Supersonic gas jet generation using a plasma accelerator

© V.Yu. Goryainov[1,2], A.V. Voronin[1]

[1] Ioffe Institute, St. Petersburg, Russia
[2] Peter the Great Saint-Petersburg Polytechnic University, St. Petersburg, Russia
E-mail: vgoryainov@mail.ioffe.ru

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We propose a method of forming a neutral helium flux using a plasma accelerator. The method consists in the transformation of a dense and cold plasma jet into a gas flow. For this purpose, the plasma was passed through a long channel, in which it could recombine as it moved. As a result of this research, conditions were found in which a jet of neutral helium with a velocity of about ten kilometers per second was mostly released at the outlet of duct. A high-velocity helium jet is planned to be used as part of a helium thermometer for deep probing of near-wall plasma in the Globus-M2 tokamak.

Keywords: plasma accelerator, triple recombination, supersonic gas jet.

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A jet of gas with large kinetic energy can effectively penetrate through the magnetic field into the central region of the tokamak [1,2]. For deep probing of plasma, there is a need to increase the jet velocity. To this end, method for generating helium jet stream is proposed in the present work, which consists in transforming a dense and cold plasma jet into a gas stream. To do this, the plasma was passed through a long channel in which it could recombine as it travelled. As a result, a gas flow with velocity close to that of the plasma flow could be formed at outlet of recombination tube.

The studies were carried out on test bench containing a set of diagnostics and a $2.5\,\mathrm{m}^3$ vacuum chamber with shutter through which it was possible to attach different variants of accelerators. The schematic diagram of experimental test bench and appearance of plasma accelerator ($C = 600\,\mu$F) [3] are shown in Figure. A long channel — recombination tube was located coaxially to plasma jet motion. The jet pressure was measured using piezoelectric sensor located at outlet of recombination tube. Efficiency of plasma-to-gas flow transformation was controlled by intensities ratio of jet radiation at the inlet and outlet of the recombination tube (PM1/PM2) using photomultiplier tubes PM1, PM2, with calibration gain factors. The jet velocity at outlet of duct was measured from the window radiation delay time and PM2 signal of the pressure sensor.

The plasma recombination rate is determined by the relation

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

where n_i and n_e — ion and electron densities, respectively, α — recombination coefficient [4]. It is assumed that the low-temperature and dense hydrogen-like plasma is dominated by the process of triple electron-ion recombination. Then

$$\alpha \approx \frac{0.6 \cdot 10^{-27} n_e}{T_e^{9/2}}\,[\mathrm{cm}^3/\mathrm{s}]. \tag{2}$$

The characteristic recombination time can be estimated by the formula

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

where T_e — temperature [eV]. It has been estimated that for dense and cold plasmas, the characteristic recombination times can range from a few microseconds to a few milliseconds. The distance L, required to transform plasma jet into gas flow, was calculated by the formula

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

where v — jet velocity. The choice of recombination tube length was determined based on density dependence of the distance required to transform helium plasma into gas. For density more than $10^{15}\,\mathrm{cm}^{-3}$, the length of recombination tube can be less than 2 m. Tube with length of 1.37 m and an inner diameter of 46 mm was used in experiment.

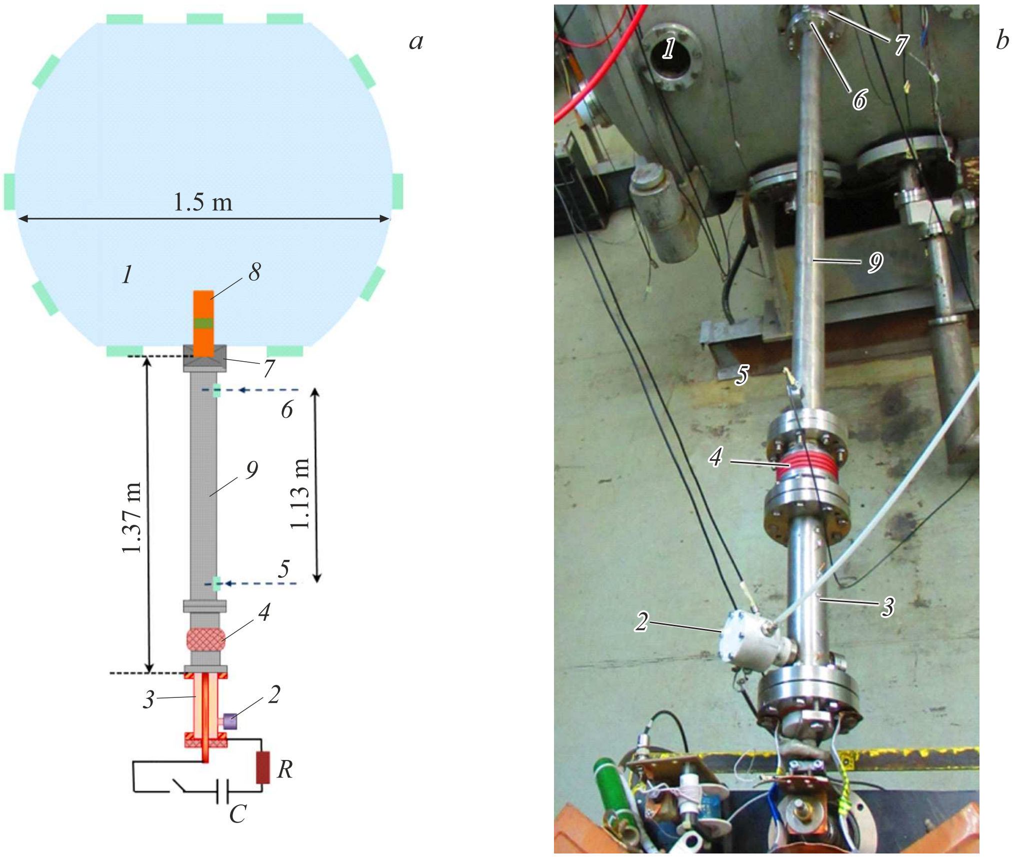
For jet velocities greater than sound velocity, the change in pressure after gas passes through seal jump must be taken into account. The full jet pressure P_{10} was calculated using formula [5]:

$$P_{10} = \frac{P_{20}\left(1 + \frac{k-1}{2}\mathrm{M}_1^2\right)^{\frac{k}{k-1}}\left(k\mathrm{M}_1^2 - \frac{k-1}{2}\right)^{\frac{1}{k-1}}}{\left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}}\mathrm{M}_1^{\frac{2k}{k-1}}}, \tag{5}$$

where P_{20} — pressure after seal jump (determined by piezo sensor measurements), k — adiabatic index (for helium $k = 1.67$), M_1 — Mach number before the jump seal. Static pressure of unperturbed jet at outlet of recombination tube was determined using Clapeyron – Mendeleev formula

$$P_1 = n m_{\mathrm{He}} R T, \tag{6}$$

where m_{He} — helium atom mass, $R = 2078\,\mathrm{J/(kg \cdot K)}$ — helium gas constant, T — absolute jet temperature [K], n —



a — scheme of the experimental test bench; *b* — external view of the plasma accelerator equipped with a recombination tube of length *L*. *1* — vacuum chamber, *2* — gas valve, *3* — plasma accelerator, *4* — metal-ceramic insulator, *5* — PM1 radiation collection window, *6* — PM2 radiation collection window, *7* — vacuum shutter, *8* — dynamic pressure sensor, *9* — recombination tube.

Measured helium jet parameters as a function of current ($T_e = 0.5$ eV)

Current, kA	Ratio of intensities PM2/PM1	Velocity jets on outlet v, km/s	Measured pressure, P_{20}, mbar	Density of unperturbed jet n, 10^{15} cm^{-3}
31.2 ± 0.8	189	5 ± 1	5 ± 2	3 ± 2
51 ± 2	100	7 ± 2	100 ± 60	10 ± 10
62 ± 3	31	12 ± 2	380 ± 80	10 ± 10
73 ± 3	17	30 ± 10	860 ± 60	14 ± 7

density of particles of the jet. Density was estimated using the formula

$$n = \frac{P_1}{m_{\mathrm{He}}RT} = \frac{P_1}{KT}, \qquad (7)$$

where K — Boltzmann constant. Unperturbed static flow pressure P_1 was calculated using Rayleigh [5] formula:

$$P_1 = \frac{P_{20}\left(k\mathrm{M}_1^2 - \frac{k-1}{2}\right)^{\frac{1}{k-1}}}{\left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}}\mathrm{M}_1^{\frac{2k}{k-1}}}. \qquad (8)$$

Jet parameters crated with plasma accelerator and recombination tube for different values of current are summarized in table. The table shows that when accelerator current was increased from 30 to 70 kA, the jet velocity increased by a factor of ~ 6, ratio of jet radiation intensities at inlet and outlet of duct decreased by a factor of ~ 10, and measured pressure P_{20} increased by a factor of ~ 200. At the same time, the density of particles in jet increased by a factor of ~ 5. The mode with current ~ 50 kA is considered for use on the tokamak.

Conditions for the formation of a neutral helium flow using a plasma accelerator and long recombination tube are demonstrated. In result of the conducted studies, parameters at which the ratio of radiation intensities of jet at the inlet and outlet of tube decreased significantly were found. The jet velocity reached 5–30 km/s, the density — over

10^{15} cm^{-3}. Helium jet is planned to be used as part of a temperature [6] diagnostic for deep probing of wall plasma in Globus-M2 tokamak.

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Conflict of interest

The authors declare that they have no conflict of interest.

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