Dedicated runaway electrons studies at the tokamak COMPASS

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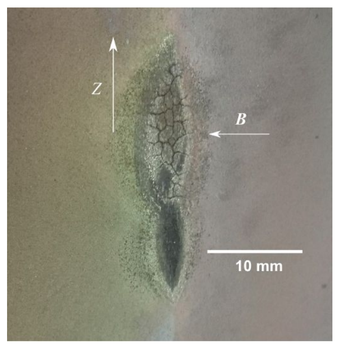
**) Panek et al, 2015 PPCF*

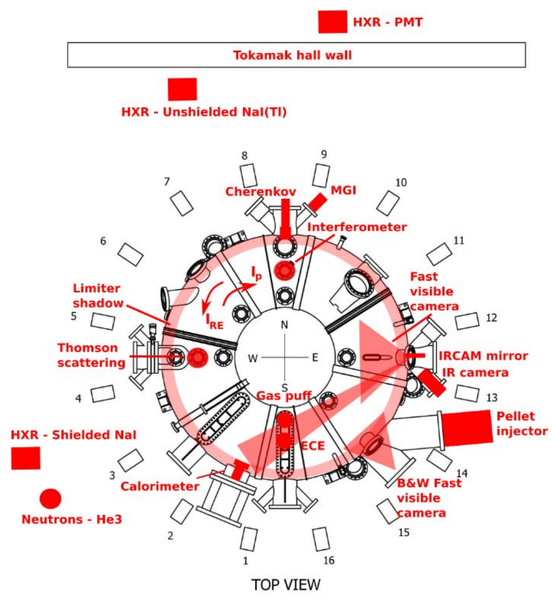
Runaway electrons (RE)

- significant role in:
  - Lightnings [Gurevich et al 1992 Phys. Lett.]
  - Solar corona & Solar wind [E Marsch, 2006 Living Rev. Sol. Phys.]
  - Sprites [Lehtinen et al. 2001, JGR]
  - Pinches [Dolgov et al. 2011, Plasma Physics Reports]
  - Tokamaks [Rosenbluth & Putvinski NF 1997 … Reux et al 2020 PRL]
- relativistic energies (non-thermal anisotropic population of fast electrons)
- serious threat for tokamaks (RE generated during break down, disruptions, current quench …) especially ITER [RE ≦ 10 MA, several tens of MeV (kinetic energy > 20 MJ) - Lehnen et al, 2015 JNM] and upcoming fusion devices



[Mlynar et al, 2019 PPCF]

COMPASS diagnostic and systems



typical experimental setup for RE dedicated campaign [Caloud, master th. 2020]

- ITER-like cross-section (1:10)
- major radius R_0=0.56m, minor radius a=0.23m
- Toroidal field B_T ≦ 1.5 T
- Plasma current in the flat-top Ip < 400kA
- average density up to 10^{20} m^{-3} (REs: 2.5x10^{19} m^{-3})
- RE research since 2014 (EUROFusion topic since 2016) - 11 dedicated campaigns (> 2000 discharges)

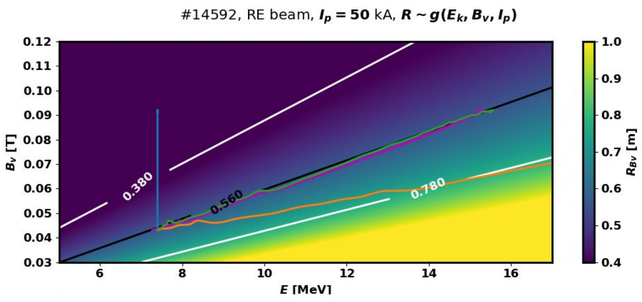
COMPASS RE relevant diagnostic and systems:

- HXR, neutron, SXR detectors [Svihra et al, 2019 FEaD, Linhart et al, 2018 IEEE]
- spectroscopy [Weinzettl et al, 2017 JoI]
- fast VIS, NIR, IR cameras [Cavalier et al, 2019 NF]
- magnetics (Internal Partial Rogowski coils (IPR) - 16 coils, 3 rings of Mirnov coils (24x3x3 coils each), EPR, flux loops, saddle coils) + external resonant magnetic perturbation (RMP) coils [Markovic et al, 2016 NF]
- V-ECE radiometer [Farnik et al, 2019 RSI]
- Cherenkov detector [Rabinski et al, 2017 JoI]
- calorimetry [Caloud, master thesis 2020]
- mitigation piezo and MGI valves (routine operation)
- solid state pellet injector (first experiments successful)

COMPASS RE activities

Control system

- additional drive off/on (+ or -)
- RE radial position feedback [Ficker et al 2019 NF] - presented by Komm on Tue at 11:05



- radial position of RE beam axis is the function of vertical field B_v and the dominant energy ⟶ inversion of B_v can bring information about the RE energy (even in cases with varying current)

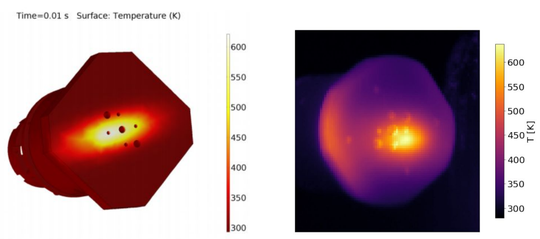
$$\langle E_k \rangle [\mathrm{MeV}] = \langle R \rangle_{pol.t.} c B_v / 10^6$$

- RE acceleration (energy increase) is based on the linear function of loop voltage

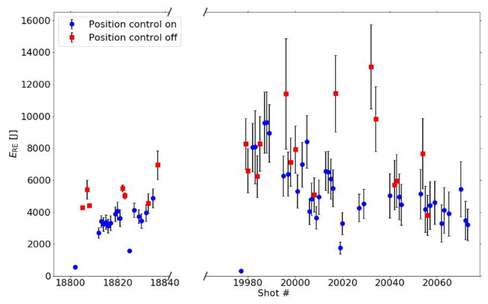
Hardware

- V-ECE radiometer [Farnik et al, 2019 RSI], SXR (medi/time pix) detectors (collaboration with CTU) [Svihra et al, 2019 FEaD, Linhart et al, 2018 IEEE], Cherenkov detector (collaboration with Poland) [Rabinski et al, 2017 JoI]
- impurity injection (gas / solid state pellet injector (collaboration with Germany) - presented by Komm on Tue at 11:05) [Mlynar et al, 2019 PPCF, Ficker et al, 2019 NF]
- fast cameras, HXR + neutron detectors etc
- upcoming synchrotron radiation and kinetic instabilities measurements (collaboration with ENEA Italy)
- calorimetry head [Caloud, master thesis 2020]
  - estimation of RE beam energy at its impact **(total energy up to 12 kJ was detected)**
  - graphite protection limiter equipped with PT100 sensors (design based on COMSOL simulations)
  - several effects studied (RE feedback, mitigation techniques, magnetic field magnitude etc)

Comparison of COMSOL simulation of heat flow vs calibrated measurements by the IR camera



Comparison of the total RE beam energy measured by the calorimeter with (blue) and w/o the radial position feedback (red). The final RE impact was lower in case of the active position feedback.

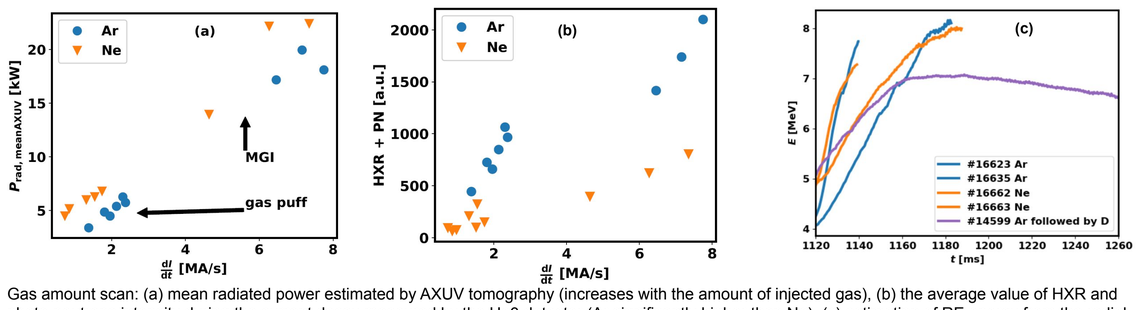


Theory and modelling + data analysis

- Full orbit particle tracer development [Cerovsky, master thesis 2018, Macusova et al EFTC 2019] - presented by Komm on Tue. at 11:05
- Analytical solution of fractional diffusion transport model [Casolari et al, 2019 EPS]
- Guiding center particle tracer ORBIT (collaboration with RFX Italy)
- Analytical solution of radiation force balance (under development)
- Kinetic Fokker-Planck simulations (LUKE) [Macusova et al 2018 EPS], (NORSE) [Vlainic et al, 2019 Atoms]
- MHD and particle tracing simulations (collaboration with GA USA) [Liu et al 2020, PoP submitted]
- Synthetic diagnostic SOFT will be applied on upcoming synchrotron radiation measurements
- Cross-machine comparison [Plyusnin et al, 2018 NF], MHD activity [Ficker et al, 2017 NF], breakdown studies etc…

Mitigation techniques studied at COMPASS

Impurity injection (high / low Z materials) [Mlynar et al, PPCF 2019, Ficker et al, NF 2019]



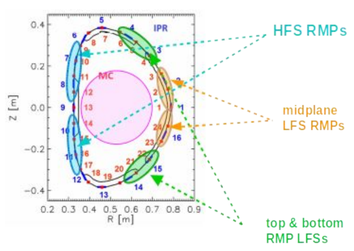
Gas amount scan: (a) mean radiated power estimated by AXUV tomography (increases with the amount of injected gas), (b) the average value of HXR and photo-neutrons intensity during the current decay measured by the He3 detector (Ar significantly higher than Ne), (c) estimation of RE energy from the radial feedback - based on the method described in Ficker et al, 2019 NF.

- **Ar causes faster current decay but large HXR fluxes and increase of average RE beam energy**
- **combination with D (second gas puff) = slower current decay, smaller HXR losses, the average RE energy doesn't increase**

Externally induced Resonant Magnetic Perturbation (RMP)

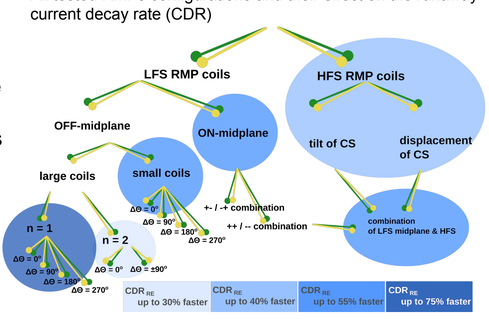
[Mlynar et al,PPCF 2019, Macusova et al, 2019 EPS, Liu et al, 2020 submitted to PoP]

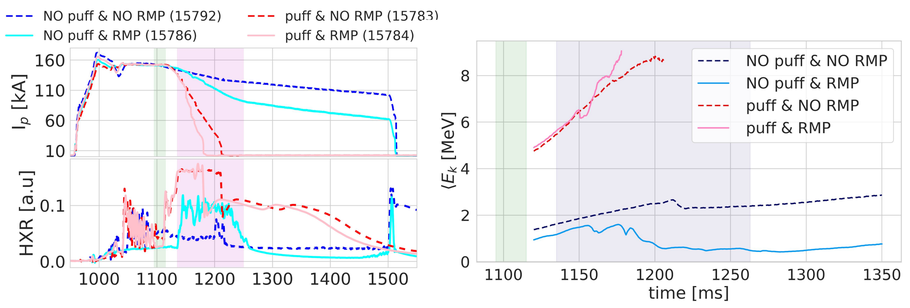
RMP coils - series of independent ex-vessel conductors = variable mode numbers of spectrum generated by RMP coils (n = 1, n = 2) and different phase shifts ΔΦ=0, 90, 180, 270 possible



- penetration time ~ 5ms
- B_{RMP}/B_T up to 10^{-2} (below the threshold for mode-locking)
- The strongest effect of RMPs on RE - ΔΦ=0 (n=1) for Ne and ΔΦ=270 (n=1) for Ar
- **RMP* + Ne ~ 20% faster CDR_{RE} than RMP* + Ar**

All tested RMPs configurations and their effect on the runaway current decay rate (CDR)

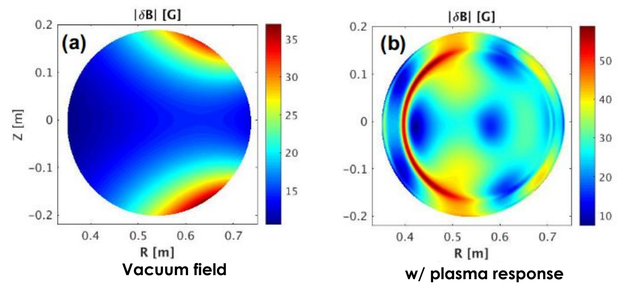




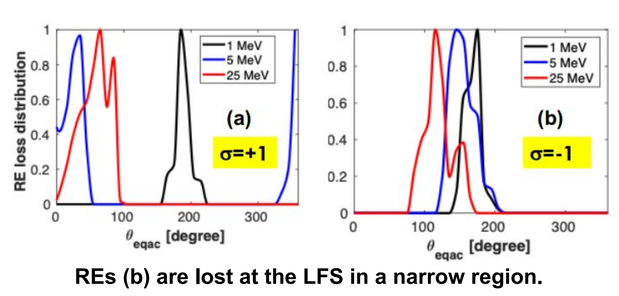
Effect of the externally induced RMP on REs in the low density discharge (blue lines - REs carry only a fraction of the current) and on pure RE beam triggered by Ar gas injection (red lines).

RMPs cause the increase of RE losses and in the case of the low density discharge also the decrease of the average energy.

Computed plasma response for the COMPASS #15752 at 1080 ms, showing (a) the amplitude of the vacuum field perturbation, (b) the amplitude of the total perturbation field including the plasma response for n=1 off-midplane ΔΦ=270 (3.5 kA) [Liu et al, 2020 PoP submitted]. MARS-F resistive MHD code [Liu et al PoP 2000] was used.



The RE loss distribution along the poloidal angle of the COMPASS limiting surface, for particles launched with initial parallel velocity being in either (a)co- or (b) counter-direction to the equilibrium plasma current. REs are launched with the initial pitch angle of λ_0= 0.1 and varying initial particle energy: 1, 5, 25 MeV. The LFS (Low field side) corresponds to 180 and HFS to 0 degrees.

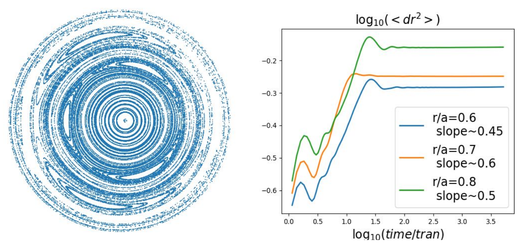


REs (b) are lost at the LFS in a narrow region.

Natural MHD activity [Casolari et al, 2019 EPS]

- Magnetic islands affect RE losses [Ficker et al, 2017 NF]
  - in some cases, they act as a barrier for REs - at the end of the discharge the rest of REs is released.
  - A coupled dynamics of REs and magnetic island can be observed in the correlation between the magnetic signals from Mirnov coils and the HXR signal.
  - A reduced transport associated with presence of MHD perturbations has been observed -> fractional transport [Spizzo et al., Nucl. Fusion 2019].
  - Simulations with ORBIT code allow to evaluate the degree of sub-diffusion (reduced diffusion)

Poincaré section in presence of magnetic perturbations (magnitude ~ 10^{-4}) and time dependence of mean-square displacement of particle orbits (ORBIT simulations). Another tool for poincaré plots was developed by Casolari et al, 2019 EPS.



Conclusions and future plans

- radial position control system for RE beam axis was developed and applied -> decrease of RE impact on PFC (plasma facing components) was detected
- dependence of the RE energy on vertical magnetic field and radial position of the beam was derived
- hardware and system tools were designed, produced and used during RE dedicated campaigns (pellet injector, calorimetry head, V-ECE, SXR detectors etc …)
- various mitigation techniques were tested:
  - secondary D puff reduces the final impact of REs on PFC (lower energy than w/o D puff)
  - the most efficient RMPs configuration was identified by MARS-F, full orbit tracer simulations and experiments
- kinetic simulations proved the importance of radial transport for small and medium size machines
- theory and modelling tools (full orbit particle tracers, fractional diffusion model etc) were or are under development
- effect of Kinetic instabilities and synchrotron radiation analysis will be performed in the last RE campaign this December

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