Radio frequency wall conditioning discharges at low magnetic fields in Uragan-2M stellarator

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Introduction

For removing impurities accumulated at the plasma facing surfaces of fusion devices, the ion cyclotron wall conditioning is used (see, e.g. [1]). It is also possible to use radio-frequency (RF) discharges with frequencies above the ion cyclotron frequency $\omega >> \omega_{ci}$ to sustain the wall conditioning discharges [2-7], corresponding to the high cyclotron harmonics regime described in [8, 9]. The use of RF discharges in low magnetic field (LMF) for wall conditioning was first realized on the Uragan-3 stellarator [4]. This method is improved and routinely used at the Uragan-3M [5] and Uragan-2M (U-2M) stellarators [6, 7]. Previously, the frame and three-half-turn antennas were used for wall conditioning in LMF at U-2M. A two-strap antenna mimicking the Wendelstein 7-X (W7-X) antenna was installed on U-2M to support Ion Cyclotron Resonance Heating experiments at W7-X [10, 11]. The first wall conditioning experiments with the two-strap antenna of U-2M were carried out at dipole phasing of the antenna straps, optimized for the pre-ionization of stellarator plasmas [7]. In the present work, an LMF wall conditioning plasma was created by the two-strap antenna in monopole phasing (without pre-ionization).

Experimental setup

The U-2M device (see Fig. 1) is a medium-size stellarator of torsatron type [10, 11]. The major radius of the device is R = 1.7 m, the toroidal magnetic field at the toroidal axis is $B_0 < 0.6$ T. The toroidal vacuum chamber with the minor radius $r_c = 0.34$ m has a volume

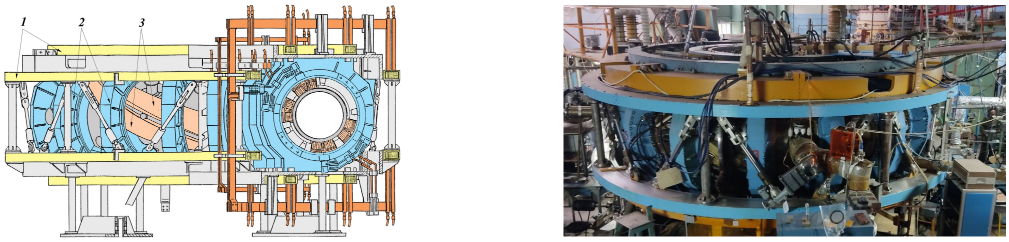

Fig. 1 The schematic view of the U-2M (left), the photo of the U-2M (right).
Poloidal field (1), toroidal field (2) and helical field coils (3).

V_c = 3.88 m^3 (without vacuum ports) and the inner surface area of S = 22.8 m^2. The vacuum chamber is pumped by three turbo-molecular pumps TMN-500, each has a pumping speed of 0.5 $m^3\ s^{-1}$. There is a mass spectrometer IPDO-2 of the omegatron type with the tube RMO-4S for measuring the residual gas partial pressures in the vacuum chamber. In the U-2M stellarator, the two RF systems “Kaskad-1” (K-1) and “Kaskad-2” (K-2) are used to produce and heat the plasma. In the wall conditioning regime, two low-power DC sources (type VD-301UZ and VDM-1601) are used to power the magnetic system with a field of 10’s of mT.

Experimental details

The two-strap antenna operated in monopole phasing was connected to RF system K-1, with an anode voltage up to 6 kV, frequency of 5 MHz, and antenna input RF power of up to ≈ 70 kW. The toroidal magnetic field at the toroidal axis was $B_0 \approx 0.01$ T. The experiments were carried out in a hydrogen atmosphere. The line averaged electron density was measured using a microwave interferometer. The ions’ charge states and plasma elemental composition were evaluated through the optical emission spectroscopy. The partial pressure of the residual gases was measured with a mass-spectrometer.

Experimental results

The condition for RF plasma production is the propagation of excited waves in the plasma and the damping of these waves on the plasma electrons. RF power absorption by electrons leads to their heating, which is needed to compensate for energy losses in inelastic collisions and to stimulate the ionization process. In a low magnetic field, fast and slow waves can propagate even in a small plasma column [2, 5]. The plasma parameters were measured for different values of neutral gas pressure and RF power. In the experiments, the time duration τ_d of the RF pulse ranged from 10 to 40 ms, the time between t_b RF pulses from 12 s to 1 minute. In the standard regime of RF plasma wall conditioning in U-2M, these times are τ_d = 30 ms, t_b = 15 s. Thus, in a 2 hours conditioning procedure 480 shots are made. After a pause with full-speed pumping, the process was repeated. Fig.2 shows the time dependencies of RF power, average density, different spectral lines intensities and neutral gas pressure. Plasma production with an average plasma density up to ~ 7×10^{11} cm^{-3} was observed. The temperature of the electrons is up to 20 eV. The intensity of the C II line increases over time (see Fig.2), which seems to be related to influx of carbon containing impurities into the plasma column. The chord distribution of the intensity of the spectral lines of excited hydrogen atoms and oxygen ion is shown in Fig. 3. The maximum intensity of the hydrogen line is observed in the central region with a short delay after the start of the RF pulse. Then, after 20 ms, the emission intensity decreases and practically remains unchanged in the whole volume until the end of the RF pulse. For oxygen, the increase in the emission intensity occurs with a delay of ~ 5 ms after the start of the RF pulse. This indicates that oxygen mainly enters the discharge from the wall. And the amount of oxygen in the volume at the initial stage of the discharge is relatively low. A similar spatially and temporally distributed emission intensity is observed for CII, CIII ions (not shown here). Figure 4 shows the dependence of the maximum average density and intensity of spectral lines on pressure. The dependence of H_α line intensity is similar to the dependence of average density on pressure, with a maximum at 2.4×10^{-2} Pa. For the O II and C II impurities, the maximum is observed at a lower pressure. This may be due to an increase in the influx of impurities into the plasma. Fig. 5 shows the evolution of the time-average spectral line intensities during the wall conditioning procedure. The intensity of the H_α line changes weakly during the wall conditioning except for the jump-up after the first shots. The intensity of the C II line slowly decreases over time, after initial jump-down. This demonstrates the decrease of the impurity in-flow the effect of wall

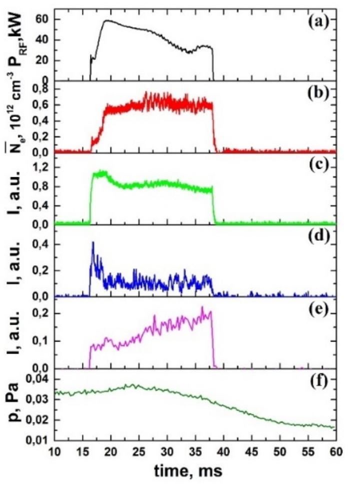

Fig. 2. Time evolutions of RF power (a); average plasma density (b); optical emission intensities of H_α, 656.2 nm (c); O II, 441.5 nm (d); C II, 229.6 nm (e) and neutral gas pressure (f), (U_a = 5.5 kV. Duty cycle: 14 ms (start), 15 ms (step-1), 16 ms (step-2), 38 ms (shutdown)).

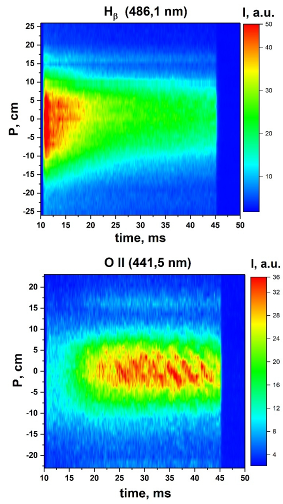

Fig. 3. Time evolution of H_β and O II chord distribution. P - impact parameter. (U_a = 5 kV, p = 2.9×10^{-2} Pa. Duty cycle: 10 ms (start), 45 ms (shutdown)).

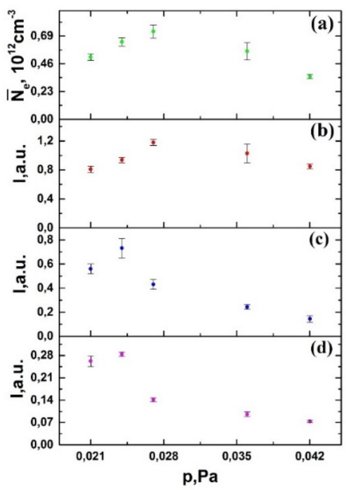

Fig. 4. Maximum average plasma density (a), optical emission intensities of H_α, 656.2 nm (b); C II, 229.6 nm (c);O II, 441.5 nm (d); as a function of the initial gas pressure. (U_a = 5.5 kV. Duty cycle: 10 ms (start), 20 ms (shutdown)).

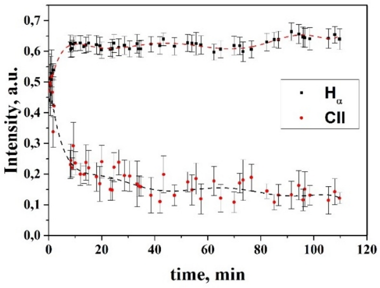

Fig. 5. Time evolution optical emission intensities of H_α (656.2 nm) and C II (229.6 nm). (U_a = 5 kV, p = 2.9×10^{-2} Pa. Duty cycle: 10 ms (start), 40 ms (shutdown), one shot every 15 seconds.)

conditioning. This is consistent with the partial pressure measurements in the vacuum chamber after RF cleaning and vacuum pumping that, show a reduction of residual gas content.

Conclusion

RF plasmas in hydrogen and at low magnetic field allow decreasing the residual gases pressure and impurity content in U-2M, demonstrating their ability to do wall conditioning. The W7-X-like antenna produced the LMF RF conditioning discharges. Based on these experiments, a proposal for similar experiments is formulated for W7-X for wall conditioning. The main positive features of RF discharge plasmas wall conditioning in low magnetic field are reliable breakdown of the conditioning discharge and good antenna loading. The low magnetic field increases plasma transport to the plasma facing surfaces and hence a rapid particle recirculation. A similar IC conditioning procedure at W7-X can be made in low magnetic field ~ 0.1-0.2 T and frequency range 25-38 MHz.

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