Radio frequency plasma production at frequencies higher than ion cyclotron frequency at Uragan-2M stellarator

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Introduction

The successful plasma production of ion cyclotron frequency range (ICRF) with strap antennas in H_2 + He mixtures has been previously demonstrated at the Uragan-2M and LHD stellarators [1,2]. RF discharge plasma is used for wall conditioning procedures in tokamaks [3] and stellarators [4]. The scenario ICRF plasma production relatively dense plasma in H_2 + He mixtures was produced near the first harmonic of the hydrogen cyclotron frequency [1, 2, 5]. In [5] the maximum plasma density is observed when $\omega_{RF} \approx \omega_{ci}$ (H^+) and also the production is observed when $\omega_{RF} \approx 2\omega_{ci}$ (H^+). The ICRF systems can be also used for radio frequency (RF) discharges at frequencies higher than ion cyclotron (IC) frequency. This study is focused on RF plasma production in H_2 + He mixtures at frequencies higher than IC frequency.

Experimental setup

The Uragan-2M (U-2M) device (see fig. 1) at Kharkiv, Ukraine, is a medium-size stellarator of torsatron type [1, 5]. The main technical parameters are presented in Table 1. In the experiments on U-2M, the frequency of the RF generator was range 4.9- 5.1 MHz, magnetic field B_0 was range 0.01 – 0.21 T. The two-strap antenna [1, 5] had 0-phasing. The experiments were carried out in the atmosphere of H_2 + He mixtures. The creation of a H_2+He gas mixture was carried out in the gas mixing system [1, 5]. 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.

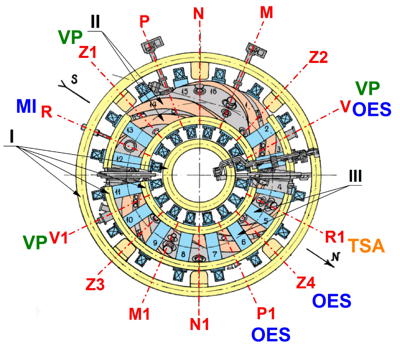

Table 1. Device characteristics

Major radius, R (m)	1.7
Minor radius, r (m)	0.34
Minor radius of helical winding, h (m)	0.44
Volume vacuum chamber, V (m^3)	~ 4
Inner surface area, S (m^2)	~ 23
Average plasma radius, r_{pl} (m)	< 0.24
Toroidal magnetic field, B_0 (T)	< 0.6

Fig. 1. The schematic view of the U-2M. Poloidal field (I), toroidal field (III) and helical field coils (II). Different toroidal cross-sections are shown by red lines and denoted by capital letters and numbers. TSA is Two-strap antenna, MI is microwave interferometer, OES is optical emission spectroscopy, VP is vacuum pumping.

Experimental results

Comparison of plasma production at $\omega_{RF} \approx \omega_{ci}$ (H^+) and $\omega_{RF} \approx 2\omega_{ci}$ (H^+)

The comparison of plasma creation at first harmonic IC $\omega_{RF} \approx \omega_{ci}$ (H^+) and second harmonic IC $\omega_{RF} \approx 2\omega_{ci}$ (H^+) was carried out under the same initial conditions, namely, H_2 + He mixture pressure and hydrogen concentration in the mixture, RF frequency 4.95 MHz and power ≈ 100 kW (U_a=7 kV, anode voltage in RF generator). Only the magnitudes of magnetic field, 0.324 T and 0.17 T, were different. The achieved maximum density at plasma production at first harmonic IC was 2.8 - 4 times higher than at second harmonic IC (see Fig. 2). The similar effect was also observed in [5]. The breakdown time determined by the appearance of the H_β line also differs. The breakdown time occurs 2 ms (see Fig. 2) earlier in case at first harmonic IC than in case at second harmonic IC. The in evolutions of the intensities of spectral lines are also different (see Fig. 2). Accordingly, creating ICRF plasma on first harmonic IC is more efficient than on second harmonic IC.

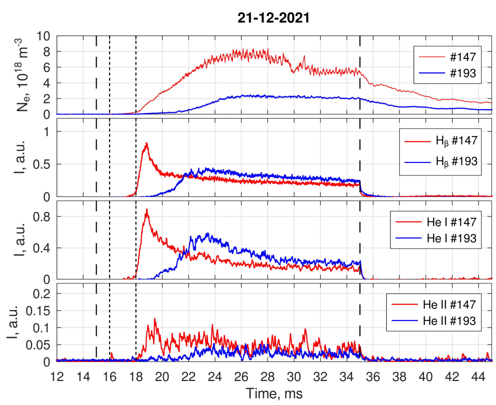

Fig. 2. Comparison of time evolutions of average plasma density and optical emission intensities for plasma production at the first harmonic, shot #147 (B_0=0.324 T, f=4.95 MHz) and second harmonic, shot #193 (B_0=0.17 T, f=4.95 MHz) of hydrogen ion cyclotron resonance. H_β, (486.1 nm), He I (471.3 nm), and ions He II (468.6 nm); emissions. U_a=7 kV, Working gas 16%H_2+84%He, p = 8.2×10^{-3} Pa. Duty cycle: 15 ms (start), 16 ms (step-1), 18 ms (step-2), 35 ms (shutdown). The vertical lines indicate the times of duty cycle of RF shot.

Plasma production at $\omega_{RF} \approx 2\omega_{ci}$ (H^+)

From Figure 3 we can conditionally distinguish several stages of RF plasma creation:

breakdown, stage to create a preliminary plasma, stage to increase the plasma density and reach the maximum value. The spectral lines of excited atoms H_β and He I come the first to be observed in time (see Fig. 3). Their intensity increases at the beginning and decreases after reaching the maximum. The increase in the intensity of the spectral lines of excited ions He II and C II is observed with a delay after lines H_β and He I. Next to the RF heating is turned off (35 ms), the plasma decays and the plasma density and spectral line intensities decrease. The pressure dependence of the maximum density in the He+H_2 mixture at second harmonic IC (see Fig. 4) is similar to that at first harmonic IC [1, 5]. There is a wide range of pressures where plasma of density close maximum achieved is produced. The maximum density in current experiments was observed to be 3×10^{18} m^{-3} under the condition on second harmonic IC and pressure 1.4×10^{-2} Pa. In the pressure range investigated, the maximum density was always always higher than 1×10^{18} m^{-3} (see Fig. 4). Plasma with these parameters can be used for wall conditioning procedures.

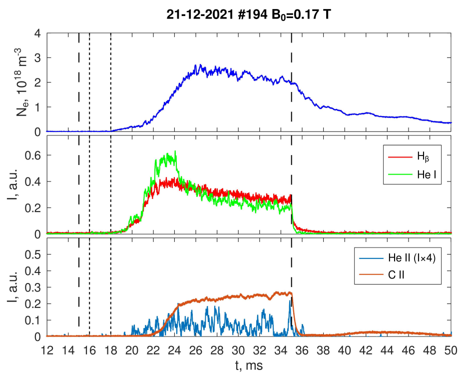

Fig. 3. Time evolutions of average plasma density; optical emission intensities of H_β, (486.1 nm), He I (504.7 nm), and ions lines He II (468.6 nm); C II (464.7 nm), (U_a=7 kV, *f*=4.95 MHz, B_0=0.17 T. Working gas 16%H_2+84%He, p = 7.1×10^{-3} Pa). Duty cycle: 15 ms (start), 16 ms (step-1), 18 ms (step-2), 35 ms (shutdown). The vertical lines indicate the times of duty cycle of RF shot.

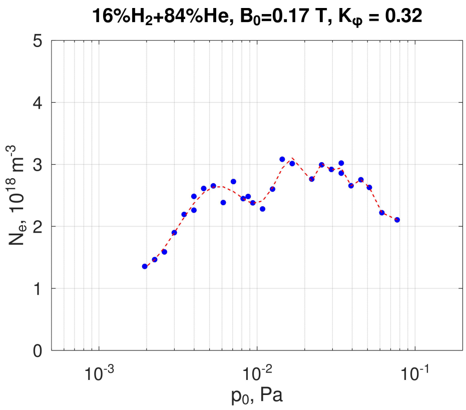

Fig. 4. Maximum average plasma density as a function of the pressure (U_a=7 kV, *f*=4.95 MHz) 16%H_2+84%He (B_0=0.17 T, K_φ=0.32).

Plasma production at $\omega_{RF} >> \omega_{ci}$

IIn low magnetic fields (see Fig. 5 and 6) plasma with density higher 1×10^{18} m^{-3} is observed at injected power up to 70 kW which is better than obtained earlier with the THT antenna [6]. In a magnetic field of 0.05 T, a density rises of up to 3×10^{18} m^{-3} (see Fig. 5). The positive features of RF discharge plasmas in low magnetic field are reliable breakdown and good antenna loading. Reduction of the magnetic field is favourable for wall conditioning discharges to increase particle recycling by decreasing of particle confinement.

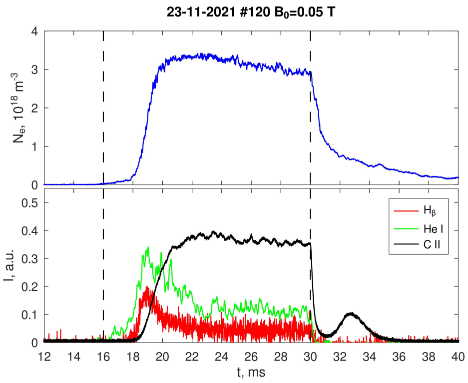

Fig. 5. Time evolutions of average plasma density; optical emission intensities of H_β, (486.1 nm), He I (504.7 nm), and ions C II (464.7 nm), (U_a=6 kV, f=5.12 MHz, B_0=0.05 T. Working gas 25%H_2+75%He , p = 1.7×10^{-2} Pa). Duty cycle: 16 ms (start), 30 ms (shutdown). The vertical lines indicate the times of duty cycle of RF shot.

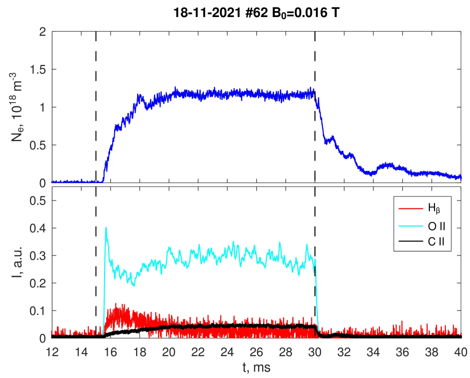

Fig. 6. Time evolutions of average plasma density; optical emission intensities of H_β, (486.1 nm) and ions O II (441.5 nm), C III (464.7 nm), (U_a=5 kV, f=5.12 MHz, B_0=0.016 T. Working gas 25%H_2+75%He, p = 3.5×10^{-2} Pa). Duty cycle: 15 ms (start), 30 ms (shutdown). The vertical lines indicate the times of duty cycle of RF shot.

Conclusion

Studies of RF plasma creation in the gas mixture H_2+He show that RF breakdown and plasma production with density higher than 1×10^{18} m^{-3} are possible at frequencies higher than the fundamental ion cyclotron frequency of hydrogen. Although at $\omega_{RF} \approx 2\omega_{ci}$ (H^+) the observed densities are 2.8-4 smaller than for RF plasma production at $\omega_{RF} \approx \omega_{ci}$ (H^+). However, such plasma is of interest for use in a wall conditioning procedure. Plasma of similar density is produced at much lower magnetic fields.

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