Analysis of RE beams in COMPASS and JET using betatron equilibrium and radiation diagnostics

O. Ficker[1,2,#], E. Macusova[1], J Cerovsky[1,2], L. Kripner [1,3], A. Dal Molin[4], S. Silburn[5],
C. Reux[6], M. Hoppe[7], C. Sommariva[8], E. Joffrin[6], G. Ghillardi[9], R. A. Tinguely[10],
J. Mlynar[1,2], E. Panontin[4], M. Nocente[4], M. Tardocchi[11], S. Jachmich[12], C. Paz-Soldan[13],
P. Vondracek[1],A. Casolari[1], M. Farnik[1,2], J. Caloud [1,2],V. Weinzettl[1], J. Cavalier[1],
J. Havlicek[1], A. Havranek[1], M. Imrisek[1,3], J. Svoboda[1,2],
M. Hron[1], the COMPASS team[a] & JET Contributors[b]

[#]ficker@ipp.cas.cz [1]IPP CAS, Prague, Czech Republic; [2]FNSPE, CTU in Prague, Prague, Czech Republic; [3]FMP, Charles university, Prague, Czech Republic; [4]Universita degli Studi di Milano-Bicocca, Milan, Italy; [5] JET, CCFE, Culham, UK; [6] IRFM, CEA, Saint-Paul-lez-Durance, France;[7]Chalmers University of Technology, Gothenburg, Sweden; [8]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland [9]ENEA, Frascatti, Italy; [10]PSFC, MIT, Cambridge, USA [11] ISTP-CNR, Milan, Italy; [12]ITER I.O., Saint-Paul-les-Durance, France; [13]Columbia University, NY, USA; [a]Author list of "M. Hron et. al 2021 'Overview of the COMPASS results' submitted to Nucl. Fusion"; [b]See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)"

Introduction

Runaway electrons (RE) still present a serious for the tokamak operation. Furthermore, the physics phenomenon itself is complicated and extrapolation to the large devices is difficult. In order to understand the RE phenomenon, it is necessary to optimise the diagnostics of the runaway electrons. Some of the properties of RE can be measured using the standard tokamak diagnostics directly (e.g. plasma or runaway current measurement by magnetic diagnostics). In some cases, it is necessary to improve the understanding of the effect of the RE on the diagnostics (e.g. electron cyclotron emission measurement by radiometer) by modelling and analytical approximations. However, often it is necessary to introduce a completely new diagnostics, that can be used specifically for RE (e.g. local loss measurement using a Cerenkov detector). In this contribution a new application of magnetic measurements for estimation of the RE energy is discussed for two European machines with extensive RE experimental program. The COMPASS tokamak[1] is a device with ITER-like plasma shape operated at the IPP of the Czech Academy of Sciences. Major radius of the machine spans $R_0 = 0.56\,\mathrm{m}$ and minor radius $a = 0.21\,\mathrm{m}$. It is operated with magnetic field $B_T = 0.9 - 1.5\,\mathrm{T}$ and the current in the runaway electron beam phase $I_p < 150\,\mathrm{kA}$. The overview of the latest RE experiments is presented at this Conference [2]. The JET tokamak is the largest tokamak device currently in full operation with $R_0 = 3\,\mathrm{m}$ and with ITER-like plasma facing component materials (Be/W). The RE experiments are typically conducted in $B_t = 3 - 3.5\,\mathrm{T}$ and with runaway electron beam currents up to 1.2 MA. In the latest RE experiments using the Shattered pellet injector (SPI) [3], very interesting results were achieved with D2 secondary injection causing increase of the RE beam current, most probably decrease of the kinetic energy and a benign termination of the RE beam triggered by the non-monotonic current profile [4].

Runaway electron equilibrium

The equilibrium of the high current RE beams was studied in high current plasma assisted modified (with toroidal field B_t added) betatrons. Later, it was also theoretically and numerically studied in the tokamak geometry by Yoshida [5]. Based on the application in the betetatron physics, the main change with respect to the tokamak equilibrium based on the poloidal mag-

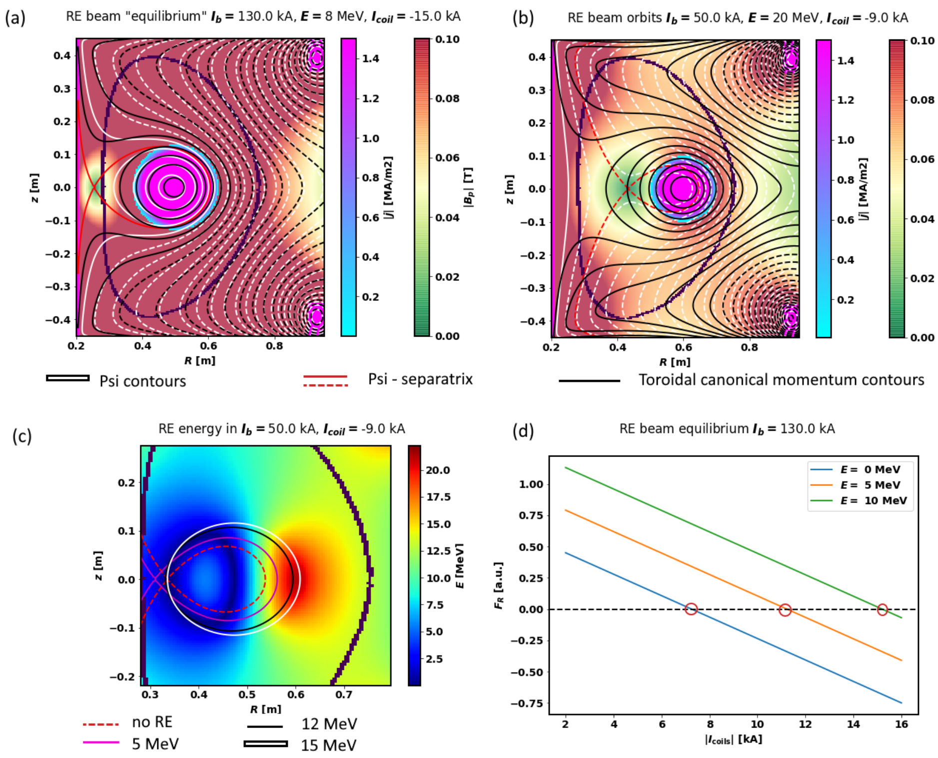

Figure 1: *COMPASS geometry: (a) Runaway electron beam with current 130 kA and energy 8 MeV in equilibrium with the magnetic field; (b) high energy fraction in the low current RE beam being limited at the LFS; (c) Map of stable energies in the* R,z *plane and separatrices for different energies; (d) Radial force acting on the mono-energetic RE beam*

netic flux Ψ, the equilibrium parameters in the RE beam are functions of toroidal canonical momentum (P_ϕ), the surfaces of constant P_ϕ are also called drift surfaces and

$$P_\phi(R,z) = \gamma m_e Rc - e\psi(R,z), \tag{1}$$

with γ being the relativistic factor, R the radius coordinate and m_e, c and e known constants. A modified version of Grad-Shafranov equation can be introduced to analyse this equilibrium, however for a quick estimate of energy with higher order effects neglected, it is possible to use 2D cyclic symmetry Biot-Savart solver in real coil geometry to simulate the equilibrium of the RE beam and the external PF coils. At COMPASS this task is relatively easy as winding that is dedicated to securing the radial equilibrium of the plasma is not connected to the winding with other purposes. The equilibrium field power supply (EFPS) and fast B_v power supplies (position stability) are actuating the radial position. The strong RE outward pressure is contributing to feedback request and may cause β_N values up to 40% when standard EFIT reconstruction is used. The effect is so strong that standard position control feedback scheme was not able to sustain the required position in case of decreasing current and increasing energy. This was solved by weakening the dependence of the control algorithm on the current, this special setup is appropriate only for the RE beam phase. In figure 1 some properties of quasi-equilibria of some combinations of RE beam current, currents in the coils and RE beam energy are shown together with a (R,z) map of optimal energies that would be sustained in given vertical magnetic field in case of no poloidal motion (external + from beam current) and Ψ or P_Φ "separatrix", which contains a HFS X-point in the vessel for low energy components and the companion plasma. The last plot shows the total radial force acting on the RE beam of given current and energy with different equilibrium coil currents.

Estimate of energy in COMPASS experiments

The experimental estimates of energy in a small device can be based on two methods using the magnetic configuration data: Method 1 - using the EFIT β_N that gives a pressure related to I_p, B_t and a: $E_\beta[\mathrm{MeV}] = 3.75\beta_N a B_t$; Method 2 - Simple inversion of radial control equation [6] $E_{FB}[\mathrm{MeV}] = RcB_v^{an}/10^6$, where B_v^{an} is the vertical magnetic field that is needed for radial stability on top of the value necessary for sustaining the plasma of the given current. The first method gives an estimate of the energy for which the beam is in equilibrium with the external vertical field, while the second gives a more dynamically evolving estimate that corresponds to the maximum energy that can be confined by the B_v^{an} only. Comparison of the two methods is given in figure 2. The RE beam in #21286 was triggered by Ne gas puf and further accelerated by fixed Ohmic current drive. The envelope as well as log-average of the HXR-derived energy spectra is rising in agreement with the derived quantities. In the Ar injection triggered discharge #21107, the synchrotron radiation power in the near IR region also follows the derived energy quantities. In figure 3 the comparison of energy estimate evolution in different gases is shown, the most important conclusion is that the D2 injection can stop the rise of energy, while the decay of current still continues though it is slowed down.

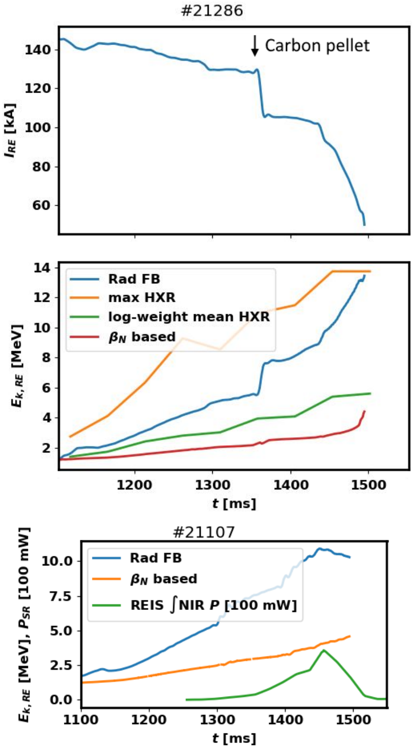

Figure 2: *COMPASS: Comparison of evolution of quantities related to RE beam energy for the discharges with additional acceleration #21286 (Ne + C pellet) and #21107 (Ar)*

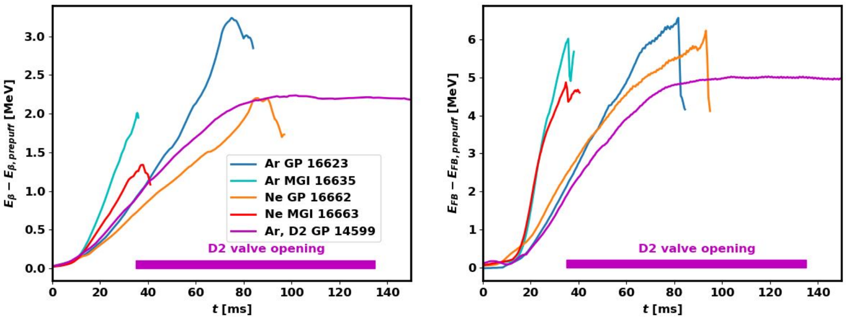

Figure 3: *COMPASS data; Left: Evolution of energy based on the EFIT βN for two MGI triggered RE beams, two beams created by the low impurity injection amount and one with secondary deuterium injection, right estimate based on radial position feedback for the same discharges.*

Estimates of energy for JET

Method 1 was used applied to JET, which is characterised by larger minor and major radius of the beams as well as larger B_t and I_{beam}. The energy evolution derived from magnetic diagnostics can be compared with the inversion of HXR data [11] that gives an estimate of the runway electron distribution function. The JET RE experiments with SPI mitigation have brought interesting results [3], [10]. Three different cases are studied in figure 4. These are based on Ar

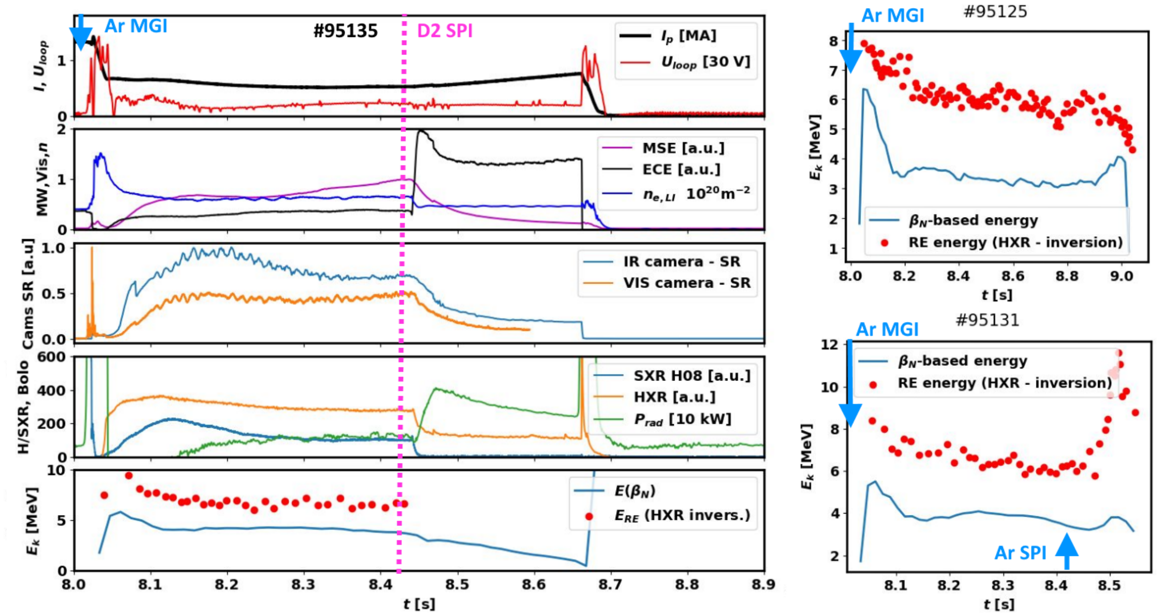

Figure 4: *JET: Comparison of average kinetic energy derived from β_N and HXR inversion, top - RE beam triggered by Ar MGI, bottom similar pulse with secondary Ar SPI.*

massive gas injection RE scenario: Ohmic plasma $I_p = 1.5\,\mathrm{MA}$, $B_t = 3.0\,\mathrm{T}$, $n_{e,li} = 4\cdot 10^{19}\,\mathrm{m}^{-2}$. In all of them the energy based on the HXRs seems to be the highest just after disruption and decreasing afterwards. In the discharge #95135 secondary D_2 (effect also further studied in [10]) SPI caused a significant changes in most of the signals: the I_p rises, HXR counts are no longer sufficient for application of the inversion method, the cameras observing the synchrotron radiation show a significant decrease of the intensity and the estimate of energy based on the β_N also gradually drops. On the other hand, injection of the secondary SPI into the RE beam causes a significant increase of energy based on the HXR emission and a small bump in the time evolution of the β_N estimate as well. It can be concluded, that low Z injection is definitely promising mitigation scenario and deserves further study.

Conclusions

An average RE energy estimate based on the equilibrium of the RE beam with the external field can be a quick and useful alternative to the more complicated methods based on the measurement of the HXR or synchrotron radiation and subsequent inversion problem solution or forward fitting of a complicated multi-parameter problem. A first comparison of the results of the method with estimates based on HXR and evolution of the synchrotron radiation intensity was done for COMPASS and JET and agreement of the main trends was confirmed. The method can support the evaluation of the different RE beam mitigation methods together with all other available diagnostics.

Acknowledgement. This work has been supported by MEYS project LM2018117 and carried out within the framework of the EUROfusion Consortium. It has also received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 with the Co-fund by MEYS project number 8D15001. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS19/180/OHK4/3T/14.

References

[1] Panek R. *et al.* 2016 *Plas. Phys. Contr. Fusion* **58** 014015
[2] Macusova, E. et al. 2021 *EPS Conf. Plas. Phys.* **I2.106**
[3] Reux, C. et al. 2021 *EPS Conf. Plas. Phys.* **I3.103**
[4] Reux, C. et al. 2021 *Phys. Rev. Lett.* **126**, 175001
[5] Yoshida, Z., 1990 *Nucl. Fusion* **30** 317
[6] Ficker, O. et al. 2019 *Nucl. Fusion* **59** (9) 096036
[7] Cerovsky, J. et al. 2021 *to be submitted to JINST*
[8] Hoppe, M. et al. 2018 *Nucl. Fusion* **58**, 026032
[9] Causa, F. et al. 2019 *Rev. Sci. Inst.* **90** 073501
[10] Sommariva, C. et al. 2021 EPS Conf. Plas. Phys. **P1.1041**
[11] Nocente, M. et al. 2017 *Nucl. Fusion* **57** 076016