Analysis of MGI disruptions and runaway electron beams at COMPASS using tomography and fast camera data

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Introduction. The phenomenon of runaway electron (RE) beam generated during a tokamak disruption is a continuous challenge for modelling. Moreover, experiments on smaller devices can only partly mimic the expected parameters of ITER disruptions and the scaling of these complex transient processes is far from being clear. Despite this, smaller machines are one of the key ingredients in the strategy to find a reliable RE mitigation method as they can help to analytically clarify the open questions related to this issue using a relatively large number of discharges and higher flexibility in the diagnostics and feedback set-up. The COMPASS tokamak[1] is a small device with an ITER-like shaped plasmas 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 $a = 0.23\,\mathrm{m}$. It is operated with magnetic field $B_T = 0.9 - 1.5\,\mathrm{T}$ and plasma current in the flat-top phase in the range $I_p = 80 - 400\,\mathrm{kA}$. Despite the main scope of the machine being the edge plasma physics and plasma-wall interaction including studies of H-mode nad L-H transition, the COMPASS RE team contributes to both the runaway studies in the flattop of low density discharges and disruptive scenarios with Ar or Ne MGI [2]. A significant attention is also given to the studies of the effect of perturbed magnetic field on RE [3], lately including the resonant magnetic field (RMP) system, as presented at this conference [4].

Tomography and AXUV detectors. The reconstruction of 2D profiles of radiation from plasma cross-section using data from multi-LOS systems is a well known and often utilised data analysis process at tokamaks. However, disruption and RE beam phase requires an especially careful check of the raw data and special border conditions so automated routines can be rarely used. The AXUV system of COMPASS consists of 6 20-LOS pinhole cameras with semiconductor chips. Unfortunately, during the disruptions with runaway electron beam generation or injection to RE dominant discharges, most of these cameras cannot be used as they are affected by HXR radiation from walls (direct or through X-ray fluorescence in surrounding metals), do not have enough signal (before injection) or are affected by strong noise. The only fully reliable camera is the AXUV "F" detector with increased slit size and location safe from high HXR fluxes (HFS bottom) which still allows to resolve radial profile. The tomographic software used at COMPASS, but also e.g. at JET, is based on Tikhonov regularisation with minimising of Fisher information (MFI) with optimal solution discriminated using the expected detector errors and preferential smoothing along magnetic flux contours. This technique can be used even with a single camera and allows to get spatially reliable reconstructions (in radial coordinate) if optimal border shape is selected. Using smooth border of a big circular plasma shape 1, slightly separated from limiters, allows to suppress apparent artefacts at the bottom of the machine and discriminate the wall radiation. On the other hand, if we are interested in RE beam or plasma - wall interaction, a layer around the chamber wall can be used as the reconstruction area. If the reconstruction can be considered reliable, useful information can be obtained: spatial and time propagation of gas during MGI ($v_{diff,AXUV}$), total radiated power (P_{rad} in the AXUV sensitivity region - comparison, time evolution), position and profile of the beam gas interaction, etc.

RE diagnostics and cameras. The full COMPASS diagnostics is listed in the overview paper [5]. The diagnostics of lost RE at COMPASS is based namely on shielded and unshielded HXR detectors and Cherenkov detector, while low energy RE in the plasma can be detected also by vertical ECE system. The evolution of the MGI disruption and RE beam phase has been observed by the two fast visible range color cameras Photron Mini UX-100 with a standard frame rate 5 kfps (4 or 8 kfps or 40 kfps in dedicated discharges with reduced field of view). For selected discharges also the state-of-the-art Photron SA-X2 has been used (up to 100 kfps as an overview camera or focused on a small area within the beam). The camera data can contribute to the studies of these scenarios in many ways: time, spatial and color (gas ion species) evolution of radiation (gas penetration,

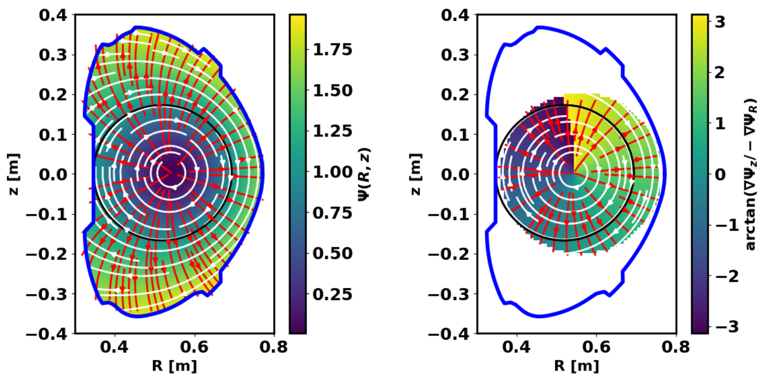

Figure 1: *Left: Normalised poloidal magnetic flux, its gradient and contours used in the MFI tomographic reconstruction. Right: Arcus tangents of the gradient ratio that is used it the smoothing matrix of MFI, limited to the optimised reconstruction area.*

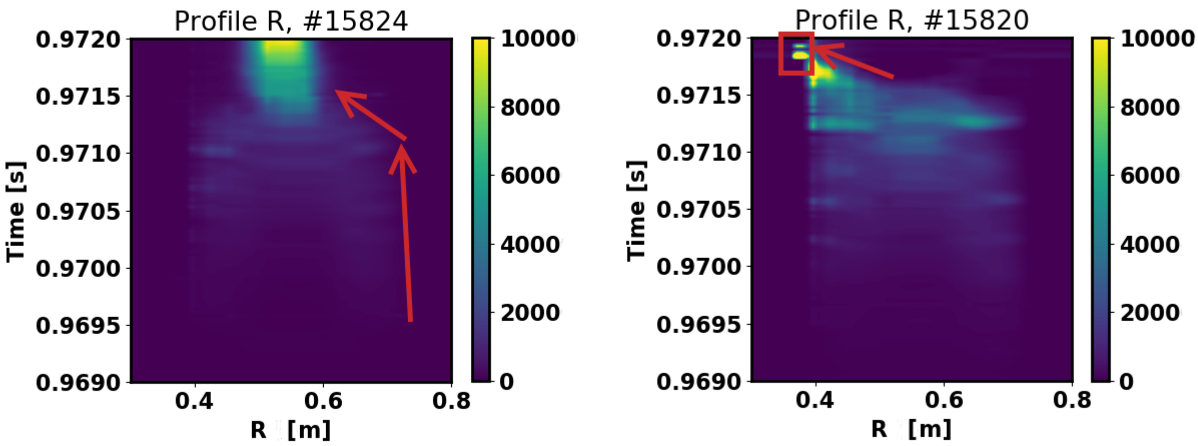

Figure 2: *Radial profile of AXUV radiation during the massive gas injection. Left: successful beam generation. Right: No beam generated, just current quench - HFS termination*

ionisation, 2 gas species interaction, beam-gas interaction position and 'profile',...), additional broad range HXR detector (number of saturated pixels/dots), analysis of instabilities, etc. Based on the spectral sensitivity range of the cameras, in case of Ne, namely Ne I lines (orange region) and in case of Ar, the Ar II lines (blue region) are detected.

Ramp-up MGI, AXUV and camera evolution. As described in the invited talk [4], the first scenario used at COMPASS for RE beam generation relies on injection of roughly 10^{20} Ar atoms to the current ramp-up stage of a low density discharge, this often leads to a classical disruption with generation of a radially unstable RE beam that carries tens of percent of the pre-disruptive current or a "full conversion" with a smooth decay of the beam. AXUV data may help to clarify the variety of possible results. A comparison of radial profiles of tomographic reconstructions for the successful beam generation and no beam disruption, which apparently ends by the HFS termination in the critical phase of RE beam generation, can be seen in 2. This kind of termination occurred for the low B_t cases in the toroidal field scan. However, the exact reason why the lower B_t discharges are unstable in the beam generation phase is still a question. Furthermore, in the case of beam generation the radiation peaks on magnetic axis almost 1 ms earlier than on the camera, which corresponds to the different energies of measured radiation and seems to be linked to the generation of the supra-thermal particles in the core. It seems that the radiation front propagation speed increases as the gas is approaching the core.

Flattop scenario - radiated power, comparison of MGI and gas puff discharges The other scenario used at COMPASS, mostly for the beam decay experiments, was also presented during the invited talk. In this case, $< 10^{19}$ (gas puff) or $\sim 10^{20}$ (MGI) Ar or Ne atoms are injected to a flattop of low density discharge with a sufficient RE seed causing a 'thermal quench' and no immediate current quench. The RE beam than decays with a rate proportional to the gas amount. Consistently with this, also the radiated power based on AXUV tomography seems to be in a linear relation with the current decay rate, slightly larger for Ne for given $\frac{dI}{dt}$.

Conclusions. The MGI triggered disruptions with occasional RE beam generation were investigated using the AXUV tomographic reconstruction. Despite only one fully reliable camera being available during this scenario, the reconstructions provided very interesting information that radiation propagates to the core with increasing speed and that it peaks on axis (AXUV) well before Ar II radiation (camera). Also, the unsuccessful cases with no beam apparently ended with radial position instability during the beam creation phase.

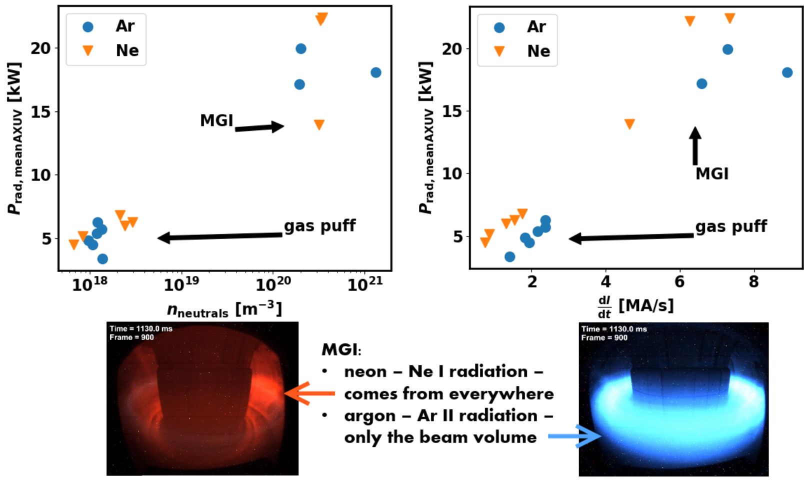

Figure 3: *Top right: Relation of the density of neutrals in the vessel after the puff and the mean radiated power. Top left: Mean current decay rate of RE beam versus the mean radiated power. Bottom: Comparison of camera images from the beam decay phase in Ar and Ne after the MGI.*

The AXUV radiation and cameras were also used in the study of beam decay phase under controlled conditions (flattop, no external loop voltage during beam decay). It appears that total radiated power is increasing linearly with the order of magnitude of the injected gas amount and with the current decay rate. The color camera allows to track the Ne I (neutral, orange) and Ar II (charged, blue) gas species/radiation.

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