First experiments on ICRF plasma start-up at Wendelstein 7-X

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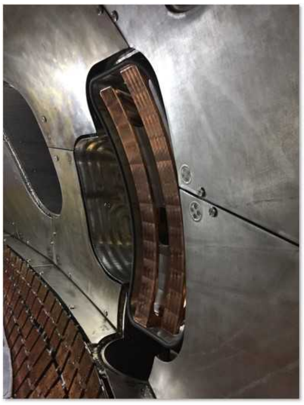
Introduction

The Ion Cyclotron Resonance Heating (ICRH) method is one of the main methods for heating plasma to high-temperatures in tokamaks and stellarators. In addition to this, the ICRH system can be used for fast ion generation, selective ion heating, wall conditioning, and providing plasma start-up [1,2]. The Wendelstein 7-X (W7-X) ICRH system has recently been installed on this machine. The first tests and experiments had been performed during the OP2.1 campaign [3] in year 2023. In support for the W7-X experimental program, the scenario of ion cyclotron frequency range (ICRF) plasma production had been developed on Uragan-2M (U-2M) and Large Helical Device (LHD) stellarators [4, 5]. The ICRF discharges can offer the possibility of plasma production and sustain in conditions where plasma generation by the available electron cyclotron resonance heating (ECRH) systems at toroidal devices is not possible. This paper presents the first results of ICRF plasma start-up at Wendelstein 7-X obtained in the latest experimental campaign OP 2.2.

Experimental setup and Experimental details

The Wendelstein 7-X is a world- largest stellarator type superconducting device located in Greifswald, Germany [6, 7]. It is a first optimized stellarator Helical-Axis Advanced Stellarator Helias (HELIAS) line. The major radius is 5.5 m, minor radius is 0.5 m and plasma volume reaches 30 m^3. The W7-X uses three systems to heat plasma: Electron Cyclotron Resonance Heating (ECRH) at 140 GHz is the main system for producing and heating plasma at the second harmonic in 2.5 T, Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH).

The ICRH system includes: the two radio frequency (RF) generators, the output impedance 50 Ω; the coaxial transmission lines; matching system; the dummy load; the two-strap antenna (phasings monopole [0,0] or dipole [0,π]); the control and data acquisition. The ICRF system for W7-X is designed to deliver up to 1.5 MW RF power. The system is designed to work in the frequency range between 25 and 38 MHz, for pulse duration of 10 s [8].



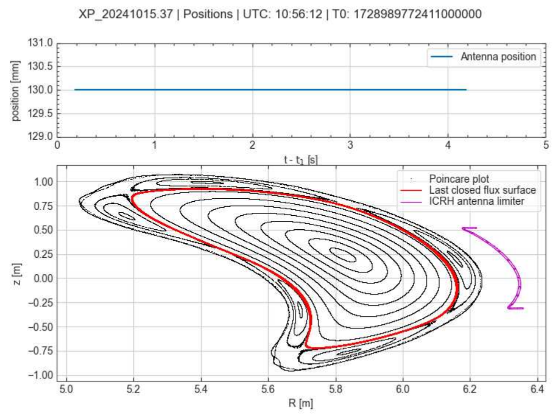


Fig. 1. Photo of two straps antenna inside vacuum chamber W-7X (photo were provided by the Laboratory of Plasma Physics of the Royal Military Academy).

Fig. 2. Antenna position (top). Poincaré plot of magnetic configuration at W-7X in antenna location (bottom). Last closed flux surface (red line). ICRH antenna limeter (magenta line).

The two straps of the ICRH antenna (see fig. 1) were operated in zero-phasing to produce the plasma. The antenna is movable and can be positioned at various distances from the last closed flux surface. The antenna location in these experiments is shown in Fig. 2. The ICRF start-up scenario at W7-X was similar to the scenarios of U-2M and LHD [4, 5]. The used frequency of 25 MHz corresponded to the fundamental cyclotron harmonic of hydrogen, and the ion cyclotron resonance zone resided in the plasma column. The magnitude of the magnetic field in the centre was 1.815 T. The working gas was helium. The time dependence of the line averaged electron density was measured using QMJ - The Integral Electron Density Dispersion Interferometer (IEDDI) [8]. The time-resolved spectroscopy was used QSD - HEXOS (High Efficiency XUV Overview Spectrometer) [9].

Experimental results

In the experiments, RF power was injected in two stages (see Fig. 3). In the first stage, RF power was injected at a level below to the maximum. In the second stage, the RF power was slowly increased to the maximum value. As an example, in shot XP: 20242015.37, the power was ≈ 44 kW in the first stage and ≈ 427 kW in the second stage. This RF power injection regime was used to prevent incidents on the antenna (arc formation, breakdown of antenna elements). Similar RF power injection regimes were previously used on U-2M and LHD in ICRF start-up experiments [4, 5].

Stable RF breakdown was observed in the W7-X experiments. The minimum RF power at which breakdown and plasma creation were observed was ≈ 25 kW while the regular shots were performed with power of up to 500 kW. The breakdown stage was characterized by the appearance of spectral lines of excited helium. The breakdown time was ≈ 50–70 ms. The temporal evolution of the density and intensity of spectral lines is shown in Fig. 3. After breakdown, spectral lines of excited helium atoms He I appear successively, followed by He II ions with a slight delay of ~ 20 ms. Next, with a delay of ~ 10 ms relative to He II, the lines of carbon ions C II, C III, and hydrogen atoms H I are observed. The appearance of spectral lines of impurity atoms and ions with a delay relative to helium is possibly related to the interaction of plasma with the wall. A similar pattern of carbon manifestation was observed in experiments on U-2M and LHD [4, 5]. It should be noted that a small amount of hydrogen was always present in the vacuum chamber. With an increase in plasma density, the intensity of all spectral lines increases and, after reaching a maximum, begins to decrease. In the case of He II, the intensity decreases below the sensitivity threshold of the spectrometer. This may be due to the effect that, at the stage of plasma density increase, the electron temperature is higher than at the quasi-stationary stage when the plasma density remains practically unchanged. According to [10], the excitation energies of He II (30.378 nm) and He I (58.4 nm) are ≈ 40.8 eV and 20.96 eV, respectively. For carbon ions C II (90.4 nm) and C III (97.7 nm), they are ≈ 13.7 eV and 12.69 eV, respectively. So, for He II (30.378 nm), the excitation energy is higher than for the other lines we're looking at, and you need a higher temperature to line emission. Keep in mind that in these experiments, the electron temperature was probably low because had not register see any highly charged impurity ions. A similar picture was observed on U-2M [4, 11] and in the first experiments on LHD [5]. After the RF power is turned off, the intensity of the spectral lines decreases rapidly. The plasma density also decreases more smoothly.

Fig. 4 shows the dependence of the maximum plasma density on RF power. As can be seen, with an increase in RF power to ≈ 200 kW, the plasma density also increases. A further increase in power does not lead to a significant increase in density.

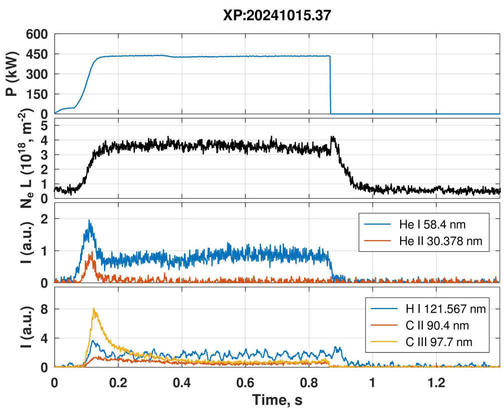


Fig. 3. Time evolutions of injection powers P, line integrated electron density density N_eL, optical emission intensities of excited neutrals He I, H I and ions He II, C II, C III.

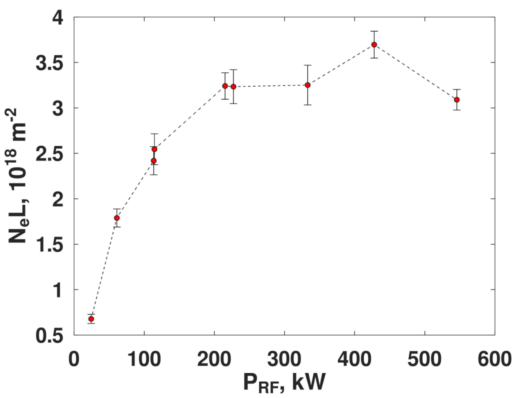


Fig. 4. Maximum line integrated electron density density as a function of the RF power.

The maximum density value was ≈ 3.5×10^{18} m^{-2}, which corresponds to ~ 3.5×10^{18} m^{-3}. A similar picture was observed on U-2M in experiments on ICRF start-up in helium, where the plasma density was up to ~ 2×10^{18} m^{-3} [11].

Conclusion

Under these experimental conditions, stable gas breakdowns and plasma generations were observed even at low values of injected RF power of ≈ 25 kW. Higher plasma densities up to ≈ 10^{18} m^{-3} were achieved with more RF power of ≈ 545 kW. In the optical emission spectrum of the plasma, lines of helium, hydrogen, and carbon are observed. Thus, the experiments conducted demonstrate the possibility of stable ICRF plasma creation on W7-X. The plasma produced by the in such a scenario can be used as a target plasma for further NBI and or third harmonic ECRH and for the wall conditioning procedures. Further experiments will be aimed at increasing plasma density and obtaining fully ionized plasma with high ion and electron temperatures.

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