

Generation and injection of intensive gas and plasma jets into the Globus-M tokamak

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One of the most attractive fusion relevant scenarios is a high plasma density regime as the fusion power depends squarely on density [1]. Globus-M has previously declared as one of the program goals the density control methods development, as well as the achievement of ultimately high densities due to unique technical characteristics of the machine [2]. Experiments with injection of the dense fast plasma jet into Globus-M have demonstrated the viability of

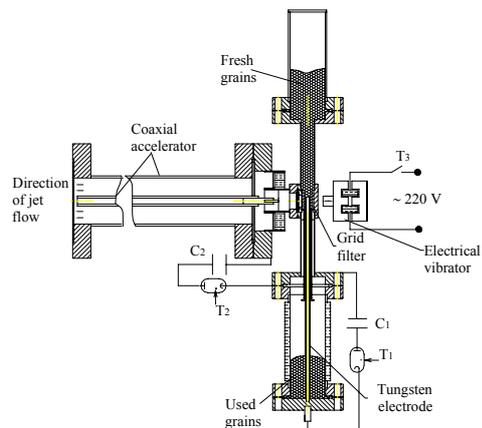


FIG.1: Latest versions of the source; fresh grains loaded before each shot

such method of fuelling with minimum plasma perturbations [3-5]. The novel double stage source of dense plasma with high-directed velocity, utilizing titanium-hydride grains was designed, constructed and investigated at Ioffe institute. The principals of operation are basically described in [6]. Hydrogen gas production, ionization and plasma acceleration are performed by intense electric discharges through titanium hydride grains and coaxial plasma accelerator (Marshal gun).

Latest design development allows loading the fresh grains before each shot (Fig. 1). It consists of two chambers for fresh and used grains, and thin channel between them where electrical discharge releases the hydrogen. An electric discharge passing through fresh grains releases constant quantity of hydrogen during each discharge. The source was able to generate stable gas flow during many shots. The plasma source

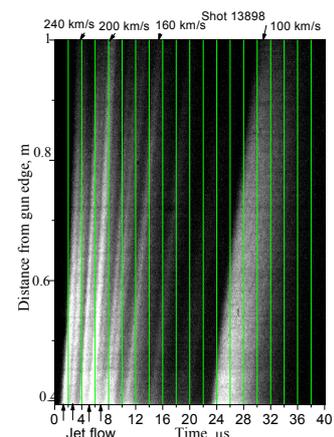


FIG.2: Jet radiation observed through a narrow slit with a streak camera; shot 13898 – perpendicular view

was installed on a test bench vacuum chamber with useful volume of 2 m³ beyond the vacuum shutter. Test bench was equipped with diagnostic and data acquisition systems.

A streak camera registered time resolved radiation of the jet viewing through a thin slit. (Fig.2). Observations showed that the flow consists of discrete jets with their own values of velocity (from 100 to 240 km/s).

AvaSpec-3648 spectrometer allowed investigations of spectral radiation of the plasma jet. Improvements of the jet source resulted in the jet pollution decrease (Fig.3). Before loading the titanium hydride grains were cleaned with a compressed air inside a vessel surrounded by a thin grid. Cell size of the grid filter was reduced from 150 μm to 40 μm. These modifications considerably reduced impurities in plasma jet. The impurity radiation was suppressed more than 100 times after cleaning the grains and gas cloud filtering.

A CCD camera registered time integrated radiation of two colliding jets (Fig.4). The distance between two oppositely directed plasma guns was 2 m. The experiment with two colliding jets confirmed earlier observation that the plasma recombined into the jet of neutrals at a distance ~0.8 m from source edge. In the middle of the way the jets collided and ionized again, as the jet of neutrals has a kinetic energy higher than the hydrogen ionisation potential.

The experiments were performed at the following conditions: aspect ratio $A=R/a=1.5$, major plasma radius $R=0.36$ m, minor plasma radius $a=0.24$ m, toroidal magnetic field at the vessel axis $B_T = 0.4$ T, plasma current $I_p = 0.2$ MA, average plasma density $n_e = 1 - 6 \times 10^{19} \text{ m}^{-3}$, pulse duration with inductive current drive $\tau_{\text{pulse}} \leq 0.1$ s. During current plateau phase the hydrogen jet was injected into Globus-M in OH deuterium plasma at the equatorial plane along the major radius from the low field side (Fig.5).

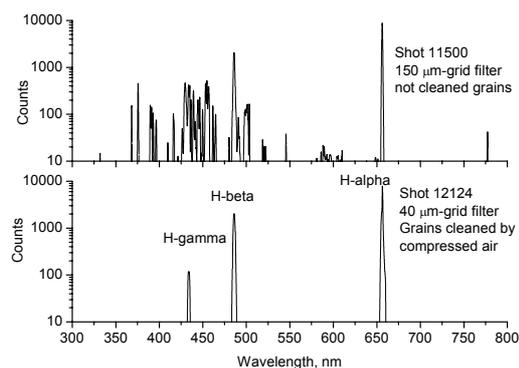


FIG.3: Plasma jet spectra viewing along the source axis into the muzzle

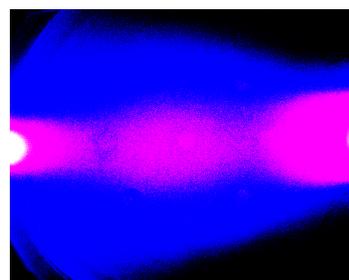


FIG.4: Radiation of two colliding jets; the plasma jet recombines into the gas jet at a distance of ~0.8 m from the gun edge; near centre of the picture jets collided and ionized again

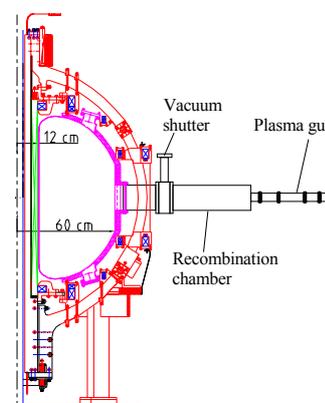


FIG.5: Two stage plasma gun placed at the spherical tokamak Globus-M

Latest experiments were dedicated for detail investigations of the jet penetration into the plasma core. The density raise was recorded both by microwave interferometer and Thomson scattering technique. AvaSpec-3648 spectrometer registered radiation of plasma jet in Globus-M viewing along the plasma gun axis.

Density profile evolution during jet injection in

Globus-M plasma was measured by Thomson scattering and presented in Fig. 6. One can see doubling of the plasma density in all spatial points of the tokamak in ~ 2 ms.

Efficiency of the jet penetration for different target plasma densities was investigated. Line integrated density enhancement along the vertical chord at $R=24$ cm in 1 ms after jet injection was measured with the interferometer. Density enhancement dependence of the on initial (target) plasma density in Globus-M is presented in Fig. 7. It is seen that the density raise decreases with increasing of the initial plasma density in the tokamak. This experimental fact confirms that the increase of the initial density of the target plasma decreases the jet penetration depth. The model for jet penetration into the tokamak was applied for the high-velocity jets accelerated by plasma gun on Globus-M [7]. The modelling showed that jet penetration into the plasma core depends on the ratio between jet and core densities (penetration depth is inversely proportional to the square root of ambient plasma density and proportional to the jet density). Therefore for higher ambient plasma density the penetration depth would be lower. The model predictions are consistent with experimental observations presented in Fig. 7.

Experiments were performed to clarify influence of the length of recombination path on jet penetration efficiency. The test bench experiments showed that the highly ionised plasma jet recombines during time of flight into the fast neutral flow. If plasma jet does not recombines completely into neutrals it may be deflected by the magnetic field to the walls. For comparison the plasma jet was injected through 0.5 and 1.5m recombination chamber. The source generated both fast plasma and slow tail of gas jet

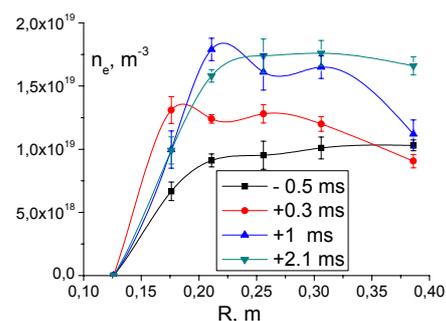


FIG.6: Evolution of the density profile in the Globus under jet injection. Thomson scattering data

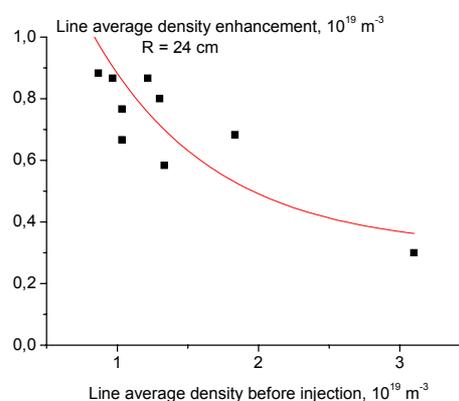


FIG.7: Dependence of density enhancement in 1 ms after jet injection on initial plasma density in Globus-M

simultaneously. Waveforms of the line integrated plasma density along different chords in Globus-M during plasma jet injection are presented in Fig. 8. The first (~ 1 ms) enhancement is a result of the fast fraction and second one (~ 4 ms) corresponds to the slow fraction. One can see that relative value of the fast fraction is higher at 1.5 m recombination chamber, but both fast and slow fractions are smaller in absolute value in this case due to the jet divergence losses.

Investigations confirmed that double stage plasma source has high potential for nuclear fusion energy researches and applications. New design allows the fresh grains loading before each shot and generating stable gas flow

for many shots. This increases reproducibility of the plasma jet parameters from shot to shot. The impurity radiation of plasma jet was suppressed more than 100 times after cleaning the grains and gas filtering. The plasma jet produced by the gun consists of discrete jets with their own velocities. The highly ionised plasma jet recombines during time of flight into the fast neutral flow and can penetrate through magnetic field. The jet of neutrals has a kinetic energy higher than the hydrogen ionisation potential. Experiments showed efficient jet penetration into the plasma core of Globus-M during current plateau phase and confirmed the dependence of the jet penetration efficiency on the ratio between jet and core densities, predicted by modelling.

The work is supported by IAEA Research Contract 12408 and RFBR grants 06-02-16709-a, 06-02-08186-ofi.

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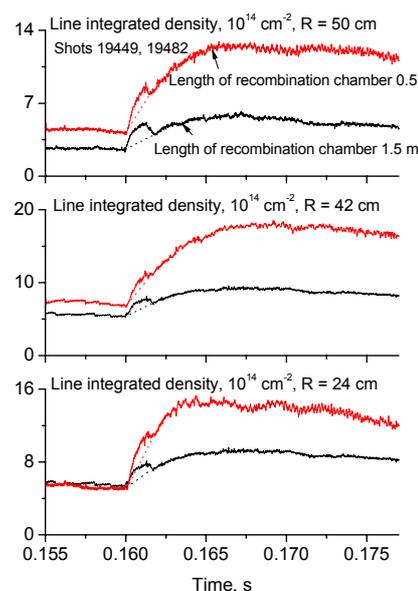


FIG.8: Waveforms of line integrated density under jet injection through 0.5 and 1.5 m recombination