RF plasma production at relatively low magnetic fields in the LHD

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Introduction

The production of plasma in low magnetic fields is of interest to provide conditions for investigating high beta plasma confinement and to create discharges suitable for wall conditioning. In low magnetic fields, plasma production by resonant electron cyclotron waves, which is routinely used at stellarators, is not possible. In this situation, the radio frequency (RF) system can be used to produce plasma. Plasma production by RF discharges is possible both in the range of ion cyclotron (IC) frequencies [1,2] and above the IC frequency $\omega >> \omega_{ci}$ [3-6]. In the case of RF discharges, no change in frequency is necessary to produce the plasma. Such RF discharges ($\omega >> \omega_{ci}$) have been applied previously for wall conditioning in smaller stellarator devices [3-5] and tokamaks [6]. Such a plasma production have a chance to be successful in large helical machines too. This paper presents the results of a study of RF plasma production in relatively small magnetic fields on the Large Helical Device (LHD).

Experimental details

The experiments used Hand-Shake form antennas (HAS) and Field-Aligned-Impedance Transforming antennas (FAIT). The antennas occupy the upper (U) and lower (L) ports. The frequency of the RF generator was 38.47 MHz with input power of up to ≈ 1.2 MW, at a range of magnetic fields of 0.4-0.5 T. The experiments were carried out in a deuterium gas atmosphere. A programmed gas injection was used. And it was realized in the following way. The gas was injected continuously into the vacuum chamber during the shot, and the value of the gas flow changed pulse. The number of pulses its duration and the time interval between them were adjustable.

Experimental results

Figure 1 shows the parameters of the RF shot in a 0.5 T magnetic field. The first gas pulse started 110 ms before the start of the RF shot. At the time, the pressure increased from ~ 4×10^{-4} to ~ 2×10^{-3} Pa. In the beginning, starts FAIT (L) antenna and after 400 ms HAS (U) antennas. The RF breakthrough occurs in a very short time. The line intensity D I (see fig. 1) begins to increase almost without delay immediately after the start of the RF shot. After ≈ 100 ms after the start, density ~ 4×10^{17} m^{-3} is reached. With only FAIT (L) antenna and a power of ≈ 0.48 MW, a maximum density of ≈ 0.5×10^{19} m^{-3} is achieved (see fig. 1). After the start of HAS (U) antenna, the plasma density begins to increase. The second gas pulse is performed at the stage of increasing plasma density. As a result, the maximum plasma density reaches a value of ≈ 1.2×10^{19} m^{-3} at injected RF power 1.2 MW. Then the plasma density decreases and a third gas pulse is made. After which the density increases. After that, the density increases to almost the maximum value. And the density dynamics repeats. After the fourth gas pulse, the plasma density drops smoothly until the end of the RF shot. The intensity of line D I increased during and after the gas pulse. Note that the dynamics of plasma density and pressure are similar (see fig. 1).The programmed gas injection allowed to make conditions favorable in pressure for RF gas breakdown and production of dense plasma. The plasma temperature apparently was not high and decreased with the gas injection. As can be seen from the figure 1 the intensity of the C III line decreased and the P_{rad} shows a relatively small decrease. Spectral line C IV was not observed. However, spectral lines of oxygen O V and O VI are observed. At the same time, the dynamics of intensities of the oxygen line are similar to line C III, i.e., the intensity decreases after the gas pulse. Supposedly oxygen is ionized in the center of the plasma where the temperature is higher and carbon in the peripheral layers of the plasma where the temperature is lower. Because the oxygen is in the volume of the vacuum chamber and carbon may come from the walls.

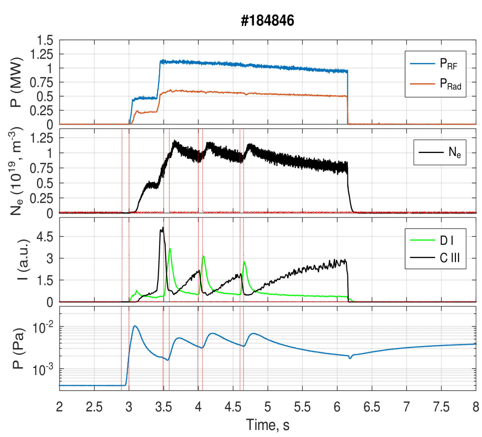

Fig. 1. Time evolutions of injection powers P_{RF} (total) and radiation power P_{rad}, average electron density N_e, optical emission intensities of D I (656 nm), C III (97.7 nm), neutral gas pressure p. Dashed dotted lines: switch -on and -off gas puff. $B_0 = 0.5$ T.

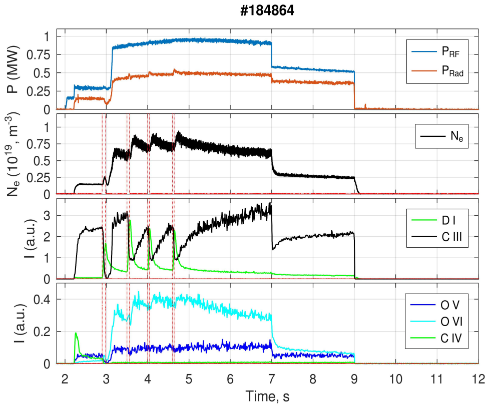

Fig. 2. Time evolutions of injection power P_{RF} (total) and radiation power P_{rad}, average electron density N_e, optical emission intensities of D I (656 nm), C III (97.7 nm), O V (63 nm), O VI (103.4 nm) and CIV (154.9 nm) neutral gas pressure p. Dashed dotted lines: switch -on and -off gas puff. $B_0 = 0.4$ T.

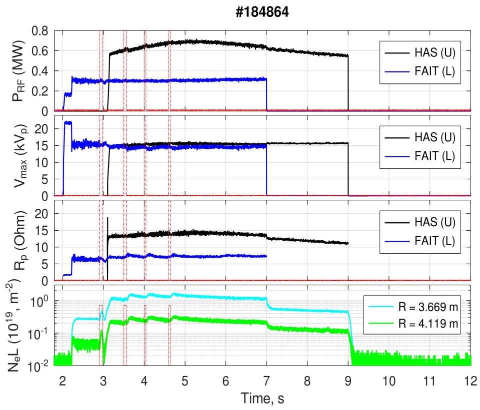

Fig. 3. Time evolutions of injection powers P_{RF} for antennas HAS (U), FAIT (L), maximum voltage at the coaxial line V_{max}, loading resistances (including vacuum loading resistance) R_p, and line integrated plasma densities N_eL. Dashed dotted lines: switch -on and -off gas puff. $B_0 = 0.4$ T.

Figures 2 and 3 show the parameters of the plasma RF shot in a 0.4 T magnetic field. In this case, the first pulse of gas was in the already prepared plasma after its production (see fig. 2). The breakdown and plasma creation at pressure ~ 4×10^{-4} Pa was ~ 200 ms after the start of the RF shot. Which is characterized by the appearance of the spectral line of deuterium, a decrease in the voltage at FAIT (L) antenna and an increase in the resistance (see fig. 3). A maximum density of ≈ 0.14×10^{19} m^{-3} is achieved at a power of ≈ 0.31 MW on FAIT (L) antenna. Spectral lines of carbon (C III and C IV) and oxygen (O V and O VI) are observed. The first gas pulse increases the plasma density to ≈ 0.25×10^{19} m^{-3}. The intensity of the carbon and oxygen lines decreases. A further increase in plasma density occurs after the start of HAS (U) antenna. Gas injection from pulse to pulse results in an increase of plasma density. The maximum density achieved in this shot ≈ 0.94×10^{19} m^{-3} at RF power ≈ 0.95 MW. A small increase in P_{rad} during and after gas injection is observed. Turning FAIT (L) antenna and correspondingly the power injected into the plasma results in a reduction of the plasma density to ≈ 0.25×10^{19} m^{-3}. The temperature of the electrons as in the 0.5 T magnetic field shots was low. Pulsed gas inflation leads to a change in density throughout the entire confinement volume (see fig. 3 and 4). As can be seen from Fig. 3 practically synchronously, the value N_eL changes both in the center of the plasma (R=3.669 m) and in its periphery (R=4.119 m). After each gas pulse, the plasma density increases in the central plasma region (see fig. 4). There are also small changes in voltage and resistance at the antennas after the gas pulse. Accordingly, the gas pulses do not lead to critical effects on the RF system.

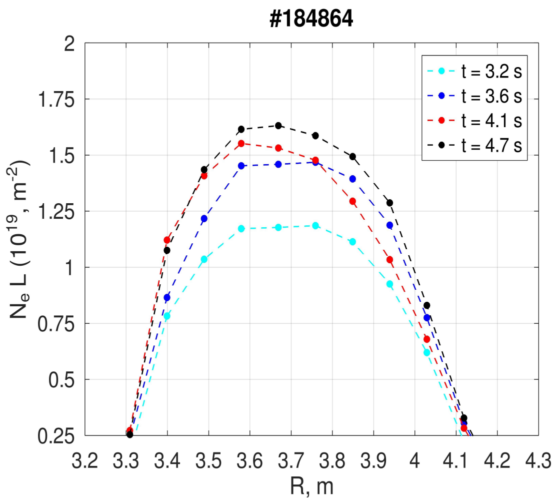

Fig. 4. Line integrated plasma densities as functions of major torus radius at different time moments. B_0 = 0.4 T.

Conclusion

To produce RF plasma in relatively low magnetic fields the LHD RF heating system was used without tuning the generator frequency. The programmable gas injection made it possible to produce a low-temperature, dense plasma by RF discharge. Plasma produced had a density suitable for wall conditioning and for further heating, e.g. with NBI. The main positive features of this RF discharge are a reliable gas breakdown and good antenna loading. Based on these experiments, a proposal for similar experiments is formulated for W7-X for wall conditioning.

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