Tearing modes driven by a Runaway Electrons current in 2D and 3D

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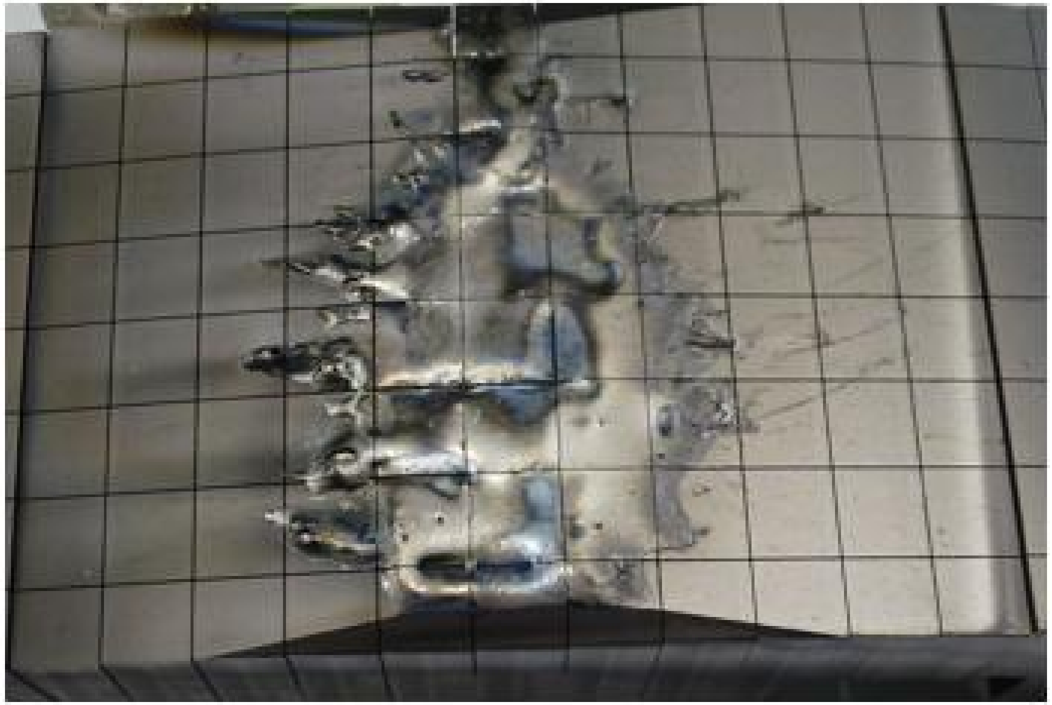
Motivation

Runaway Electrons (RE) represent a serious threat for high current Tokamak devices. In machines such as ITER these can **acquire energies up to tens of MeV damaging** the Plasma Facing Components (**PFC**). In extreme cases, the PFCs cooling system can be affected as well.



Damaged caused by the RE beam in JET #86801

Multiple solutions investigated:

- Shattered Pellet Injection (SPI) (JET, DTT, ITER)
- Resonant magnetic perturbation coil (REMC) (DIII-D, SPARC)
- Sacrifical limiters (DEMO, DTT)
- …

L. Chen, 5th Asia Pacific Conference on Plasma Physics, 26 Sep-1 Oct 2021

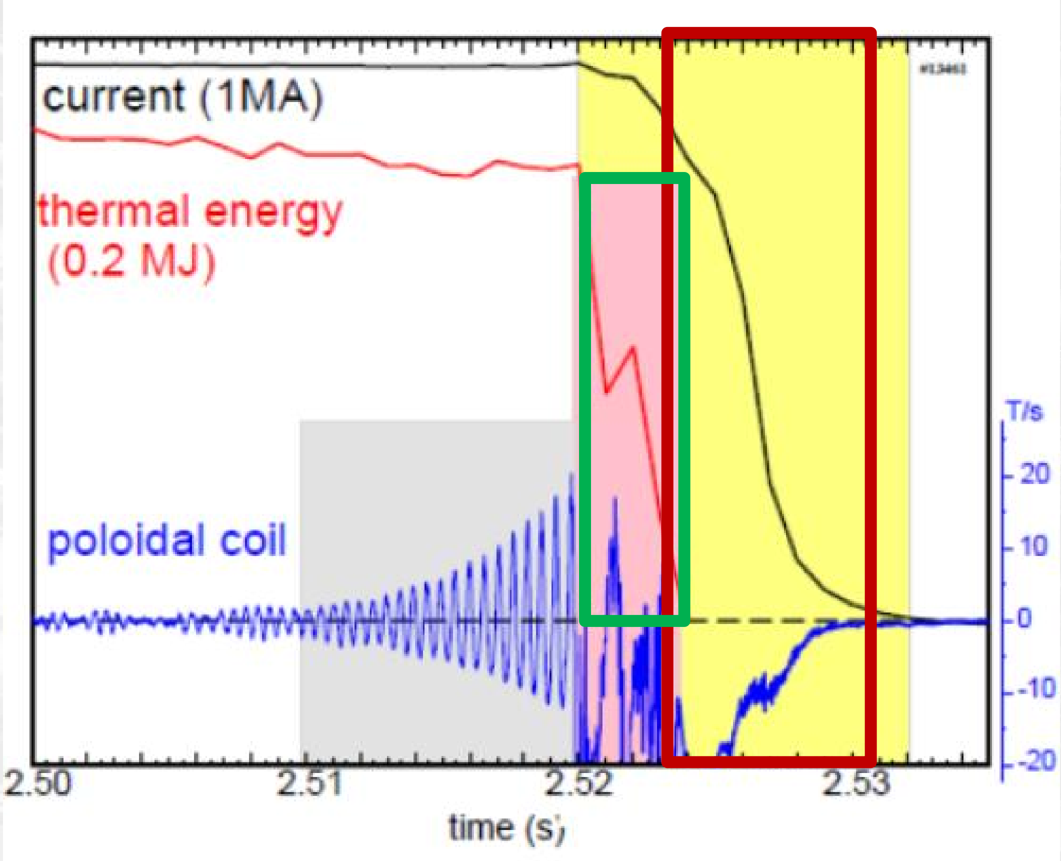
Overview

We contribute to the study of these solutions by investigating two fundamental aspects of the runaway electron (RE) dynamics:

- Analysis of the **RE interaction with the core plasma**. Fundamental to understand the effectiveness of the SPI and REMC in mitigating a RE population

- Study of **RE impact on the Tokamaks First Wall**. Important for the design of the sacrificial limiter

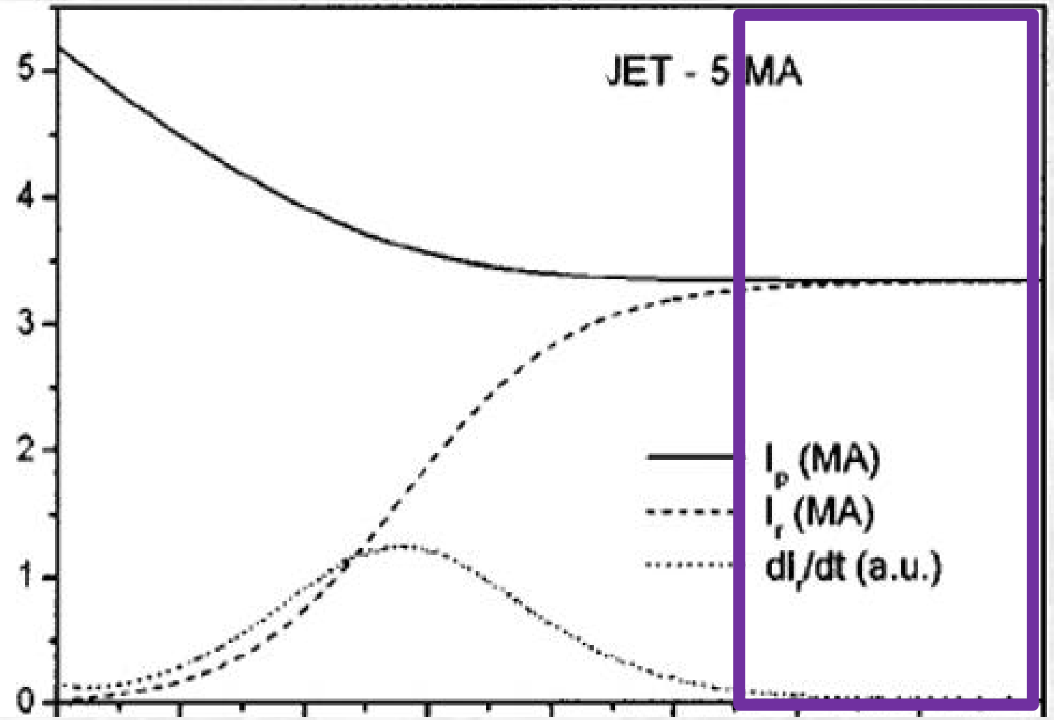
Runaway Electrons: current going down



Thermal quench: rapid cooling of the plasma

Current quench: the plasma current and the poloidal magnetic field decay

Runaway Electrons: rise of the runaways



Thermal quench: rapid cooling of the plasma

Current quench: the plasma current and the poloidal magnetic field decay

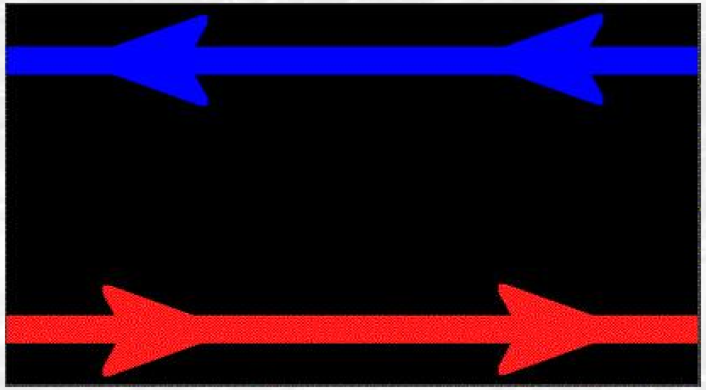
Toroidal electric field increases → Acceleration of electrons → **RUNAWAY ELECTRONS**

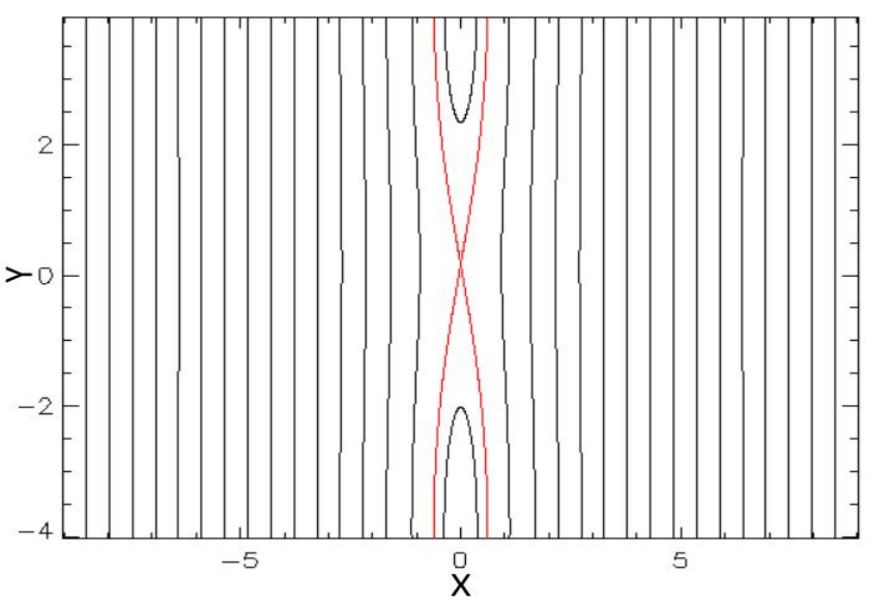
Once generated, how do they interact with the plasma before reaching the wall?

Martin-Solis et al. PoP 7 2000

Some bits of theory: magnetic island formation

- It is known from theory (Helander et al, Liu et al) that a RE current can drive tearing instabilities in a post disruption plasma.
- The evolution of a tearing-mode instability can cause the magnetic field lines to reconnect, i.e. magnetic reconnection.

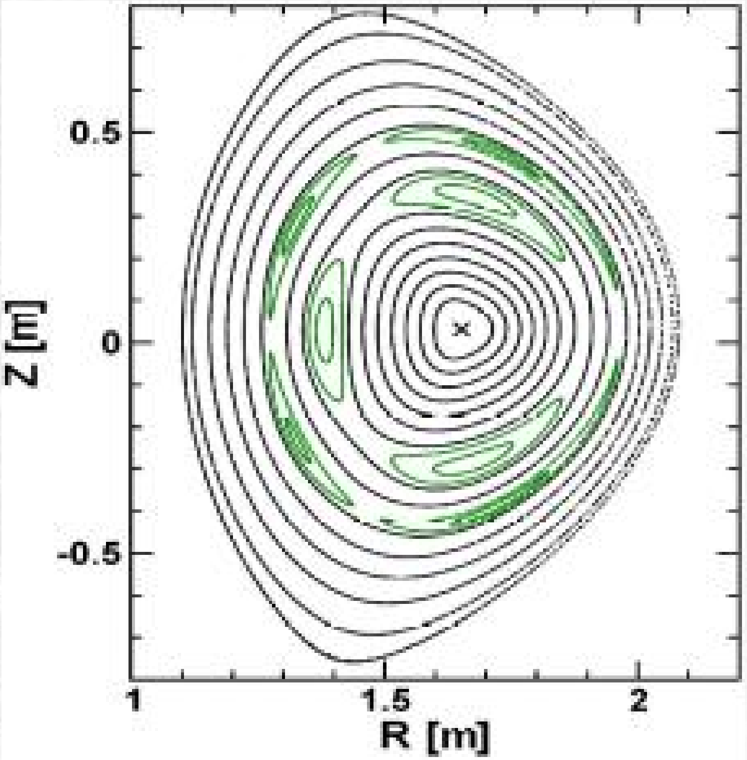


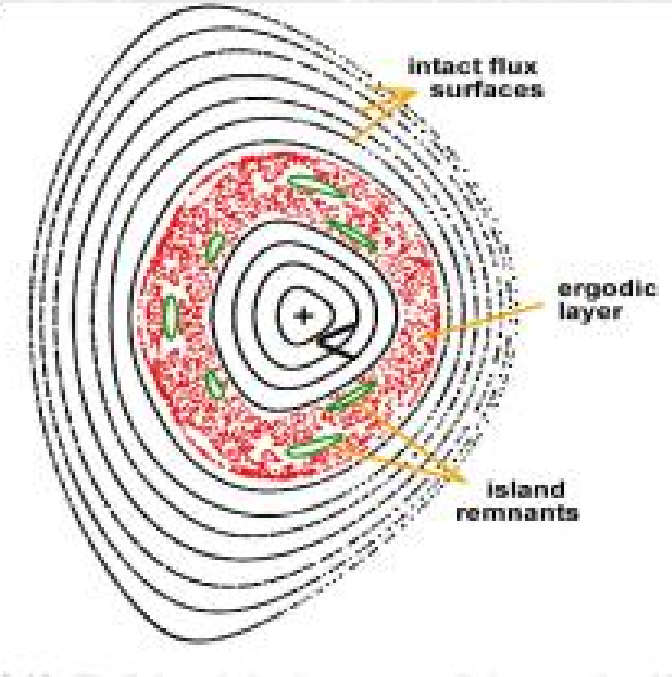


- The magnetic reconnection leads to the formation of a **magnetic island** changing the magnetic field topology

Some bits of theory: magnetic island stochasticity

- In presence of **multiple magnetic islands** these can interact and give origin to **magnetic field stochasticity**





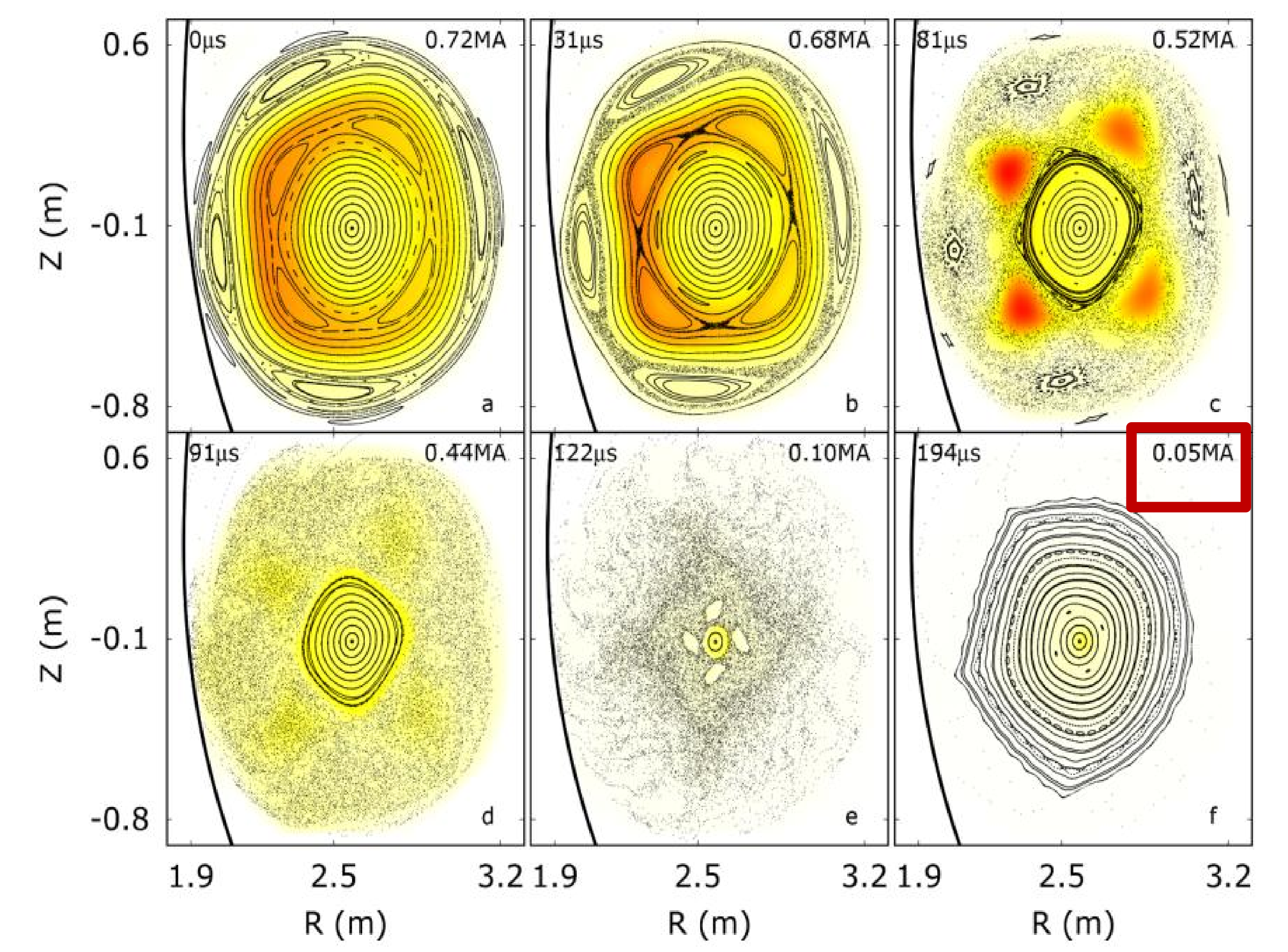
JET #95135: MHD simulation

Bandharu et al (2021) demonstrated that the magnetic chaos can cause a rapid loss of RE without damaging the wall. This numerical demonstration was carried through the JOREK code to explain the RE losses observed experimentally in JET #95135

Bandaru et al, PPCF **63** (2021)

JET #95135: simulation results

- The **simulation** was **started** from a **reconstructed magnetic equilibrium** leading to the formation of two m=4 magnetic island chain in the inner region and one m=5 mangnetic island chain in the outer region.
- The **interaction** of the **island chains** corresponding to m=5 and m=4 causes the **stochastization of the magnetic field lines**
- While the stochasticity is moving inward we have a **continuous loss of the RE population**
- **At the end**, we have the reformation of the magnetic flux surfaces and a **nearly complete loss of RE**



Bandaru et al, PPCF **63** (2021)

Open questions

Bandharu's work have demonstrated that the fast RE losses are caused by the evolution of a large MHD instability leading to the magnetic field stochastization. However, some questions about the nature of RE interaction with the core plasma and the impact of such a current on the First Wall needs to be answered:

- How does the **RE current influence the magnetic stochasticity**? → Analysis of the mutual interaction between a RE current and magnetic islands using SCOPE3D in 2D and 3D

- What are the **implications of such interaction for the RE beam impact on the wall**? → Investigation of the RE energy deposition as a function of impact angle and wetted area

State of the art

- Helander et al (2007) have shown that the **Runaway Electrons** (RE) can **strongly influence the magnetic reconnection process.**
- Morevoer, further studies by Liu et al (2020) demonstated that **tearing modes in presence of RE causes the island to rotate and the apperance of a microlayer on the RE current profile**. This study was done in linear regime. In addition, the authors pointed out the **likewise influence of the electron inertia on the evolution of the magnetic reconnection in case a microlayer is present**.

………………………………………………………**GAP**………………………………………………

- Bandaru et al (2021) stated that the **stochastization of the plasma magnetic field can cause the RE to spread over a large area of the First Wall** without damaging the wall.

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Some bits of theory: extended MHD equations

We consider a **two fluid model** with a typical Tokamak magnetic field which is almost uniform and unidirectional,

$$\boldsymbol{B} = \boldsymbol{B}_z + \boldsymbol{B}_\perp = \mathrm{B_z}\mathbf{e_z} + \nabla\psi \times \mathbf{e_z}$$

The **Reduced normalized** (on Alfvén time and equilibrium scale length) **equations**,

Ohm's law

$$\frac{\partial F}{\partial t} + [\phi, \mathrm{F}] + \frac{\partial \phi}{\partial z} = \rho_s^2[U, \psi] + \rho_s^2\frac{\partial U}{\partial z} - \varepsilon_\eta(\nabla^2\psi + \boldsymbol{j_{RE}})$$

Continuity equation

$$\frac{\partial U}{\partial t} + [\phi, U] = [J, \psi] + \frac{\partial J}{\partial z} \qquad \text{with} \qquad \mathbf{V} = \mathbf{e_z} \times \nabla\phi$$

RE current density equation

$$\frac{\partial j_{RE}}{\partial t} + [\phi, j_{RE}] - \frac{c}{v_A}\left([\psi, j_{RE}] - \frac{\partial j_{RE}}{\partial z}\right) = 0$$

$$F = \psi + d_e^2 J = \psi - d_e^2\nabla^2\psi \qquad \mathrm{U} = \nabla^2\phi$$

with $\rho_s = \sqrt{\frac{eT_e}{enB}}$ ion sound Larmour radius, $d_e = \frac{c}{\omega_{pe}} = c\sqrt{\frac{m_e}{4\pi n e^2}}$ electron skin depth

Helander et al., Phys Plasmas 14 (2007)

Problem description

- Reconnection event driven by a RE current considering a static equilibrium:

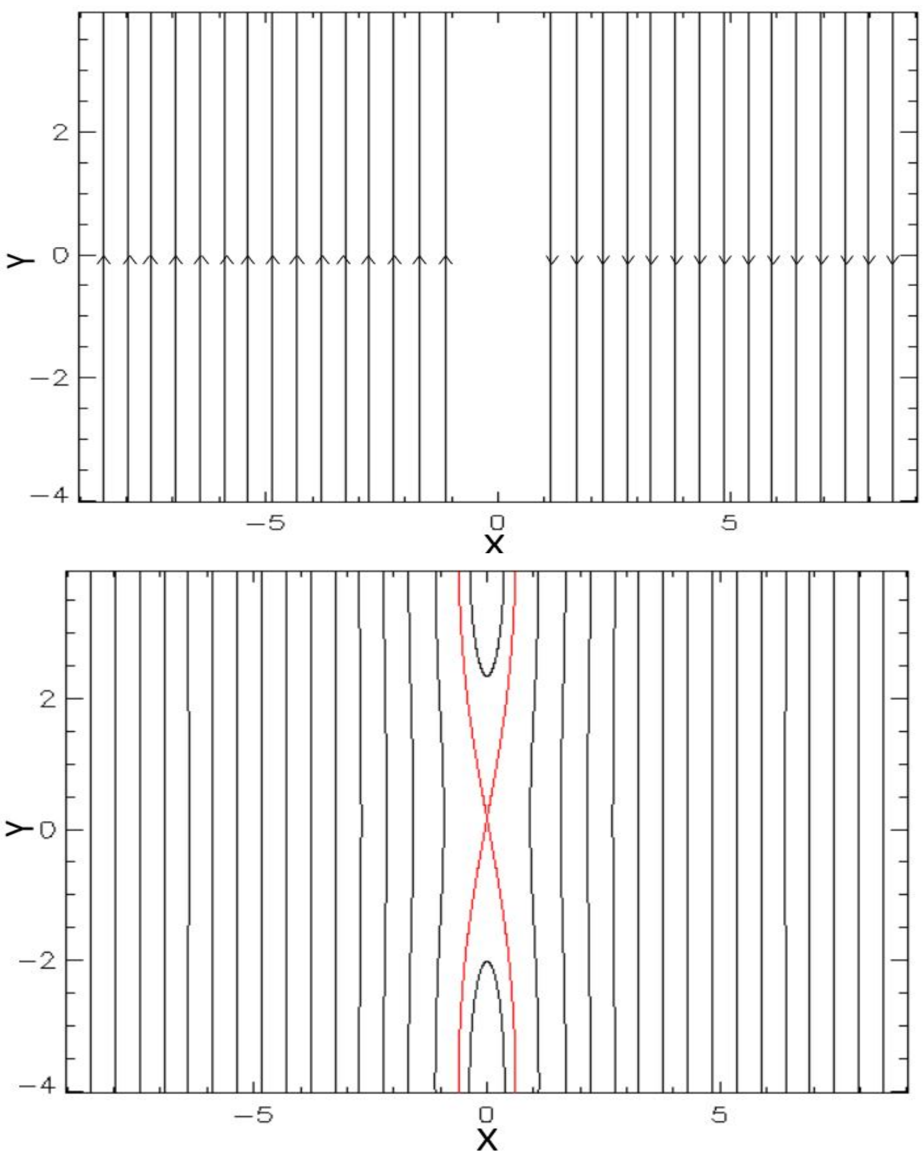
$$\varphi(x, y, 0) = 0$$

$$\mathrm{B}_{y,eq}(x) = \nabla\psi_{eq}(x)$$

$$j_{re}(x, y, 0) =- \nabla^2\psi_{eq}(x) = j_{eq}(x, y, 0)$$

$$\tilde{f} = \hat{f}(\mathrm{x})\exp\left(\mathrm{i}k_y y + ik_z z\right)$$

- Single helicity problem $\rightarrow h = \frac{k_z}{k_y} = fixed$
- Slab geometry
- The simulations are started with a **linearly unstable mode** that leads to a **spontaneous magnetic reconnection event**



Current distributions during the linear phase

During the evolution of the tearing instability, the RE current leads to the formation of a microlayer (called δ_2 here) which is much narrower than the resistive layer characteritisic of a tearing instability (called δ_1 here). The presence of a microlayer causes the current to become extremely localizzed around the rational surface of the magnetic island.

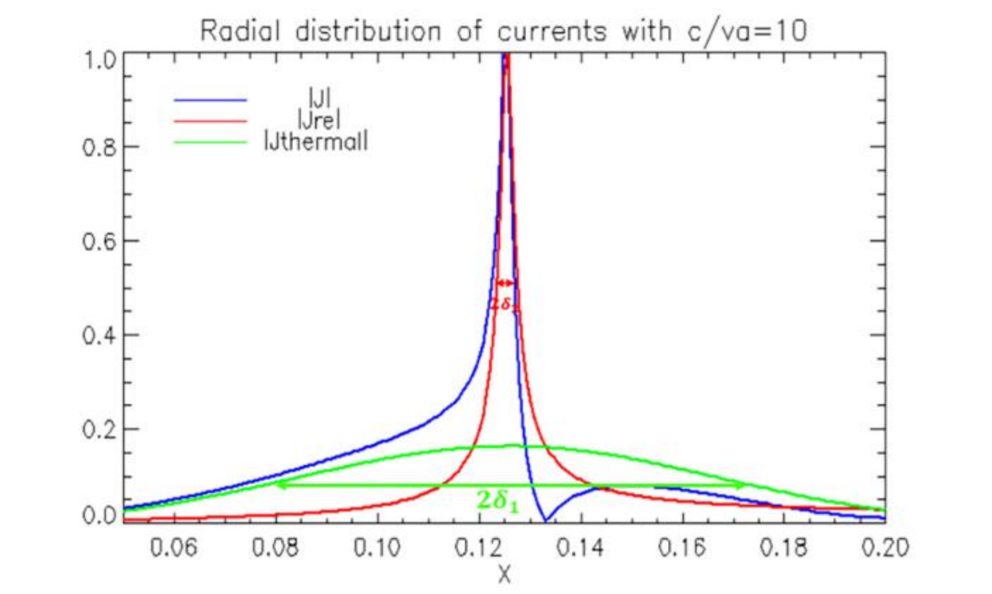


FIG. 6. Eigenfunction of mode 1 for total current (blue curve), runaway current (red curve), and thermal electrons current (green curve) profiles showing the inner layer δ_2 on the runaway current profile and the resistive layer δ_1 on the thermal electrons profile for $\eta = 1 \times 10^{-4}$, $\Delta' = 6.057$ and $c/v_A = 10$, $d_e = 0$, and $\rho_s = 0$.

L. Singh et al, Phys. Plasmas 30, 122114 (2023)

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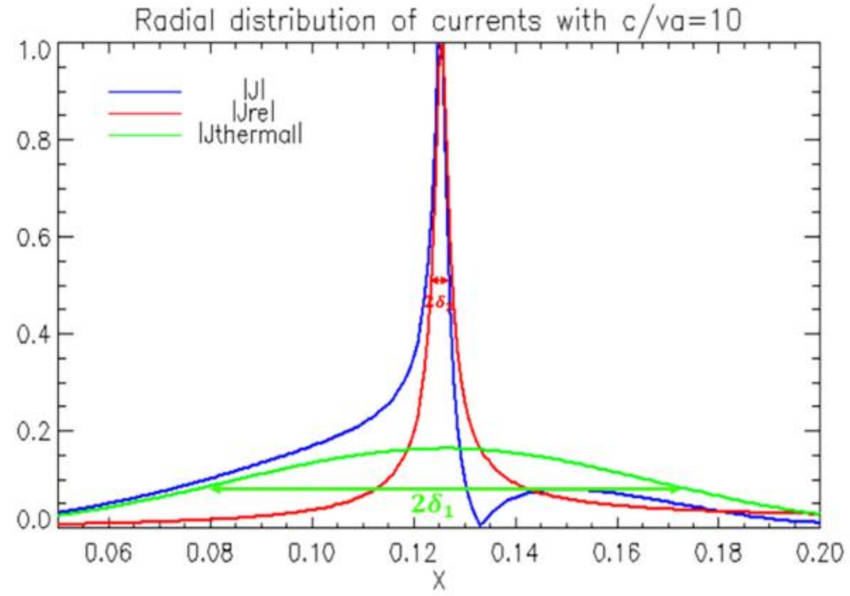

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L. Singh et al, Phys. Plasmas 30, 122114 (2023)

The microlayer width is inversely proportional to $\frac{c}{v_A}$. In our case, $\frac{c}{v_A} = 10$, however, in laboratory plasmas the ratio is > 100. This has a direct consequence on the postdisruption plasma stability in large Tokamak as demonstrated in L.G. Eriksson et al (2004) «**for typical JET and ITER parameters the current channel is predicted to narrow considerably and the axis current density to increase. This could make the postdisruption plasma less stable.**»

Current distributions during the nonlinear phase

- **During the non linear evolution of the tearing instability, the RE current radial distribution is characterized by multiple peaks.**

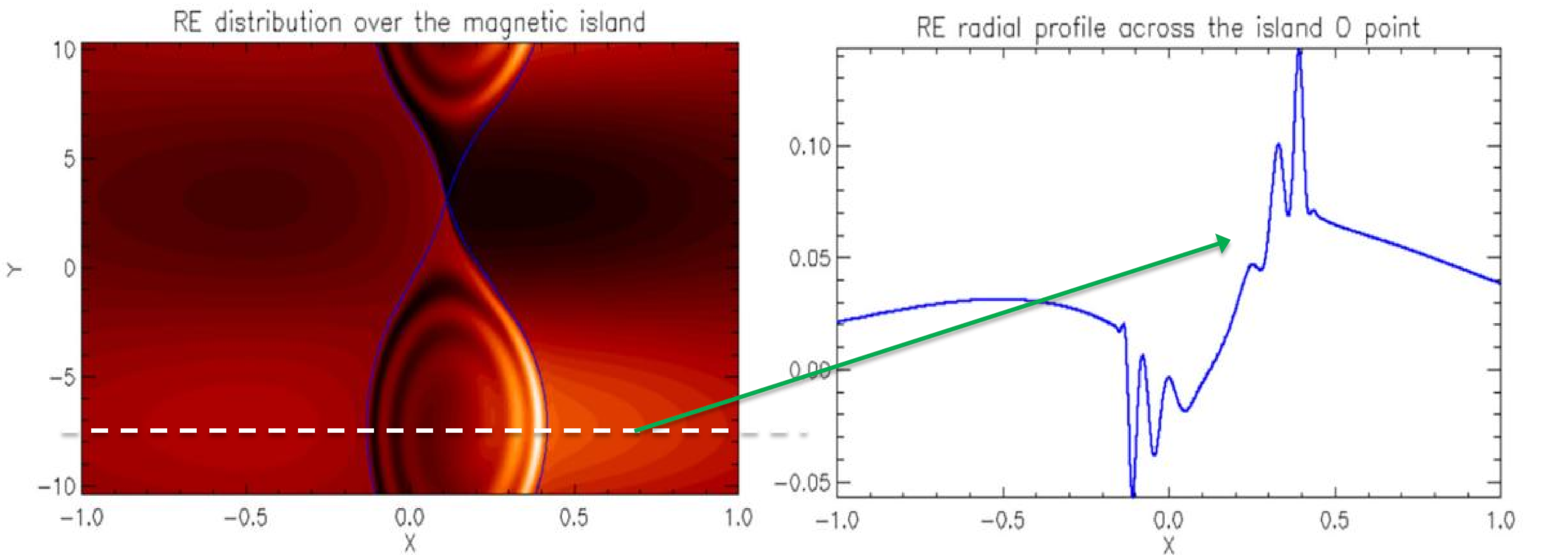
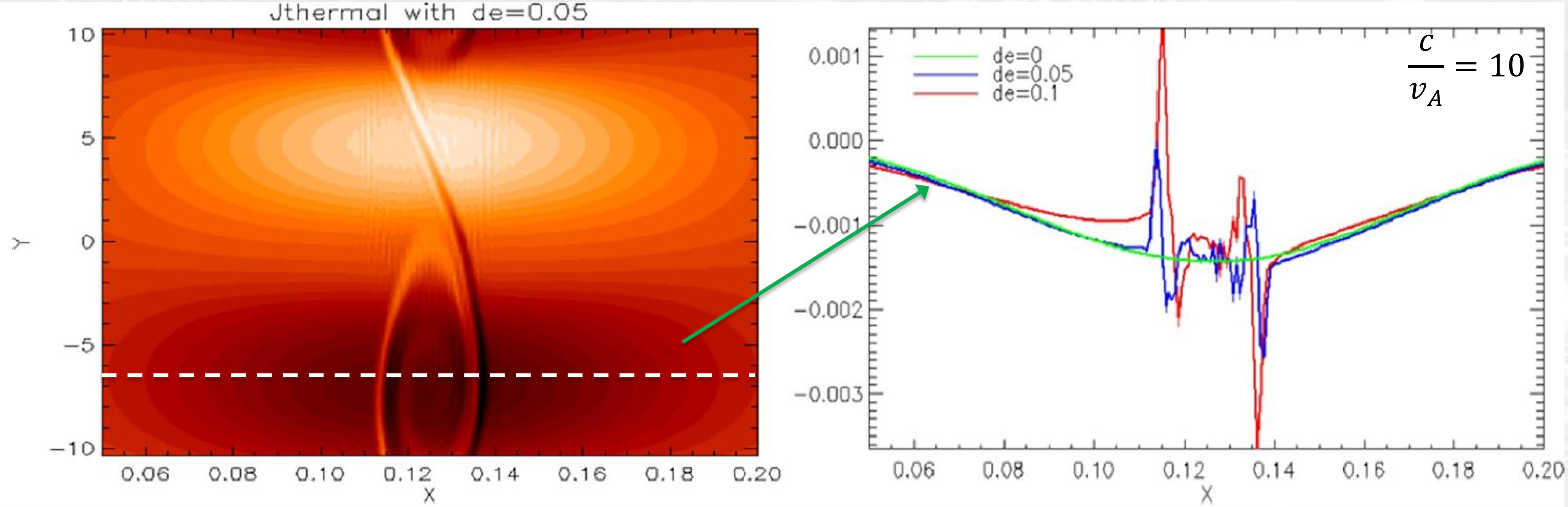


FIG. 13. Distribution of the perturbed runaway electrons current with the corresponding magnetic island (blue line) during the nonlinear phase (left) and RE profile (right) at t = 2500 across the island *O*-point for $\eta = 1 \times 10^{-4}$, $c/v_A = 1$, and $\Delta' = 6.057$, $d_e = 0$, $\rho_s = 0$.

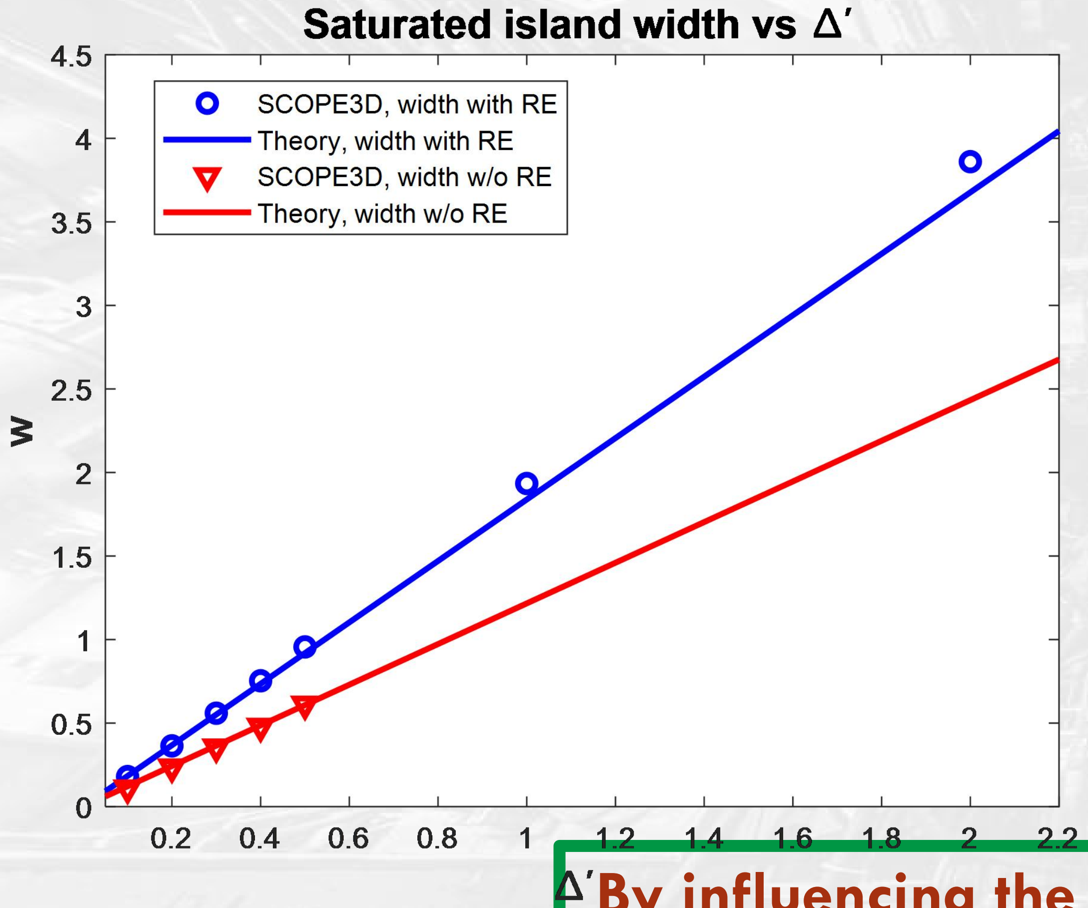
Current distributions: electron inertia effects

d_e in presence of runaways changes the distribution of the thermal electrons which are not characterized by the resistive layer anymore. However, the effect of such a current distribution on the plasma stability has to be clarified, yet.



L. Singh et al, Phys. Plasmas 30, 122114 (2023)

Island width at saturation



- **The magnetic island width at saturation is around 50% higher in the presence of RE. In addition, no divergence is seen with increasing Δ'** remaining always in the small Δ' regime.
- The solid lines are the analytical widths of the islands at different Δ' :

  $w = 3.70\,\Delta'$ **with runaways**

  $w = 2.44\,\Delta'$ **without runaways**

By influencing the growth of magnetic islands, the RE can change the dynamics of the magnetic field stochastization

Daniela Grasso et al 2022 J. Phys.: Conf. Ser. 2397 012004

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- Investigation of the RE energy deposition as a function of impact angle and wetted area

Magnetic reconnection in 3D

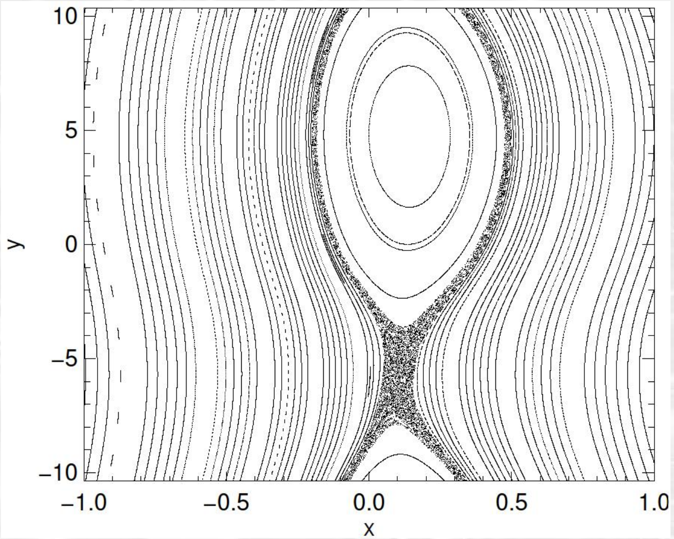
- Is this 2D scenario still valid in 3D?
- We studied numerically the evolution of an **initial magnetic perturbation with a dominant (k_{y*}, k_{z*}) mode component** and a **set of linearly unstable fluctuations of small amplitude**, uncorrelated and equipartitioned, **with multiple helicities**

$$\psi_1(x, y, z) = \hat{\psi}_{k_{y*},k_{z*}}(x)e^{i(k_{y*}y+k_{z*}z)} + \sum_{k_y}\sum_{k_z}\hat{\psi}_{k_y,k_z}(x,t)e^{i(k_y y+k_z z+\xi_{k_y,k_z})}$$

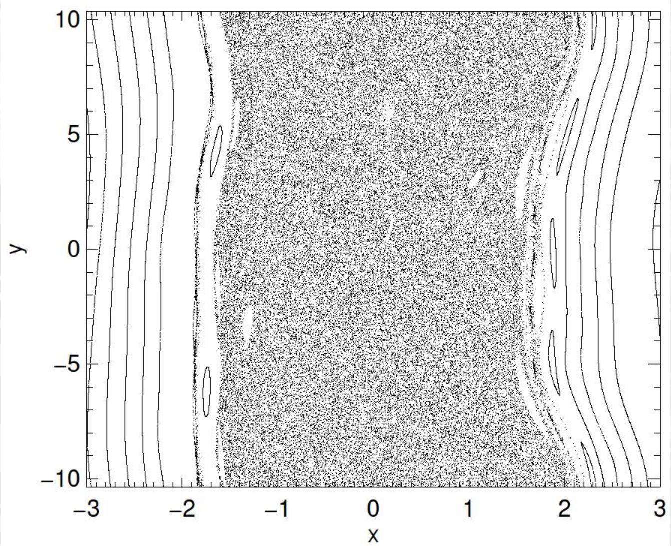
where ξ_{k_y,k_z} is a random phase and $\hat{\psi}_{k_y,k_z} = 10^{-3}\hat{\psi}_{k_{y*},k_{z*}}$

3D vs 2D MR driven by RE current in a post-disruption plasma

a)



b)

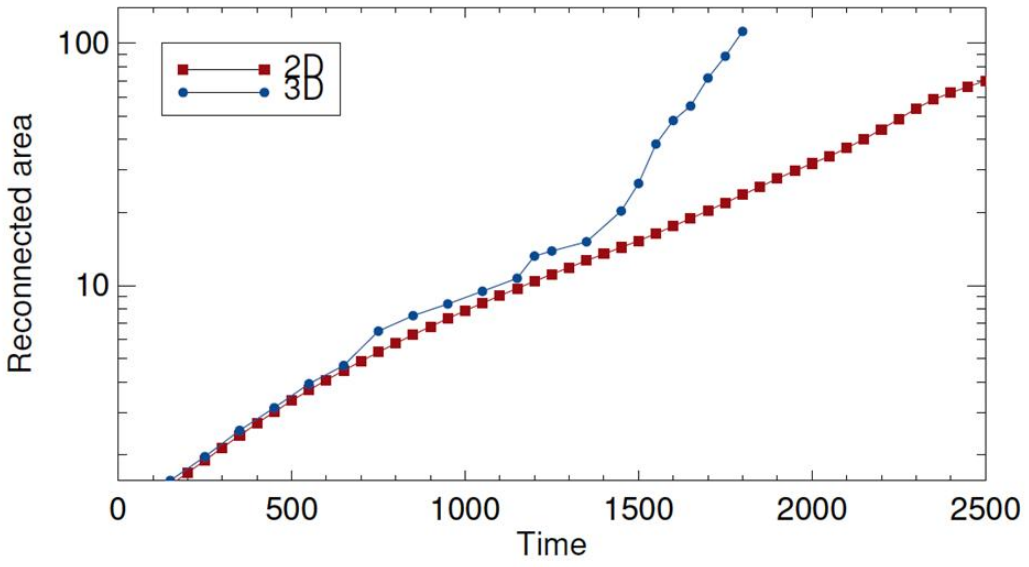


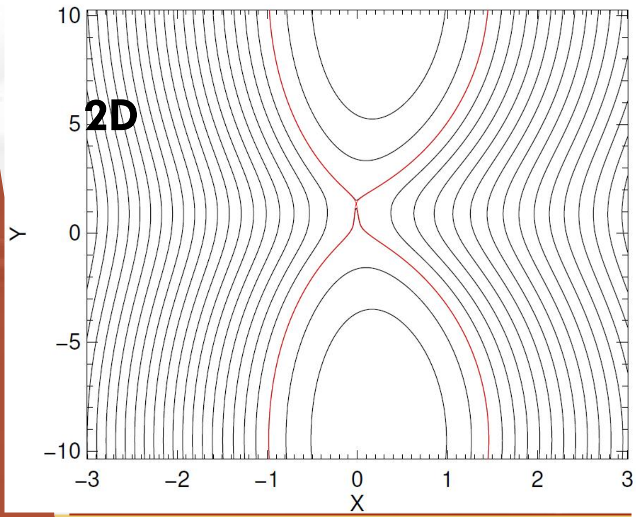
- **Poincarè maps** of the magnetic field lines show the **topology of the magnetic field on the sections $z = const$**

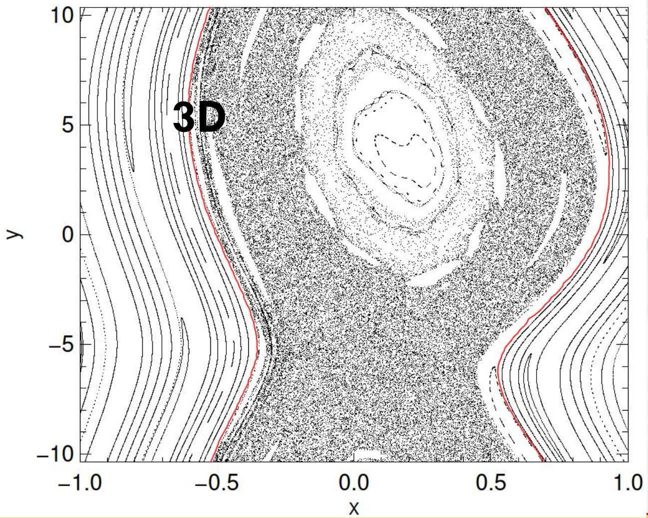
- The early phase (a) of the process is characterised by the dominant component of the initial condition. Magnetic field lines chaoticity localized around the separatrices of the $(1,1)$ unperturbed island

- In the nonlinear phase (b) of the evolution, **multiple helicity modes with comparable amplitude coexist**. Their interaction leads to the **global stochastization of the domain**

3D vs 2D MR driven by RE current in a post-disruption plasma







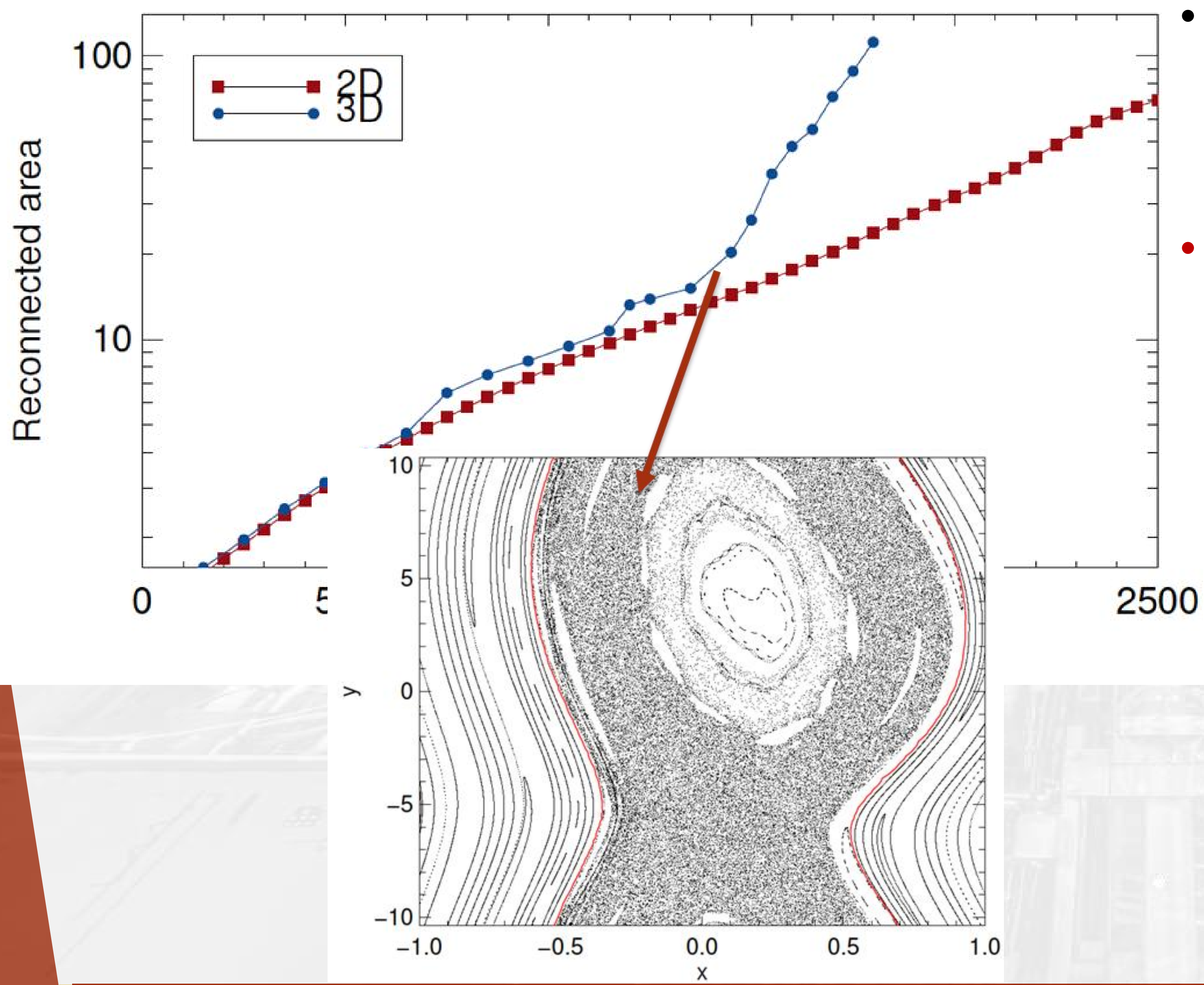
- No multiple helicity noise in 2D
- According to Borgogno et al. PoP 2005 we measure the **reconnection rate by means of the area of the region where the topological modifications induced by MR are located reconnected area A_{rec}**
- In **2D A_{rec}: area of the magnetic island**
- A_{rec} generalizes the standard 2D measure, based on $\frac{\partial \psi_X}{\partial t}$, where ψ_X is the magnetic flux at the island X-point

$$A_{rec} \propto W \propto \psi_X^{1/2}$$

- In **3D A_{rec} is numerically evaluated from the Poincarè maps** of the magnetic field lines on a generic section $z = const$

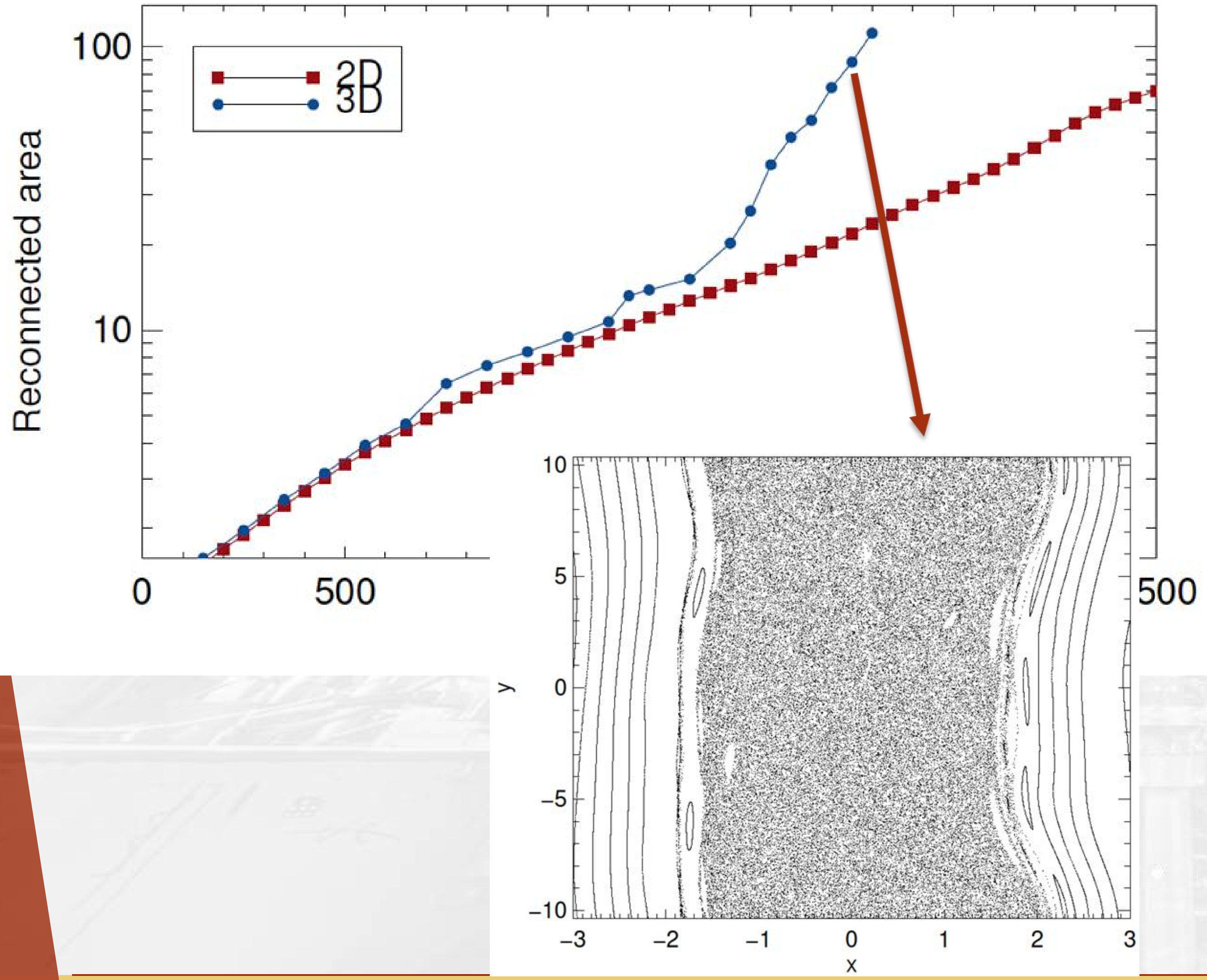
- In **3D A_{rec} contains both regular KAM surfaces and stochastic regions**

3D vs 2D MR driven by RE current in a post-disruption plasma



- MR exhibits a **similar evolution in 2D and 3D configuration in the linear and early nonlinear regime**
- **Explosive growth of the reconnected area in 3D** begins when the stochastic layer width is of the order of the equilibrium scale length

3D MR driven by RE current in a post-disruption plasma



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- Explosive growth of the reconnected area in 3D begins when the stochastic layer width is of the order of the equilibrium scale length
- **Global stochastization of the domain before reaching the saturation**

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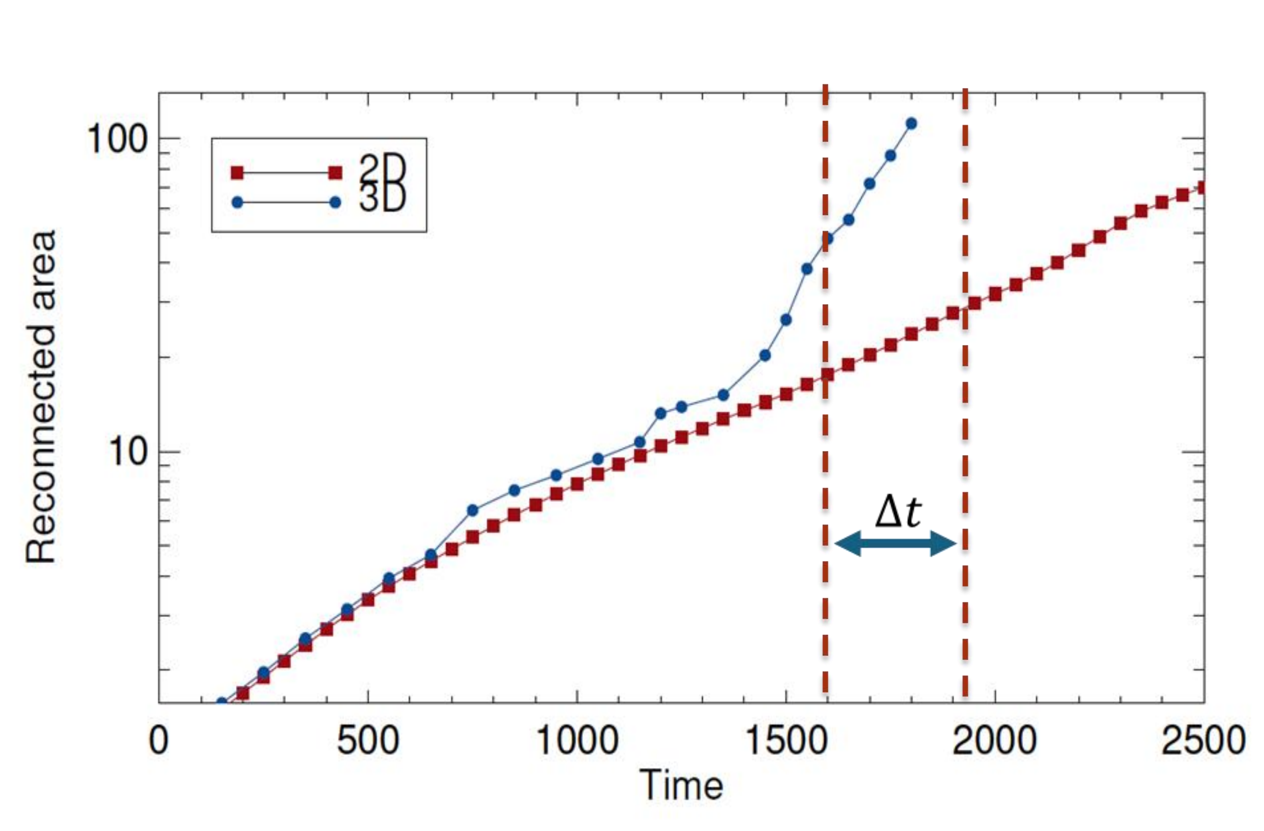
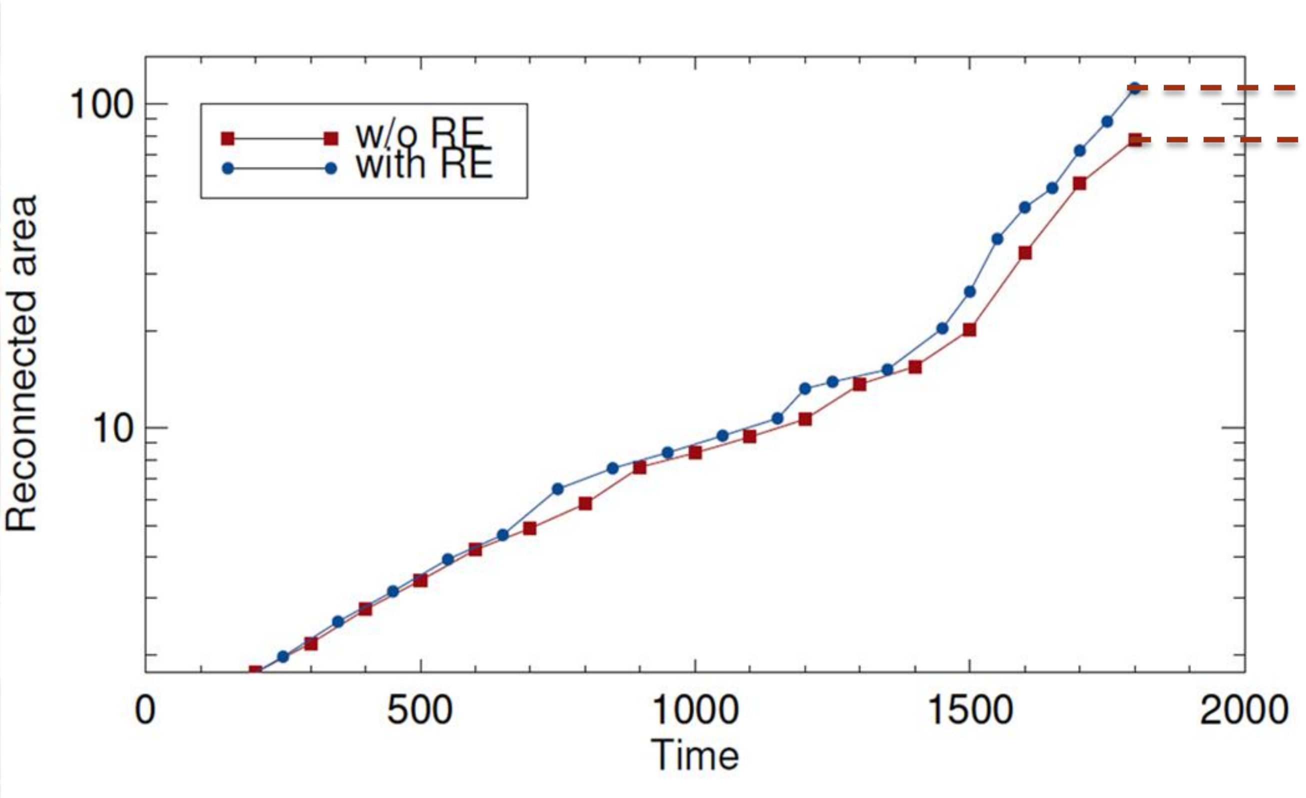


- MR exhibits a similar evolution in 2D and 3D configuration in the linear and early nonlinear regime
- Explosive growth of the reconnected area in 3D begins when the stochastic layer width is of the order of the equilibrium scale length
- Global stochastization of the domain before reaching the saturation
- **Transition from local to global stochasticity in $\boldsymbol{\Delta t \sim 300\tau_A \sim 10\mu s}$** ($B_0 = 3.49\ T$, $n = 10^{19}\ m^{-3}$, $L = 1\ m$), in agreement with Bandaru et al., PPCF 2021.

3D MR with and without RE



$\Delta A_{rec} \sim 50\%$

- Comparison of MR growth in a **runaway** and **thermal plasma**
- Nonlinear explosive growth both with and without REs
- A_{rec} in presence of REs is almost 50% larger than in the Ohmic case, in agreement with 2D results

Open question

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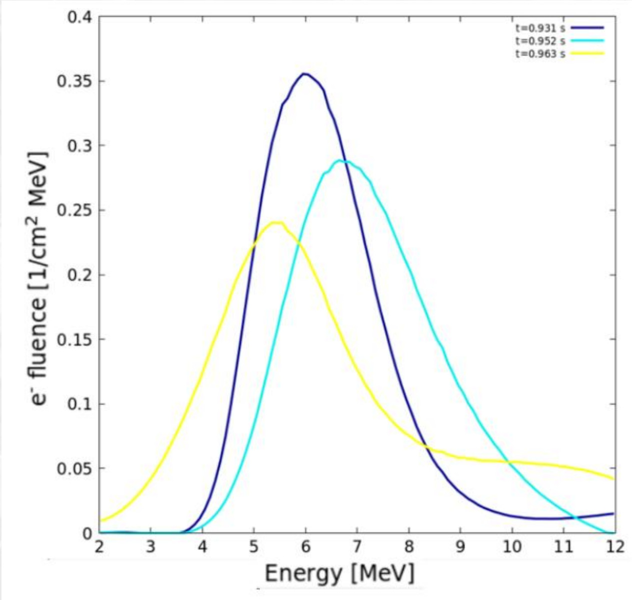
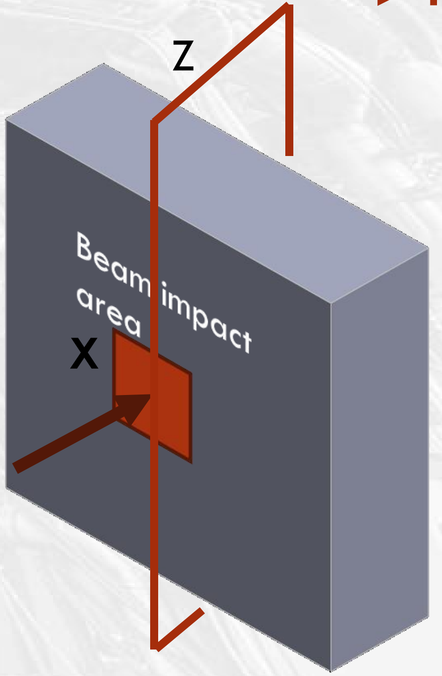
Investigation of the RE energy deposition on the Tokamak FW tiles

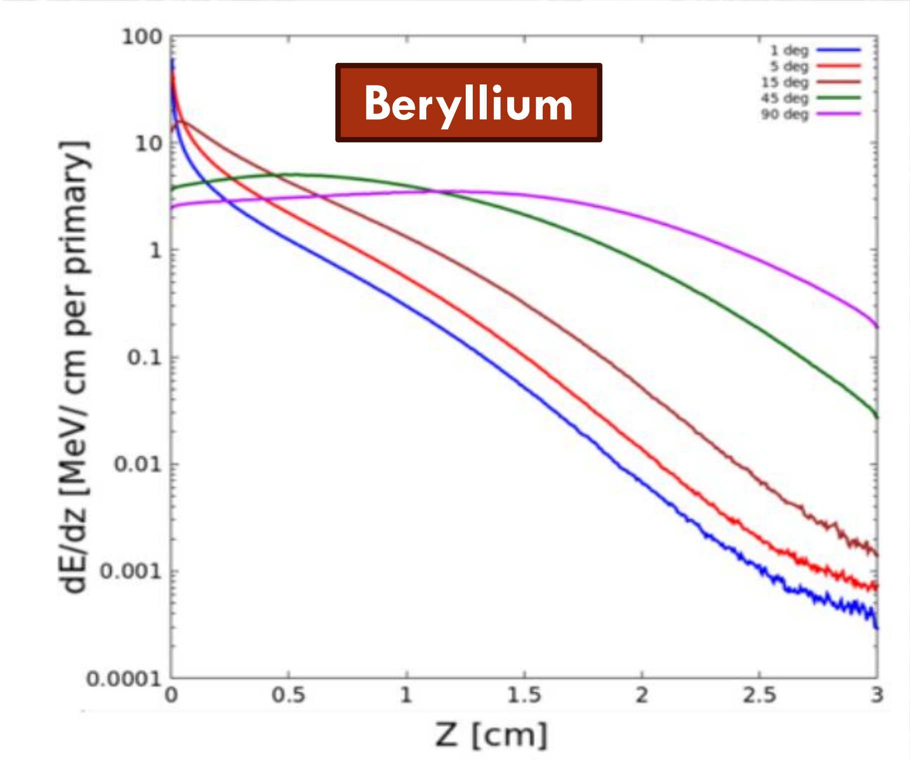
- Bergstrom et al. (2024) demonstrated that stochasticity influences the impact angle and area of the RE beam on the First Wall (FW).
- We analyze the influence of changing impact angle and area on the energy deposition of RE in the FW tiles

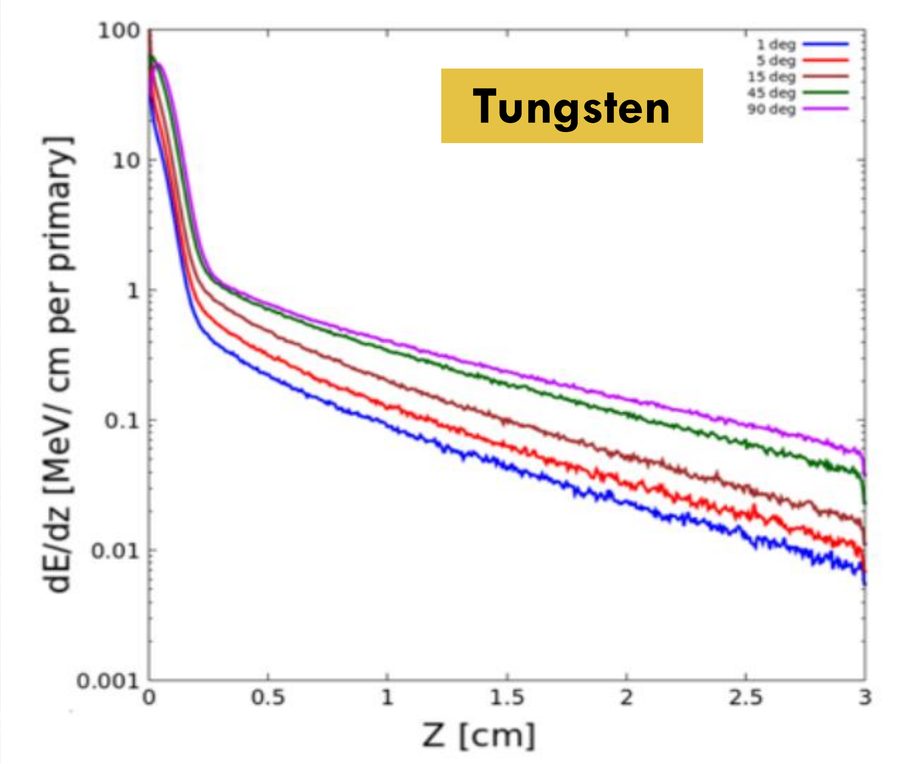
1. **Beam characteristics (RE energy distribution function, impact angle, etc)**
2. **Geometry** → **FLUKA** → **Energy deposition profiles**





Energy deposition dependence on the impact angle

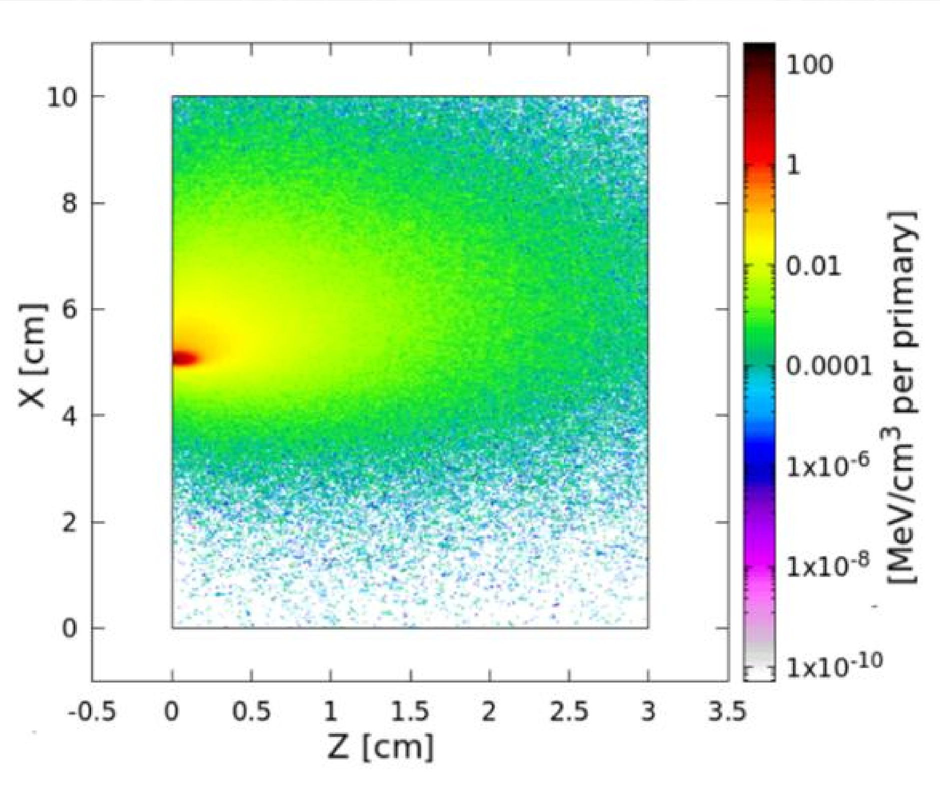


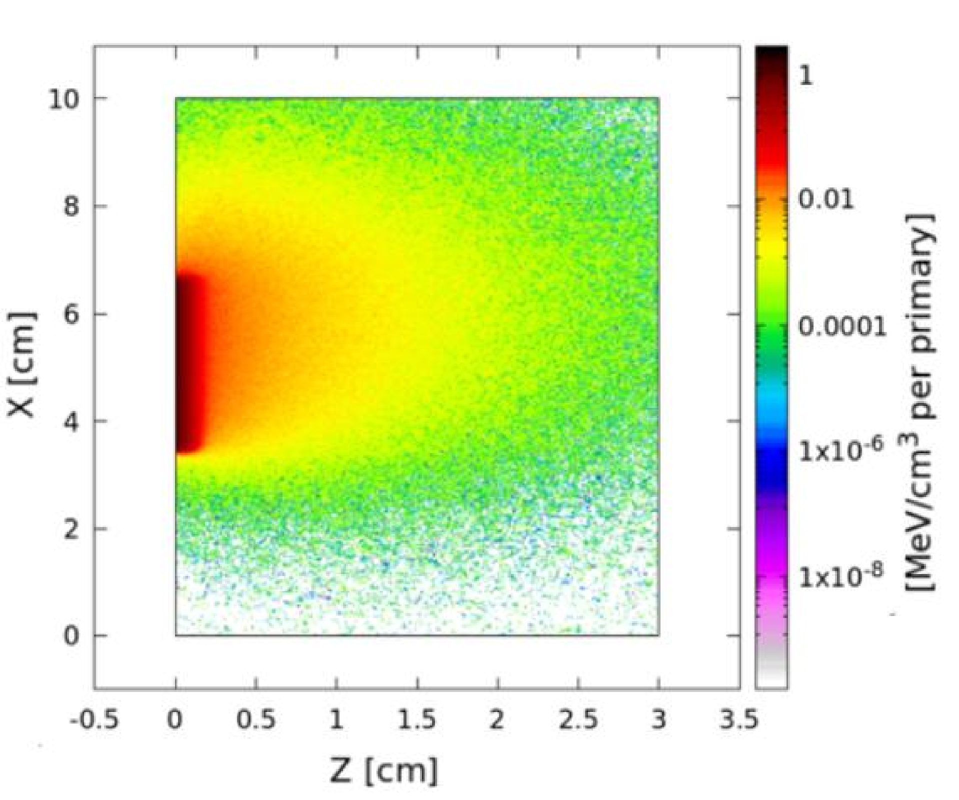


- In Tungsten the energy deposition is much more compact than in Beryllium
- A **decrease and a shift in the maximum with increasing impact angle** is observed for Beryllium with angle > 15° and > 45° for Tungsten

A higher impact angle leads to a deeper penetration of RE into the wall, which is problematic for the structural materials

Energy deposition dependence on the wetted area





2D projection of the ED on the XZ plane for W at the right panel with a point beam impacting at (X,Y,Z)=(5,5,0) cm with 5 degrees impact angle with respect to the X direction

A large wetted area leads to a low volumetric energy deposition which is beneficial for the material

Outlook

- The final goal of this study is to investigate the reconnection physics with runaways in a stochastic plasma, since a stochastic scenario is beneficial for RE benign termination.
- The **presence of runaways** leads to **an increase of 50% in the island width at saturation**
- In the linear phase, **the generation of an inner layer take place on the RE radial profile** which divides into small scales when the runaway current become non linear
- The electron inertia could turn on interesting physics which is important at small scales
- **Explosive acceleration of the magnetic reconnection growth in 3D**, resulting in magnetic **stochastization on a global scale**
- **Fast decrease in runaway electron current** and **homogenisation** on the chaotic regions
- The evolution of **stochasticity influences the characteristics of the RE beam impact onto the wall**. In particular, **it affects the impact angle and the wetted area**.
- **A large impact angle and small wetted area are not benign for RE termination**

Backup

Transition from linear to non linear phase

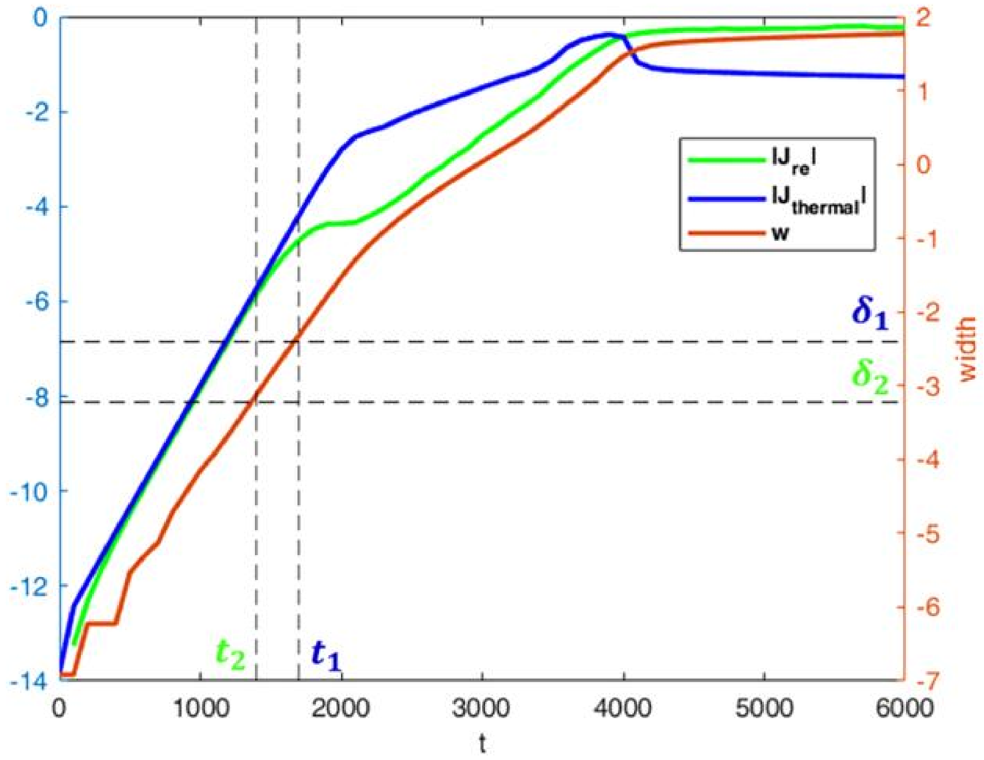


FIG. 11. Temporal evolution of the eigenfunction of mode m = 1 associated with the runaway (green) and thermal (blue) current, and the width of the islands (rust) for a purely resistive regime $\eta = 1 \times 10^{-4}$, $c/v_A = 1$, and $\Delta' = 6.057$. The vertical dashed lines identify the times when the transition to the nonlinear stage occurs for runaway ($t_2 = 1400$) and thermal electrons ($t_1 = 1700$). The dashed horizontal lines identify the magnetic island widths corresponding to these times. The sizes of the island at t_1 and t_2 are comparable with δ_1 and δ_2, respectively.

- The microlayer width δ_2 **controls the transition of the runaway electron to the nonlinear stage** while the resistive layer width δ_1 **controls the transition of the tearing instability to the non linear stage**

- Microlayer width $\delta_2 = \frac{\gamma v_A}{k_y c}$

- Resistive layer width $\delta_1 = \gamma^{1/4} \eta^{1/4} k_y^{-1/2}$

Island rotation

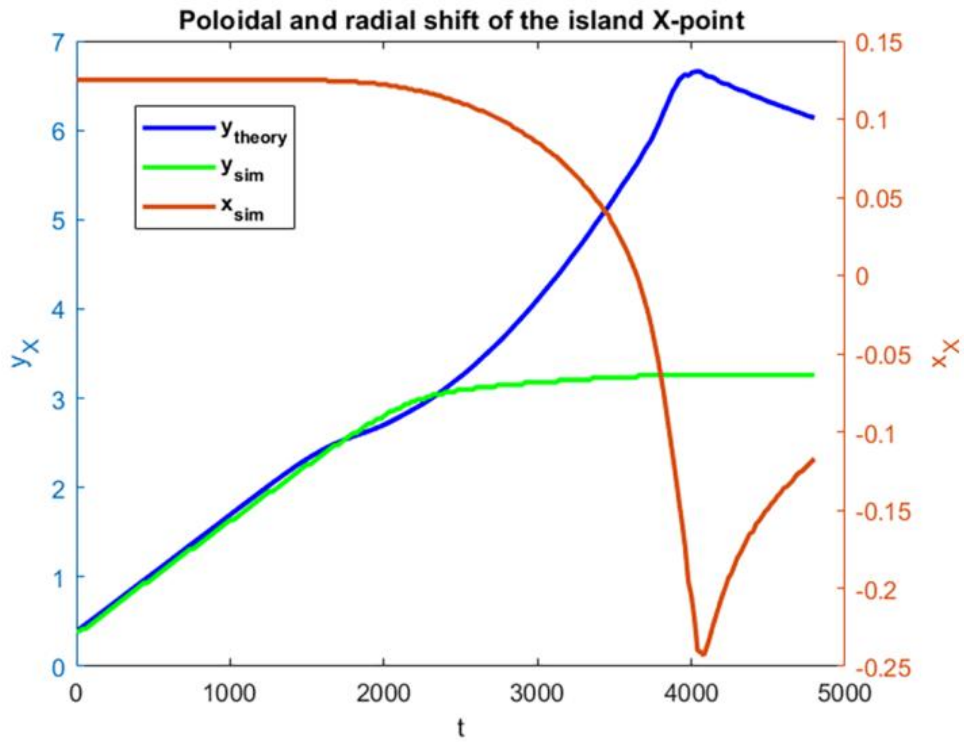


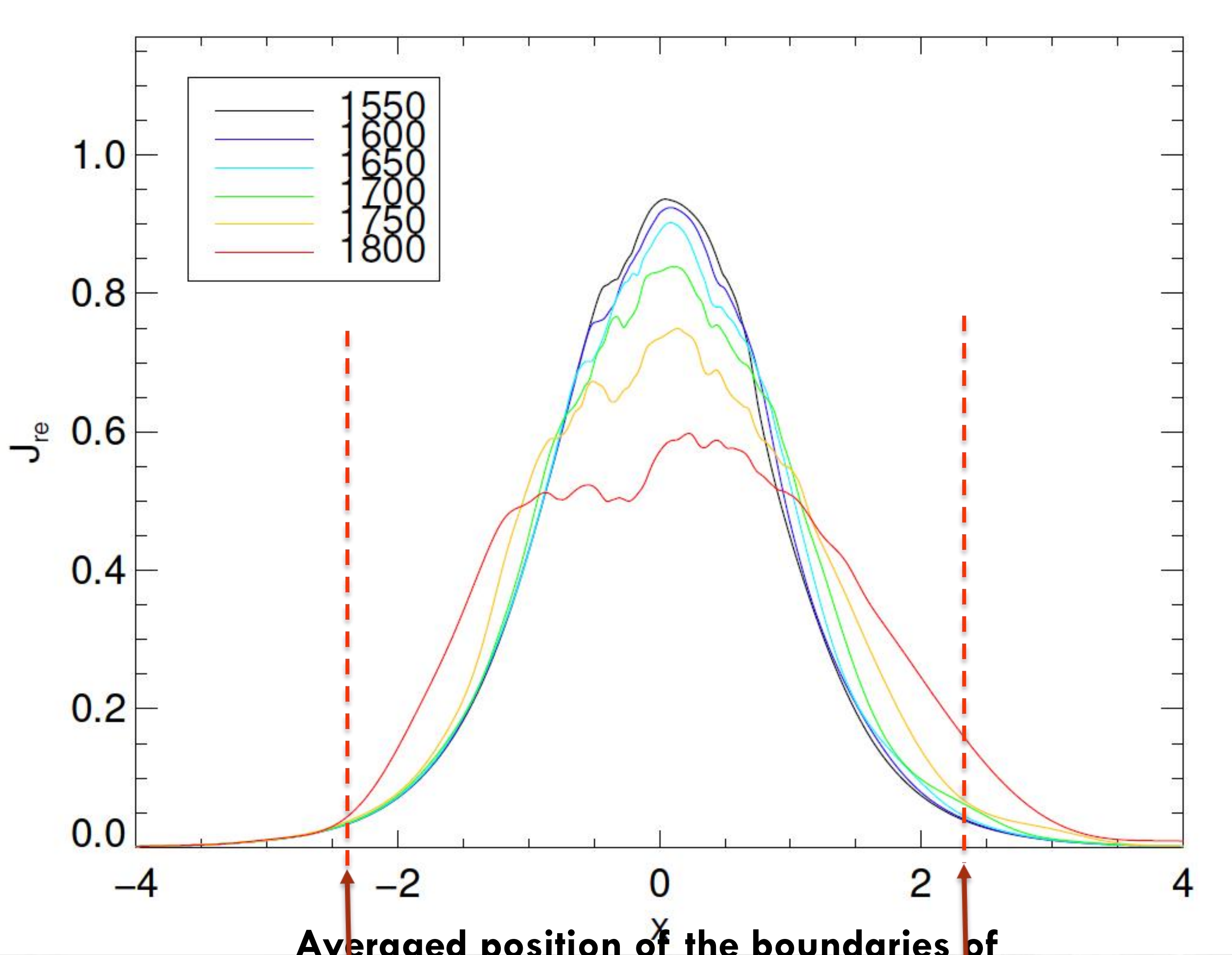
FIG. 14. Temporal evolution of the X-point position of the magnetic island in the case $\eta = 1 \times 10^{-4}$, $c/v_A = 1$, and $\Delta' = 6.057$, $d_e = 0$, $\rho_s = 0$. The green line shows the numerical poloidal shift, while the blue line corresponds to the theoretical prediction according to the formula (15). The rust line represents the displacement along the x direction.

- Dispersion relation

$$\frac{\gamma^{5/4}}{\eta^{3/4}\, k_y^{1/2}} \frac{2\pi\Gamma(3/4)}{\Gamma(1/4)} = \Delta' - i\pi \frac{k_y j'_{RE0}}{|k_y|}$$

During the linear stage the numerical island rotation is in line with the analytical epression. However, **during the nonlinear stage**, the numerial rotation goes to zero → **the island locks in at saturation**

RE current distribution



Averaged position of the boundaries of the chaotic region

- **Radial profile of J_{RE}** averaged over y and z
- Tendency of the **RE to uniformly distribute in the chaotic region** as the time increases

Runaway Electrons: interaction with the plasma (JET #95135)

- Disruption triggered by **massive injection of Argon** which leads to the **generation of RE**

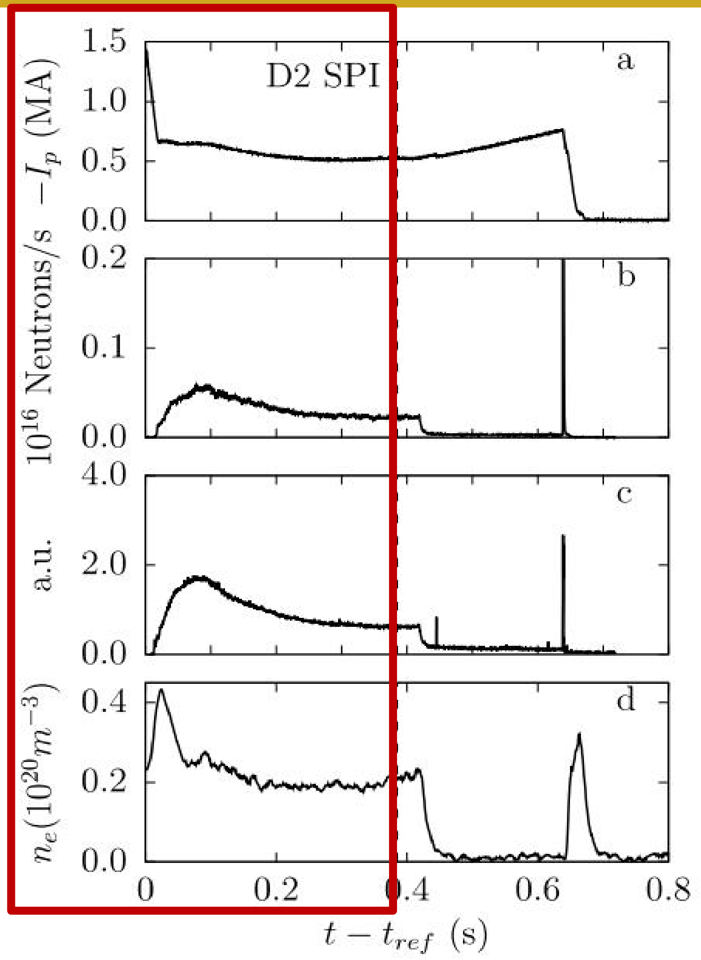


Figure 1. Time traces of (a) plasma current, (b) neutron rate, (c) HXR signal, and (d) line-averaged electron density from the experimental shot #95135. The time corresponding to $t_{\mathrm{ref}} = 48.0233$ s in the discharge is taken as reference. The dashed vertical line represents the instant of D_2 SPI.

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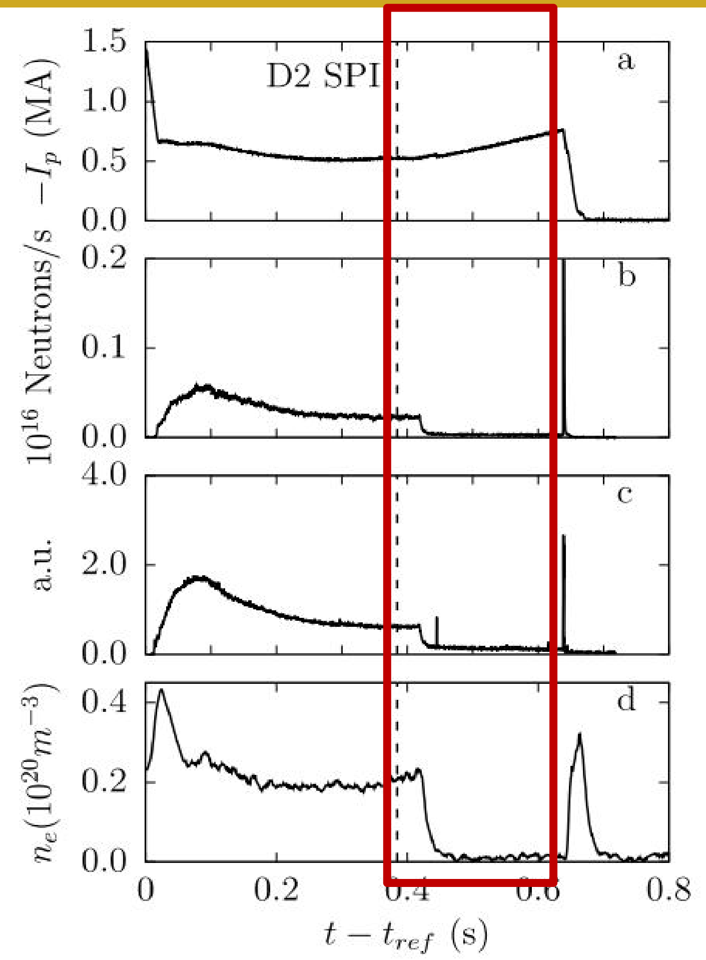
- At t-tref=0.4 **second injection** of **D2** to study the RE termination. The D2 causes the **plasma** to **recombine** and the **flush out of Argon** from the plasma
- The flush out of high Z impurtiy leads to a **drop** in the **effective resistivity**. As a consequence the **plasma current increases**



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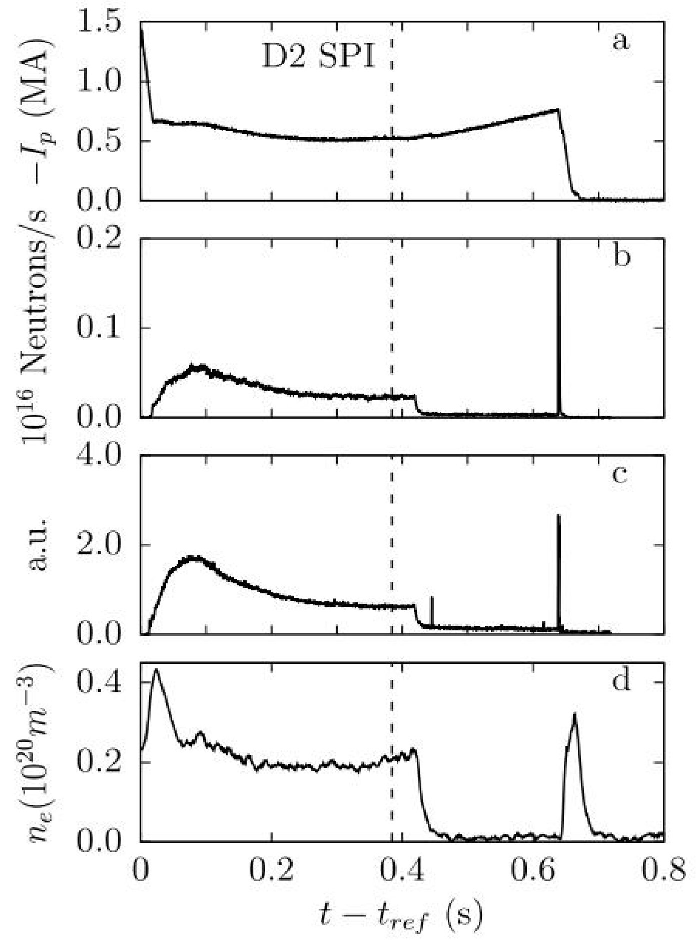
- The flush out of high Z impurtiy leads to a **drop** in the **effective resistivity**. As a consequence the **plasma current increases**
- When the **current reaches 0.75 MA** a fast and **near complete loss of RE** take place
- This fast loss of RE without damaging the wall→ **benign termination**



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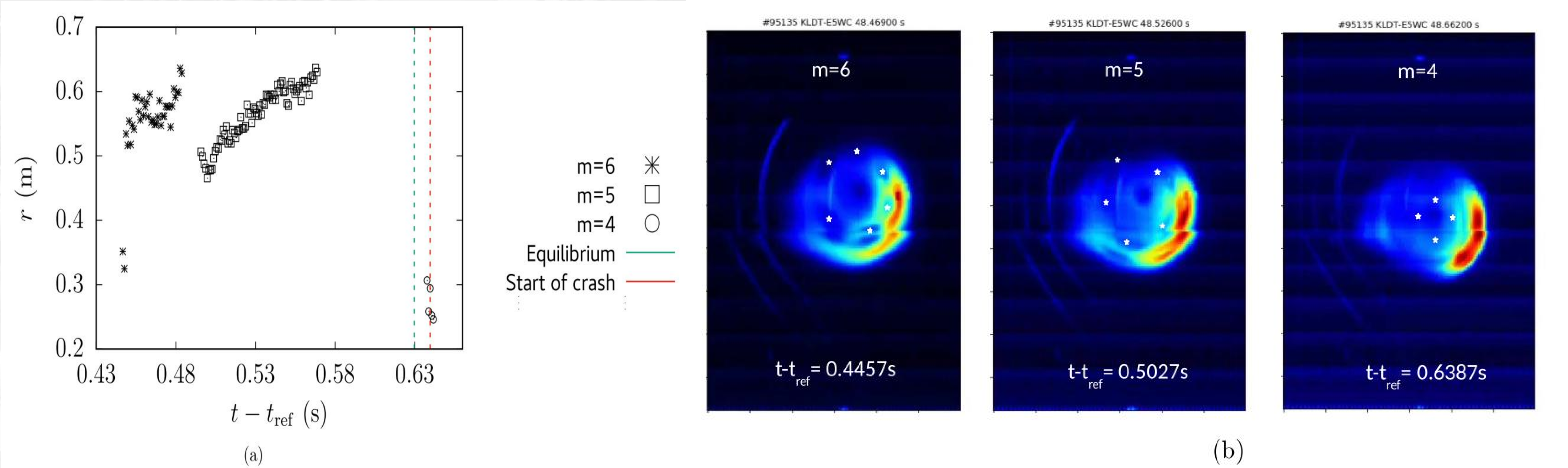
JET #95135: diagnostics images

While the current is increasing:



(a) Approximate minor radial location of magnetic structures at various time points until the final crash. (b) Synchrotron images showing the magnetic structures, highlighted by the 'star' symbols.

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