Investigation of discharge initiation by ICRF antenna on URAGAN 3-M

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Introduction

The experiments on ICRF discharge initiation were performed on the $l = 3$ URAGAN 3-M (U-3M) torsatron with a natural helical divertor located in Kharkiv, Ukraine in frame of the EU (Belgium) - Ukrainian collaboration on ICRF Plasma Production. The experimental motivations were: (i) to study the dependencies of the breakdown time on the neutral gas pressure and the antenna power and (ii) investigate the hypothesis for the gas breakdown trigger as the moment of *LHR* generation in the antenna-field vicinity [1] by Langmuir probe measurements. The standard Frame antenna [2] was operated at $f = 8.6$MHz, variable RF power ($P = 15-130$kW, RF voltage at generator, $V_{RF} = 3-9$kV), confining magnetic field $B_T = 0.01-0.72$T to produce RF plasma in hydrogen at a continuous gas flow with pressure range $p_{H_2} \approx 1\cdot10^{-3} - 2\cdot10^{-2}$Pa. Whereas sustaining a fully ionized hydrogen RF plasma takes place in the Alfvén wave range of frequencies ($\omega < \omega_{ci}$) for the given operation frequency at higher magnetic fields ($B_T \sim 0.72$T). The hydrogen gas RF breakdown moment is characterized by dominant concentration of the hydrogen molecular ions H_2^+ [1]. This results in the breakdown performance in the U-3M case in the frequency range $\omega > \omega_{ci}$, which allows existence of the *LHR* for all tested B_T values.

Experimental results

During the ICRF discharge initiation experiments on TEXTOR, ASDEX Upgrade, JET and TORE SUPRA, a breakdown event was defined as the moment when the antenna voltage V_{RF} drops and H_α signal rises [3]. This definition is adopted as well during the experiments on the U-3M. It is observed that the signals of antenna voltage V_{RF} and H_α showed uncontrolled low amplitude oscillations caused by EM interference between RF heating and diagnostic electronics and hindering correct estimation of the breakdown time t_{bkdn} as shown in figure 1(a). Figure 1(a) demonstrates the V_{RF} and H_α signals for a typical shot on U-3M together with the time evolution of the average electron density $\langle n_e \rangle$ obtained from a microwave interferometer located in vicinity of the Frame antenna. The rise in H_α signal and drop in V_{RF} signal occur clearly at

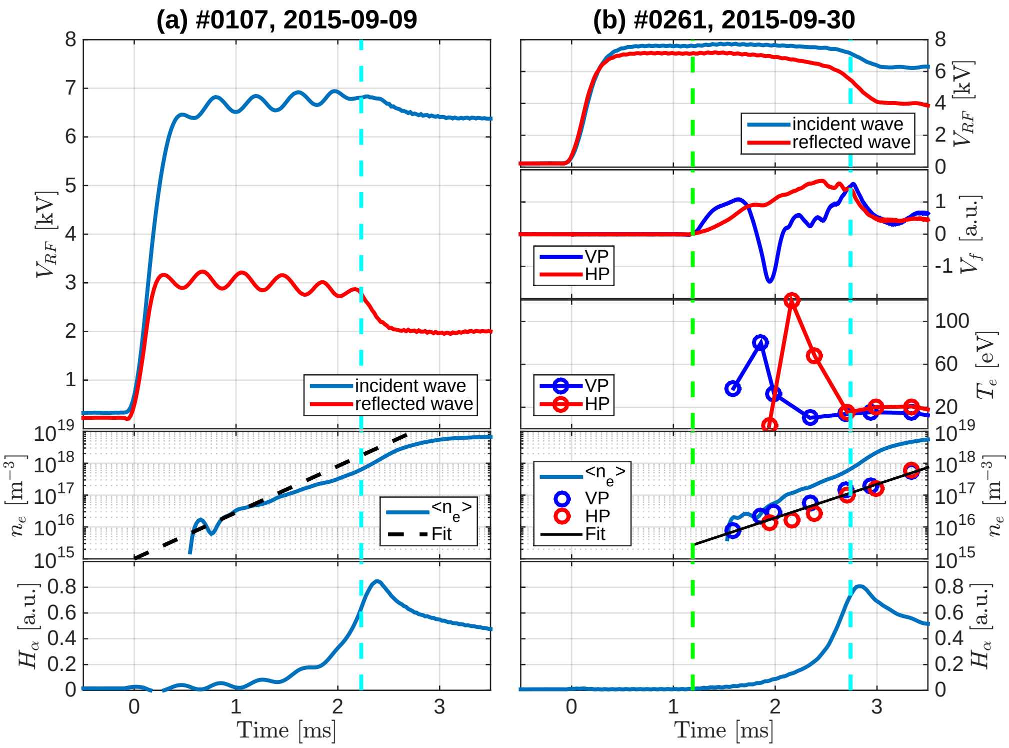

Figure 1: Comparison of experimentally observed indications of gas breakdown during ICWC in U-3M for shot at $V_{RF} = 6\text{kV}$, $p_{H_2} = 6.3 \cdot 10^{-3}\text{Pa}$ and $B_0 = 0.72\text{T}$ (a) in the first part of the experiment with oscillations of the signals and (b) improved measurement without oscillations. Time traces of forward (blue) and reflected (red) RF power delivered to the Frame antenna from generator, average electron density $\langle n_e \rangle$, and H_α signal, additionally in (b) floating potential registered by the antenna-near vertical Langmuir Probes, electron temperature T_e, electron density n_e by LP and by interferometer.

different time instances: the antenna voltage drop occurs around $\approx 2.2\text{ms}$ (cyan dashed vertical line) and corresponds to $\langle n_e \rangle \approx 6 \cdot 10^{17}\text{m}^{-3}$, and the H_α signal rises around $\approx 1.1\text{ms}$. The $\langle n_e \rangle$ signal is extrapolated (black dashed line) to reach the LHR density in the U-3M antenna vicinity ($n_{e-LHR} \approx 3 \cdot 10^{15}\text{m}^{-3}$ at $f = 8.6\text{MHz}$, $B_{ant} \approx 0.64\text{T}$, on-axis $B_0 = 0.72\text{T}$, and $n_{H_2^+}/n_{H^+} = 20$), resulting in a breakdown time of about $\approx 0.4\text{ms}$. Nevertheless, this fit isn't very trustworthy as the fitted densities are close to the detection limits. Furthermore it is clearly visible that the discharge is already initiated at the moment of the V_{RF} drop.

In a selected number of shots, 40 out of 540, the oscillations could be successfully mitigated. In this part of the experiment additional measurements of the plasma floating potential, electron density and temperature were obtained using vertical and horizontal arrays of the Langmuir probes illustrated in figure 1(b). One of the LP arrays ("vertical probes", VP) was inserted into the vacuum chamber from the top in the Frame antenna vicinity: at $\sim 3\text{cm}$ from the antenna edge and 14.5cm from the torus midplane. Another LP array ("horizontal probes", HP) was placed horizontally from the LFS far from the antenna (1.8 period-distant from the antenna feeding point) at ~ 0.5cm inside from the plasma edge. The first response of the antenna voltage V_{RF} in this improved measurement is visible around ≈ 1.2ms (green dashed vertical line) which occurs at the same time with the first response on the floating potential V_f measurements by the antenna-near vertical (VP) and horizontal (HP) Langmuir probes, and also with the rise of the H_α signal. The drop in V_{RF} again occurs later at density $\langle n_e \rangle \approx 6 \cdot 10^{17}\mathrm{m}^{-3}$ (cyan vertical line). The I-V characteristic of the Langmuir probes are used to estimate the electron temperature and density evolution in time. The results of the n_e and T_e evolutions are also illustrated in Figure 1(b) (third and fourth figure from top). Due to strong RF perturbations the electron density n_e and temperature T_e could be reliably analized starting with delay ~ 0.4ms with respect to the first increase in V_f ($n_e \approx 7 \cdot 10^{15}\mathrm{m}^{-3}$, $T_e \approx 37$eV). Extrapolation of the density curve to the gas breakdown moment defined as the first appearance of the radiation, assuming constant ionization rate (black line), indicates density of the order of $\sim 3 \cdot 10^{15}\mathrm{m}^{-3}$, which is in an agreement with the predicted LHR density in the U-3M antenna vicinity.

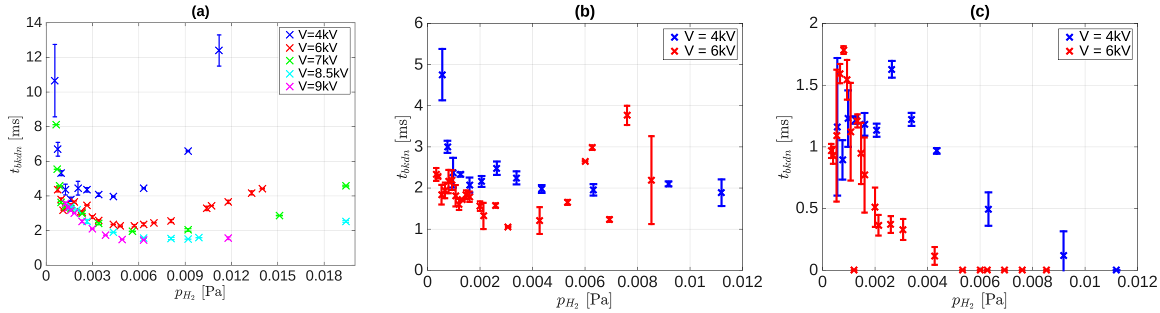

Figure 2: (a) The breakdown time t_{bkdn} (V_{RF} drop) t_{bkdn} dependency on the varying neutral gas pressure for different strap voltages, $V_{RF} = [4; 6; 7; 8.5; 9]$kV; The t_{bkdn} dependency on the varying neutral gas pressure for different strap voltages, $V_{RF} = [4; 6]$kV for the 'breakdown' definitions: (b) H_α signal rise (c) reaching the *LHR* threshold density.

The discrepancy between the different defined breakdown moments (i) drop in the antenna voltage V_{RF}), (ii) rise in H_α signal and (iii) possible theoretical breakdown definition (*LHR* threshold density) shows the challenge in defining the breakdown moment in ICRF plasma initiation. All mentioned breakdown definitions were tested and compared in Figure 2 where the breakdown time dependency t_{bkdn} on the neutral pressure p_{H_2} is plotted. In Figure 2(a) t_{bkdn} is defined as the moment of antenna voltage drop, Figure 2(b) shows t_{bkdn} defined as the moment of H_α signal rise and Figure 2(c) illustrates definition of the t_{bkdn} as the moment of reaching the n_e^{LHR}. All three definitions shows slightly different dependencies, but only the definition by the voltage drop could be consistently registered during the whole experiment. Extrapolating of the interferometry density data to *LHR* resonance was not reliable, while the

H_α signal was difficult to interpret due to its low amplitude oscillations. Therefor to study the breakdown moment dependency on the neutral gas pressure and the antenna power for all 500 shots in more details the experimental definition of the antenna voltage drop (cyan dashed line in Figure 1) is used.

The dependencies of the experimental breakdown time on the neutral gas pressure and the antenna voltage are plotted in Figure 2. In the case of the varying pressure (Figure 2(a)), the results show the existence of an optimal value for the pressure which result in the lowest breakdown time for each antenna voltage. This optimal pressure is shifting towards higher pressures with the increasing antenna voltage. The breakdown time is decreasing with increasing magnitude of the voltage on the strap.

Conclusion

The experiment carried out on U-3M in Ukrain illustrated the challenge of defining 'breakdown' of ICRF plasmas. The experimental breakdown definition, connected to the antenna voltage drop, occured on U-3M at a higher electron density by an order of two ($n_{e,br}^{exp} \approx 6 \cdot 10^{17}\mathrm{m}^{-3}$) than the prediction by the theoretical threshold density, $n_{e,br}^{LHR} \approx 3 \cdot 10^{15}\mathrm{m}^{-3}$. Appearance of H_α radiation occurs well before the RF voltage drop but after reaching the LHR threshold density. In addition simulations of the ICRF discharge initiation with `RFdinity1d3v` demonstrates that the first clear plasma behavior and subsequent acceleration of the ionization rate is visible around $\omega = \omega_{p,e}$. This condition is another 2 orders below LHR critical density [4]. Starting from the vacuum the electron density evolution crosses several important threshold densities while reaching a density which produces a floating potential, is detectable by interferometry, detectable via H_α radiation, and/or sensible by RF diagnostics. Up to now we do not have any indications in the experiments that one of the critical densities is dominant or the most influential for the density evolution. Depending on parameter range one may dominate over the other. Furthermore these observations cannot directly confirm the LHR as being trigger for the breakdown due to difficulties to measure such low electron density.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training pro- gramme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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