Runaway electron mitigation by *n=1* and *n=2* magnetic perturbations in COMPASS

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Introduction. Understanding the mechanisms behind Runaway Electron (RE) generation and the ways RE formation can be prevented is of paramount importance for future fusion reactors. In fact, RE with energies of several MeV generated during the sudden cooling involved in disruptions may cause severe damage to the plasma facing components and vacuum vessel wall [1]. Even if massive gas and shuttered pellet injection (MGI, SPI) are the main solutions presently envisaged to mitigate or avoid the RE avalanche, also 3D fields -in synergy with these methods- might further contribute to reduce the RE negative effects. In particular, the successful results recently obtained by applying magnetic perturbations (MPs) in ASDEX Upgrade [2] have motivated new experiments with this technique also in the COMPASS tokamak [3].

COMPASS features ITER-like plasma shapes with major radius R_0 = 0.56 m and minor radius a = 0.23 m, typical toroidal field B_T = 0.9–1.5 T and a plasma current in the flat-top phase I_p < 350 kA. In the RE experiments discussed in this paper the toroidal magnetic field, with magnitude B_T = 1.15 T, is oriented in the same direction of I_p (clockwise, from the top view) and limiter circular plasmas are considered. The upper/lower MP coil systems in COMPASS allow the application of perturbations with toroidal mode numbers *n=1* and *n=2* both before and after the RE beam generation. The current (I_{MP}) flowing in the MP coils can be increased up to 4 kA corresponding to a radial field normalized to the main toroidal field of $b_{MP}/B_T \approx 10^{-2}$. The sign of the current in the upper and lower set of coils can be varied in order to obtain different configurations (or differential phasing $\Delta\phi$) for the poloidal spectrum of the applied perturbations. When n = 1 the number of phasing available is four ($\Delta\phi$ = 0°, 90°, 180°, 270°); if n = 2 only two configurations are possible: even ($\Delta\phi$ = 0°) and odd ($\Delta\phi$ = ±90°) orientation.

RE discharges and mitigation with n=1 MPs. Fig.1 shows an example of a standard COMPASS discharge (black line) where a disruption is induced by Argon puffing (1.2 *bar*) in the time interval 1095 – 1115 *ms*. As reported in panel (a) the plasma current increases up to 160 *kA* during the ramp-up followed by the flattop phase and is converted into runaway electron (RE) current after the disruption event. The electron density in panel (b) rises from about

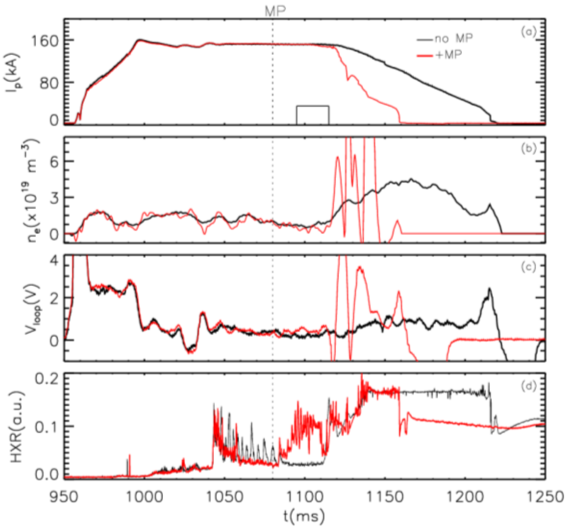

Figure 1. *Example of disruptive discharges in COMPASS without (black, #15774) and with (red, #15775) MP applied; from the top: (a) plasma current, (b) electron density (oscillations in the red trace after disruption are caused by fast variations of the radial RE beam position and of other signals), (c) loop voltage and (d) HXR radiation. MP pulse starts at the time corresponding to the vertical dotted line and the Ar injection is represented by a rectangle in the top panel.*

~$1.5-2\cdot10^{19}$ m^{-3} to slightly greater than $3\cdot10^{19}$ m^{-3} after the Ar injection while the loop voltage, in panel (c), keeps almost constant value of about 0.5 V. The presence of RE is confirmed by the plot in panel (d) reporting the signal from hard-x-rays (HXR) detector due to the wall-RE interaction which also shows that a RE seed is already present before the disruption and rapidly increases up to saturation after the Ar injection.

In the same figure the red trace refers to a similar discharge but with n = 1 resonant magnetic perturbations (I_{MP} = 3.5 kA, phasing 270°) applied from a time (t_{MP} = 1080 ms, vertical dotted line) preceding the Ar puffing. The resulting RE current, reported in panel (a), is characterized by a faster decay with respect to the unperturbed discharge and by a shorter duration of the RE beam (- 43%); the HXR radiation - in panel (d) - already starts to rapidly increase when the MP is applied (i.e MPs can affect and de-confine the pre-disruption RE seed too). These experiments have been repeated by varying the phasing of the $n=1$ mode and the current in the MP coils. The magnitudes of pre-MGI applied MP were limited in the experiment in order to avoid locking of magnetic island rotation that disrupts the discharge without RE generation (this occurs for MPs with $\Delta\phi$=0°, 90°, I_{MP}>1 kA or with $\Delta\phi$=180°, I_{MP}>3 kA). Results are summarized in Fig.2-(a) with the RE beam duration Δt_{RE} - measured from the end of Ar puffing (1115 ms) to the time when the RE current drops below 30 kA - as function of I_{MP}; each color/symbol corresponds to a different phasing. Up to I_{MP} = 1.5 kA a significant effect of the MPs on the RE beam is not visible: for all $\Delta\phi$ values the duration is similar to the one typical of unperturbed reference discharges (empty circles). On the contrary, for I_{MP} > 2 kA and $\Delta\phi$=270° the duration decreases in the range 40−60 ms. Similar experiments

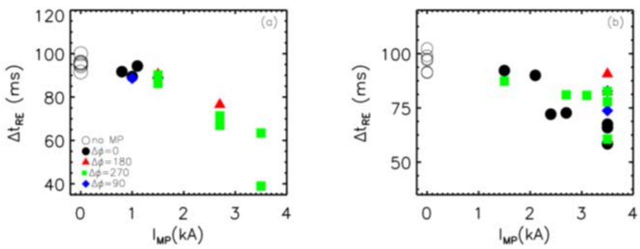

Figure 2. *Runaway beam duration (Δt_{RE}) as function of MP amplitude (I_{MP}) for different phasing values (colors/symbols). In (a) MPs have been applied before the disruption, in (b) after.*

have been performed with perturbations applied after the disruption (at t_{MP}=1135 ms), when the RE beam is fully generated; a summary of the main findings is reported in Fig.2b. An almost linear trend can be observed for the phasing $\Delta\phi = 0°$. Also $\Delta\phi = 270°$ (green-squares) can slightly reduce the RE beam duration but with a lower efficiency than $\Delta\phi = 0°$ except for on single case at 3.5 kA where Δt_{RE} drops down to ~55 ms.

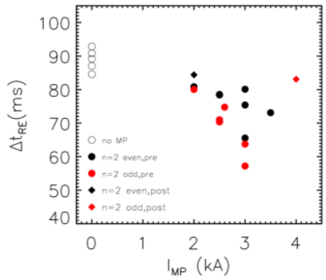

Figure 3. *Runaway beam duration (Δt_{RE}) as function of amplitude (I_{MP}) of odd and even parity n=2 MP, applied before or after disruption.*

RE mitigation with n=2 MPs. Further discharges have been performed using MP with n = 2 instead of n = 1. Results are summarized in Fig. 3 both for perturbations applied before and after the runaway beam generation. As clear from circle symbols, pre-existing MPs with n = 2 in most the cases reduce the duration of RE beam (from ~ 85 to ~ 55 *ms)* but with an impact partially lower than that of n = 1. The effect in particular is stronger for odd parity, where the RE beam duration can decrease of ≈ -30%. On the contrary, *n=2* MPs applied after the disruption (diamonds) have little to no effect on the value of Δt_{RE} (-9% in the odd parity case). Moreover, as shown in Fig.4 (left hand side plot), when *n=2* odd MPs are applied before the disruption the measurements of the local plasma fluctuations from Mirnov coil, located at LFS midplane, show the presence of a strong MHD activity during the Ar gas puffing (about 5 kHz, around 1100 ms), probably related to a magnetic island formation. In this case the level of magnetic fluctuations is increased by about 200% in comparison with even parity *n=2* MPs (right hand side plot) - which implies a significant increase of transport - and is accompanied by oscillations of the loop voltage (not shown) and of HXR traces. Both the radial position of the RE beam and the vertical field are affected by this phenomenon which terminates in a faster current decay.

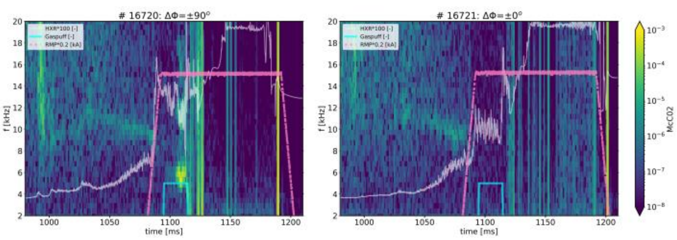

Figure 4. *Time-frequency spectrogram from Mirnov coil signal (T) when n=2 MPs with odd (left) or even (right) parity are applied before disruption. White line corresponds to HXR signal, pink to the MP amplitude and cyan to Ar injection.*

A fraction of discharges has been performed also using Ne instead of Ar for MGI and is characterized by a larger variation of the RE beam duration (80-140 ms). The application of *n=1,2* MPs - both before and/or after the disruption - also in this case has a clear impact on the runaways but less systematic with respect to Ar; more experiments to reinforce the statistics are required.

Interpretation by the code MARS-F. The interpretation of the results reported in the previous sections has been performed taking into account the plasma response to the applied MPs by using the code MARS-F [4]. The computed components of the perturbation field whose pitch angle (*m* and *n*) is aligned with magnetic field lines on q = *m/n* = 2/1 and q = 3/1 flux surfaces are plotted in Fig.5 as a function of Δϕ, both in vacuum approximation and considering the plasma response to MPs. They present a maximum for the *m* = 2 (3) components at Δϕ = 230° (270°) in vacuum which is shifted to Δϕ = 330° (350°) if plasma response is included; thus, these numerical simulations allow to interpret the experimental data described in Fig. 2(b) as a result of resonance between MPs and pre-disruption plasma equilibrium: indeed – for the same I_{MP} - the strongest effect is observed at Δϕ = 0°. On the other hand, it is not possible to make a direct comparison between simulations and experiments with pre-existing MP (Fig.2(a)), since a complete scan in the MP current was available only for one phasing (270°) because of lock modes or disruptions in the rest of Δϕ values. Similar simulations by MARS-F for the *n=2* perturbations confirm the presence of a stronger plasma response in the odd parity configuration as occurs in experimental discharges when MP application precedes the disruption.

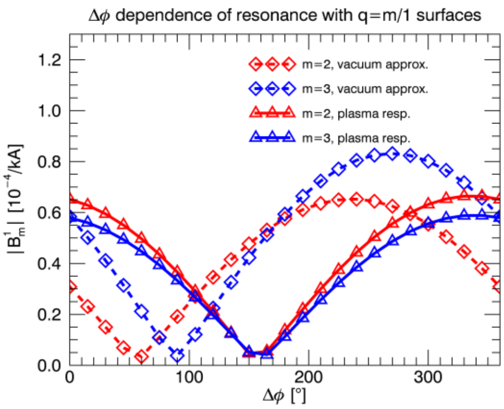

Figure 5. *Perturbed field at resonant positions q = 2 (red) and q = 3 (blue) in vacuum (diamonds) and with plasma response (triangles) as function of the phasing for n = 1 MP.*

Conclusions. Runaway electrons mitigation experiments by 3D fields have been performed in the COMPASS tokamak. Magnetic perturbations with *n=1*, depending on their amplitude, poloidal spectrum and time interval of application, successfully decrease the duration of the RE beam which is almost halved in the most efficient scenario. Also *n=2* modes exhibit similar features but with a reduced impact which requires further investigation and a larger statistics. The configuration of the coils which is more powerful in suppressing the RE beam is the one which maximizes the plasma response as computed by the code MARS-F.

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