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Injection of intense plasma jet in the spherical tokamak Globus-M

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Abstract Progress in the theoretical and experimental development of the plasma jet source and injection of hydrogen plasma and neutral gas jets into the Globus-M spherical tokamak is discussed. A procedure to optimize the accelerator parameters so as to achieve the maximum possible flow velocity with a limited discharge current and a reasonable length of the coaxial electrodes is presented. The calculations are compared with experiment. Plasma jets with densities of up to 2×10^{22} m^{-3}, total numbers of accelerated particles (1--5) x 10^{19}, and flow velocities of 50--100 km/s were successfully injected into the plasma column of the Globus-M tokamak. Interferometric and Thomson scattering measurements confirmed deep jet penetration and a fast density rise (<0.5 ms) at all spatial points up to a radius $r \approx 0.3a$. The plasma particle inventory increase by ~50% (from 0.65 x 10^{19} to 1 x 10^{19}) did not result in plasma degradation.

1. Introduction

The problems of plasma fuelling and density profile control are topical for any high-performance magnetic-trap operation. The fuel must have a high enough directed energy to pass through the dense and hot plasma border prior to reaching the central plasma region. The total number of accelerated particles has to be 10^{19}--10^{23} for densities $>10^{21}$ m^{-3} and flow velocities of up to 800 km/s.

Fuelling of fusion plasma by gas puffing has a low efficiency. Pellet injection being fundamentally limited by the velocity, is hardly an adequate approach to fuelling central regions in tokamak reactors [1, 2]. Neutral beam injection method requires further increase of beam energy up to the MeV range before it is accepted for reactor fuelling [3]. Magnetically confined plasma (compact tori) injection has a limit on its density. To increase the total number of particles one has to increase the plasma ring volume [4]. There are no guns that could generate dense, highly ionized and pure plasma jets with a high directed velocity.

Research carried out at the Ioffe Physico-Technical Institute has culminated in development of a fuelling method and a pulsed accelerator producing an intense, dense hydrogen (eventually deuterium) plasma jet [5]. The source consists basically of two stages. The first (gas generating) stage contains titanium grains loaded with hydrogen. An electric discharge passing through the grains releases high-pressure hydrogen. Neutral hydrogen passing through a specially designed grid fills the accelerator electrode gap to a high pressure in a few tens of microseconds. The second (plasma generating) stage is actually a system of coaxial electrodes. Electric discharge fired through the gas between the coaxial electrodes provides gas ionization and plasma acceleration in the classical “Marshall gun scenario”.

Experiments with plasma injection into the spherical tokamak Globus-M [5--8] have demonstrated the viability of this method of fuelling with minimum plasma perturbations. The present communication reports on a theoretical and experimental study of such plasma sources and of injection of plasma and gas jets from a modified source into Globus-M.

2. Numerical optimization and experimental investigation of the plasma gun

The goal of the present research was to develop a source which would produce a plasma with a high kinetic energy and with an as low as possible impurity content, because fuel injected into a fusion reactor must be pure. A plasma jet with the highest possible specific kinetic energy has to be produced with a minimum discharge current in the coaxial accelerator. We resorted to numerical simulation to analyze the acceleration process in a coaxial accelerator with a variable capacitor battery restricted by the condition of fixed energy conservation at zero losses. Electrodynamic plasma acceleration along the *z* axis can be described in the simplest case by coupled equations by Artsimovich [9].

An experimental test bed including a 2-m^3 vacuum chamber was built to study the parameters of intense plasma jets [10]. The plasma density was measured with a He--Ne laser interferometer. A movable piezoceramic probe measured the pressure profile and total kinetic energy of the jet. The H_α and H_β hydrogen lines were isolated with a two-channel spectrometer. The flow velocity was measured with two collimated PM tubes recording the light near the gun edge and at the opposite wall of the vacuum chamber. A CCD camera registered time-integrated radiation emitted by the jet. A permanent movable C-magnet (5 cm gap) was mounted beyond the gun edge to separate neutrals from the charged particle flow.

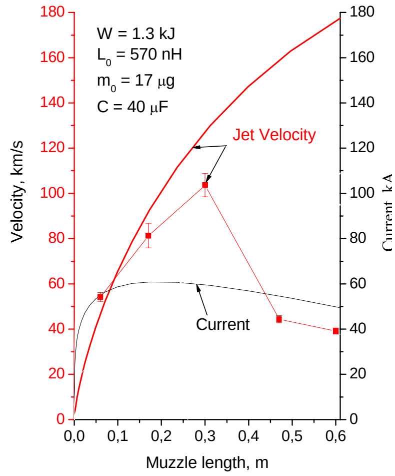
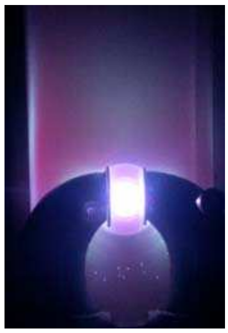


FIG. 1. Evolution of plasma velocity and discharge current distribution along the muzzle length of coaxial electrode accelerator

Simulation suggests that in order to achieve the maximum plasma jet velocity for a given stored energy and limited muzzle length, the current layer amplitude along the whole length of the muzzle should be as large as possible. This is the case of capacitance, C_p = 40 µF. Experimental measurements of the plasma jet velocity were carried out on the test bed for different muzzle lengths. The experimental points in Fig. 1, while following correctly the pattern of the theoretical curve up to muzzle lengths of 0.3 m, lie below the calculated values, apparently because of the model not including the losses. The strong discrepancy between experiment and simulation for longer muzzles remains unclear but could be attributed to some disregarded factors, in particular, minor design flaws. Further experiments were conducted with close to optimum parameters of coaxial accelerator length and power supply (muzzle length 0.3 m, C_p = 40 µF).

B = 0.3 T, view rpendicular to the source axis



B = 0.3 T, view along the source axis

FIG. 2. Radiation of the plasma jet passing the transverse magnetic field

The plasma temperature of the jet is of the order of ~1 eV. The kinetic energy of the jet is as high as 100--500 J (for a stored capacitor energy of 0.65--1.3 kJ). An optimized source generated during ≤50 µs pure, highly ionized hydrogen plasma jet with a density up to 2 × 10^{22} m^{-3}, total number of accelerated particles (1--5) 10^{19}, and a flow velocity of 50--110 km/s.

We studied jet penetration across transverse magnetic field generated by the magnet placed near the gun edge. The radiation of the jet crossing a magnetic field can be viewed in Fig. 2. No visible radiation was detected beyond the magnet. As expected, the magnetic field stops the injected plasma if its specific kinetic energy or pressure is lower than the pressure of the transverse magnetic field. In this particular case of a magnetic field of 0.3 T, plasma flow velocity of 50 km/s, and density $\leq 10^{22}$ m^{-3}, the pressure measured beyond the magnet was found to be near zero.

The dependence of jet pressure on the distance between the permanent magnet (B = 0.3 T) and the gun edge is presented graphically in Fig. 3. Measurements were taken at different magnet positions and constant jet velocity when the magnet was moved between the gun edge and the probe location. It is seen that the jet pressure increases with increasing distance between the gun edge and the magnet, and at the distance of 75 cm reaches the same pressure value as it was without any magnetic field.

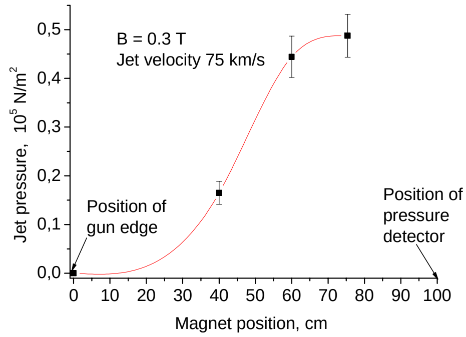


FIG. 3. Plasma jet pressure plotted vs distance between the permanent magnet and the plasma gun edge

3. Jet injection into the Globus-M Spherical tokamak

Experiments on the plasma jet interaction with the magnetic field and plasma of Globus-M were performed during 2003-2005 years. In the previous campaigns injection was performed at a small angle (15 degrees) to the vertical axis, and the plasma jet velocity did not exceed 70 km/s [5, 6, 8]. During recent experiments plasma jet was injected into Globus-M from the equatorial plane, along the major radius from the low field side. The jet speed was increased up to 110 km/s.

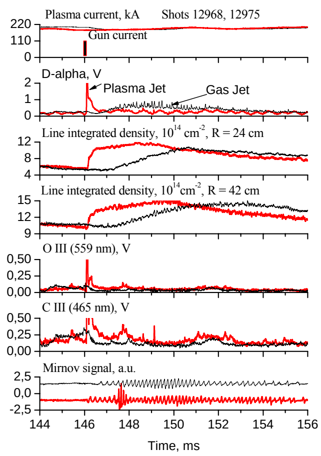


FIG. 4. Waveforms of plasma discharge parameters in Globus-M under plasma and gas jet injection

Figure 4 (red curves) demonstrates a fast density rise (<0.5 ms) recorded by the interferometer along the peripheral (R = 24 cm) and central (42 cm) chords. In this case, the density rise time was shorter than the diffusion time, and it could roughly be identified with the time necessary for injected particles to equilibrate along the field lines. While the plasma particle inventory increased by 50% (from 0.65 x 10^{19} to 1 x 10^{19}), it did not result in plasma degradation (as, e.g., a drop in plasma current, contamination by impurities, MHD activity enhancement). Initial short peaks recorded by H_α, OIII, CIII detectors are due to strong blackbody radiation of the jet illuminating the vessel interior. After time interval of 2--3 ms all the signals, including bolometer and Mirnov signals returned to the initial (before injection) level. The first measurements of the electron density evolution in these experiments were conducted by the Thomson multi-pulse scattering diagnostics (Fig. 5). Preliminary data suggest that 0.5 ms after a plasma gun shot, the density increases at all spatial points up to the radius $r \approx 0.3a$, thus evidencing deep plasma jet penetration. The decrease of the toroidal field from 0.4 to 0.3 T and the plasma current from 200 to 120 kA did not lead to better (faster and deeper) penetration of the plasma jet into the tokamak plasma as may be expected.

To compare the efficiency of plasma jet injection with gas puffing, experiments were conducted with the first stage of the plasma gun used as gas generator. Test bed experiments showed the first stage is able to generate a fairly fast (1--5 km/s) neutral gas jet. This jet was injected into Globus-M and penetrated efficiently into the magnetic field. The density rise time of ~2.5 ms observed (Fig. 4, black curves) is shorter than that achieved customarily with conventional gas puffing (4--5 ms) while being much longer than that characteristic of plasma jet injection (<0.5 ms).

4. Discussion

The test bed experiment demonstrated that an injected plasma jet is stopped by a magnetic field if its specific kinetic energy or pressure is lower than the pressure exerted by the magnetic field. Nevertheless deep jet penetration into the plasma column of Globus-M and fast density increase in the core plasma region was observed. This may indicate transformation of a sizable fraction of the charged particle flux to a high-density flux of neutrals during the transit time ~10 μs. In a plasma jet with the parameters reached in test bed experiments ($n \sim 10^{21}$--10^{22} m^{-3}, $T \sim 1$ eV), the rate of three-body radiative recombination is very high. Assuming the measured transit time to be roughly equal to the characteristic three-body recombination time ($\tau_{rec} \approx 1.8 \cdot 10^{38}\, T^{9/2}$ eV/n^2 m$^{-3} \approx 10^{-5}$ s), we obtain ~1 eV and ~4 10^{21} m^{-3} for the parameters of the jet recombining in this time. The fairly low measurement accuracy and the order-of-magnitude character of the above calculations do not permit unambiguous identification of the mechanism by which the plasma jet penetrates across a magnetic field. At the same time, recombination of a plasma jet to form a jet of neutrals appears a most likely candidate for the process resulting in efficient penetration of particles into a magnetic field.

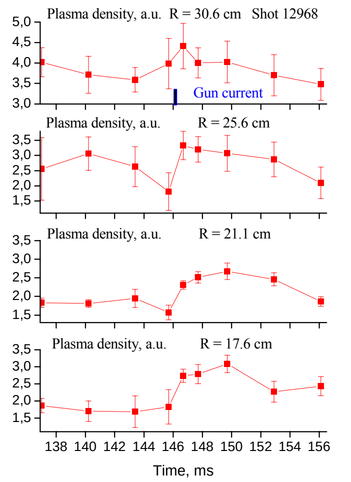


FIG. 5. Electron density evolution at different spatial points of the plasma column as derived from multi-pulse Thomson scattering diagnostics. The geometric axis of the column is at R = 33 cm

From experiments performed we can conclude that our non-sophisticated double stage plasma gun, producing plasma jet with 50 μs duration, density 10^{22} m^{-3}, total number of accelerated particles >10^{19} could increase plasma particle inventory in Globus-M by ~50 % (from 0.65×10^{19} to 1×10^{19}) in a single shot without target plasma parameters degradation.

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References

[1] Gouge M.J., Fueling of ITER-scale fusion plasmas ANS Conference Nashville (1998)

[2] Combs S. K., Rev. Sci. Instrum. 64 (1993) 1979.

[3] ITER Physics Basis Nucl. Fusion 39 (1999) 2416, 2521.

[4] R. Raman, et al., Nuclear Fusion 37 (1997) 964.

[5] Voronin A.V. and Hellblom K.G., Plasma Phys. and Controlled Fusion 43 (2001) 1583.

[6] Abramova K.B. et al, (Proc. 30th EPS Controlled Fusion and Plasma Phys. Conf. St.Petersburg 2003) 27A CD-ROM file P-3.110.

[7] Gusev V.K. et al, (Proc. 31st EPS Plasma Phys. Conf. London 2004) 28G CD-ROM file P1-109.

[8] Abramova K.B. et al, Plasma Physics Reports 31 (2005) 1.

[9] Artsymovitch L.A. et al, Soviet Journal of Experimental and Theoretical Physics 33 (1957) 3.

[10] Gusev V.K. et al, Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) (Vienna: IAEA) CD-ROM file FT/P1-26.