Electron Cyclotron Resonance Heating Assisted Plasma Start-up in the Tore Supra Tokamak

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Abstract. In ITER and future fusion reactors, plasma startup will have to be achieved with a low in-vessel toroidal electric field (≤0.3 V/m in ITER) due to the use of superconducting coils and the presence of thick toroidally continued in-vessel structures. The benefit of using additional power to assist plasma startup has been demonstrated and studied in several devices, however some uncertainties remains on the requirement on the ECRH pulse characteristics for ITER. This paper reports on further results obtained on ECRH assisted startup on Tore Supra (R = 2.4 m) at the fundamental and second harmonic EC resonance as it is foreseen to be used for ITER start-up. Tore Supra ECRH system is based on two 118 GHz gyrotrons (<600 kW). The power is injected into the plasma as Gaussian beams by an antenna located on the low field side which, using actively cooled mirrors inside the vacuum vessel, allows control of both poloidal and toroidal injection angles.

Pre-ionization was obtained with one gyrotron in less than 1 ms at the fundamental resonance location. Successful plasma startups were obtained with EC assistance down to 0.15 V.m^{-1} at 5 mPa deuterium filling pressure (~300 kW). It was possible to initiate the discharge at up to 25 mPa deuterium pressure at 0.3 V.m^{-1} with ~225 kW of ECRH (5 mPa maximum without). This significantly enhances the start-up reliability and limits the runaway electrons generation. After a disruption, the use of two gyrotrons (~525 kW) during 70 ms helped reducing the number of failed attempts compared to the case with lower power.

The location of the resonance was varied from R ~2.2 m, near the center of the torus toward the inner wall, R ~1.9 m, and startup was achieved up to mid-radius. Besides, the toroidal and poloidal injection angles were both varied, respectively from -30° (co-current) to 0° (perpendicular) and from -15° (aiming at the centre of the torus) to +2° without any observed significant difference.

Second harmonic EC assist startups were also achieved at half field and slightly higher loop voltage (0.5 V.m^{-1}) either with perpendicular and co-current launch angles.

1. Introduction

In ITER and future fusion reactors, plasma start-up will have to be achieved with a low in-vessel toroidal electric field (≤0.3 V/m in ITER) due to the use of superconducting coils and the presence of thick toroidally continued in-vessel structures [1, 2]. Plasma start-up has already been obtained at such low electric fields in some tokamaks, however, the robustness and reliability were found to be poor in particular in the restart phases following vacuum vessel venting and after plasma disruptions. Therefore, ECRH is planned to be used in ITER to assist the plasma initiation and impurity burnthrough phases. The benefit of using additional power to assist plasma start-up has been demonstrated and studied in several devices [3-5], however some uncertainties remains on the requirement on the ECRH pulse characteristics for ITER. This paper reports on further results obtained on ECRH assisted start-up on Tore Supra at the fundamental EC resonance and at the second harmonic as it is foreseen to be used for ITER start-up.

2. Experimental setup

Tore Supra is a large size superconducting tokamak designed to run long pulse discharges, with a circular cross-section (R = 2.4 m, a = 0.72 m). Its first wall is covered with a set of water cooled stainless steel panels. Six CFC poloidal inner bumpers protect the inner wall and the top of the vessel from plasma excursions while a mobile poloidal outboard CFC limiter protects the outer part. The main plasma-wall interaction takes place on the bottom Toroidal Pumped Limiter (TPL), a high heat flux component covered with CFC tiles. Additional heating is provided by RF systems only (ICRH, LHCD and ECRH). Four of the six RF antennas are equipped with pair CFC limiters. In total, 15% of the inner vessel surface (~100 m^2) is covered with CFC.

The toroidal magnetic field is provided by 18 superconducting coils (NbTi). An iron core, a central copper solenoid and 8 poloidal field copper coils control the plasma current, position and shape. The inner vessel resistance is ~1.1 mΩ. One important electrical feature, in particular at the plasma startup, is the conductive passive loop constituted by the TPL (resistance ~1 mΩ). This loop is very close to the plasma and generates a significant "stray" magnetic field ($B_\perp$).

The toroidal electric field is measured with a set of flux loops. The prefill pressure is measured with a baratron gauge (capacitance manometer). The line integrated density is measured by a multi-chord infrared interferometer. A tangential fast CCD camera (Phamtom v.7) with a broad angle view (800x600) allows for the monitoring of the plasma formation.

The present Tore Supra ECRH/ECCD system is based on two 118 GHz gyrotrons. The power, up to ~600 kW, is injected into the plasma as Gaussian beams by an antenna located on the low field side which, using actively cooled mirrors inside the vacuum vessel, allows extensive control of both poloidal and toroidal injection angles [6].

The toroidal field in the centre of the vessel is normally at B_T~3.87 T which gives a fundamental electron cyclotron resonance at R~2.17 m, on the high field side. The polarization of the wave is controlled by a pair of actively cooled corrugated mirrors in each matching optics unit allowing pure O-mode or pure X-mode power injection for all injection angles.

3. Plasma startup with fundamental EC assist

3.1. Comparison with low voltage ohmic startup

The standard ohmic startup in Tore Supra is performed at high voltage, typically 25 V, which corresponds to a toroidal electric field in the centre of the vessel of ~1.7 $V.m^{-1}$ (R = 2.4 m), with a deuterium prefill pressure usually around 20 mPa [7].

By reducing the prefill pressure and optimising the magnetic field map, it was possible to successfully initiate the discharge without assistance down to 4.5 V or ~0.3 $V.m^{-1}$ at the maximum toroidal field (B_T = 3.87 T). Below, the "stray" magnetic field $B_\perp$ resulting from the pre-magnetisation currents and the eddy currents induced in the structure and notably in the toroidal pump limiter (passive loop) hinders the breakdown of the gas or the ramp up of the plasma current. When decreasing the loop voltage, the prefill pressure is more and more difficult to adjust (dependent on wall loading) and the reliability of the breakdown strongly decreases.

EC-assisted discharge initiation has been recently studied on Tore Supra [7]. ECRH power is injected a few ms after the application of the loop voltage at the end of the pre-magnetisation sequence (in other devices, ECRH power is usually applied before the loop voltage for pre-ionisation). In the figure 1, an EC-assisted plasma initiation is compared to an ohmic one. The EC power, provided by one gyrotron (A1 ~ 225 kW), is injected perpendicularly in O-mode for fundamental resonance heating (B_T = 3.87 T, R_{O1} = 2.17 m). With ECRH, the plasma current initiates when ECRH is applied, a few ms earlier than in ohmic in this case. The ionization occurs within a couple of ms at the resonance layer location as shown by the time evolution of the vertical IR interferometer chord (R_{Ch3} ~ 2.2 m). The plasma expansion is also faster and the impurity burnthrough is earlier as indicated by the spectroscopic measurements. The EC pulse length of 50 ms is long enough to insure proper plasma initiation (end of burnthrough). The assistance of ECRH also lowers the loop voltage resulting in a poloidal flux saving of ~0.13 V.s at the end of the initiation phase available for extending the current flattop duration.

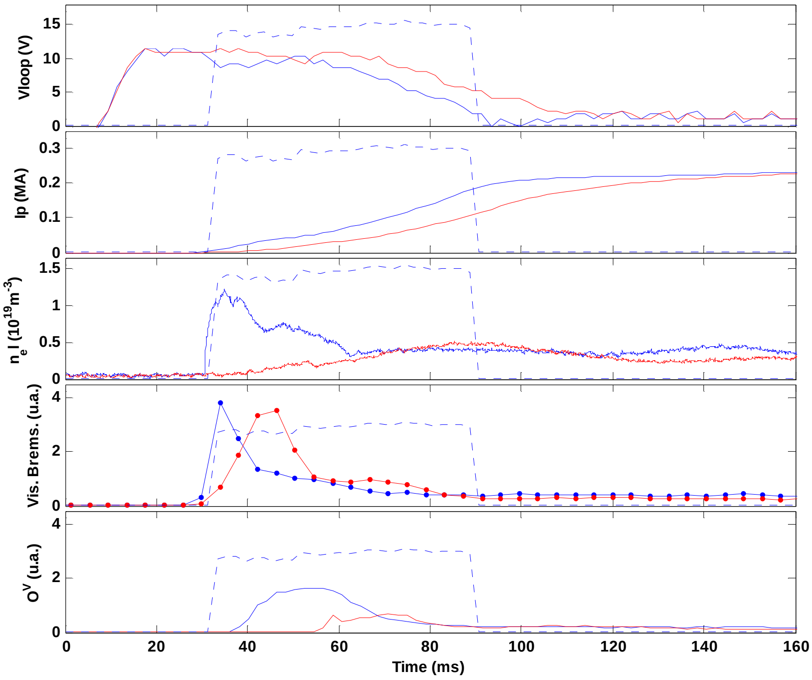

FIG 1. Ohmic startup (red; TS-41434) compared compared to ECH startup at fundamental resonance (blue; TS-41433) in Tore Supra. Time evolution of Vloop, Ip, n_el (vertical chord at R~2.2 m), visible bremsstralung and OV line; ECH power (225 kW) is represented in arbitrary unit in the different panels.

With one gyrotron in O-mode it was possible to initiate the plasma down to 0.15 V.m^{-1}, half the maximum electric field that should be available in ITER, at 3.87 T and 5 mPa with the full pre-magnetisation (high “stray” magnetic field $B_\perp$ conditions).

3.2. Influence of prefill pressure

In ohmic startup, the prefill pressure is constrained by the loop voltage according to the Townsend avalanche condition [2]. ECRH assistance allows avoiding this constraint.
At low toroidal electric field, ~0.2 V.m^{-1}, a scan in prefill pressure has been carried out with one gyrotron (~200 kW in O-mode) to investigate the maximum achievable startup pressure. The results are reported in figure 2. It was possible to initiate the plasma at up to 25 mPa with a 50 ms duration ECRH pulse. The plasma current ramp up rate decreases with the pressure from 1 MA.s^{-1} at 6 mPa to 0.3 MA.s^{-1} at 30 mPa. At 15 mPa, a maximum is reached in the electron density at the resonance location (n_el_3 from vertical chord at R~2.2 m) indicating a possible optimum pressure for that level of ECRH power. The maximum plasma density reached ~8.3 10^{18} m^{-3} in the resonance region to be compared to ~5.5 10^{18} m^{-3}, the estimated average D atom density in the vessel before the ECRH application. A rough estimate of the total number of electron from all the vertical chords gives 20% ionization after 10 ms and 2 kJ of ECRH (~250eV/ionisation). Above 15 mPa, an increase in ECRH power should result in an increase of the plasma density and the current ramp up rate.

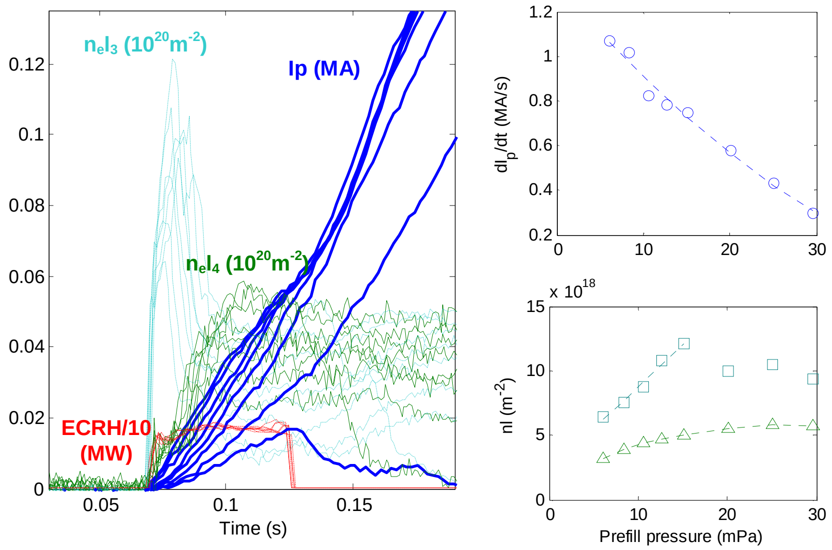

FIG 2. Prefill pressure scan (D_2). Left: time evolution of the plasma current, line-integrated electron density (chord #3: EC resonance location, chord #4: central chord) and ECRH power for 8 consecutive discharges with increasing prefill pressure (TS-40730→TS-40737). Right top: corresponding plasma current ramp up rate (until maximum nl_3 is reached) versus prefill pressure. Right bottom: corresponding maximum nl_3 and maximum nl_4 versus prefill pressure.

3.3. Influence of EC power

The EC power was varied using the two available gyrotrons (A1 ~ 300 kW, A2 ~ 225 kW) in order to investigate the influence of the EC power during plasma initiation. The three discharges presented in the figure 3 have been performed with the same parameters at fundamental resonance except the total EC power (P_{D2} ~ 7mPa, $E_{//}$ ~ 0.2 V/m, B_T= 3.87 T).

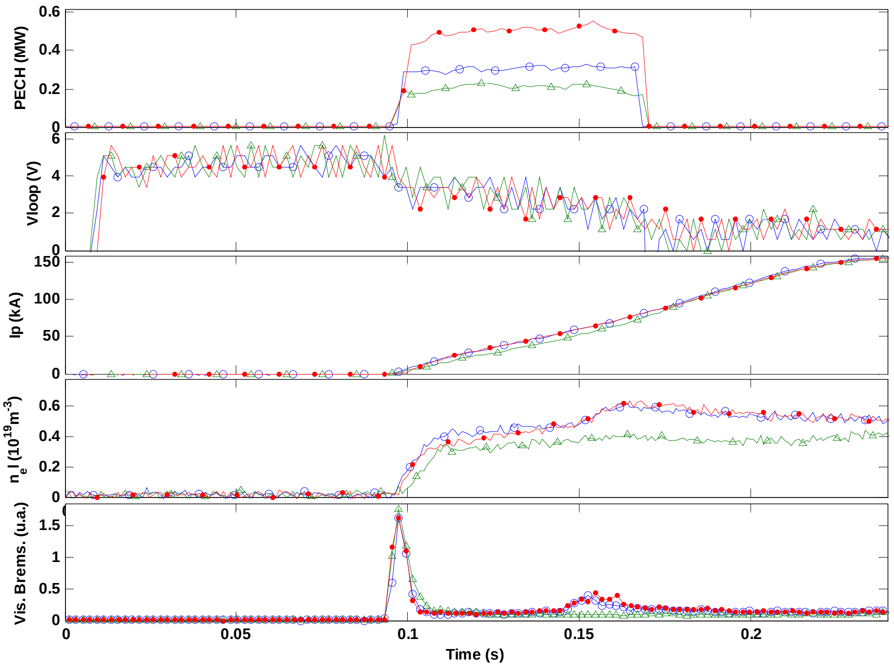

FIG 3. Influence of ECRH power during plasma initiation; time evolution of PECRH power, loop voltage, plasma current, central line integrated electron density and visible bremsstralung (red dot: TS-40759; blue circle: TS-40756; green triangle: TS-40757).

In these conditions, there is no gain using the two gyrotrons. With the weaker gyrotron (A2~225 kW), the plasma current ramp up rate is slightly lower and the plasma density substantially lower. With A1 and both gyrotrons, the time evolutions are quite similar indicating that 300 kW could be an optimum for that prefill pressure. Besides, there is some impurity release as can be seen from the visible bremsstralung after 50 ms possibly due to an excessive ECRH power not absorbed by the plasma.

After a disruption, the use of two gyrotrons during 70 ms helped to survive the impurity burnthrough phase reducing the number of failed attempts compared to the case with lower power.

3.4. Influence of EC resonance location

The influence of the resonance location was also investigated. The available position range at the fundamental resonance is limited to the high field side. Attempts have been made from ~2.17 m to ~1.9 m (ρ ~ 0.7). As illustrated in the figure 4, the plasma current barycentre is initiated at the resonance location. This is confirmed by the IR interferometer measurements.

As the plasma current is increased, the current barycentre moves outwards reducing the effect of ECRH power. After ~30 ms of ECRH, the plasma current starts to decreases when R_{O1}<2.17 m and eventually the current channel is destabilized by the TPL induced current when R_{O1}~1.9 m (TS-41293). Nevertheless, successful startup was easily achieved for $\rho \leq 0.55$. A better control of the current channel formation position should allow keeping the resonance inside the plasma and extend furthermore the resonance location operating window.

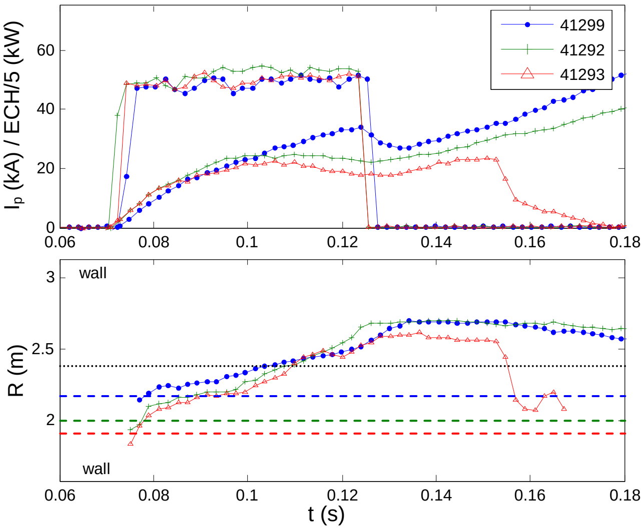

FIG 4. Resonance location scan. Top: time evolution of plasma current and ECRH power for three different discharges. Bottom: time evolution of the barycentre of the plasma current; the location of the resonance is plotted in dashed line, the dotted line indicates the request for plasma major radius.

3.5. Influence of the EC launch angle

The EC launch angle influence has been investigated at fundamental resonance with one gyrotron (A1~300 kW) and low loop voltage (0.25 V.m^{-1}). Both the toroidal and poloidal injection angles were varied, respectively from -30° (co-current launch) to 0° (perpendicular launch) and from -15° (aiming at the centre of the torus at the resonance) to +2° (aiming at ρ ~ 0.5 at the resonance) without any observed significant difference.

4. Comparison with second harmonic EC assist

Second harmonic ECRH is envisaged in ITER for half B_T operation. Experiments in X2-mode have been performed in Tore Supra in the perspective of ITER. Both gyrotrons A1 and A2 were used (~525 kW) at $B_T = 1.93$ T. The ionisation was found to be slightly more difficult in X2-mode. In fundamental O-mode, the ionisation starts whenever the EC power is applied while in X2-mode, at the same ECRH power, a proper magnetic configuration is required depending on the connection lengths. Indeed, the ionisation can be delayed until the magnetic configuration fits. A delay of ~30 ms is observed in TS-42270. At half B_T, connection lengths are halved and, in the present magnetic configuration, 0.5 $V.m^{-1}$ were necessary to get successful startup in X2-mode (no ionisation at all without EC assistance in the same conditions).

The plasma initiation observed with the fast CCD visible camera is shown in figure 5 for O1-mode and in figure 6 for X2-mode. In the first case the ECRH power was applied at ~66 ms (V_{loop} ~ 4.5 V) and in the second at ~45.5 ms (V_{loop} ~ 7 V). In both cases, the power was launched perpendicularly, the prefill pressure was ~9 mPa and the breakdown was sustained.

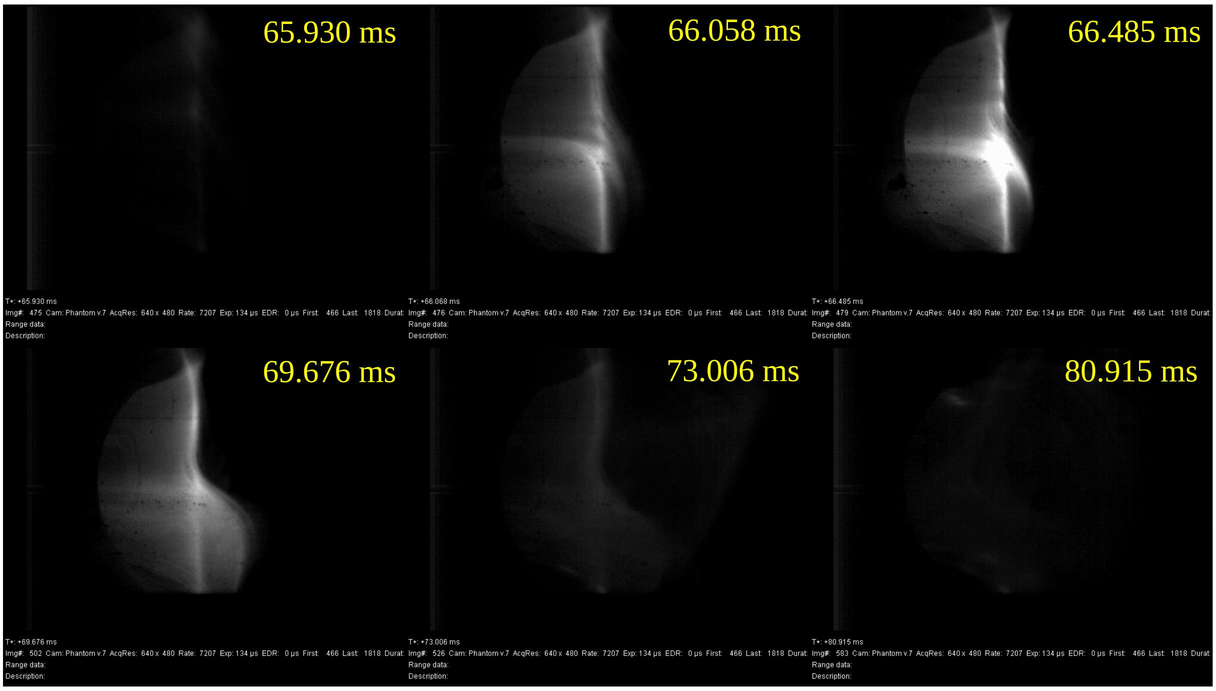

FIG 5. Plasma initiation with fundamental resonance EC assistance; frames from a visible CCD fast camera, Exp = 134 µs (TS-42249).

The ionisation patterns are somewhat different: in O1-mode the resonant layer is perfectly resolved and the maximum emission is already reached ~1 ms after the EC injection, while in the X2-mode, the ionisation is more homogeneous (confirmed by IR interferometer measurements), the absorption at the resonant layer being still the dominant absorption mechanism as expected by theory. Polarization scrambling after multiple wall reflections seems to be limited. It has to be noted that the exposition time of the camera is nearly four times higher in the X2-mode startup.

The closure of the flux surfaces can also be observed and occurred ~10 ms after the beginning of the ionisation at about 10 kA. In some non sustained breakdowns, plasma currents up to 20 kA could be driven without closing the flux surfaces.

Tangential launch angles for X2-mode injection has also been attempted. It was also possible to initiate the plasma in co-current launch (-30°) at 8.5 V (~0.6 $V.m^{-1}$).

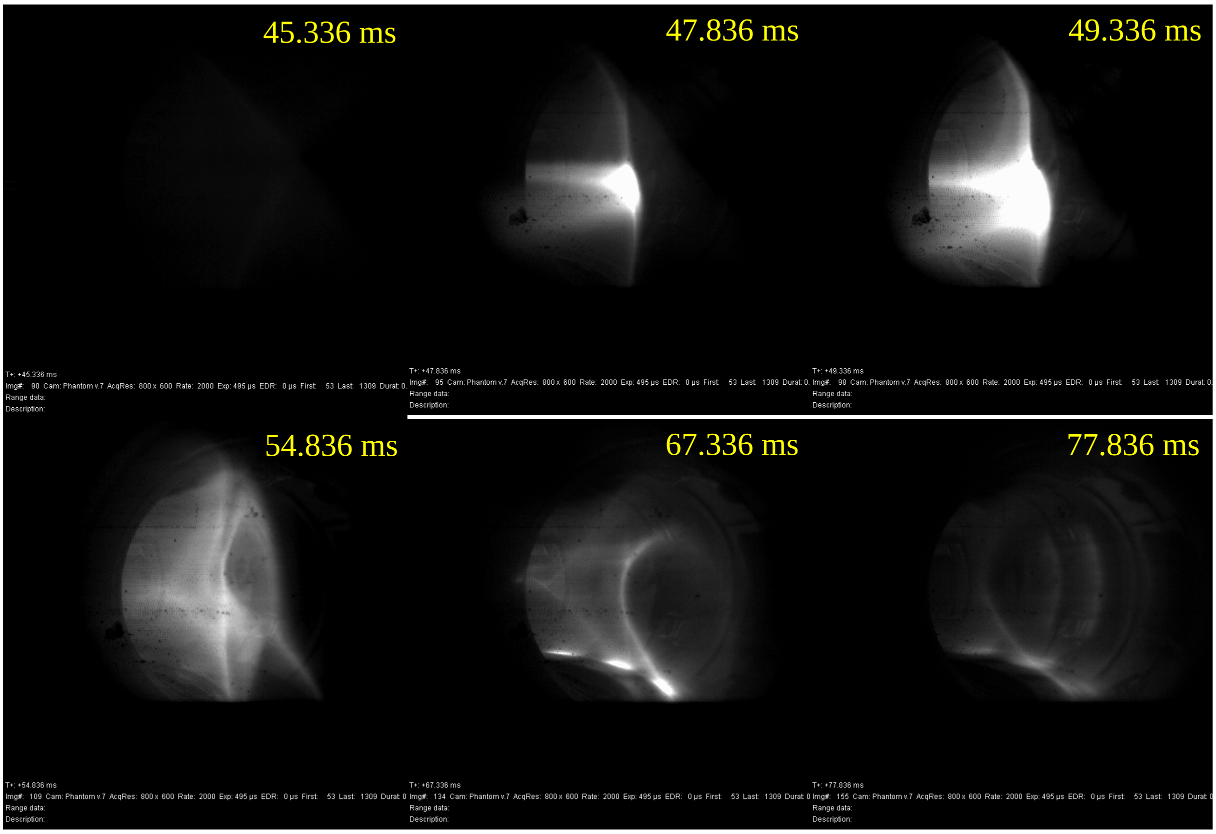

FIG 6. Plasma initiation with second harmonic EC assistance; frames from a visible CCD fast camera, Exp = 495 μs (TS-42261).

5. Discussion

The results reported in this paper confirm previous works carried out on other devices [2, 5]. They indicate that plasma startup is feasible, at least in Tore Supra, at ITER maximum electric field and even lower at fundamental resonance. The ECRH assistance widely opens the ohmic startup windows as illustrated in figure 7. It allows minimising runaway electron generation and reduces the sensitivity to wall conditions.

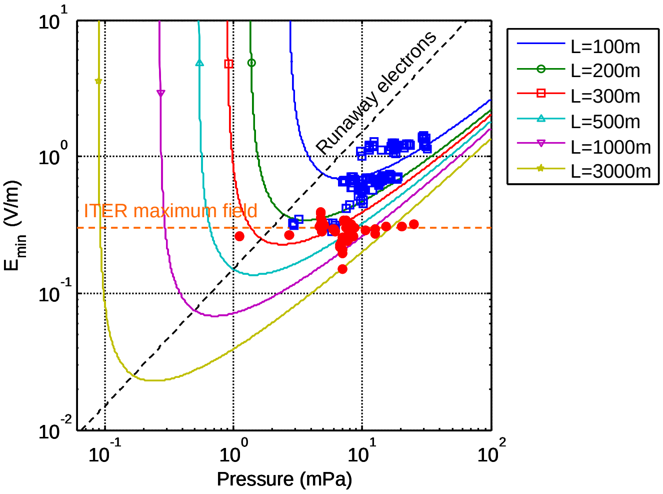

FIG 7. Successful plasma startups in the pressure - toroidal electric field diagram. Each open square (blue) corresponds to an ohmic startup, each full circle (red) to an ECRH assisted startup (fundamental resonance).

The ECRH power exhibits an optimum value which is a function of the prefill pressure. Above this value, the plasma current ramp up rate saturates (and radiated power increases). In Tore Supra, 200 kW of ECRH power at fundamental resonance was found to be sufficient to get robust plasma startup at the ITER toroidal electric field.

The resonance location is not an issue for pre-ionization in fundamental O-mode providing that it is inside the plasma vessel. Keeping the resonance inside the plasma column as the current is raised is a difficult task that implies an early control of the position of the current channel formation region. A better control of the current channel radial and vertical position (Ip < 50 kA) should allow to even increase the ECRH assisted plasma startup operating window. Second harmonic is more troublesome and require some careful optimisation of the startup sequence.

Assuming similar impurity content, 1 MW of ECRH power at fundamental resonance could be enough to reliably start-up ITER plasmas at the fundamental resonance (from ITER/TS radius ratio). Second harmonic EC assist might require more power. Further experiments in X2 mode are needed to provide a sound estimation.

6. Acknowledgement

This work, supported by the European Communities under the contract of Association between EURATOM and CEA, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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