Runaway electrons generation in FTU during EC assisted breakdown discharges

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Introduction. The necessity to use EC (Electron Cyclotron) power to assist plasma start-up in future large devices (JT60-SA, ITER, DEMO) is a matter of fact, considering the low electric field (0.3 V/m) foreseen. An effort has been done both in experimental [1] and in simulation [2] activities to define requirements of EC power, configuration and prefilling pressure for a reliable start-up. In ITER up to 4 MW of additional power are considered to initiate and sustain plasma start-up. EC power in a low density plasma can be a concern for the possibility of fast electrons formation that potentially can be accelerated by the toroidal electric field up to the run-away condition. The studies on Runaway Electrons (RE) formation in tokamak are usually carried out during current flat top or at disruption, [3]. Even if the electric field in EC assisted break-down is generally low and well below the Dreicer limit [4], it is necessary to complement these studies considering the start-up phase of the current in presence of strong RF wave heating. The consolidated theory based on toroidal electric field, as source for RE acceleration, must be extended in presence of high frequency waves resonating with thermal electrons and transferring them perpendicular momentum that can modify the electric field threshold. In this paper the FTU data base on EC assisted start-up, extended over 10 years of different experiments, is analysed, with the aim to give a starting point for future comparative inter-machine studies on RE generation in the initial phase of the plasma current formation.

Experiments Conditions. FTU is a cylindrical (R=0.935m, a=0.3m), full metal-wall machine, equipped with an ECRH system (140GHz, 0.5s, up to 1.6 MW) here used to perform experiments on EC assisted breakdown at low toroidal electric field [5]. During such

[*] See the appendix of See the appendix of G. Pucella et al., Proc. 25th IAEA FEC, St Petersburg, Russia, 2014

experiments an unexpected generation of RE was observed even at moderate (300 kW) RF power injection. This occurred in conditions of electric field below the Dreicer field threshold (E_D) for thermal electron acceleration up to RE condition, which do not show noticeable RE generation during ohmic start-up, as illustrated in Fig.1. The presence of RE is revealed by gamma ray diagnostic (NEU213 detector) compared with the signal for neutrons detector (BF3, insensitive to gamma rays). A discharge with a ratio between these two signals larger than 3 has been classified to have RE. Partial data from a new Cherenkov probe, recently installed in FTU, have confirmed RE presence even if an unfavourable setting of the sensitivity gave only a qualitative signal. The total database consists of approximately 220 shots, however distributed over a number of years so that as a whole it may be not sufficiently coherent and systematic for the exploration of the RE generation conditions. Only for the most recent studies (~100 shots) a measurement of internal pressure during the shots has been introduced. Moreover, as the main purpose of the collected experiments was to demonstrate the possibility to sustain breakdown, no attention was paid to the diagnostic of electron energy (like FEB) or to the availability of the temperature measurement in the initial phase. ECE signal is often disturbed by RE presence, so it is necessary to rely on Thomson Scattering that has a reduced reliability at low density. EC power was at 300 kW level (one gyrotron) while both injection in perpendicular or in oblique injection (20°) have been both used. A small bunch of experiments (16) was performed at half field (2.5T), exploiting the second harmonic extraordinary mode (XM2) interaction; most of the database refers to fundamental resonance ordinary mode polarization (OM1). The toroidal electric field in the date base was varied from 0.4 V/m to 2.5 V/m, while the filling pressure (at least in the data set in which it was measured) ranged from $5\ 10^{-6}$ mbar to $1.2\ 10^{-4}$ mbar.

Electric Field The ratio between toroidal electric field (E), during EC, and the Dreicer field, $E_D = e^3 n_e \ln\Lambda/(4\pi\varepsilon_0^2 T_e)$, has been computed and compared with that for pure ohmic discharges (see Fig.1). When EC waves are present, for the same ratio E/E_D, which determines the Dreicer production of runaway electrons, substantial amounts of RE can be found in comparison with the ohmic start-up. This suggests that interaction with the wave modifies the electrons distribution functions (giving perpendicular momentum) in such a way that the threshold conditions for RE generation are relaxed and more RE are produced. We have to mention that this eventually lower limit has not been identified in our data, suggesting that it is below the limit for a sustained breakdown in FTU. Looking at the temporal evolution of the discharges (see Fig.2) the NEU213 signal (related to RE presence) starts to grow during the

EC power pulse and even increases after, until the growing density damps the RE. This behaviour is representative of the whole database.

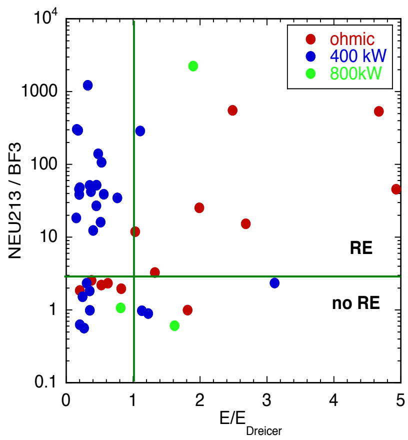

Fig. 1 –FTU database: EC assisted start up (blue and green) and pure ohmic one (red) comparison. Vertical axis reports RE presence vs E/E$_D$. B=5.3T with various filling pressure and injection angles.

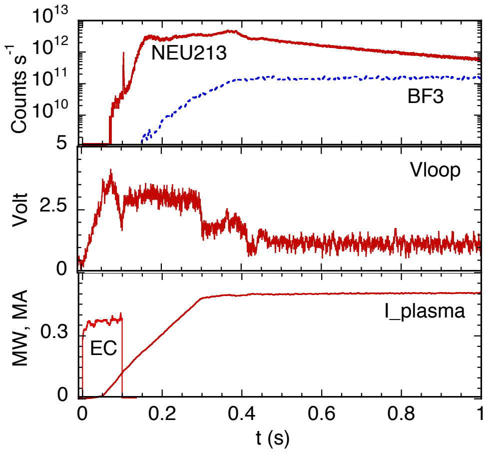

Fig. 2 - Time trace of an EC assisted discharge (#39754). Prefilling pressure was 5 10^{-5}mbar, magnetic field 5.3 T, OM1 wave was central injected with 20° toroidal angle

Neutral Gas Pressure Effect. The database has been analyzed in order to find a parameter controlling RE generation, assuming that the electric field in not the only relevant parameter. The exploration has led to a dependency on the pre-filling pressure (see Fig.3) more that on the plasma density during the EC pulse. Collisions between electrons and neutral atoms seem to play the major role in controlling the acceleration of electrons in these conditions. The data are scattered due to the fact that the exact pressure in the vacuum vessel is not known (the measure is taken in a port 1.5 m apart from the chamber) and to the high recycling factor of FTU (due to its cold walls). Generally, we observe RE presence in many discharges, as it is difficult to operate the machine at pressure above 10^{-4}mbar (which seems to be the marginal pressure limit for RE in FTU) especially when is contaminated by impurities.

XM2 vs OM1. From the analysis of the data set at half field (2.5 T) we found that RE are not generated when injecting XM2. In all the plasma discharges usable for this analysis, no RE have been revealed by NEU213 detector, even if the pressure was below 5 10^{-6} mbar. This occurs both with perpendicular or oblique (20°) injection, with electric field in the range 0.6 - 1.3 V/m. In Fig.4 a comparison between a discharge at first harmonic and one at second harmonic is reported. All the main parameters are similar (also the prefilling pressure), only polarization and magnetic field are changed.

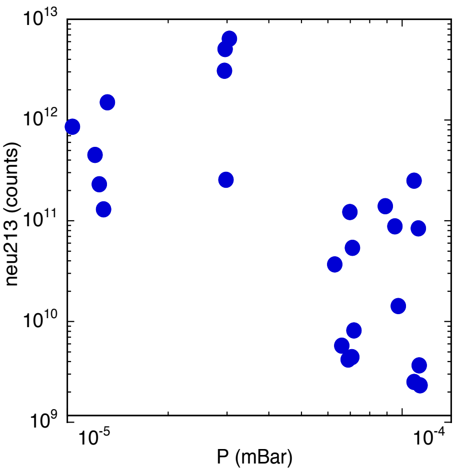

Fig. 3 – Gamma ray counts from neu213 detector vs filling pressure. EC power was 350 kW and B =5.3T for OM1 polarization. Toroidal electric field varied between 0.5 to 5.1 V/m.

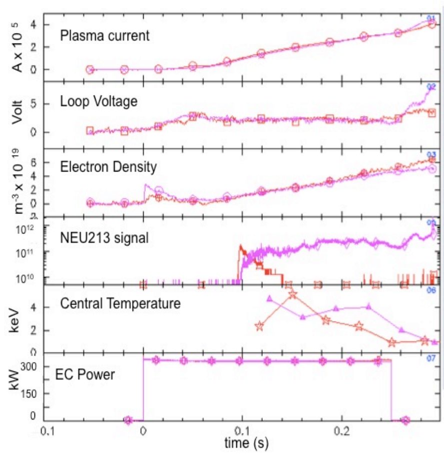

Fig. 4 - Time trace of two EC assisted discharges comparing OM1 (#38400 magenta) and XM2 (#38418 read) injection (with 20°). Pressure was 910^{-5}*mbar,* $B_T = 5.3$ *T and 2.6 T, respectively.*

Conclusion. It is necessary to complement the studies on RE generation during plasma flat top with those during the plasma current start-up when EC waves are applied to sustain plasma and burn-through, like in ITER. A first analysis of the FTU database on EC assisted start-up experiments is presented. The presence of RF waves likely reduces the field threshold for RE generation well below the limit for sustained breakdown. It is therefore important to find different parameters to avoid this. From the presented analysis, the most promising seems to be the prefilling pressure, that acts for different launching conditions and electric fields. In addition, there are results that indicate the absence of RE in case of injection of wave in XM2 polarization, even for a small number of cases.

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Acknowledgement This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.