RE beam generation in MGI disruptions on COMPASS

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Introduction. Despite extensive experimental and modelling work in the last several decades that was intesified in the last couple of years, it is yet unsure whether a generation of runaway electron (RE) beam in ITER during the mitigated disruption may be prevented. And if not, whether we have an efficient tool to safely terminate and mitigate the beam itself [1]. High Z impurity massive gas injection (MGI) or pelet triggered disruptions in medium size and large machines are currently the major tool of experimental investigation of this phenomena, while modelling focuses on solutions of the individual problems in the field where many key questions still remain open and the effort to model the disruption with RE beam generation in its full complexity is at the very beginning. The COMPASS tokamak[2] is a small device with an ITER-like shaped plasmas operated by the Institute of Plasma Physics of the Czech Academy of Sciences. Major radius of the machine spans $R_0 = 0.56\,\mathrm{m}$ and minor radius $a = 0.23\,\mathrm{m}$. The typical toroidal field is $B_T = 1.15\,\mathrm{T}$ and plasma current in the flat-top phase may be in the range $I_p = 80-400\,\mathrm{kA}$. The divertor D-shaped configuration allows routine H-mode operation, either Ohmic or NBI assisted (2x300 kW, 40 keV), while the limiter circular configuration is useful, among others, for the studies of runaway electrons (RE). The COMPASS tokamak has been contributing to the RE-related research since 2014. The COMPASS experiments are normally deuterium fuelled and the typical pulse length is about 0.4 s, although the low current circular discharge with high fraction of RE can last up to one second. COMPASS RE team contributes to both the runaway studies in the flattop of low density discharges and disruptive scenarios with Ar or Ne MGI. Interesting effects of shaping [3] and relation of RE losses and various magnetic oscillations [4] have been observed in the flattop. The continuing effort in the terms of understading of MGI generated RE beams has been reported namely in [5].

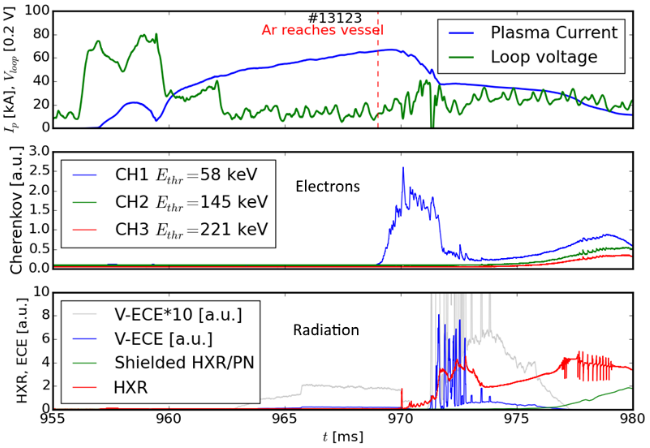

Figure 1: *Ramp-up MGI RE scenario*

Diagnostics. COMPASS is equipped by a large set of diagnostics coils [6], e.g. $3 \times 3 \times 24$ Mirnov coils and 16 calibrated internal partial Rogowski coils, that allow for a detailed study of MHD perturbations during the disruption. The diagnostics of lost RE is based namely on two HXR NaI(Tl) scintillation detectors and one Pb-shielded composite scintillator sensitive to photoneutrons and high flux of HXR. These detectors are typically measuring the interaction with the outer midplane protection limiter or central column limiters. Moreover, the lost runaway electrons may be detected earlier by the state-of-the-art Cherenkov detector (developed by NCBJ). This detector is located at a radially movable manipulator on the outer midplane of COMPASS. The detecor measures directly electrons with a 3-channel energy resolution ($E_{thr1,2,3} = 58, 157, 211\,\text{keV}$) thanks to the different thickness of the Mo coating layer of the CVD diamond crystal. Another rather special diagnostics is a 16-channel radiometer (76-90 GHz) measuring the suprathermal component of electron population via the 3^{rd} and the higher harmonics of the electron cyclotron emission (ECE). As the line of sight of the detector is vertical (VECE), there is no influence of $B_T(r)$ and the measured radiation is a function of parallel and perpendicular components of electron velocity only. This detector should be sensitive to electrons namely in the range of 50-100 keV. The evolution of the MGI disruption has been also observed by the fast visible range camera Photron Mini UX-100 with a standard framrate 8 kfps.

Scenario. The typical disruption with RE beam generation is achieved in the current ramp-up phase, 10-25 ms after the plasma breakdown with a pre-disruptive current $I_p = 60 - 100\,\text{kA}$. With B_T constant in time, this gives rather high $q_{95} = 5 - 6$. The disruption is triggered by an Ar MGI (solenoid valve placed outside the reach of large magnetic fields) in the pressure range $p_{MGI} = 0.8 - 3\,\text{bar}$. This corresponds to number of injected Ar atoms $N_{Ar} = 1 - 5 \cdot 10^{20}$. In

Fig. 1, time traces of the relevant signals are displayed - in the top graph (displaying plasma current I_p and loop voltage U_{loop}) the phases of the disruption may be identified - after the Ar injection, thermal quench (TQ) occurs (sligthlty visible in ECE, Thomson scattering signal not displayed here), followed by the current quench easily noticeable in the I_p signal. The current does not reach zero like in a normal disruption but stabilises at the value of several tens of kA - it enters the RE beam plateau phase, which later terminates due to position instability or decay of the beam. In the center graph of Fig. 1, the signals from the three channels of the Cherenkov detector are displayed. Interestingly, the first channel shows a strong signal immediatly after the Ar injection, while the other two experience continuous increase of signal in the beam plateau phase. The VECE displayed in the third graph shows very interesting spiky signal already in the beam plateau phase, which is analysed in further text, while the HXR unshielded detector shows spikes during the current steps in the CQ and rather continuous signal later. Given the energy range of the different detectors, it can be perhaps concluded that 50-100 keV runaway electrons dominate the disruption phase.

MHD perturbation during current quench. The relation between the magnetic perturbation level in the CQ and the resulting RE current in MGI disruptions was considered important and analysed on various machines, e.g. TEXTOR[7]. However it seems that different components of the frequency spectrum may be important. Moreover, COMPASS MGI disruptions with RE generation seem not to follow the claim that the RE beam generation should not be possible in $B_T < 2\,\mathrm{T}$ [4]. In Fig. 2, the effect of perturbations from the high frequency part of the spectrum ($f > 10\,\mathrm{kHz}$) on the runaway beam generation (achieved runaway current) for COMPASS ramp-up MGI discharges is displayed. The whole set of 16 Mirnov coil encricling the plasma poloidally is used for the analysis and thus the effect of position instability is partially compensated. However, toroidal asymmetries (MGI vs coil ring position) and different vessel conditions may still affect the observations. It seems that for higher mean square amplitude of magnetic perturbation, the generation of the beam is less probable, although it is difficult to obtain a clear threshold. Similarly, a linear decreasing trend may be observed in Fig. 2 but the points are rather clusterised. The relative perturbation is in the order of 10^{-3} which is expected to be the critical value to allow the generation of the beam.

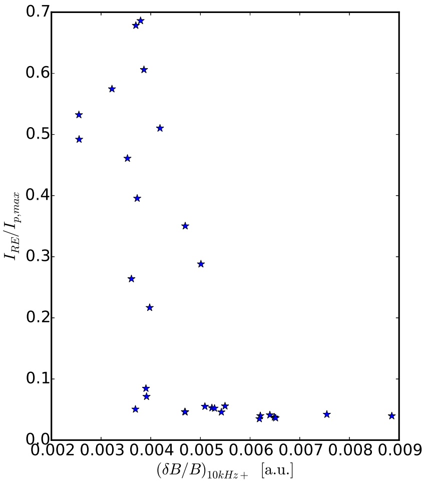

Figure 2: *High frequency magnetic perturbation during CQ vs runaway current*

Beam plateau stage - filaments. The most interesting and unique feature observed in the MGI experiments on COMPASS are the highlighted filaments in the early beam plateau phase (see Fig. 3, center frame) that appear to be accompanied by the spikes of the vertical ECE, small Mirnov coil bursts and followed by an increase of Cherenkov CH1 signal and later also HXR signal. The FWHM of the spikes in the ECE signal seems to be $20\,\mu$s. This value compared, to the frame rate of the fast camera (8 kfps), may explain why the filaments are caught always just in one frame. As the exposure time is smaller that the inverse value of the framerate, some filaments might be missed. To prove that the spikes in the ECE data and filaments in the camera correspond to the same phenomena it is neccesary to correlate the time stamps of the events. The result is positive, almost each large peak coincides with a filament in the studied discharges.

Conclusions. MGI disruptions using argon in the ramp-up phase of the COMPASS discharge may lead to generation of the runaway electron beam. It seems that lower global levels of magnetic perturbations are more beneficial for the beam generation and larger beam current. Suprisingly, low toroidal field of COMPASS is still sufficient for the beam generation. The current quench is accompanied by prompt losses of low energy RE, detected by the Cherenkov detector. Furhtermore, small bursts of magnetic perturbation, spikes of fast-particle-related signal on the VECE and loss increases measured by HXR or Cherenkov detector in the early beam plateau phase are correlated with filaments observed in the camera images. This indicates that the phenomena might be related to a MHD-like decay of the beam at the early stage.

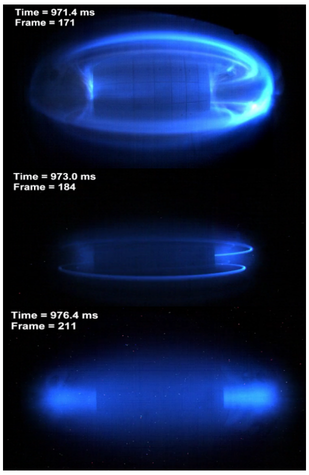

Figure 3: *Camera images of CQ and RE beam phase*

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