*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.164 (2007)*

Plasma Start-up Optimization with 2nd Harmonic ECR pre-ionization in T-10 Tokamak

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Pre-ionization with help of Electron Cyclotron Resonance (ECR) waves and ECR assisted plasma start-up are considered as useful tools for discharge initiation in next step devices, in particular in ITER to save the poloidal flux and to avoid an electron beam generation. Second Harmonic ECR waves are proposed for these issues during the first stage of ITER operation. Recently the 2nd Harmonic ECR pre-ionization has been experimentally investigated in JT-60U [1] and DIII-D [2] tokamaks. This paper is devoted to the investigation of the breakdown conditions and ECR assisted start-up with 2nd harmonic ECR waves in T-10 tokamak (R=1.5 m, a=0.3 m) in Deuterium plasmas.

1. Optimization of Ohmic breakdown conditions

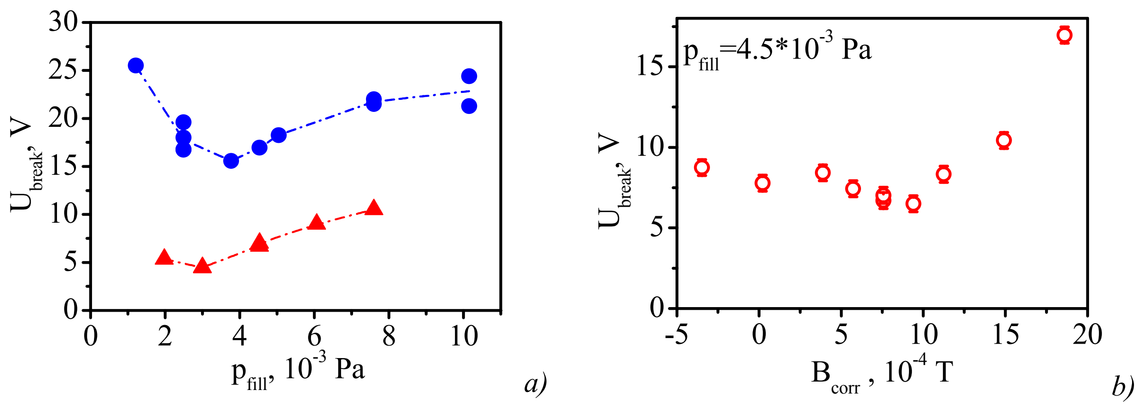


Fig. 1 Ohmic breakdown. (a) Dependence of the breakdown voltage (U_{break}) on a prefill pressure (p_{fill}) for two values of vertical correcting field $B_{corr}=2*10^{-3}$ T (circles) and $B_{corr}=0.8*10^{-3}$ T (triangles). (b) dependence on the vertical correcting field taken at $p_{fill}=4.5*10^{-3}$ Pa.

At the first step ohmic breakdown conditions were optimized by changing of the neutral gas pressure and by compensation of the error fields (Fig.1). It led to the decrease of the breakdown voltage down to the value of 4.2 V (in comparison with the value of ~16-20 V in usual case of T-10 operation). That corresponds to the electric field value $E_{||}\cong 0.44$ V/m.

Delay of the plasma breakdown in relation to the application of ohmic voltage at the minimum of $U_{break}(p_{fill})$ dependence has been found to be 15 ms. Breakdown has occurred in a wide area (r~a). The decrease of the prefill pressure below the $p_{fill}=3*10^{-3}$ Pa has led to the appearance of the electron beam, that has been observed by X-ray and ECE diagnostics.

2. ECR wave initiated breakdown

ECR power $P_{EC}\cong0.3$-1.1 MW (2nd ECR harmonic, X-mode, linear polarization) has been used for pre-ionization and ECR assisted startup. Important feature of these experiments is the usage of one gyrotron (P_{EC} up to 0.45 MW) equipped by a focusing mirror. Diameter of the beam of this gyrotron has been equal to 1.6 cm at e^{-1} level. Beams formed by two other gyrotrons in use (total power up to 0.55 MW) had the beam width d=8 cm at e^{-1} level. Investigation and optimization of the pure EC breakdown conditions (without application of ohmic voltage) has been done. Development of the ECR initiated breakdown is presented in Fig. 2.

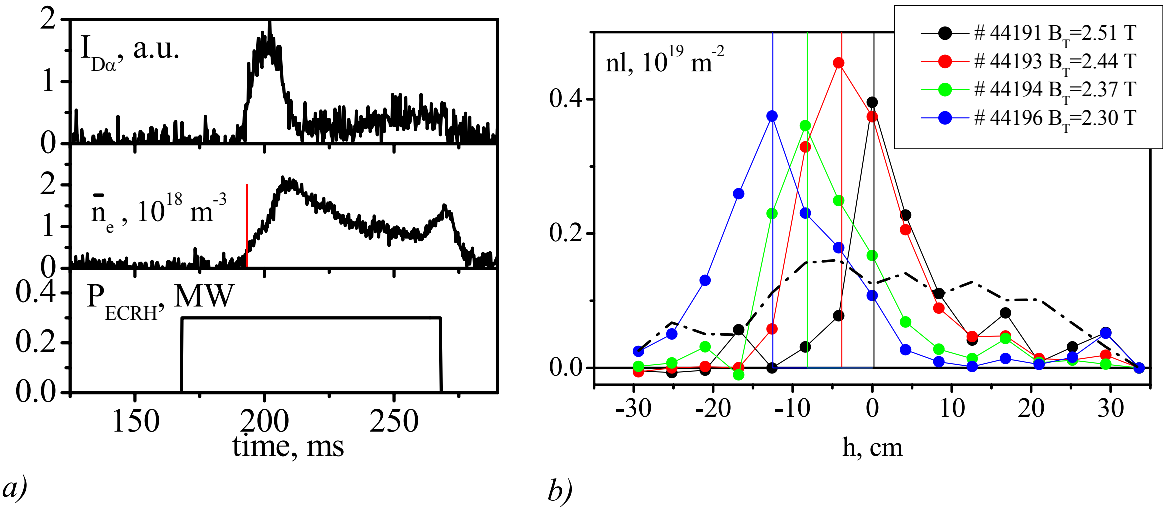
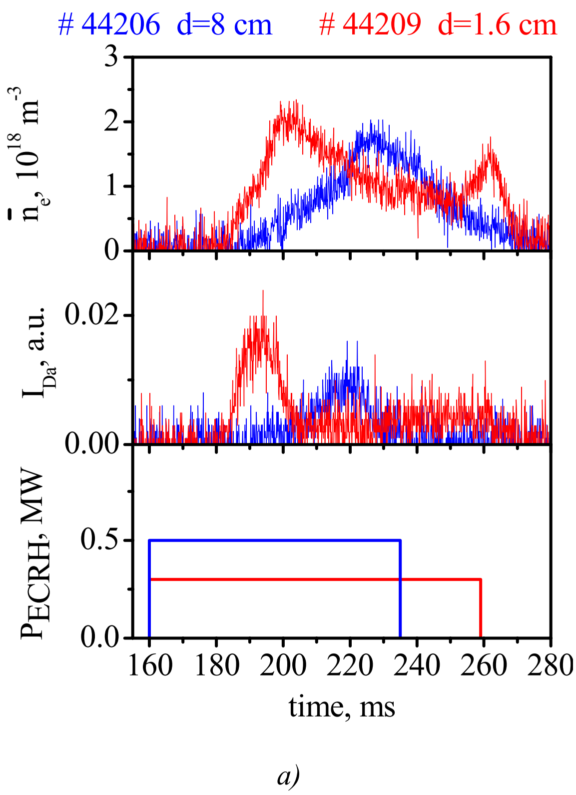


Fig. 2 Pure ECR breakdown. Gyrotron with focused beam has been used (a) development of the breakdown: signal of D_α emission, line average density measured along the central chord of HF interferometry, ECR power value; (b) breakdown area for shots with the different toroidal magnetic field value. nl – interferometer signals, i.e. the plasma density integrated along the relevant chord. Time instant when the profiles have been taken is shown in Fig.2,a by a red line. The nl(h) profile for the ohmic breakdown (multiplied by 4 for better presentation) is presented by dashed line. h=0 corresponds to the center of the vacuum chamber.

Experiments with variation of the toroidal magnetic field have been done to analyse a link between breakdown position and EC resonance position. Magnetic field has been changed in a range of 2.3-2.51 T that corresponds to the relative shift of resonance position up to 12 cm. Results of the magnetic field scan are shown in Fig. 2, b in terms of line integrated density profiles. It is seen that the breakdown position corresponds to the EC resonance position (marked by solid lines in Fig. 2, b). The line integrated density profiles are given for Ohmic breakdown case for comparison. It is seen that the breakdown area in case of the EC assisted breakdown becomes narrower than in case of OH breakdown.

Existence of two beams with different width allowed us to investigate dependence of breakdown conditions on power density or wave electric field amplitude. Results of these experiments are shown on Fig. 3. Power distribution inside of the EC beam is shown on Fig. 3, b.



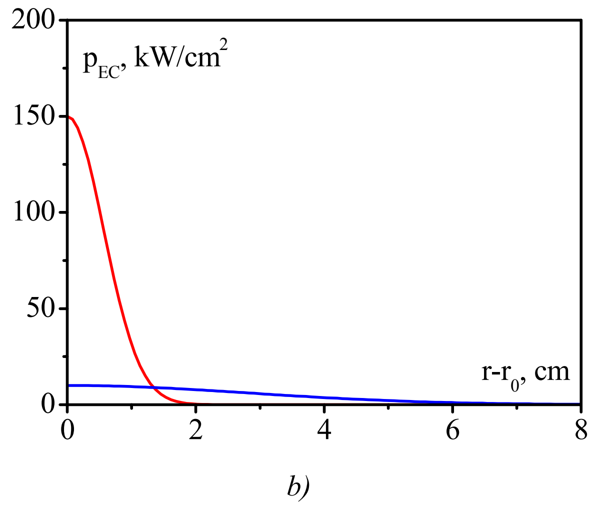


Fig. 3 Comparison of plasma ECR initiated breakdown with different width of ECR beams. (a) – scenario of the experiment, (b) – EC power deposition inside of the beam for the shots presented in Fig. 3,a. r_0 – position of the beam axis.

It is clearly seen in Fig. 3,a that in case of narrow EC beam the breakdown occurs earlier and the density increment is higher even in spite of the lower total power value. It is necessary to note that EC wave assisted breakdown in T-10 has been achieved at low EC power value (2nd harmonic ECR), $P_{ECRH} \leq 0.5$ MW. As it is seen from the Fig. 2, 3, time delay of the ECR assisted plasma breakdown is ~10 ms.

Dependence of the breakdown development on toroidal launch angle has been examined using focusing gyrotron. Comparison has been made between oblique launch with φ_T=21° and perpendicular EC power launch φ_T=0°. It can be proposed that in T-10 conditions oblique power launch is more favorable than perpendicular one (see Fig. 4 for comparison).

3. ECR assisted plasma start-up

Optimization of the discharge start-up conditions using ECR waves allowed us to decrease the loop voltage and toroidal electric field up to the value close to the ITER requirements at the instant of breakdown and during further discharge development. Plasma current ramp-up rate has been chosen to be equal to 1 MA/s and has been automatically controlled by the feedback control system. Results of the experiments are shown in Fig. 4 for both oblique and perpendicular power launch. Advantage of the scheme with oblique power launch is pronounced: breakdown delay time is shorter; the density reached after the breakdown is higher. It is important to note that the loop voltage during the current ramp-up in case of the oblique EC power launch the loop voltage is close to the ITER requirements at the very beginning. Further increase of the loop voltage is the result of a peculiarity of the discharge positioning control and is the task for further improvement.

It is necessary to note here that additional reduction of the loop voltage value up to the 2.6 V ($E_{\|}\cong 0.28$ V/m) has been achieved by the decrease of the current ramp-up rate down to the value of 0.7 MA/s.

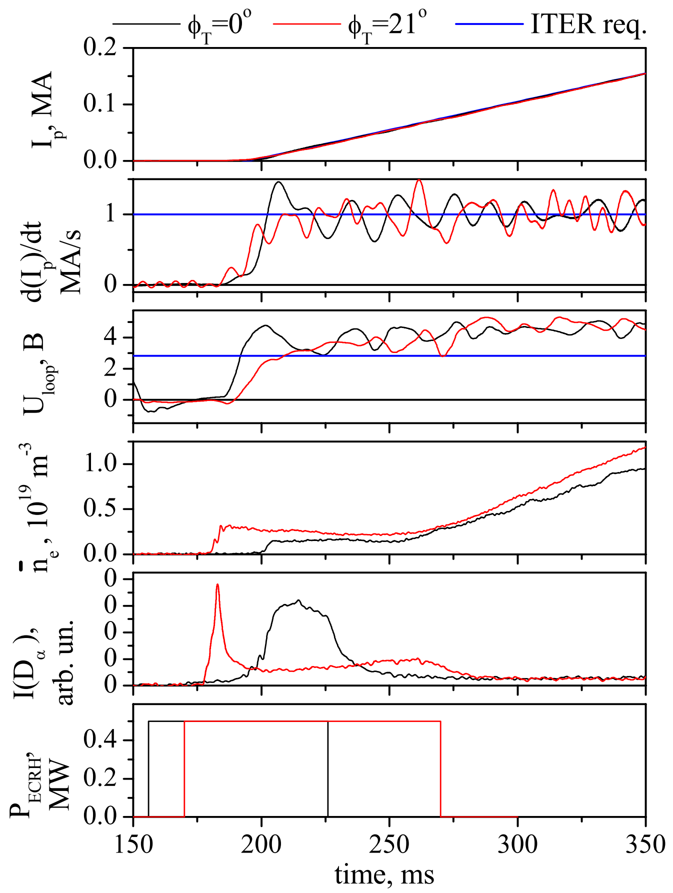


Fig. 4 ECR assisted discharge start-up with two different schemes of power launch. ITER requirements are also shown.

This work has been supported by Nuclear Science and Technology Department of Rosatom and Scientific School Grant (Contract No. 02.516.11.6068)

[1] K. Kajiwara et al, Nucl. Fusion 45 (2005) 694

[2] G.L. Jackson et al, Bull. Am Phys. Soc., 51(2006)272, Presented at APS-DPP 2006 (Philadelphia, Pa), 30-Oct-3Nov. 2006; G.L. Jackson et al submitted to Nucl. Fus., 2006