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Development of Intense Plasma Jet Fuelling Source

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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 $10^{19} \div 10^{23}$, with 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.

Studies and development of the original titanium hydride fuelling source [1] as well as successful experiments with plasma injection into the tokamak Globus-M [2,3] demonstrated principal capability of plasma fuelling with the minimal plasma perturbations. 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 jet produced by modified source into tokamak Globus-M are presented in the report.

Peculiarities of plasma source for plasma filling.

We designed, constructed and investigated novel double stage source of dense plasma with high directed velocity, utilising titanium-hydride grains. The principals of operation are basically described in [1]. 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 between electrode gap at 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) 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".

The goal of present plasma source developing is generating the matter with high kinetic energy with minimal impurity content, because it is very important to inject clean fuel in fusion 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 acceleration of mass between coaxial electrodes (muzzle) is presented in [4]. By numerical simulations we analysed the constant mass acceleration in coaxial source with capacitor battery at condition of energy conservation (2 kJ) without losses. Dependencies of plasma velocity and displacement of the discharge current along the muzzle length for different capacitance are presented in Fig.1. Obviously that the highest velocity can be achieved with any 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 current only.

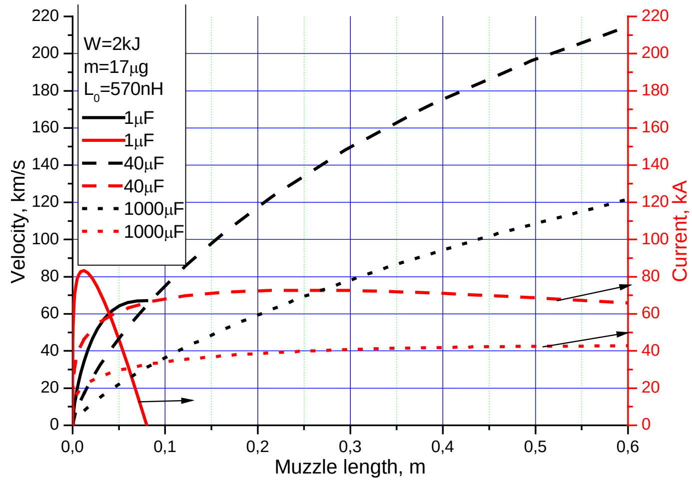

Fig.1: Dependencies of plasma velocity and displacement of the discharge current along the muzzle length

Experiment

Experimental test stand, based on 2 m^3 vacuum vessel, was developed for investigation the intense plasma jet (Fig.2). Plasma source (muzzle length 60 cm) was connected to vacuum chamber over vacuum shutter. Both stages of the source were connected to modified with 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 pressure 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 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.

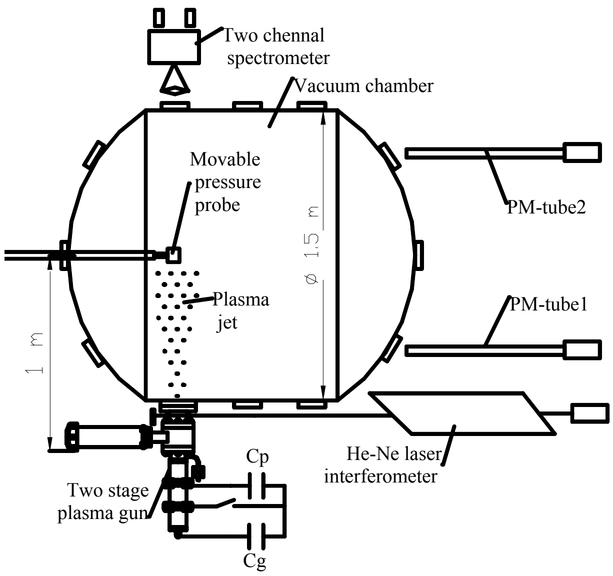

Fig.2: Stand for investigation of the plasma source

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 kJ. Preliminary experiments on interaction of optimised plasma 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.

Results

Evolution of plasma source parameters are presented in Fig.3. It allows deriving velocities of the gas, plasma and energy flow by measuring corresponding time delays between signals. These velocities varied with discharge currents 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 indicates two enhancement corresponding to fast and relatively slow velocities of the plasma fraction. Time integrated jet radiation along and perpendicular

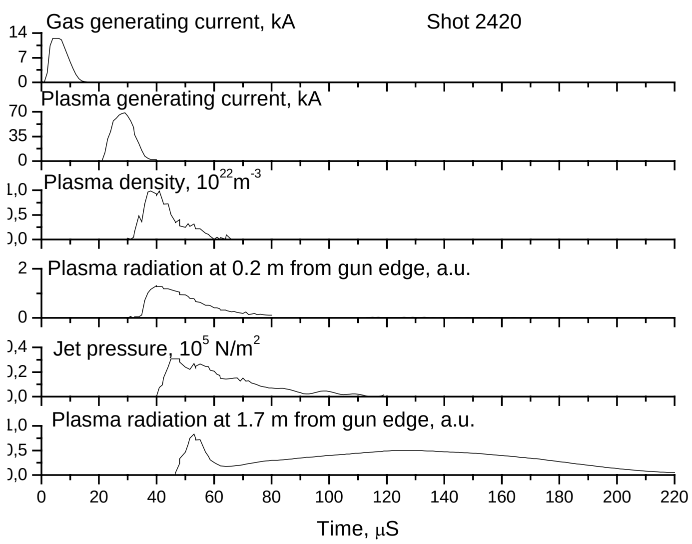

Fig.3: Evolution of plasma source parameters

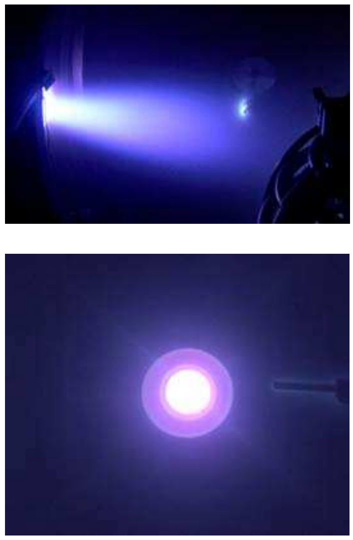

Fig.4: Plasma jet radiation

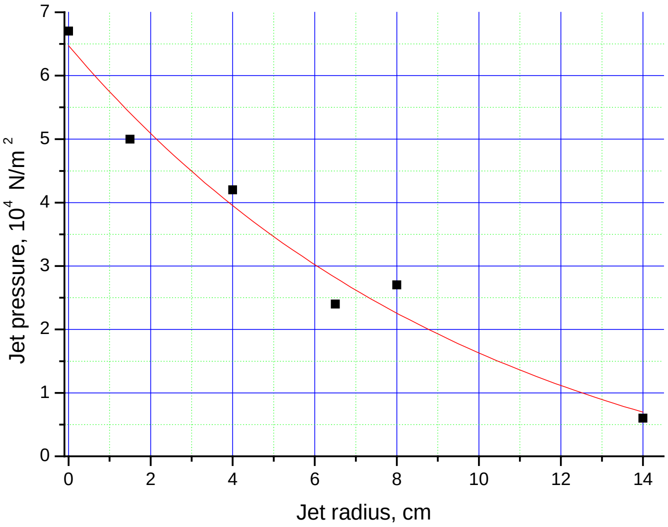

Fig.5: Dependence of jet pressure on jet radius at 1 m from the gun edge

source axis is shown in Fig.4. It is seen regular, directed and sharp boundary jet, with cross section diameter 10 cm at the distance of 1 m from the source edge. Plasma temperature achieved 1÷5 eV. It was derived from measured value of $H_\propto/H_\beta$ 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).

Preliminary experiments with optimised plasma source at the Globus-M demonstrated effective penetration of the injected plasma into toroidal magnetic field up to 0.4 T. It was achieved steep enhancement of the density up to 3 10 ^{19} m^{-3} in 2 ms (Fig.6). During injection it was not observed any considerable changes of radiation monitored by bolometer and spectrometer.

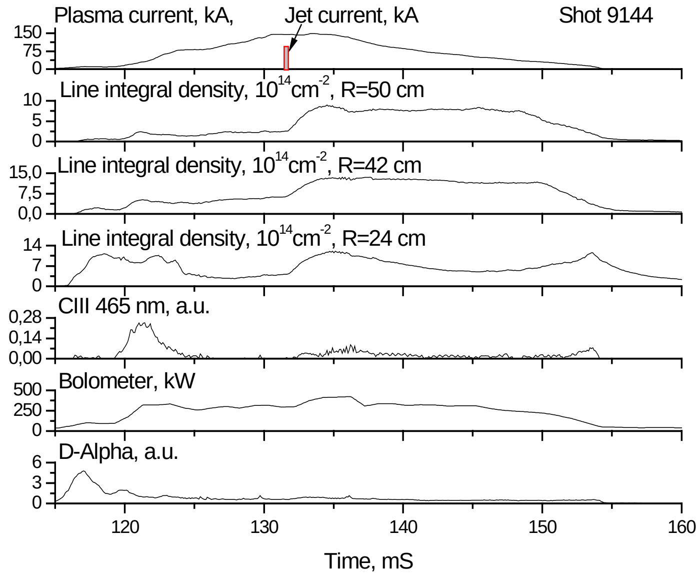

Fig.6: Evolution of plasma parameters in Globus-M

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. 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 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). 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. Increased jet kinetic energy compared to first experiments [2,3] resulted in deeper penetration of the jet into toroidal magnetic field. It was achieved increasing of the density up to 3 10 ^{19} m^{-3}in 2 ms

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