Plasma behavior to hydrogen supersonic molecular beam injection in the Uragan-2M stellarator

Yu. V. Kovtun[1], A. V. Lozin[1], A. N. Ozerov[1], V. E. Moiseenko[1,2,3], M. M. Kozulya[1], A. N. Shapoval[1], R. O. Pavlichenko[1], N. V. Zamanov[1], S. M. Maznichenko[1], D. I. Baron[1], A. Yu. Krasiuk[1], S. A. Tsybenko[1], I. E. Garkusha[1,2], A. Dinklage[4], T. Wauters[5]

and the Uragan-2M Team

[1]*National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine*

[2]*V.N. Karazin Kharkiv National University, Kharkiv, Ukraine*

[3]*Ångström Laboratory, Uppsala University, Uppsala, Sweden*

[4]*Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[5]*ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France*

Introduction

Magnetically confined controlled fusion experiments use supersonic molecular beam injection for fuelling, plasma diagnostics, and other applications [1, 2]. Previously, the additional pulsed gas injection was used in experiments on Uragan-3M [3] and Uragan-2M (U-2M) stellarators, but without usage of the supersonic molecular beam injection (SMBI) technology. Studies on ion-cyclotron resonance radio-frequency (ICRF) discharge plasma production in helium with hydrogen minority are being conducted on the U-2M stellarator [4-6]. The maximum during the shot line averaged plasma density depends on the gas pressure provided by the continuous gas puff and has a maximum at the certain gas pressure value. Therefore, it was of interest to investigate the influence on this maximum plasma density value of the additional hydrogen SMBI. The SMBI system was designed, manufactured, and installed on the U-2M. This work presents the first results of using the SMBI system in U-2M.

Experimental setup

The U-2M device (see fig. 1a) at Kharkiv, Ukraine, is a medium-size stellarator of torsatron type of the major radius R = 1.7 m and minor radius of the vacuum chamber r_c = 0.34 m, the toroidal magnetic field at the toroidal axis is B_0 < 0.6 T [4-6]. The two RF systems "Kaskad-1" (K-1) and "Kaskad-2" (K-2) are used to produce and heat the plasma. There are three types of antennas on the U-2M: the frame antenna (see fig. 1b), three-half-turn antenna and two-strap antenna [7] (see fig. 1b). The creation of a H_2+He gas mixture with different concentrations was carried out in the gas mixing system [8].

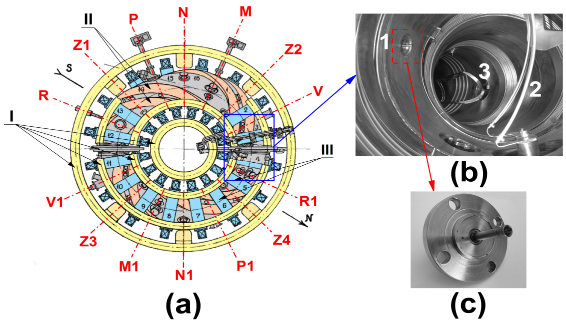


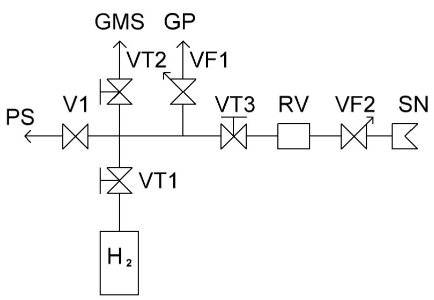
Fig. 1. Scheme of U-2M (I, II and III poloidal, helical and toroidal (1–16) field coils, respectively. The red lines showing is different toroidal cross-sections) (a); Photo of the supersonic nozzle and antennas inside the U-2M device (1 is the conical supersonic nozzle, 2 and 3 is the Two-strap and Frame antennas, respectively) (b); Photo of the supersonic nozzle at the flange (c).

Supersonic molecular beam injection (SMBI) system

Figure 2 shows a scheme of the SMBI system. The system includes a pulse inlet valve (VF2), piezovalve model PEV-1 [8], and a supersonic nozzle (SN). The piezovalve was operated by a pulse unit allowing operation in two modes: a single pulse with a duration from 2 to 120 ms and a series of consecutive pulses. The supersonic nozzle is mounted at the end of the pipe on a DN40 flange (see fig. 1c). Flange with a nozzle was installed against the two-strap antenna (cross-sections R1, see fig. 1a) perpendicular to the antenna straps on the high magnetic field side (see fig. 1b). Diameter of the outlet and throat of the conical supersonic nozzle 7.5 and 1.5 mm, respectively. The calculated value of the Mach number for hydrogen is M = 5. The variation of density with distance along the main radius calculated from the approximate model [9] is shown in Fig. 3.

Experimental results

The SMBI system has been used in experiments on ICRF plasma production at the hydrogen minority regime. Hydrogen was used for the additional pulse gas injection into the helium or hydrogen-helium plasmas. In these two experimental series first, by neutral gas pressure scan



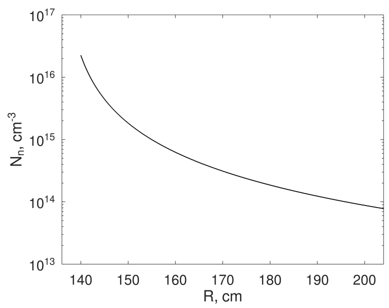


Fig. 2. Scheme of SMBI. The following elements are shown in the scheme: gas regulating valves (V1); pumping system (PS); gas reducers VT1- VT3; gas mixture system (GMS); inlet valve (VF1); gas puffing (GP); reserve volume (RV); pulse inlet valve (VF2); supersonic nozzle (SN).

Fig. 3. Calculated variation of gas density with distance along the major radius of steady supersonic jet (M = 5 for hydrogen) expanding into a vacuum. Plenum pressure is 1.5 bar.

with the continuous gas puff, the discharge was found which has maximum plasma density. In the second experimental series, the SMBI is applied to this discharge. This discharge is compared with the analogous discharge without SMBI taken from the previous series. Figure 4 shows a comparison of ICRF discharge in helium and with and without of hydrogen SMBI. In both experiments, helium was injected continuously into the vacuum chamber. Shot #59 is without additional SMBI and # 65 has hydrogen SMBI. In shot #65, the hydrogen was injected 3 ms before the start of the RF pulse. A small quantity of hydrogen is always present in plasma. For this reason, at least a small intensity of the spectral lines of hydrogen was always observed (see fig. 4, #59). The intensity of hydrogen lines increases significantly after additional hydrogen SMBI (see fig. 4, # 65). The maximum line average plasma density was increased from 1.9×10^{12} cm^{-3} to 4×10^{12} cm^{-3}, i.e. by a factor of 2.1. The increase in density is likely due to the formation of hydrogen-helium plasma and a turning the ICRF heating conditions to better, see [4-6].

In experiments with the initial hydrogen-helium gas mixture, additional hydrogen SMBI was performed in the prepared plasma at its average density of $\approx 2\times10^{12}$ cm^{-3} (see fig. 5). Shots #082 without additional gas injection and # 118 with an additional hydrogen SMBI. The intensity of the hydrogen H_α line begins to increase 2 ms after the start of hydrogen injection (see fig. 5, # 118). There is also an increase in the intensity of the H_α line on the plasma

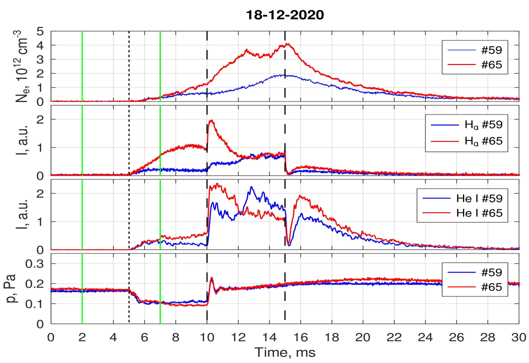


Fig. 4. Time evolutions of average plasma density, optical emission intensities of H_α, (656.2 nm), He I (447.15 nm), and gas pressures. (Frame antenna $U_a = 4$ kV, f=5 MHz, Two-strap antenna U_a = 7 kV, f=4.92 MHz, B_0= 0.346 T, K_φ=0.324. Working gas He). Duty cycle: Frame antenna - 5 ms (start), 10 ms (shutdown); Two-strap antenna - 10 ms (start), 15 ms (shutdown). The vertical black lines indicate the times of duty cycle of RF shot. The vertical green lines indicate the times of duty cycle of gas injection.

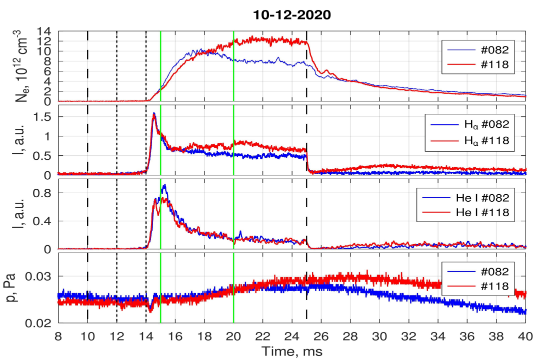


Fig. 5. Time evolutions of average plasma density, optical emission intensities of H_α, (656.2 nm), He I (447.15 nm), and gas pressures. (Two-strap antenna U_a=8 kV, f=4.96 MHz, B_0=0.348 T, K_φ=0.321. Working gas 86%He+14%H_2). Duty cycle two-strap antenna: 10 ms (start), 12 ms (step-1), 14 ms (step-2), 25 ms (shutdown). The vertical lines indicate the times of duty cycle of RF shot. The vertical green lines indicate the times of duty cycle of gas injection.

density decreasing. This can be explained with electron temperature decrease and hydrogen recombination. And a higher hydrogen concentration than in the shot #082 without additional hydrogen injection. The pressure is also higher after the RF discharge in shot #118. The maximum plasma density was observed to increase from 10×10^{12} cm^{-3} to 13×10^{12} cm^{-3} after SMBI injection. Accordingly, the density has been increased by 30%.

Summary

The SMBI device was developed, constructed, and installed at the U-2M device for additional injection gases in plasma. The first experiments with SMBI were conducted, which aimed on increase of the plasma density in U-2M. The maximum average density of helium plasma was increased 2.1 times up to 4×10^{12} cm^{-3} after SMBI pulse. In hydrogen-helium plasma discharge SMBI increased plasma density by 30% up to 13×10^{12} cm^{-3}. Use of SMBI widens the operational frame of U-2M. In the future it is planned to use hydrogen, helium and their mixtures in the SMBI experiments.

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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