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ECRH assisted start-up studies and experiments on FTU

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Introduction. Plasma start-up is one of the historical applications of electron cyclotron heating (ECRH) in tokamaks. It was experimentally found that pre-ionization via electron cyclotron heating (ECH) could help obtaining ohmic discharges with a lower loop voltage in JT-60U [1], DIII-D [2, 3], T-10 [4], Tore Supra [5], and ASDEX-U experiments [6]. Moreover it could reduce flux consumption of the ohmic systems. In ITER plasma start-up will have to be achieved with a low in-vessel toroidal electric field (≤0.3 V/m) due to the use of superconducting coils and the presence of thick in- vessel structures. In order to prepare and support the modelling of this initial plasma phase, tokamaks equipped with ECRH systems have been asked to exploit experiments on assisted plasma start-up and compare results. On FTU this kind of experiments have the double objective of studying the ECRH start-up conditions for ITER and of preparing scenarios with large flux saving for the long pulse plasma of FAST project [7, 8]. In this work we present the preliminary results obtained in the last experimental campaign on this topic.

Experiment set up. FTU is a circular cross section tokamak (R_0=0.935m, a=0.3m) with a very wide magnetic field range (2.5 – 8 T) working at currents from 0.25 MA to 1.6 MA and line averaged density from 0.2 to 3.5 $10^{20}m^{-3}$ (in standard fuelled plasma). The ECRH system is composed by four 140 GHz/0.5 s gyrotrons (1.6 MW at plasma) fed by two HV series regulators, the beams are launched in the tokamak vessel trough a single port where the four independent launching mirrors are located. The mirrors can be steered vertically (± 25 cm) or toroidally (at fixed angles) shot by shot.

Assisted start-up has been studied in a 0.5 MA/ 5.2 T discharge, developing a plasma scenario with a marginal ohmic break down obtained at loop voltage, V_{loop} = 8 V. In this scenario the current ramp-up in the transformer (I_T) is feedback controlled with respect to the programmed plasma current (I_P), without the open-loop phase (the so called "commutation") used to increase the I_T derivative by commutating the current path on a resistors bank. The standard robust ohmic break-down in FTU, with commutation, is at V_{loop} = 15 V. The full control of I_T evolution allows controlling the loop voltage level at the breakdown, without major changes in the discharge development.

Results. In the first step of the experiments, ECRH power has been perpendicularly injected at t = 0 varying the pre-filling pressure (D2) starting from to levels where the pure ohmic breakdown fails because of too high pressure. The use of 0.4 MW of ECRH power has been found to extend the maximum pressure for a sustained breakdown by a factor 4 (from 4.3×10^{-4} mBar to 1.7×10^{-3} mBar). The growth rate of the current (time to rise from 0 to 100 kA) is plotted versus the pre-filling pressure in Fig. 1, where pure ohmic start-up is compared with the EC assisted case. The I_p rate decreases with increasing pressure in both cases, even if the use of ECRH allows a working range increased of a factor 4. A shot has been also performed with a toroidal injection angle of 20° of EC power: in this case a lower pressure threshold (8.5×10^{-3} mbar) has been found. An accurate power scan has not yet been done and is scheduled for further experiments. The injection of EC power always produces an immediate onset of Hα emission in all the pressure conditions, even when the breakdown is not sustained. The Hα intensity evolution suggests that the “burn-through” phase is not overcome in high pressure cases (0.4 MW of ECRH). Similar behaviour has been observed during the conditioning phase of the past campaign restart, when a high concentration of light impurities (C and O_2) was present in the vessel due to thin layer of organic compound that was deposited on the metallic wall following an accident on the insulator of some in vessel measurements. The low ECRH absorption at these conditions (~1% for $T_e \sim 30$ eV and $n_e \sim 0.5\ 10^{19} m^{-3}$) was not able to push plasma temperature above the radiation limit for light impurities, even at high power level (800 kW).

A second part of the experiment has been devoted to found the minimum value for electric field required for start up using ECRH. A low range of pre-fill pressure has been chosen ($2 \times 10^{-4} - 3 \times 10^{-4}$ mbar) while 400kW of EC power has been injected at t = 0. The transformer current was fed forward in the first 200 ms of the discharge (corresponding to the current ramp-up) in order to preset the loop voltage. The minimum value obtained is 2.5 V (corresponding to 0.38 V/m of electric field), while at lower value (2. V i.e. ~0.3 V/m) break down was not sustained. The minimum field has been obtained using 800 kW of power, where 400 kW were not enough. In Fig. 2 the plasma current derivative as a function of loop voltage is shown in different conditions: ohmic, 400kW of ECRH with pulse lengths of 50ms, 100ms and 200ms and 2 different powers at 20° of toroidal injection angle. At low breakdown electric field (pure ohmic case or short ECRH pulse) the derivative of the current is constant with respect the loop voltage, while for longer ECRH pulse (at the same E-field) I_p derivative increases with the pulse length. The lower derivative, achievable at minimum electric field, can be obtained only with ECRH. The introduction of toroidal angle reduces the I_p rate requiring, for the same value, to double the power. This suggests that a beneficial effect could be played by the standing wave established in case of perpendicular injection (absent in oblique case).

The short pulse ECRH (50ms) exhibits a higher threshold in electric field (0.8 V/m). This can be explained considering that the field null in FTU is moving across the vessel during the initial phase. From the ECE measurements, it is clear that ECRH is able to increase the temperature only after 60ms from the beginning, when the ECRH resonance crosses the null (or the forming plasma column) (fig.4) as confirmed by equilibrium reconstruction.

In a first attempt of moving the resonance 4 cm outwards no plasma has been obtained, suggesting that the alignment between resonance and field null is crucial.

The start up at minimum electric field allows saving transformer flux, as shown in figure 3 where a standard 500 kA discharge is compared with few ECRH assisted start up shots. But if we compare the flux (in Volt seconds) at same I_p and flat top length it is clear that the saving is modest: of the order 6% and essentially related to the resistivity reduction due to temperature increase obtained with ECRH in the I_p ramp. Nevertheless it has to be mentioned that in this preliminary result, the ramp up condition has not been optimized and a more solid conclusion can be taken only after further experiments dedicated to develop an optimized configuration that also minimize the ℓ_i term, being this last dominant in the flux consumption during the ramp up phase.

Conclusion. Summarizing the preliminary result obtained on FTU we have confirmed the possibility of low electric field start up using an appropriate ECRH power (at least 800kW in perpendicular injection). The limit value reached in FTU (0.38 V/m) can be further reduced with a more accurate plasma control positioning. The oblique launch increase the power needed to obtain a sustained breakdown, suggesting the existence of a beneficial effect of standing wave due to the power reflected by the wall in case of perpendicular injection. The transformer flux saved by using ECRH seems to be due only to the reduction of resistivity due to the higher temperature reached in ramp-up phase.

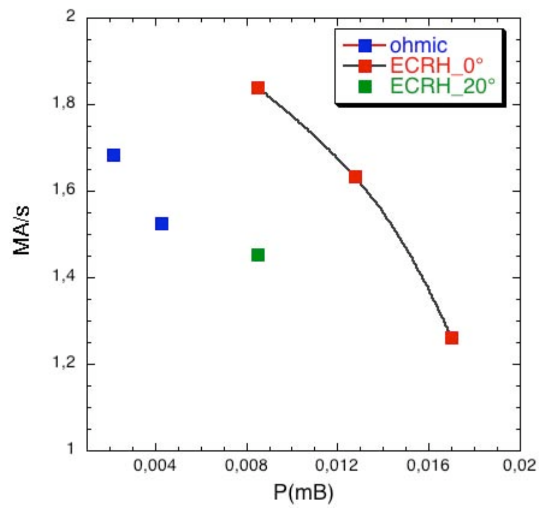

Fig.1 Comparison of Ip rate vs prefill pressure with/without 400kW of EC power in O-mode injected at 0° or 20° of toroidal angle

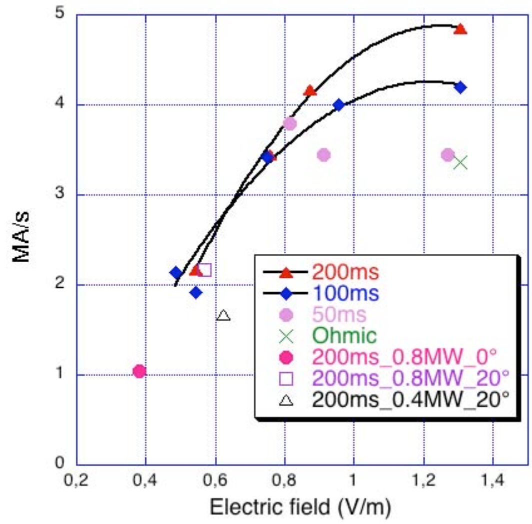

Fig.2 I_p derivative vs Electric field in different conditions. Filled point are at 0°injection

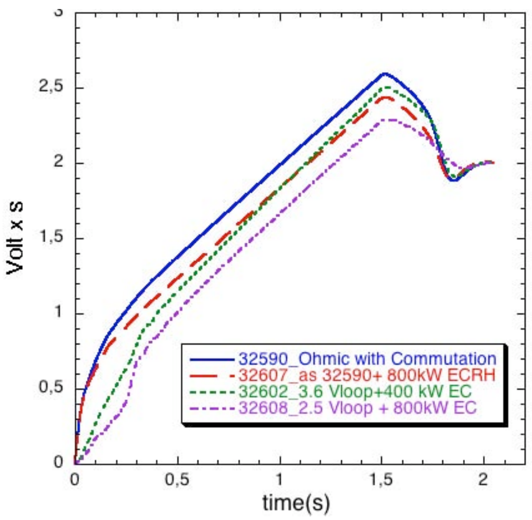

Fig.3 Comparison of toroidal Flux expressed in Volt s for different conditions: the flat top in case of low Vloop is shorter

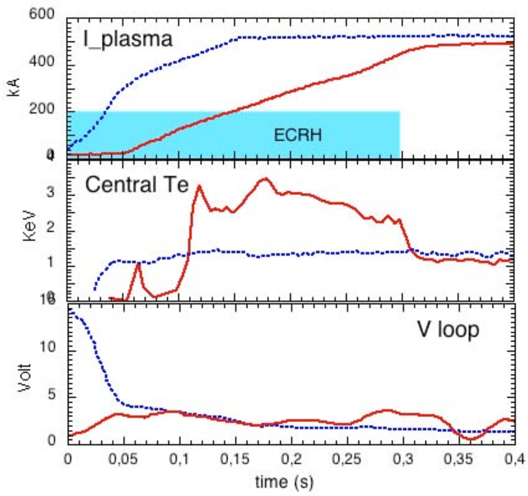

Fig.4 Comparison of standard break down (32509 blu dotted line) and low voltage ECRH (32602 red full line) assisted with 400kW at 0° toroidal injection.

References

[1] Kajiwara K. *et al* 2005 *Nucl. Fusion* **45** 694

[2] Jackson G. L. *et al* 2007 *Nucl. Fusion* **47** 257

[3] Jackson G. L. *et al* 2007 *Proc. 34th EPS Conf. (Warsaw, 2007)* vol 31F (ECA) P-1.141

[4] Kirneva N. A. *et al* 2007 *Proc. 34th EPS Conf. (Warsaw, 2007)* vol 31F (ECA) P-1.164

[5] Bucalossi J. *et al* 2008 *Nucl. Fusion* **48** 054005

[6] A.C.C. Sips et al., 22nd IAEA Fusion Energy Conf., paper IAAEA-CN-165/IT/2-2

[7] G.Calabrò *et al 2009 Nucl. Fusion* **49** 055002

[8] F. Zonca, *The FAST proposal*, this Conference