^2, R^2\rho\right\} + \left\{R^4\rho\omega, u\right\}$$
$$-R\nabla\cdot\left[R^2\nabla_{pol}u\nabla\cdot(\rho\mathbf{v})\right] + \{\psi, j\} - \frac{F_0}{R}\frac{\partial j}{\partial \phi}$$
$$+\left\{P, R^2\right\} + R\mu(T_e)\nabla^2_{pol}\omega.$$ (+ hyper-viscosity)

// momentum $$B^2\frac{\partial}{\partial t}\left(\rho v_{\parallel}\right) = -\frac{1}{2}\rho\frac{F_0}{R^2}\frac{\partial}{\partial \phi}\left(v_{\parallel}B\right)^2 - \frac{\rho}{2R}\left\{B^2 v_{\parallel}^2, \psi\right\} - \frac{F_0}{R^2}\frac{\partial P}{\partial \phi} + \frac{1}{R}\{\psi, P\}$$
$$-B^2\nabla\cdot(\rho\mathbf{v})\,v_{\parallel} + B^2\mu_{\parallel}(T_e)\nabla^2_{pol}v_{\parallel}.$$

Mass conservation (impurities) $$\frac{\partial}{\partial t}\rho_{imp} = -\nabla\cdot\left(\rho_{imp}\mathbf{v}\right) + \nabla\cdot\left(D_{imp}\nabla\rho_{imp}\right) + S_{imp}$$ MGI/SPI

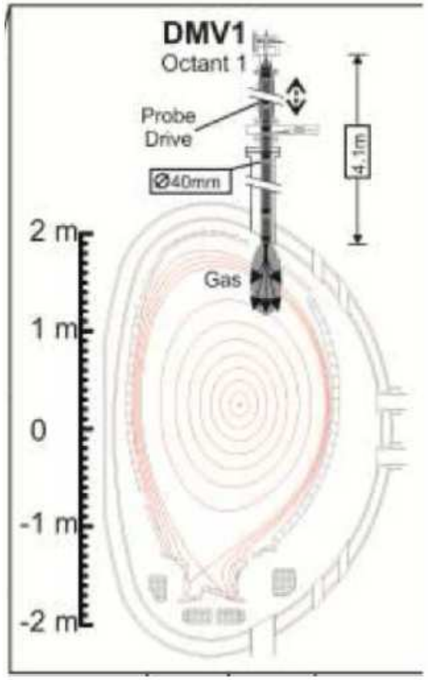
Mass conservation (all) $$\frac{\partial}{\partial t}\rho = -\nabla\cdot(\rho\mathbf{v}) + \nabla\cdot\left[D_D\nabla\left(\rho - \rho_{imp}\right)\right] + \nabla\cdot\left(D_{imp}\nabla\rho_{imp}\right) + S_D + S_{imp}$$

Energy density $$\frac{\partial P^*}{\partial t} + \nabla\cdot\left(\mathbf{v}P^*\right) = -(\gamma - 1)P\nabla\cdot\mathbf{v} + \frac{2}{3R^2}\eta(T_e)j^2 + \nabla\cdot\left(\kappa_\perp\nabla_\perp T + \kappa_\parallel\nabla_\parallel T\right)$$
$$-n_e n_{imp}P_{rad}(T_e) + \frac{\gamma - 1}{2}\mathbf{v}\cdot\mathbf{v}\left(S_D + S_{imp}\right).$$

where $P^* \equiv P + (2/3)n_{imp}E_{ion}$

Description of a typical simulation

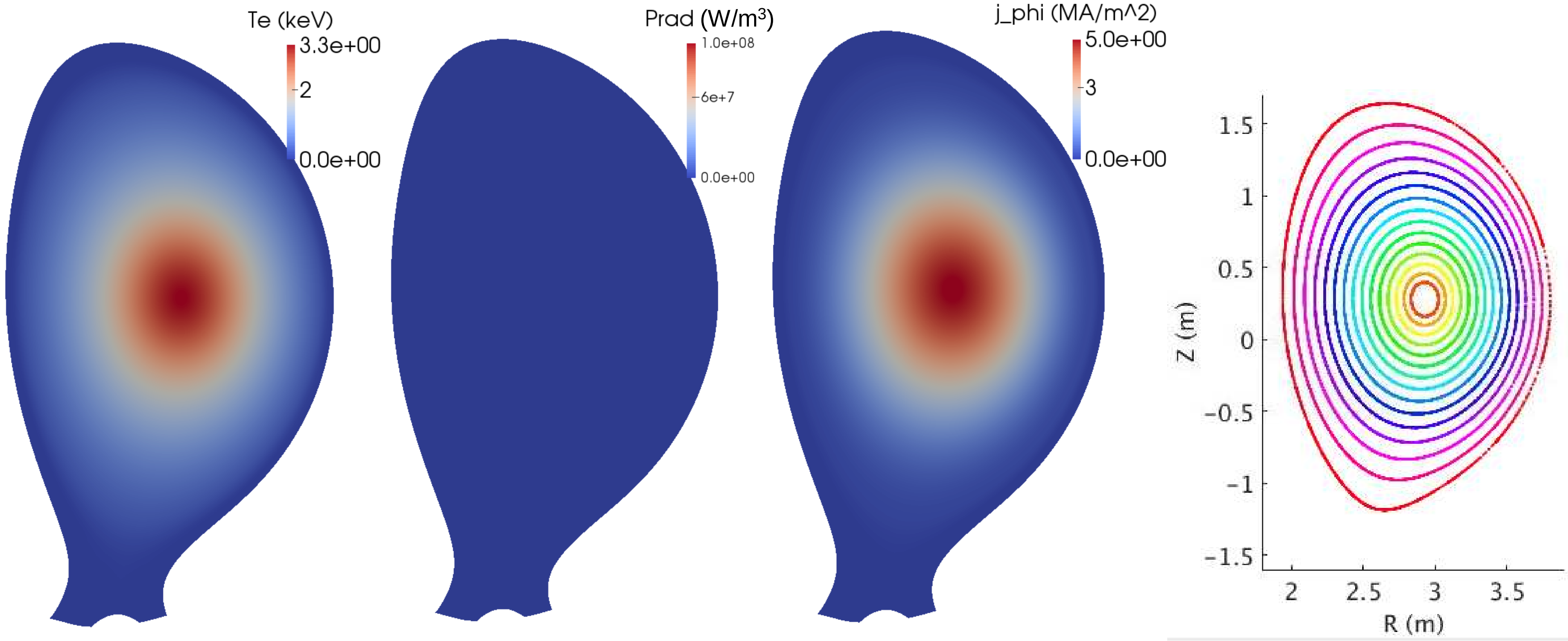
- Simulated pulse: JET #85943
  - Ohmic, 2MA, 3T, T_{e0}=3.3keV, $n_{e0}=2.1\times10^{19}m^{-3}$
  - Pure Ar MGI from Disruption Mitigation Valve 1 (DMV1) at 33 bar into a healthy plasma



- Simulation setup:
  - Time dependence of Ar source based on Euler equations, but P_{DMV} is reduced to account for fuelling efficiency <<100%
  - Realistic (Spitzer) resistivity and (turbuent) viscosity & diffusivities (+ scans)
  - For numerical reasons, parallel flows are artificially damped

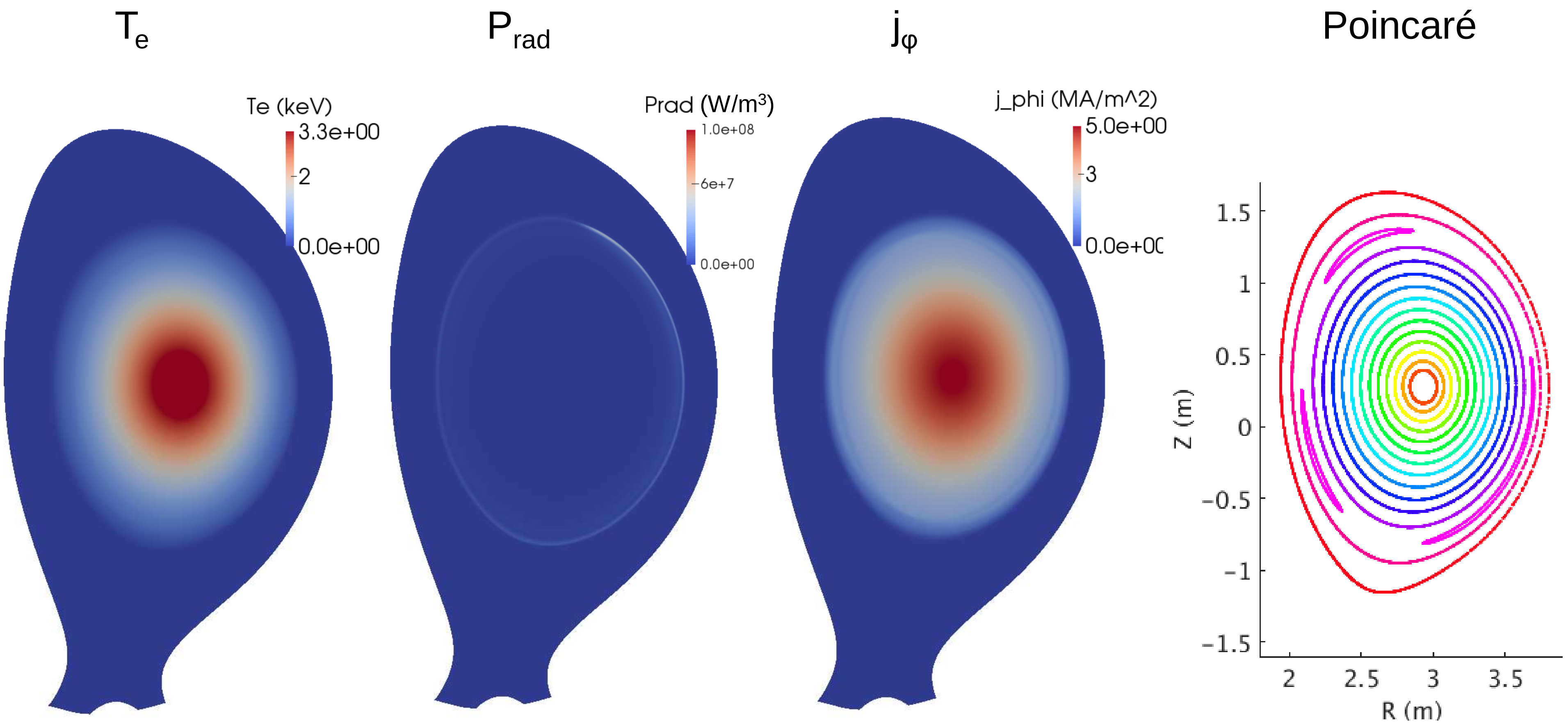
Initial state

T_e P_{rad} j_φ Poincaré



(Poloidal cuts in the plane of DMV1)

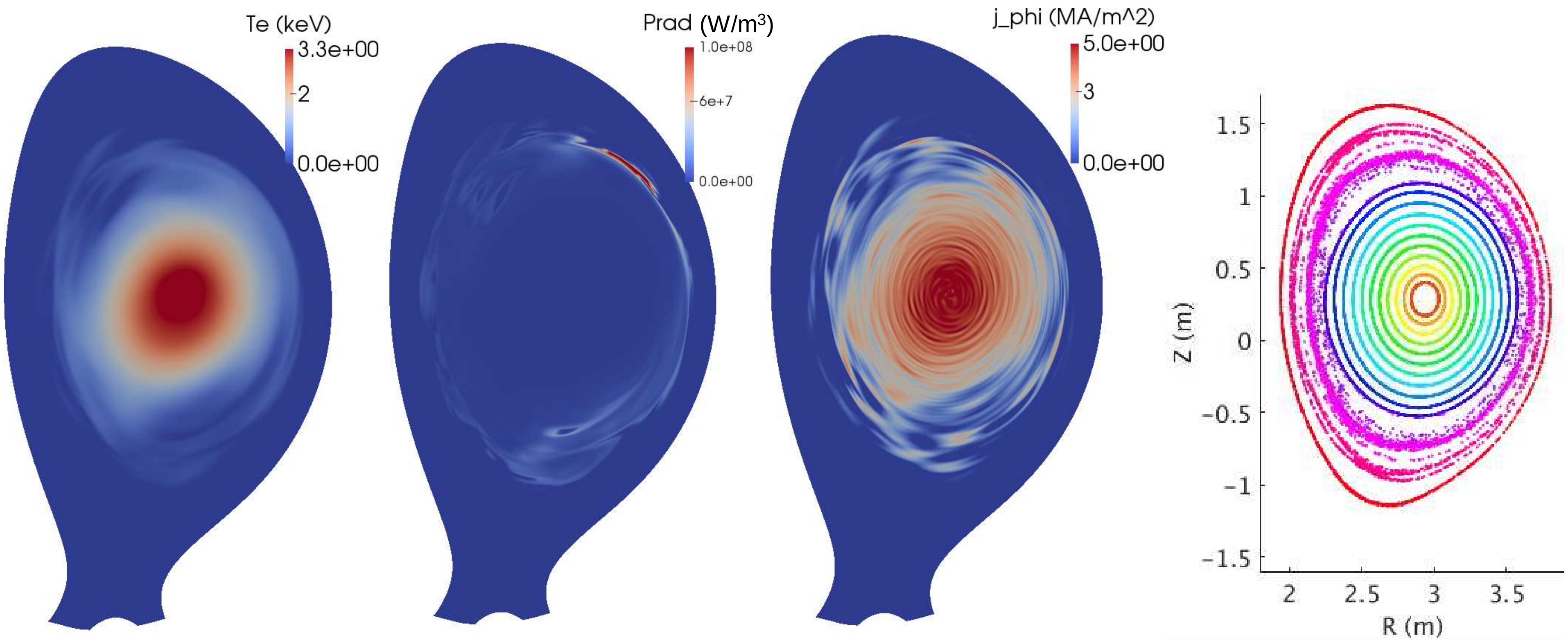
2.70ms after gas arrival



- Thin radiating ring → cold front → current profile contraction
- Growth of tearing modes (here m/n=3/1 island visible)

3.77ms after gas arrival

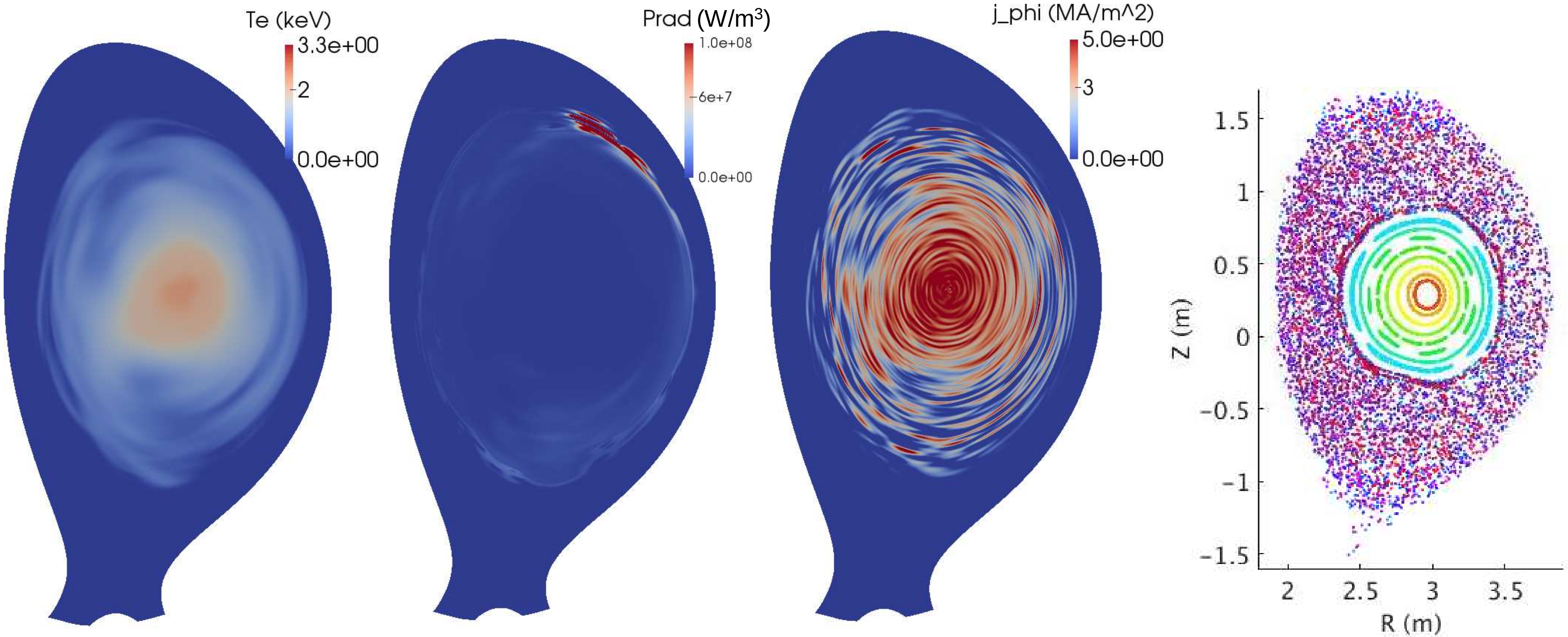
T_e P_{rad} j_φ Poincaré



- Growth of 2/1 mode
- Some stochasticity

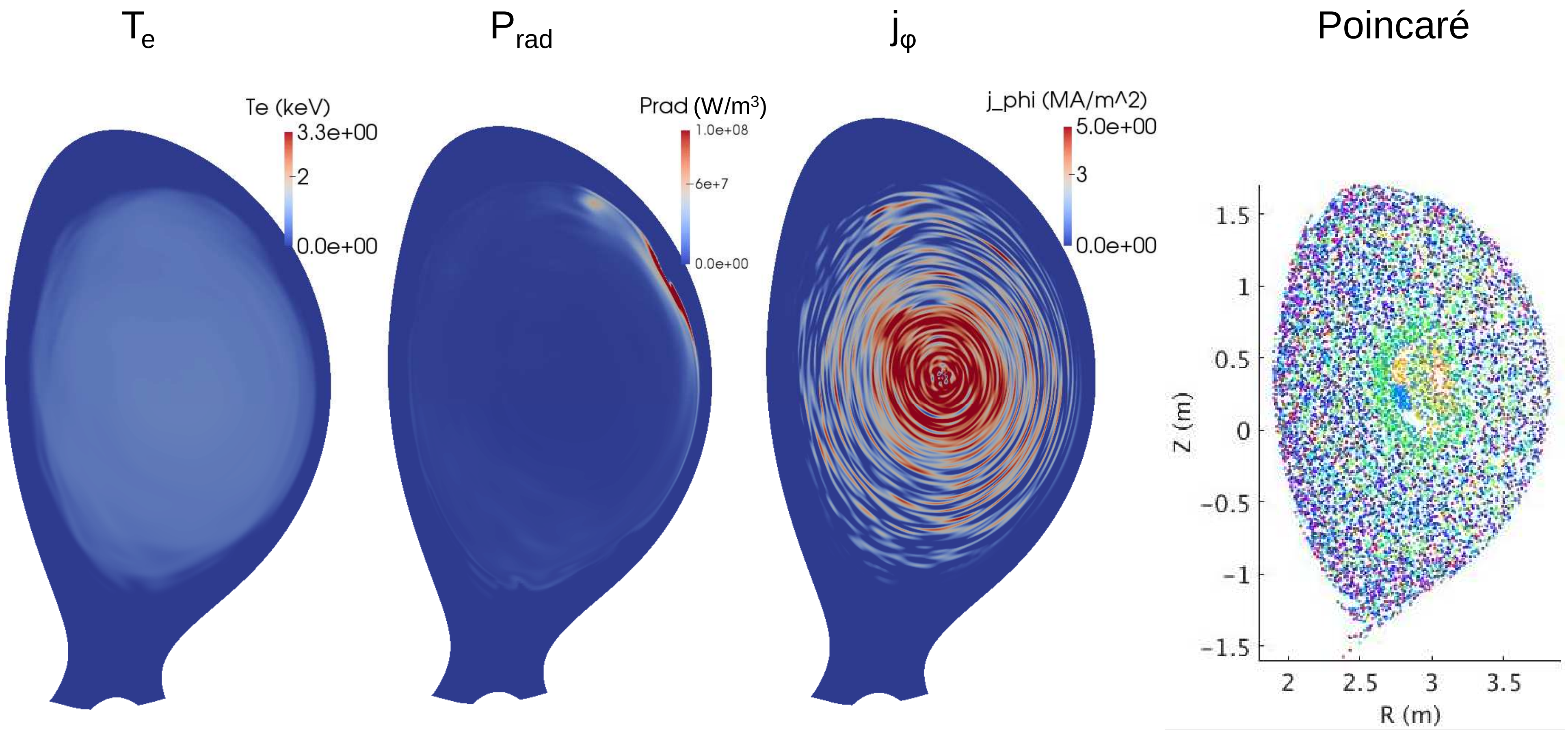
3.86ms after gas arrival

T_e P_{rad} j_φ Poincaré



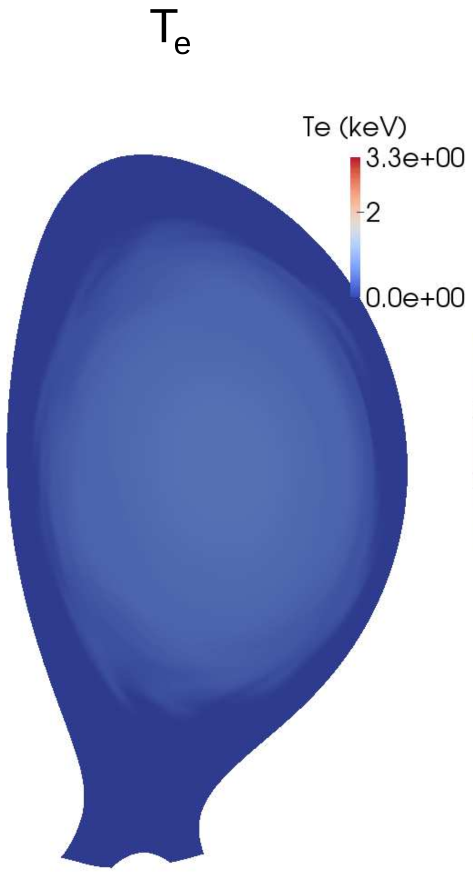
- Thermal Quench (TQ) onset
- Stochastic region expands fast
- Heat flux conducted into region where n_{imp} is large → large localized P_{rad}

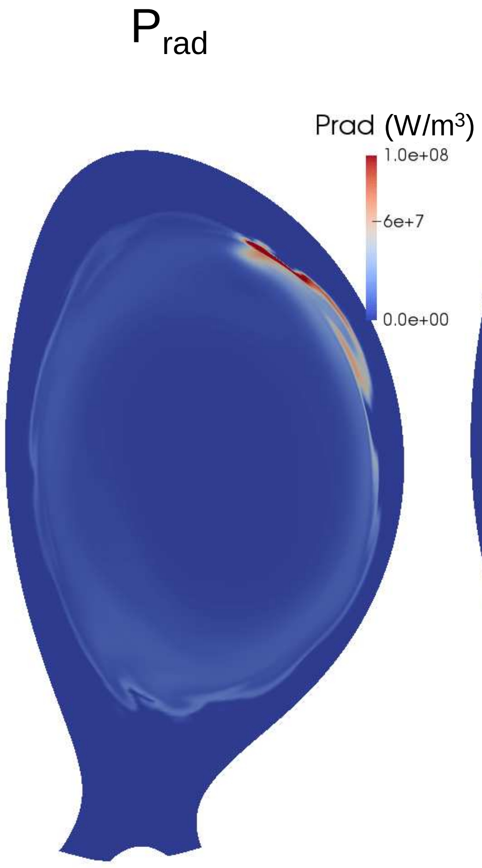
4.08ms after gas arrival

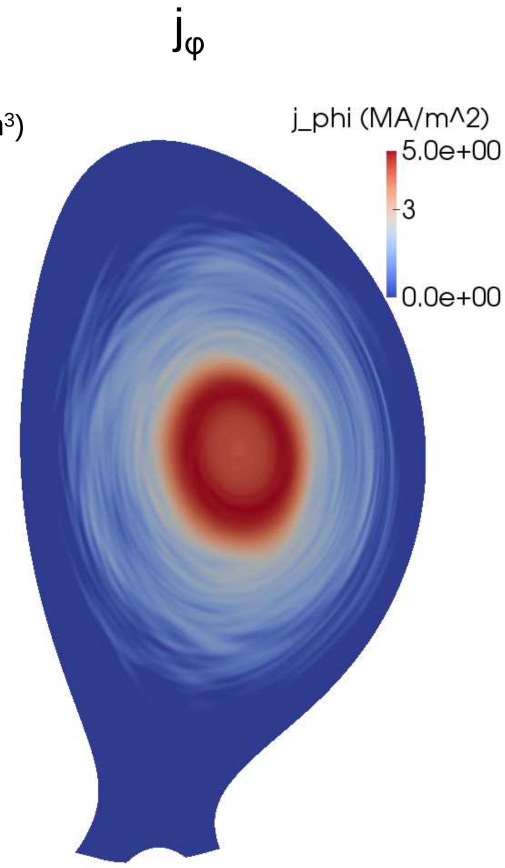


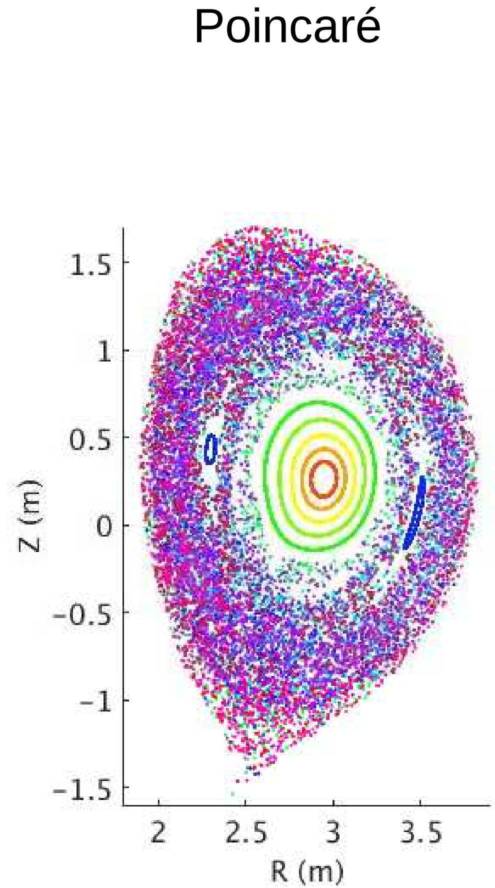
- Global stochasticity → global T_e flattening (TQ)

4.54ms after gas arrival









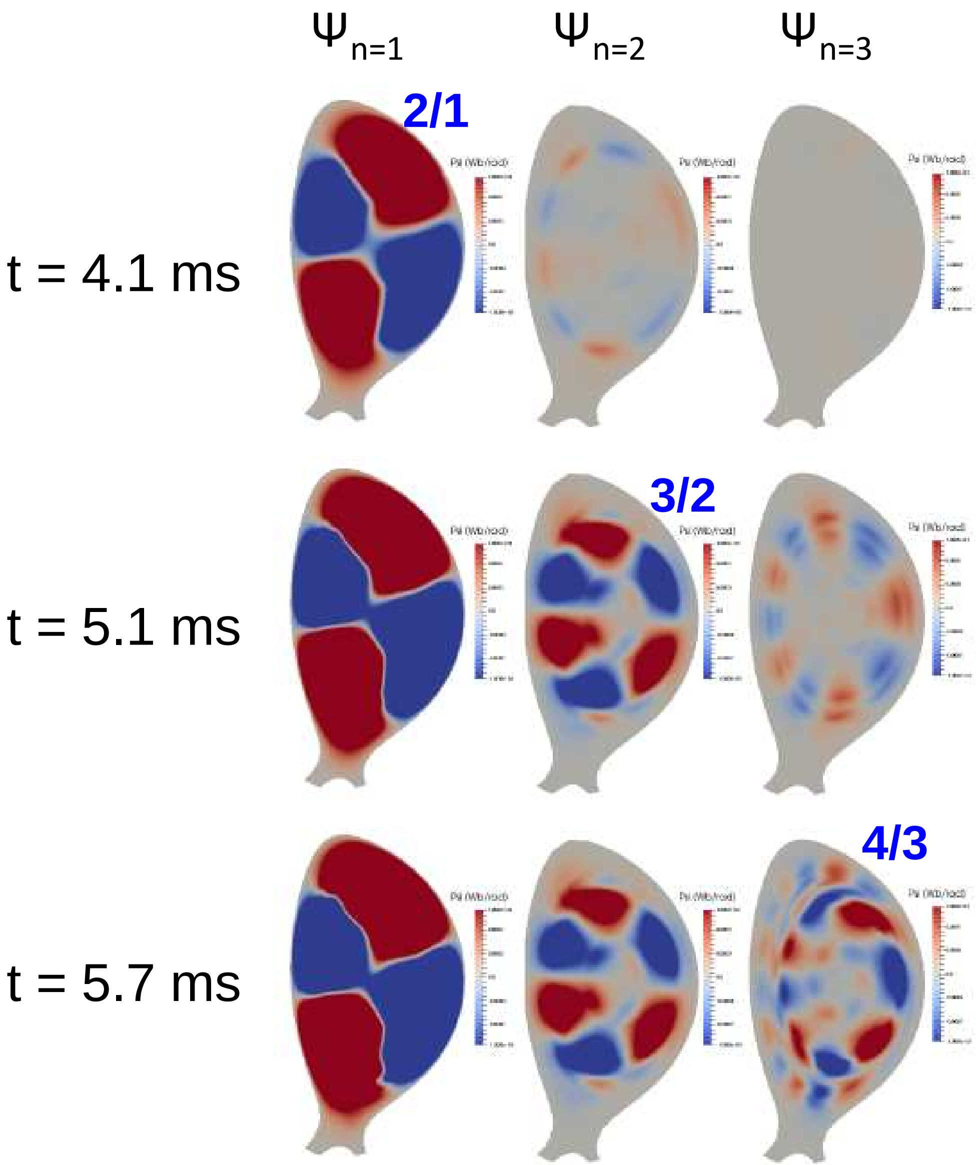
- After the TQ, flux surfaces start reappearing in the core

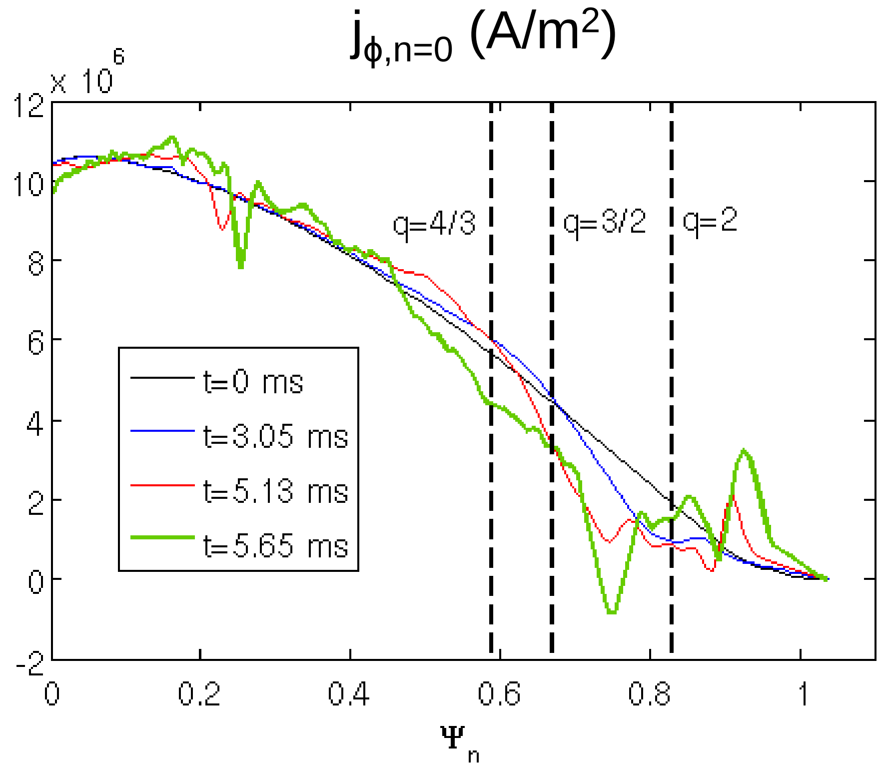
Mechanisms leading to the Thermal Quench (TQ)

(Here, a D_2 MGI simulation is shown but the same process occurs with Ar MGI)

[E. Nardon et al., PPCF 59 (2017) 014006]

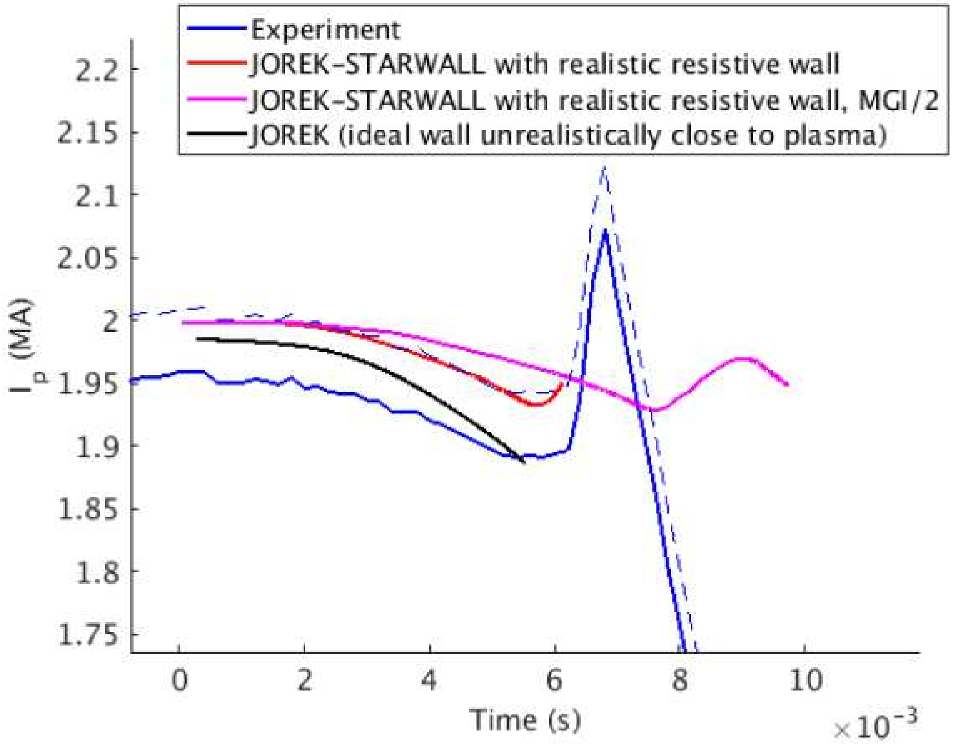
- The thermal quench is triggered by a "current profile avalanche" effect





- Island overlap → magnetic stochasticity → TQ

A realistic wall is needed to reproduce the pre-TQ I_p evolution



- Using a realistic resistive wall (red and magenta curves), the pre-TQ I_p drop is well matched
  - Pre-TQ I_p drop ~independent of the gas amount (red vs. magenta)
- In contrast, an ideal wall close to the plasma (black curve) makes the pre-TQ I_p drop too large
- Consistent with theory [Artola et al., submitted]
  - Current lost in the edge is largely re-induced in the still hot plasma
  - The process does not depend on the timescale, only on geometry

Physics of the TQ and I_p spike

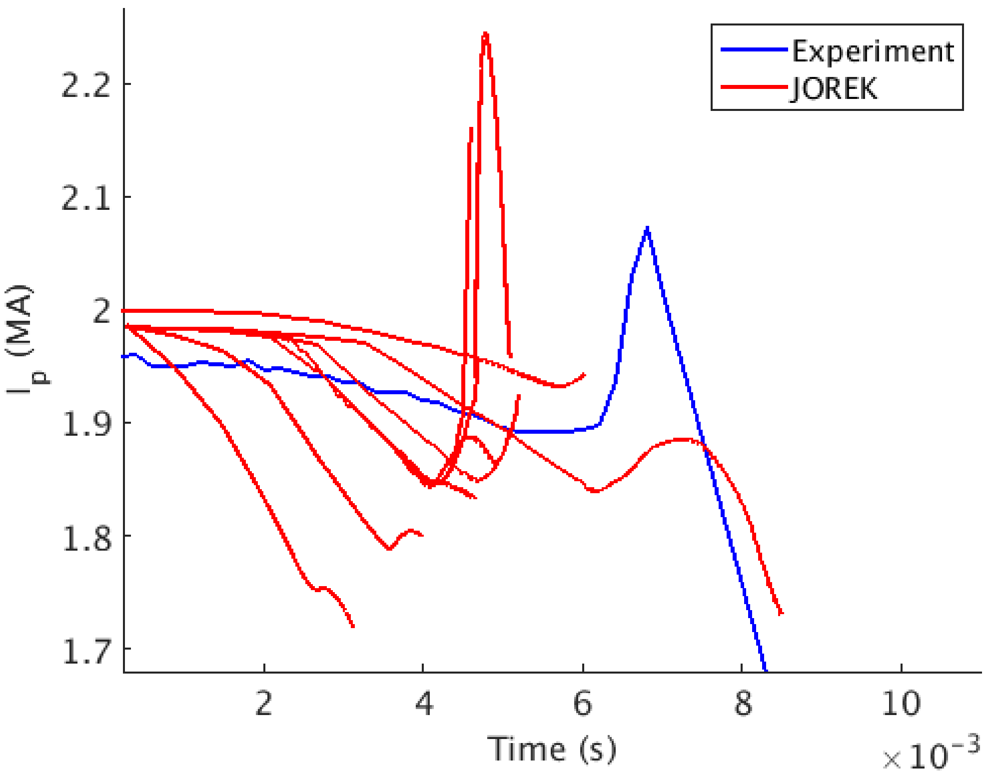
Context

- Mechanism of the I_p spike [D. Biskamp, *Nonlinear MHD*]:
  - MHD relaxation at TQ → broadening of current profile
    - Detailed mechanism, according to A. Boozer [PPCF 2018 and NF 2019]: magnetic stochasticity connects regions with different $j_{||}/B$ → excitation of shear Alfvén waves by $\nabla_{||}(j_{||}/B)$ term in vorticity equation → redistribution (homogenization) of $j_{||}/B$
  - Conservation of magnetic helicity $H \equiv \int \mathbf{A}\cdot\mathbf{B}\, dV$ → I_p has to increase
  - Can be modelled in 2D via hyper-resistivity (mean field model)
    - Done in JOREK by Javier Artola

- In the past, 3D non-linear MHD simulations always underestimated the I_p spike (as far as I know)

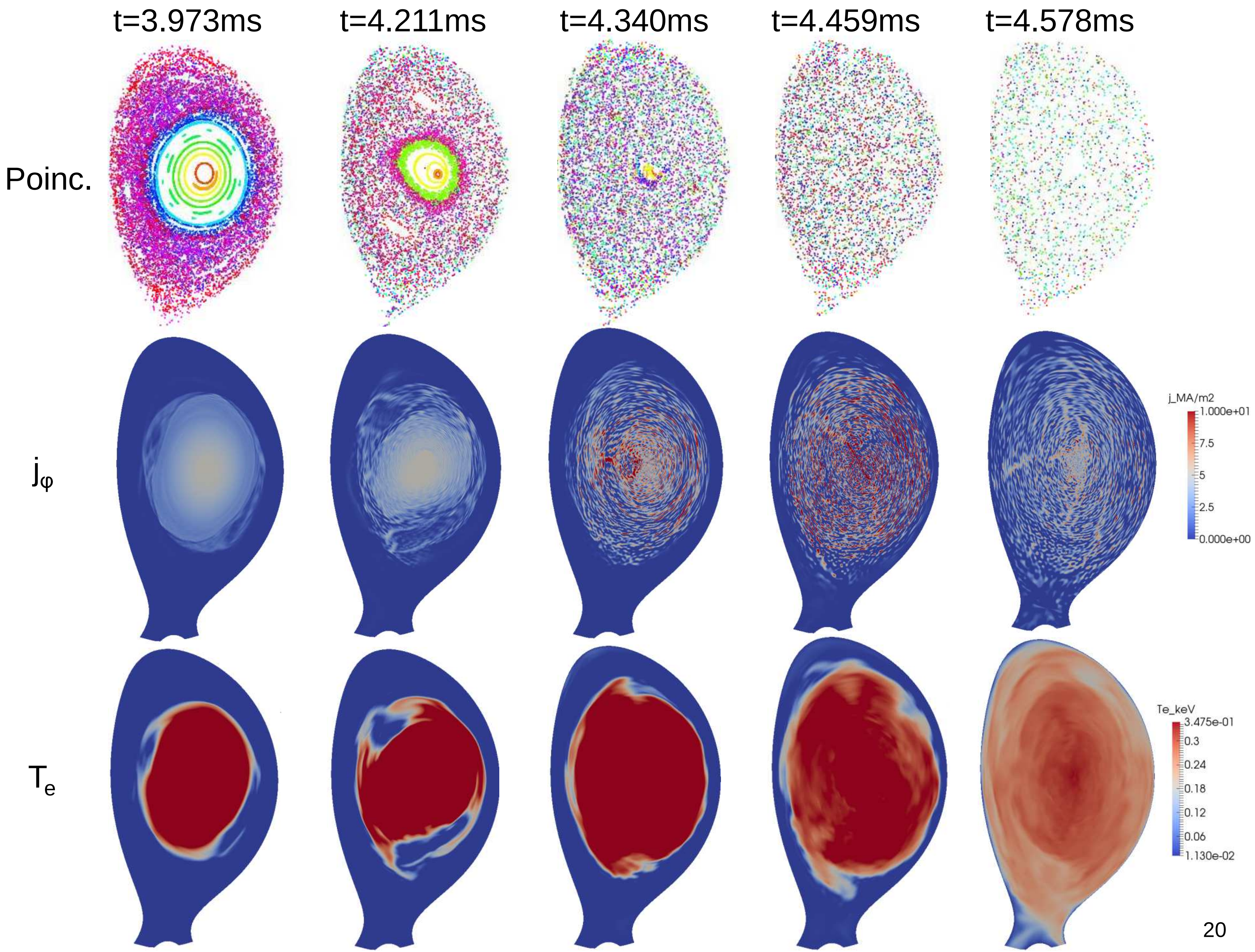
  ⇒ MHD relaxation not well captured?

  ⇒ Unreliable predictions on electron stochastic losses (which play an important role in runaway electron generation)?



- This year, got first JOREK simulations with an I_p spike comparable to experimental data
  - Even larger in certain cases!

- Large I_p spike associated to violent MHD activity and small scale excitation across the whole plasma (see simulation in next slide)
  - Could well be Alfvén waves turbulence



t=3.973ms
t=4.211ms
t=4.340ms
t=4.459ms
t=4.578ms
Poinc.
j_φ
T_e
j_MA/m2
1.000e+01
7.5
5
2.5
0.000e+00
Te_keV
3.475e-01
0.3
0.24
0.18
0.12
0.06
1.130e-02

What determines the I_p spike height?

- Unfortunately, no clear-cut conclusions yet…
  - Simulations take weeks and many fail during the TQ

- However, based on existing simulations, my *impression* is that:
  - The I_p spike height correlates with the amplitude of the low n modes (m/n=2/1, 3/2, …)
  - …which correlates with the sharpness of the skin current generated by the cold front
  - …which correlates with
    - the Lundquist number used in the simulation
    - the « abruptness » of the radiative collapse
      - In fact, JOREK simulations with the largest I_p spikes had a bug in the call to ADAS routines, making the radiative cooling rate artificially large
      - Now that the bug is solved, the I_p spike is smaller than in the experiment again (but the radiative collapse may be too slow due to the coronal eq. assumption…)

Testing Boozer's formula

- Boozer provides a « heuristic » formula connecting the hyper-resistivity (Λ_m) of the 2D mean field model to the field lines diffusion coefficient ($D_{FL} \sim \Psi_t^2/N_t$) of the 3D system [A. Boozer, PPCF 61 (2018) 024002]:

$$\Lambda_m \approx \frac{1}{144}\frac{2\kappa_0}{1+\kappa_0^2}\frac{\mu_0}{4\pi}\frac{V_A^2\Psi_t^2}{N_t}$$

(Ψ_t ≡ radial extent of stochastic region in toroidal flux units
N_t ≡ number of toroidal turns for a field line to travel across this region)

- Analogous to Rechester-Rosenbluth formula but for magnetic helicity diffusion instead of heat diffusion

- Could allow extracting an estimate of D_{FL} from $I_p(t)$ experimental data, with no need for 3D simulations!

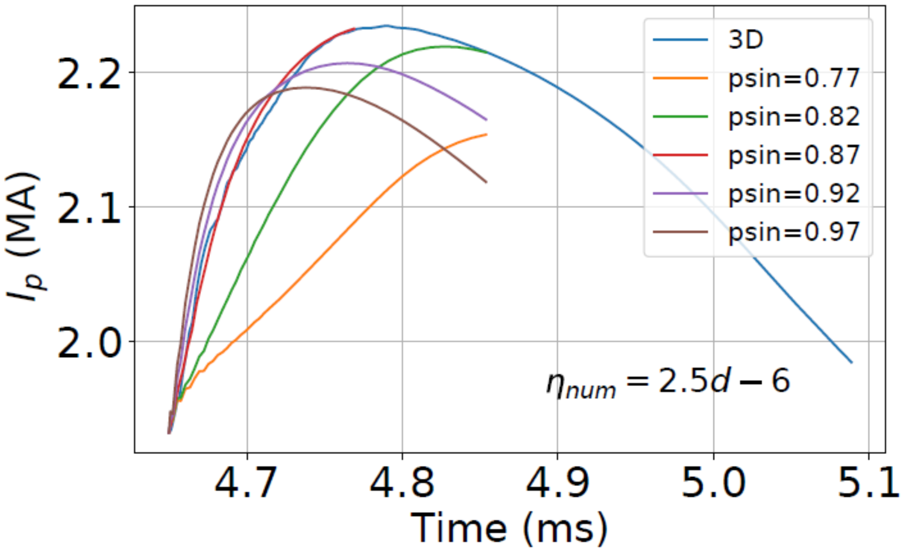
→ Use JOREK simulations to test Boozer's formula

- Idea: run 2D « mean field model » simulations and look for hyper-resistivity settings which allow matching 3D simulations

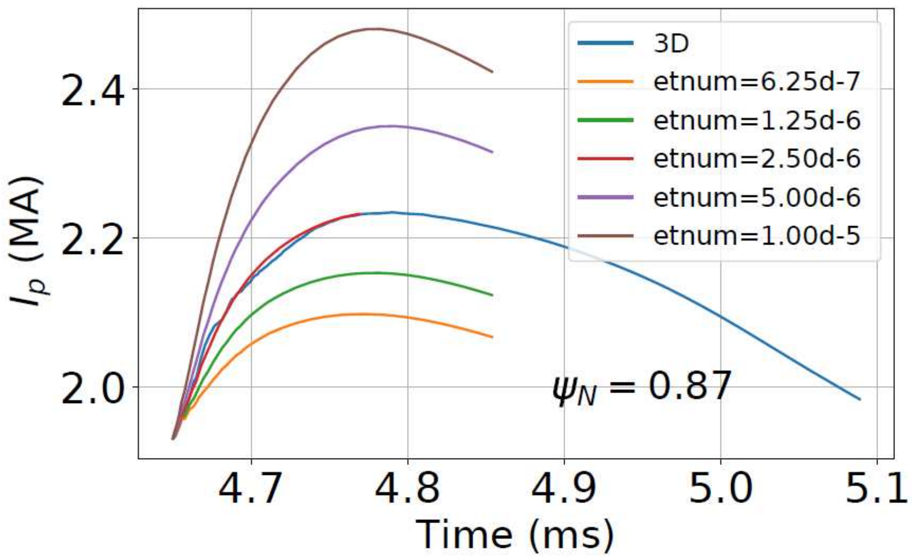
- Parameterization of hyper-resistivity: $\Lambda_m = \Lambda_{m0}(1+\tanh((\Psi_N-\Psi_{N,cut})/0.01))/2$
  - In principle, $\Psi_{N,cut} \leftrightarrow$ edge of the stochastic region

- Good match to 3D simulation for $\Psi_{N,cut} = 0.87$ and $\Lambda_{m0} = 2.5\text{x}10^{-6}$

$\Psi_{N,cut}$ scan



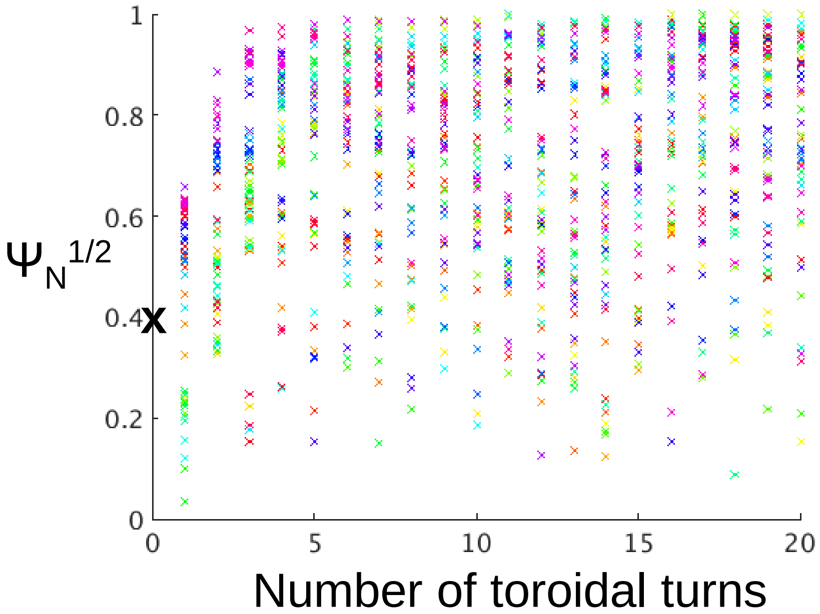
Λ_{m0} scan



Boozer's formula converted into JOREK units reads: $\Lambda_{m0} = 2x10^{-5}/N_t$

$\Rightarrow$ Estimate N_t from field line tracing in 3D simulation

Crude method: initialize many field lines at $\Psi_N^{1/2}$=0.4, track them and plot their radial position vs. number of turns (here at t=4.654ms)



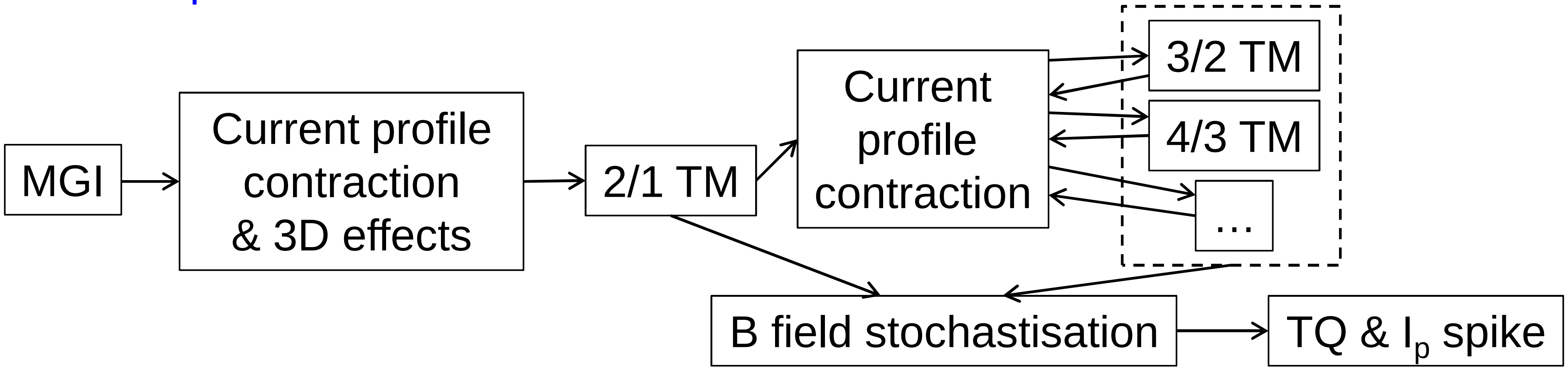
$\Rightarrow$ By eye, $N_t \sim 3 \rightarrow \Lambda_{m0} \sim 7x10^{-6}$, to be compared to $2.5x10^{-6}$ found in previous slide

$\Rightarrow$ Order of magnitude seems OK

Conclusion

Conclusion

- JOREK simulations suggest the following picture for MGI-triggered disruptions:



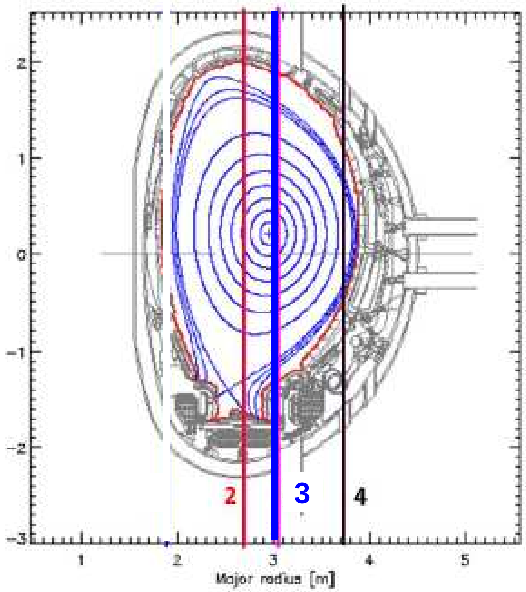
(Note: role of the 1/1 mode still to be clarified)

- The above picture seems to apply (to some extent) to SPI as well

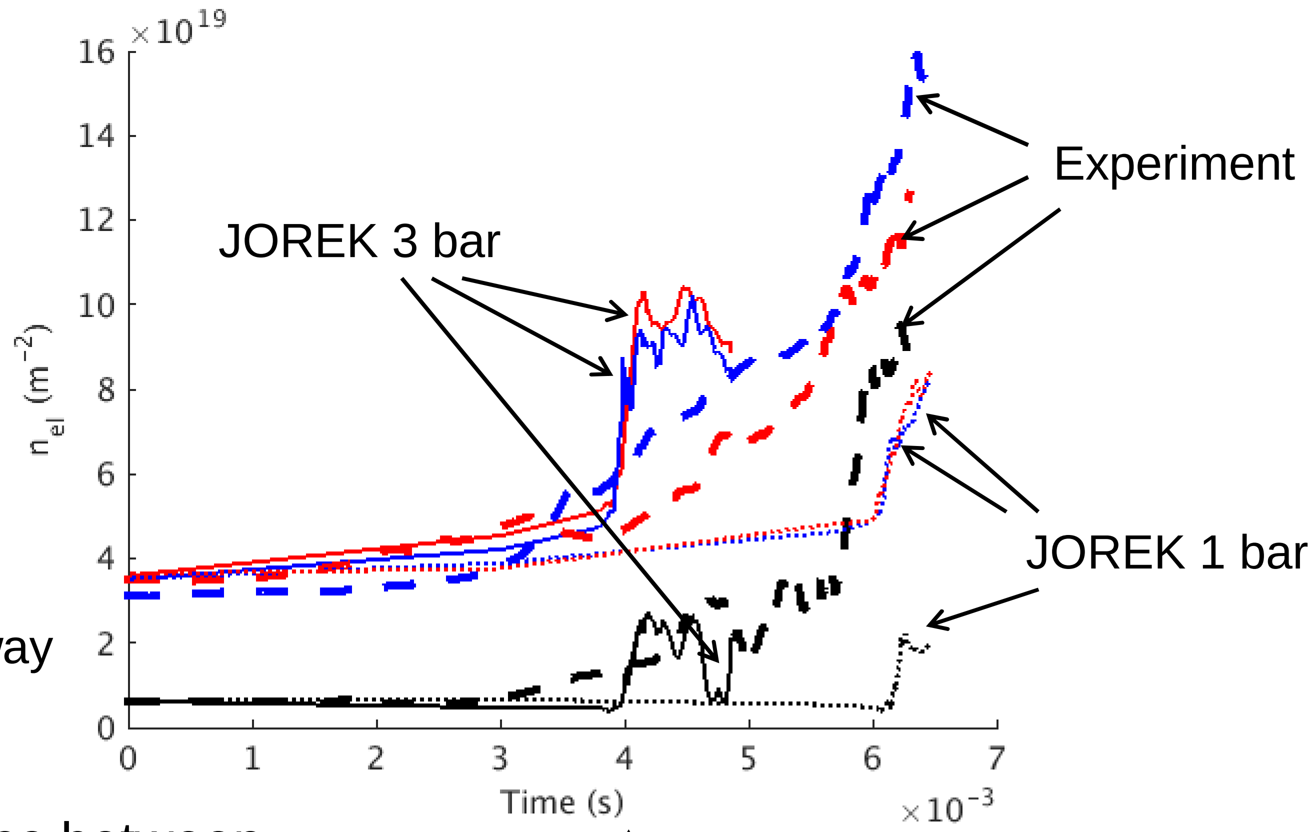
- The height of the I_p spike gives information on the « intensity » of the whole process
  - Too small a spike likely indicates underestimated stochasticity

- Preliminary investigations of Boozer's formula are promising

Interferometry comparison



(Interferometer is ~π/2 away toroidally from DMV1)



TQ, JOREK 3 bar

TQ, exp. & JOREK 1 bar

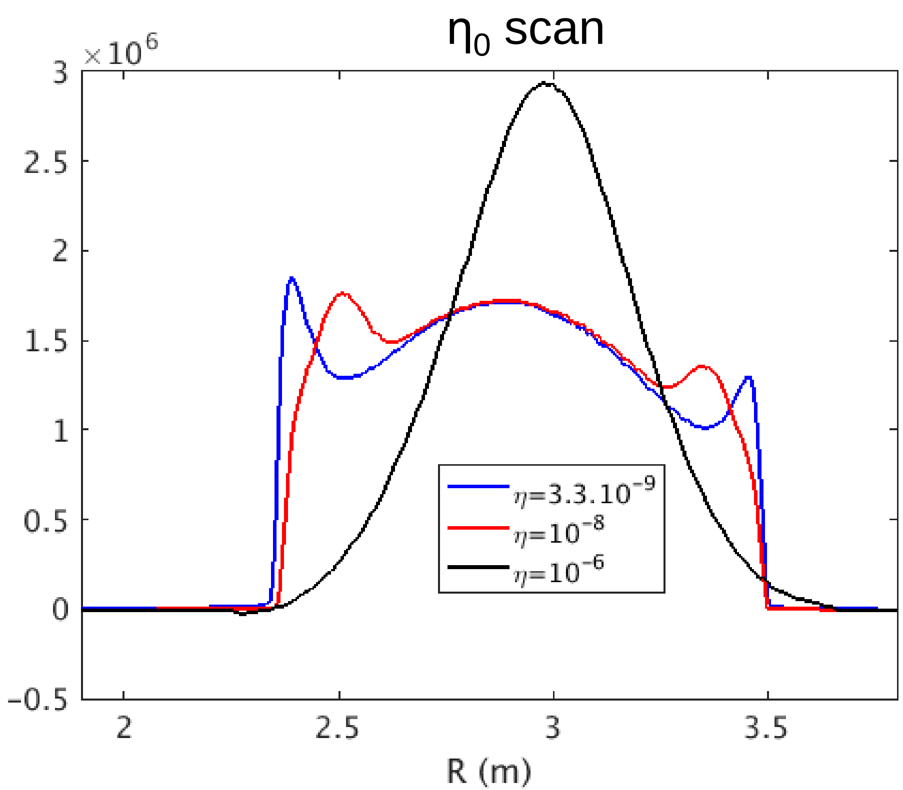
- Vague resemblance between JOREK and experiment
- n_{el} increases at TQ
  - Sharp increase in sim., not as sharp in exp.

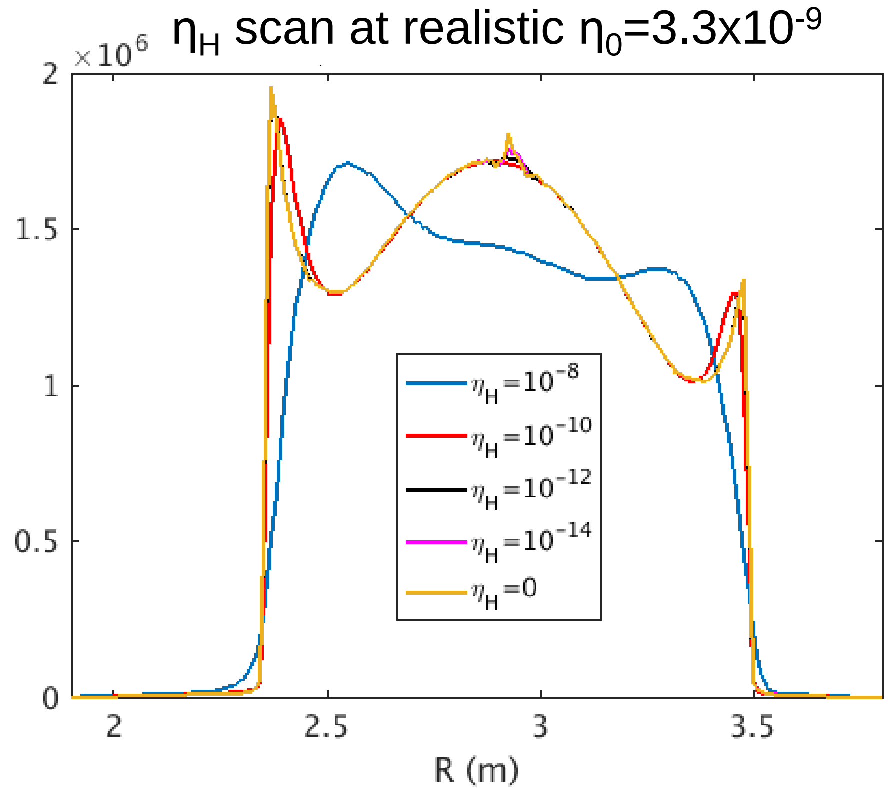
About the choice of resistivity η_0 and hyper-resistivity η_H

$$\partial_t\Psi = \;\dots + \eta_0(T/T_0)^{-3/2} j_\varphi + \eta_H \Delta j_\varphi$$

For numerical stability

Current density profile (axisymmetric Ar MGI simulations)





- Larger η_0 → smoother skin current → milder MHD and TQ

⇒ **Need to use a realistic η_0, at least in the pre-TQ phase**

- η_H=10^{-10} smooths profile w/o affecting skin current much
- Consequences on fine structures during TQ are uncertain…

Preliminary
Current Quench (CQ) investigations

- Almost all simulations stop converging at some point during the TQ
- However, it is easy and interesting to prolong a TQ simulation in axisymmetric mode
- Here, a large perpendicular heat diffusivity is used
  - Mimics end of TQ
  - Otherwise, localized current sheets (which seem related to local maxima in $L_{rad}(T)$)
- Also, need to add impurities in the core, otherwise no radiative collapse (the core even re-heats due to Ohmic heating)

- I_p decay rate increases with amount of impurities

- When the experimental I_p decay rate is matched (« 7.5 bar » case), P_{rad} is also matched
    - No surprise because $P_{rad} = P_{Ohm} \sim d(I_p^2)/dt$ during CQ

- Spiky P_{rad} in simulations related to treatment of radiation at very low T (sharp cut-off under a certain T, …)