DE LA RECHERCHE À L'INDUSTRIE

TRANSPORT AND ACCELERATION OF FAST ELECTRONS AS TEST PARTICLES IN A JOREK SIMULATED DISRUPTION

RUNAWAY ELECTRON MEETING 2017

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PLAN

Introduction

Models and tests

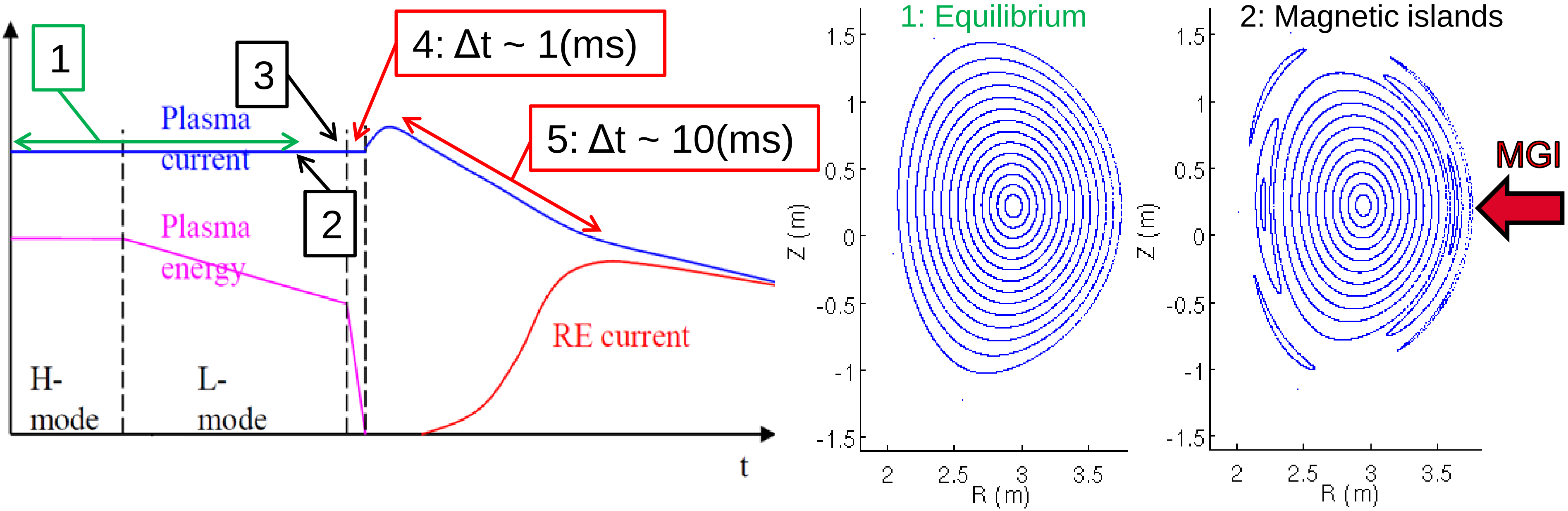
Electron transport in disruption (neglecting collisions)

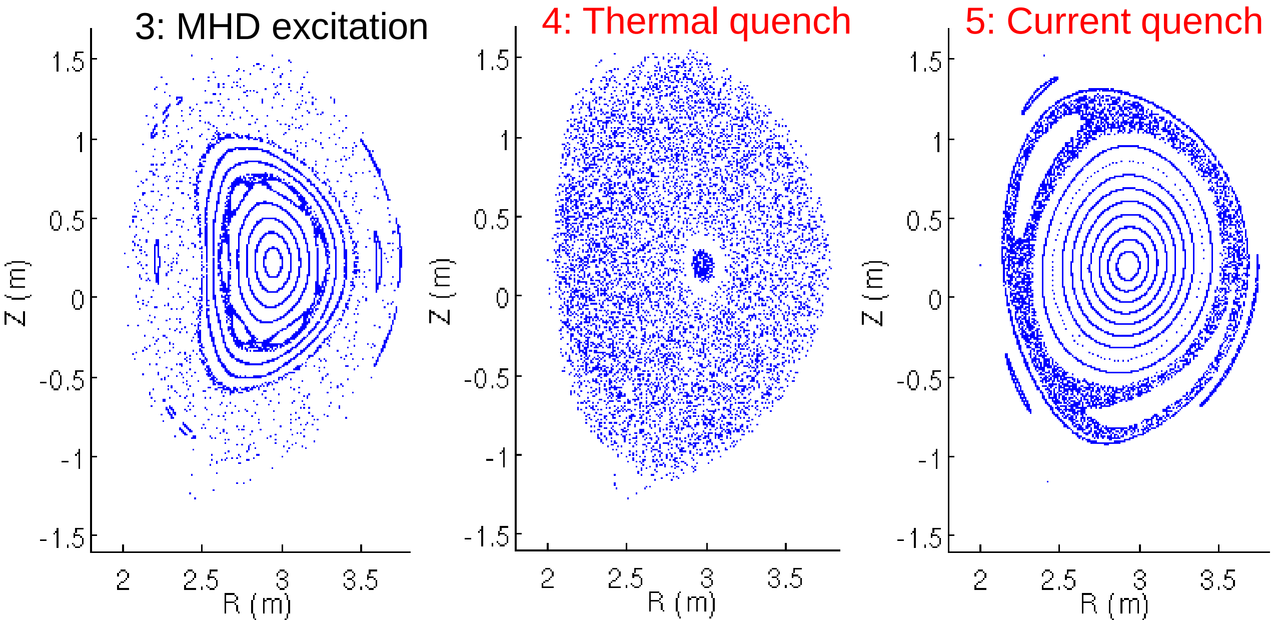
RE production in disruption

Summary and future work

INTRODUCTION

DISRUPTION PHENOMENOLOGY (SIMULATION OF JET PULSE 86887)





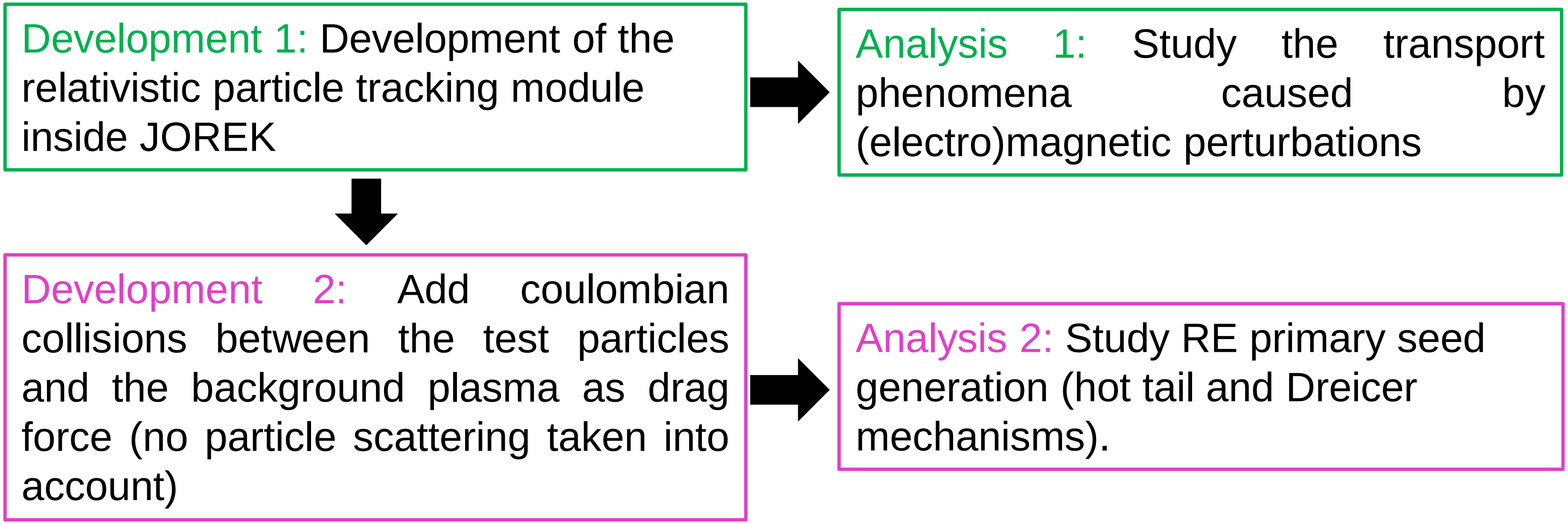
- Current quench = decrease in plasma current ⇒ generation of toroidal electric field ⇒ electron acceleration ⇒ Runaways Electrons production

CONTEXT AND WORK PLAN

Context: Most of the works on REs dynamics are conducted using equilibrium magnetic fields but electron deconfinement during the Thermal Quench is a critical open question

Objective: Understand the runaway electrons dynamics in the presence of realistic disruption-like (electro)magnetic perturbations

Method: Simulate runaway trajectories in 3D disruption MHD fields obtained with JOREK (test particle approach)



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

Analysis 1: Study the transport phenomena caused by (electro)magnetic perturbations

Development 2: Add coulombian collisions between the test particles and the background plasma as drag force (no particle scattering taken into account)

Analysis 2: Study RE primary seed generation (hot tail and Dreicer mechanisms).

MODELS AND TESTS

MODELS FOR PARTICLE DYNAMICS

Full Orbit (FO) particle model:

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

Guiding-center approach (GC) [3] : elimination of the electron gyromotion: bigger time steps with respect to full orbit simulation and smaller memory consumption

Validity conditions: electromagnetic fluctuations time and space scales are bigger than particle displacement in a gyroperiod.

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

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

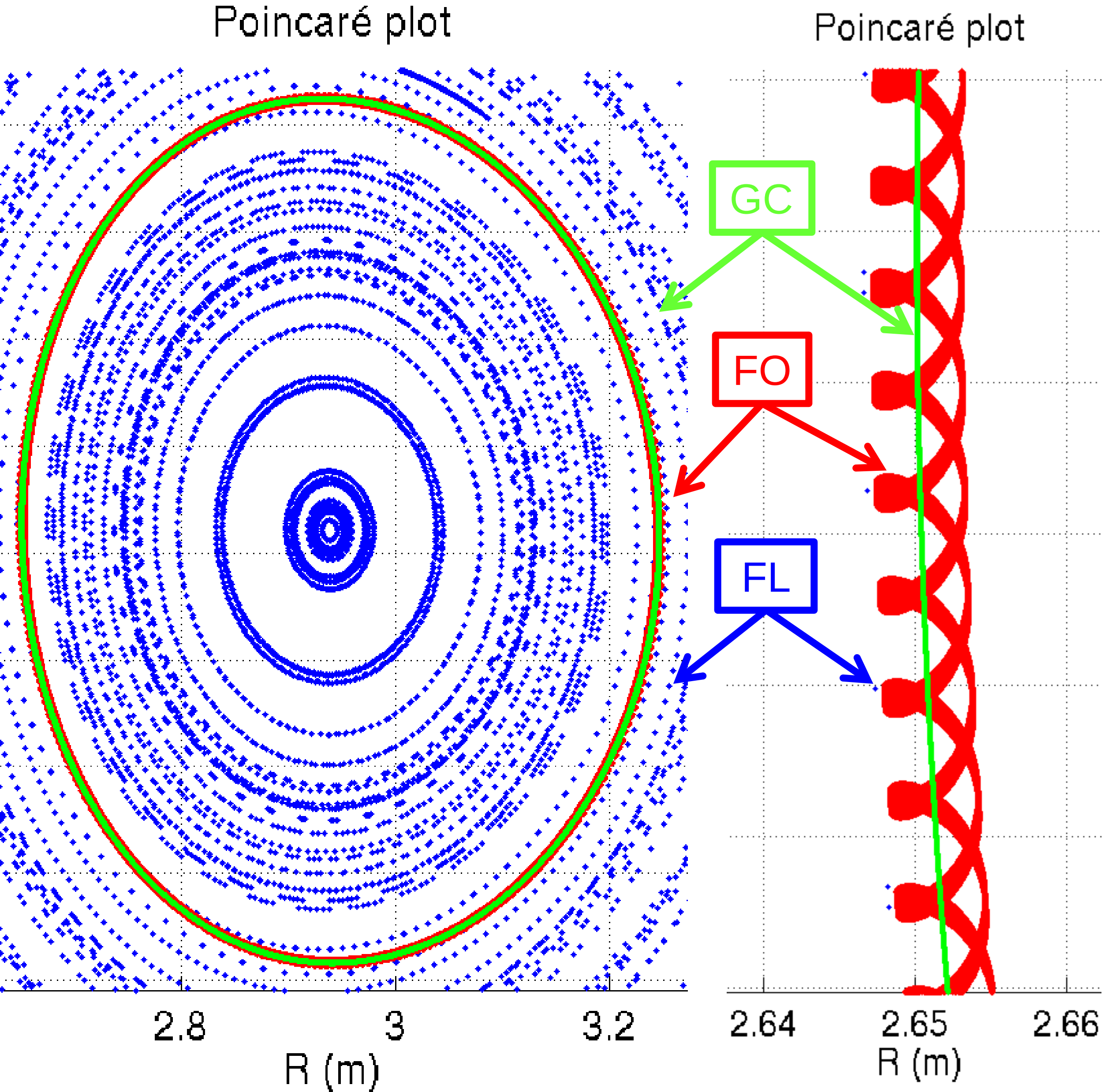
with $\vec{B}^*\equiv p_{/\!/}\nabla\times\hat{b}+q\vec{B}$ et $\gamma\equiv\sqrt{1+(\frac{p_{/\!/}}{mc})^2+\frac{2\mu B}{mc^2}}$

Numerical Method: Volume Preserving Scheme [4] for FO and Runge-Kutta 4(5) for GC dynamics with time-space interpolations of the MHD fields obtained by JOREK.

[3] J.R. Cary, A.J. Brizard, Rev. Mod. Phys., 2009

[4] R.Zhang et all., PoP, vol.22, pp.044501, 2015

TEST 1: CORE REGION PASSING PARTICLE



Test: passing particle in equilibrium axis-symmetric JOREK field.

Total tracking time: 1ms

Initial conditions:

- R=3.25m, Z=0.21m, φ=45°
- E=10MeV, θ=170°, χ=0°

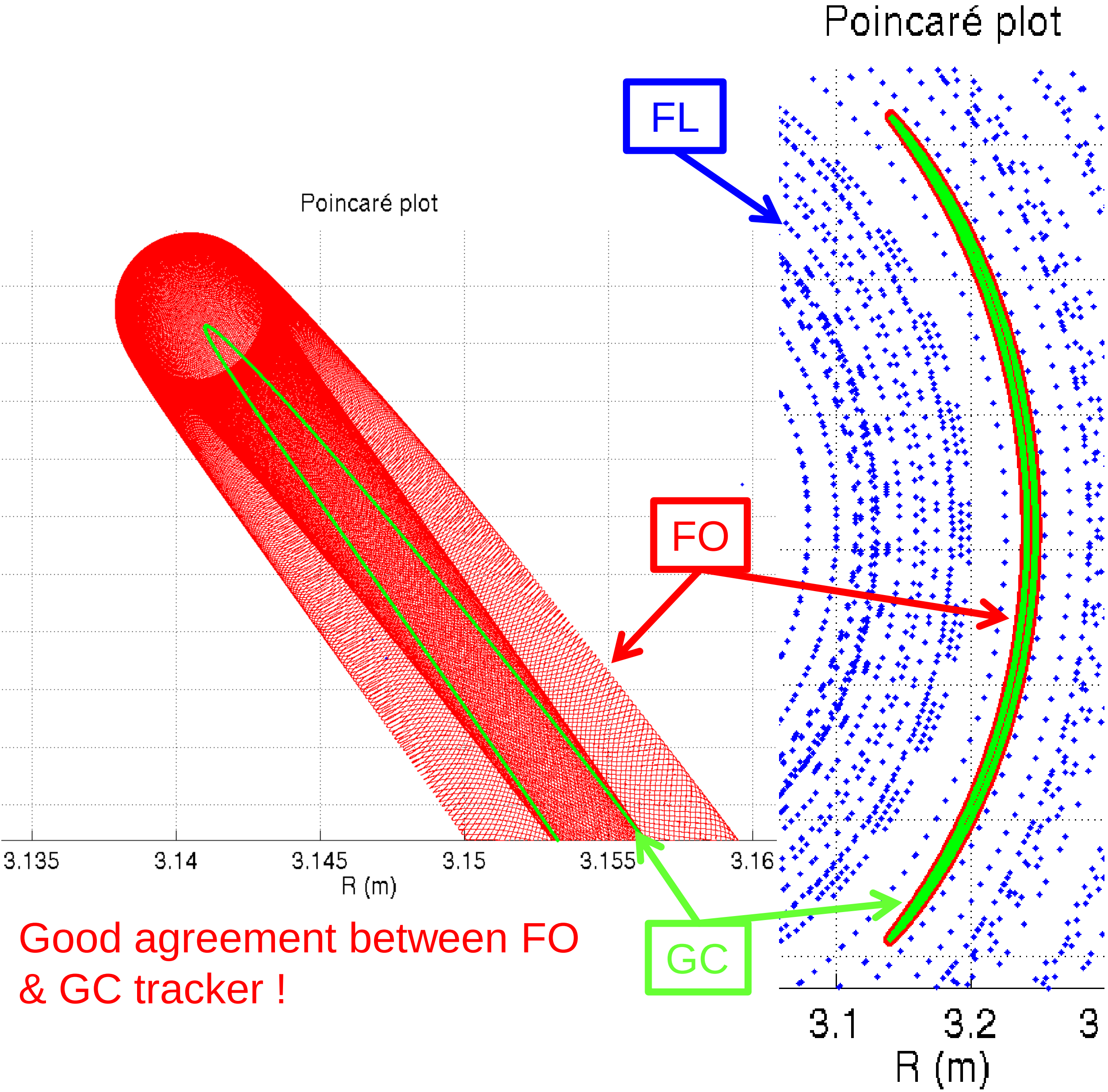
Δt	**E error**	**P_φ error**
0.09	9e-10 %	3e-7 %
0.009	2e-9 %	9e-9 %

FO tracker maximum numerical error

Δt	**E error**	**P_φ error**
90.0	1e-4 %	8e-4 %
9.0	1e-4 %	8e-4 %
0.9	1e-4 %	8e-4 %
0.09	1e-4 %	8e-4 %

GC tracker maximum numerical error

TEST 2: CORE REGION TRAPPED PARTICLE



Good agreement between FO & GC tracker !

Test: trapped particle in equilibrium axis-symmetric JOREK field.

Total tracking time: 1ms

Initial conditions:

- R=3.25m, Z=0.21m, φ=45°
- E=1MeV, θ=100°, χ=0°

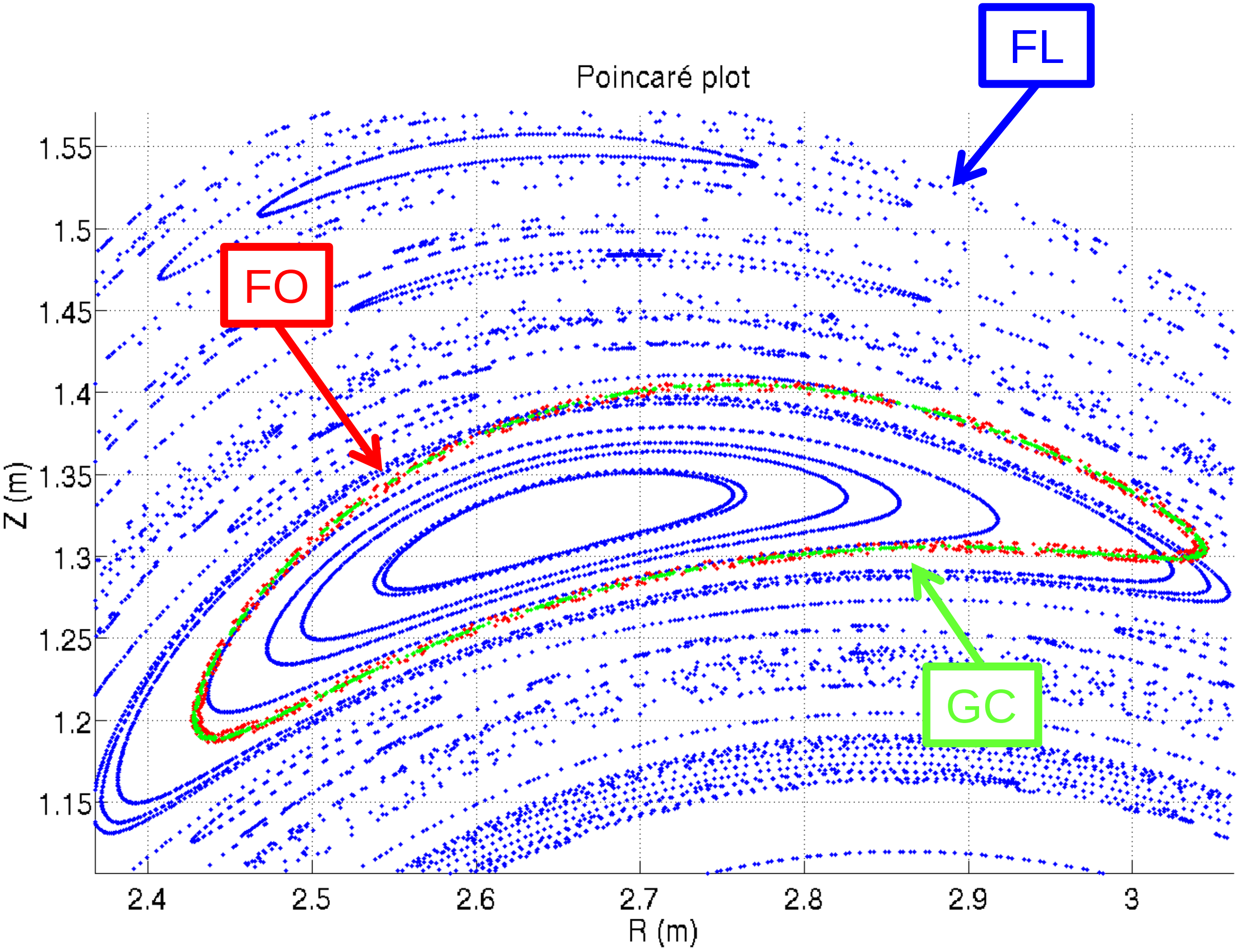
Δt	E error	P_φ error
0.09	1e-9 %	6e-6 %
0.009	1e-9 %	9e-8 %

FO tracker maximum numerical error

Δt	E error	P_φ error
90.0	2e-5 %	7e-7 %
9.0	1e-6 %	6e-7 %
0.9	1e-6 %	1e-6 %
0.09	1e-6 %	1e-5 %

GC tracker maximum numerical error

TEST 3: PASSING PARTICLE IN MAGNETIC ISLAND



Good agreement between FO & GC tracker !

Test: passing particle in n=1 m=2 magnetic island (from JOREK disruption simulation)

Total tracking time: 1ms

Initial conditions:

- R=2.98m, Z=1.3m, φ=45°
- E=10MeV, θ=170°, χ=0°

Δt	E error
0.09	1e-8 %
0.009	4e-9 %

FO tracker maximum numerical error

Δt	E error
90.0	7e-3 %
9.0	7e-3 %
0.9	7e-3 %
0.09	7e-3 %

GC tracker maximum numerical error

MODEL FOR GUIDING CENTER COLLISIONAL DRAG

Collisional drag model for GC: collisions are treated as drag force acting on $p_{/\!/}$

- The main effect is to reduce the GC energy:

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

The drag force $F_{coll/\!/}$, [5] , in JOREK takes into account fast electron collisions with background plasma (electrons+nuclei) and with molecular deuterium neutral impurities:

$$F_{coll/\!/} = -\frac{q^4}{4\pi\varepsilon_0 E_{0,e}}\frac{\gamma\left((\gamma+1)\alpha_e + \alpha_i\right)}{(\gamma-1)^{\frac{3}{2}}}\frac{p_{/\!/}}{m_e c}$$

$$\alpha_e = n\ln(\Lambda_{ef}) + n_{D_2}\ln(\Lambda_{eb})$$

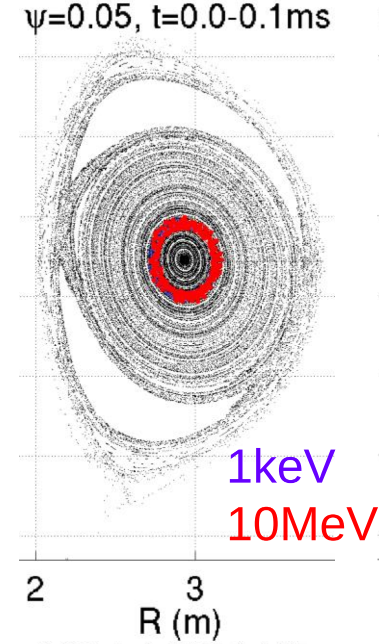
$$\alpha_i = n\ln(\Lambda_{if}) + n_{D_2}\,(Z_{nucl})^2\ln(\Lambda_{nucl})$$

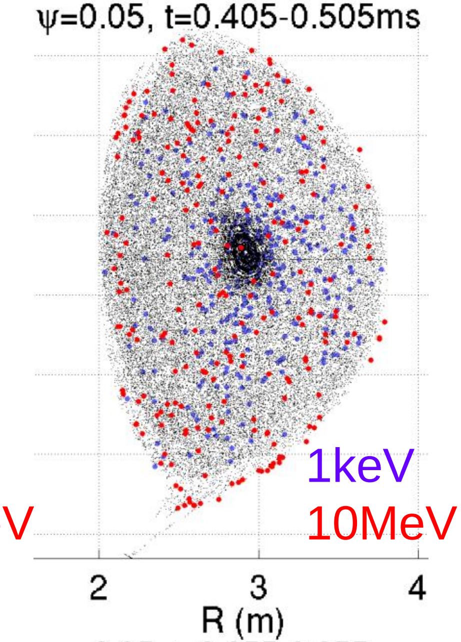
Denoting with Λ the Coulomb logarithm of different collisional mechanisms and with Z_{nucl} the neutral net nuclear charge

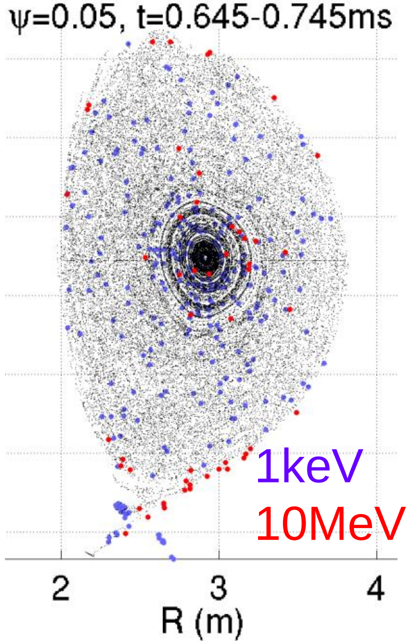
[5] J. R. M.-Solis et all., PoP, vol.22, pp.092512, 2015

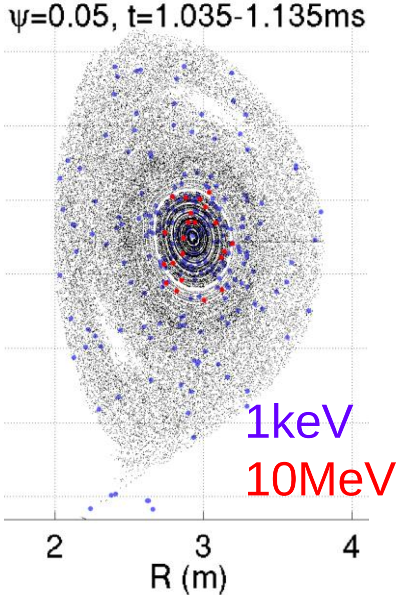
ELECTRON TRANSPORT IN DISRUPTION (NEGLECTING COLLISIONS)

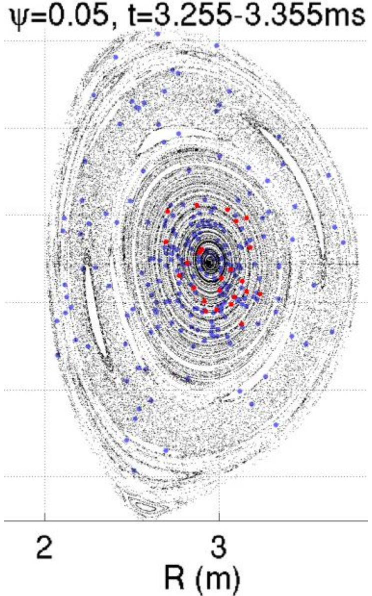
DISRUPTION SIMULATIONS: OVERVIEW OF ELECTRON DYNAMICS IN THE JET PULSE 86887 SIMULATION











Pseudo-Poincaré: particle within an angular sector of δφ and ΔT time interval are plotted on the selected Poincaré plane:

φ=45° δφ=±30°

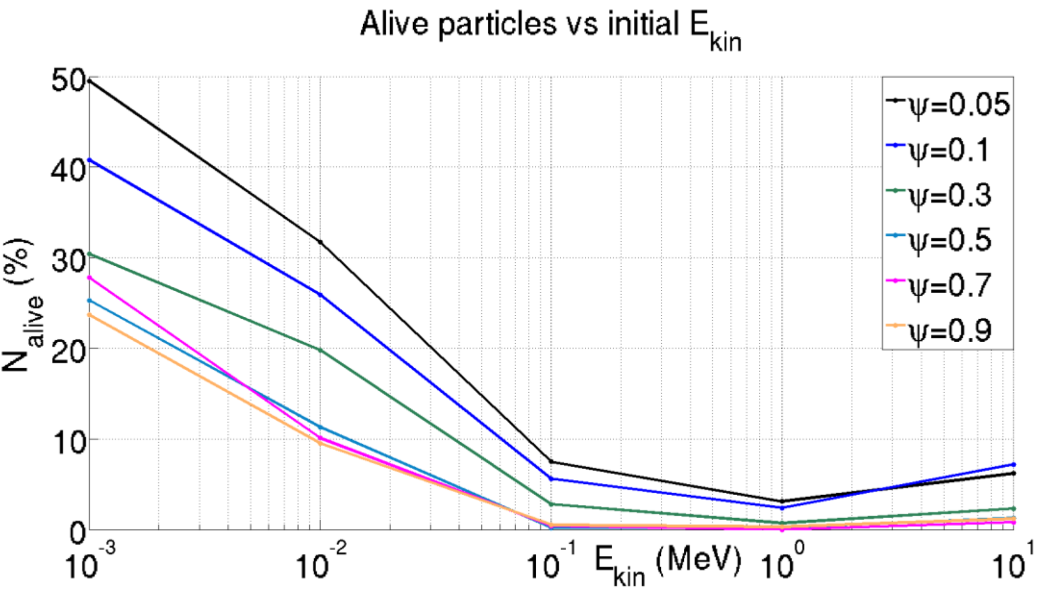
ΔT=0.1ms

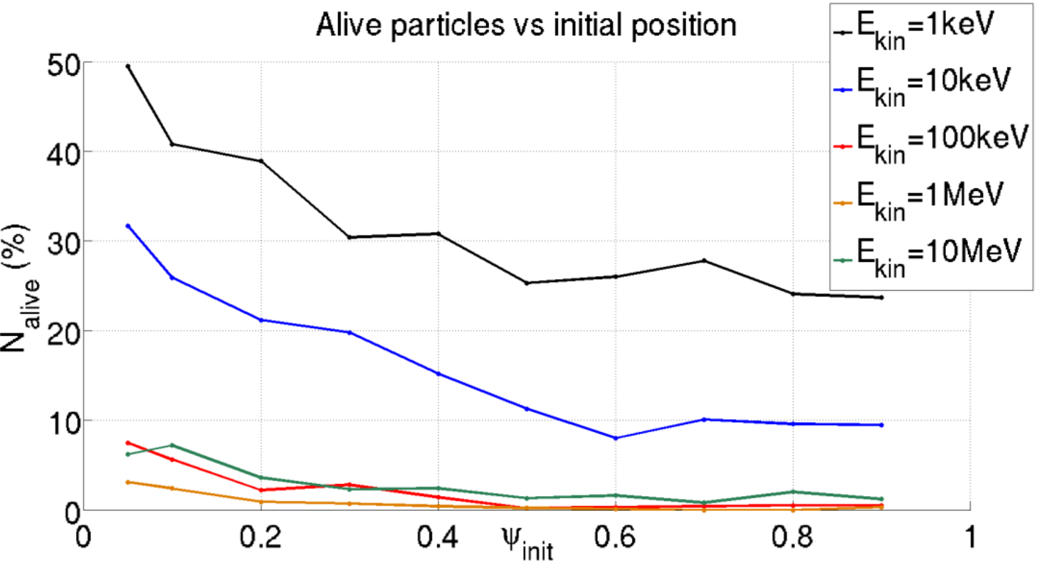
Particle dynamics in disruption simulation:

- Orbits followed from completely developed 2/1 magnetic islands to the CQ beginning
- Electric field from dψ/dt neglected => no GC acceleration before TQ
- Random initialization around ψ=0.05
- Initial kinetic energies: 1keV and 10MeV
- Initial θ=170°

→ Particles are reconfined due to reformation of closed magnetic flux surfaces during the CQ phase

DISRUPTION SIMULATIONS: FRACTION OF SURVIVING PARTICLES VS INITIAL ENERGY AND POSITION

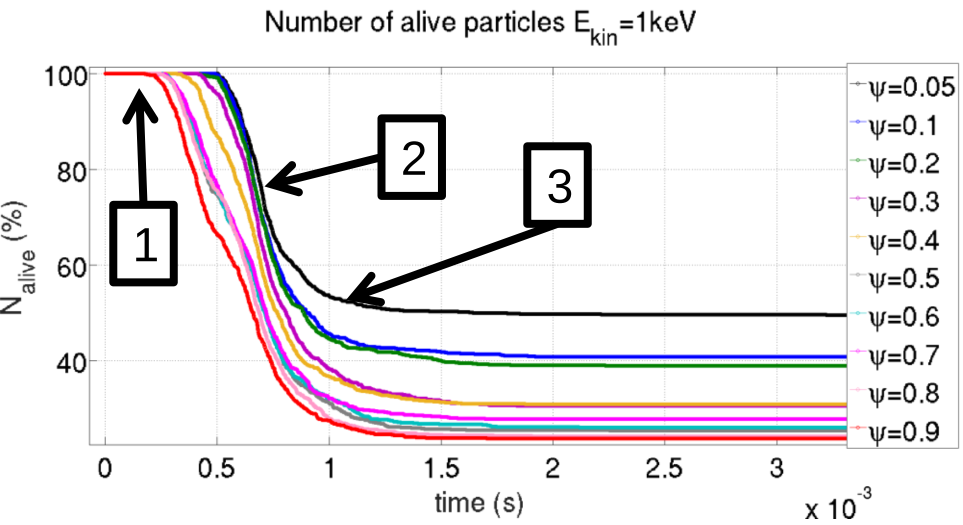

Alive particles vs initial E_{kin}

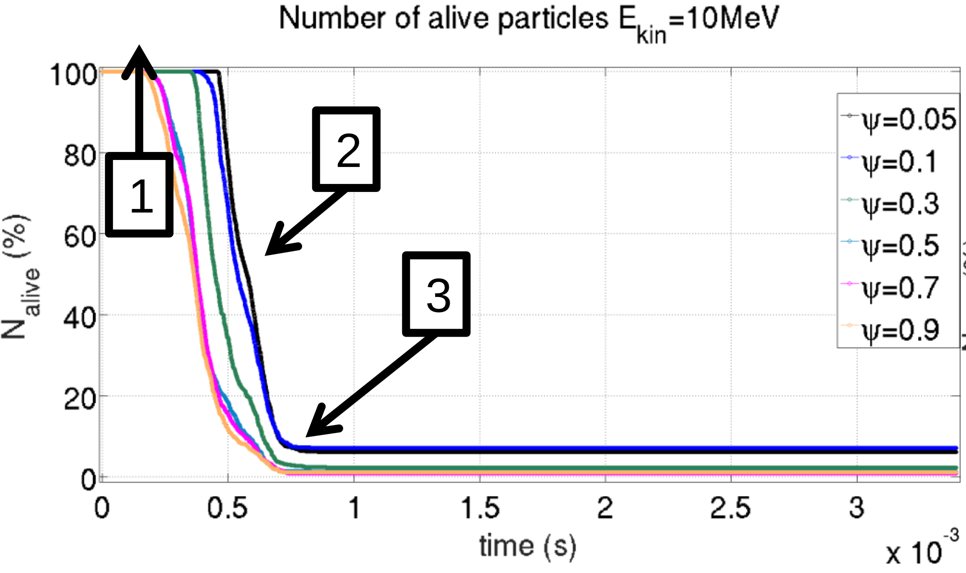

Alive particles vs initial position

Particle loss profile during a disruption:

- A fraction of the initial particle population survives the TQ in most of the cases
- General rule: The highest the particle energy the highest is the deconfinement probability => the dominant transport seems to be parallel to the field lines
- Profile slope decrease up to inversion between 1MeV and 10MeV: Orbit-averaging effect (reduced particle sensitivity to the magnetic perturbations)
- General rule: the deeper in the core the particles are the lower is their deconfinement probability.

DISRUPTION SIMULATIONS: ELECTRON LOSS TIME PROFILES


Number of alive particles E_{kin}=1keV

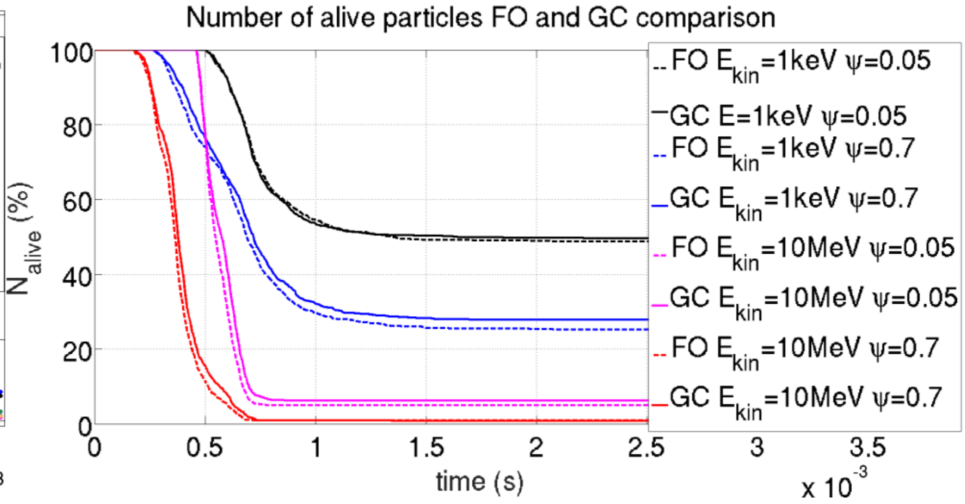

Number of alive particles E_{kin}=10MeV

Loss profiles reveal 3 typical stages:

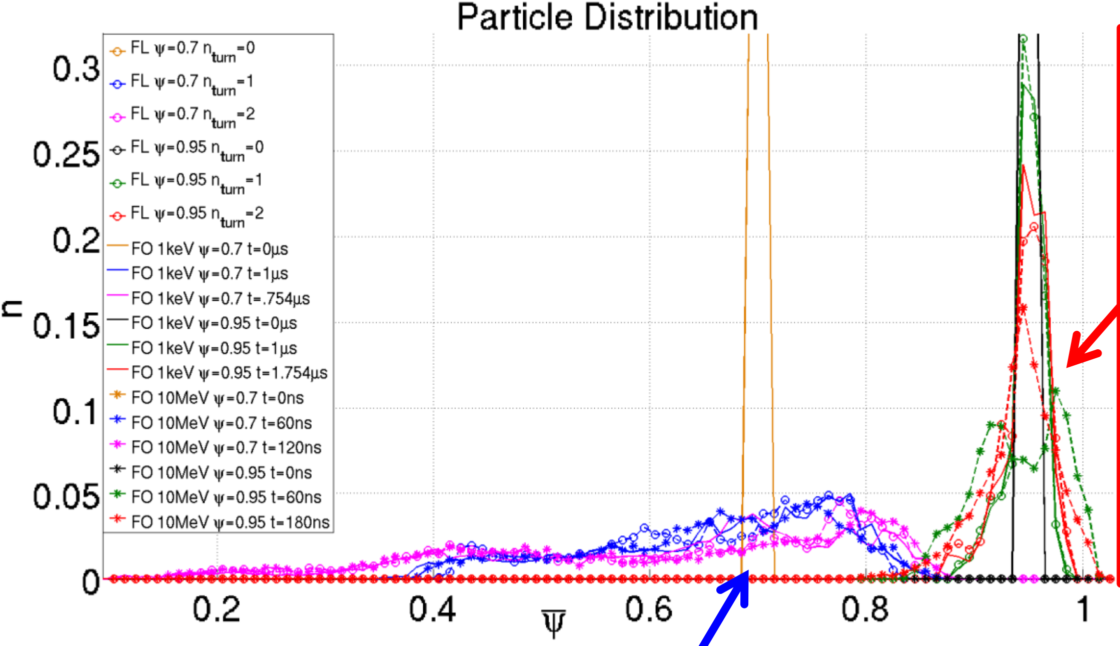
1) Particles diffuse and start to be lost
2) Electron loss (deconfinement)
3) Magnetic surfaces reform => losses stop => particles are reconfined

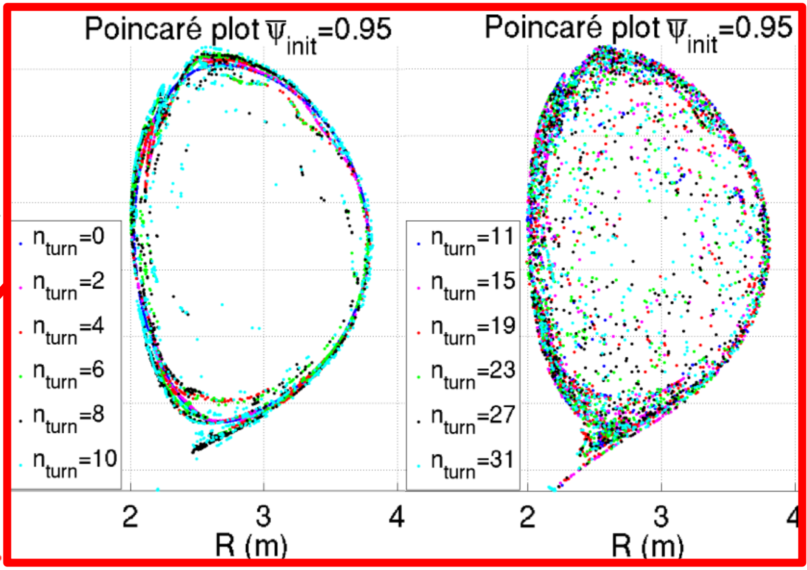
⇒ Reformation of magnetic surfaces in two steps: (1^{st}) fast generation in the core, ($2^{nd)}$ later formation at the edge

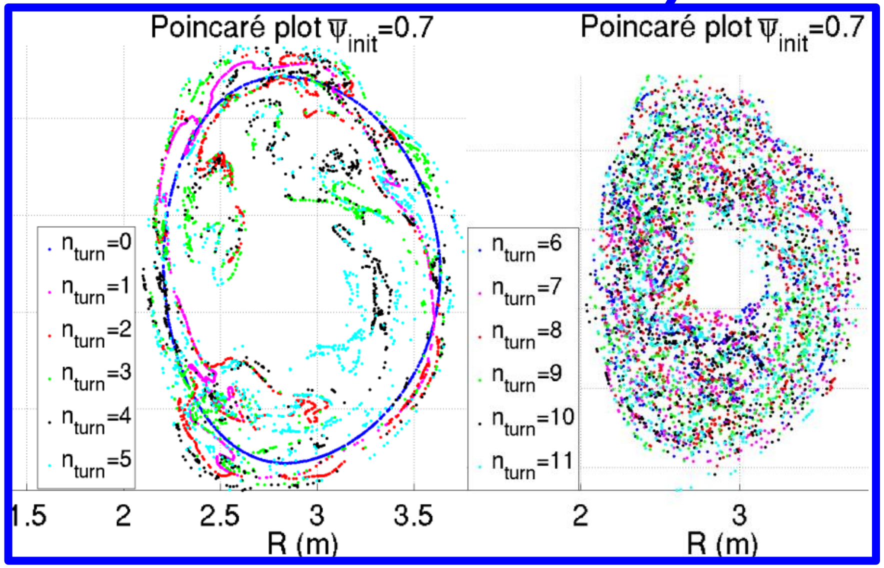
⇒ Loss profiles of FO and GC are in good agreement (within statistical uncertainty)


Number of alive particles FO and GC comparison

COMPARISON BETWEEN ELECTRON AND FIELD LINE TRANSPORT DURING THE TQ







Perturbation (transport) intensity is not homogeneous:

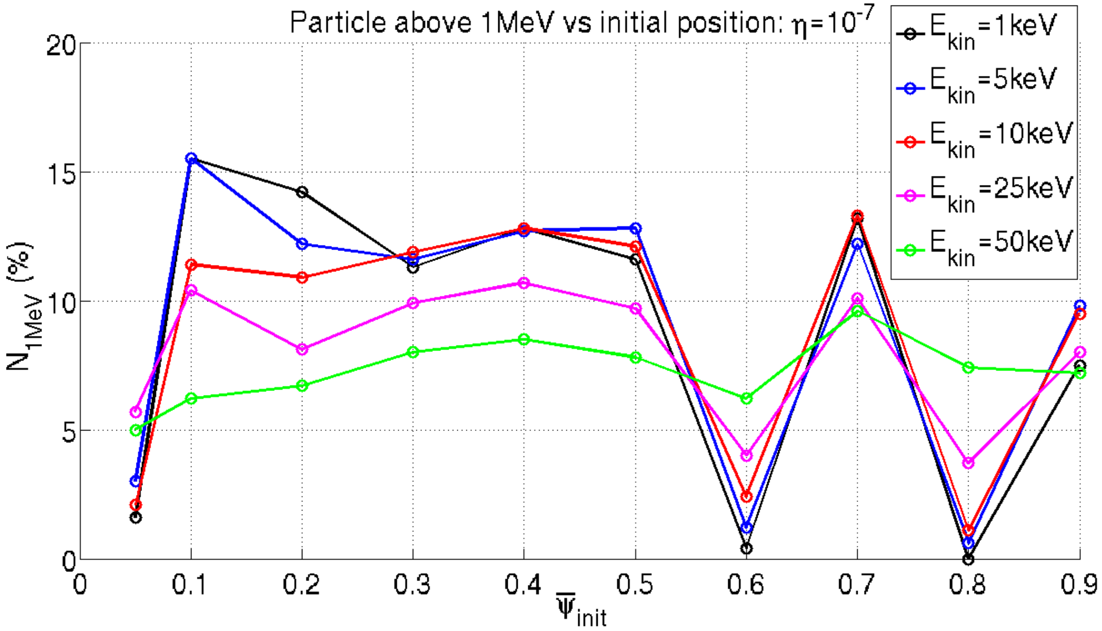
⇒ Most of the plasma is characterized by strong transport => electron propagation towards the core

⇒ Reduced magnetic fluctuations at the edge (and core) => increased confinement

Possible bias due to boundary condition closer to the plasma than reality

RE PRODUCTION IN DISRUPTION

RELATIVISTIC ELECTRON POPULATIONS OBTAINED DURING THE JET PULSE 86887 DISRUPTION SIMULATION



Electron test particle simulation during the disruption TQ:

- Full electric field is used (electric potential + magnetic flux time variation)
- Drag force due to collision is used
- Passing particles having a kinetic energy of 1keV are initialized at the TQ beginning (no persistent closed flux surfaces)

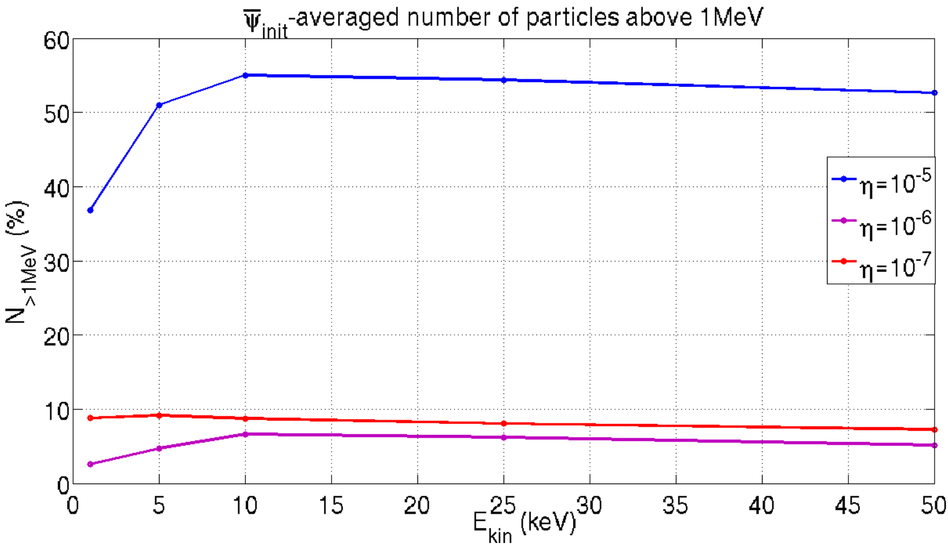
➢ Runaway electrons are generated and can reach relativistic energies

In JET pulse 86887 no RE are observed

➢ A possible explanation: too high resistivity used in JOREK simulation (~$10\eta_{JET}$)

➢ test with extremely high resistivity ($\eta=10^{-5}$) shows an increase in RE production

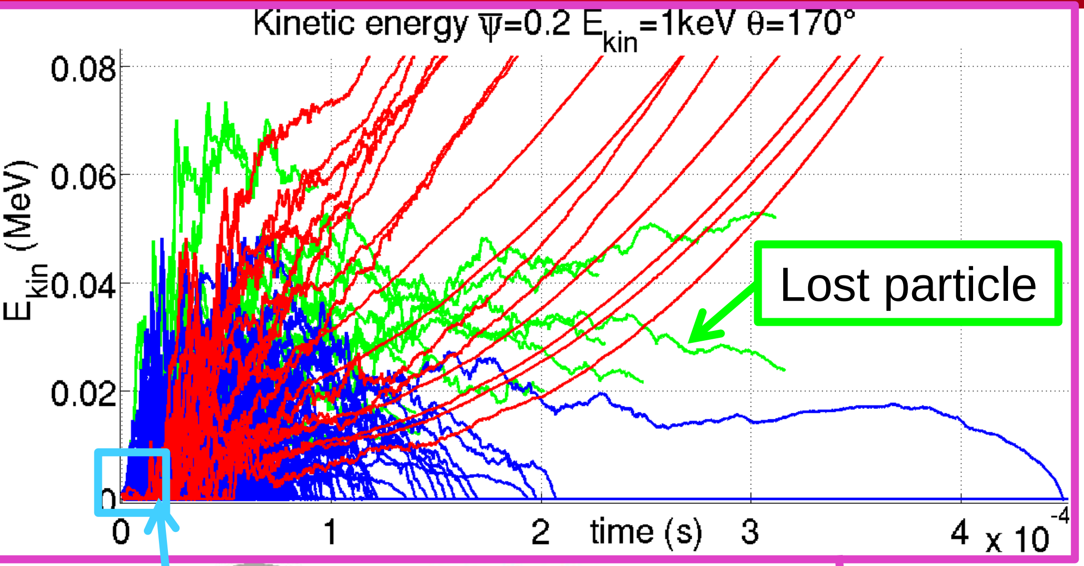
➢ Work in progress……



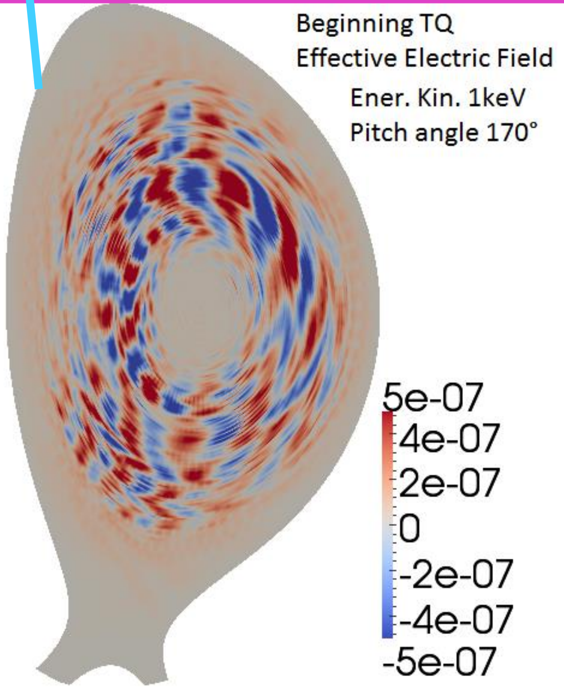
A POSSIBLE CONNECTION BETWEEN ELECTRIC FIELD FLUCTUATION DURING THE TQ AND RE GENERATION

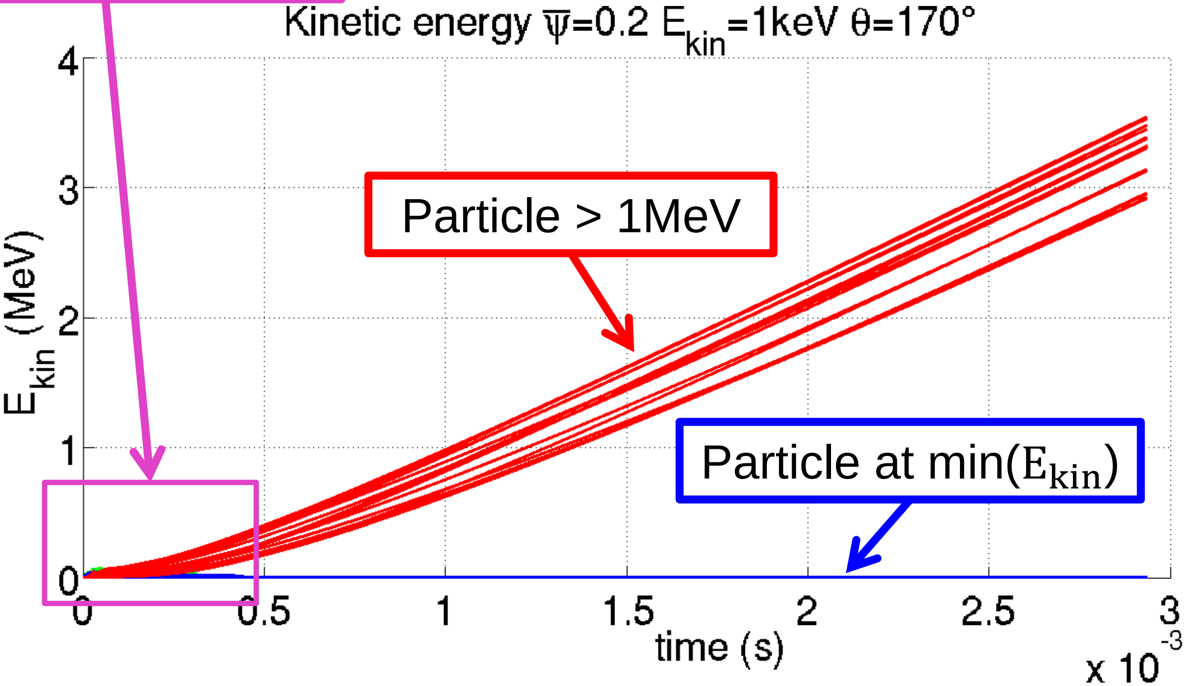
1. Cells of strong effective electric field ($E_{eff} = (qE_{\parallel} + F_{coll\parallel})/|q|$) appear during the TQ
2. A fraction of particles can be accelerated up to RE conditions by driving cells
3. After surviving the TQ, they might contribute to RE seed production

→ Still work in progress



Lost particle





Particle > 1MeV

Particle at min(E_{kin})

SUMMARY AND FUTURE WORK

SUMMARY

- Transport results show that particles are diffused by electromagnetic chaoticity in the whole plasma volume. However, when magnetic surfaces reform at the end of the TQ, they are confined again.

- Particle distribution simulations highlight a reduction of particle transport at the plasma core and edge regions which might improve the confinement of fast electrons (to be confirmed by simulations using realistic walls)

- Preliminary results with full electric field and collisional drag force exhibit generation of RE populations during the TQ phase

- The mechanism underneath the production of RE is likely to be related to strong electric perturbations taking place during the disruption TQ phase. These perturbations can accelerate electrons up to high enough energies for becoming RE during the CQ phase

- Simulation are not consistent with JET pulse 86887 experiment where no RE are seen: this is possibly due to the high plasma resistivity used in these simulations (underway).

FUTURE WORK

- Finer characterization of RE generation in disruptive magnetic fields

- Continue the scan in plasma resistivity for assessing its role in RE generation mechanism (underway)

- Try to obtain JET disruption simulations at realistic plasma resistivity

- Try to obtain JET disruption simulations using realistic resistive wall (JOREK-STARWALL)

- Implementation of an improved guiding center collisional operator taking into account collisional scattering

- Study RE/disruption dynamics in other JOREK simulations
    - Disclaimer: The present work is based on only a few JOREK D_2 MGI-triggered disruptions which are not quantitatively validated
    - JET SPI-triggered disruptions simulations are underway (by Di Hu at ITER)
    - JET non-D_2 MGI-triggered disruption simulations are planned
    - Implementation of fluid model for RE studies during CQ and plateau phases (V. K. Bandaru at IPP Garching)

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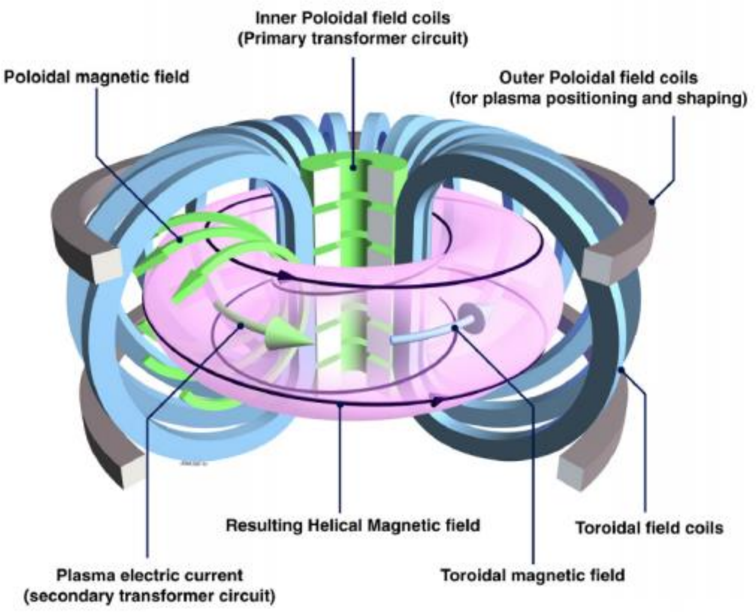
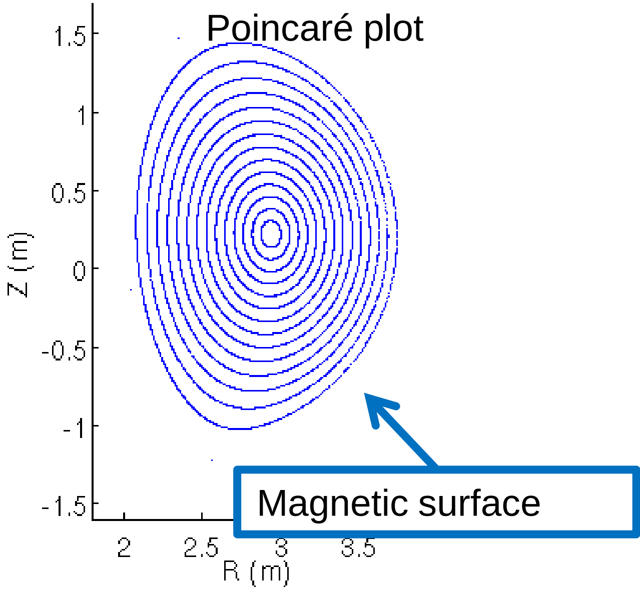
INTRODUCTION

- Tokamak: reactor using a toroidal magnetic field in order to confine a hot plasma
- The confinement is achievable within a stability domain
- Overcoming the stability limits ⇒ disruption: fast plasma shutdown due to loss of confinement which can damage the machine
- Disruption mitigation: induce a lower intensity (safer) disruption using for example massive gas injection (MGI)
- This work is within the international disruption simulation framework based on the non-linear magnetohydrodynamic code JOREK




Poincaré plot

Magnetic surface

DANGERS RELATED TO RUNAWAY PRODUCTION

Expected RE characteristics in ITER:

- Current: 10MA[1]
- Kinetic energy: 20MJ[2]

Dangerous operations if the current of REs >2 MA[2]:

- CFP melting
- Risk of PFCs perforation causing a cooling fluid leakage in the vacuum chamber (happened in Tore Supra)

T+: +403.948 ms
Img#: 807 Cam: Phantom v.7 AcqRes: 800 x 600 Rate: 2000 Exp: 495 µs EDR: 0 µs First: -293 Last: 1596 Durat: 0.945 s
Range data:
Description:

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[1] M.Lehnen , J. of Nucl. Mat., 2014
[2] M.Sugihara, ITR/P1-14,2012

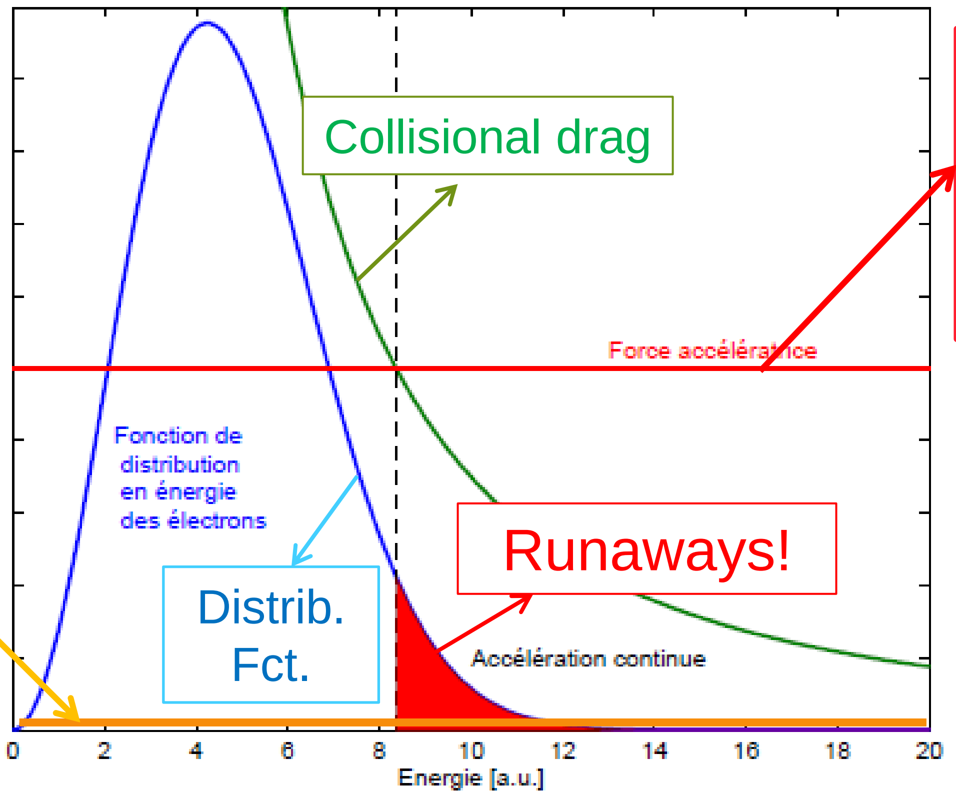
RUNAWAYS ELECTRONS (RE)

Runaway electrons (RE): electrons above the energy threshold at which the electric field force is stronger than the collisional drag

Normal operations: small electric field

↓

No runaway electrons generation



Disruptions: high electric field

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Generation of runaway electrons