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Losses of runaway electrons in MHD-active plasmas of the COMPASS tokamak

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Abstract. Significant role of MHD effects in mitigation and losses of Runaway Electrons (RE) was documented in dedicated experimental studies of RE at the COMPASS tokamak. The MHD activity analyses were based on data from the extensive magnetic diagnostic system of COMPASS, while the RE losses were monitored by the hard X-ray (HXR) scintillation detectors. RE in COMPASS are normally produced in the current ramp-up phase due to the increased toroidal electric field. Role of this RE seed on subsequent RE population proved significant. The contribution is focused on studies of periodic oscillations in the HXR intensity. We show that frequencies of the oscillations are clearly coherent with magnetic data oscillations in the presence of tearing modes. Second, a strong relation between the HXR intensity oscillations and the coil current noise due to the COMPASS power supply (the flywheel generator frequency) is documented. This observation is complemented by measurements of heat flux oscillations on the limiter provided by fast infrared camera in the case of high level of RE population.

1. Introduction

Control and/or mitigation of Runaway Electrons (RE) present one of the key tasks for experimental work of present tokamaks in support of the ITER programme. Indeed, estimations from codes predict RE with several tens of MeV to carry up to 70% of pre-disruptive plasma current [1]. As deposition of RE beam can be highly localised, it could severely damage plasma facing components and blanket modules of ITER.

Following recent experiments and modelling efforts it appears that one of the key elements on the way to the safe operation of ITER relies on better understanding of the link between the complex dynamics of evolution of magnetic surfaces during the disruption and the RE confinement and losses [2]. However a detailed study of the evolution of the magnetic configuration during the disruption is very difficult due to timescales and significant loads on most diagnostics that can lead to saturation or degradation of their signals. The equilibrium reconstruction is also ruled out for a fast discharge termination. In this respect, it is crucial to understand the response of RE to magnetic perturbations under the controlled conditions, i.e. in the flat-top phase of the discharge and then move forward to the disruptions in co-ordination with the magnetohydrodynamic (MHD) modeling (e.g. JOREK [3]).

The COMPASS tokamak [4][5] is a medium-size experimental fusion device with ITER-like plasma cross-section, major radius $R_0 = 0.56$ m and minor radius $a = 0.23$ m. The typical toroidal field is $B_T = 1.2$ T and plasma current in the flat-top phase $I_p > 100$ kA. The COMPASS plasmas can be operated in both limiter and divertor configuration, the latter allowing for routine H-mode operation [4]. Neutral beam heating at 40 keV can inject up to 600 kW of additional power. Population of RE is observed at densities $n_e < 4.10^{19}$ m^{-3}, with a strong dependence on gas fuelling scenario and plasma shape [6]. The experiments are normally run in deuterium, the typical pulse length is about 0.4s, although the low current circular discharge with high fraction of RE can last up to 1s. The disruptive scenario with RE beam generation was achieved in COMPASS [7] and it is further studied.

The COMPASS tokamak features a rich magnetic diagnostics, allowing for a rather detailed measurements of both poloidal and toroidal characteristics of plasma MHD activities, in particular, the magnetic islands. It consists of three poloidal arrays of Mirnov (pick-up) coils (MC) at different toroidal positions covering all three components of magnetic field (r,θ,φ) by 24 coils each (i.e. 3x3x24 coils in total). Furthermore, 16 Internal Partial Rogowski coils (IPR) covering poloidal cross section (measuring plasma current when summed up), several flux loops and extensive number of saddle coils may be used in the study of magnetic configuration and perturbations. For the analysis reported further in this paper, namely outer midplane (OMP) coils of all arrays are used. Main diagnostics used for the RE studies present a NaI(Tl) scintillation detector with photomultiplier for hard X-ray (HXR) measurements and a ZnS(Ag) scintillation detector embedded in a plastic matrix with photomultiplier, shielded with 10 cm of lead. Although the latter detector features an enhanced sensitivity to photoneutrons, the experience at COMPASS tokamak demonstrated that the relative intensity of HXR is high enough to overrun the neutron signal and make the main component of the ZnS(Ag) data. Therefore, it will be referred to as the Shielded HXR detector, sensitive to HXR energies of approx. 500 keV and above. The NaI(Tl) scintillation detector is not shielded so that the energy range of its sensitivity starts approximately at 50 keV. Due to high HXR signal during RE experiments this detector typically works in the current mode operation. The approximate distance of both detectors from the tokamak main axis is 4 m, for their location see FIG. 1. The density was monitored and the feedback was carried out by the standard 2mm interferometer. In the last campaign the Fast IR camera Telops FAST-IR 2K placed on tangential port at the outer midplane (OMP) in the direct view of the OMP protection limiter (made of graphite) was used for study of first wall heat loading due to the RE losses. Camera was run with framerates up to 30 kHz with a pixel resolution ~1 mm/pixel.

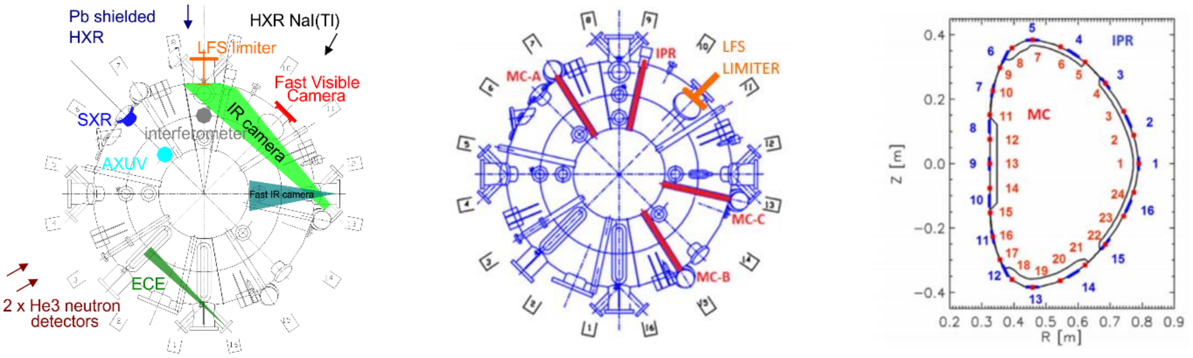

FIG. 1. Left: The most recent layout of the RE diagnostics, center: Toroidal positions of the MHD coil arrays, limiter position corresponding to section 3.1, right: poloidal distribution of MC and IPR coils.

2. RE generation control by the density and timing of the initial puff

The following studies were possible namely due to the experience with the control of the RE generation achieved in the previous COMPASS campaigns. The RE seed generated in the plasma current ramp up phase proves to be well controlled by the plasma fuelling in the initial 15 ms of the discharge. Without the RE seed, the RE generation in the current flat-top phase appears only at very low plasma densities, approximately at 1.10^{19} m^{-3}. Once the RE seed is present, the RE confinement is much better in the divertor configuration and in the elongated limited plasma compared to the circular limited plasma [6]. Indeed, in the limiter configuration it is sufficient to increase the density to 3.10^{19} m^{-3} to initiate relatively fast decay of RE population.

3. Results

The main results are presented in two sections. The first section is focused on studies of RE losses due to magnetic islands. In the second section, two different phenomena connected to characteristic oscillations of the power sources are described.

3.1 RE losses and the tearing modes

Magnetic islands appear often in COMPASS discharges, depending on the safety factor profile q(r). They were studied systematically from various points at COMPASS, see [8]. This section is focused on the RE discharges with densities $n_e = 1\text{-}3.10^{19}$ m^{-3} and a rather high loop voltage (i.e. where RE are present while carrying just a small fraction of plasma current). In these discharges, interaction of RE with the background plasma may be studied. Observation of oscillations in the HXR signal intensity with frequencies similar to the Mirnov oscillations in the magnetic data (corresponding to mg. islands in rotating plasmas) was first reported in [8]. The interplay between HXR data and magnetic data was later confirmed in dedicated COMPASS RE campaigns in all discharges with a measurable population of RE and with Mirnov oscillations of a sufficient amplitude. From the measurements it can be concluded that the magnetic islands influence confinement of RE at the plasma edge. Indeed, the coherence diagram in FIG. 2 shows that the HXR oscillations follow the frequency changes of the island rotation achieved by small steps in the plasma current waveform. The discharge displayed in this figure made part of a plasma elongation scan which also demonstrated a clear decrease of the intensity of the RE losses when no magnetic islands were present.

In order to investigate whether it is the O-point or the X-point of the magnetic island that leads to the enhanced RE losses – in simplified terms, whether the HXR intensity is in phase or in counter phase to the Mirnov oscillations – a method was developed using the available data, i.e. the non-localised HXR measurements and the rich and localised magnetic diagnostics. In near future these measurements shall be complemented with localised measurements of the Cherenkov detector [9] to analyse this phenomenon in detail and similarly to FTU [10]. The present method is based on the assumption that most of the RE are lost to the OMP protection limiter and correspond to the n=1 islands although it might be modified for higher toroidal mode numbers. From the analysis of the phase shifts between the integrated signals of the OMP coils of the 4 poloidal arrays (as displayed in FIG. 1) and the HXR NaI(Tl) detector data it can be concluded that the enhanced RE losses correspond to the O point of the magnetic islands. An example of the time evolution of the correlation delays due to the phase shifts is shown in FIG 3. However, this technique is not fully reproducible for all COMPASS discharges due to multiple reasons, including a significant presence of higher toroidal mode component, saturation in the

HXR data and also a limited validity of the key assumption that the HXR intensity oscillations originate in the OMP limiter. A significant damage from the RE was also observed on the HFS.

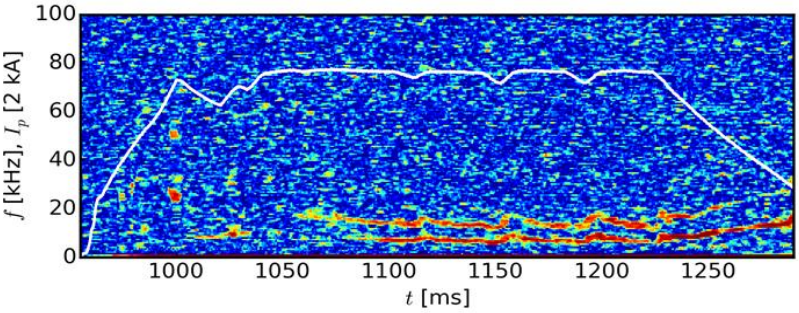

FIG. 2. A coherence diagram of the Mirnov coil signal and the signal of the HXR detector together with the time evolution of the plasma current, discharge #10004. The magnetic island rotation and accordingly modulated HXR signal is clearly visible at approx. 8 kHz and at the second harmonic.

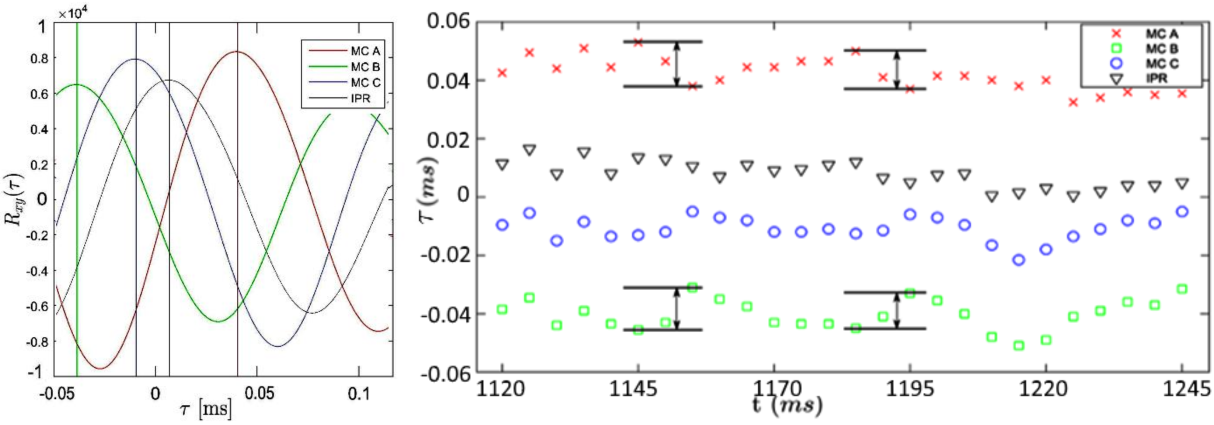

FIG. 3. Left: example of delays derived from correlation analysis between the reference HXR data and data from magnetic coils located at four different toroidal positions (FIG. 1). Right: time evolution of the delays, demonstrating that RE losses culminate when a field perturbation passes the OMP limiter.

3.2 Effects of poloidal magnetic field PS oscillations on the RE losses

The main power supplies (PS) of the COMPASS tokamak consists of two flywheel (FW) generators and a set of thyristor AC/DC convertors [5], [11]. For the experiments presented here only one FW was used with stored energy up to 45 MJ. The FW typically rotates at 1400 RPMs at the beginning of the discharge, the rotation frequency decreases approximately by 100-200 RPMs towards the end of the discharge. The poloidal field PS use 12-pulse convertors while the toroidal field PS use 24-pulse converters. Due to these technical constraints, the current in the poloidal field windings - and therefore the loop voltage, the equilibrium and the shaping poloidal field - exhibit an oscillating component with typical frequency approx. 840 Hz (double in the case of the toroidal field). The effect of these PS oscillations on the COMPASS plasma is in general negligible, however it becomes very important in case of sensitive phenomena like the RE losses. In particular, small oscillations in the radial position in the order of several mm with frequency approximately 400 Hz appear due to the reaction of the real-time position control (the COMPASS PID controller) to the above mentioned PS oscillations. These oscillations of plasma position modify the losses of RE namely in discharges with large RE. Modulation of the losses by radial position was recently confirmed in the fast IR camera data that correspond to heat flux on the OMP protection limiter [12], see FIG 4. The figure also indicates that the increasing heat flux comes primarily from the growing RE population.

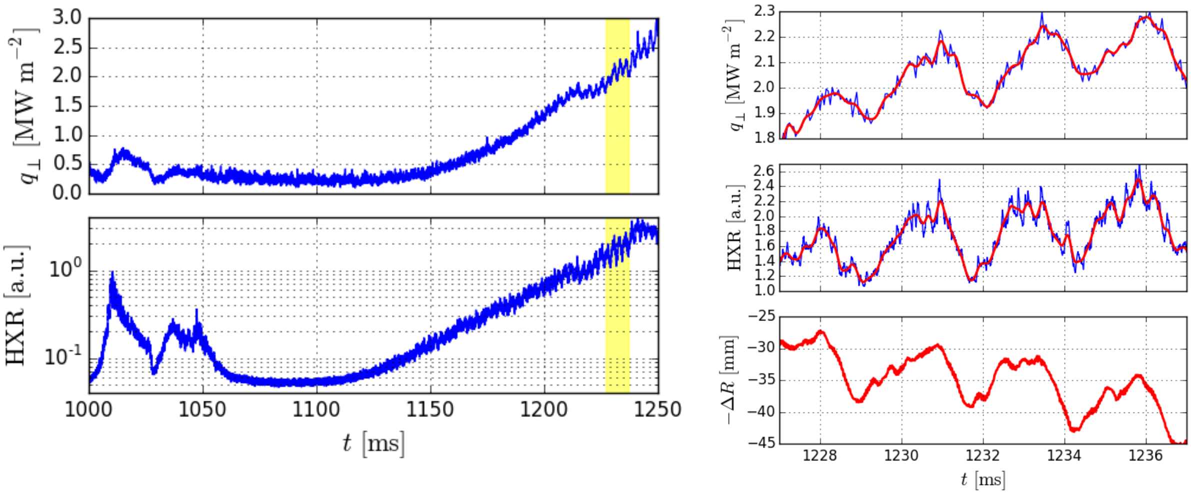

FIG. 4. Left: Time evolution of the heat flux measured by fast IR camera and the HXR signal from low density discharge with strong RE generation. Right: The detail of the highlighted region including the oscillation of the radial positon of the magnetic axis.

However, radial plasma oscillations do not present the only occurrence of an interplay between RE losses and PS oscillations. Interestingly, in case of smaller RE population (e.g. in the current flat-top of the discharges where RE were seeded during the plasma breakdown), very well pronounced periodic peaks (with a frequency close to 1 kHz) were observed in the signals of all HXR detectors. In order to determine whether this phenomena was connected to the power source oscillations, the initial frequency of FW was changed in a series of almost identical discharges. Resulting comparison of a pair of representative discharges is presented in FIG. 5. Indeed, the results demonstrate that the change in the FW rotation frequency (which drives the oscillations of the loop voltage signal) is directly proportional to the change of the frequency of the HXR intensity peaks.

This presents a very robust result, however it was also clearly observed that in different discharge scenarios with the same FW speed the frequency of the HXR periodic peaks achieved different values. Therefore, 14 relevant discharges were systematically analysed in order to determine the key parameters behind this phenomenon. Although it often proved difficult to identify the correct HXR oscillation in the discharge, namely when it was overwhelmed by signal of stronger periodic losses of RE (magnetic islands, sawtooth instability, position oscillations, etc.), it has been found that the frequency of the losses indicate significant dependence on the value of the edge safety factor q_{95}: the lower the q_{95}, the higher the frequency of the HXR peaks. The left part of FIG. 6 shows the ratio of the HXR and the loop voltage oscillation frequencies as a function of q_{95}. Interestingly, a weak magnetic structure (perhaps a small magnetic island) at 8-12 kHz can be usually observed in the spectrogram of the OMP IPR coil in this type of the RE losses (see the right part of the FIG.6).

The results in FIG. 6 help to interpret nature of the phenomenon. One of the possible explanation is based on a superposition of current oscillations in the poloidal and toroidal magnetic field coils. As the field line helicity on the low field side (LFS) becomes significantly higher for lower q values, the perturbing effect of the toroidal field (faster oscillations due to the thyristor setup) gets more important while for higher q values the effect of the oscillations of the poloidal field is dominant, and therefore the resulting perturbation tend to be closer to the frequency of the poloidal field oscillations. This effect may also prevent proper evolution of the edge magnetic islands - this can explain the weak trace in the spectrogram and the observed transitions from this mechanism of the RE losses to the mechanism dominated by large magnetic islands as described in the previous section. However, a more complicated interaction between the oscillations and the magnetic islands, dependent on their mode number, can be also found responsible for the observed effects. Further measurements, including the fast IR camera and Cherenkov detector are expected to shed more light on the role of the plasma helicity. In this respect, the influence of the resonant magnetic perturbation (RMP) coils (n=2) on this type of RE losses is also worth mentioning – preliminary experiments indicate that in configuration with the RMP midplane component applied, the frequency of the RE losses is doubled, while the RMP configuration without this component has no effect on the RE losses.

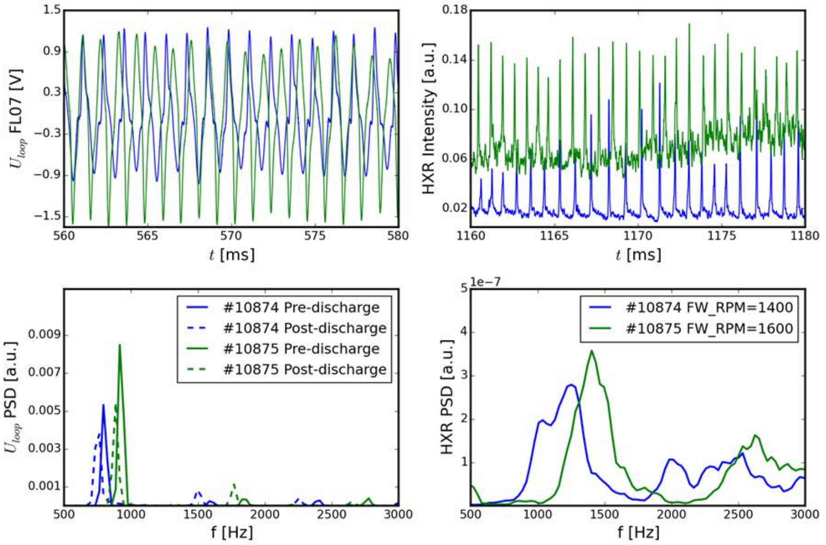

FIG. 5. Comparison of the loop voltage (left) and HXR (right) oscillations in the two discharges with different flywheel frequency. Time traces of the signal (top) and the frequency analysis (bottom).

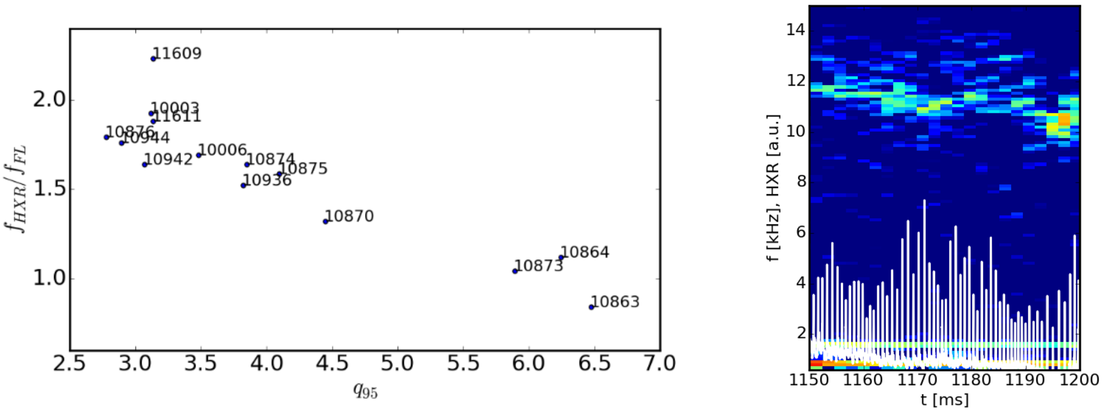

FIG. 6. Left: The dependence of the ratio of the frequency of periodic peaks of HXR (f_{HXR}) signal and the dominant frequency of the poloidal field oscillations (as measured by the flux loop f_{FL}) on the safety factor value at the edge q_{95}, Right: Spectrogram of LFS IPR coil, with a weak trace at 10-12 kHz, periodic HXR intensity peaks in white.

4. Conclusions

In this contribution, the effect of the magnetic field perturbations on the RE losses in the COMPASS tokamak is studied using a rich set of magnetic diagnostics and HXR scintillation detectors. In the flattop of low density discharges the effect of periodic RE losses to the OMP limiter caused by magnetic island rotation was observed and the phase order was identified. Furthermore, the influence of the radial position oscillation (due to a power source noise) on the HXR losses was confirmed using both the HXR detectors and the IR camera measurements. Finally, the role of the power source oscillations was documented in the case of periodic HXR intensity peaks together with a dependence of this phenomenon on the edge safety factor. It is planned that these experimental results will be further extended in future and compared to the RE generation and confinement experiments in the disruptive scenarios. The results shall also contribute to benchmarking of the advanced RE models.

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References:

[1] HENDER, T.C. et al., “Chapter 3: MHD stability, operational limits and disruptions”, Nuclear Fusion 47 (6), S128

[2] SOMMARIVA, C. et al., “Modeling Runaway Electron dynamics in realistic fields from 3D non-linear MHD disruption simulations”, 43rd EPS Conference on Plasma Physics. Leuven, Belgium (2016), P2.006

[3] CZARNY, O. and HUYSMANS, G: “Bézier surfaces and finite elements for MHD simulations“, J. Comp. Phys. 227 (16), (2008) 7423

[4] PANEK, R. et al., “Status of the COMPASS tokamak and characterization of the first H-mode”, Plasma Phys. Control. Fusion 58 (2016) 014015

[5] PÁNEK, R., et al., “Reinstallation of the COMPASS-D tokamak in IPP ASCR”. Czechoslovak Journal of Physics, 56(S2), B125-B137, (2006), DOI: 10.1007/s10582-006-0188-1. ISSN 00114626.

[6] MLYNAR, J. et al., “Effects of Plasma Control on Runaway Electrons in the COMPASS Tokamak”, 42nd EPS Conference on Plasma Physics, Lisbon, Portugal, ECA Vol.39E (2015) P4.102

[7] VLAINIC, M. et al., “Post-disruptive runaway electron beams in the COMPASS tokamak”, J. Plasma Phys. 81, (2015) 475810506

[8] WEINZETTL, V. et al., “Experimental evidence of neoclassical tearing modes on COMPASS tokamak”. 40th EPS Conference on Plasma Physics, Espoo, Finland, ECA Vol.37D (2013) P5.143

[9] RABINSKI, M., “Progress in development and applications of cherenkov-type detectors for fast electron studies in tokamaks”, Voprosy Atomnoj Nauki i Tekhniki, (1-17/71), 164-166, (2011), 42092737

[10] CAUSA, F. et al., “Cherenkov diagnostic observations of fast electron losses in FTU and interpretation with gyrokinetic simulations”, 42nd EPS Conference on Plasma Physics, Lisbon, Portugal, ECA Vol.39E (2015) O4.134

[11] HAVLÍČEK, J., et al., “Design and Preliminary Results of the COMPASS Power Supplies Filters”. Annual Conference of Doctoral Students – WDS, Prague, Czech Republic (2013)

[12] VONDRÁČEK, P., et al., “Fast infrared thermography on the COMPASS tokamak”. 29th Symposium on Fusion Technology in Prague, Czech Republic (2016) P2.059

[13] GRANETZ, R.S. et al., “An ITPA joint experiment to study runaway electron generation and suppression”, Phys. Plasmas 21 (2014) 072506

[14] MOYER, R.A. et al., “Impact of Core Modes, Islands, and Instabilities on Runaway Electron Confinement”. Proc. 25th IAEA FEC, St. Petersburg 2014, General Atomics Report GA-A27773

[15] REUX C. et al., “Runaway electron beam generation and mitigation during disruptions at JET-ILW”. Nucl. Fusion 55 (2015) 129501

[16] PLYUSNIN, V. et al., “Comparison of Runaway Electron Generation Parameters in Small, Medium-sized and Large Tokamaks – A Survey of Experiments in COMPASS, TCV, ASDEX-Upgrade and JET”, in Proc. 26th IAEA Fusion Energy Conference, Kyoto, Japan (2016)

[17] MARTIN, P. et al., “Physics, control and mitigation of disruptions and runaway electrons in the EUROfusion Medium Size Tokamaks science programme”, in Proc. 26th IAEA Fusion Energy Conference, Kyoto, Japan (2016)

[18] PAPP, G. et al., “Runaway electron generation and mitigation on the European medium sized tokamaks ASDEX Upgrade and TCV”, in Proc. 26th IAEA Fusion Energy Conference, Kyoto, Japan (2016)

[19] VLAINIC M. et al., “Synchrotron radiation from runaway electrons in the COMPASS tokamak”. 42nd EPS Conference on Plasma Physics in Lisbon, Portugal, Europhysics Conference Abstracts 39E (2015) P4.102

[20] ESPOSITO, B. et al., “First experimental results of runaway beam control in TCV”, in Proc. 26th IAEA Fusion Energy Conference, Kyoto, Japan (2016)

[21] CARNEVALE, D. et al., “Analysis of runaway beam suppression experiments in FTU”, in Proc. 26th IAEA Fusion Energy Conference, Kyoto, Japan (2016)

[22] MARTIN SOLIS, J.R. et al., “Current profile shape effects on the formation and termination of runaway beams in tokamak disruptions and implications for ITER”, in Proc. 26th IAEA Fusion Energy Conference, Kyoto, Japan (2016)

[23] PLYUSNIN, V. V., L. JAKUBOWSKI, J. ZEBROWSKI, et al. “Use of Cherenkov-type detectors for measurements of runaway electrons in the ISTTOK tokamak”. Review of Scientific Instruments. 79(10), 10F505-. (2008), DOI: 10.1063/1.2956960. ISSN 00346748.