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Gas jet formation using a plasma accelerator

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A method for forming a neutral helium flux using a plasma accelerator is proposed. The method consists in the transformation of a dense and cold plasma jet into gas stream. For this purpose, the plasma was passed through a long channel in which it could recombine as it moved. A gas stream could form at the outlet of recombination duct, velocity of which is close to plasma flow velocity. As a result of conducted research, conditions were found under which jet of neutral helium was mainly coming out of duct at velocity of about ten kilometers per second. Helium jet moving at high velocity is planned to be used as part of helium polychromator for deep penetration into wall plasma in Globus-M2 tokamak.

Keywords: plasma accelerator, supersonic gas jet, helium polychromator, plasma diagnostics, recombination .

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Introduction

Currently, plasma accelerators are successfully used for controlled thermonuclear fusion tasks. The plasma jet is actively used to initiate the discharge and fuel supply of installations with magnetic confinement, as well as to simulate the conditions of plasma interaction with the first wall of the reactor [1,2]. Gas injection into plasma is also currently used to solve various problems. A jet of gas with large kinetic energy can effectively penetrate through the magnetic field into the tokamak central region. Helium injection into hydrogen or deuterium plasma was actively used for diagnostic purposes in experiments on tokamaks FT-2, COMPASS, MAST, DIII-D, TEXTOR, MST, JET, ASDEX-U, JT-60, etc. and stellarators TJ-II, LHD [3–5]. The gas flow velocity in these experiments was limited and close to the sound velocity (~ 1 km/s). It is necessary to increase the jet velocity for deep probing of plasma. To this end, this paper proposes a method for generating a helium jet moving at a velocity of several tens of kilometers per second. The method consists in the transformation of a dense and cold plasma jet into a gas stream. For this purpose, the plasma was injected through a long channel in which it could recombine as it moved. As a result, a gas flow with velocity close to that of the plasma flow could be formed at outlet of recombination tube.

The results of the formation of a helium stream produced using a coaxial plasma accelerator and a long recombination tube are presented in this paper. The conducted studies revealed conditions under which a jet of helium was released from the source at a velocity of several tens of kilometers per second.

1. Factors affecting plasma recombination

The parameters of the experimental setup were selected based on the calculations presented below. It is known [6] that the plasma recombination rate is determined by the ratio

$$\frac{dn_i}{dt} = -\alpha n_e n_i, \tag{1}$$

where n_i and n_e — densities of ions and electrons, respectively, [cm^{-3}]; α — recombination coefficient, [cm^3/s].

Various recombination mechanisms may prevail in plasma depending on its parameters: photorecombination, dielectronic, dissociative, electron-ion triple recombination, etc. Plasma jet parameters created by this accelerator are presented in Ref. [7,8]. The characteristic values of the plasma jet density, velocity, and temperature did not exceed $10^{22}\,\mathrm{m}^{-3}$, 100 km/s, and 0.5 eV, respectively.

It is assumed that the low-temperature and dense hydrogen-like plasma is dominated by the process of triple electron-ion recombination [6]. Then the recombination coefficient has the form

$$\alpha \approx \frac{0.6 \cdot 10^{-27} n_e}{T_e^{9/2}}, \tag{2}$$

where T_e — temperature, [eV].

The characteristic recombination time can be estimated by the formula

$$\tau = \frac{1}{\alpha n_e} = 1.67 \cdot 10^{27} \frac{T_e^{9/2}}{n_e^2}, \ \ [\mathrm{s}]. \tag{3}$$

Fig. 1 shows the dependence of the triple recombination time on density for a plasma with two temperature values.

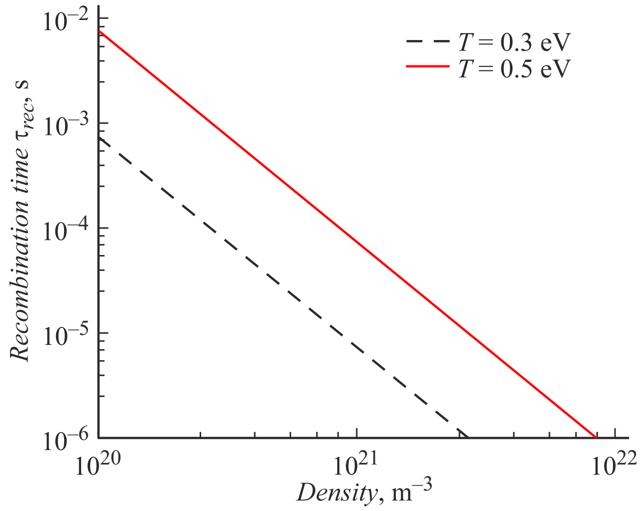

Figure 1. Dependence of the triple recombination time on the plasma density with temperatures 0.3 and 0.5 eV.

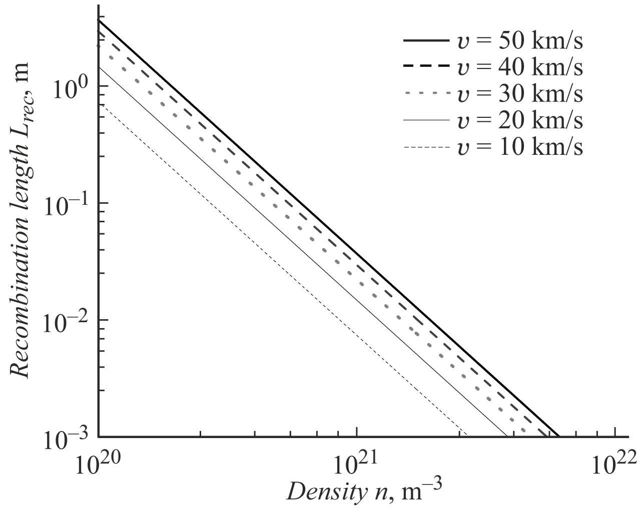

Figure 2. Dependences of the distance required for plasma recombination with a temperature of 0.5 eV, on density for different jet velocities.

It can be seen that for dense and cold plasmas, the typical recombination time can range from a few microseconds to several milliseconds.

The distance L required for the transformation of the plasma jet into a gas stream was estimated using the formula

$$L = \upsilon \cdot \tau = \upsilon \cdot 1.67 \cdot 10^{27} \frac{T_e^{9/2}}{n_e^2}, \tag{4}$$

where υ is the velocity of the jet.

The length of the recombination tube was determined from the graph of dependence of distance required for transformation of plasma into gas on density (Fig. 2).

It is apparent that the length of the recombination tube can be less than 2 m for density greater than $10^{20}\,\mathrm{m}^{-3}$. A 1.37 m long stainless steel tube with an inner diameter of 46 mm was used in the experiment, which corresponded to the diameter of the external electrode of the accelerator.

2. Experimental bench

Process of plasma jet transformation into gas was studied using a test bench containing a set of diagnostics and a 2.5 m^3 vacuum chamber with a shutter through which it was possible to attach different variants of accelerators. The jet could flow freely into the chamber. The schematic diagram of experimental test bench and appearance of the plasma accelerator are shown in Fig. 3.

Coaxial plasma accelerator was powered by a capacitive storage device $C = 400\,\mu$F with an electrode voltage of up to 5 kV. The limiting resistance R was $0.05\,\Omega$. Working gas was injected into accelerator prior to discharge using a high-speed electrodynamic valve. Total number of working gas particles was set in the range $(0.5-1) \cdot 10^{19}$. A current was initiated in the accelerator in $\sim 400\,\mu$s after opening the valve. The resulting plasma was accelerated in the channel by the Ampere force and exited the accelerator. The duration of the current pulse was about $40\,\mu$s. The accelerator schematic diagram is shown in Fig. 3 (left), *3*. Detailed information about operation of the accelerator and its parameters can be found in Ref. [7,8]. The recombination tube, in which plasma could transform into a gas stream as it moved, was positioned coaxially behind the accelerator.

The jet pressure was measured using a gauge located at the outlet of the tube. CTS19 piezoceramic tube with a diameter of 18 mm and a length of 22 mm was used as a sensing element. The wall thickness was 1 mm. The side of the tube facing jet was covered with a 2 mm thick plexiglass disc. Gauge and the supply wires were shielded with metal foil. The gauge was calibrated using a certified pressure sensor from PCB piezotronics.

The efficiency of plasma-to-gas flow transformation was evaluated using RM1/RM3 ratio of the glow intensities of the jet in visible region of the spectrum at inlet and outlet of the recombination tube using photomultiplier tubes with calibrated gain factors. The distance between photomultiplier tubes was 1.14 m.

The dependence of variation of the velocity of jet along tube $\upsilon(L)$ was calculated using time delays between signals PM1-PM2, PM2-RM3 and RM1-RM3 (Fig. 3). Measurements were carried out between the beginnings of signal leading edges. The jet velocity at outlet was determined by extrapolating dependence $\upsilon(L)$ to tube edge.

The radial expansion velocity of the gas jet was measured using two double probes *8* (Fig. 3), located at different depths in the side tube near the outlet of recombination tube. We assume that the jet expands adiabatically, and this velocity corresponds to velocity of sound in the gas [9]. Delay time between leading edges of probe signals was recorded. A constant voltage from capacitors was applied to each probe through LEDs and limiting resistors. The

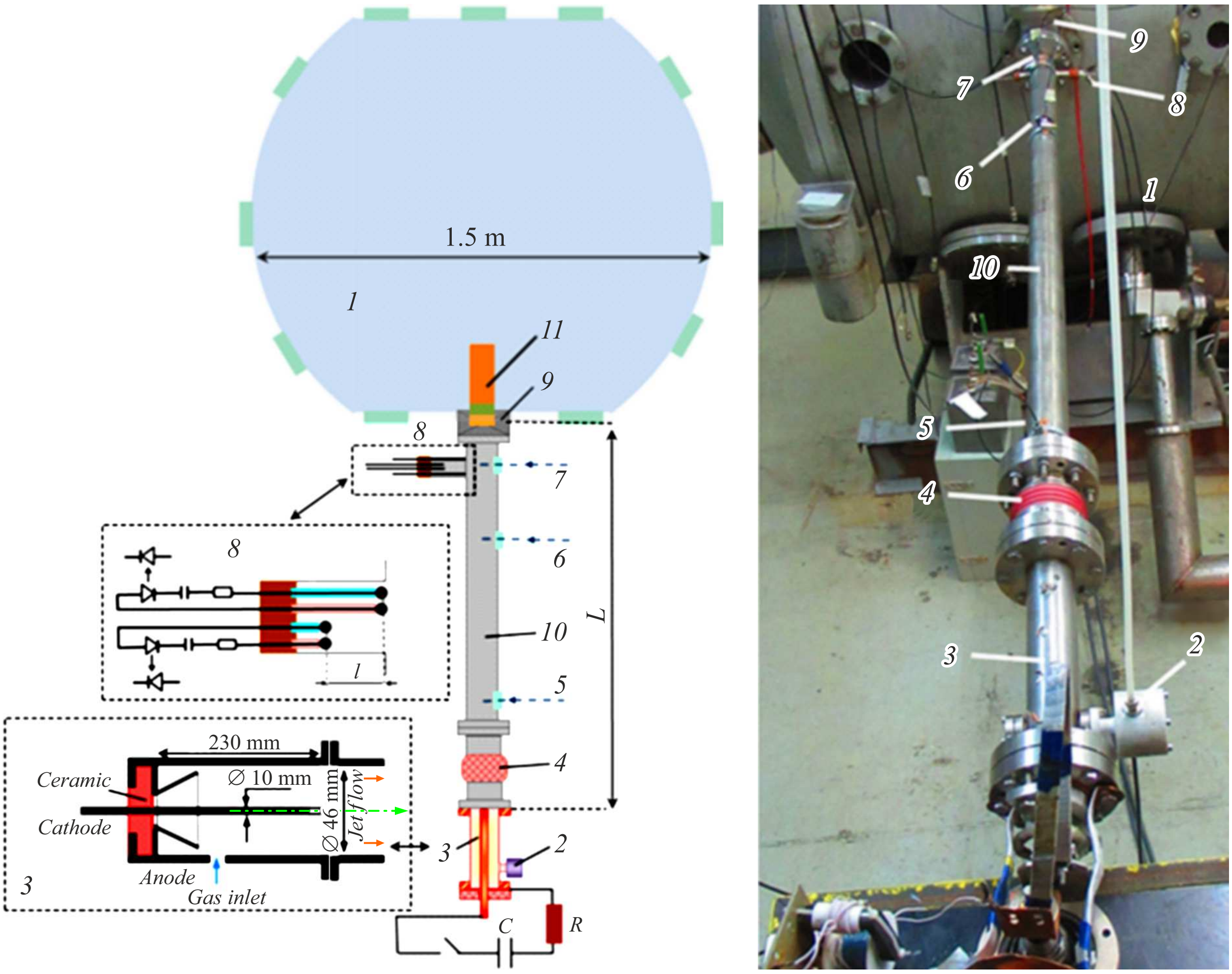

Figure 3. Diagram of the experimental stand (left) and the exterior of the plasma accelerator equipped with a recombination tube L (right). *1* — vacuum chamber, *2* — gas valve, *3* — plasma accelerator, *4* — metal-ceramic junction, *5* — window for collecting PM1 radiation, *6* — window for collecting PM2 radiation, *7* — window for collecting PM3 radiation, *8* — probes for measuring the thermal velocity of the jet, *9* — vacuum gate, *10* — recombination tube, *11* — piezoelectric pressure gauge.

voltage and resistance were 1−2 kV and 1 kΩ, respectively. A current flowed in circuit during the contact of probe with plasma, which was recorded using optical coupler and ADC. Time delay between leading edges of the currents, radial velocity of the jet or the speed of sound in the gas was calculated using the formula

$$\upsilon_s = l/\Delta t_{prob}, \tag{5}$$

where l — the distance between probes, Δt_{prob} — delay time between signals received by probes. Jet temperature was calculated using the formula [9]:

$$T = \frac{m\upsilon_s^2}{kK}, \tag{6}$$

where m —molecular weight of the helium atom, K — Boltzmann constant, k — adiabatic index; for helium $k \approx 1.67$.

3. Results

Figure 4 shows time dependences of jet parameters generated by the accelerator.

It can be seen that the working gas was injected into accelerator for 150 μs before the start of discharge. A current was initiated in the accelerator in $\sim 400\,\mu$s after opening the valve. The amplification coefficients of photomultipliers were calibrated relative to each other. It can be seen that amplitude of the PM1 signal at the input was greater than the amplitude of the PM3 signal at output, and duration of the PM1 signal turned out to be less than the duration of the PM3 signal. It can be assumed that decrease of output signal was caused by partial recombination of plasma into gas. The increase of duration of output signal is probably attributable to spread of particle velocities in plasmoid. This effect could lead to stretching of the jet along tube.

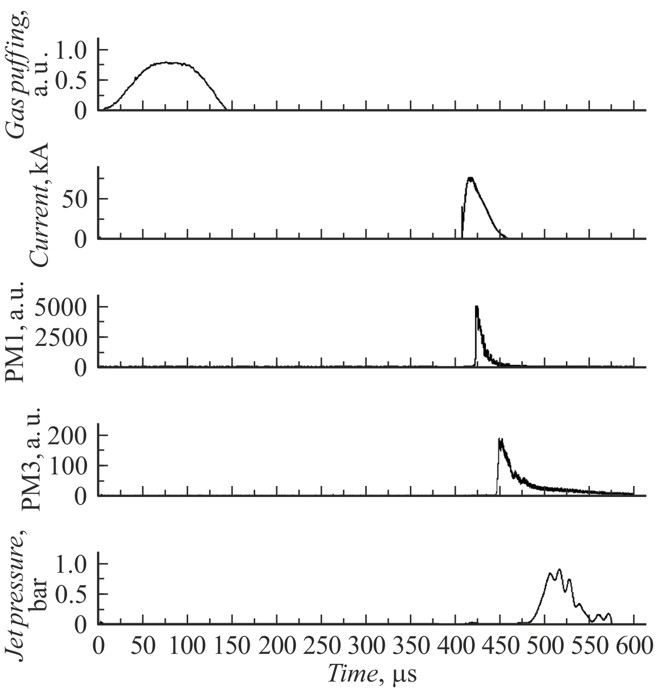

Figure 4. Dependences of jet parameters on the time created by plasma accelerator.

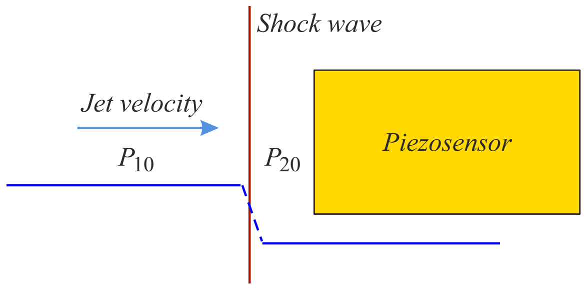

Figure 5. Layout of the pressure sensor relative to the pressure shock.

The jet velocity was not calculated using time delay between the PM3 signals and the pressure gauge due to the difference of temporal physical factors causing the response of these detectors. For instance, the PM3 reacted to radiation from ionization front of jet, and the piezo gauge recorded the pressure of jet passing through the shock wave. This could lead to a disproportionate increase of the delay between the PM1-PM3 signals and the PM3 piezo gauge.

For the jet velocity to be greater than the sound velocity, it was necessary to take into account the pressure loss after the gas passes through pressure shock formed in front of surface of pressure sensor. The jet's mechanical energy is lost after passing the pressure shock. In this case, the quantitative value of the irreversibility of gas passage through the pressure shock is taken to be the ratio of the total pressure after the pressure shock to the pressure and before pressure shock $\frac{P_{20}}{P_{10}}$ [10]. Fig. 5 shows the layout of pressure sensor relative to the direct shock of the seal.

In this case, the piezo sensor measured not the pressure P_{10}, but the total pressure P_{20}. The jet pressure was calculated using the formula [10]:

$$P_{10} = \frac{P_{20}\left(1+\frac{k-1}{2}M^2\right)^{\frac{k}{k-1}}\left(kM^2-\frac{k-1}{2}\right)^{\frac{1}{k-1}}}{\left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}}M^{\frac{2k}{k-1}}}, \tag{7}$$

where $M = \frac{v}{v_s}$ is the Mach number before pressure shock. The particle density in jet was estimated using Clapeyron–Mendeleev formula:

$$n = \frac{P_1}{m \cdot R \cdot T}, \tag{8}$$

where P_1 — static jet pressure at outlet of recombination tube, $R = 2078\,\mathrm{J/(kg{\cdot}K)}$ — helium gas constant. Static pressure P_1 was calculated using Rayleigh formula [10]:

$$P_1 = \frac{P_{20}\left(kM^2-\frac{k-1}{2}\right)^{\frac{1}{k-1}}}{\left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}}M^{\frac{2k}{k-1}}}. \tag{9}$$

The results of study of jet parameters are presented in graphs in Fig. 6. A significant difference in pressure values before and after shock wave formed in front of the surface of the pressure sensor was found. The pressure ratio after and before the pressure shock was more 10-fold. It can be seen that the temperature and sound velocity of the jet in studied current range did not exceed 1 eV and 8 km/s, respectively. The jet velocity increased from 15 to 40 km/s with an increase in current from 28 to 38 kA, proportion of neutral component decreased from about 13 to 2%, and the actual jet pressure increased from 0.5 to 1.5 bar. At the same time, density of particles in jet increased from $0.1 \cdot 10^{21}$ to $5 \cdot 10^{21}\,\mathrm{m}^{-3}$.

It is planned to use the helium jet flowing at high velocity in a helium thermometer for deep sensing of wall plasma in the Globus-M2 tokamak [11,12]. Selected accelerator current is to be 28–30 kA at which a jet of helium will exit the tube at a velocity of ~ 10 km/s, density $10^{20}\,\mathrm{m}^{-3}$ and pressure ~ 1 bar. The diameter of jet ~ 50 mm may be suitable for local sensing of periphery of Globus-M2 plasma, since its characteristic dimensions exceed 1 m. Jet density is comparable to background plasma density in tokamak reactor, reaching more than $10^{20}\,\mathrm{mm}^{-3}$. Earlier experiments on the injection of an accelerator plasma jet with density of $\leq 10^{22}\,\mathrm{m}^{-3}$ in Globus-M showed that it could penetrate into volume without disturbing the stability of trapped tokamak plasma [13]. The temperature values obtained using a helium thermometer fitted with a jet accelerator will be verified by comparison with data obtained, for example, using probes.

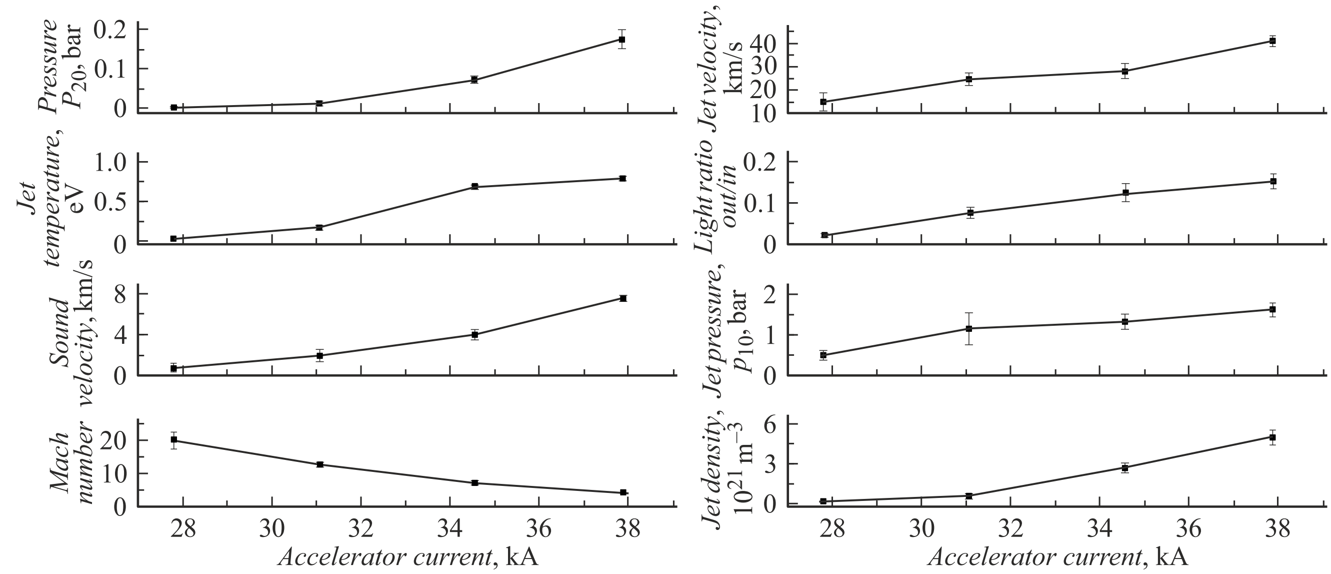

Figure 6. Dependences of the jet parameters on the amplitude of the current generated using a coaxial plasma accelerator and a recombination tube.

Conclusion

The conditions for the formation of a helium flow using a coaxial plasma accelerator and the length of a recombination tube are demonstrated. The accelerator current of 28–30 kA was selected in the result of completed studies at which a jet of neutral helium mainly exited the pipe at a velocity of ~ 10 km/s and a density of $\sim 10^{20}\,\mathrm{m}^{-3}$. It is planned to use the helium jet flowing with such velocity in a helium thermometer for deep sensing of wall plasma in the Globus-M2 tokamak.

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Conflict of interest

The authors declare that they have no conflict of interest.

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