High Kinetic Energy Jet Injection into Globus-M Spherical Tokamak

A.V.Voronin[1], K.B. Abramova[1], V.K.Gusev[1], G.S.Kurskiev[1], V.B.Minaev[1], E.E.Mukhin[1], Yu.V.Petrov[1], V.A.Rozhansky[2], N.V.Sakharov[1], I.Yu.Senichenkov[2], I.P. Shcherbakov[1], S.Yu.Tolstyakov[1], I.Yu.Veselova[2]

1-Ioffe Physico-Technical Institute, RAS, 194021, St.-Petersburg, Russia

2-St. Petersburg State Polytechnical University, 195251, St.-Petersburg, Russia

E-mail: voronin.mhd@mail.ioffe.ru

Abstract Progress in 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. Injection of pure, highly ionized hydrogen plasma jet with a density up to 2×10^{22} m^{-3}, total number of accelerated particles (1-5)$\times10^{19}$ and a flow velocity of ~125 km/s was used as instrument for the density control. The gas and plasma jets were injected into Globus-M and penetrated efficiently into the magnetic field. The density rise time of ~2.5 ms (for gas jet) observed is shorter than that achieved customarily with conventional gas puffing (4--5 ms) while being much longer than that of characteristic density raise time by plasma jet injection (<0.5 ms). It increased plasma particle inventory in Globus-M by ~50 % (from 0.65×10^{19} to 1×10^{19}) in a single shot without plasma parameter degradation. Fast density increase in all spatial points of the plasma column including the plasma central region confirmed density rise during the time less than 1 ms, which is the signature of deep jet penetration. Plasma startup in tokamak with the help of the plasma jet in conditions of double swing CS operation regime demonstrated faster heating of the discharge as compared to gas puffing with RF pre-ionization. The model for gas jet penetration into the tokamak is applied for the high-velocity jets accelerated by plasma gun on Globus-M. First numerical simulations showed that due to the large initial velocity such jet should penetrate deep (10-20cm) in the Globus-M plasma. The model predictions are consistent with experimental observations. The density raise recorded by interferometer and Thomson scattering is consistent with simulations. The fuelling by high velocity plasma jet might be preferable than Laval nozzle technique, especially for injection from high field side.

Introduction

Developing of effective plasma fuelling methods for future thermonuclear reactor like ITER has special importance. One of the most attractive fusion relevant scenarios is a high plasma density regime as the fusion power depends squarely on density. Plasma accelerators, producing clean, high density, high speed plasma jets could be used for this purpose. On the other hand the problem of plasma jet accelerating to high kinetic energy has its own fundamental and application significance. Spherical tokamak Globus-M program has the density control method development as one of the main goals to achieve and maintain regimes with high and ultimately high densities. Unique technical characteristics of the machine allow the achievement of high densities [1]. Method of density control alternative to gas puffing was used and developed at Globus-M. Experiments with injection of dense fast plasma jet into the spherical tokamak Globus-M [2--6] have demonstrated the viability of such method of fuelling with minimum plasma perturbations. The results currently obtained suggest the development and injection of plasma jets with specific kinetic energies in excess of those reached in earlier study. Experiments on plasma startup with the help of the plasma gun are continued. The present report is devoted to a further development of such fuelling method.

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 plasma jet [7]. The source consists basically of two stages (Fig.1). 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".

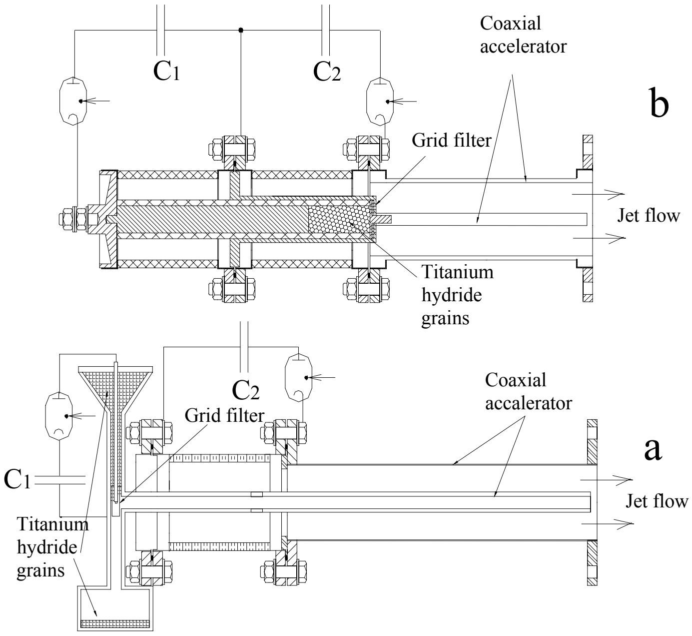

Fig.1: Two versions of gas generating stage; a- fresh grains loaded before each shot; b-fresh grains loaded before series

Numerical optimization and experimental verification of 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 [8].

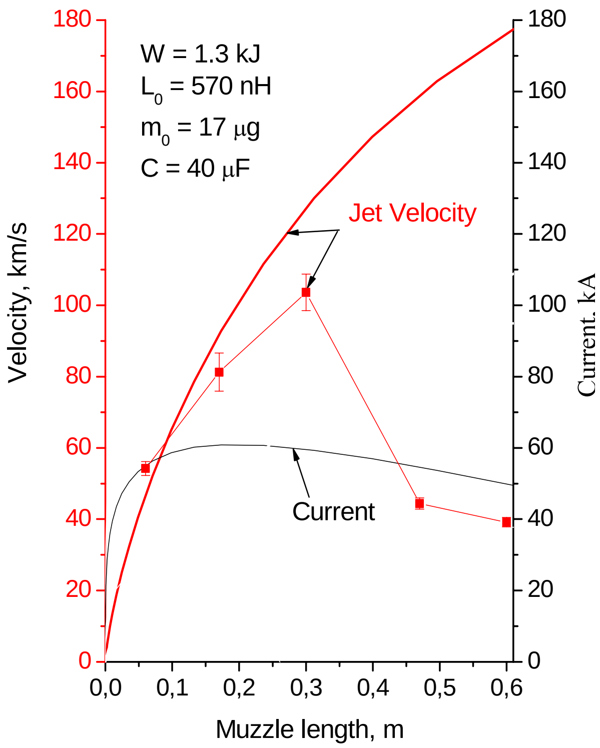

FIG.2: Evolution of plasma velocity and discharge current distribution along the muzzle length of coaxial electrode accelerator. Squares with the error bars represent experimental velocity values for the gun with C=40 μF power supply

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. 2, 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).

Plasma jet investigation at the test bed

An experimental test bed was built to study the parameters of intense plasma jets [9]. Existing 2-m^3 volume chamber was used as the vacuum stand. The stand was equipped with diagnostics and data acquisition system. 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.

Several modifications of the plasma gun were tested to get higher plasma jet parameters (velocity or density). Results of the successful experiments are presented bellow.

Gas generating and plasma accelerating stages were equipped with special separate switches to increase the specific kinetic energy of the jet. Time delay between the stage switching was optimized which allow increasing the plasma density from 1×10^{22} to 2×10^{22} m^{-3} and achieving of the jet velocity ≥100 km/s at the muzzle length of 0.3m.

The increase of muzzle length (more than 0.3 m) didn't result in jet velocity raise and the discrepancy between simulation results and experiments took place for longer muzzles. To clarify this effect we conducted an experiment with two accelerating stages connected in series. Double accelerating stage allowed increasing plasma flow velocity on ~25% as comparison with acceleration by one stage.

Efforts for alternative mechanism of gas release from the grains of titanium hydrate were performed. The attempt was made to produce gas release by irradiation of the titanium hydride grains by the Ruby laser. The laser with the output beam energy of 100 J and 1.2 ms duration was used. Laser beam irradiated grains (~1 mm^3) and produced gas cloud, which were ionized and accelerated in the coaxial gun. The plasma jet with similar characteristics was produced to the jet produced by traditional (electrical) grains activation.

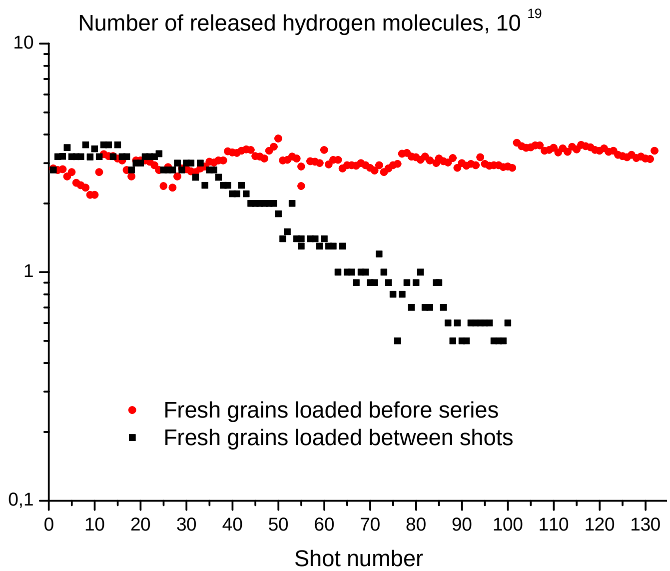

Fig.3: Dependences of number hydrogen molecules on shot number

Previous experiments were conducted with fresh titanium hydride grains loaded before the series of 50 shots (Fig.1b). An electric discharge passing through the whole package of 3 cm^3 grains releases quantity of hydrogen decreasing with a shot number. Present construction [10] allows loading the fresh grains before each shot (Fig.1a) consists of two chambers for fresh and used grains, and thin channel between where electrical discharge releases the hydrogen. The grains fell down through the channel immediately after discharge by high gas pressure or vibrator. An electric discharge passing through fresh 3 mm^3 grains releases stable quantity of hydrogen for many shots. Dependences of number hydrogen molecules on shot number for two constructions are presented in Fig.3. It is seen that with a shot number gas release decreases for version (b) and stable for version (a).

Jet injection into the Globus-M during current plateau phase

The basic design characteristics of Globus-M are as follows: aspect ratio $A = R/a = 1.5$, major plasma radius $R = 36$ cm, minor plasma radius $a = 24$ cm, average plasma density $n_e = (1\text{--}7)$ 10^{19} m^{-3}, pulse duration with inductive current drive $\tau_{pulse} \leq 0.12$ s. Plasma current amplitude was in range 150--250 kA at the quazi-stationary discharge phase. The toroidal magnetic field was changed in the range 0.3--0.4 T.

The hydrogen jet was injected into Globus-M in OH deuterium plasma during current plateau phase from the equatorial plane, along the major radius from the low field side. The jet speed was increased up to 110 km/s. The jet density near the gun edge reached 2×10^{22} m^{-3}.

Waveforms of plasma discharge parameters in Globus-M under plasma jet injection are presented. Figure 4 (red curves) demonstrates a fast density rise (<0.5 ms) recorded by the interferometer along the peripheral (R = 24 cm, 50 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. To verify whether density is increased over the whole plasma column cross section, or it is peripheral effect, the laser scattering measurements were made with

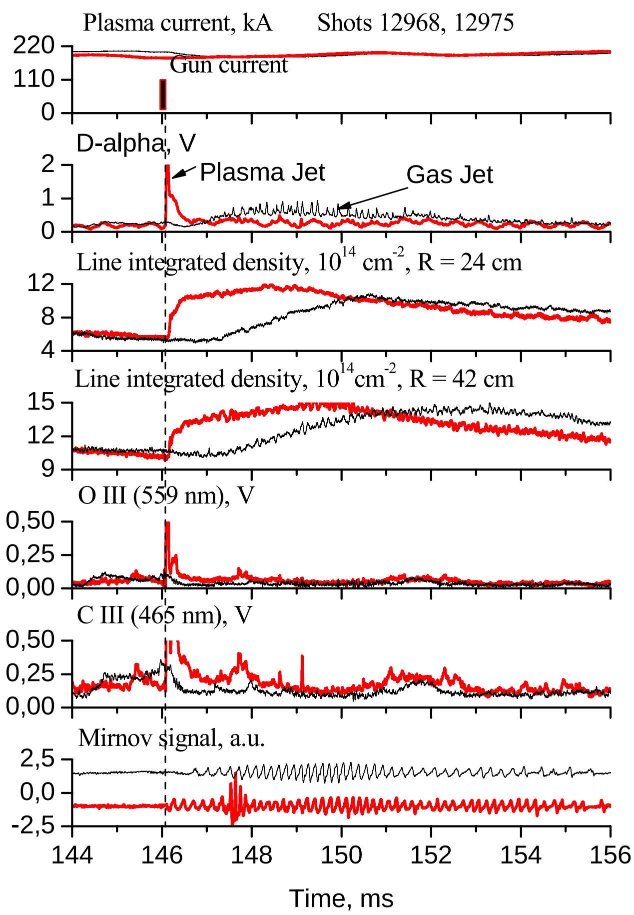

FIG.4: Waveforms of plasma discharge parameters in Globus-M under gas jet (black lines) and plasma jet (red lines) injection

ultimate temporal resolution. Time interval between successive laser shots before and during plasma jet injection was decreased down to 1 ms. Fig.5 demonstrates the temporal variation of electron density, measured by this diagnostics in different spatial points inside plasma column. The time at which jet injection took place is marked as vertical dotted line, labeled gun current. One can see, that density begins to rise already in a half of a millisecond interval (may be shorter) after the jet injection over the whole plasma cross section. The characteristic time of the density increase seems to be significantly shorter than for gas puff density control, while these measurements were not made for the gas puff. The data suggest that 0.5 ms after a plasma gun shot, the density begins to increase at all spatial points, 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.

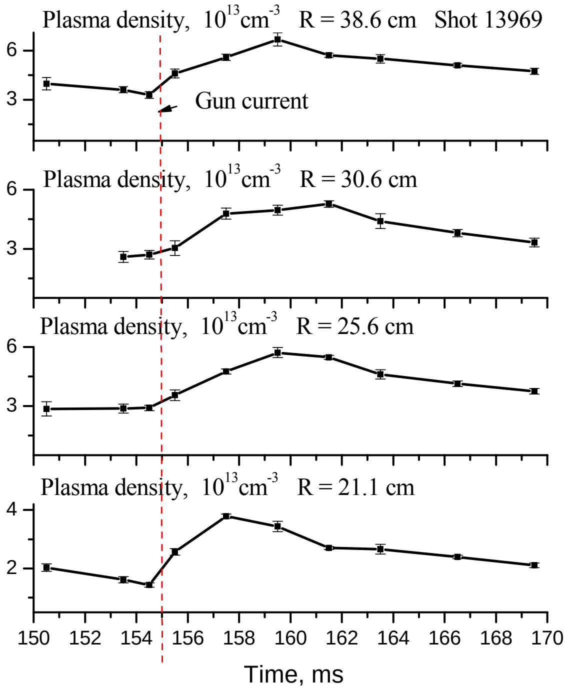

FIG.5: Time and space resolved density variation before, during and after the injection of the plasma jet as derived from multi-pulse Thomson scattering diagnostics. The geometric axis of the column is at R = 33 cm

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).

For comparison two different versions of gas generating stages in gun were used for plasma injection (Fig.6). Waveforms (a) correspond to version where fresh grains loaded before each shot and (b)-fresh grains loaded before 50 shots series. It is seen that it led to fast rise (<0.5 ms) the plasma average

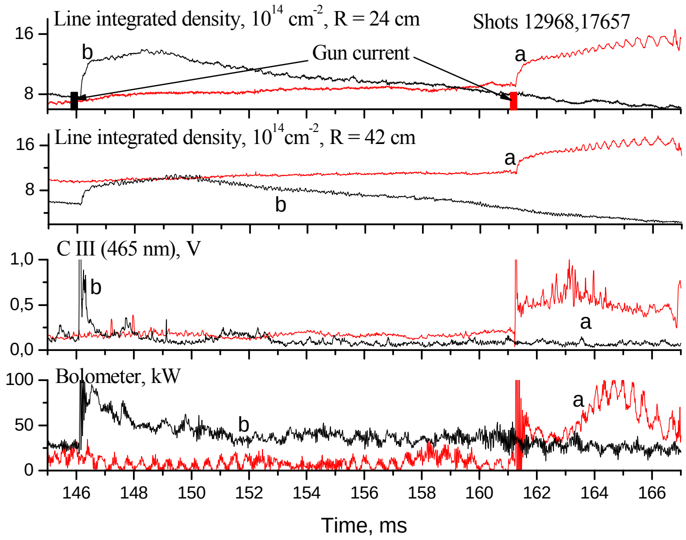

Fig.6: Waveforms of plasma discharge parameters in Globus-M under plasma jet injection; a- fresh grains loaded before each shot; b-fresh grains loaded before series of shots

density, line radiation CIII and black body radiation recording by bolometer.

The bolometer signal, the density increase along the peripheral (R = 24 cm) and central (42 cm) chord is equal both for a-and b version. But the increases for line radiation CIII is higher for a-case. Possibly in a-version source intense electric discharge passing through the grains in thin channel may release not only hydrogen but also some impurities. Additional efforts should be made to separate hydrogen cloud from impurities.

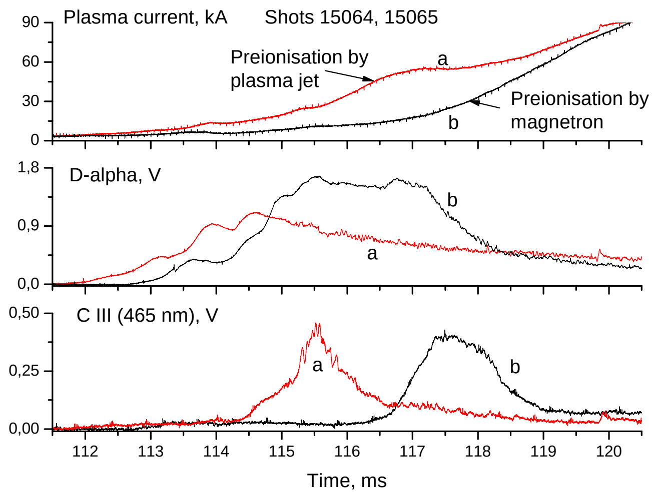

Fig.7: Time dependence of some plasma parameters in Globus-M at different discharge initiation conditions; a-with plasma gun; b-with gas prefill and UHF preionozation.

Plasma startup in tokamak with plasma gun in conditions of double swing central solenoid operation regime

Plasma source was placed at the equatorial plane on 0.5 m from tokamak. Initial plasma velocity reached 100 km/s; number of injected particles was comparable with total number of the particles in tokamak ($5x10^{18}$-- 10^{19}). The plasma discharge, initiated by means of plasma jet is shown in Fig.7. One could see that plasma current ramps up faster with the plasma gun initiation, than with traditional method. It is also seen that maximum of the spectral line intensities (D-alpha and CIII) are shifted to the beginning of the discharge. Higher plasma current and earlier spectral lines excitation may confirm more intensive plasma heating at the initial stage of the discharge.

Modeling of jet penetration

The penetration of jet into the core plasma requires sophisticated theoretical consideration. For the jet penetration modeling the approach was used described in [11].

The heating, expansion and ionization of the jet penetrating towards the tokamak center are calculated for the typical density and temperature profiles measured by TS diagnostics. It is found that the initially neutral jet is getting ionized within $\tau_i = 0.5\ \mu s$, i.e. penetrates up to 5

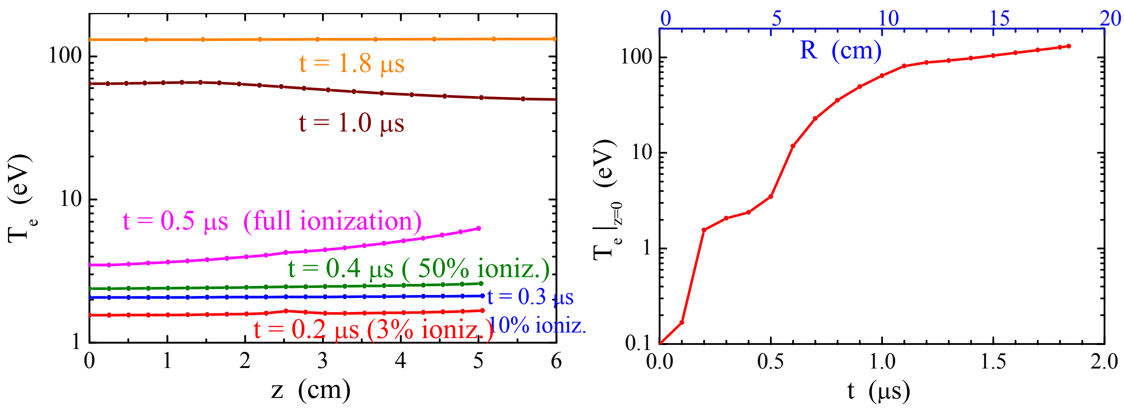

Fig. 8: Evolution of the jet temperature. Left: profiles along the magnetic field; Right: equatorial plane (z=0) temperature versus time.

cm assuming constant velocity. Temporal evolution of the jet temperature is shown in Fig 8. Note that the timescale of full ionization is of the same order as in experiments on Tore-Supra and ASDEX-Upgrade [12,13], where the jet with similar parameters was accelerated by pressure gradient through Laval nozzle.
The penetration of ionized jet in the injection direction is provided by polarization electric field $\vec{E}_0 = \left[\vec{B} \times \vec{V}_0\right] / B^2$ and $\vec{E} \times \vec{B}$ drift. However, this polarization and jet velocity $\vec{V}_{jet}$ respectively reduce due to two deceleration processes. First are currents in the Alfven wave emitted into the ambient plasma (the effect of so-called Alfven conductivity). The second is vertical ∇B-induced currents. Due to emission of Alfven wave the ionized jet decelerates exponentially and penetrates inside Globus-M plasma up to $V_0 \tau_\Sigma \approx 8$ cm, where $\tau_\Sigma \approx 0.8$ μs - characterizing deceleration time. Consequently, in the Globus-M deep penetration up to $V_0(\tau_i + \tau_\Sigma) \approx 12$ cm $\approx$ a/2 is possible, while on ASDEX-Upgrade $V_0 \tau_\Sigma \approx 1.5$ mm $<< a$, and jet practically could not cross the separatrix. Note that τ_Σ is inversely proportional to the sqrt of ambient plasma density and proportional to the jet density, therefore for higher ambient plasma densities and lower jet density the penetration depth would be smaller.

The second process accelerates the jet towards the low field side. The ∇B-induced current leads to acceleration towards the low field side, however, this current in the jet expanding along the magnetic field vanishes at timescale $R\sqrt{m_i/(T_e + T_i)}$ due to rotational transform, which leads to a displacement of the same order [14]. As both processes are going simultaneously consideration is more complex, but one can expect that significant part of injected particles should be deposited inside the separatrix, mainly at the plasma periphery when the jet was injected from the equatorial plane. This does not contradict experimental observations. If one could imagine jet injection from high field side the depth of injection into the plasma column will increase significantly.

Important result of the simulations is the weak sensibility of particle deposition to the initial ionization degree of the jet. It is explained by rather fast ionization, so that the ionization time is smaller that any other characterizing time in the problem.

Conclusions

The new gas generating stage of the jet source allows loading the fresh grains before each shot and produce stable gas release for many discharges. Velocity of the gas jet was increased up to 5 km/s and plasma flow velocity up to 125 km/s. The results currently obtained confirm that the injection of plasma jets with specific kinetic energies is in excess of those reached in earlier study. Additional efforts should be made to separate hydrogen cloud from impurities. Plasma startup in tokamak with the help of the plasma gun in conditions of double swing central solenoid operation regime showed better performance tokamak startup compared to conventional scenario. From experiments performed we can conclude that our non-sophisticated double stage plasma gun, producing plasma jet with, density 2×10^{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. The model for gas jet penetration into the tokamak is applied for the high-velocity jets accelerated by plasma gun on Globus-M. The model predictions are consistent with experimental observations. It is demonstrated that with high velocities achieved by plasma gun it is possible to get a deep jet penetration into the tokamak plasma.

The authors wish to thank the scientific, technical and engineering staff of the MHD Phenomena and Hot Temperature Plasma Physics Laboratories.

The work is supported by IAEA, Research Contract No 12408 and RFBR grants No 04-02-17606 and 06-02-16709a.

References

1. Gusev V.K. et al, Nuclear Fusion 41 (2001) 919.
2. Gusev V.K. et al Proceedings of the 20th IAEA FEC, 20th IAEA Fusion Energy Conference 1 - 6 November 2004Vilamoura, Portugal FT/P1-26 and http://www-naweb.iaea.org/napc/physics/fec/fec2004/datasets/index.html.
3. Gusev V.K. et al Proceedings of the 20th IAEA FEC, 20th IAEA Fusion Energy Conference 1 - 6 November 2004Vilamoura, Portugal EX/P4-24 and http://www-naweb.iaea.org/napc/physics/fec/fec2004/datasets/index.html.
4. Abramova K.B. et al, Plasma Physics Reports 31 (2005) 1 and http://www.maik.ru/cgi-bin/search.pl?type=contents&name=plasphys.
5. Voronin A.V. et. al, Nuclear Fusion 45 (2005) 1039 and http://stacks.iop.org/0029-5515/45/1039.
6. Voronin A.V. et al, (Proc. 32nd EPS Conference on Plasma Phys. Tarragona, 27 June-1 July 2005) ECA Vol. 29C CD-ROM file P-1.099 (2005) and http://eps2005.ciemat.es/papers/html/v_index.htm.
7. Voronin A.V. and Hellblom K.G., Plasma Phys. and Controlled Fusion 43 (2001) 1583.
8. Kolesnikov P.M., Electrodynamics acceleration of plasma (Moscow: Atomizdat) (1971) p.198.
9. Voronin A.V. et al, Nukleonika 51 (2006) 85
10. Voronin A.V. et al, (Proc. 33nd EPS Conference on Plasma Phys. Roma, 19 23 June 2006) P-4.105.
11. V. Rozhansky et al. Nucl. Fusion 46 (2006) 367-382
12. J.Bucalossi et al, Proceedings of 29th EPS Conference on Contr. Fusion, Montreaux, 2002, ECA Vol. 26B, O-2.07 (2002).
13. P T Lang et al. Plasma Physics and Controlled Fusion 47 (2005), 1495-1516
14. V. Rozhansky et al. Plasma Phys. Contr. Fusion 46 (2004) 575-591