Plasma jet source parameter optimisation and experiments on injection into Globus-M spherical tokamak

V.K. Gusev, Yu.V. Petrov, N.V. Sakharov, A.A. Semenov, A.V. Voronin,

A.F. Ioffe Physico-Technical Institute, RAS, St. Petersburg, Russia

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

Abstract. Results of theoretical and experimental research of the plasma source and injection of plasma and gas jet produced by the modified source into tokamak Globus-M are presented. Experimental test stand was developed for investigation of intense plasma jet generation. Optimisation of pulsed coaxial accelerator parameters by means of analytical calculations is performed aiming to achieve the highest flow velocity at limited coaxial electrode length and discharge current. Optimal parameters of power supply to generate plasma jet with minimal impurity contamination and maximum flow velocity were determined. Comparison experimental and calculation results is made. Plasma jet parameters are measured, such as: impurity species content, pressure distribution across the jet, flow velocity, plasma density and etc. Experiments on interaction of higher kinetic energy plasma jet with magnetic field and plasma of the Globus-M tokamak were performed. Experimental results on plasma and gas jet injection into different Globus-M discharge phases are presented and discussed. Results are presented on investigation of plasma jet injection as the source for discharge breakdown, plasma current start up and initial density rise.

1. Introduction

The problem of plasma fuelling and density profile control is of great importance for any magnetic trap high performance operation. Especially important is the developing of effective plasma fuelling methods for future thermonuclear reactor. The fuel has to have a high enough directed energy of motion to pass the dense and hot plasma body and to reach the central plasma region. The total number of accelerated particles has to be $10^{19} \div 10^{23}$, density $> 10^{21}$ м $^{-3}$, velocity of flow up to 800 km / s. On the other hand the problem of plasma accelerators development, producing jets, or clusters with high kinetic energy has it's own fundamental and application significance.

There are developed injectors of condensed substances with relatively low velocity of flow motion. And there are accelerators of low density plasma with high velocity of flow. Most of plasma guns relates to the second type of accelerators. But none of known plasma sources generates simultaneously dense highly ionised and pure plasma cluster. The results of research, carried out at the Ioffe Physico-Technical Institute, allow to propose such fuelling method and prototype of pulsed accelerator generating intense dense hydrogen (deuterium in future) plasma jet. The principals of operation are basically described in [1].

It was proposed to utilise the grains of condensed substances for gas storage and it's intense generation. Electric discharge passing through the grains releases the gas cloud. Separation of the gas from non-gas impurities was done with a grid-filter placed between grains and coaxial plasma-accelerator. Electric discharge passing through coaxial electrodes provides gas-ionisation and plasma-acceleration. The source consists of two stages. The first (gas generating) stage contains titanium grains loaded with hydrogen. Intense electric discharge passing through the grains releases the gas cloud. This neutral gas (hydrogen) passing through the specially designed grid fills the inter electrode gap up to thousands atmospheres in few microseconds. This is one of the principal distinguishing features of the design, helping in achievement of compact or dense plasma cluster. The second one (plasma generating stage) is made of stainless steel electrodes with coaxial geometry. Intense electric discharge through the gas between coaxial electrodes provides gas-ionisation and plasma-acceleration in a classical “Marshall gun scenario”.

Successful experiments with plasma injection into the tokamak Globus-M [2,3,4] demonstrated principal capability of plasma fuelling with the minimal plasma perturbations. First experiments showed that the injected plasma penetrated deep into the target plasma of the spherical tokamak Globus-M, increased the plasma average density, did not disturb the tokamak plasma, did not significantly increased the impurity contamination. Injection of plasma before the discharge created better conditions for building up plasma current at lower MHD activity as compared with gas puffing. Plasma injection during current plateau phase led to the faster increase of the plasma density as compared with gas puffing.

Further increase of the plasma density, energy and flow velocity requires detailed analyses of plasma production and acceleration in coaxial plasma gun. Results of theoretical and experimental research of such plasma source and injection of plasma and gas jet produced by modified source into tokamak Globus-M are presented in the report.

2. Peculiarities of plasma source for plasma filling and calculations of accelerator parameters.

The goal of present plasma source developing is generating a matter with high kinetic energy with minimal impurity content, because it is very important to inject clean fuel into the fusion

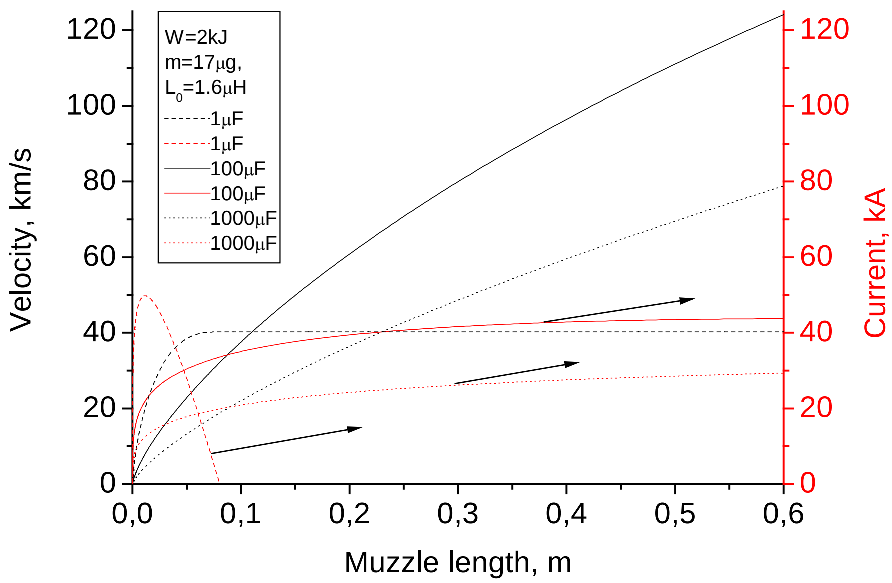


FIG.1. Evolution of plasma velocity and discharge current along muzzle length

reactor. This is an essential deference of such source in comparison with conventional plasma guns used in other applications. So, the substance with highest kinetic energy (or plasma velocity) has to be generated with lowest discharge current in coaxial accelerator. Theoretical consideration of mass acceleration between coaxial electrodes (muzzle) is presented in [5]. By numerical simulations we analysed the constant mass acceleration in coaxial source with capacitor battery at condition of energy conservation (2 kJ) without losses. Evolution of plasma velocity and discharge current along the muzzle length for different capacitance are presented in Fig.1. Obviously that the highest velocity can be achieved with highest capacitance and enough long muzzle length. But the length of the coaxial electrodes is practically limited by ~1 m. It is seen that for certain length the highest current can be localised whether near inlet (C_p=1μF) or outlet (C_p=1000μF) of the muzzle, or can be movable (C_p=100μF) along the muzzle length. Inlet and outlet localised current generates plasma flow with low velocity and can produce impurities coming from the electrodes. So, the highest velocity of clean plasma at certain stored energy and limited muzzle length can be achieved with the movable or spreading current only. Further experiment were carried out with approximately optimal parameters of coaxial accelerator and power supply predicted by the calculation (muzzle length 0.6 m, capacitance of accelerating stage C_p = 40 μF, charged voltage 4 ÷ 10 kV).

2. Set-up

Experimental test stand, based on 2 m^3 vacuum vessel, was developed for investigation the intense plasma jet (Fig.2). Plasma source (muzzle lengths 6 and 60 cm, outer electrode diameter 35 mm) was connected to vacuum chamber over vacuum shutter. Both stages of the source were connected to modified low inductance capacitor power supplies (Lo = 570 nH, Cg=20μF, Cp=40μF, Uo=4÷8 kV). Plasma density was measured with He-Ne laser interferometer. Movable probe (based on piezoceramic) measured pressure profile and total kinetic energy of the jet. Impurity and hydrogen lines were detected with two channel spectrometer. Velocity of flow was measured

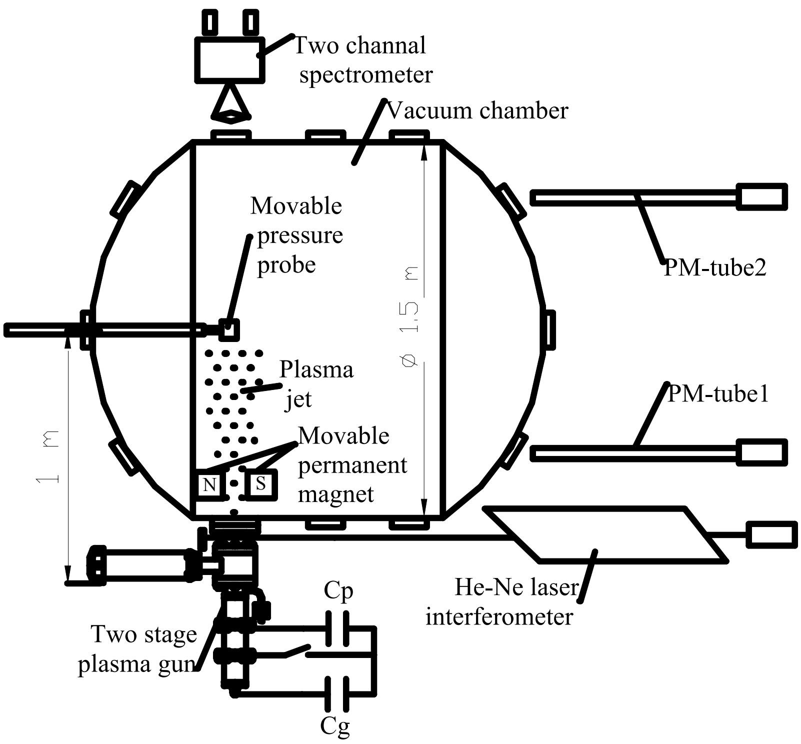


FIG.2. Stand for investigation of the plasma source

with two collimated photomultiplayer tubes placed near the gun edge and opposite wall of the vacuum chamber accordingly. CCD camera registered time integrated jet radiation. Discharge current spreading (or voltage drop) along the muzzle observed with number of light diodes connected to the different parts of outer electrode of the coaxial accelerator. Permanent movable magnet (gap 50 cm) placed near the gun edge for separation neutrals from charged particle flow.

Optimised source generated during ≤ 50 μs clean highly ionised hydrogen plasma with density 10^{22} m^{-3}, total number of the accelerated particles 1 ÷ 5 10^{19} and flow velocity 50 ÷ 150 km / s, total kinetic energy 100 ÷ 500 J.

Experiments on interaction of optimised jet with magnetic field and plasma of the Globus-M tokamak were performed. The jet source was connected to the tokamak vacuum vessel trough inclined port with vacuum shutter [3]. Injection was performed nearly along vertical chord of poloidal cross section, passing through the vessel centre (15 degree to the vertical axis). Line integrated plasma density was measured by 1 mm interferometer along three vertical chords (at R=24, 42, 50 cm) 30 mm aside of the plasma source position. Bolometer registered radiation losses. Spectrometer detected line radiation of $H_\propto$ and carbon.

4. Results

4.1. Test stand

Evolution of plasma source parameters is presented in Fig.3. It allows deriving velocities of the gas, plasma and energy flow by measuring corresponding time delays between signals.

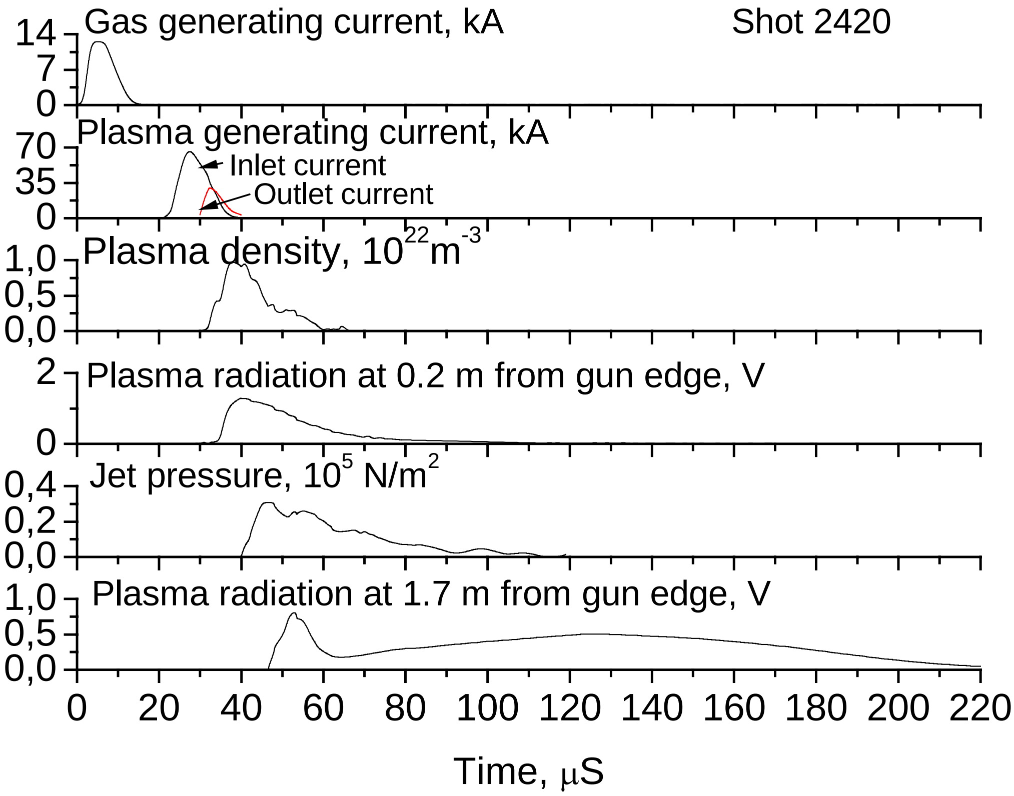


FIG.3. Evolution of plasma source parameters

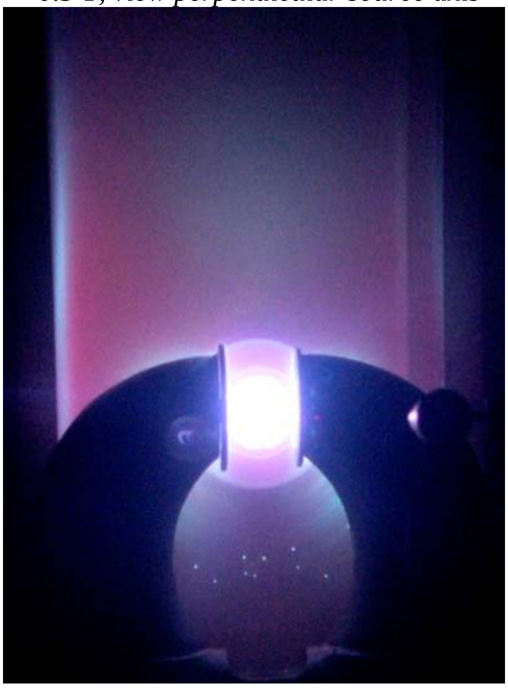
These velocities varied with discharge current as 1 ÷ 20, 50 ÷ 150, 40 ÷ 100 km / s accordingly. Measured plasma velocity was ~ 30 ÷ 50% lower than predicted by the calculations. Radiation near opposite wall indicated two enhancements apparently corresponding to fast and relatively slow velocities of the jet fractions. Time integrated jet radiation perpendicular to the source axis is shown in Fig.4 (B = 0 T). It is seen regular, directed and sharp boundary jet, with cross section diameter of 10 cm at the distance of 1 m from the source edge. Plasma temperature achieved 1 ÷ 2 eV. It was derived from measured value of H_∞/H_β and assumption of Bolzman energy distribution. Pressure profile of the jet was measured with movable probe at the distance of 1 m from the source edge (Fig.5). It is seen that the energy flow is concentrated near the jet axis with diameter 10 cm. Kinetic energy of the jet achieved 100 ÷ 500 J (stored capacitor energy was 0.65 ÷ 1.3 kJ). Observation of the discharge current spreading along the muzzle confirmed the calculations (Fig.3). It is seen that the discharge is pushed out to the gun edge. It has single outlet current enhancement. The outlet current delayed to the inlet current. The amplitude and time duration of the outlet current is 2 ÷ 3 times less than the parameters of the inlet current.

Jet penetration through transverse magnetic field created with movable permanent magnet placed near the gun edge was investigated. Jet pressure registered with piezoceramic detector located behind the magnet (Fig.6).. It is seen that the pressure decreases with increasing the magnetic field strength. Radiation of the jet in transverse magnetic field 0.3 T is presented in Fig.4. There was not observed any visible radiation behind the magnet. As it was predicted the injected plasma cluster is stopped by the magnetic field if it's specific kinetic energy or pressures are lower than the pressure of the magnetic field. For this case the magnetic field of 0.3 T stops the plasma flow with velocity of 50 km / s and density ≤ 10^{22} m^{-3} (measured pressure behind the magnet is near zero).

Dependence of the jet pressure from the distance between the magnet (0.3 T) and plasma source is presented in Fig.7. It is seen that the jet pressure increases with the distance increasing. The

B =0 T

= 0.3 T, view perpendicular source axis



B = 0.3 T, view along source axis

FIG. 4. Radiation of the jet passing transverse magnetic field.

magnetic field does not stop the jet at distance ≥ 70 cm. It is seems to be the highly ionised plasma jet recombines into fast neutral flow at this distance and easy penetrates through magnetic field.

Estimated recombination time and path (for plasma temperature 1 eV, velocity 50 –100 km / s and density 10^{22} m $^{-3}$) are 20 -40 μs and 0.5 – 1 m accordingly. It means the plasma flow transforms into neutral particle flow on distance of ~1 m. This is a way of neutral beam creation with velocity and density equal to plasma ones.

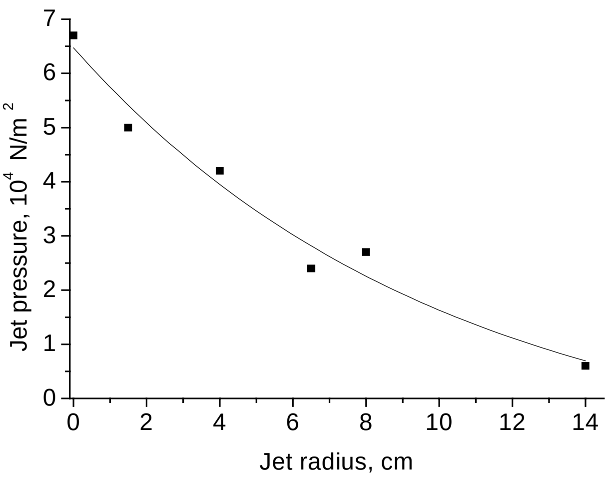


FIG.5. Dependence of jet pressure on jet radius at 1 m from the source edge

4.2. Jet injection into tokamak during current plateau phase

Injection of the plasma jet with improved parameters (density 10^{22} m $^{-3}$, total number of accelerated particles ~ 10^{19}, flow velocity ~ 100 km / s) into Gl;obus-M was investigated and reported in [4]. It was observed deep jet penetration into toroidal magnetic field 0.2 ÷ 0.4 T and achieved the density increase from 1.5 × 10^{19} up to 3 × 10^{19} m $^{-3}$. But. the rise time of the density (1 ÷ 2 ms) during plasma injection was not decreased essentially as compared with experiments at lower jet velocity (30 ÷ 70 km / s) presented in [2,3]. Probably achieved kinetic energy of the plasma jet is not enough and it penetrates into confining magnetic field (0.2 ÷ 0.4 T) of the tokamak after recombination.

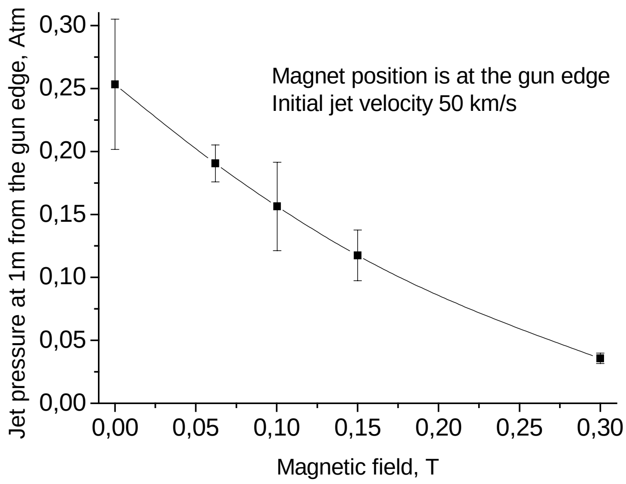


FIG.6. Dependence of jet pressure from magnetic field

The test stand experiments showed that the first stage of the source generates fast (5 – 20 km / s) gas jet. Such jet was injected into tokamak Globus-M. The experiment demonstrated effective penetration of the gas jet into toroidal magnetic field up to 0.4 T. It was achieved steeper enhancement of the density (~1 ms) as compared with

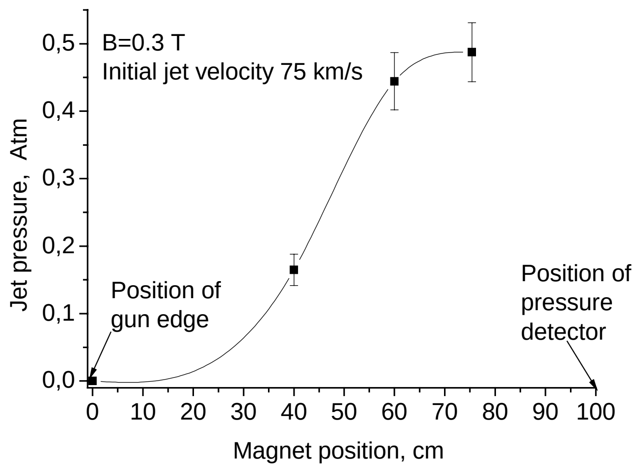


FIG.7. Dependence of jet pressure from distance between magnet and plasma source edge

plasma injection experiments. (Fig.8). During injection tolerable increase of radiation monitored by bolometer and spectrometer was recorded.

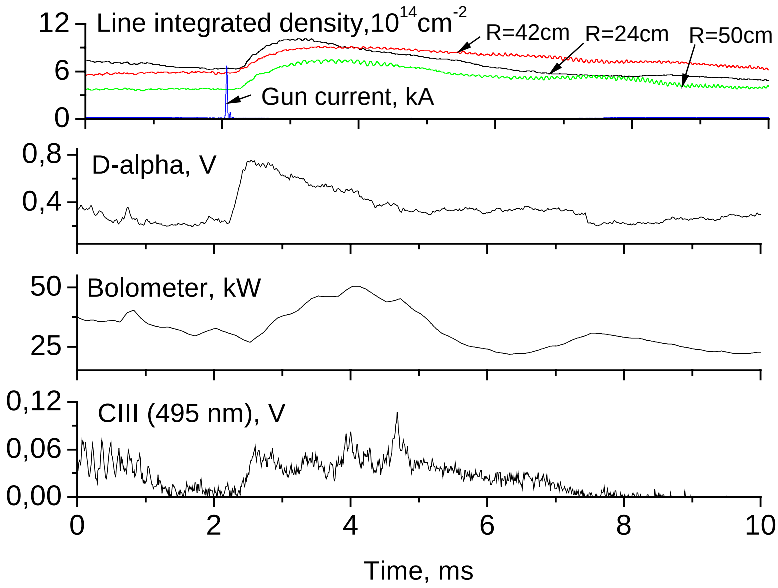


FIG.8. Evolution of plasma parameters in Globus-M at supersonic gas injection (shot 10130)

Basing on this results one can suggest several directions of future experiments for fuelling with plasma gun. The first one is plasma injection with high enough kinetic energy (velocity > 200 km / s or density > 10^{22} m^{-3}). In this case further plasma source developing is required. The second way is neutral particle injection with high energy. Possibly it can be created with developed plasma source placed at 1 m distance from the toroidal magnetic field boundary of the tokamak. Plasma jet will recombine into high energy jet of neutrals on 1 m path and more efficient penetrate through confining magnetic field.

Further investigation of plasma jet injection as the source for discharge breakdown, plasma current start up and initial density rise was performed. The discharge was initiated by means of plasma jet at maximum current in central solenoid and 0.4 T toroidal field instead of ECR preionisation (Fig.9). Earlier experiment was made at zero current in central solenoid and 0.25 T toroidal magnetic field [2,3]. One could see that plasma current, density and radiation of D-alpha ramped up like with gas-puffing and pre-ionisation system.

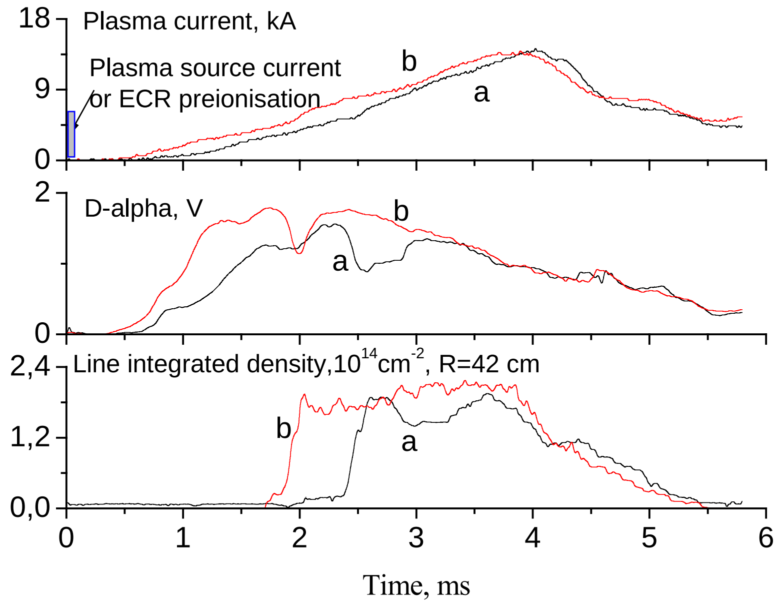


FIG.9. Plasma discharge initiation; a-with plasma gun (shot 10167); b-with gas puffing and pre-ionisation (shot 10165)

5. Conclusions

Optimisation of pulsed coaxial accelerator parameters by means of analytical calculations is performed aiming to achieve the highest flow velocity at fixed coaxial electrode length and stored capacitor energy. Experimental test stand was developed for investigation of intense plasma jet generation. As a result, optimal parameters of power supply to generate plasma jet with minimal impurity contamination and maximum flow velocity were determined. Modification of the power supply with the requirements of acceleration theory was done. It resulted in the increasing of the plasma velocity from 70 km/s [3] up to 150 km/s. Measurements of detailed plasma jet parameters and specific properties of the plasma injector are presented (distribution of pressure across the jet cross-section, flow velocity and plasma density, recombination path of the jet, energy and temperature of the flow). Improved injector generates hydrogen plasma jet during < 50 μs with density 10^{22} m $^{-3}$, total number of accelerated particles > 10^{19}, flow velocity > 100 km/s. Experiments on interaction of plasma and gas jet with magnetic field and plasma of the Globus-M tokamak were performed. It was observed deep plasma jet penetration into toroidal magnetic field of 0.2 ÷ 0.4 T and increasing of the density from 1.5 10^{19} up to 3 10^{19} m^{-3} . The gas jet (velocity 10 km / s) was injected into tokamak Globus-M. The experiment demonstrated effective penetration of the gas jet into toroidal magnetic field up to 0.4 T. It was achieved steeper enhancement of the density (~1 ms) as compared with plasma injection experiments. During injection there were not observed any considerable changes of radiation monitored by bolometer and spectrometer. Future experiments for fuelling with plasma source are planned. The first is plasma injection with velocity > 200 km / s or density > 10^{22} m $^{-3}$, which further plasma source developing requires. The second is neutral particle injection with developed plasma source placed at distance ~ 1 m from the toroidal magnetic field of the tokamak. Plasma jet seems to be recombine into high energy neutral jet on 1 m path and more easy penetrate through confining magnetic field.

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