Simulation of trajectories of runaway electrons for support diagnostics at the COMPASS tokamak

J. Cerovsky[1,2], O. Ficker[1,2], J. Mlynar[1], J. Urban[1], E. Macusova[1], V. Weinzettel[1], M. Farnik[1,2], J. Zebrowski[3], M. Rabinski[3], M. J. Sadowski[3], R. Panek[1], M. Hron[1] and the COMPASS team

[1] *Institute of Plasma Physics of the CAS, Prague, Czech Republic*

[2] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*

[3] *National Centre for Nuclear Research (NBJC), Otwock-Swierk, Poland*

Runaway electrons (RE) represent a significant threat to future fusion facilities and it makes from them object of interest in the current fusion research. The runaway electrons are high energetic particles, which are created in tokamak especially during low density discharges or after plasma disruptions. In the last years the runaway electrons are extensively investigated at the COMPASS tokamak [1]. Due to size of COMPASS tokamak and its ITER-like plasma shape the majority of experiments are dedicated to physics of the plasma edge but it shows, that COMPASS is capable also provide valuable information about physics of runaway electrons.

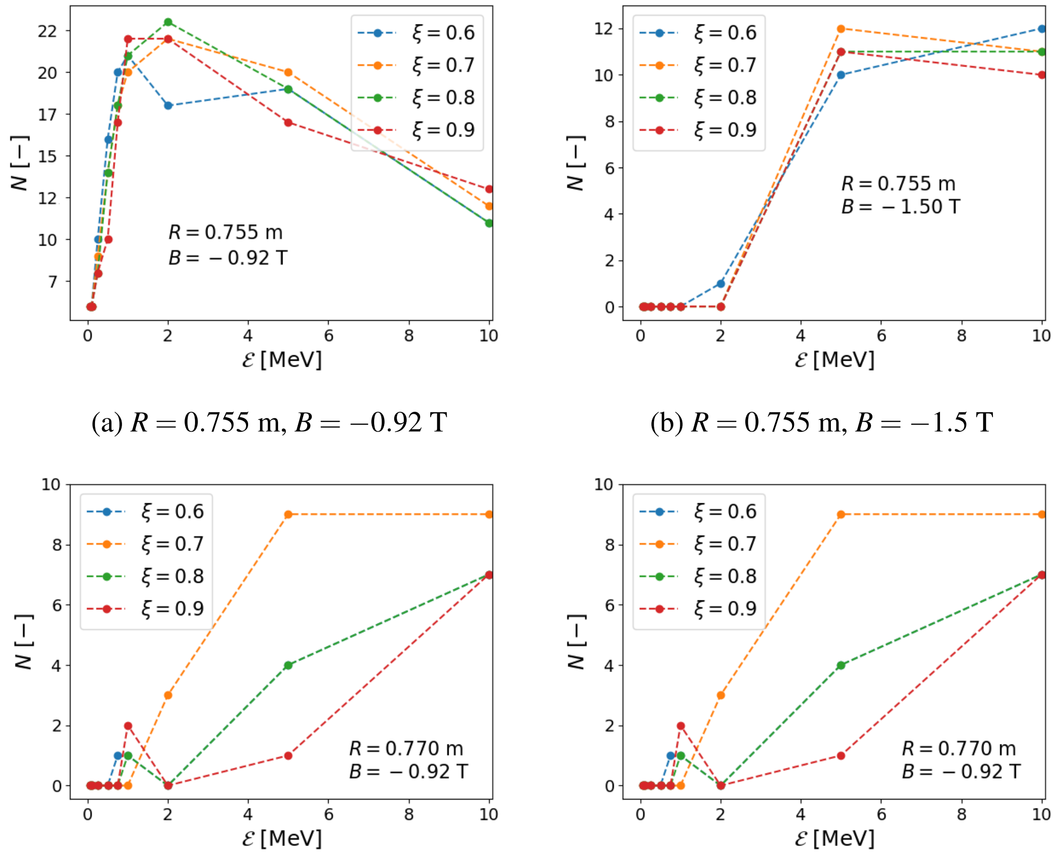
For runaway electrons research the COMPASS tokamak is equipped by scintillation detectors for detection of HXR and neutrons. Additionally, two ^{3}He detectors are used for monitoring the number of neutrons. The fast cameras observing the plasma provide valuable information especially during the MGI (Massive Gas Injection) experiments. MHD activity of the plasma, which can affects the loses of runaway electrons, is monitored by extensive number of coils. Another two relatively new diagnostics tools are installed during runaway electron experiments: V-ECE and the Cherenkov detector [2].

The Cherenkov detector is a unique diagnostic tool, which does not rely on a detection of secondary x-ray radiation caused by a runaway electron interaction with the wall. The Cherenkov-type detector is capable of a direct observation of in-flight runaway electrons escaping from the plasma. In the moment when enough energetic electron penetrates though the crystal of the Cherenkov detector (radiator), electron emits radiation, then the emitted radiation is transmitted by optic fibers into a photomultiplier. Each radiator is covered by a light proof layer made from Al/Ti/Au and an additional energy threshold can be set by layer from Mo.

The Cherenkov detector is on COMPASS always situated in the horizontal port on the mid-plane at LFS. The detector is mounted on a movable support and thus can be placed on a particular radial position. From safety reasons the Cherenkov detector is operated exclusively in the shadow of the LFS protection limiter. During the runaway electron experiments the three channel Cherenkov type detector is usually used. The energy threshold of each channel is 58 keV (without covering layer of Mo), 145 keV (35 μm of Mo), 221 keV (70 μm), respectively. The Cherenkov detector is one of few diagnostics, which are capable to detect in-flight runaway electrons, but in spite this unique feature the detector suffers from difficult interpretation of recorded signals. The recorded signals from all channels of the Cherenkov detector show almost identical behavior in most discharges. However, it is very valuable especially during the Argon induced disruptions.

For a better interpretation of experimental data from the Cherenkov detector the full orbit particle tracker was implemented in Python. For acceleration of the calculation the module Numba is used. This module also enables computing on GPU cards, which would again increase performance of the algorithm. For the right description of dynamics of runaway electrons the relativistic integrators were implemented (relativistic version of Boris algorithm, VPA [3], ...) and a conservation of integrals of motion in axisymetric magnetic field of the tokamak was verified. The main motivation for implementation of the algorithm was a determination of parameters of potentially detectable runaway electrons by the Cherenkov detector. For this purpose the simplified model of escaping RE from the plasma volume was developed. At the beginning of the simulation the particles were initialized in the vicinity of the last closed magnetic surface but outside the plasma volume, then the particles were tracked until reaching the solid surface or until the end time of simulation. Then the trajectories of particles were checked whether they intersect the location of the measuring head of the Cherenkov detector. For each simulation run the same number of particles were initialized with the same energies $\mathscr{E}$ and same pitch $\xi = \frac{v_{\parallel}}{v}$ and an analysis of results was done afterwards. It has to be noted, that used simplifications can be a source of errors and have to be considered during the drawing of conclusions from the model.

Firstly, influence of the orientation of the toroidal magnetic field was studied and no significant effect on the detection efficiency was observed, but the from the simulation it can be concluded that only high energetic electrons (with MeV energies) were capable to reach the Cherenkov detector. This observation could explain the same behavior of all three channels of the Cherenkov detector because the runaway electrons with energies above 1 MeV can be detected by all of them, because their energy thresholds are much lower. Secondly, influence of the magnitude of the toroidal magnetic field was also studied. In this case, the effect of the change topology of the magnetic field on RE detection was clearly visible. The results of the simulations are shown in the Fig. 1. Again it is clearly visible that majority of detectable particles has MeV energies but the number of detectable particles is greater for a lower magnetic field (−0.92 T). From the figures it can be seen that with the decreasing radial position of the detector the number of detectable particles increases. It is in agreement with the experimental observations. Due to the fact that the simulation program uses for a reconstruction of the magnetic field the EFIT code, it is not possible to study with a help of the developed simulation code the situations, where the Cherenkov detector provides valuable information about runaway electron dynamics - induced Argon disruptions.



(a) $R = 0.755$ m, $B = -0.92$ T

(b) $R = 0.755$ m, $B = -1.5$ T

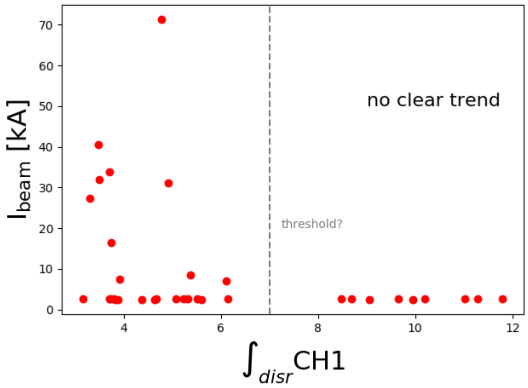
(c) $R = 0.770$ m, $B = -0.92$ T

(d) $R = 0.770$ m, $B = -1.5$ T

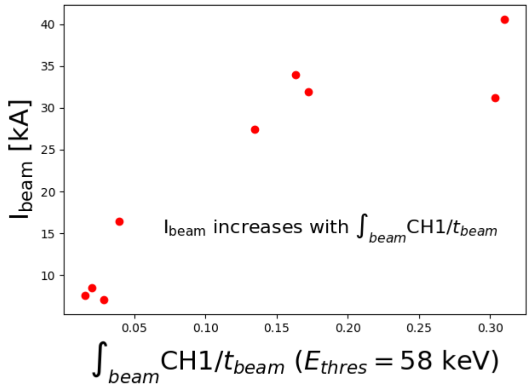
Figure 1: The dependence the number of detectable runaway electrons by the Cherenkov detector on their energy $\mathscr{E}$ is shown for the different radial positions R of the Cherenkov detector and various pitch ξ of the runaway electrons.

The Cherenkov detector proves its usefulness particularly in Argon induced disruption. At the moment of the disruption only the first channel of the Cherenkov detector records the burst of radiation. In the RE beam phase the signals from all channels of the Cherenkov detector behave similarly and increase with the decreasing plasma current, which is in this phase carried purely by the runaway electrons. These observations suggest that during this kind of disruptions only RE with energies lower than 109 keV are lost. In the RE beam phase the RE escape from the plasma with higher energies and thus can be detected by all channel of the Cherenkov detector.

In the Fig. 2 dependence of the current carried after disruption by RE on the integral value of the signal from the first channel of the Cherenkov detector from different stages of the induced disruptions is shown. In Fig. 2a it can be seen that the RE beam was created only for smaller values of the integral values. This observation suggests, that RE beam can be created only if sufficient amount of runaway electrons survives the disruption and is confined. Oppositely, in Fig. 2b the dependence of I_{beam} on the mean value of the signal from the first channel of the Cherenkov detector during the RE beam phase is displayed. It is clearly seen that the current carried by the RE after the disruption I_{beam} increases with the mean value of the signal from the first channel of the Cherenkov detector.



(a) During the disruption.



(b) During the RE beam phase.

Figure 2: Dependence of the current carried by the runaway electrons after the disruption I_{beam} on the integral value of the signal from the first channel of the Cherenkov detector $\int$CH1 recorded in different phases of the discharges.

Acknowledgement. The work has been supported by the grant GA18-02482S of the Czech Science Foundation. This work has been supported by MEYS projects LG14002 and LM2015045 and carried out within the framework of the EUROfusion Consortium. It has also received funding from the Euratom research and training programme 2014-2018 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. SGS17/138/OHK4/2T/14.

References

[1] Panek, R., et al. Plasma Phys. Control. Fusion 2016 **58** 014015.
[2] Jakubowski, L., et. al. Czech. J. Phys. 2016 **56** B98-B103
[3] Zhang, Ruili, et. al. Phys. of Pl. 2015 **22.4** 044501.