DE LA RECHERCHE À L'INDUSTRIE

# Modelling of gas penetration, MHD activity and Runaway Electrons in disruptions mitigated by massive gas injection

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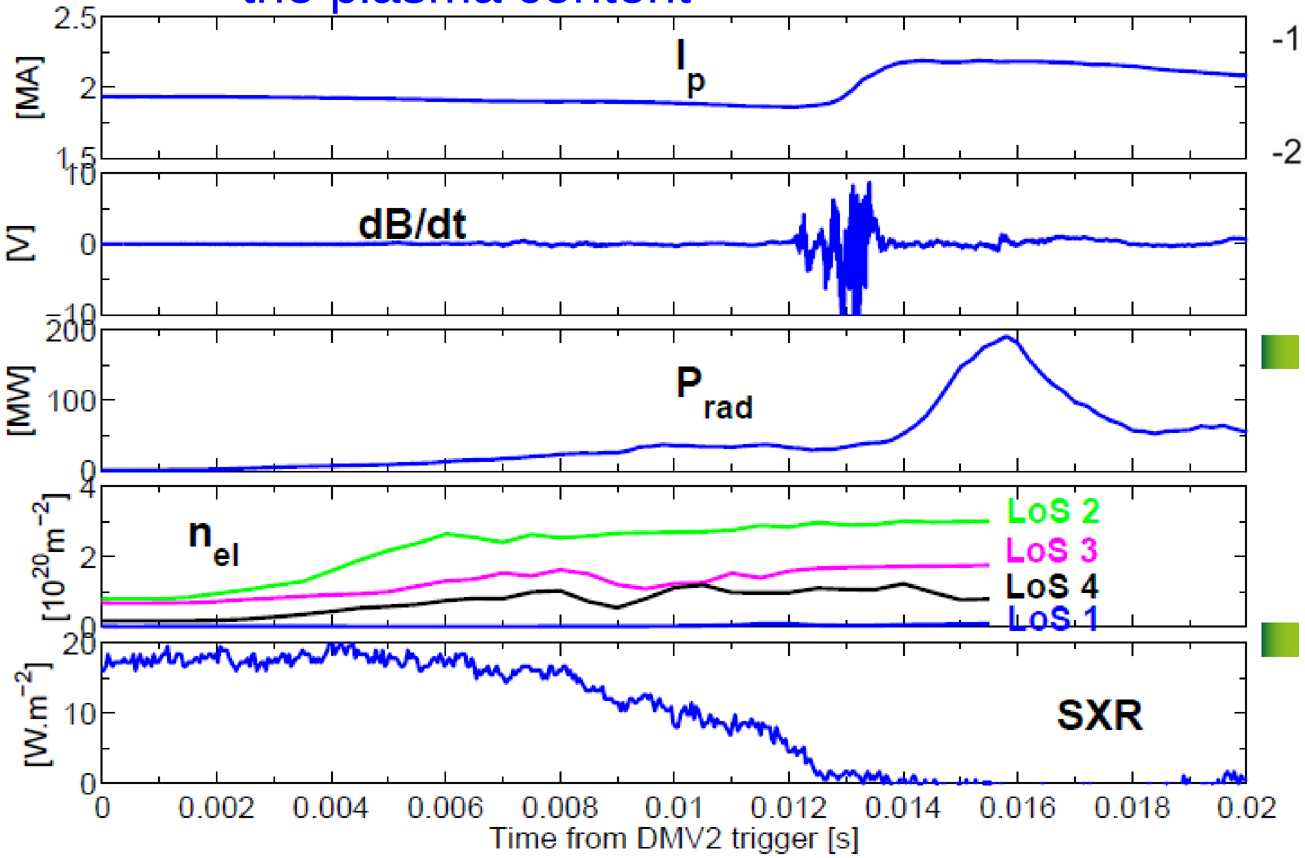
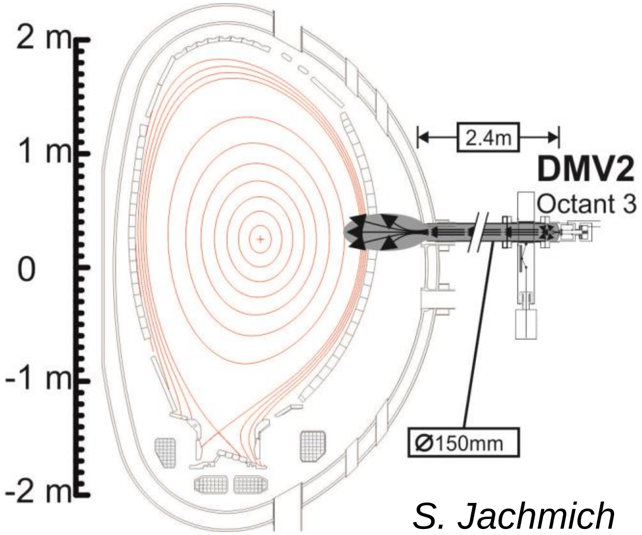
# Outline

- The simulated experiment: MGI-triggered disruption in JET 86887
- Investigating different parts of the physics with different modelling tools:
  - Gas penetration physics – IMAGINE 1D fluid modelling
  - MHD aspects – JOREK 3D non-linear reduced MHD modelling
  - Runaway electron generation – JOREK + test particles modelling

# The simulated experiment: JET pulse 86887 (Ohmic, 2 MA, 2 T, $q_{95}$=2.9)

- $D_2$ MGI with DMV2 into a « healthy » plasma
  - Mitigation normally done with radiating impurities but $D_2$ easier to model
  - Initial content of gas reservoir ~100 times the plasma content





*S. Jachmich*

- First effects of the gas visible from about 2 ms after DMV2 trigger
- Thermal Quench (TQ) takes place 12 ms after DMV2 trigger

# Gas penetration physics
# -
# IMAGINE modelling

# IMAGINE =
# fluid dynamics (gas) + profiles evolution (plasma)

- Geometry = 1D radial, slab
- Fluid dynamics:

Euler equations

$$\boxed{\partial_t n_n = -\partial_r(n_n V_n)} - n_e n_n I + n_e^2 R$$

$$\boxed{\partial_t(m_n n_n V_n) = -\partial_r(m_n n_n V_n^2 + P_n)} - n_n n_e(I + \boxed{\sigma_{cx} V_{cx}}) m_n V_n$$

$$\boxed{\partial_t(\frac{3}{2}P_n + \frac{1}{2}m_n n_n V_n^2) = -\partial_r(\frac{5}{2}P_n V_n + \frac{1}{2}m_n n_n V_n^3)} - n_n n_e(I + \boxed{\sigma_{cx} V_{cx}})(\frac{3}{2}P_n/n_n + \frac{1}{2}m_n V_n^2)$$

$$+ n_e(n_e R + \boxed{n_n \sigma_{cx} V_{cx}})\frac{3}{2}eT_i$$

Charge exchange → Energy and momentum transfer between ions and neutrals

- Plasma profiles:

$$\partial_t n_e = n_e n_n I - n_e^2 R + \partial_r(\boxed{D}\partial_r n_e)$$

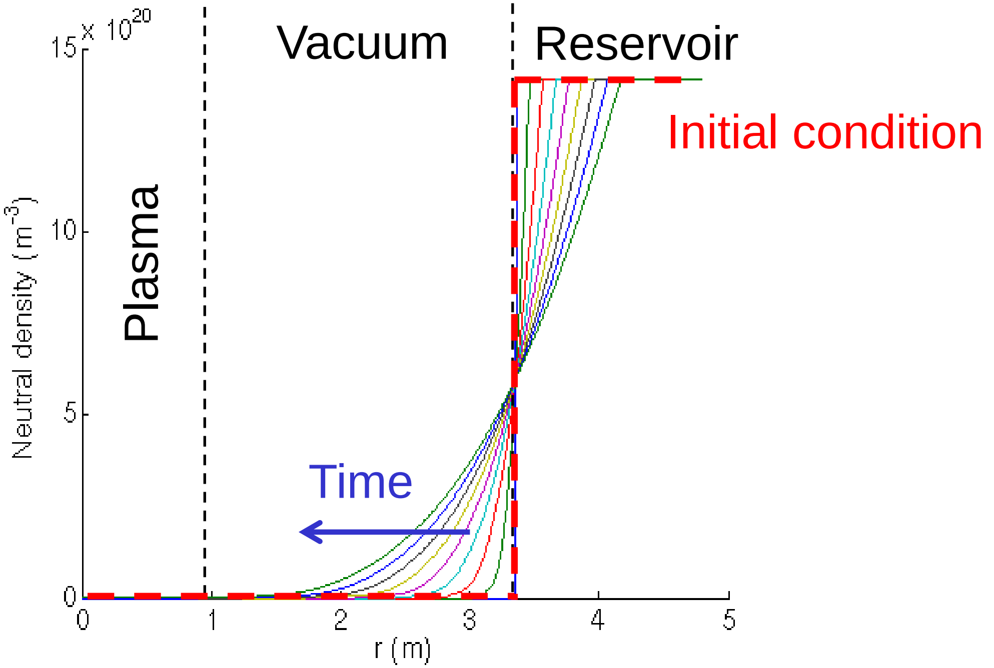
Only « free » parameters (but small effect)

$$\partial_t(\frac{3}{2}n_e e T_e) = -n_e(n_n I E_{ion} + n_n L_{lines} + n_e R\frac{3}{2}eT_e) - n_e^2 L_{brem+rec} + \partial_r(\boxed{\chi} n_e \partial_r(eT_e))$$

$$\partial_t(\frac{3}{2}n_e e T_i) = \frac{3}{2}n_e(I P_n - n_e R e T_i - \boxed{\sigma_{cx} V_{cx}}(n_n e T_i - P_n)) + \partial_r(\boxed{\chi} n_e \partial_r(eT_i))$$

# Simulation domain = plasma + vacuum + reservoir

Neutral density at different times



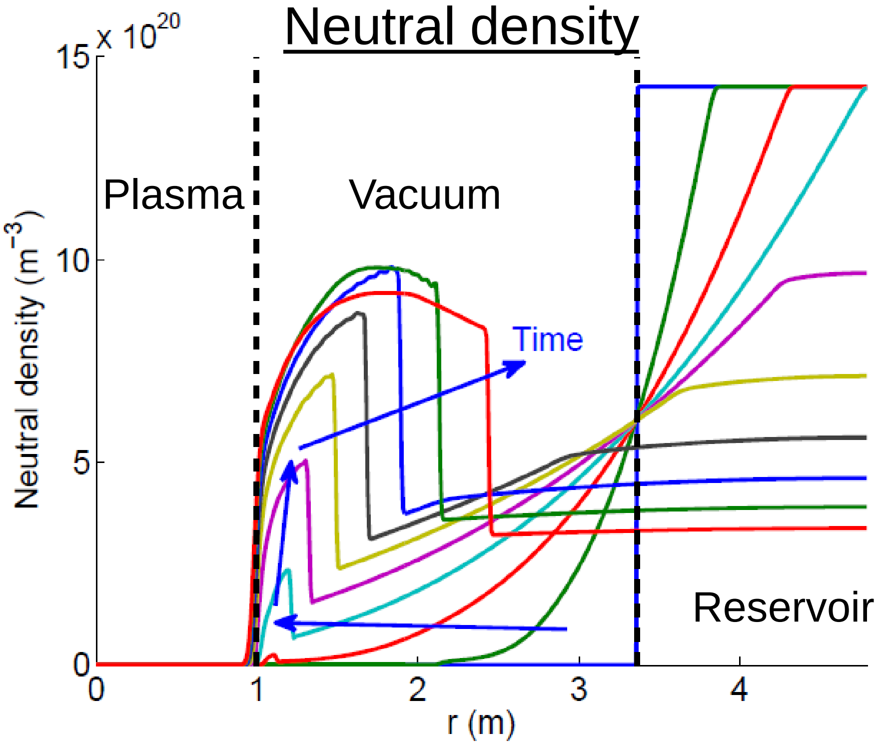
→ Rarefaction wave with first particles travelling at $3c_{s,res}$

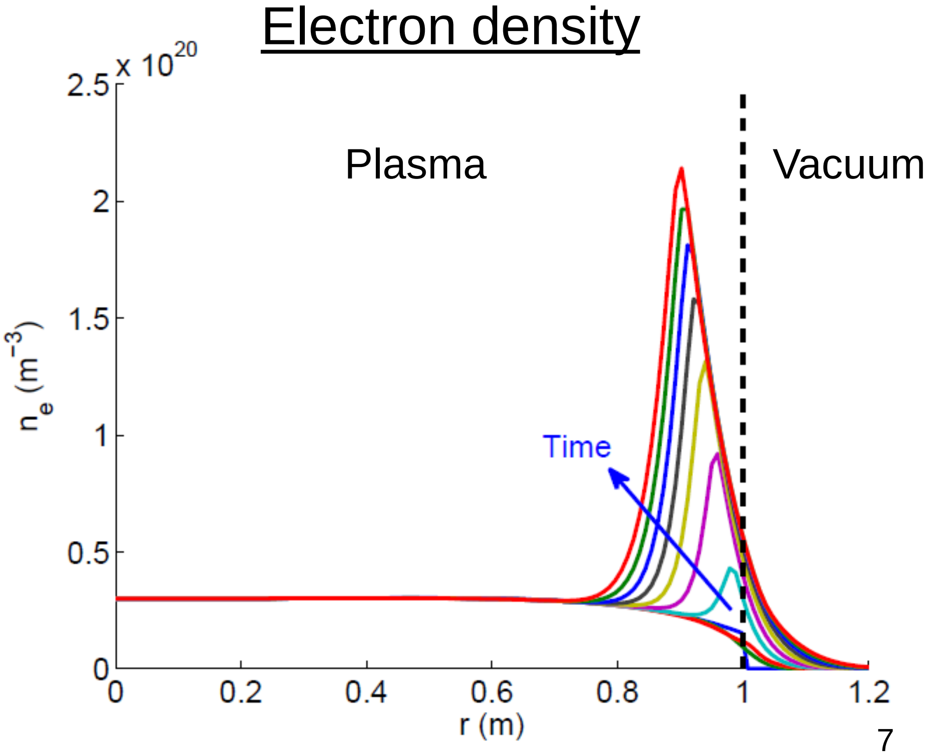
- Known analytic solution [Bozhenkov NF 2011]
- 3D modelling gives results similar to 1D [Nkonga 2016]

# Gas penetration is hindered due to gas heating by plasma

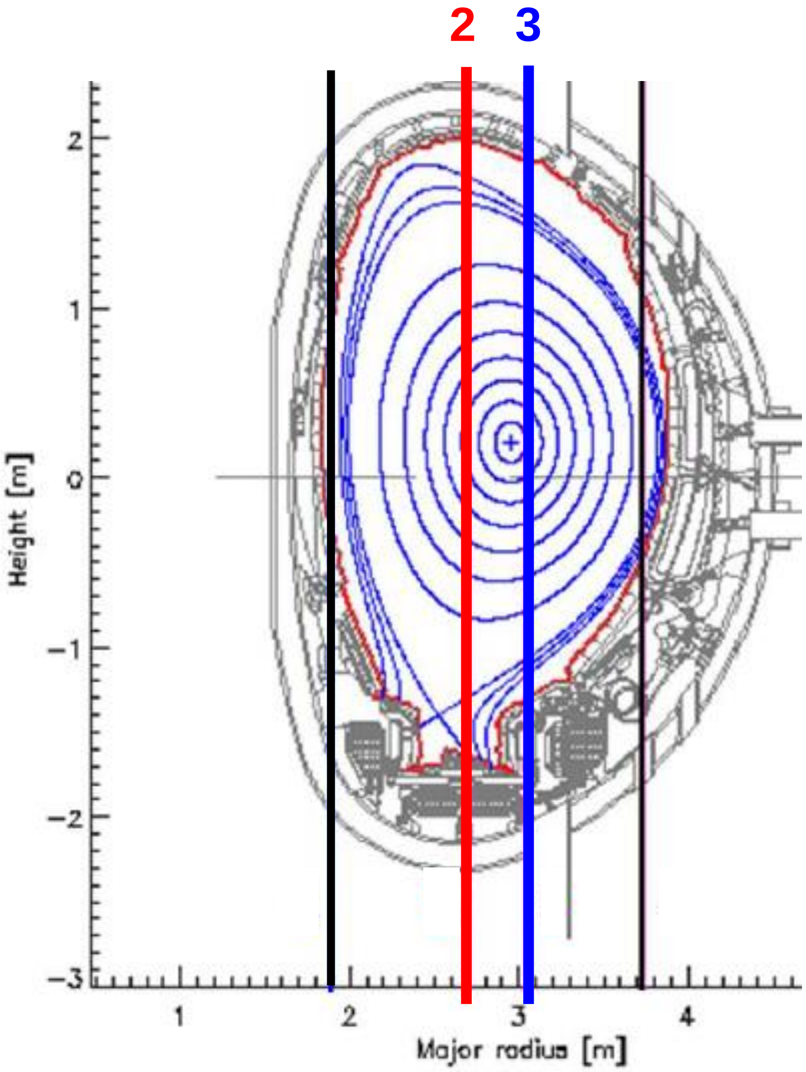
- Ions heat neutrals (by CX mainly)
  - → Gas pressure $P_n$ ↑
  - → $\nabla P_n$ brakes incoming gas
  - → A shock wave forms
  - → Most of the gas does not penetrate the plasma

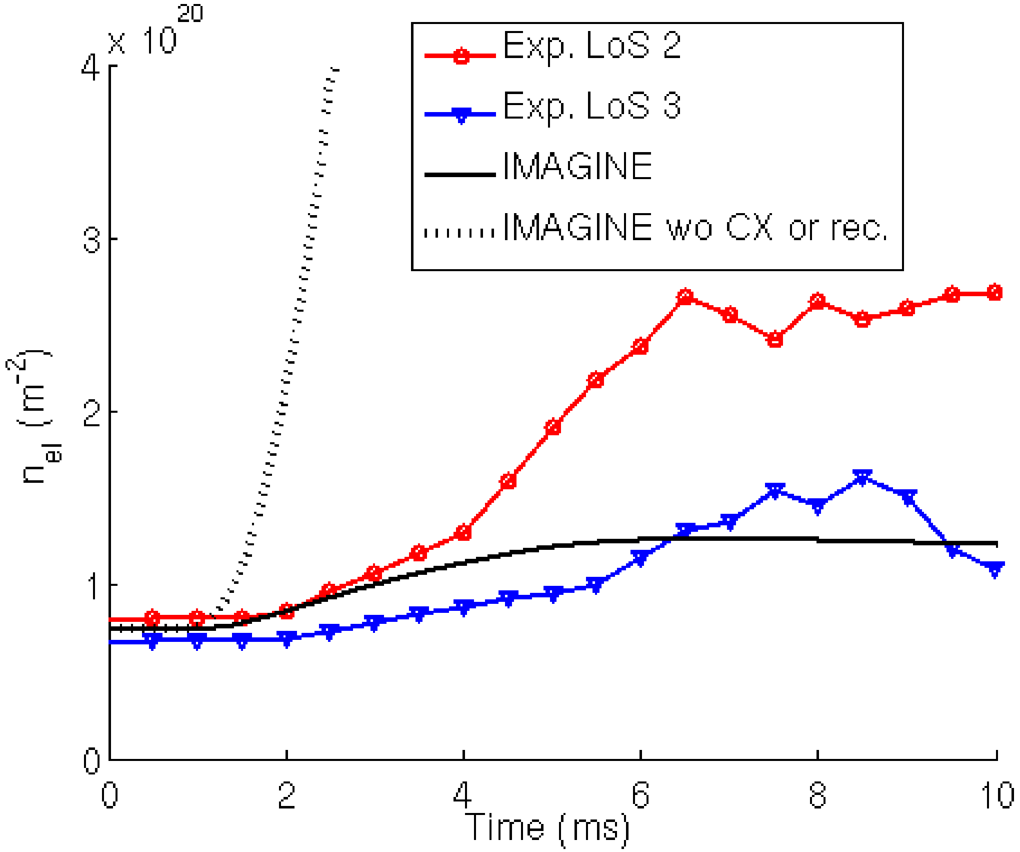
- $n_e$ ↑ at the edge by factor ~5 only


Neutral density


Electron density

# Synthetic interferometry shows that IMAGINE gets the right order of magnitude





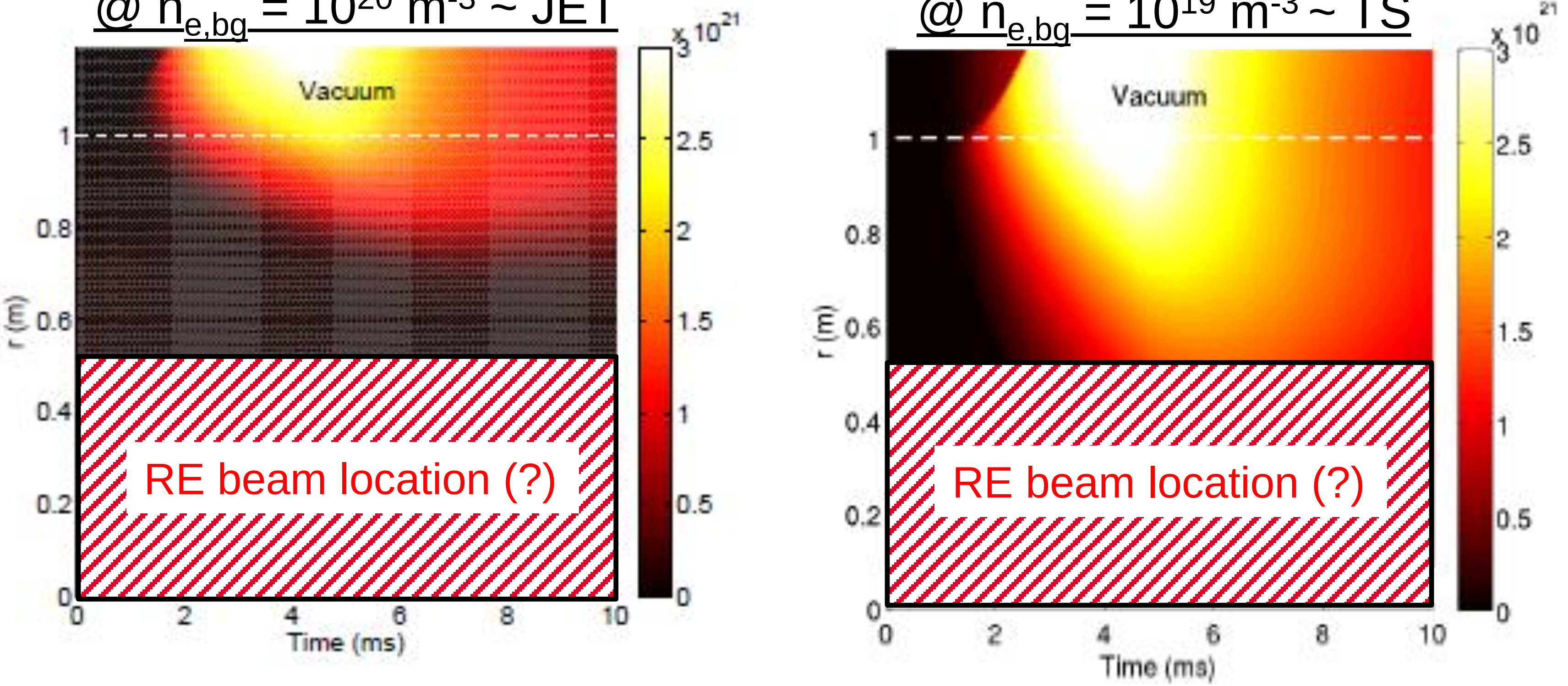
# Absence of MGI effect on runaway beam in JET could be due to lack of gas penetration

- 2nd injection to mitigate RE beam is considered for ITER
- Works on Tore Supra [Saint-Laurent FST 2012], DIII-D [Hollmann NF 2013] and ASDEX Upgrade [Pautasso, previous talk] but no effect on JET! [Reux NF 2015]
- A possible explanation supported by IMAGINE simulations: RE beam may be “shielded” by the high density background plasma

IMAGINE: $n_{e,free+bound}$ vs. time and radius

@ $n_{e,bg} = 10^{20}$ $m^{-3}$ ~ JET

@ $n_{e,bg} = 10^{19}$ $m^{-3}$ ~ TS



RE beam location (?)

RE beam location (?)

# MHD aspects
# -
# JOREK modelling

# JOREK and its model for $D_2$ MGI

- JOREK is a 3D non-linear reduced MHD code [Huysmans NF 2007] [Czarny JCP 2008] so far mainly applied to ELMs [Pamela EPS 2015]
- JOREK is however well suited also for MGI modelling

Equations of the $D_2$ MGI model in JOREK:

Neutral density: $$\frac{\partial \rho_n}{\partial t} = \boxed{\boldsymbol{\nabla}\cdot(\boldsymbol{D}_n : \boldsymbol{\nabla} \rho_n)} - \boxed{\rho\rho_n S_{ion}} + \boxed{\rho^2\alpha_{rec}} + \boxed{S_n}$$

Ion density: $$\frac{\partial \rho}{\partial t} = -\boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}) + \boldsymbol{\nabla}\cdot(D_\perp\boldsymbol{\nabla}_\perp\rho + D_\parallel\boldsymbol{\nabla}_\parallel\rho) + \boxed{\rho\rho_n S_{ion}} - \boxed{\rho^2\alpha_{rec}}$$

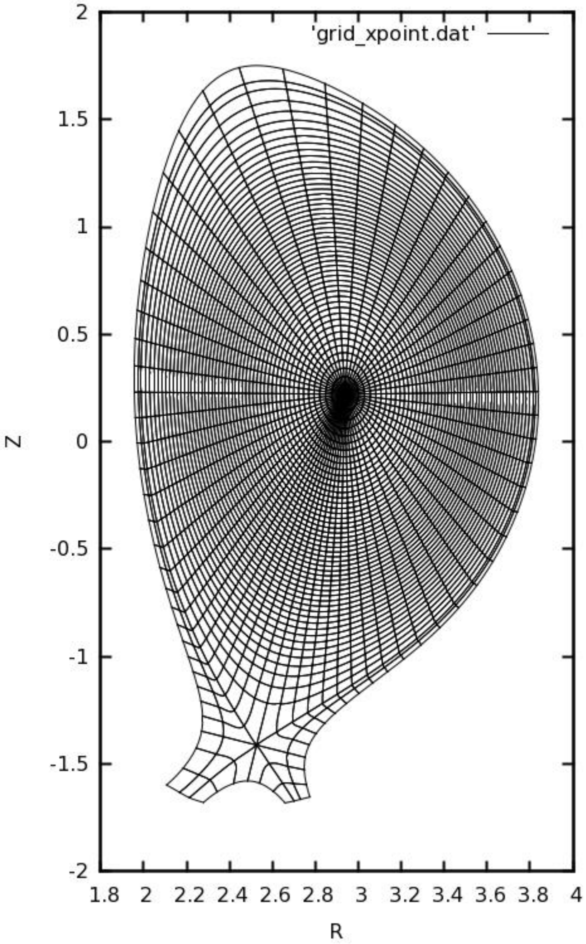
(+ 6 other equations)

Important features:

- $S_n$ = volumetric source of neutrals – localized at the edge, outer midplane
- Ionization and recombination using coefficients from ADAS
- Neutral transport is diffusive
- Resistivity $\eta = \eta_0 \, (T_0/T)^{3/2}$

# Typical simulation parameters

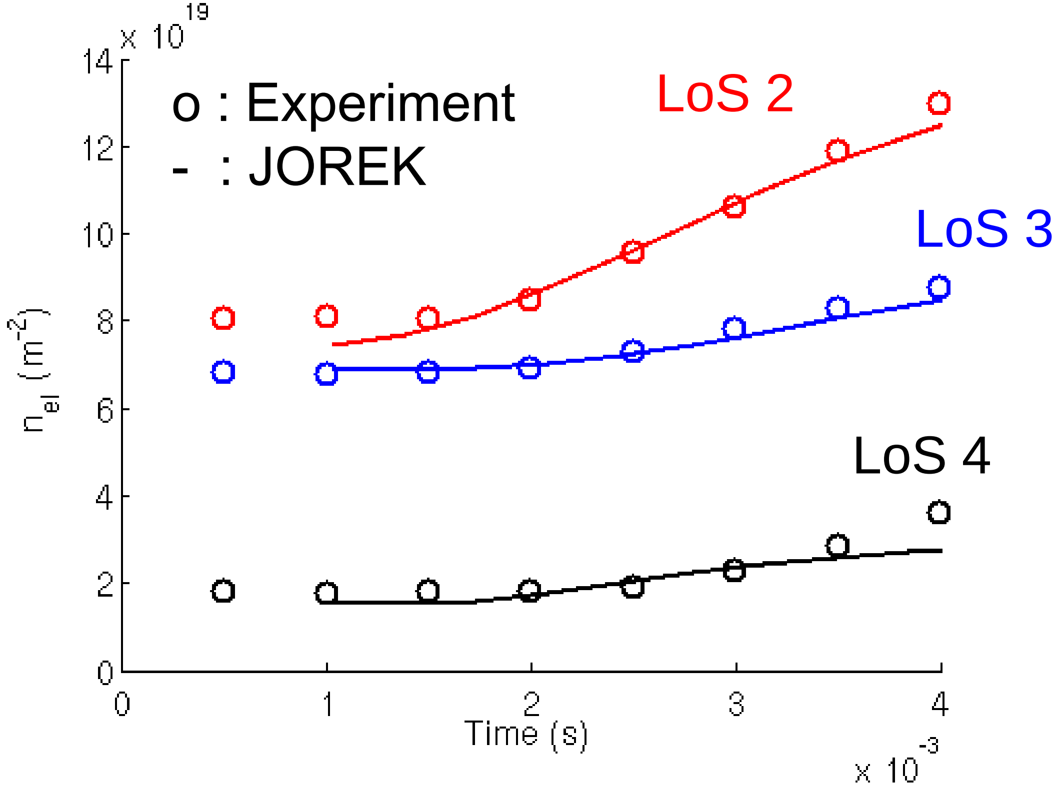
- Resistivity $\eta \sim$ 2-20 times Spitzer
- // heat conductivity $\chi_{//} \sim$ 10 times smaller than Spitzer-Härm
- $D_\perp \sim \chi_\perp \sim 1\ m^2/s$ ~ typical turbulent value
- Treat n=0-5 toroidal Fourier components
- ~3000 elements in the poloidal plane
(n_flux = 51, n_theta = 64)



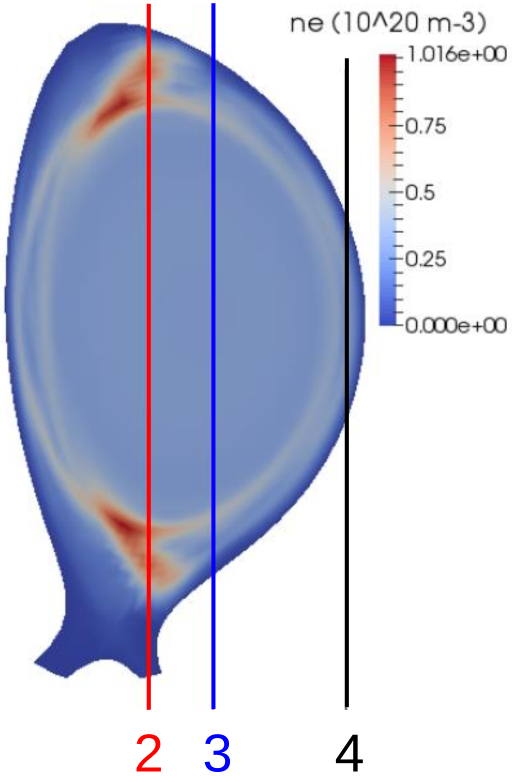
# Gas source is set so as to match interferometry measurements

- Divergence of LoS 2 and 3 = 3D effect

Line integrated density

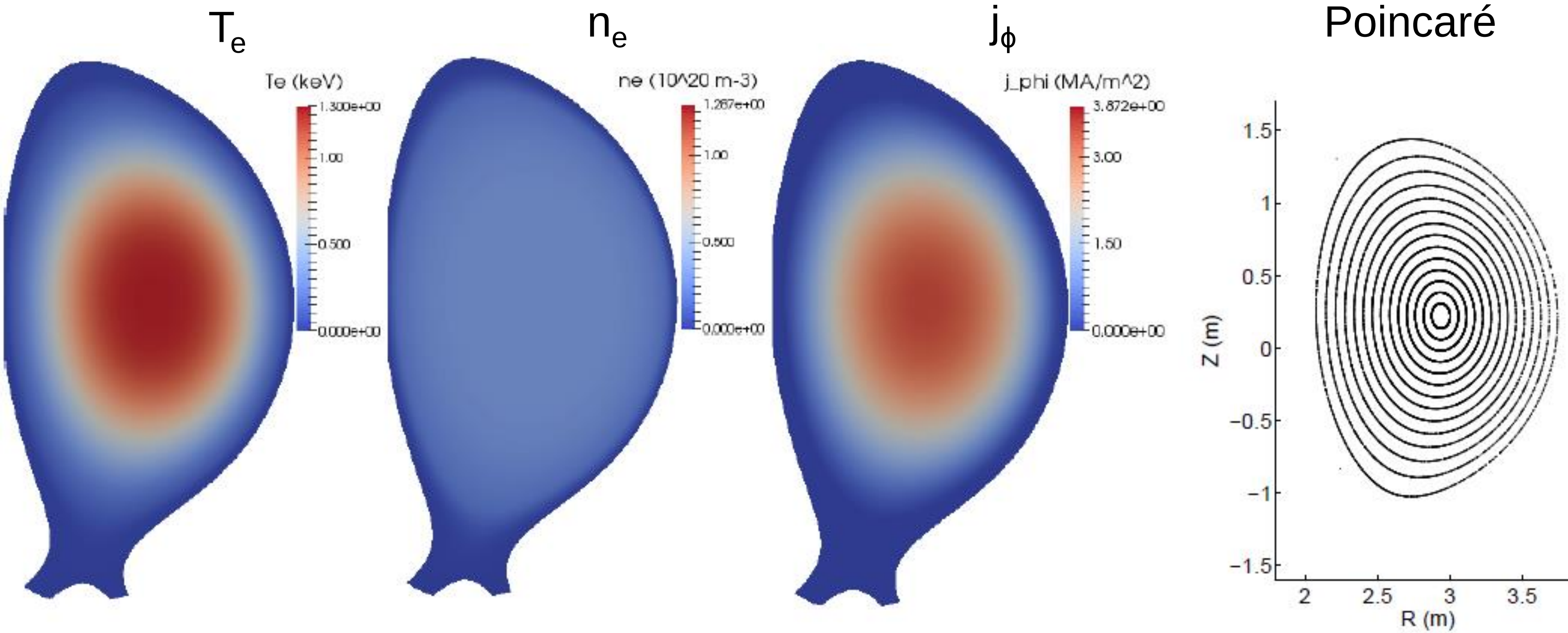


Simulated $n_e$ in interferometer plane (180° away from MGI)



# Overview of a JOREK simulation

t = 0 ms

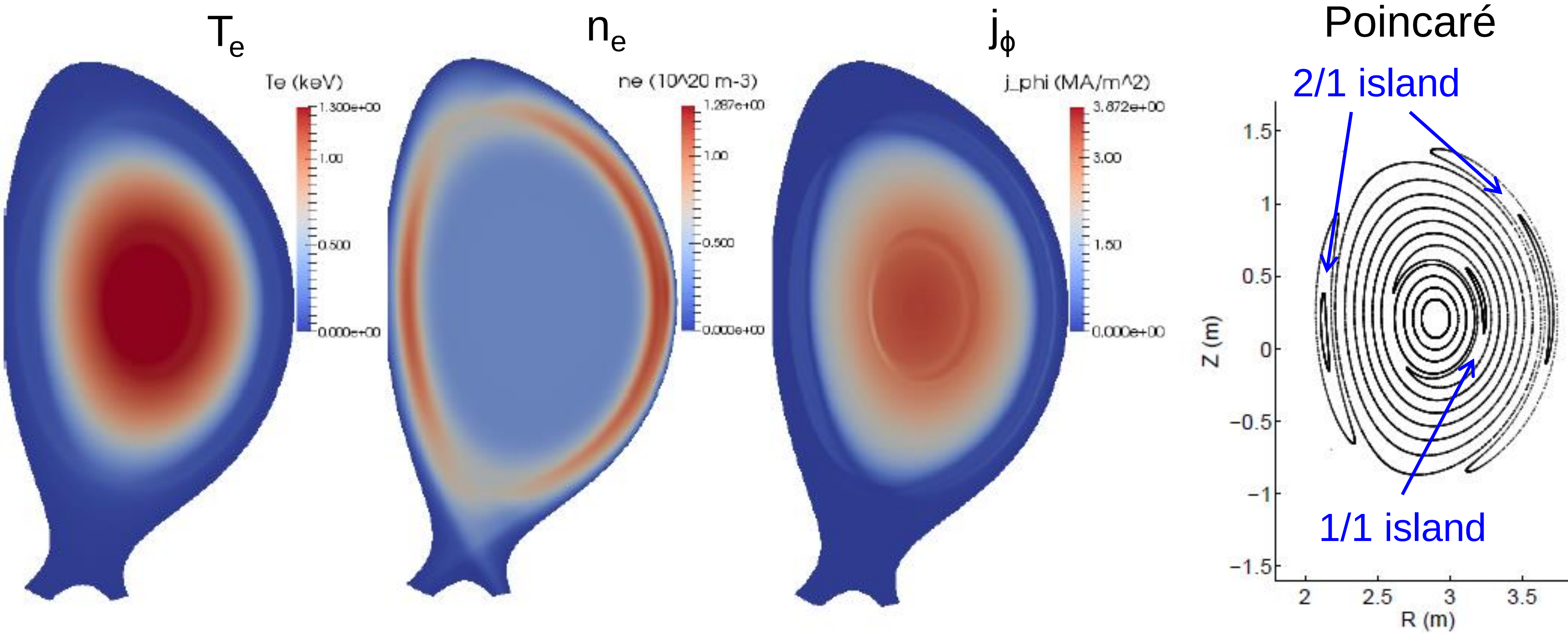


$T_e$ $n_e$ $j_\phi$ Poincaré

Poloidal cuts @ MGI position

# Overview of a JOREK simulation

t = 4.1 ms: pre-TQ phase



$T_e$

$n_e$

$j_\phi$

Poincaré

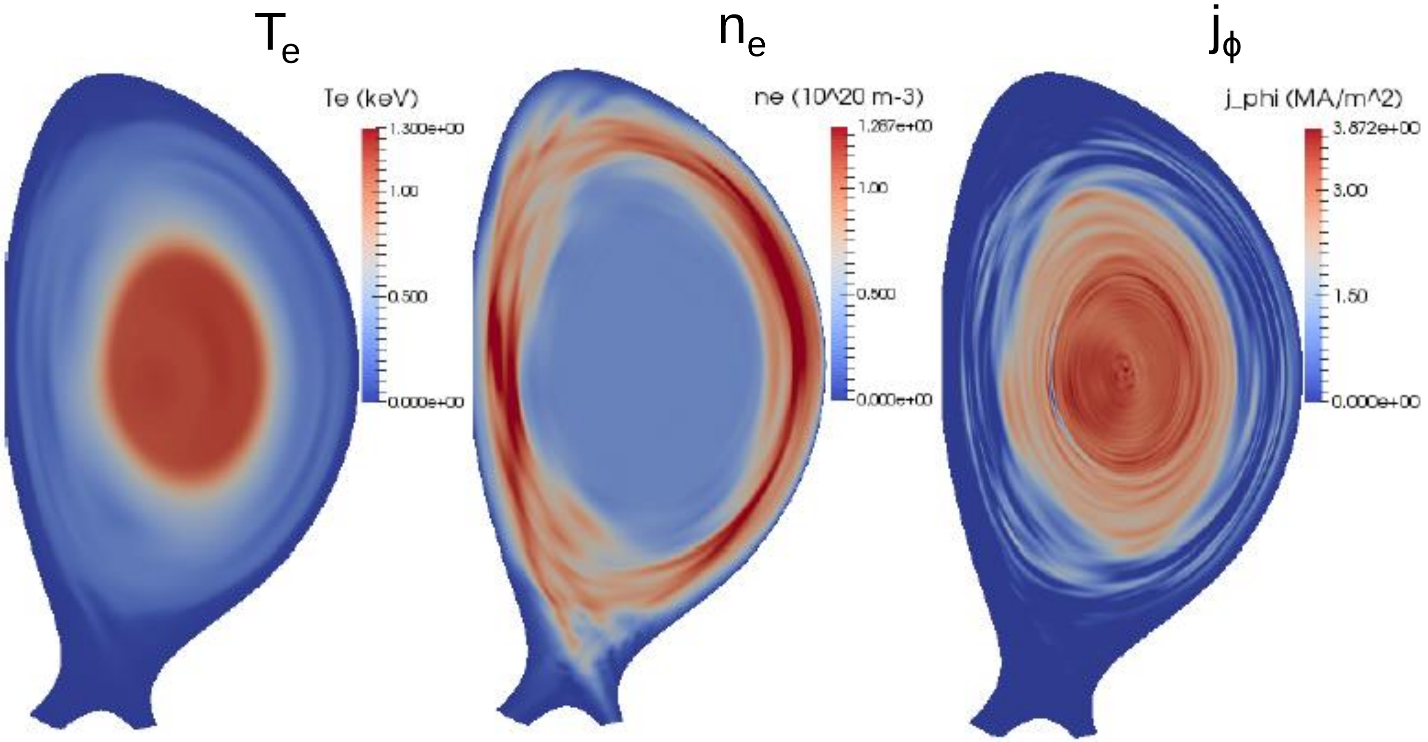
2/1 island

1/1 island

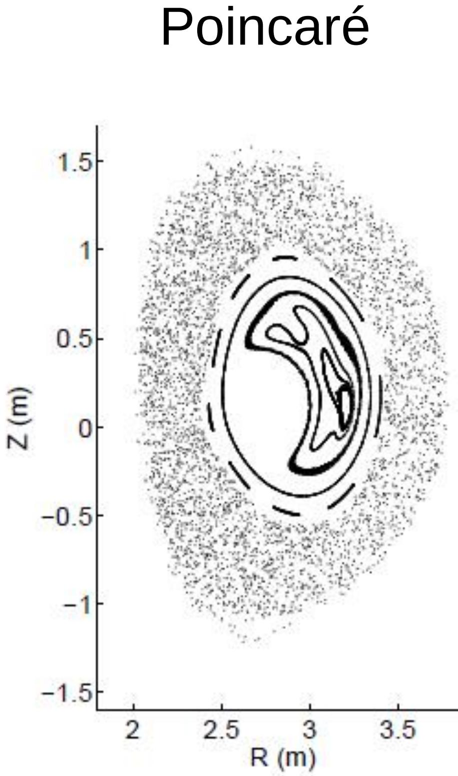
Poloidal cuts @ MGI position

# Overview of a JOREK simulation

t = 5.7 ms: beginning of the TQ



$T_e$ $n_e$ $j_\phi$

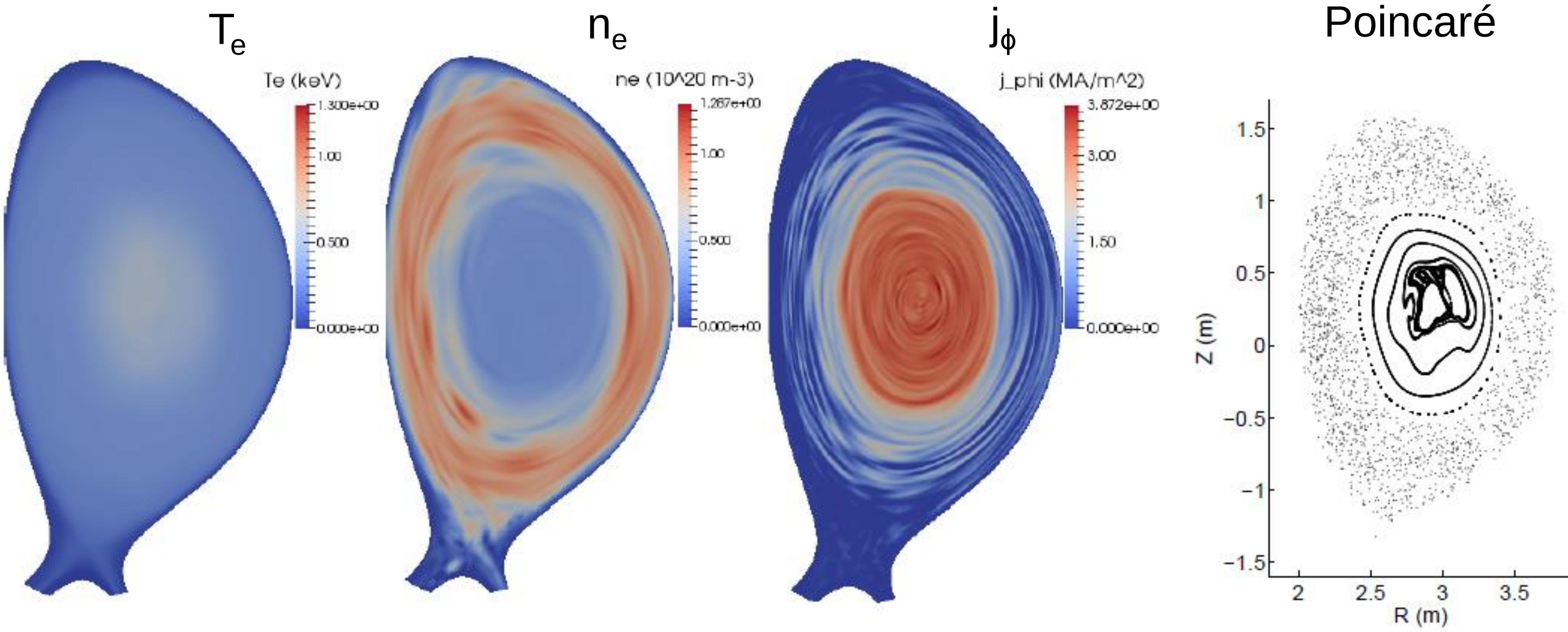


Poincaré

Poloidal cuts @ MGI position

# Overview of a JOREK simulation

t = 6.2 ms: end of the TQ



$T_e$ $n_e$ $j_\phi$ Poincaré

Poloidal cuts @ MGI position

# Let's try to understand what happens. But first… A quick introduction to tearing mode physics

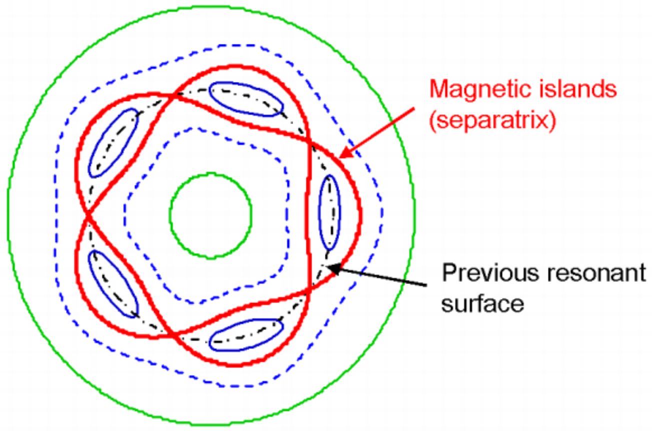
- Tearing Modes (TM) are related to rational q surfaces (e.g. q=2, 3/2, …)

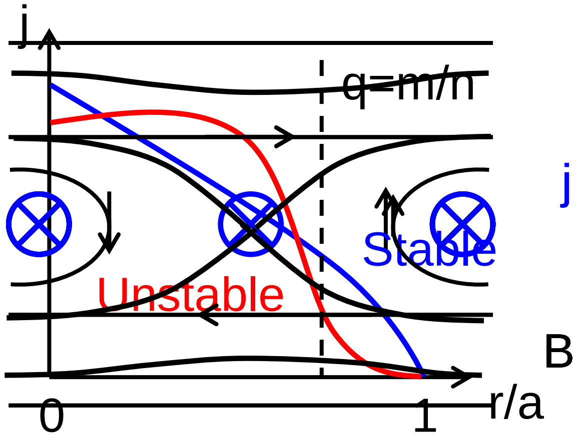
- TM change the magnetic topology (reconnection), forming magnetic islands

- Important driving mechanisms for TM:
  - Current profile
  - Local suppression of current

  Note: Slab configuration → X-point at missing j position
  **but** Tokamak configuration → O-point at missing j position

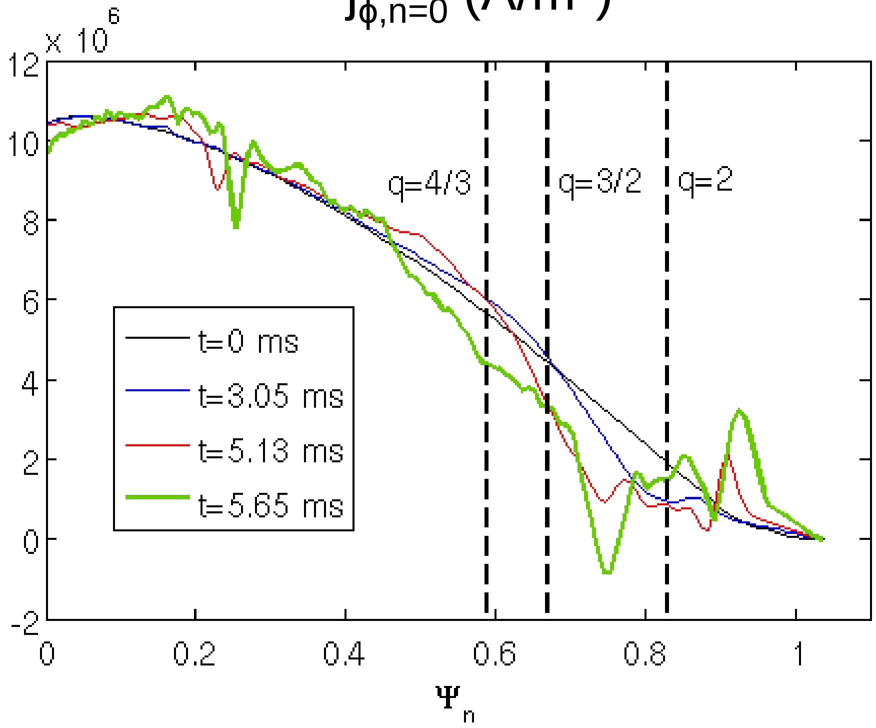
- Consequences of TM:
  - Flattening of T in the island
  - Flattening of j in the island





# The thermal quench seems to be triggered by a current profile avalanche effect

$j_{\phi,n=0}$ (A/m²)

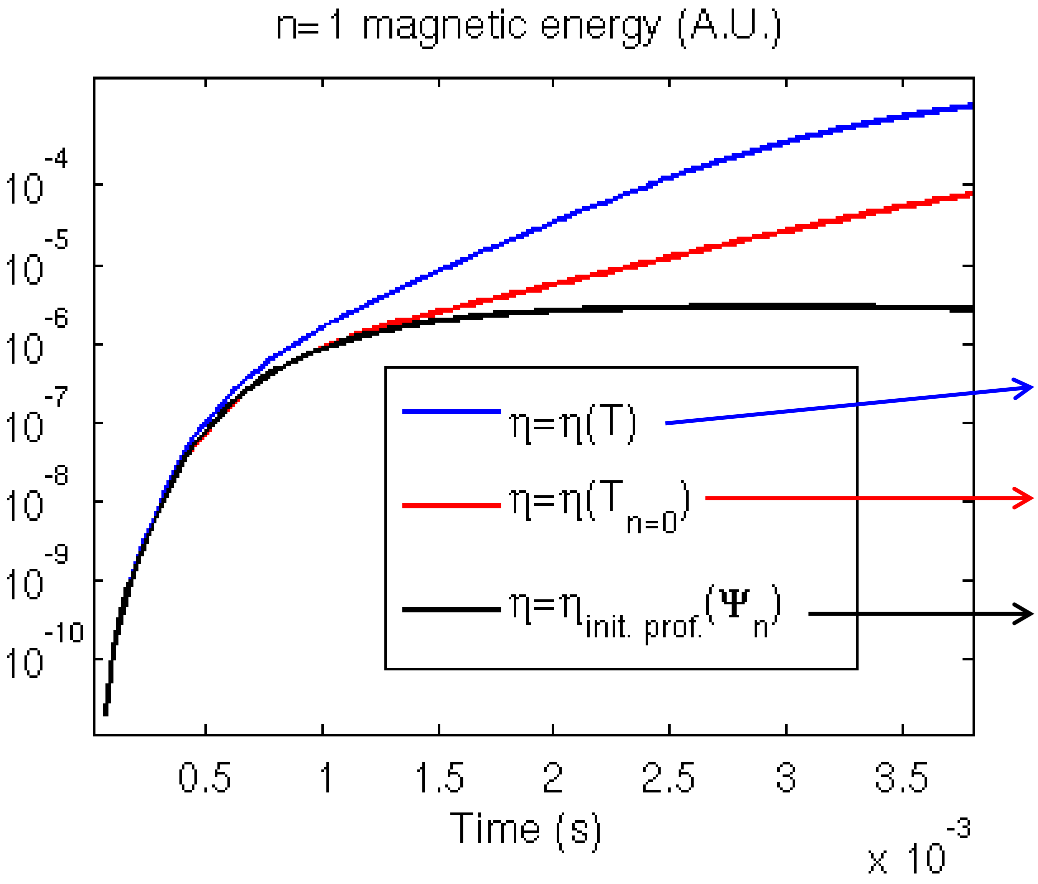


- Island overlap → magnetic stochasticity → TQ

# What starts the avalanche?
# i.e. how does MGI generate the 2/1 island?

- One may think of (at least) 3 mechanisms:
  - 3D equilibrium: MGI changes pressure field, j and B need to adjust so as to maintain j x B = ∇p
  - Resistivity effects:
    - Current profile effect: MGI → penetration of a cold front with a large η → contraction of current profile → drive for 2/1 tearing mode
    - Local current suppression effect: MGI → localized cooling and increase in η → localized drop of j → magnetic island with O-point at MGI position

# Numerical experiments with JOREK allow discriminating between the different mechanisms



All effects present

No local current suppression

No η effect

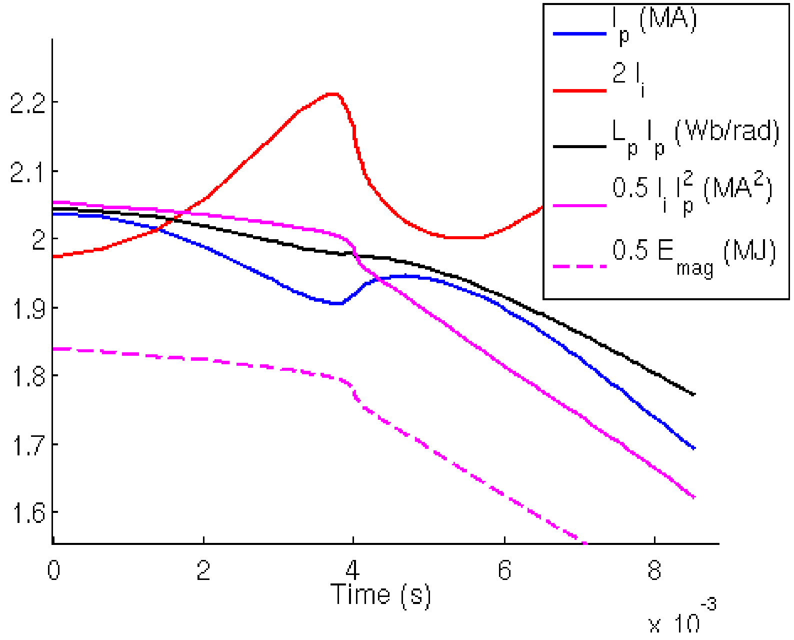
⇒ Initial growth not related to η effects

⇒ Provides a small seed from which island grows via η-related mechanisms

⇒ Local current suppression effect plays an important role

In JOREK simulations, the island O-point is indeed at the MGI deposition point, as observed experimentally [Lehnen NF 2015]

# An $I_p$ spike is observed in the JOREK simulations, but it is smaller than in the experiment



- $I_p$ spike = characteristic sign of the TQ
- Classic explanation: TQ releases magnetic energy ($\sim l_i I_p^2$) at constant $\Psi_b \sim L_p I_p$ (because $\tau_{TQ} \ll \tau_{wall}$) $\rightarrow l_i \downarrow$ and $I_p \uparrow$
- JOREK simulations are consistent with this explanation
- However, $\Delta I_p$ is too small in simulations

→ Probably too weak MHD in these simulations

- Effects which could strengthen the MHD (e.g. background impurities) are under investigation

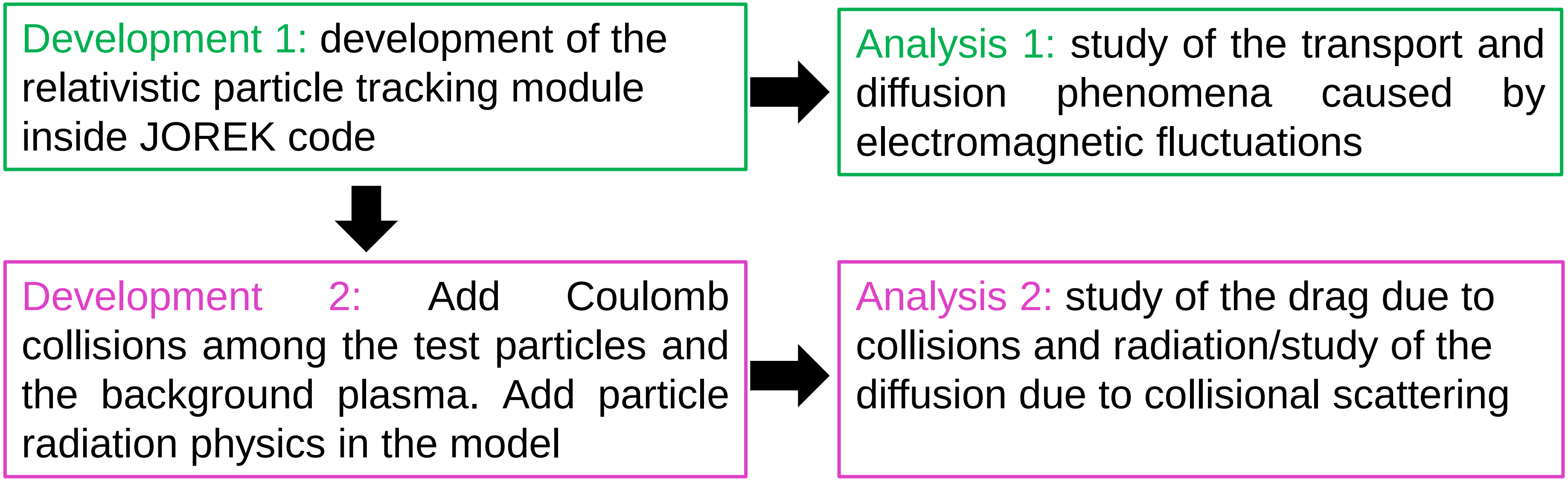
# Runaway generation physics - JOREK + test particles modelling

# CONTEXT OBJECTIVES AND PROJECT PLAN

Context: most of the works on REs dynamics is conducting using equilibrium magnetic fields

Objective: understand the runaway electrons dynamics at the presence of disruption induced magnetic perturbations

Method: Simulating runaway trajectories in disruption MHD fields obtained by JOREK (particle test approach)



Development 1: development of the relativistic particle tracking module inside JOREK code

Analysis 1: study of the transport and diffusion phenomena caused by electromagnetic fluctuations

Development 2: Add Coulomb collisions among the test particles and the background plasma. Add particle radiation physics in the model

Analysis 2: study of the drag due to collisions and radiation/study of the diffusion due to collisional scattering

# RELATIVISTIC GUIDING CENTER MODEL

Guiding-center approach: expansion of the electron gyromotion: bigger time steps with respect to full orbit simulation and smaller memory consumption (reduced phase space)

Validity conditions: electromagnetic fluctuations time and space scales are much bigger than particle gyromotion. The particle displacement in the magnetic direction is smaller than the parallel electromagnetic variation length scale

$$\frac{d\vec{R}}{dt} = \frac{1}{\hat{b}\cdot\vec{B}^*}\left(q\vec{E}\times\hat{b} - p_{/\!/}\frac{\partial\hat{b}}{\partial t}\times\hat{b} + \frac{\mu\hat{b}\times\nabla B}{\gamma} + \frac{p_{/\!/}\vec{B}^*}{m\gamma}\right)$$

$$\frac{dp_{/\!/}}{dt} = \frac{\vec{B}^*}{\hat{b}\cdot\vec{B}^*}\cdot\left(q\vec{E} - p_{/\!/}\frac{\partial\hat{b}}{\partial t} - \frac{\mu\nabla B}{\gamma}\right)$$

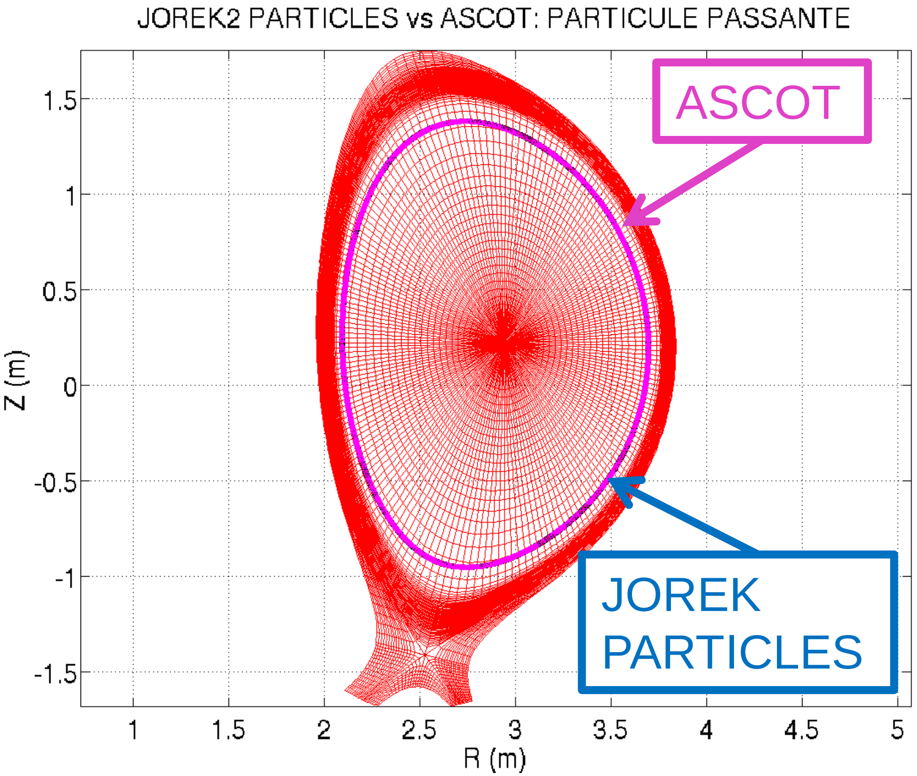
$$\text{avec } \vec{B}^* \equiv p_{/\!/}\nabla\times\hat{b} + q\vec{B} \;\; \text{et} \;\; \gamma \equiv \sqrt{1 + \left(\frac{p_{/\!/}}{mc}\right)^2 + \frac{2\mu B}{mc^2}}$$

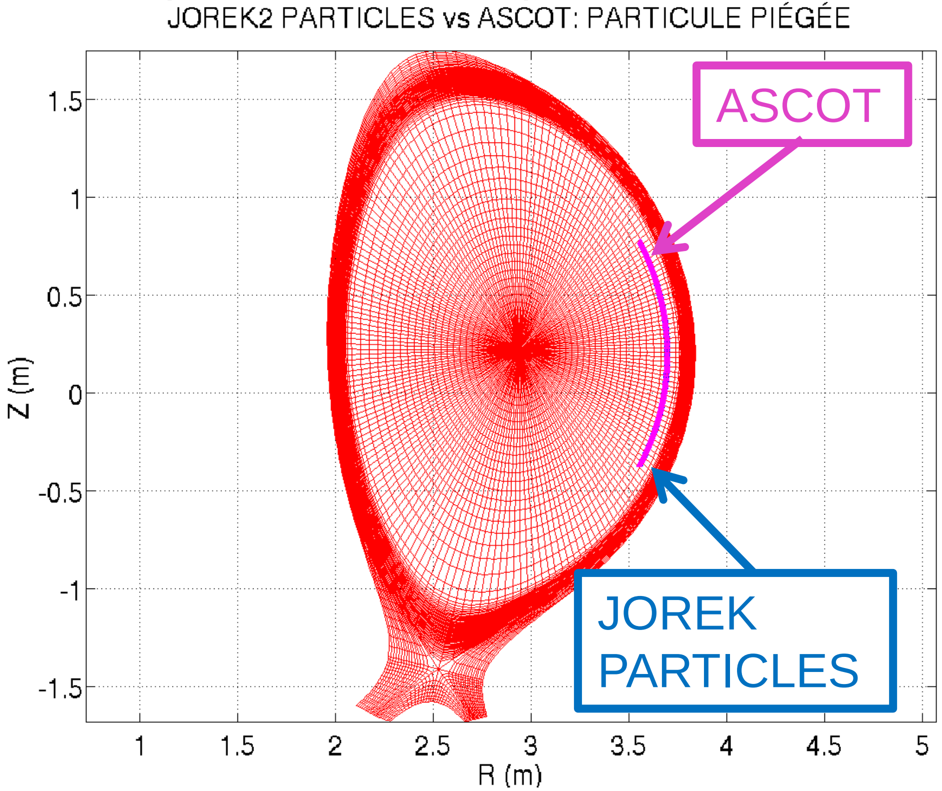
Numerical Method: Runge-Kutta 4(5) with time-space interpolations of the magnetohydrodynamic fields obtained by JOREK.

[Cary, Rev. Mod. Phys., 2009]

# BENCHMARK AND CODE VERIFICATION

## Benchmark with ASCOT code (U. Aalto, Finland)


JOREK2 PARTICLES vs ASCOT: PARTICULE PASSANTE


JOREK2 PARTICLES vs ASCOT: PARTICULE PIÉGÉE

Conservation of the constant of motion after a physical time of: 1(ms)

Passing particle (initial energy: 10(MeV)):

- Total energy: $6 \cdot 10^{-3}$ %, canonical toroidal momentum: $6 \cdot 10^{-1}$ %

Trapped particle (initial energy: 10(keV)):

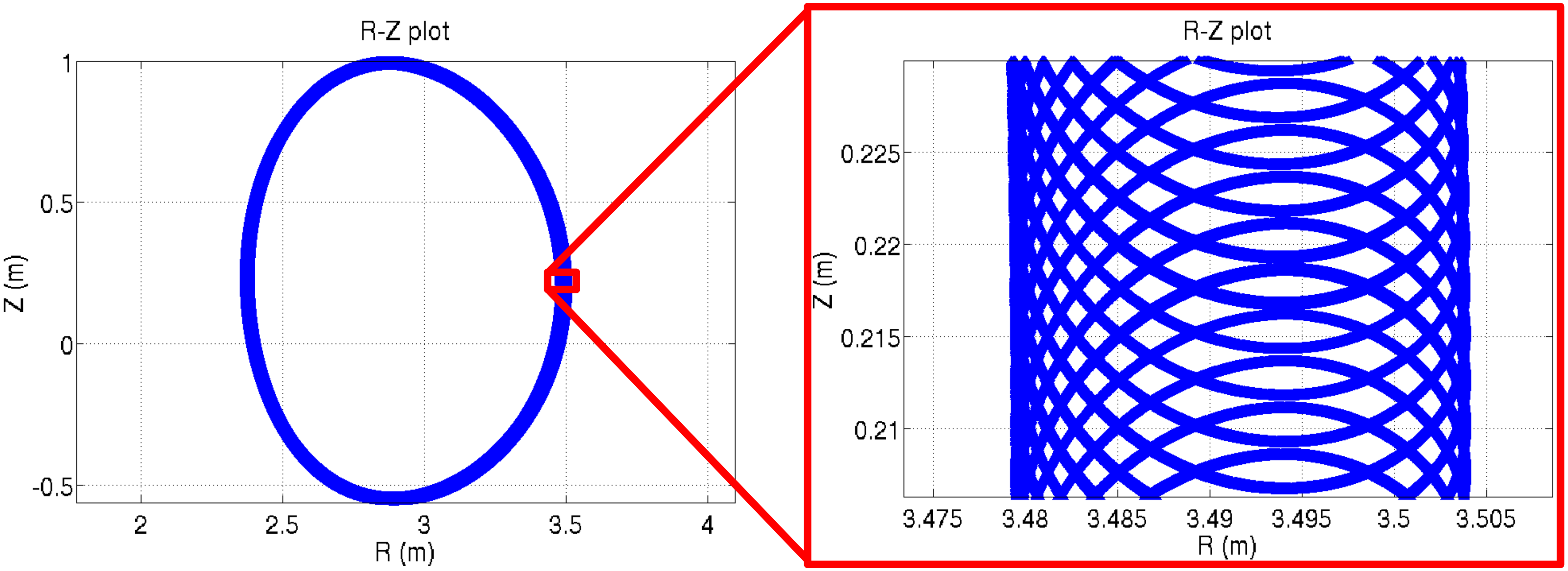
- Total energy: $6 \cdot 10^{-6}$ %, canonical toroidal momentum: $8 \cdot 10^{-7}$ %

# FULL 6D ORBIT CALCULATION

Lorentz's Equations:

$$\frac{d\vec{x}}{dt} = \frac{\vec{p}}{m\gamma}, \quad \frac{d\vec{p}}{dt} = q\left(\vec{E} + \frac{\vec{p}}{m\gamma} \times \vec{B}\right), \quad \gamma = \sqrt{1 + \frac{\vec{p}\cdot\vec{p}}{(mc)^2}}$$

- Equations of motion are integrated using the symplectic algorithm called Volume Preserving Scheme (VPA) [Zhang, PoP, 2015]



Conservation of the constant of motion after a physical time of: 2.5(μs)

Passing particle (initial position: LFS –mid plane, energy: 10(MeV), pitch angle: 45(°)):

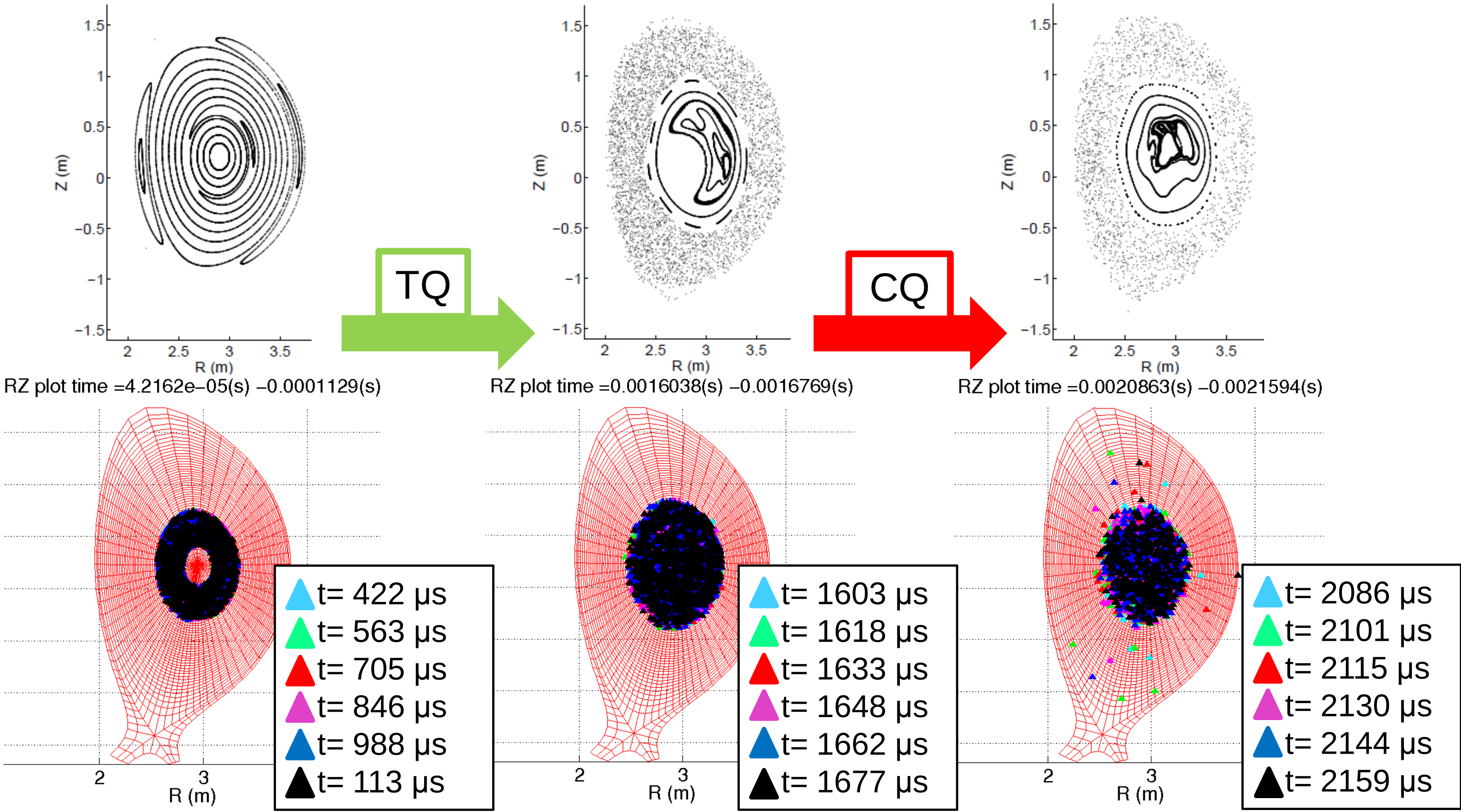
- Total energy: $4 \cdot 10^{-11}\%$, canonical toroidal momentum maximum fluctuation: $2\%$

# FIRST RESULTS

# FIRST TEST IN DISRUPTION WITH INTERNAL KINK

Proof of principle 1: particle dynamics in a disruption having an internal kink mode:

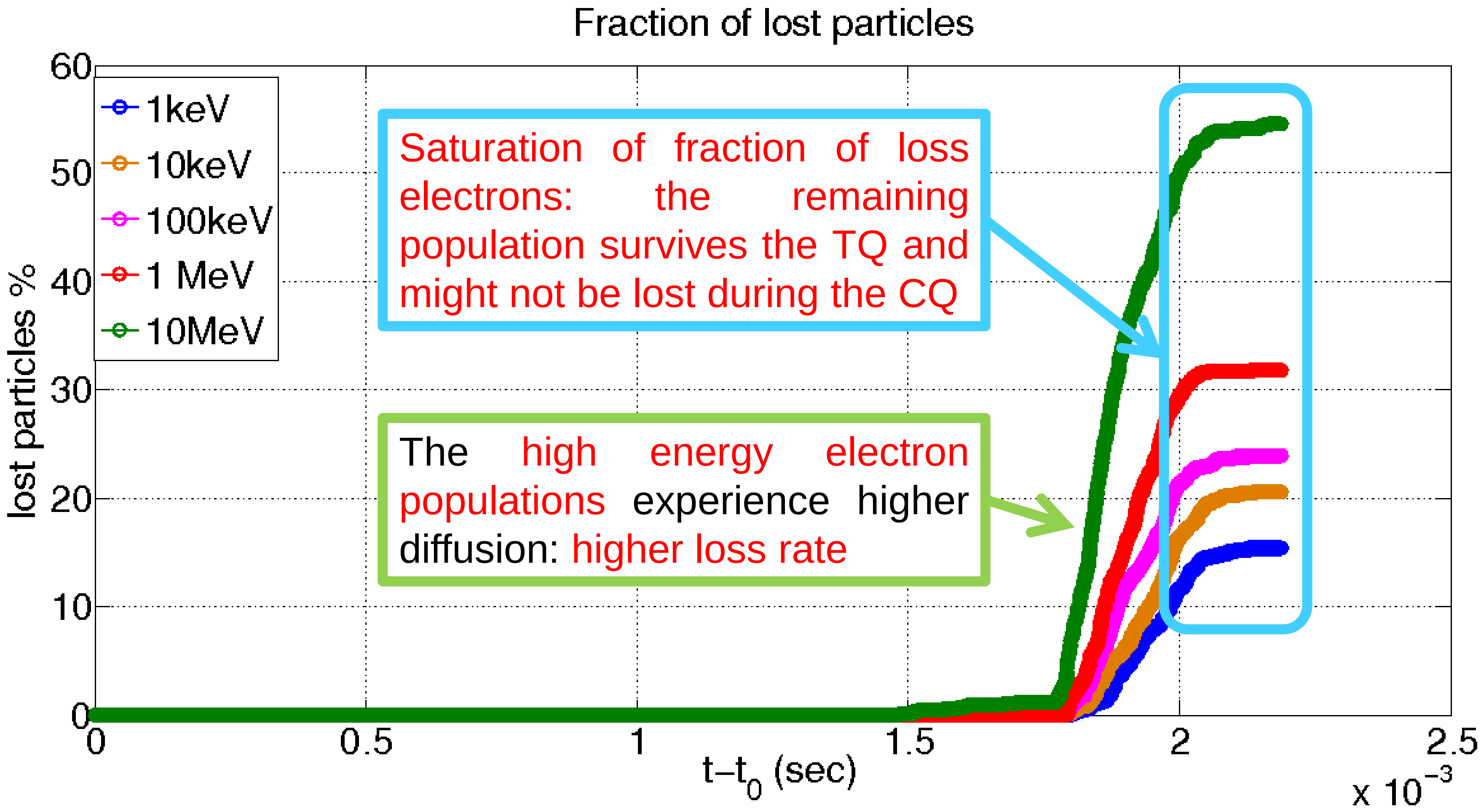
- Particle initialization: $\tilde{\psi}_{eq} = 0.1,\ \varphi = 0(°),\ \theta = 10(°)$ counter current, 1000 particles
- Warning: $I_p$ spike much smaller than the real experimental one
  - → The MHD activity might be underestimated



# FIRST TEST IN DISRUPTION WITH INTERNAL KINK

Proof of principle 1: particle dynamics in a disruption having an internal kink mode:

- Fraction of lost population due to magnetic chaos



Saturation of fraction of loss electrons: the remaining population survives the TQ and might not be lost during the CQ

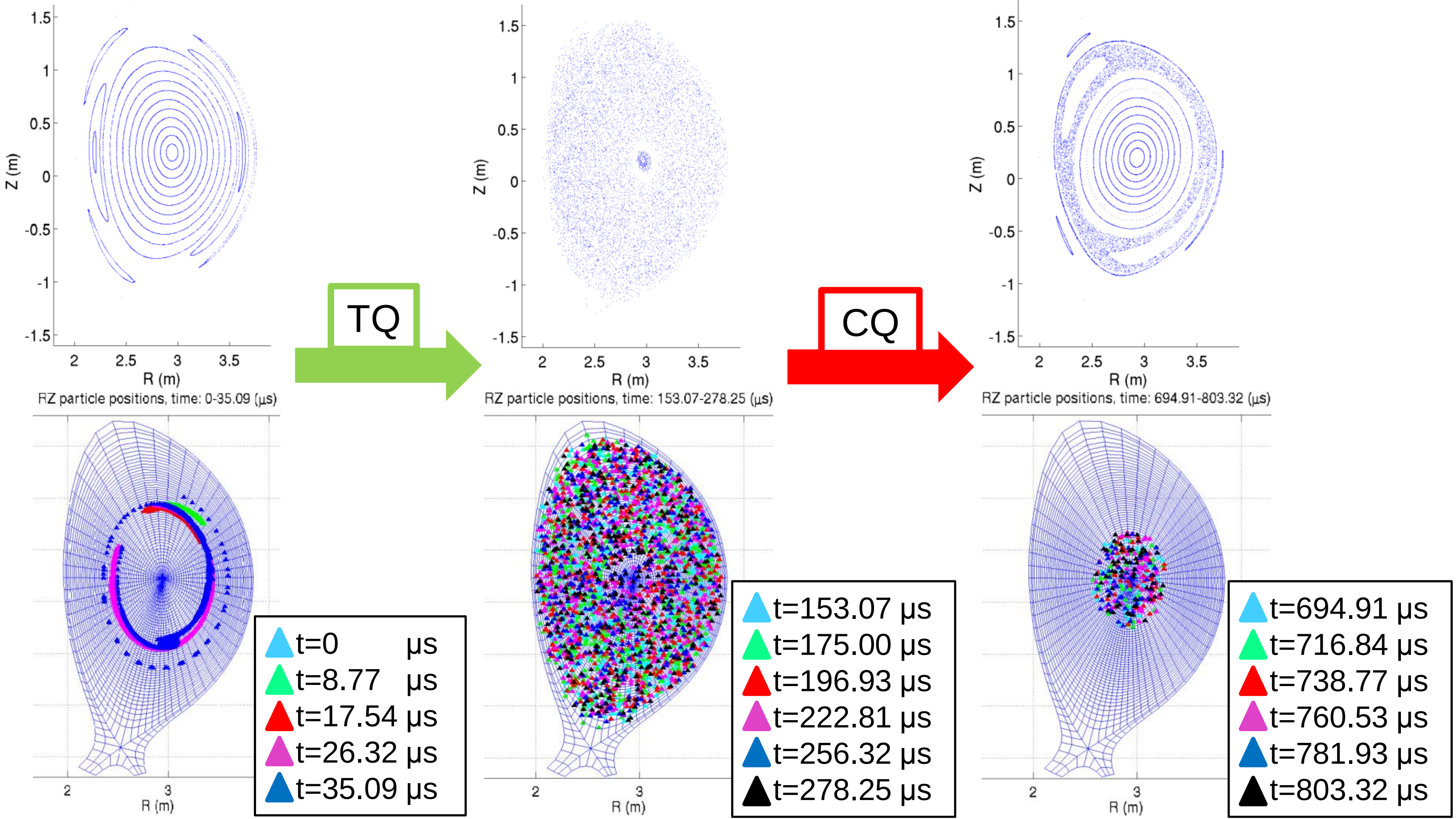
The high energy electron populations experience higher diffusion: higher loss rate

➢ Computation of particle advection and diffusion coefficient is underway

# How does MHD activity impact RE formation?

Proof of principle 2: particle dynamics in a disruption without an internal kink mode:

- Particle initialization: $3.4 \leq \mathrm{R(m)} \leq 3.41,\ 0.2162 \leq \mathrm{Z(m)} \leq 0.2262,\ \varphi = 0(°),\ E_{kin} = 1(\mathrm{keV}),\ \theta = 10(°)$ counter current, 1000 particles
- After TQ, ~5% of the electrons remain confined in the core

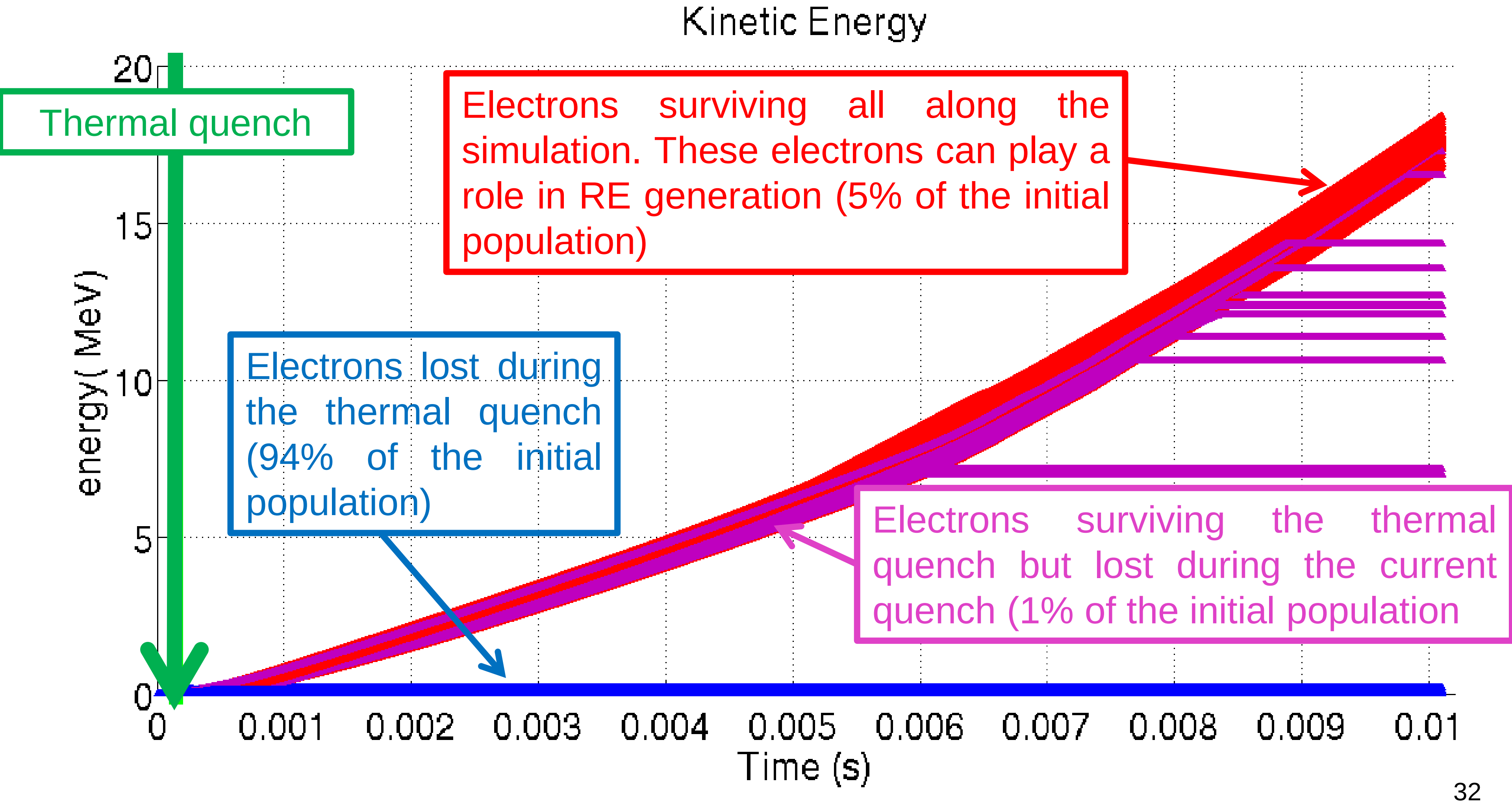


# DISRUPTION SIMULATIONS: 961 ELECTRONS

Proof of principle 2: particle dynamics in a disruption without an internal kink mode:

- Warning: No collisional or radiation operator:

  → Acceleration might be overestimated



Thermal quench

Electrons surviving all along the simulation. These electrons can play a role in RE generation (5% of the initial population)

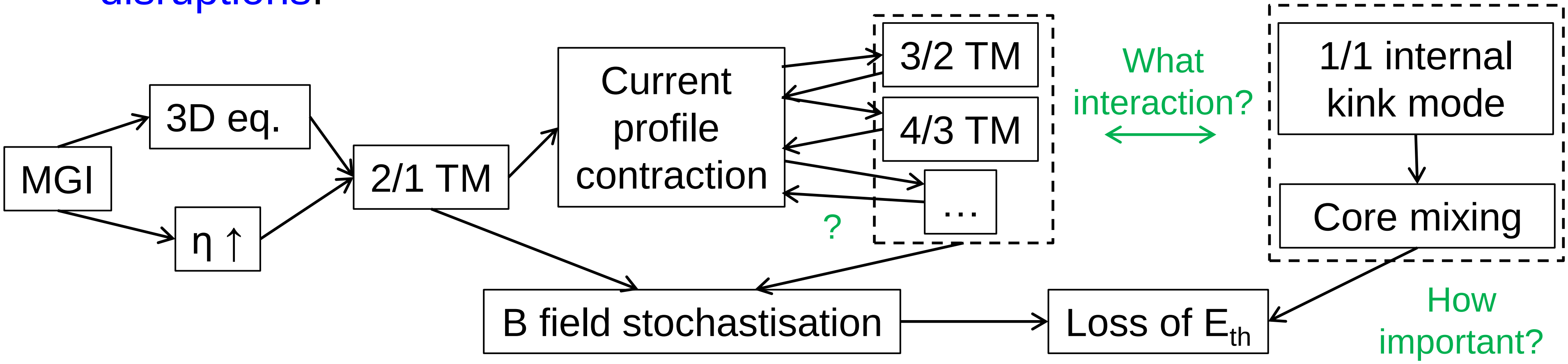
Electrons lost during the thermal quench (94% of the initial population)

Electrons surviving the thermal quench but lost during the current quench (1% of the initial population

# SUMMARY AND FUTURE WORK

# Summary and perspectives

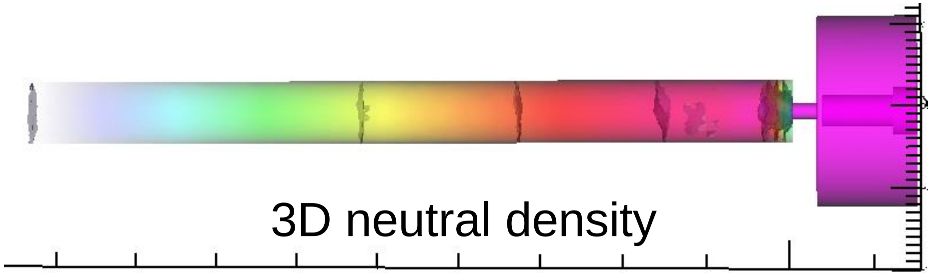
- Gas penetration is hindered by heat and momentum exchange between plasma and neutrals due to atomic physics
- JOREK simulations suggest the following picture for MGI-triggered disruptions:



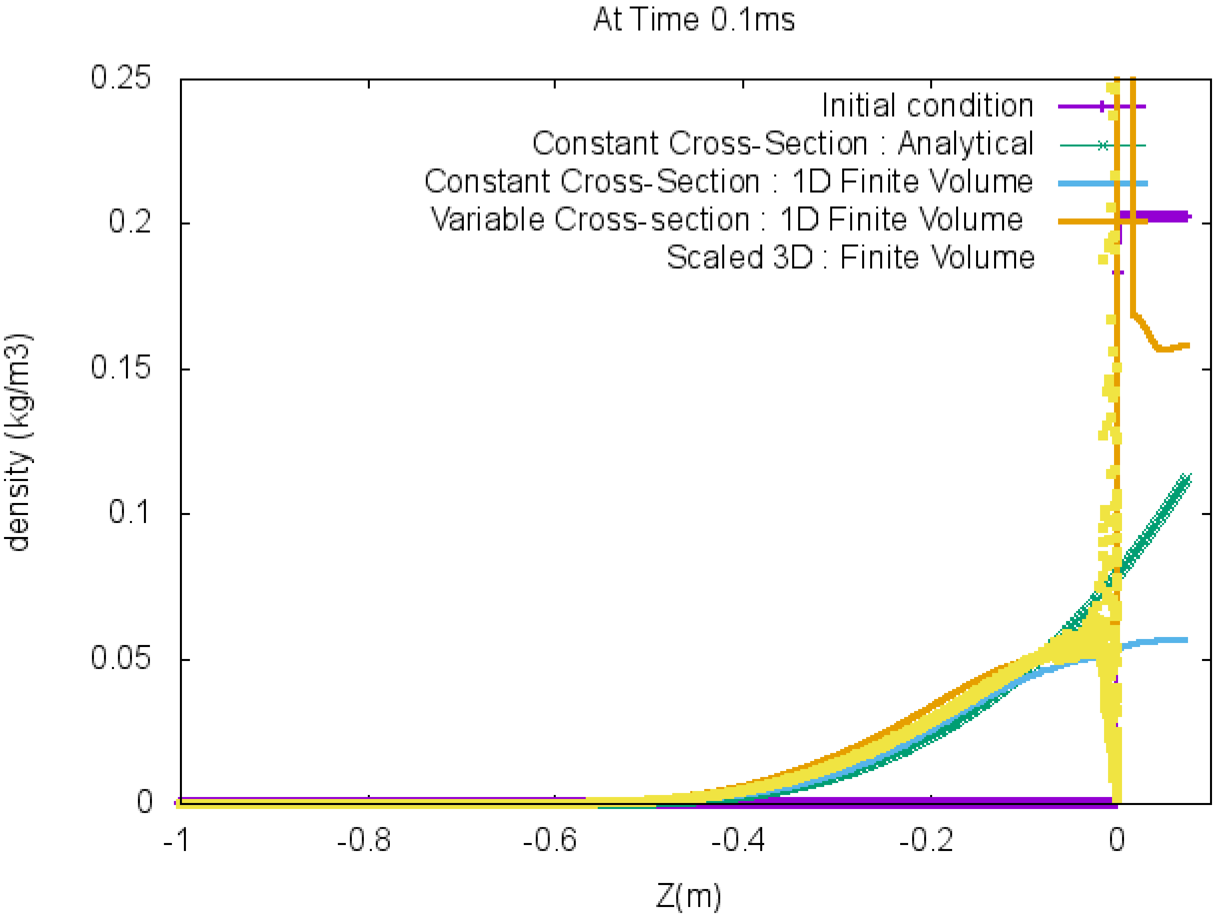
- Too small $I_p$ spike probably indicates too weak MHD in present simulations
- A small fraction of electrons might survive the thermal quench
- Perspectives:
  - Improve quantitative match for JOREK $D_2$ MGI simulations
    - JET and ASDEX Upgrade
  - Simulate non-$D_2$ MGI with JOREK (model ready)
  - Apply JOREK + test electrons to understand RE formation
  - Simulate SPI with JOREK

# BACKUP SLIDES

# Gas flow modelling:
# 3D gives results similar to 1D

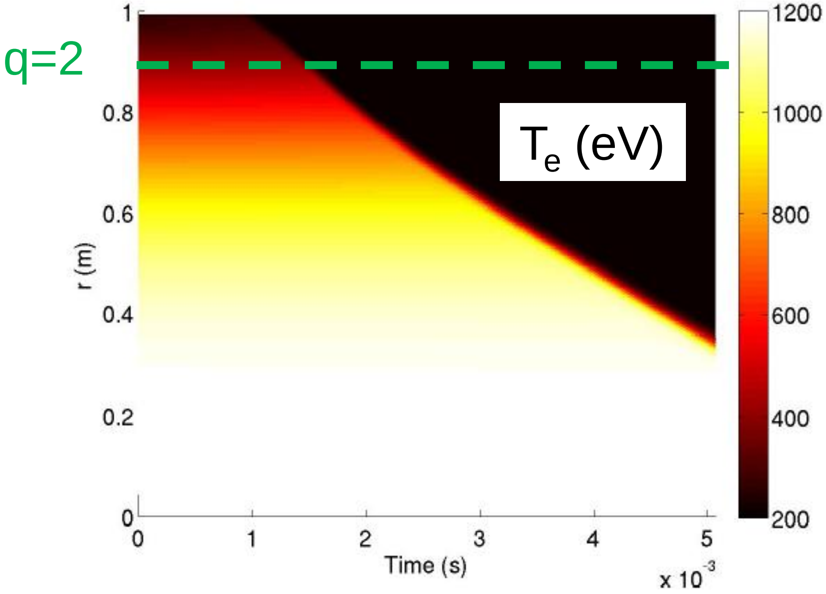


[Nkonga 2016]

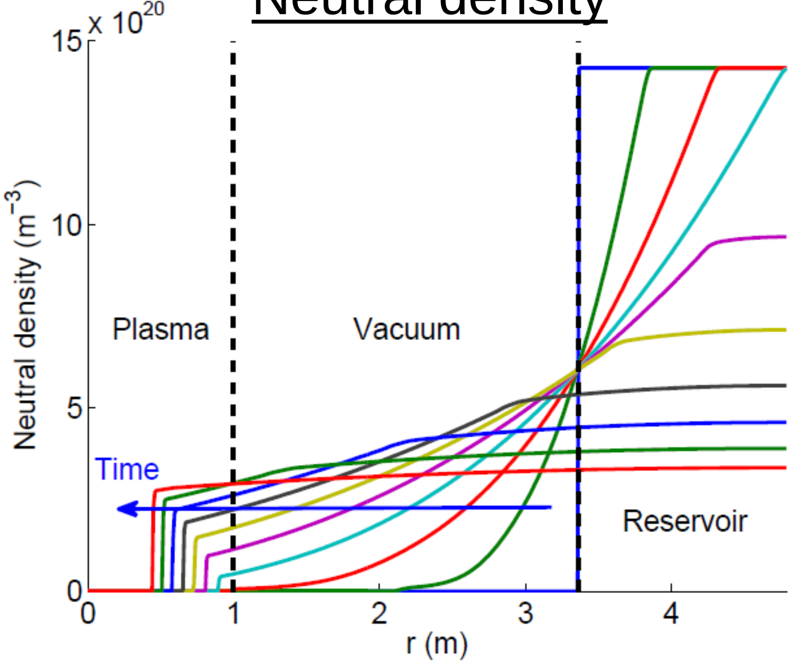


# Neglecting charge exchange and rec., the gas penetrates unrealistically easily

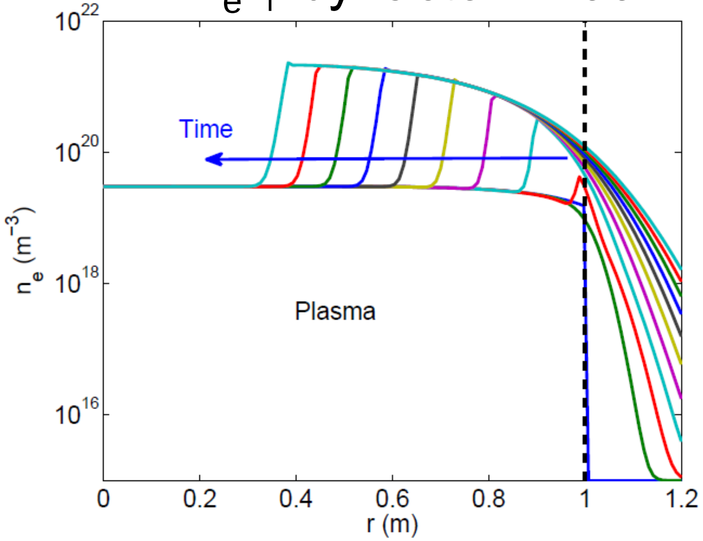
- Too short penetration time:
  - ~1.5 ms up to q=2 (r~0.9 m)
  - ~8 ms up to plasma center
  - Recall that TQ onset time ~12 ms



Neutral density



- $n_e$ ↑ by factor ~100

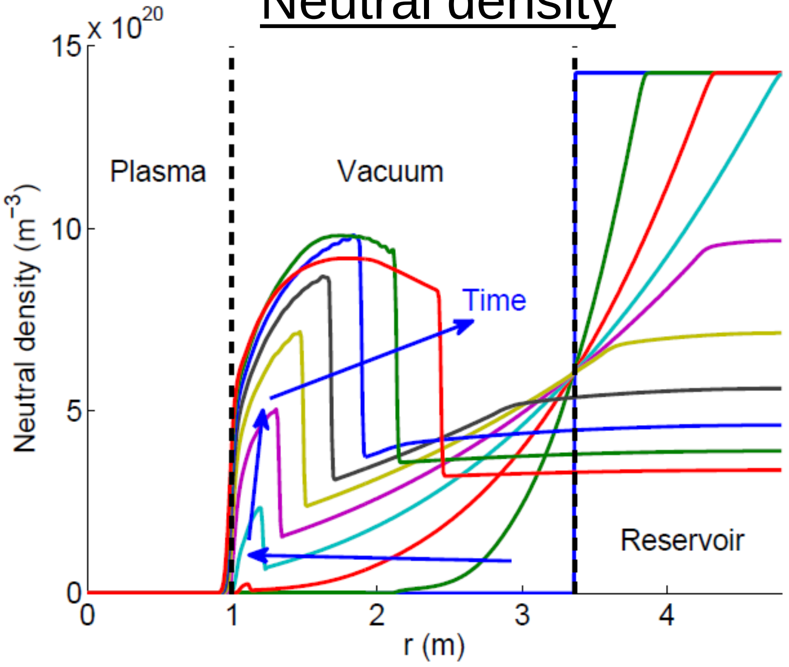


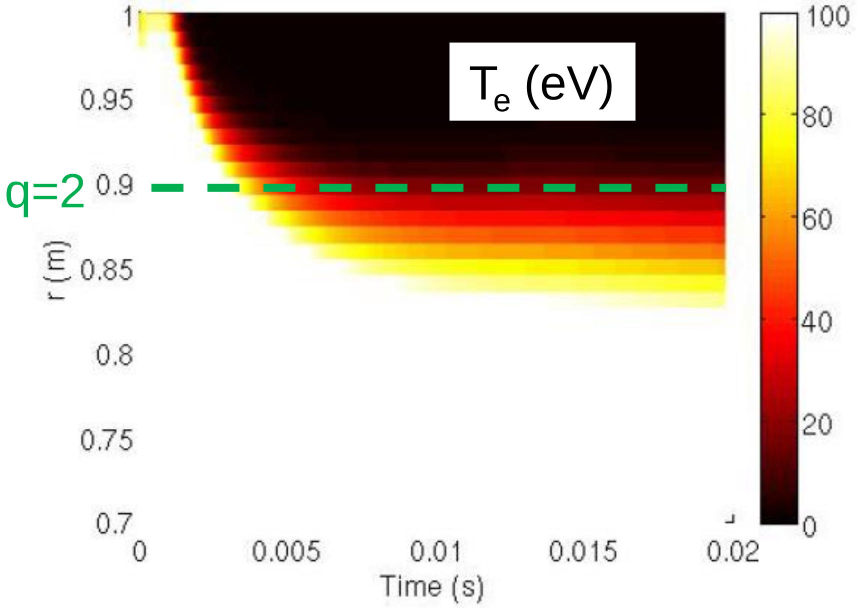
# Including charge exchange (and rec.), gas penetration is significantly reduced

- Much slower penetration (consistent with TQ onset time)

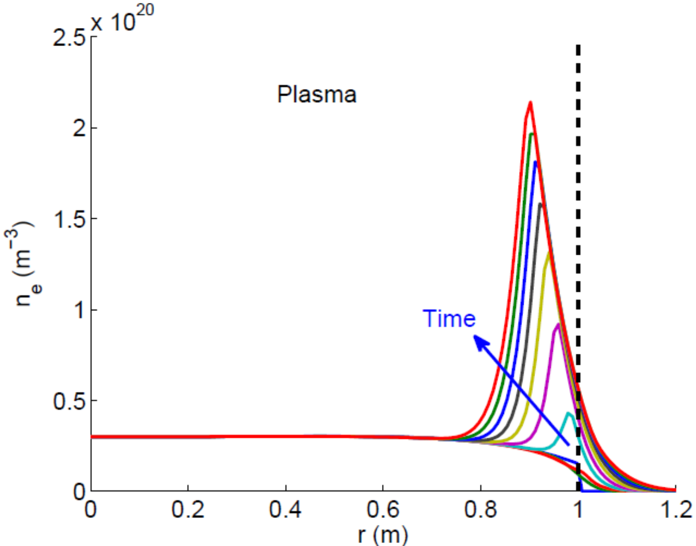
- Neutrals are heated by ions which creates a shock wave and strongly brakes the incoming gas

Neutral density





- $n_e$ ↑ by factor ~5 at the edge



# Context and motivation

- ITER Disruption Mitigation System (DMS) planned to be a hybrid Massive Gas Injection (MGI) - Shattered Pellet Injection (SPI) system

- Practical questions for the design of the DMS are connected to more fundamental physics questions, e.g.:

  - How to minimize radiation asymmetries?
    → How do MGI/SPI and MHD activity interact?

  - How to avoid runaway electrons (RE)?
    → What mechanisms determine RE formation during disruptions?

  - If an RE beam appears, will MGI be able to reach it for dissipation?
    → What mechanisms determine gas penetration?

- Modelling is needed to gain the necessary physical understanding

# State of the art

- Quite a few MGI modelling works have been published
  - ASTRA [Leonov PPCF 2005] [Fable NF 2016], TOKES [Landman FED 2011] [Petschanyi FED 2012], SOLPS [Pautasso IAEA 2008], NIMROD [Izzo NF 2011]

- However, fuelling efficiency ($\equiv \Delta N_{e,plasma}/N_{e,reservoir}$) is not predicted for various reasons, e.g.:
  - Simulations do not include gas dynamics
  - Gas transport is treated as a diffusion

- In reality,
  - Gas dynamics matters
  - Gas transport is fundamentally convective

- The IMAGINE code has been designed to address these points

[Nardon NF submitted]