Plasma Start-Up Results with EC Assisted Breakdown on FTU

G. Granucci 1), G. Ramponi 1), G. Calabrò 2), F. Crisanti 2), G. Ramogida 2), W. Bin 1), A. Botrugno 2), P.Buratti 2), O. D'Arcangelo1, D. Frigione 2), G. Pucella 2), A. Romano 2), O. Tudisco 2) and FTU team*

1) Associazione EURATOM-ENEA, IFP-CNR, Via R. Cozzi 53, 20125 Milano, Italy
2) Associazione EURATOM-ENEA, C.R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy

E-mail contact of main author: granucci@ifp.cnr.it

Abstract. Several experiments aimed at optimizing plasma pre-ionization by using EC (Electron Cyclotron) waves have been carried out on many tokamak in recent years as the basis of a multi-machine comparison study made to define the best operation scenarios for ITER, where the plasma break down will have to be achieved with a toroidal electric field of only 0.3 V/m. The FTU (Frascati Tokamak Upgrade, R=0.935 m, a=0.3 m) contribution to this study is the main subject of the present work. A reduction in electric field, as can be obtained with pre-ionization by ECH, can lower the transformer flux consumption in the start-up phase leading to a longer plasma current flat top. This point is of particular attention in the conceptual design of the steady state scenario of the proposed FAST tokamak and has been addressed too. In the FTU experiment the scan in pre-filling pressure has evidenced the capability of EC power to increase, by a factor 4, the range of working pressure useful for plasma start-up. Varying the breakdown a minimum electric field of 0.41 V/m has been found with 0.8 MW of EC in perpendicular injection. A toroidal launching angle of 20° exhibits a reduced efficiency needing a factor 2 in power to obtain similar results. A scan in magnetic field has evidenced that plasma start up is likely insensitive to alignment between EC resonance and null position. A total transformer flux saving of 22% has been found acting on plasma resistivity (by increasing electron temperature) and on plasma starting point (for an internal inductance reduction).

1. Introduction

Several experiments aimed at optimizing plasma pre-ionization by using EC (Electron Cyclotron) waves have been carried out in the last years. These efforts are the basis of a multi-machine comparison study made to define the best operation scenarios for ITER [1]. Indeed the pre-formation of a low density plasma allows the start-up of plasma current with a reduced electric field. This is of the utmost importance for ITER where the plasma start-up will have to be achieved with a low in-vessel toroidal electric field ($E \leq 0.3$ V/m). Therefore a detailed experimental study finalized to better define the possibilities of ECRH ITER system to guarantee a robust and reproducible start-up has been planned on many Tokamaks [1-7]. The FTU (Frascati Tokamak Upgrade, R=0.935 m, a=0.3 m) contribution to this study is the subject of the present work.

The study of EC assisted breakdown on FTU has been directed also to develop scenarios with increased plasma duration. A reduction in electric field and internal inductance, as can be obtained with pre-ionization by ECH, can lower the transformer flux consumption in the start-up phase leading to a longer plasma current flat top. This is a point of particular attention also in the conceptual design of steady state scenarios of the FAST tokamak [8,9].

2. Experimental Setup

For the first series of experiments we have used up to 0.8 MW of EC power at 140 GHz (resonance at 5 T) produced by two of the four gyrotron of the FTU ECRH System [10] and launched to the plasma as O-mode, first harmonic (O1) by two independent steering mirrors.

* See Appendix of A. A. Tuccillo et al., paper OV/4-2, this conference

The two beams were directed to the center of the vessel in perpendicular (0°) or oblique (20°) direction with respect to the toroidal magnetic field, kept superimposed for all the cases. The EC power has been triggered at time t = 0 s, at the begin of the transformer current swing (commutation phase corresponding to the inclusion of a resistive bank in the circuit to increase the current drop in the primary winding) with a preset pulse duration of 100 or 200ms. The FTU null position (see Fig.1 left) is usually located in the high field side (HFS) of the vessel, moving outward as the equilibrium vertical magnetic field increases. The basic target for these experiments was an ohmic startup optimized at low loop voltage (V_l =8 V) without commutation, this in order to have a “marginal” breakdown and to be in a condition in which the EC power clearly influenced the plasma startup. The filling pressure is not measured on FTU during the startup sequence; therefore the pressure in vessel at the time of breakdown has been determined by opening time multiplied to the calibrated rate of the used valves. The calibration is performed on a dedicated vacuum system usually before any experimental campaign. The propagation time of the gas in the port is around 100 ms while the filling valves are opened 200ms before the t = 0. The studies on minimum electric field were done excluding the feedback control on plasma current for the first 200 ms of the ramp up phase and directly controlling the derivative of the current in the transformer.

3. Pre-filling Pressure studies

One of key parameters in plasma breakdown is E/p (ratio between electric field and pressure) that must be within a defined range depending on machine geometry, error field amplitude and null extension. In view of ITER (that will be limited in E) it is of great importance to be able to obtain sustained breakdown also for high pressure. A pressure scan on FTU has been done varying the gas valves opening interval. Using 0.4 MW of perpendicular injected EC power a sustained breakdown is obtainable until 9.5 mP, this represents an increased of a factor 4 with respect to the maximum achievable with pure Ohmic start up (2.3 mP) . For oblique injection the maximum pressure (4.6 mP) is only a factor 2 greater (see Fig. 1 right).

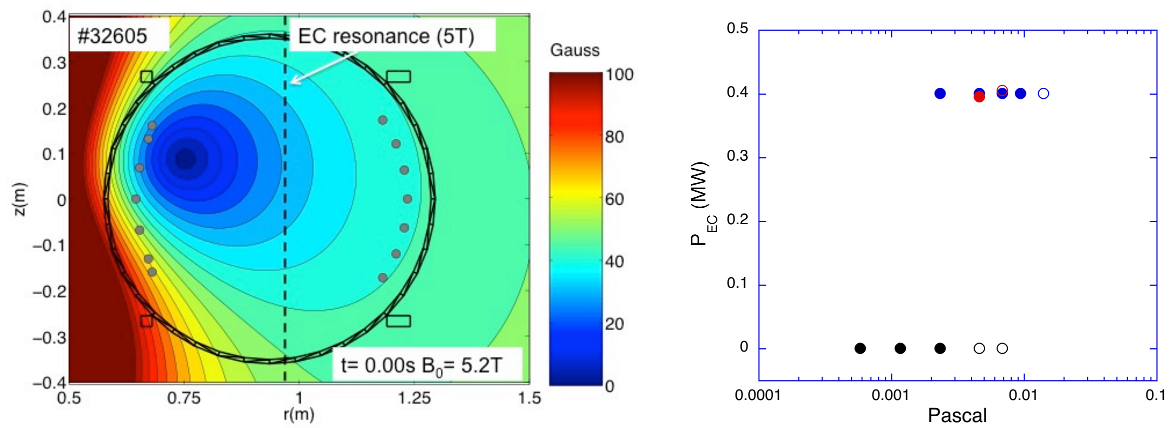

Fig.1: Left: FTU poloidal field at 0.0s. Toroidal and poloidal limiter together with the position of the EC resonance are shown. Right: Pressure scan for EC injected power; open circle: Not Sustained Breakdown, close circle: Sustained Breakdown. In blu perpendicular injections (0°) in red oblique (20°), in black pure ohmic cases.

The density growth rate at switch on of EC power, measured by SIRIO, the fast scan CO_2 interferometer of FTU [11], is inversely proportional to pressure indicating a key parameter in the power per neutral particle. After a peak, that seems independent of initial pressure, the density decreases in few milliseconds and electron temperature (Te) starts to increase (fig.2 left). The following burn-trough phase (when radiation losses dominates) is overcome if the absorbed power it is enough to increase Te. A different behavior is obtained with oblique launch. At 20° of toroidal angle a density growth rate 2.5 times higher than the perpendicular injection in the same conditions (pressure and power) is obtained and it increases with pressure, see Fig.2 right.

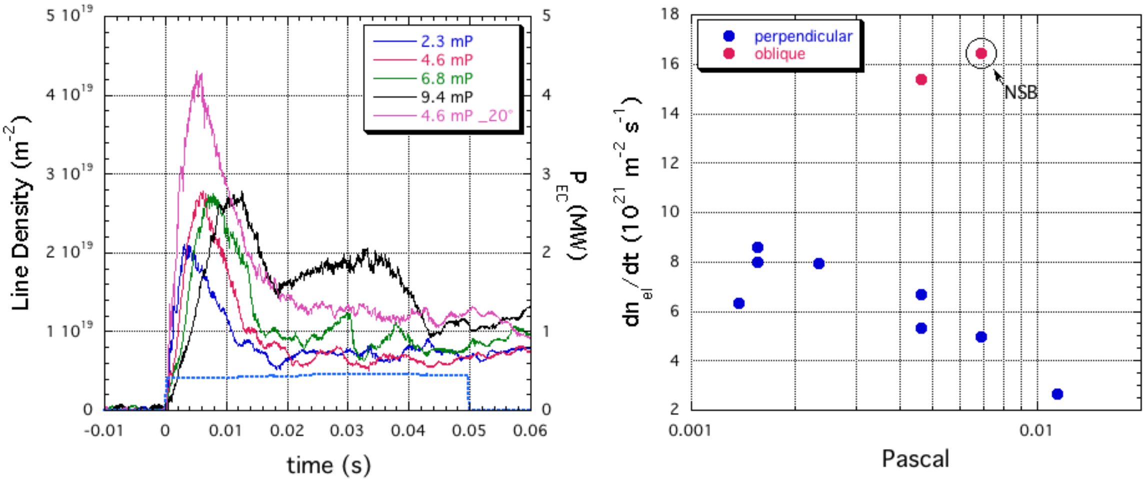

Fig.2 (left) Central line density evolution at different pressures. EC power is on right scale, in all cases toroidal angle is 0° except for the magenta one (20° of oblique injection); electric field is 1.5 V/m and B_0=5.3T. (right) Max of n_{el} time derivative as a function of pressure. Blue points refer at 0° and sustained breakdown. Red points for 20° of oblique injection, for the circled one sustained break down has not been achieved.

A comparison of density profiles also confirms a higher effectiveness of oblique injection in generating density. In all cases (line average) density profiles are peaked at the resonance, slowly degrading towards the LFS (Low Field Side) and wider in the case of oblique injection (see Fig. 3). This effect is enhanced by working at higher pressure, but it is also visible in case of low pressure and electric field (see following section).

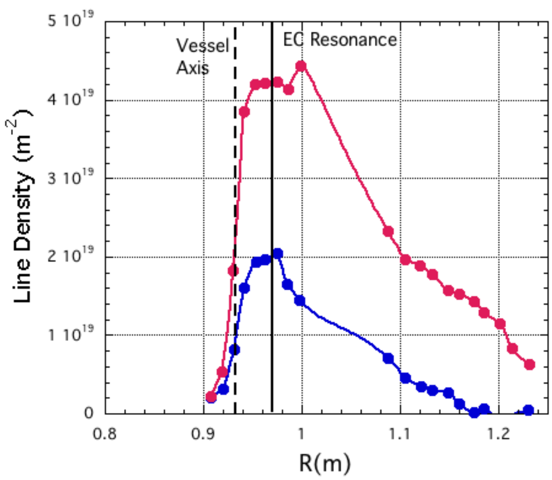

Fig.3 Line Density profiles for two different injection toroidal angles: 0° (blue) and 20° (red) at 3 ms after switch on of 0.4 MW of EC power. Pre filling pressure 4.6 mP.

The break down pressure limit increases with EC assistance with a wider range in case of perpendicular injection with respect to 20° oblique injection. This observation can be interpreted with a standing wave effect (beating between forward and wall reflected wave) that can locally double the power at resonant surface if the toroidal injection angle is 0° and that is not effective if the angle is oblique and the reflected wave is not backward.

4. Electric field studies

The main purpose of using EC power to preionize neutral gas is to obtain a reliable startup in case of low electric field (0.3 V/m the field expected in ITER). On FTU the minimum electric field for a sustained breakdown using EC power it is 3 times lower than that required for pure Ohmic breakdown. The minimum (0.41 V/m) has been found only in case of perpendicular injection, while for oblique injection more exploration is required.

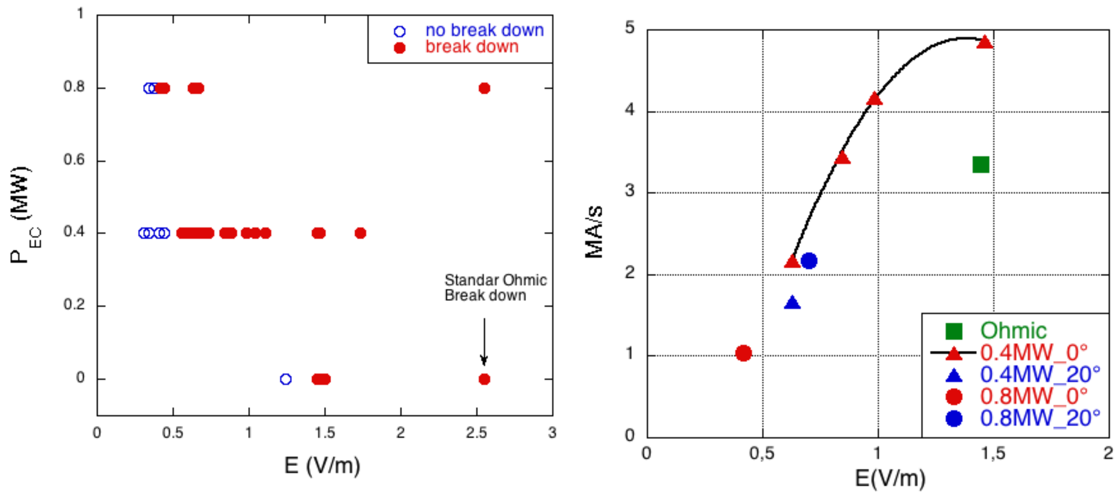

Fig.4 (left) FTU results for break down as function of electric field and EC power. (right) I_p derivative vs Electric field in different conditions of EC assisted break down. Pulse length is 200ms and pressure below 2 mP.

As a slower current ramp follows the reduced electric field, it is necessary to optimize accurately the equilibrium vertical field (B_v) in order to sustain plasma current in finding the real minimum. Such optimization has not yet done on FTU although it is at the basis of higher field limit found with respect to the other tokamaks [1].

The limit electric field depends on EC power (Fig.4 left) while the plasma current ramp rate (for low electric field case) is higher in case of perpendicular injection (Fig.4 right) and higher power. For injection at 20° it is required to double the EC power to obtain similar current derivative.

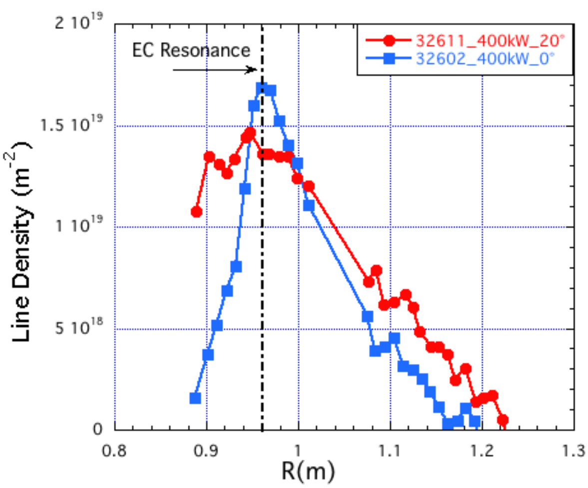

Fig.5 Line Density profiles measured 1 ms after EC switch on for 0° and 20° of injection angles.

The effect of reflection from the front wall in case of perpendicular injection is confirmed by measurements with sniffer probes located one at the top of the launcher sector and another displaced 60° toroidally. The stray field detected in the port is strongly reinforced for 0° injection, while at far away from the launcher the stray (i.e. not absorbed power) for oblique injection is equivalent to that of perpendicular. It has to be mentioned that part of the power injected in oblique direction is XM polarized **(11%)** and it is likely lost in multiple reflections. Line density profiles for oblique injection are wider with respect to perpendicular cases and without a pronounced peak (see Fig.5). This effect can be justified by considering that, in case of oblique injection, the reflection on the inner wall produces a partial depolarization of the wave, converting the OM in XM that at the upper hybrid frequency layer is then converted in electron Bernstein wave and quickly absorbed. This behavior is described in [12] and [13]. The wider density profile for oblique injection can be related to the wider region of absorption due to the above described mechanism.

5. Resonance position studies

One of the characteristics the experiment on FTU is the delay between application of EC power and the initial ramp up of the current (see Fig 6, left).

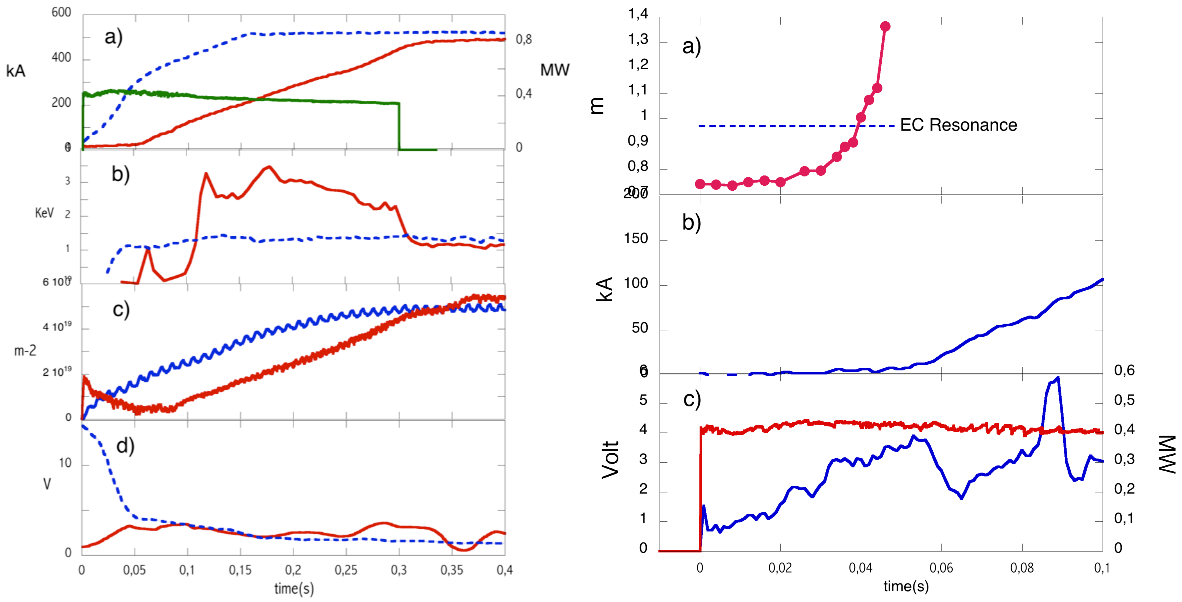

Fig.6 (left) Comparison between Ohmic startup (#32590, dotted blue) and a low E field EC assisted one (#32602, solid red): a) plasma currents and EC power (green), b) central Te, c) central line density, d) Vloop. (right) First 100 ms of the same shot. a) centre of the null evolution, b) plasma current, c) EC power (red line) and loop voltage (blue line).

One possible explanation was that the magnetic field null, formed on the inner side of the vessel (see Fig.1 left) and moving outer as the vertical field increased, crosses the EC resonance cylinder only few tenth of ms later with respect the time of power application (Fig.6, right); so that preionized plasma can be confined and originate plasma current only when or if R_{null}~ R_{EC}.

In order to confirm this interpretation, a scan of relative position between field null and EC resonance layer has been done by changing toroidal field in the same poloidal field configuration. At the same pressure and electric field conditions we have applied 400 kW of EC power (perpendicularly injected) in 3 different magnetic fields: B_{T0}= 4.8, 5.3 and 5.8 T. The resonance was therefore -12cm, +2cm and +14cm respect to R_0 and therefore at +6.5 cm, +20.5 cm and +32.5 cm with respect to the null. In all cases we obtain breakdown (electric field marginal ~1.4V/m); the fast density measurement and ECE profiles (see Fig. 7) evidence that the plasma is always initiated close to the resonance until the toroidal current, above 40-50 kA, establishes a tokamak configuration and a magnetic axis is formed in the usual location.

In case of resonance in LFS plasma current initiation occurs 10 ms early, with a lower breakdown electric field (1.3 V/m) and a higher electron temperature during the current ramp up phase (see Fig.8). The case with resonance in the HFS has the lower T_e during the current rise that begin 2ms early with respect the central resonance. Both off axis resonances exhibit a lower density for the first 100ms and a faster current ramp. In addition off-axis assisted startups have a flux saving of around 16% at the end of the current ramp with respect to the on axis one.

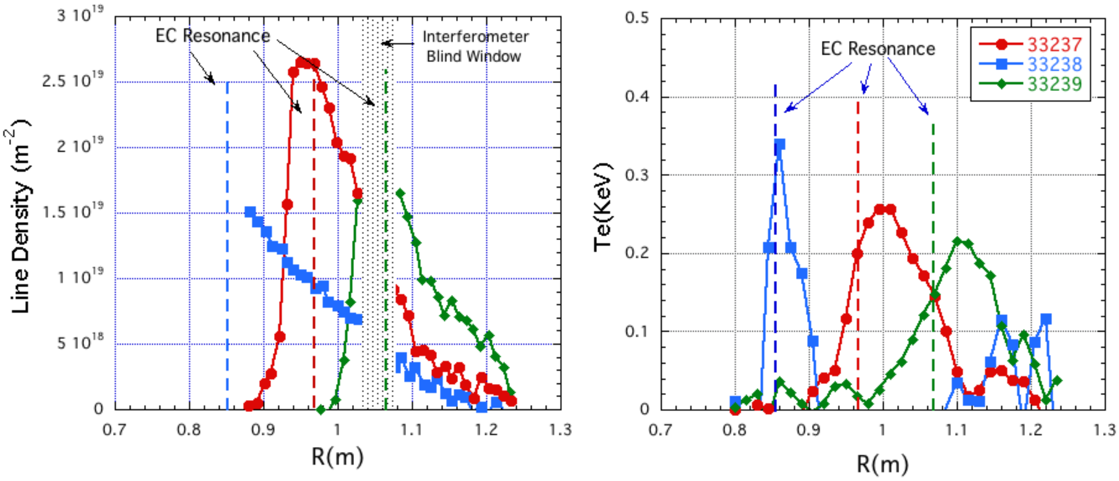

Fig.7 (left) Line density profiles versus major radius taken 5ms after 0.4MW of EC switch on for different resonance positions (dotted lines). The gray region is the blind window of CO_2 interferometer. (right) Electron temperature profiles from ECE-Michelson taken at 50 ms.

6. Flux saving

One of the expected advantages in using ECRH power to assist breakdown and plasma current ramp-up is the possibility to reduce the flux consumption and to extend the plasma

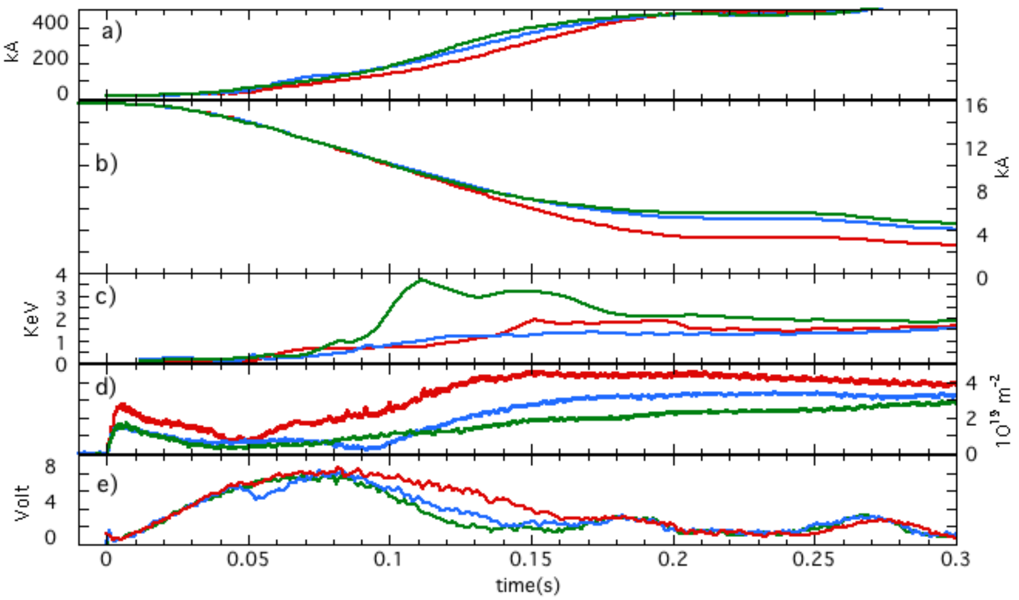

Fig.8 Time evolution of a) plasma current, b) ohmic transformer current, c) central electron temperature, d) line density at EC resonance major radius and e) loop voltage. Red lines refer to #33237 with R_0 -R_{EC} = +2cm; blue lines to #33238 with R_0 -R_{EC} = +12cm and green lines to #33239 with R_0 -R_{EC} = -14 cm. ECRH power are switched on at 0s with perpendicular injection.

current flat top when inductively sustained. The start up at reduced electric field is expected to save transformer flux, for the elimination of the commutation phase. But the comparison of fluxes (in Volt seconds) at same I_p and flat top lengths shows a modest saving: of the order 6% and practically related only to the resistivity reduction due to temperature increase obtained with ECRH during the I_p ramp. In fact the plasmas with reduced start up electric field have a slower current ramp with a shorter plasma flat top (being previously defined the end of the current). But from experiments described in the previous section, it is found that, when EC resonance is moved off-axis, saved flux can be further increased of ~16%. Moreover if the inner position of the resonance can be favoured by better alignment with the field null, it is not clear the reason why a strong reduction is observed also for the outer case, where electron should be faster lost. Even assuming that the equilibrium code fails in null reconstruction and the null is outer, the question cannot be solved because FTU poloidal coils configuration is compatible with only one null and the inner case should remain unexplained.
The internal inductance (ℓ_i), calculated starting from the equilibrium code ODIN [14] using the experimental pressure profiles derived from the data of Fig.7, is presented in Fig.9.

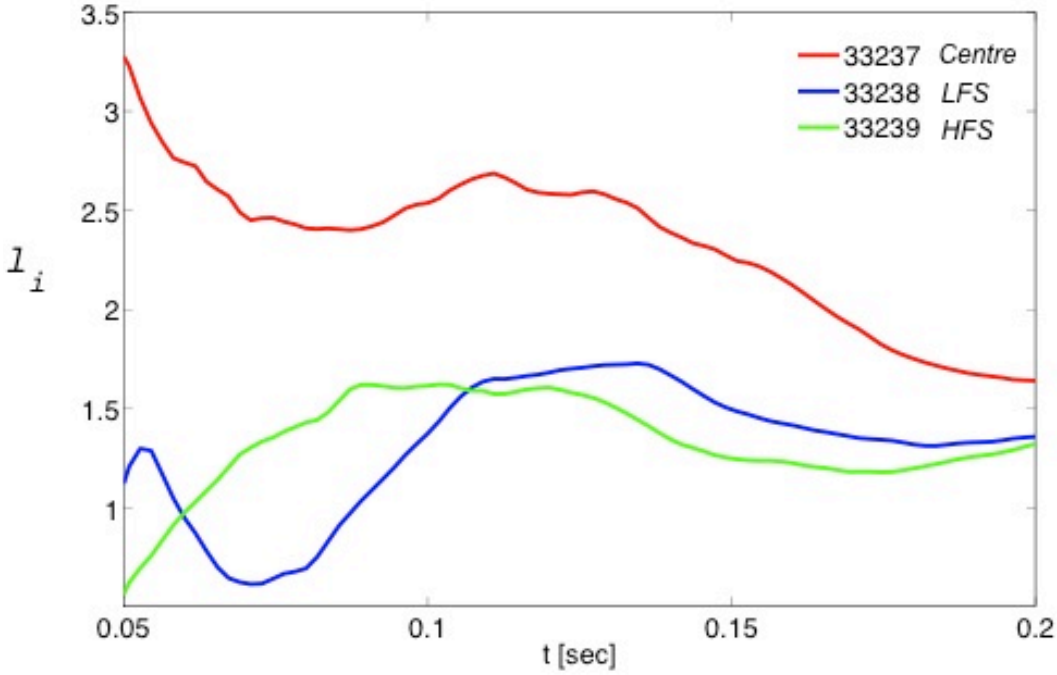

Fig 9. Evolution of internal inductance (normalized to $\mu_0 R$) calculated from ODIN reconstruction data and experimental pressure profiles. The line colours refer to different R_{EC} (the same of fig.8).

The off-axis cases have a sensible reduction of inductance for the first 200 ms of plasma, corresponding to the current rise phase. It is has to mention that, during the fast variation of plasma magnetic configuration the error in the reconstruction can be large. It is noticeable, in any case, the reduction of ~ 60% of ℓ_i when R_{EC} is at half radius on the HFS or on the LFS.

It is clear that a more and better controlled experiment done varying the distance R_{EC}-R_{wall} is essential to understand timing of I_p ramp and of the other important parameters (internal inductance and plasma resistance). Nevertheless it has to be mentioned that magnetic configuration has not been optimized and a more solid conclusions can be taken with further experiments dedicated to develop an optimized configuration that also minimize the term, that it is expected to be dominant in the flux consumption during the ramp up phase.

7. Data evidence interpretation and conclusions

The initial FTU studies on ECRH assisted plasma startup have demonstrated the capability to extend the useful pressure range of a factor 4 in useful breakdown. A reduced efficiency is found by launching with a toroidal angle different from perpendicular one, and a factor 2 in power is needed to obtain same results. This is likely connected with the positive effect of wall reflection in case of 0° injection that locally double the power. Also the possibility to obtain a sustained breakdown with a minimum electric field close to that foreseen on ITER has been demonstrated. In FTU the minimum electric field at 0° toroidal angle at 800kW is 0.4V/m. This value could be further optimized with a better control of the vertical equilibrium field; for 20°angle more experiments are required to find the minimum electric field. From the presented experiment the oblique injection exhibits a reduced efficiency in plasma ramp up rate and to pass radiation barrier (burn trough phase). This can be explained with a lower electron temperature reached with oblique injection, even if it has to mention that no direct measurement are available at that low T_e. On the other hand 20° angle has better performance in generating plasma density, with higher and wider profiles. This is supposed to be related to a different absorption mechanism of the XM polarization generated, for oblique propagating wave, after the first reflection from the wall. An increase of experimental database and a more theoretical approach are required to explain these results since in ITER 20° will be the toroidal injection angle of Equatorial Launcher to have the resonance close to the center and the determination of the required power for EC assisted breakdown could be different from 0° injection. The breakdown successful has been found to be insensitive to resonance position at least in the range ±0.5 r/a, while with the off-axis resonances a faster current ramp is obtained with a sensible (16%) reduction in flux consumption with respect to the central resonance position. In this last case the flux reduction as been found to be modest (6% in case of FTU) and essentially due to the resistive reduction which is a consequence of the higher temperature, during the current ramp, when EC power is used. In any case summing of the two effects a pulse extension of 22% can be obtained. Further optimizations are required also in this case, especially to clarify the reason for the strong reduction observed whit off-axis resonance positions.

8. References

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