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Stable Operation at Disruptive Limits by Means of EC at ASDEX Upgrade

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Introduction. The technique of disruption avoidance based on the use of electron cyclotron (EC) waves has been established in recent years with experiments in FTU [1], ASDEX Upgrade [2] and DIII-D [3] in various types of disruptive scenarios. The proposed scheme uses a combination of precursors to trigger the Electron Cyclotron (EC) power directed at a q rational surface to reduce amplitude of the main MHD mode, delaying or even avoiding the current quench. In view of the application to ITER, the disruption avoidance technique should be complemented by a strategy of safe plasma shut-down using ECCD instead of ECRH as required for NTM control. As plasma disruption is definitely accompanied by MHD activity, whatever is the initial reason for instability start up, the EC wave can be effective, exploiting its high localization and local power density, as well done in the MHD control experiments [4]. This paper reports on experiments aiming to demonstrate the capability of EC power to avoid disruptions in AUG triggered in high performance plasma close to β_N or density limits.

Experimental Setup. Two different experimental setups were used to obtain disruptions. The first scenario was an H-mode with 7MW of NBI at 1MA and 2.2 T to destabilize NTM mode at high β_N limit; the second was an L-mode plasma at 0.6 MA, 2.5 T with pre-set gas puffing to push density above the limit. In both cases EC power was triggered by precursors, related to MHD presence and initiation of current quench. The EC launcher steering was slaved to a reference aiming to inject the power onto q=2 rational surface, using the real time (RT) reconstruction of equilibrium [5] and an accelerated TORBEAM ray tracing [6], based on density profile reconstruction. Approaching the disruption reconstructed profiles and the diagnostics exhibit fast variations, easily leading to errors in RT reconstructions inducing

[*] See http://www.euro-fusionscipub.org/mst1

steering mirrors to wrong positions, this has been addressed by real-time TORBEAM calculation. In the experiments the new AUG ECRH system was used, at the frequency of 140 GHz with power up to 1.3 MW (3 gyrotrons).

High Beta limit Experiments and results. The most challenging target was the high β_N disruption scenario, in which the Lock Mode signal (LM) and Vloop were used to trigger the EC power at q=2 surface, where (2.1) mode develops and grows. Both ECRH and ECCD were tested on a repetitive target, obtaining complete disruption avoidance when the power was injected in the island. The EC power, (see Fig.1 left), is effective to maintain plasma stable also if the mode is still locked. During the EC pulse the same RT algorithm used in [4] maintained power at q=2 rational surface. At EC switch off the mode rotates again, leading to disruption in the Ip ramp down. A radial scan was performed (Fig.1 right) by adding a fixed offset to the deposition reference, aiming to demonstrate that it is the action on the main instability that avoids the disruption, and not an increase of the total power in the plasma.

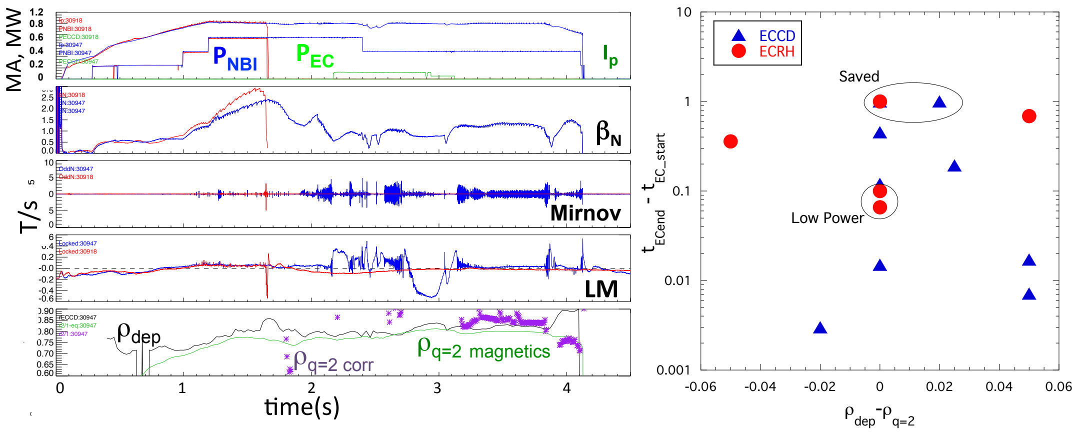

Figure1: Left: Plasma evolution during high β_N experiment. In red signals of disruptive target (#30918) in blue a plasma saved (#30947) by ECCD (toroidal injection of 9°). Right: high β_N disruption radial scan with ECRH and ECCD results in term of surviving time of the plasma, expressed with duration of EC pulse (max length pre-set at 1s). Close to q=2 surface spread of results is due to errors in RT reconstruction. EC power: 0.6 - 1.3MW.

This has obtained in both cases (CD or pure heating) although a greater precision on the deposition location was needed in the ECCD case (the most effective with NTM), for which the proper deposition is crucial to avoid disruption. In fact CD deposition inside the resonant surface even accelerate the disruption, in agreement with Rutherford equation [7]. This represents the challenge of such a technique, as the real time reconstruction of the target (mode position and beam localization) during a disruptive phase might be difficult and not reliable, at least with the actual status of diagnostics. A further RT tool to detect MHD onset and mode analysis is under study and was successfully applied off-line to data. It is based on SVD technique (Singular Value Deconvolution) described in [8] and capable to detect the most relevant mode using combination of Mirnov coils signals. Such an analysis has shown that in many disruption avoidance experiments after a successful mitigation of the (2,1) dominant mode, the plasma is killed by one external mode (typically a (3,1) or (4,1) and not by an internal (3,2) mode. This observation suggests a strategy for future experiments, using several gyrotrons aiming at different rational surfaces.

Density limit Experiments and results. The EC has been also used to avoid disruptions occurring at the density limit. In this case a L-mode at 0.6 MA, 2.5 T was chosen as scenario on which increase electron density by pre-programmed gas puffing up to density limit (0.6 Greenwald) and automatically switch on EC power just before the current quench: the most reliable precursor to trigger EC power was found to be the Vloop (threshold value 1.5 V).

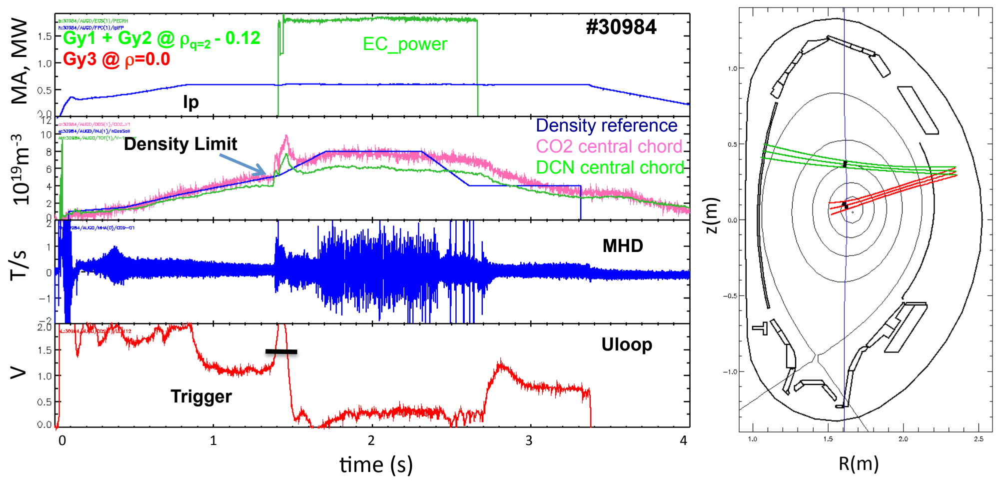

Figure2: Left: Plasma evolution of main parameters during density limit disruption avoidance experiment (#30984). ECRH power is triggered by Vloop threshold at 1.5 V, the line averaged density (CO2 and DCN central chords are shown) is pre-programmed at 8 $10^{19}m^{-3}$, two times the onset of disruption (start of MARFE). Right: the beam tracing of the used gyrotrons in the experiment. All the beams are in pure heating scheme.

The system reaction time is around 7 ms. In these experiments the RT tracking of q=2 resonant surface was used to compensate the RF beam refraction. This effect was the limit of the previous experiments with no RT reported in ref [2] in which the EC deposition radius was moving away as density increases. This technique makes it possible, as shown in Fig.2 left, to maintain stable a discharge with a density 1.5 times the disruptive limit (MARFE, locked 2/1-mode). It is necessary to mention that in this scenario seems to be crucial to have a good core profile with sawteeth, obtained with EC central heating. This has to be further investigated in the future. In Fig.2 right, the used launching scheme is represented with two gyrotrons at q=2 surface (green path) and a third one aimed at the plasma centre (red path). All the gyrotrons were triggered at the same time. The analysis of the density evolution, during the phase above the limit, has demonstrated that the profiles maintain their peaking factor, suggesting the confinement of particle has been ameliorated. Further detailed analysis of confinement and transport are on going.

Conclusion and future work The technique of disruption avoidance based on the use of EC waves with RT control of steering mirrors has been successfully applied to ASDEX Upgrade in two types of disruptive scenarios: H-mode with high β_N and L-mode at density limit. The power, automatically triggered by precursor signals and directed on the resonant q=2 surface, is able sustain the plasma current for the duration of EC pulse, and in some case also afterwards. The ECCD has been demonstrated to be effective in disruptions caused by β_N limit, driven by NTM: compared to ECRH (which is also effective) a higher precision in power localization is necessary. For operation above the density limit ECRH has been used. In both the cases a proper RT reconstruction of equilibrium and ray tracing is at the basis of the success of the technique as well as the proper choice of the disruption precursors. The presented experiments were performed exploiting the LM detector and Vloop, while in future experiments a combination Mirnov coils signal could be used to detect mode onset and its kind. In view of the application to ITER, the disruption avoidance technique, more promising the case of high β_N for the less power required, should be complemented by a more general strategy of safe plasma shut-down, developing a routine tool to be used in plasma operations.

References

[1] B.Esposito, G.Granucci et al. Phys.Rev.Let., **100** (4), 045006 (2008)

[2] B.Esposito, G.Granucci, M.Maraschek et al, Plasma Physics and Contr. Fusion, **53**, 124035 (2011)

[3] F.Volpe et al., Physics of Plasmas, **16**, 102502 (2009)

[4] M.Maraschek – This EPS conference, P1.112

[5] L. Giannone et al., Fusion Engineering and Design **88**, 3299 (2013).

[6] M. Reich et al., Fusion Eng. Design, online: http://dx.doi.org/10.1016/j.fusengdes.2014.04.024

[7] S. Nowak et *al*., Physics of Plasmas, **19**, 092508 (2012)

[8] C. Galperti et al, Plasma Phys. Contr. Fusion **56**, 114012 (2014)

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