EUROFUSION WPMST2-PR(16) 15440

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Preprint of Paper to be submitted for publication in
43rd European Physical Society Conference on Plasma Physics (EPS)

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.

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 formation of fast electrons 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 electrons and transferring them perpendicular momentum that can modify the electric field threshold. In this paper the FTU data base extended over 10 years of different experiments on EC assisted start-up is analysed, with the aim to give a starting point for future comparative inter-machine study 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

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[*] See the appendix of P. Buratti et al., Proc. of the 24th IAEA Fusion Energy Conf., San Diego, USA, 2012.

experiments an unexpected generation of RE was observed even at moderate (300 kW) RF power injection. This occurred in conditions of accelerating electric field below the Dreicer field threshold for primary RE generation, as shown in Fig.1. The presence of RE is revealed by gamma ray diagnostic (NE213 detector) compared with the signal for neutrons detector (BF3, insensitive to gamma rays). A discharge with a ratio between this two signals larger that 3 has been classified to have RE. Partial data from a new Cherenkov probes, recently installed in FTU [Causa_EPS2015?], 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 REs 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 relay on Thomson Scattering that has a reduced reliability at low density. EC power was at 300 kW level (one gyrotron) while injection in perpendicular or in oblique injection (20°) have been both used. A small bunch of experiments (16) was done 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, during EC, and the Dreicer field threshold for primary RE generation, has been computed and compared with that for pure ohmic discharges (see Fig.1). When EC waves are present the threshold seems to be no more valid, as we found shots with or w/o RE independently from the ratio. On the contrary in case of ohmic start-up the calculated values fall within the limits expected. This suggests that interaction with the wave modifies the electrons distribution functions (giving perpendicular momentum) in such way that the threshold becomes lower. We have to mention that this eventually lower limit has not been individuated 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 NE213 signal (related to RE presence) starts to grow during the EC power pulse and even increases after, until the growing density damps REs. This behaviour is representative of the whole database.

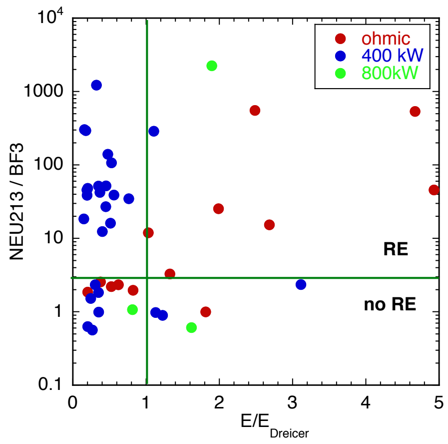

Fig. 1 –FTU database: EC assisted start up (blue and green) and pure ohmic one (red) comparison. Vertical axis reports REs presence vs ratio between electric and the Dreicer fields. B=5.3T with various filling pressure and wave injection geometry.

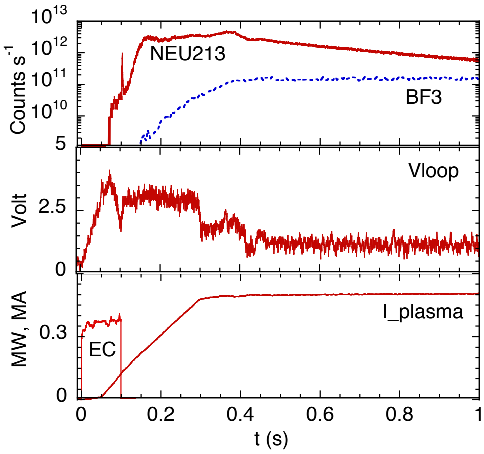

Fig. 2 - Time trace of a EC assisted discharge. Prefilling pressure was 5 10^{-5}mbar, magnetic field 5.3 T, OM1 wave was central injected with 20° toroidal angle.

Neutral Gas Pressure Effect. The database has been analyzed in order to find a parameter controlling REs generation, assuming that it is not (only) the electric field. 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 REs acceleration 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 form the chamber) and to the high recycling factor of FTU (for its cold walls). Generally we observe RE presence in many discharges as it is difficult operating 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 REs are not generated when injecting XM2. In all the plasma discharges usable for this analysis, no REs have been revealed by NE213 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.

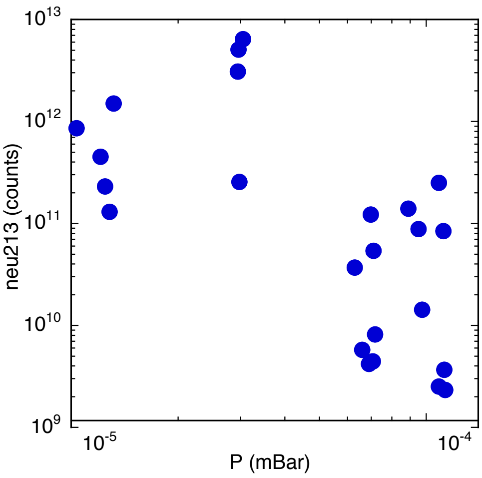

Fig. 3 – Gamma ray counts from neu213 detector vs filling pressure. EC power was 350 kW and B =5.3T for OM1 polarization. Toroidal electric field varied between 0.5 to 5.1 V/m.

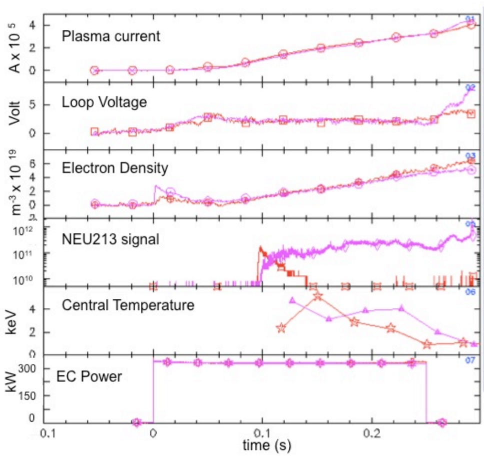

Fig. 4 - Time trace of two EC assisted discharges comparing OM1 (#38400 magenta) and XM2 (#38418 read) injection (with 20°). Pressure was 910^{-5}mbar, $B_T = 5.3$ T and 2.6 T, respectively.

Conclusion. In the frame of the studies on REs generation it necessary to complement these studies during plasma flat top with those in the start-up of current when EC waves are applied to sustain plasma and burn-through, like in ITER. A first analysis of FTU database on EC assisted startup experiment 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 parameter to avoid this. From the presented analysis, the most promising seems to be the prefilling pressure, that acts for different launching condition and electric field. In addition there are results that indicate the absence of RE in case of XM2 polarization, even for a small number of cases.

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