COMPASS
INSTITUTE OF PLASMA PHYSICS ASCR

The impact of resonant magnetic perturbations on runaway electron dynamics

E. Macusova[1], O. Ficker[1,2], T. Markovic[1,3], M. Tomes[1,3], Y. Liu[4], M. Gobbin[5], A. Casolari[1], J. Mlynar[1,2], F. Jaulmes[1], L. Kripner[1,3], J. Decker[6], Y. Peysson[7], G. Papp[8], J. Cerovsky[1,2], G. Pokol[9], D. Carnevale[10], M. Carr[11,12], J. Havlicek[1], A. Havranek[1], P. Kulhanek[1,2], M. Hron[1], D. Naydenkova[1], R. Panek[1], V. Plyusnin[13], J. Urban[1], P. Vondracek[1], V. Weinzettl[1], COMPASS team[1] and the EUROfusion MST1 Team*

1) Institute of Plasma Physics of the CAS, Prague, Czech Republic; 2) FNSPE, Czech Technical University in Prague, Czech Republic; 3) FMP, Charles University, Czech Republic; 4) General Atomics, San Diego, USA; 5) Consorzio RFX, Padova, Italy; 6) EPFL, Lausanne, Switzerland, 7)CEA, IRFM, France; 8) Max Planck Institute for Plasma Physics, Garching, Germany; 9) NTI Budapest University of Technology and Economics, Budapest, Hungary; 10) Universita' di Roma Tor Vergata, Roma, Italy; 11) Luffy Al Limited, Didcot, UK, 12) CCFE, Culham Science Centre, Abingdon, UK; 13) IPFN, Lisbon, Portugal, *)See the author list o f'B. Labit et al., 2019 Nucl. Fusion 59 086020'

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EUROfusion

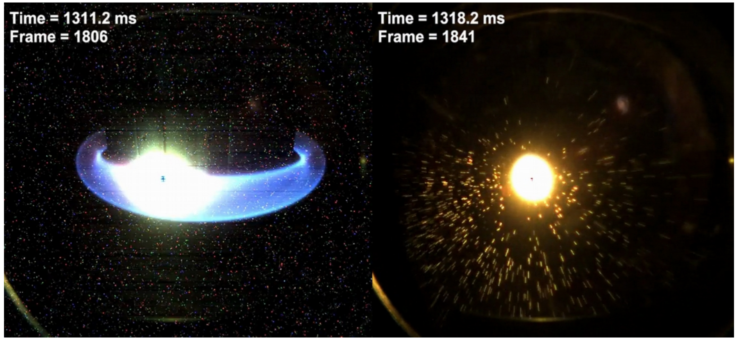
Outline

→ Runaway electrons (RE) and motivation

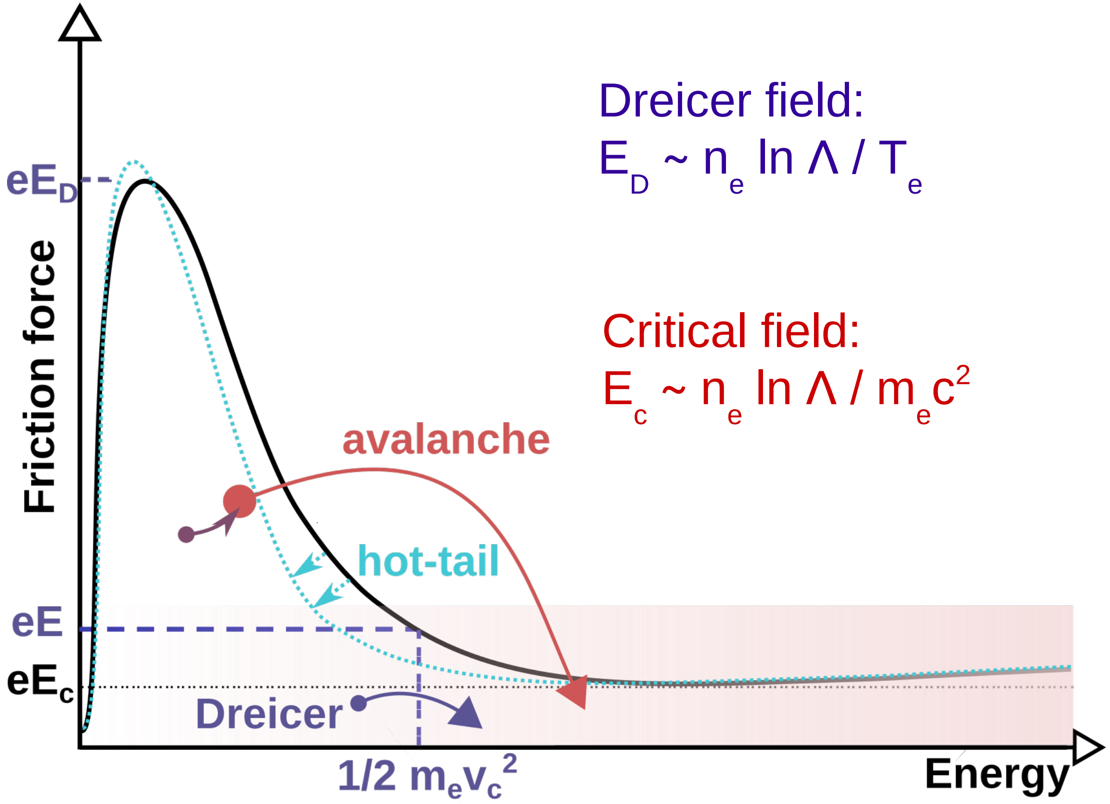
→ RMPs at COMPASS

→ RE & RMPs on COMPASS (measurements)

→ RE & RMPs on COMPASS (simulations)



Runaway electrons



Dreicer field:
$E_D \sim n_e \ln \Lambda / T_e$

Critical field:
$E_c \sim n_e \ln \Lambda / m_e c^2$

Generation mechanisms

Primary: Dreicer
Hot-tail
Compton scattering & Tritium decay

Secondary: Avalanche: exponential grow

→ **Disruptions** (TQ – Thermal Quench)
- quick cooling of plasma

→ **CQ** - Current Quench ($\sigma \sim T_e^{3/2}$)
- fast I_p decay → induce **E**

→ **E/Ec > 1 in experiments**
- simulations = partial explanation **[Hesslow et al PRL 2017, Liu et al PRL 2018]**
- transport

Runaway electrons

Runaway electrons (RE) [Breizman et al NF 2019]

- relativistic energies
- tokamaks - disruptions, fast Ip decay etc – source of RE

→ **serious threat for ITER and other devices**

Motivation

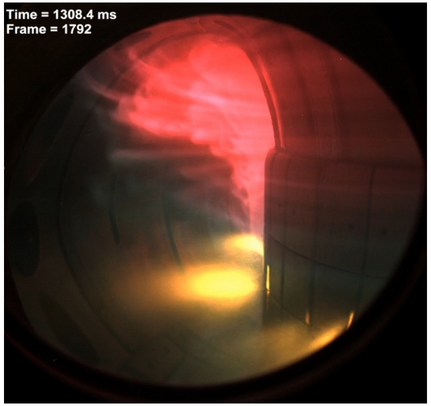
→ **protection** of current and future devices necessary

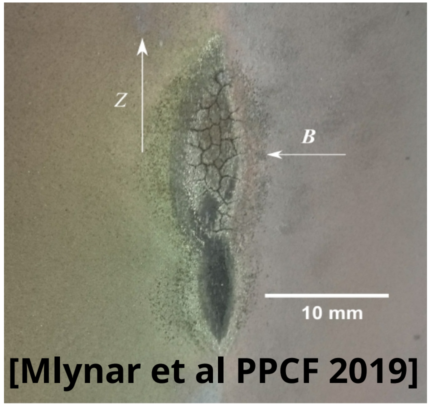
→ efficient mitigation/prevention **requires deep knowledge** – not possible without **theory and modeling**

→ alternative/complementary approaches & feedback

- resonant magnetic perturbations (RMPs) → transport ...
- kinetic + MHD instabilities → pitch angle scattering ...

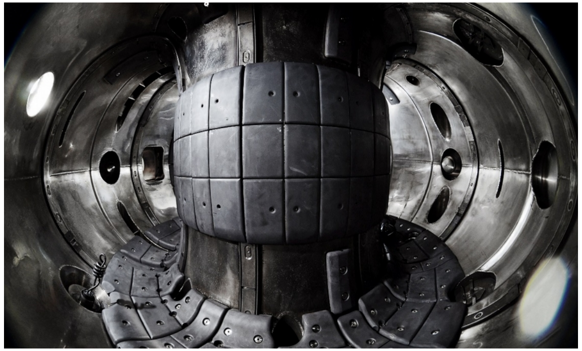
Could RMPs be one/part of the mitigation technique?



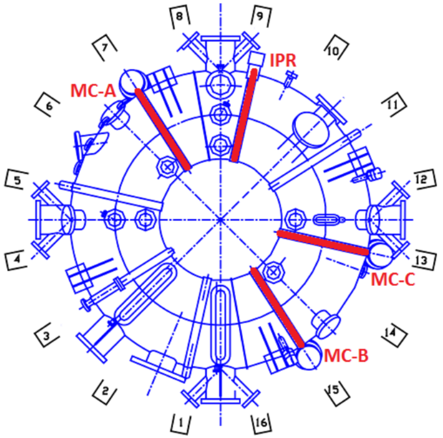


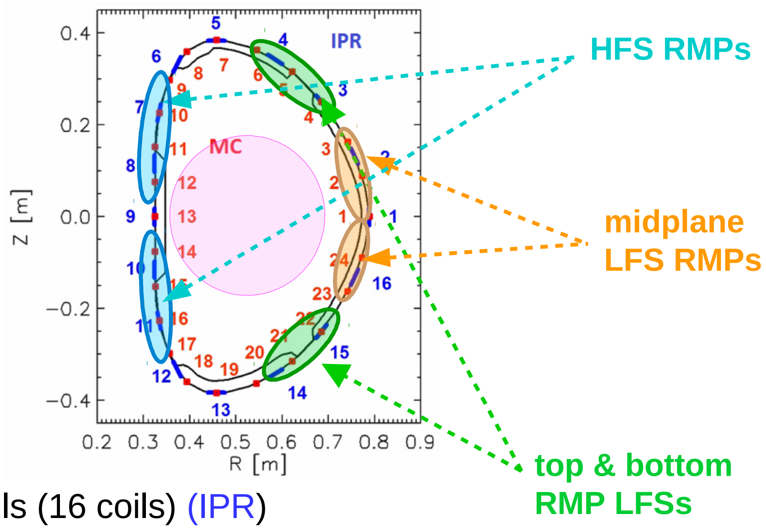
COMPASS protruding graphite inner limiter tile

COMPASS settup



- **ITER-like plasma** → R_0/a = 0.56m/0.23m
- B_T = 0.9 T – 1.6 T & $I_p \lesssim$ 350 kA & q_{95} <= 3
- MHD, basic and RE diagnostics
- **RMP coils**
  - **HFS**
  - **LFS – off-midplane**
  - **LFS – on-midplane**
  - 4 Power Supplies (I_{RMP}~1-4kA)
  - penetration time ~ 5ms
  - **B_{RMP}/B_T up to 10^{-2}**



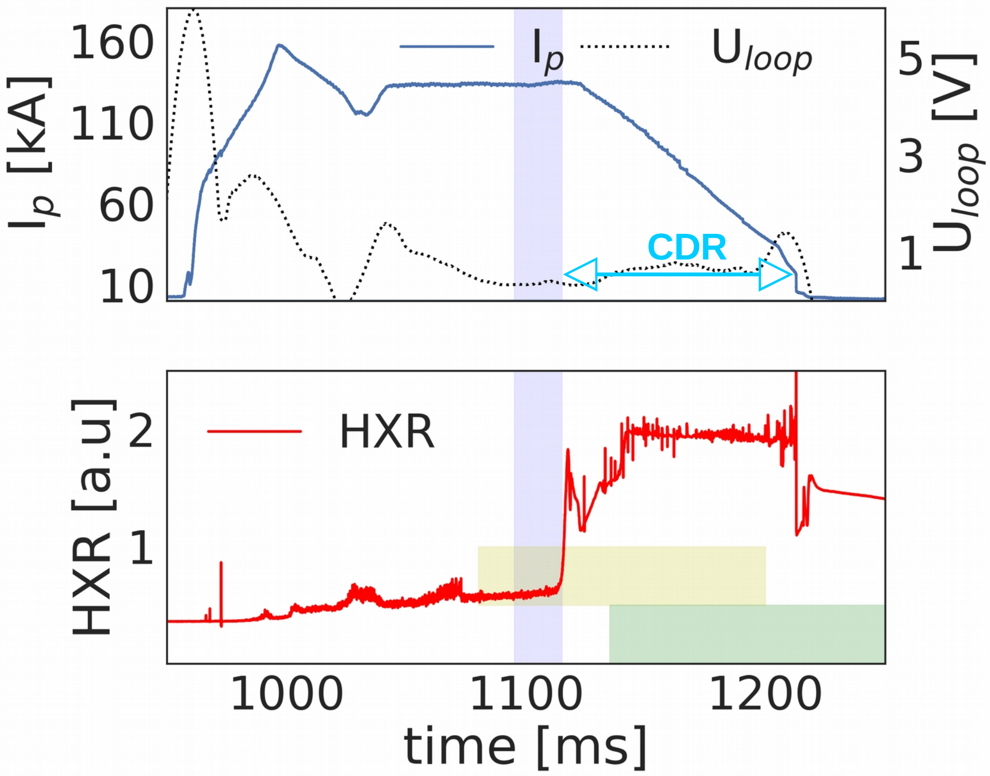


- Internal Partial Rogowski coils (16 coils) (IPR)
- 3 rings of Mirnov coils (24x3x3 coils each) (MC)
  → radial, toroidal, poloidal magnetic field
- EPR coils + flux loops + saddle coils

RE diagnostics - HXR, photoneutrons, V-ECE, Cherenkov, scintillators, calorimetry head, fast cameras (VIS + IR), SXR, spectroscopy, MediPix, Thomson scattering, interferometer.. [**Weinzettl et al. NIST 2017, Havranek et al. FED. 2017**]

RE scenario

Reference RE scenario



→ reproducible

→ gas injection (purple area) = destruction of the thermal plasma

→ “zero” U_{loop} **[Ficker et al NF 2019]**

→ CDR (Current Decay Rate) = dI_{RE}/dt

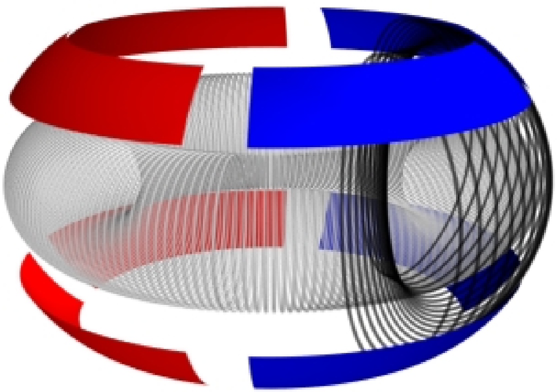
→ **pre-disruption** scenario = RMP applied **before** gas injection (lower RE energy)

→ **post-disruption** scenario = RMP applied **after** gas injection (direct impact on RE, low T_e background plasma)

RMP configurations used during RE campaigns

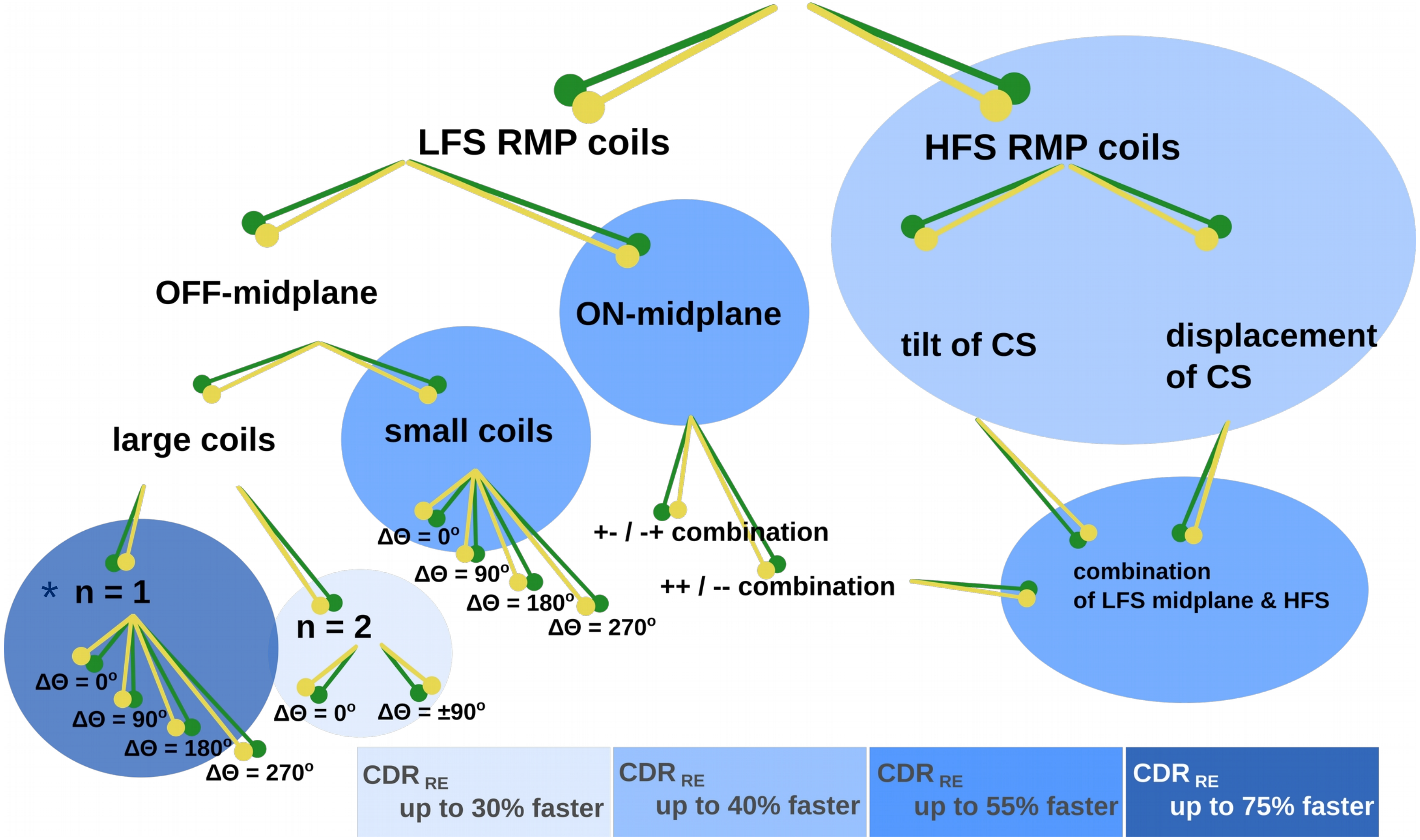
RMPs configurations combined with
→ different gas (Ar, Ne, D & their mixtures)
→ different types and number of valves

Impact on **CDR_{RE} (Current Decay Rate)**
→ **the strongest effect (RMP*)** ~ ¾ faster CDR
→ **the weakest effect** ~ **a few %** faster CDR



→ the effect **scaled** with
- → the size, position, phase and current in RMP coils
- → with gas / valve type and amount
  - → RMP* + **Ne ~ 20% faster CDR_{RE} than RMP* + Ar**
- → other effects – screening, RE energy etc – simulations necessary

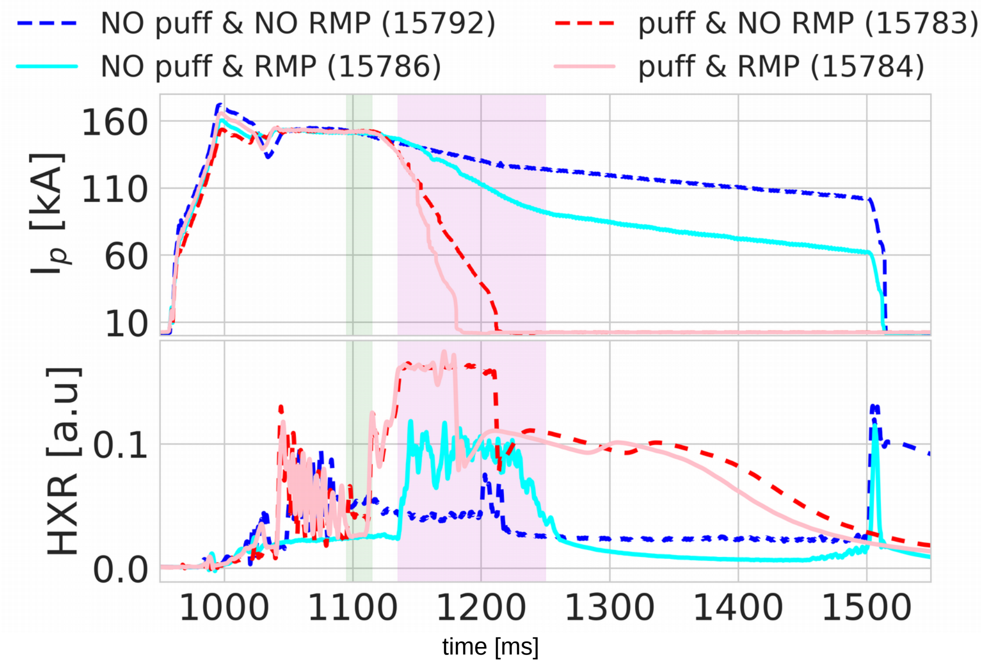
RMP configurations used during RE campaigns



Overview of main experimental results I

What is affected by RMPs? → amount & energy of RE / RE transport / level of radial fluctuations / plasma response / ...

RMP only / RMP + gas injection



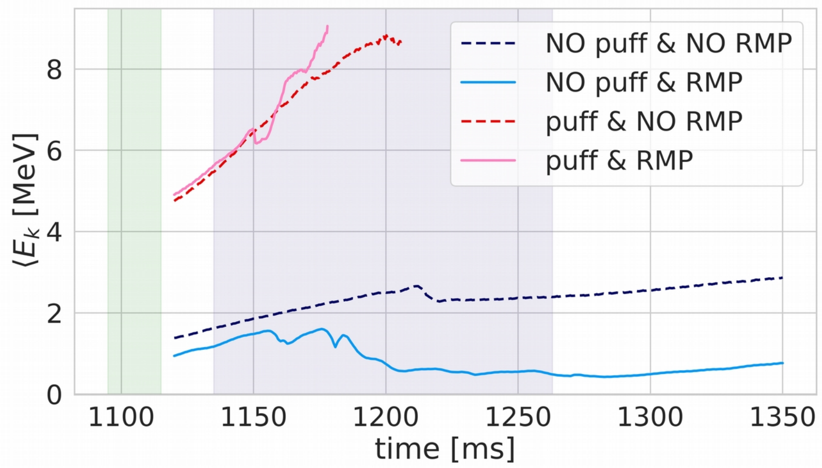
→ RE losses already present when RMPs are energized

→ HXR signal - saturated (end of the gas injection) => $n_{RE} > 10^{15}$

Energy dependence **[Ficker et al NF 2019]**

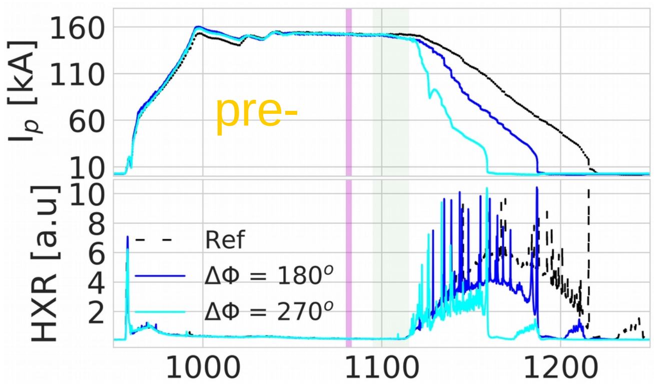
$$\langle E_k \rangle \propto R_0 B_v ec$$

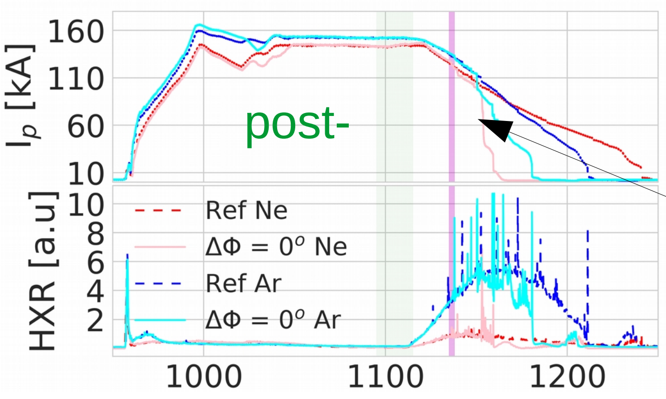
E_k → direct dependence on the radial position R_0 and vertical magnetic field B_v

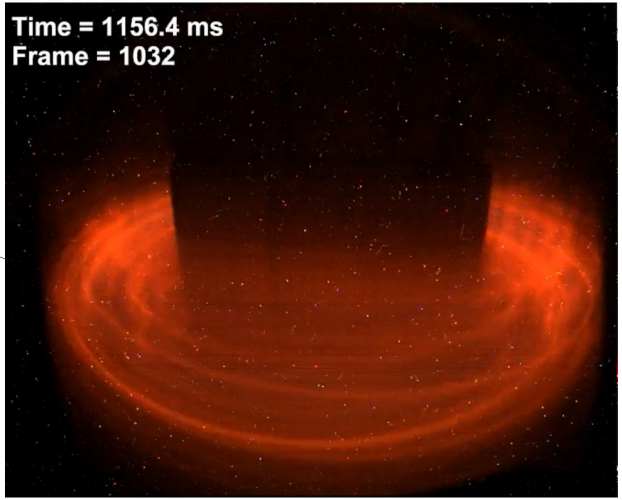


Overview of main experimental results II

off-midplane LFS RMP (n = 1)







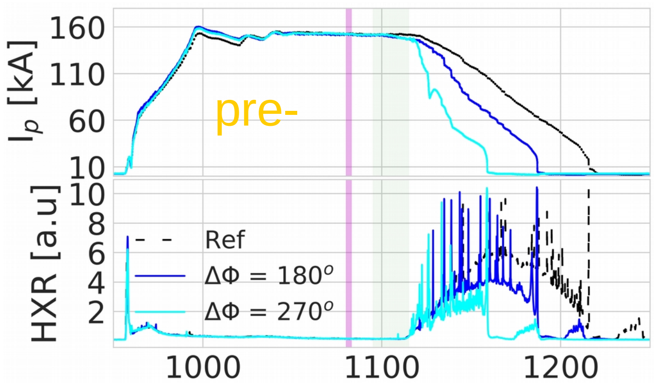
Ar case → for Δϕ=270° (pre, max -60%)
→ for Δϕ=0° (post, max -45%)

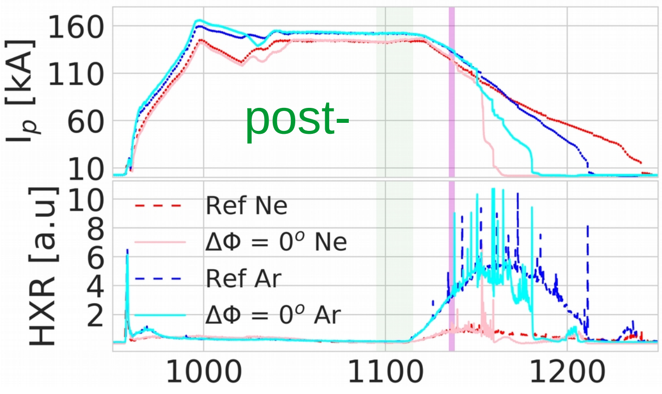
scaling with Δϕ, Z_{eff}, I_{RMP}

Ne case → longer RE current (~ 40 ms > Ar)
→ Δϕ=0° **(post, max -75%)** - more scattered effect

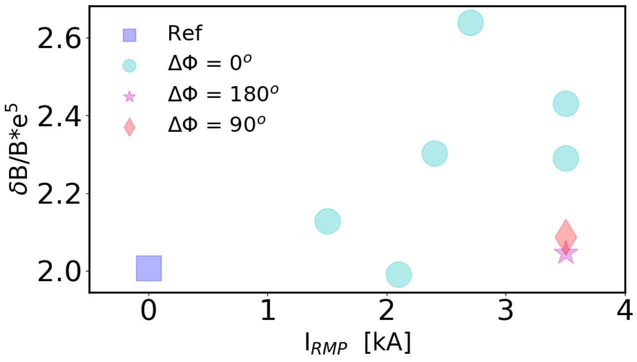
Overview of main experimental results II

off-midplane LFS RMP (n = 1)

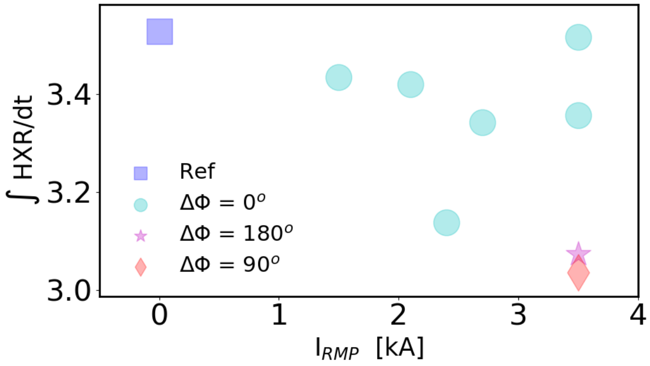




post-



post-



Ar case → for Δϕ=270° (pre, max -60%)
→ for Δϕ=0° (post, max -45%)

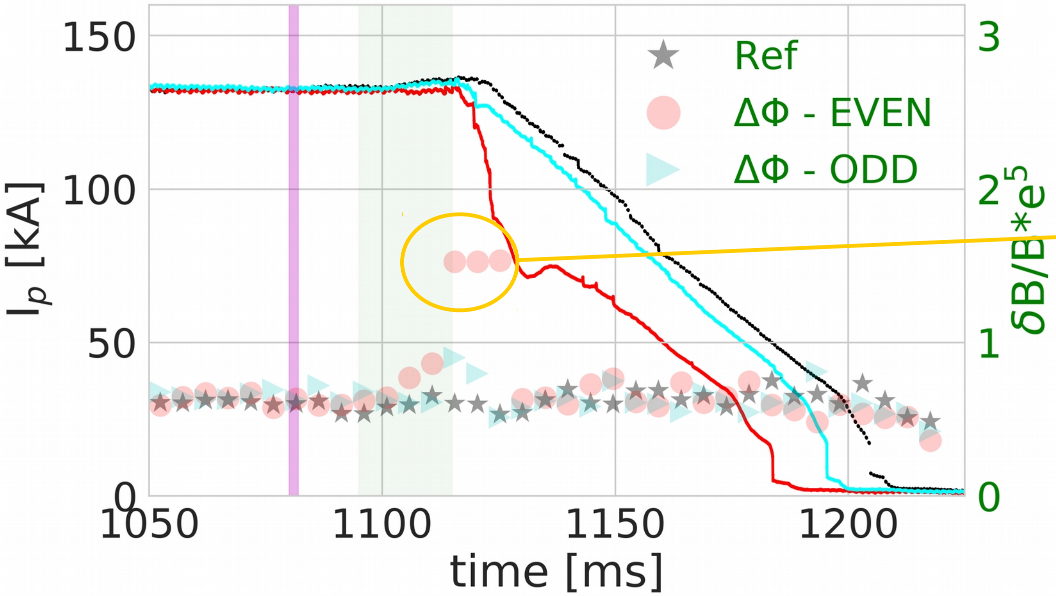
scaling with Δϕ, Z_{eff}, I_{RMP}

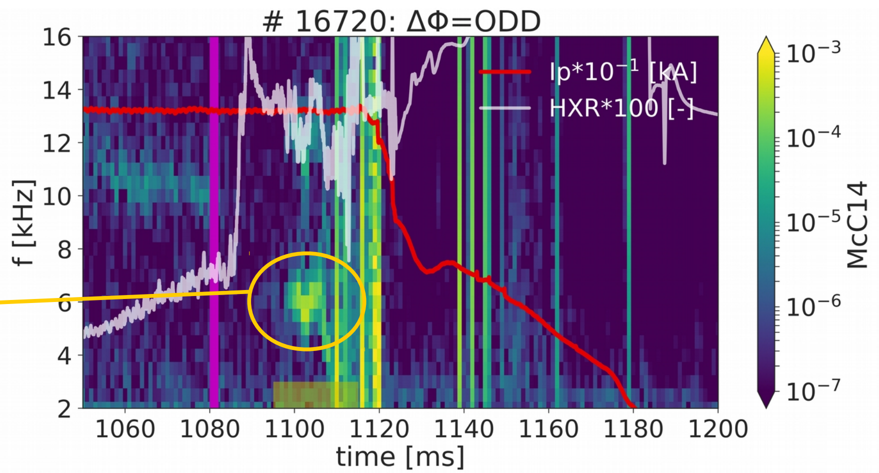
Ne case → longer RE current (~ 40 ms > Ar)
→ Δϕ=0° **(post, max -75%)** - more scattered effect

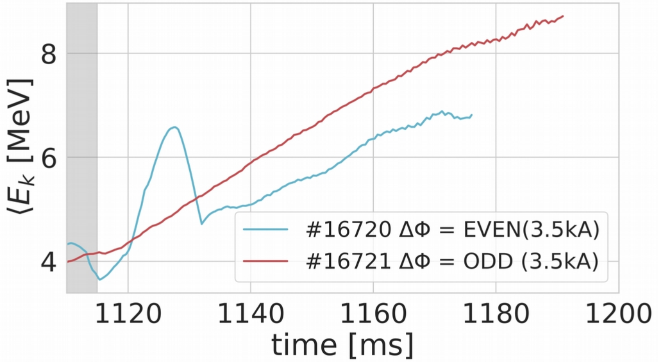
Radial fluctuations $\delta B_r/B_T$ and ∫HXR/dt scaled with I_{RMP} (post-)

Overview of main experimental results III

off-midplane LFS RMP (n = 2)





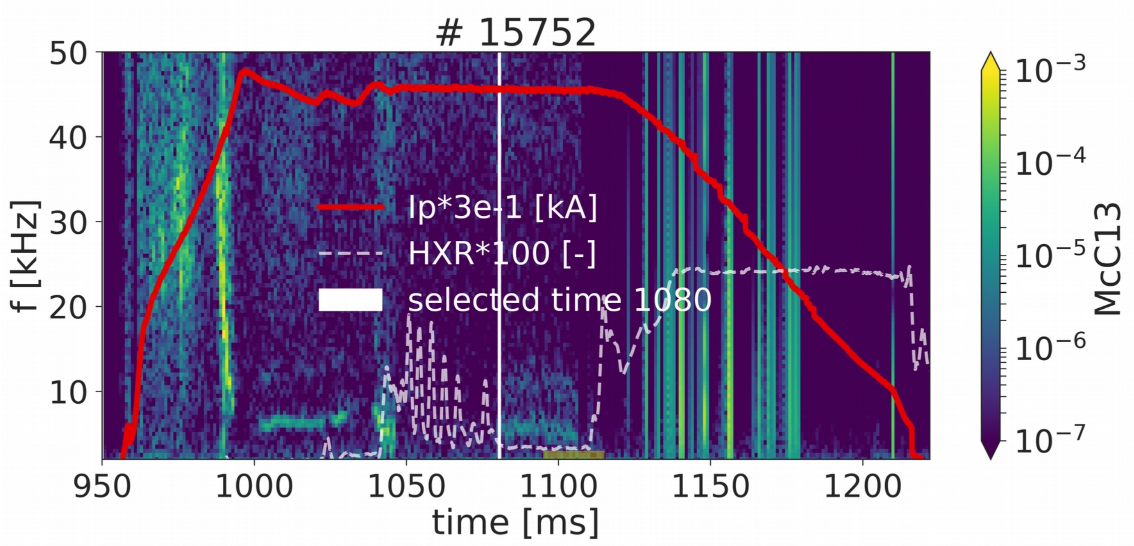


→ MHD activity – rotating island formed (n=1) for Δϕ – ODD
- increase of radial fluctuations $\delta B_r/B_T$ → drop of Ip & drop of averaged Ek / n_{RE}

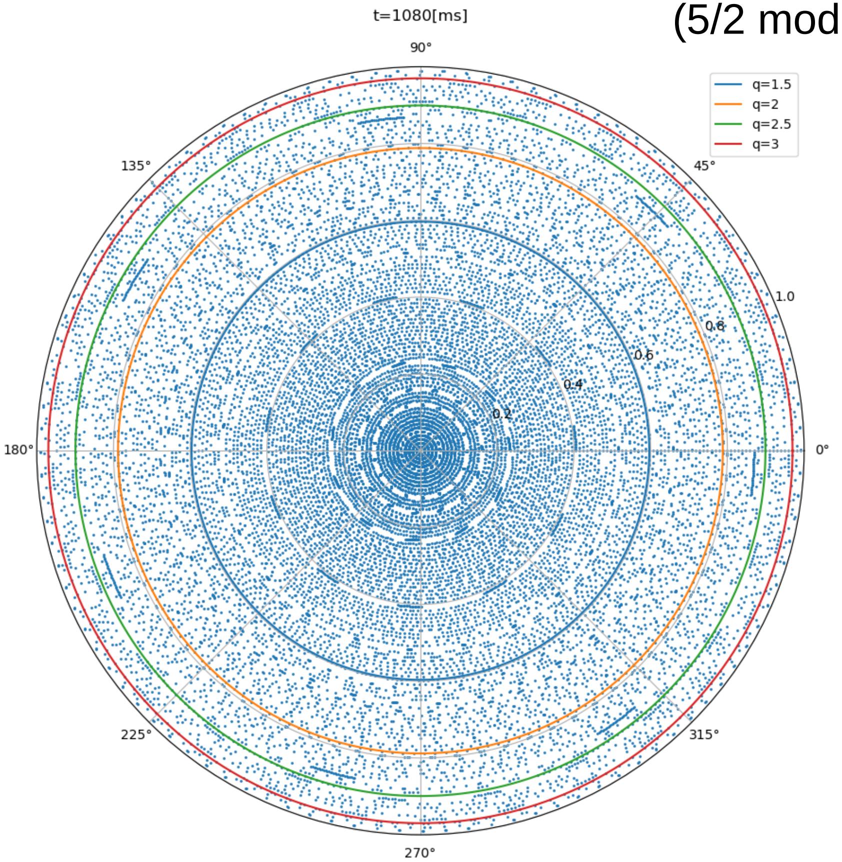
[Gobbin et al EPS 2019, Macusova E et al APS 2018]

Test case for following simulations

Test case - LFS off-midplane RMP (n = 1) + Ar

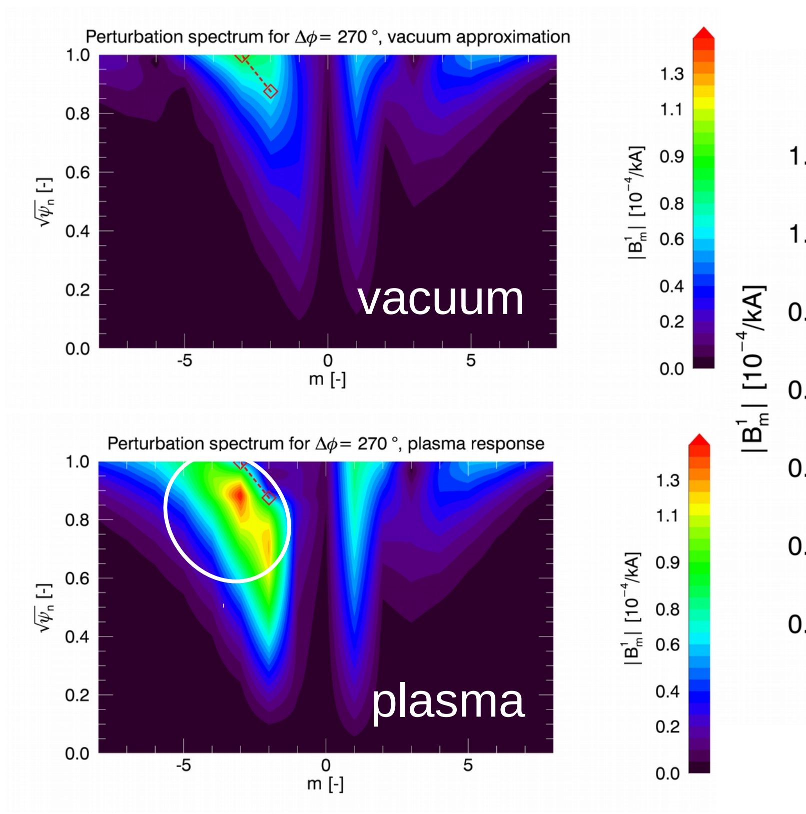


(5/2 mode)



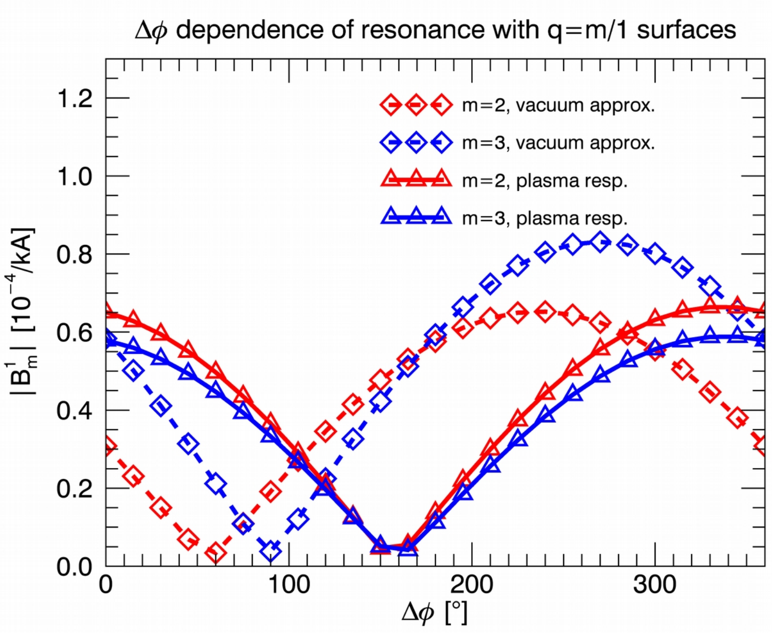
→ only weak MHD (5/2) – flux surfaces not influenced
→ t = 1080 ms (MARS-F & tracing time)
→ reconstruction of the magnetic topology
[Casolari et al EPS 2019]

Plasma response (MARS-F simulations)



[Mlynar et al PPCF 2019]

MARS-F (n=1)



MARS-F

[Liu et al PP 2000]
[Liu et al NF 2016, NF 2019]

- → resistive MHD code
- → one fluid
- → toroidal geometry
- → curve-linear mag. coord.
- → guiding center drift orbit module for RE
- → input: T_e, T_i, n_e, v_Φ profiles
- → outputs:
  - eigenvalue solver
  - total field including plasma response

→ plasma response → m=2 & m=3 maxima shifted to higher $\Delta\phi$ values **[300°- 360°]**

→ similar shift observed at ASDEX **[Gobbin et al NF 2018]**

The role of transport

→ **RE** - strongly passing (small pitch angle), almost collisionless (high energy RE are immediately lost)

→ **RMP or disruption** - **stochastic** magnetic field at the plasma edge → enhancement of the cross-field transport = increase of losses = can prevent avalanche **[Helander et al PoP 2000]**

→ COMPASS (mainly Dreicer) → RE seed + lower energies

Radial transport – diffusion

[Myra & Catto 1992, Rechester and M. N. Rosenbluth PRL 1978, Izzo et al NF 2011, Abdullaev et al PP 2012...]

→ D_{RE} depends on: collisionality, electric and magnetic field fluctuations

$$D_{RE} = D_{coll} + D_{EF} + D_{MF}$$

$D_{coll} = \langle \Delta x^2 \rangle / \tau_c$ ($\Delta x \sim q/\sqrt{\varepsilon}\, r_L$) → the main effect arises from the Banana-orbit (one order > RE Larmor radius (r_L)) → $10^{-4} - 10^{-5}$ m^2/s

D_{EF}, D_{MF} → caused by electrostatic (ES) and magnetic (M) fluctuations - can cause **orbit decorrelation**

→ fluctuations are associated with a potential flow: $v_{E,M} \sim \hat{b} \wedge \nabla \Phi$

The role of transport

ES & M drifts - caused by E∧B, grad-B and curvature
- their perturbation part do not average to zero over 1 poloidal average = non-zero transport

$$D_E = \pi q R_0 \frac{1}{v_{\|}} \left(\frac{\tilde{E}}{B} \right)^2 \quad < \quad D_M = \pi q R_0 v_{\|} \left(\frac{\tilde{B}}{B} \right)^2$$

Small-Kubo-number ($K = \tau_c / \tau_{fl}$) regime: τ_{fl} (time of flight for 1 corr. length) $> \tau_c$ (corr. time of the perturbation)

→ particle do not explore the field structure
→ consistent with standard diffusion - D_{RE} analytical formulas **[Hauff & Jenko 2009] -** scaling with E_{RE}

$D \sim E^{-1}$ w/o FLR correction, $D \sim E^{-2}$ with FLR

Large-K regime: → strongly affected by the field structure (can be trapped into coherent structures (magnetic islands) – subdiffusion, analytical formulas rare - **[Gruzinov et al 1990]**

$$D \sim \lambda^{1.3} V^{0.7} \tau_c^{-0.3}$$

Frozen magnetic field – τ_c replaced by $L_{\|}/L_{\perp}$ → $K \sim \delta B/B * L_{\|}/L_{\perp}$

REs - expected to be **in orbit-decorrelation regime** and to be trapped in magnetic islands (subdiffusion)

Advection – amplified losses in regions where islands are not present **[Sarkimaki et al PPCF 2016]**

The role of transport

COMPASS specific characteristic:

→ **steep** B-field, E-field, & other **gradients**

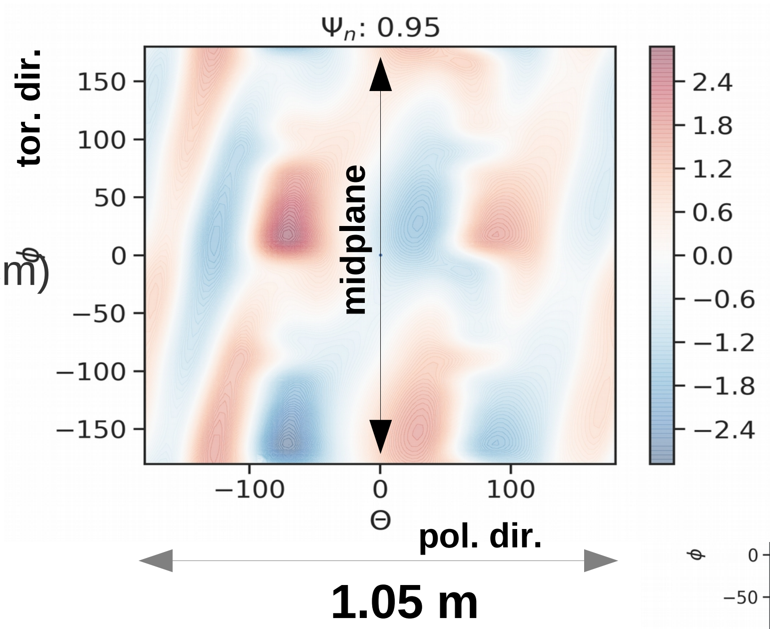
→ small R_0 = larger toroidal curvature

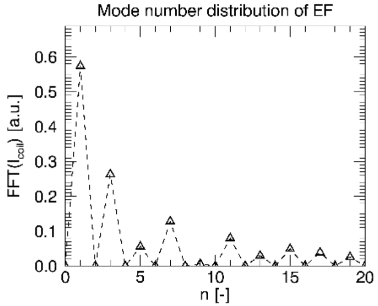
→ r_L comparable with 0.1 Ψ_n (at the edge ~ 1 cm)
and size of δB/B (higher energies)
→ $r_{L\text{-}1\,MeV}$ > 0.15 cm
→ $r_{L\text{-}5\,MeV}$ > 0.7 cm
→ $r_{L\text{-}10\,MeV}$ > 1.4 cm

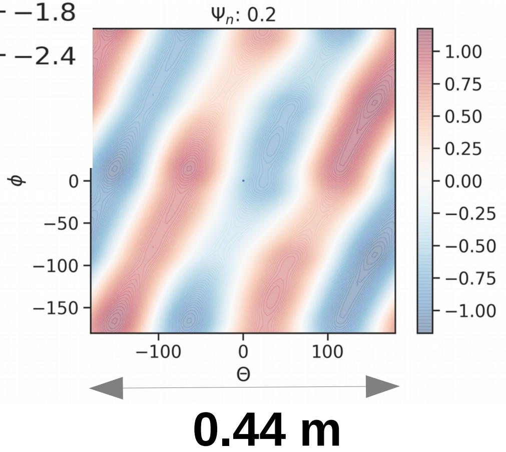
→ RMPs penetrate deep

→ **we need FO (Full Orbit)**

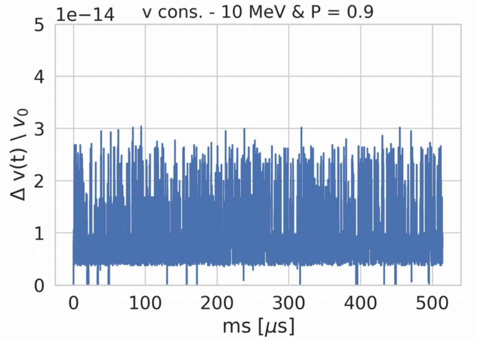
$\Delta\phi=0°$







Full Orbit particle tracking code (developed at COMPASS – version 1.0)



modular = each module - different physics or data source

- **3D B**-field – equilibrium & **3D E**-field (toroidal symmetry)
- **3D magnetic perturbation** (MARS-F results) – **no toroidal symmetry**
- particle tracer solves the relativistic equation of motion (1)
- **radiation losses** – LAD force in the Landau – Lifshitz representation **[Landau and Lifshitz 1971, Carbajal et al PP 2017]**
- no collisions - for currently used time-scales (> 1ms; Δt = 1e-13s) - future plans
- r_L **averaging** (post processing) **– GC** (future parameter)

$$\frac{d\mathbf{p}}{dt} = -e[\mathbf{E}(\mathbf{x}) + \mathbf{v} \times \mathbf{B}(\mathbf{x})] + \mathbf{F_R} \qquad (1)$$

$\mathbf{x}$ and $\mathbf{v}$ - position and velocity of particle

$\mathbf{p} = m_e \gamma \mathbf{v}$ is the relativistic momentum

$\gamma = (1 - v^2/c^2)^{-1/2}$ and $\mathbf{F_R}$ is the radiation reaction force

→ validation against experiment

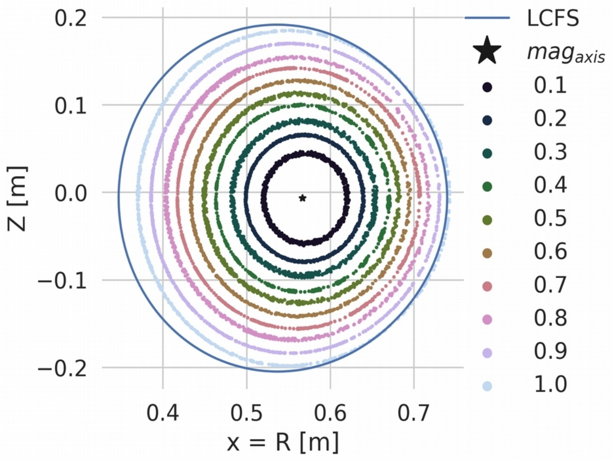
→ first validation against ORBIT* (w/o perturbation) was made (>2MeV) **[Gobbin et al NF 2016]**

→ comparison with REORBIT [MARS-F] **[Liu et al NF 2019]**

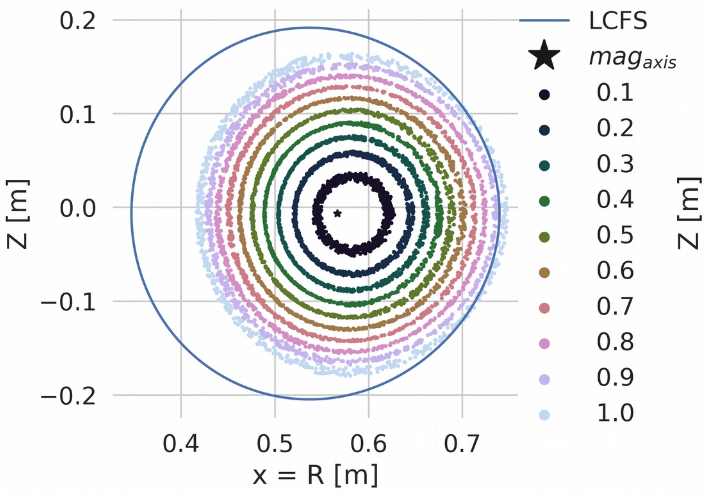
The role of transport – orbits scan (1 – 10 MeV)

RMP **off** & E on & F_R on & ξ = 0.9 → simulations - 20 μs (ξ consistent with **[Vlainic et al JPP 2015]**)

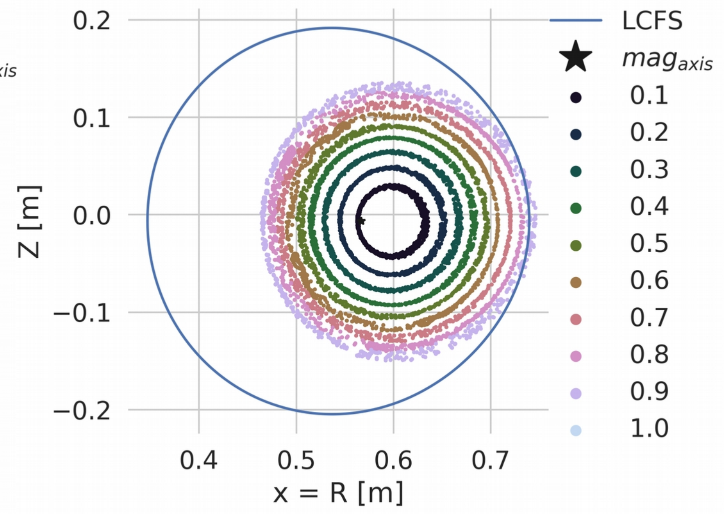
1MeV: $r_{L\text{-}1\ MeV}$ = 0.14-0.18 cm



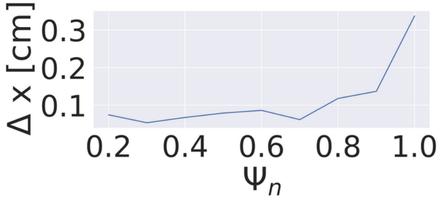
5MeV: $r_{L\text{-}5\ MeV}$ = 0.72-0.75 cm



10MeV: $r_{L\text{-}10\ MeV}$ = 1.45 - 1.6 cm



→ displacement up to 0.1 cm for 1MeV – flat radial profile



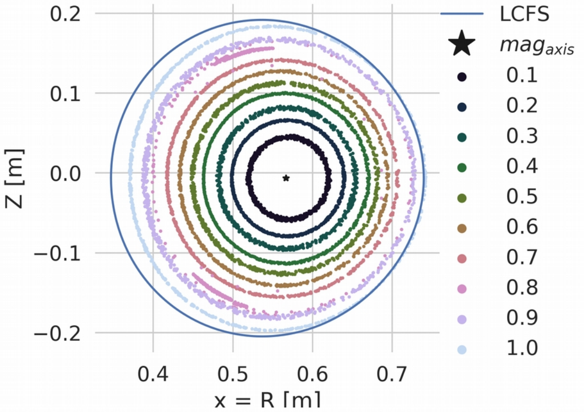
→ displacement up to 0.2 cm

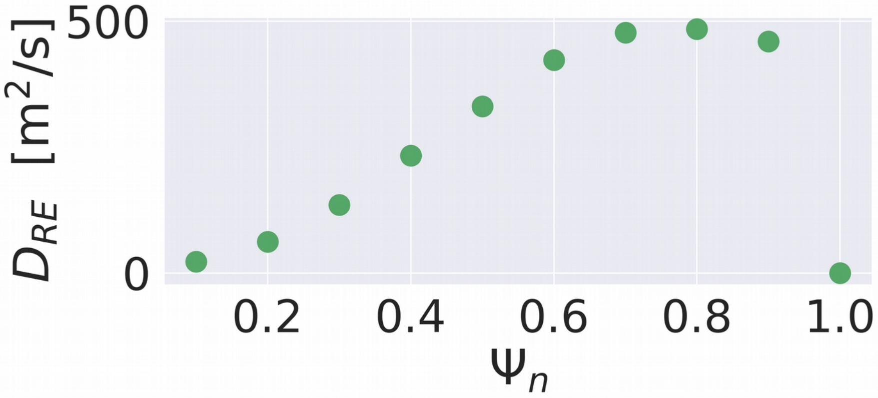
→ time of one poloidal turn ~ 0.02μs

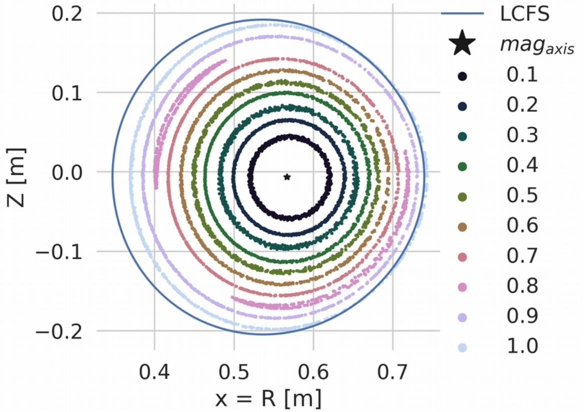
similar simulations have been done [**Papp et al PPCF 2012**]

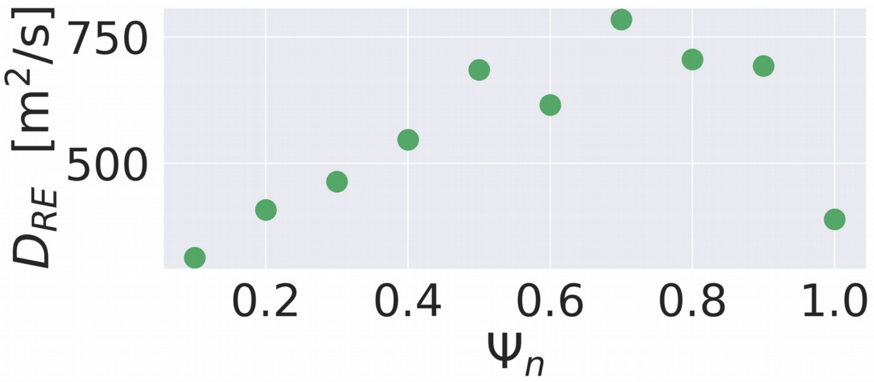
The role of transport
RMP on (1MeV)

RMP **on** & E - & F_R - & ξ = 0.9

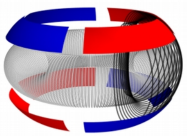




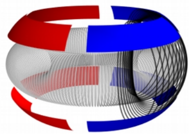




Δϕ=180°
δB/B up 1*10^-3



Δϕ=0°
δB/B up 1*10^-3



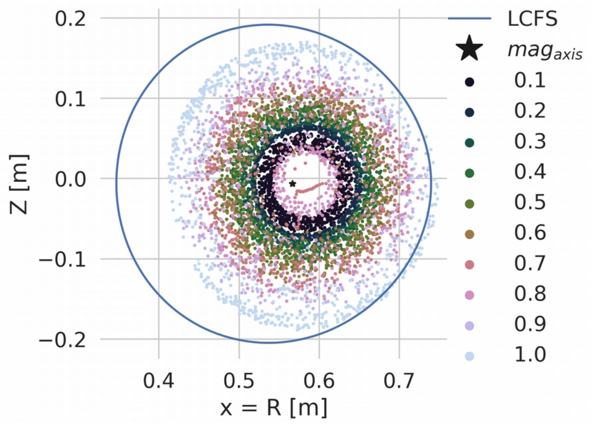
RMP phase shift (Δϕ)

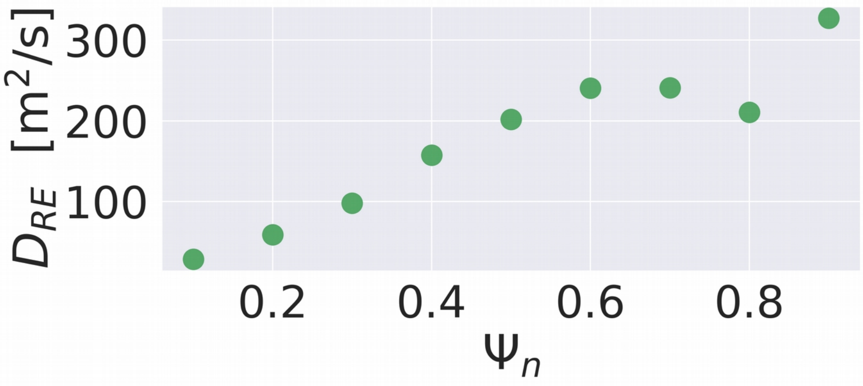
The role of transport RMP on (5 & 10MeV)

RMP **on** & E on & FR on & ξ = 0.9

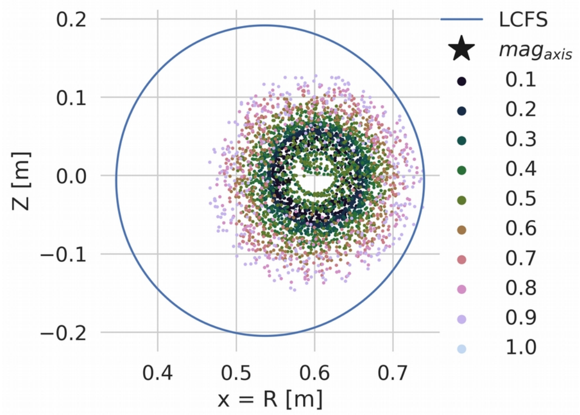
Δϕ=0º
δB/B up 7*10^{-3}

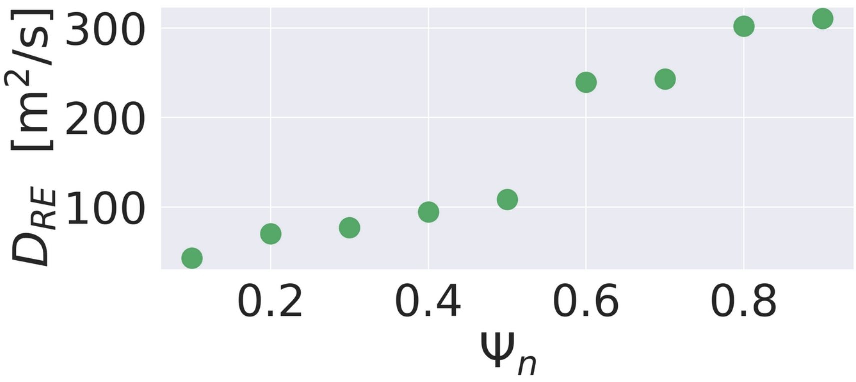
5MeV





10MeV



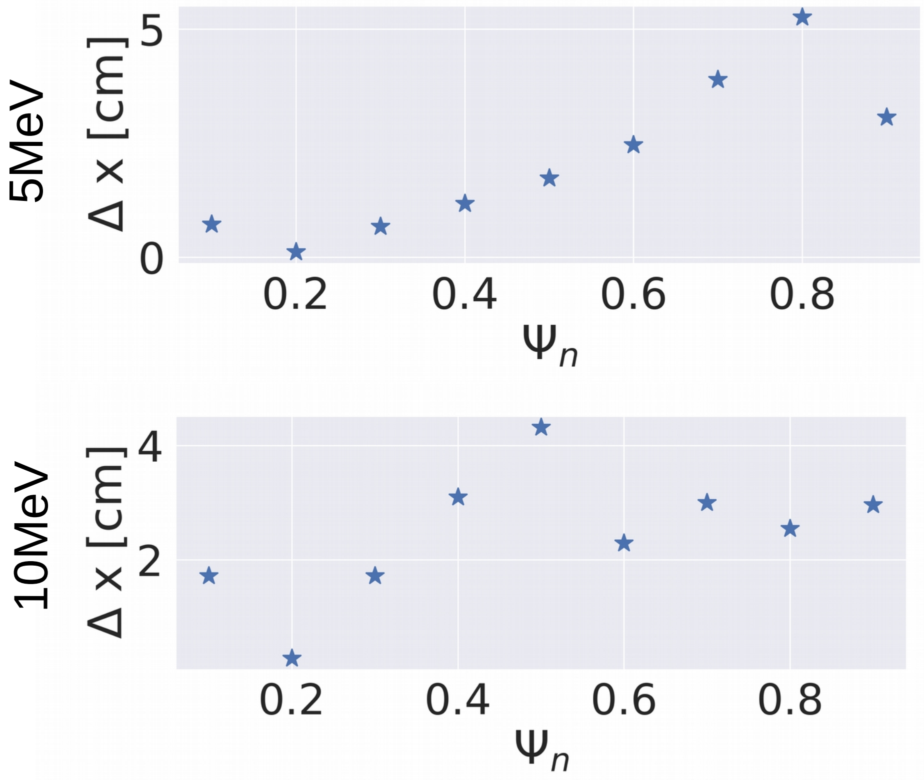


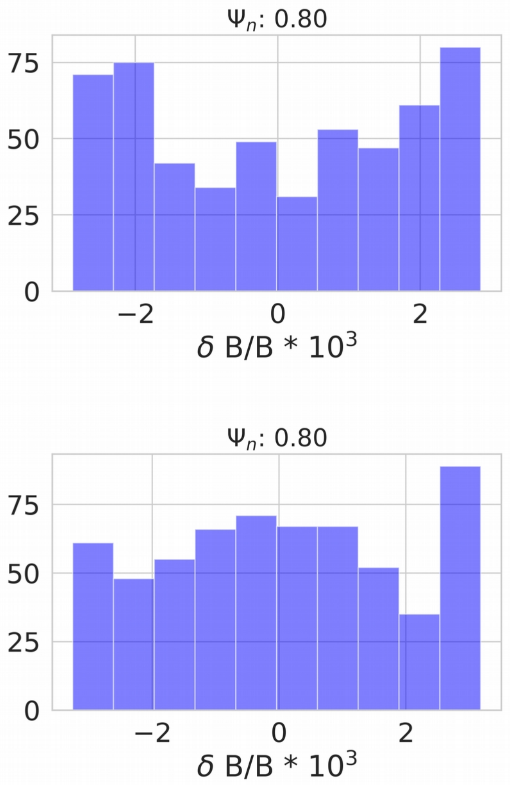
energy ↓

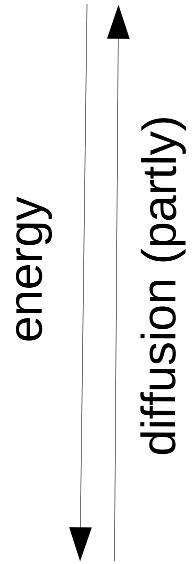
diffusion (partly) ↑

The role of transport
RMP on (10 MeV)

average poloidal displacement







REORBIT – I_{RMP} scan

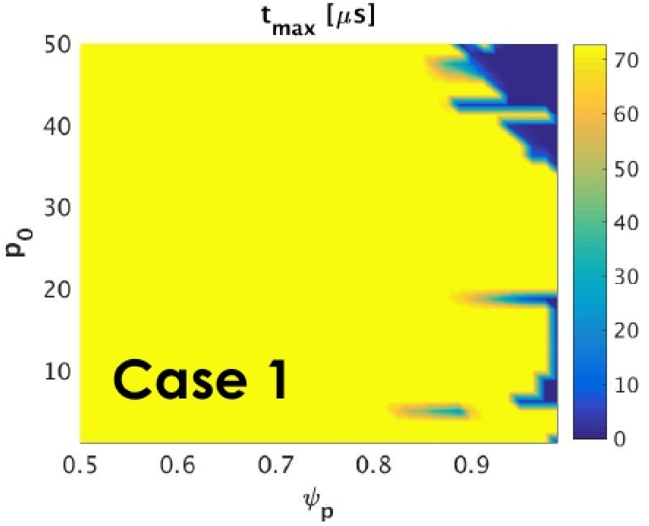
Simulations provided by REORBIT (MARS-F) for n=1 off-midplane LFS RMP **[Liu et al. 2019 NF]**

→ relativistic RE guiding center drift orbit model

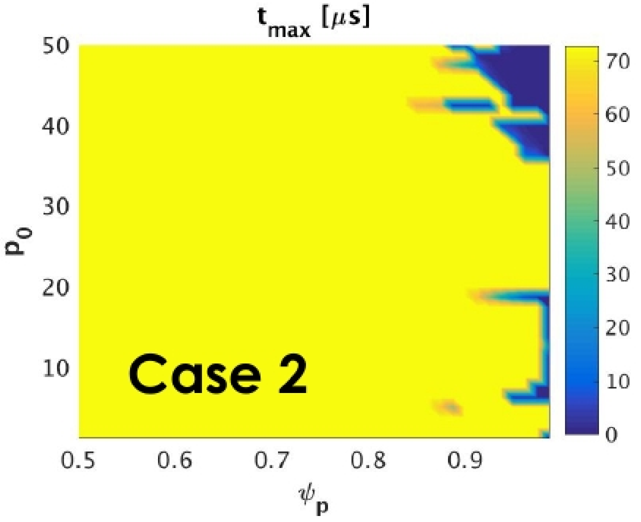
→ small angle collision with impurity nucleus & SR & Bremsstrahlung drag

I_{RMP} - 2D scan (Ψ_p x p_0) at fixed ξ = 0.1 (max. simulation time t_{max} before the particle is lost)

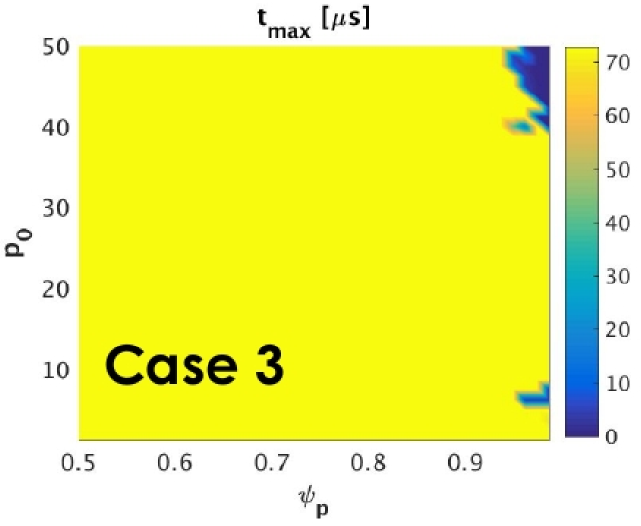
$\Delta\phi$= 270° (I_{RMP} = 3.2 kA)



$\Delta\phi$= 270° (I_{RMP} = 2.8 kA)



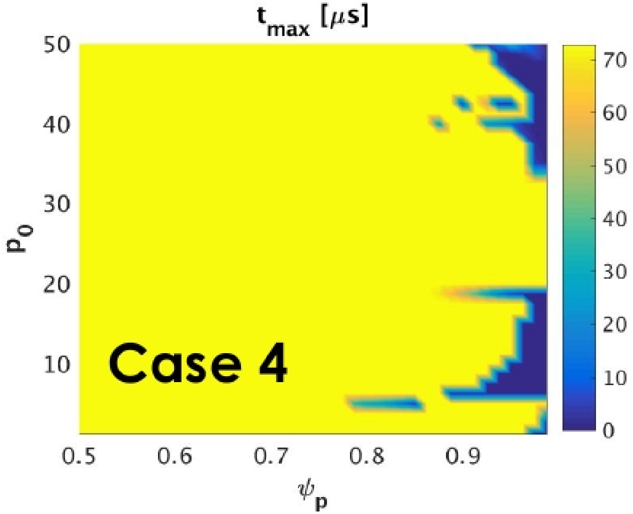
$\Delta\phi$= 270° (I_{RMP} = 1.2 kA)



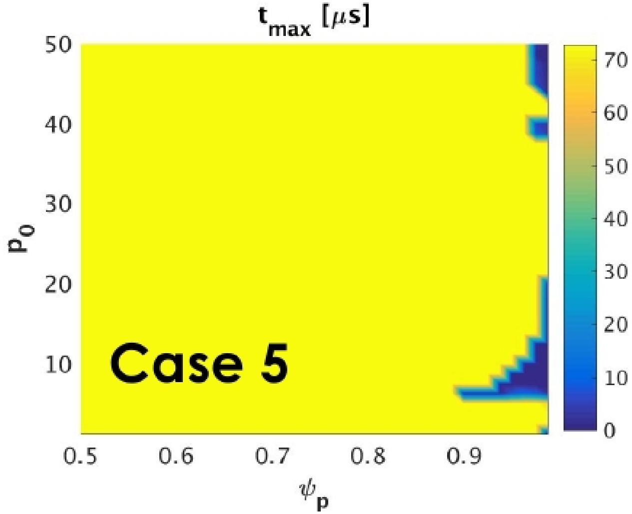
REORBIT (MARS-F) simulations [Liu et al. 2019 NF]

Δϕ - 2D scan (Ψ_p x p_0) at fixed ξ = 0.1 (max. simulation time t_{max} before the particle is lost)

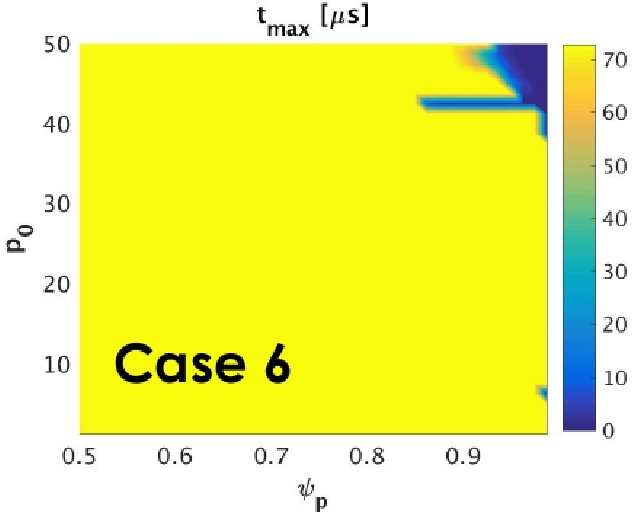
Δϕ=0° (I_{RMP} = 3.2 kA)



Δϕ= 90° (I_{RMP} = 3.2 kA)



Δϕ=180° (I_{RMP} = 3.2 kA)



Conclusions

Effect of RMPs at COMPASS

→ significant impact on RE population

- smaller CDR + τ_{RE}
- **reduction of their energy and amount**
- smaller final impact of RE on the vessel (∫HXR/dt – smaller)
- different loss regimes (dependent on I_{RMP}) – excellent for simulations and theoretical predictions testing

→ RMP influence the RE trajectories (dependent on the I_{RMP} and phase)

- **fast losses within 10 µs were detected**
- low energetic particles were lost only for the phase when the plasma response was the strongest (preferable energy range < 7 MeV)
- increase of poloidal orbit displacement (grows with I_{RMP} and $\Delta\phi$, not always with energy)
- could be a **solution for small compact machines (COMPASS-Upgrade, SPARC etc)**

Plans

→ particle simulation of the post-disruption scenarios & other phases & amplitudes & MHD modes

→ more modules (collisions / more particles / kinetic solver)