ICRF PLASMA PRODUCTION AND HEATING IN LHD


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Ion cyclotron range of frequencies (ICRF) plasma production is of interest for stellarators, especially for cases when the electron cyclotron plasma production is not applicable. Based on experiments for plasma production at Uragan-2M (U-2M), the discharges are proposed in [1-3] for production of fully ionized ICRF plasma in stellarators. The scenario requires the presence of light minority ions for which the ion cyclotron resonance zone exists in the plasma column. Plasma production is realized using the same poloidal strap antennas that are used for the ICRF heating. The scenario couples power to the electrons in a wide plasma density range, from very low at the initial stage to high at the final stage (see also Ref. 4). At high plasma densities the electron heating is made in the mode conversion regime [5] which is widely practiced. At low plasma densities, the direct slow wave excitation by the antenna is necessary to heat the plasma electrons. The scenario is prospective for Wendelstein 7-X (W7-X) since, if successful, it could be used at 1.7 T [6] with the hydrogen minority (heating frequency is about 26 MHz). This scenario has been studied in some depth at U-2M which is quite smaller than LHD and W7-X and which has an order of magnitude lower magnetic field. So, the scalability of this scenario should be checked in experiments on larger machines.

Previously, at LHD, only few shots were made with plasma production in ICRF in this regime [7]. In those experiments, the ICRF plasma production was for the first time demonstrated using the field-aligned antennas in neutral gas with pressures suitable for further plasma heating. The major constraint of the experiments is the low RF power. As a result, the low plasma density is obtained, and the antenna-plasma coupling was not high. Also, the full ionization of neutral gas was not achieved.

After this, in continuation of such studies, a series of experiments were carried out at LHD. The major distinctive feature of this series is higher RF power. To avoid a dangerous voltage increase on the RF system elements, especially at the initial stage of plasma production, the ramp-up of the RF power is set slightly sloped. A similar approach is realized at U-2M where the RF power is increased stepwise [1]. Another distinctive feature of this series is gas fuelling control. Two modes of gas fuelling are employed: continuous and pulsed. In continuous mode, a gas mixture is created in the LHD vacuum vessel by independent fuelling of hydrogen and helium. In pulsed mode, helium is injected in addition to the constant gas puff. In both modes fully ionized plasma is obtained with high electron temperature.

In the experiments, the magnetic field is 2.75 T at the magnetic axis. For heating frequency used, 38.47 MHz, the hydrogen cyclotron zone crosses the plasma column. The ICRF heating system in LHD includes a hand-shake form (HAS) antenna and a field-aligned-impedance transforming (FAIT) antenna. Each antenna consists of two parts, upper (U) and lower (L), which can be enabled independently.

In the continuous mode the discharge was initiated by the HAS (U) antenna. Then, with the delay of 700 ms the FAIT (L) antenna starts. The plasma density ramps up very slow up to $1 \times 10^{19}$ m$^{-3}$ (see Fig. 1, left). The electron temperature ramps up quicker achieving its maximum of 1 keV at the density value $\approx 5 \times 10^{18}$ m$^{-3}$ and then goes almost unchanged. This regime is very sensitive to gas fuelling rate.

In case of pulsed gas injection, again, the HAS (U) antenna starts first and with a delay of 900 ms the FAIT (L and U) antenna is powered. The discharge shows density steps associated with gas injection pulses (see Fig.1, right). The plasma temperature is higher, about 2 keV.
Fig. 1. Time evolutions of injection power $P_{\text{ICRF}}$ (total), radiation power $P_{\text{rad}}$, average electron density $N_\text{e}$ and electron temperature $T_\text{e}$ in continuous gas puff mode (left) and in pulsed gas puff mode (right). The data of far-infrared (FIR) laser interferometer, $R = 3.669$ m and Thomson scattering (TS), $R = 3.602$ m are given.

In this experimental series plasma production and heating with ICRF heating only is demonstrated for the first time in a large stellarator type of fusion device.

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