Runaway electron studies during the flattop phase in COMPASS

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Outline

- characteristics of flattop discharges with RE
- how is the MHD activity connected with RE
- preliminary estimation of RE current
- future plans and ideas for RE modelling
- new scenarios development for RE suppression

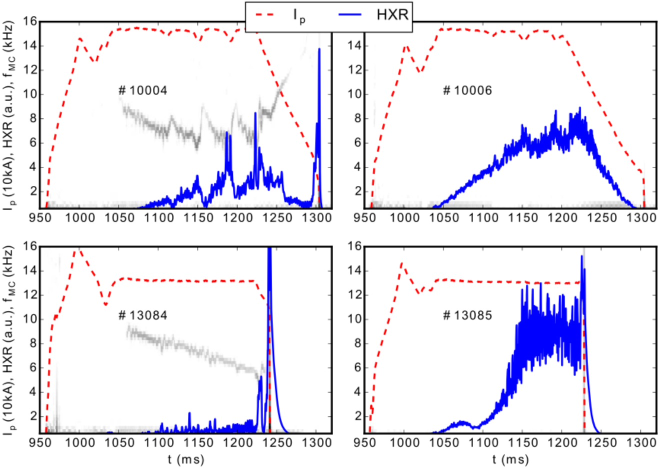
Discharges description

- circular or slightly elongated plasma (up to $\kappa \sim 1.2$)
- Ip < 150 kA, $B_T = 1.15$T
- density scan 1.5 – 4e19
- $>$10 discharges with requested loop voltage oscillations
- different types of MHD activity

RE related diagnostic

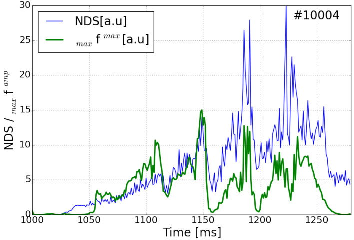
- rich set of magnetic diagnostics
- HXR diagnostics - NaI(Tl) scintillation detectors, composite scintillator ZnS(Ag)
- ^{3}H neutron detectors
- fast IR and visible camera
- Cherenkov detector, ECE, ...
- + standard diagnostics - Thomson, interferometer, ...

RE losses + MHD

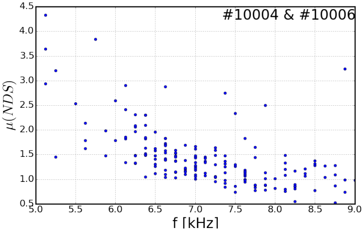


Ficker et al., Nucl. Fusion 57 (2017)

RE losses + MHD



time evolution of the frequency f of the rotation of the magnetic island-MI (green) and signal from neutron detector NDS (blue)



frequency f of the rotation of the MI versus signal from neutron detector $\mu(NDS)$

MHD + RE

- Rapid magnetic reconnection events cause large induced electric fields, capable of accelerating electrons to relativistic energies
- Conservation of magnetic helicity prevents the removal of plasma current on a short time scale
- Magnetic surfaces rapidly re-form, thus being able to trap energetic electrons inside flux tubes*

* Boozer, Allen H., Physics of Plasmas 23.8 (2016): 082514.

A model to study both the bulk plasma evolution (MHD) and the energetic electrons (gyrokinetics) is necessary:

Hybrid MHD Gyrokinetic Code (HMGC)

Originally designed to study interaction between energetic ions and toroidal Alfven modes*, it can be applied to the study of energetic electrons+

* Briguglio, S., et al., Physics of Plasmas 2.10 (1995): 3711-3723.
+ Causa, F., et al., 42nd EPS Conference on Plasma Physics, Lisbon, Portugal, ECA. Vol. 39. 2015.

Bulk plasma dynamics is solved by integrating a system of reduced-MHD equations:

$$\frac{\partial \psi}{\partial t} + \frac{cR^2}{R_0 B_0}[\phi, \psi] + \frac{c}{R_0}\frac{\partial \phi}{\partial \varphi} = \eta \frac{c^2}{4\pi}\nabla^2 \psi$$

$$\rho\left(\frac{\partial}{\partial t}\nabla^2\phi + \frac{cR^2}{R_0 B_0}[\phi, \nabla^2\phi]\right) + \nabla\rho\cdot\left(\frac{\partial}{\partial t}\nabla\phi + \frac{cR^2}{R_0 B_0}[\phi, \nabla\phi] - \frac{c\,\partial\phi}{R_0 B_0\,\partial Z}\right) = -\frac{B_0}{4\pi c}[\psi, \nabla^2\psi] - \frac{B_0}{cR_0}\nabla\cdot\left[R^2(\nabla P + \nabla\cdot\Pi_H)\wedge\nabla\varphi\right]$$

with

$$[A, B] = \nabla\varphi\cdot\nabla A\wedge\nabla B$$

Energetic particles are evolved by solving the gyrokinetic equation:

$$\frac{d\bar{R}}{dt} = \bar{U}\hat{b} + \frac{e_H}{m_H\Omega_H}\hat{b}\wedge\nabla\phi - \frac{\bar{U}}{m_H\Omega_H}\hat{b}\wedge\nabla a_{\parallel} + \left[\frac{\bar{M}}{m_H} + \frac{\bar{U}}{\Omega_H}\left(\bar{U} + \frac{a_{\parallel}}{m_H}\right)\right]\hat{b}\wedge\nabla\log B$$

$$\frac{d\bar{U}}{dt} = \frac{1}{m_H}\hat{b}\cdot\left\{\left[\frac{e_H}{\Omega_H}\left(\bar{U} + \frac{a_{\parallel}}{m_H}\right)\nabla\phi + \frac{\bar{M}}{m_H}\nabla a_{\parallel}\right]\wedge\nabla\log B + \frac{e_H}{m_H\Omega_H}\nabla a_{\parallel}\wedge\nabla\phi\right\} - \frac{\Omega_H\bar{M}}{m_H B}\hat{b}\cdot\nabla\log B$$

Self-consistency:

Energetic particle contribution to pressure (implemented):

$$\Pi_H(x) = \frac{1}{m_h^2}\int d^6\bar{Z} D_{Z_c\to\bar{Z}}\bar{F}_H(t,\bar{R},\bar{M},\bar{U})\left[\frac{\Omega_H\bar{M}}{m_H}I + \hat{b}\hat{b}\left(\bar{U}^2 - \frac{\Omega_H\bar{M}}{m_H}\right)\right]\delta(x-\bar{R})$$

Energetic particle contribution to current (to be implement):

$$J_H(x) = q_H\int d^6\bar{Z} D_{Z_c\to\bar{Z}}\bar{F}_H(t,\bar{R},\bar{M},\bar{U})\bar{U}\delta(x-\bar{R})$$

Current status and perspectives

Simulation of a given runaway population propagating in an externally imposed static magnetic perturbation:

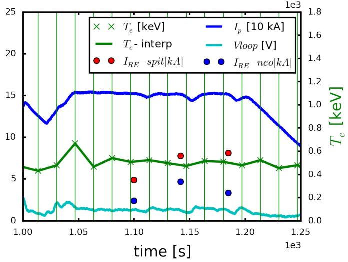
"The simulations show that in the outer region, the particle density perturbation exhibits the same poloidal and toroidal periodicity of the magnetic island, consistently with the experimentally observed correlation of enhanced RE losses and the passage of the island O-point in front of the Cherenkov probe."*

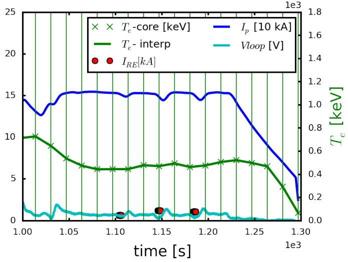
Next step: simulate the onset of a tearing mode and check if a thermal population of electrons develops an energetic tail

* Causa, F., et al., 42nd EPS Conference on Plasma Physics, Lisbon, Portugal, ECA. Vol. 39. 2015.

Basic idea

$$I_{RE} = I_p - I_\Omega = I_p - \frac{AE_{par}}{\eta} = I_p - \sigma A E_{par} \sim I_p - \mathbf{T}_e^{\frac{2}{3}} \frac{A}{2\pi R}\left(V_{loop} - L\frac{dI_p}{dt}\right)$$





E_{par} from V_{loop} + T_e, n_e as average values - **sufficient?**

METIS $\rightarrow$ from values $(E_{par}, T_e, n_e, \eta)$ to profiles

- transport code
- input data = real data + output data validated against observations
- calculate global plasma parameters such as E_{par} and plasma equilibrium

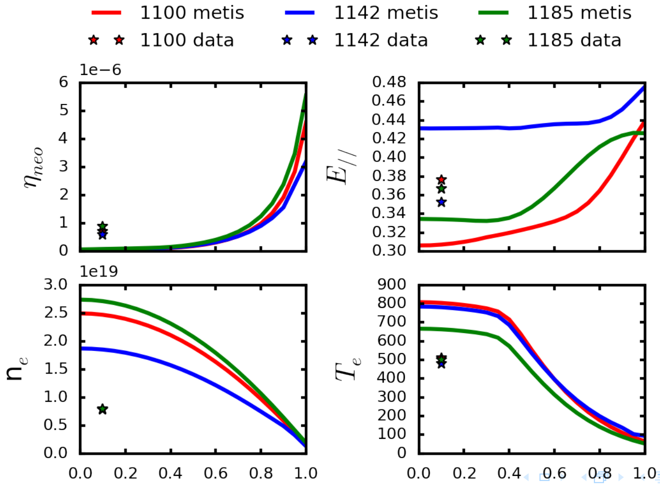
RE current

$$\frac{dI_{RE}}{dt} = (\Gamma_{RE} - \frac{1}{\tau_{conf}}) * I_{RE} + S_{RE}$$

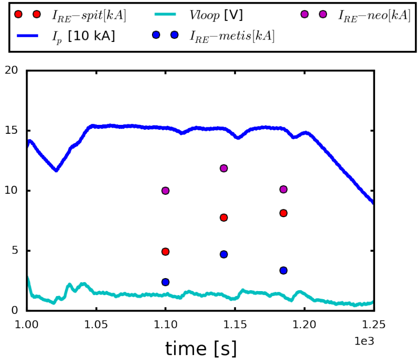
where

$$S_{RE} = e * \nu_{e,crit}(\langle n_e \rangle - \langle n_{trap} \rangle)\nu_{ee} * S_{//}$$

Profiles from METIS output



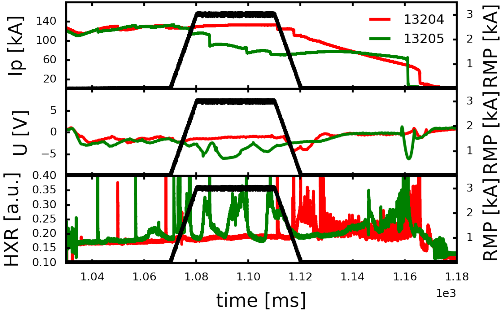
Future plans



preliminary estimation

- set of equations with - more unnown (I_{RE}, η)
- implementation of current diffusion
- parametrisation of equations
- better profiles fitting - Thomson
- estimation of losses and other influences
- implementation to METIS ?
- linking with LUKE

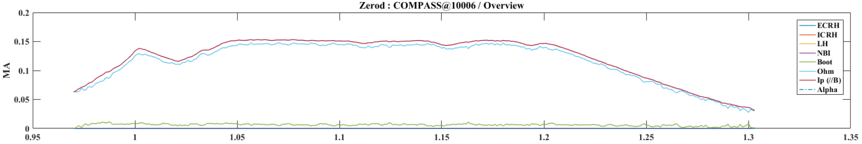
RMP+plans

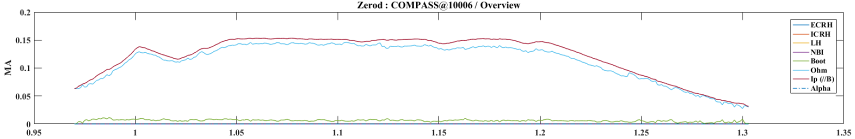


- ex vacuum vessel (close to separatrix)
- on-midplane + off-midplane LFS
- on-midplane + off-midplane HFS
- four toroidal quadrants (toroidal mode numbre n=1,2)

- single-turn coils
- independent power sources
- Imax = 5 kA per RMP coil
- current waveforms - rectangle, triangle, trapezoid
- phase scan in the next campaign

RE current -


Zerod : COMPASS@10006 / Overview
MA
ECRH
ICRH
LH
NBI
Boot
Ohm
Ip (//B)
Alpha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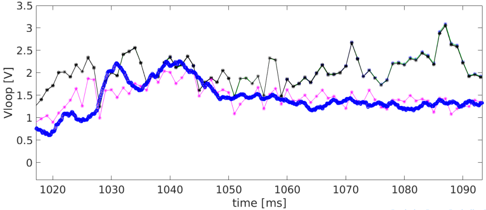
Vloop [V]
time [ms]

13202

LUKE

- n_{re} - calculated by LUKE simulation - blue line (fig. on the right)
- n_{re} - very reactive to the change of loop voltage