Control of tokamak discharge parameters using a plasma jet

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Abstract. Results of the experimental study of the ability of plasma jet of coaxial accelerator to breakdown and ionization the working gas at the initial discharge phase in Globus-M2 spherical tokamak are presented. Studies of the development of the initial stage of discharge initiated with a plasma jet showed that the plasma current in the discharge began to grow earlier by 2 ms than using the standard inductive breakdown. The breakdown voltage decreased from 6.1 to 3.1 V (~49%) at 4.7 kV accelerator electrode voltage. The emission intensity of line Dα decreased during formation of the discharge with the help of plasma jet without additional gas puffing. Radiation level CIII in the discharge generated by the plasma jet was the same as the radiation in discharge produced by induction breakdown of the gas. At the stage of increase in the plasma current the most intense visible radiation of the plasma was found near duct through which the jet was injected. Discharge radiation decreased and spread out along the cross section of the plasma column during plasma current plateau.

1. Introduction
Technology of working gas breakdown, plasma fueling, and optimization of the discharge scenario are actual tasks that stand in the way of solving the effective management of tokamak parameters. At present time the control methods based on sources of high-frequency radiation, high-energy neutral atoms [1], plasma jets, compact torus [2], and others are being considered and applied. The paper presents the results of controlling the discharge parameters by injecting a plasma jet created by coaxial accelerator. The possibilities of effective use of plasma accelerator were previously experimentally demonstrated at Globus-M tokamak with magnetic field of ≤ 0.4 T [3]. As a result it was possible to increase the particle density by 30% in the central region of the plasma column without plasma current disruption. Significant increase in the plasma jet energy has been achieved using an original coaxial accelerator with flow velocity of 100-200 km/s, plasma density of >10^{22} m^{-3}, and pressure on the jet axis of > 0.4 MPa [4]. This work is extension of earlier research on development of plasma accelerator with high kinetic energy and its application on spherical tokamak Globus-M2 and Kazakhstan Tokamak of Materials Science (KTM) with magnetic field up to 1 T.

The paper presents the results of experimental study of capability of coaxial plasma jet accelerator for breakdown and ionization of working gas in the initial phase of discharge in Globus-M2 spherical tokamak. The research results are supposed to be used to develop technology for gas breakdown and ionization, as well as to optimize the scenario of the initial phase of the discharge as applied to the parameters of the KTM.

2. Experiment
Studies of the breakdown and ionization of the working gas at the initial phase of the plasma discharge using coaxial plasma jet accelerator at Globus-M2 tokamak were carried out at magnetic field of 0.7 T (close to the magnetic field of ~1 T created on the KTM). For comparison, the main parameters of tokamaks are presented in table 1.

| Parameter                        | Globus-M2 | KTM    |
|----------------------------------|-----------|--------|
| Major radius, m                  | 0.36      | 0.9    |
| Minor radius, m                  | 0.24      | 0.45   |
| Aspect ratio                     | 1.7       | 2      |
| Plasma volume, m$^3$              | 1         | 5      |
| Toroidal magnetic field on the axis, T | 0.7      | 1      |
| Plasma current, MA               | 0.5       | 0.75   |
| Current duration, s              | 0.35      | 5      |
| Plasma density, m$^3$             | (2-10)$\times$10$^{19}$ | (3-5)$\times$10$^{19}$ |

Experimental layout with lines of view of the used in the experiment diagnostics on Globus-M2 tokamak are presented in Figure 1. The video camera made it possible to obtain the evolution of plasma visible radiation inside the tokamak. According to the data of diagnostics of carbon emission, the level of impurities in the discharge was determined, since the inner wall of the tokamak chamber was covered with graphite plates. Dα emission was recorded using a detector located vertically on the upper dome. The averaged plasma density was measured using a microwave interferometer along a chord extending in the vertical direction and located at a distance of 42 cm from axis of the torus. Additional gas puffing into the tokamak was carried out using piezoelectric valves located on the upper and lower domes of the chamber.

![Figure 1](image)

**Figure 1.** (a) Experimental layout with plasma accelerator and diagnostics on Globus-M2 tokamak, equatorial cross-section without first wall. (b) Poloidal cross-section.

Original coaxial plasma accelerator with conical insert in the region of discharge formation is shown in Figure 2a. The diameters of the outer and central electrodes are 46 and 10 mm, respectively, length of 250 mm. The accelerator was powered by 160 μF capacitor, voltage up to 5 kV, discharge current up to 120 kA, pulse duration up to 25 μs. Deuterium was injected under pressure of 2.5 atm...
through side surface of outer electrode in the initial section of accelerator using electrodynamic valve. After 400 μs gas pulse the discharge in the accelerator was initiated. Electric discharge fired through the gas between the coaxial electrodes provides gas ionization and plasma acceleration in the classical “Marshall gun scenario”. In Figure 2b shows the dependences of the voltage and discharge current. It can be seen that the total pulse duration, including inverse half period of the current, was ~ 24 μs. Previously a system using electrically activated titanium hydrate granules, which can be found in articles [5, 6], was used to inject working gas into the accelerator. This gas puffing method was inferior to method using an electrodynamic valve in the stability of shots and large number of impurities.

The deuterium plasma jet was injected into Globus-M2 tokamak chamber in the equatorial plane in major radius direction from the side of low magnetic field. The distance from the accelerator to tokamak was 0.37 m. The arrangement and connection of accelerator in tokamak is shown in Figure 1. Jet velocity at the exit of accelerator reached more than 100 km/s with particle density of more than $10^{22}$ m$^{-3}$. Number of injected particles was comparable with the total number of particles in tokamak plasma and reached to $~10^{19}$-$3\cdot10^{20}$. Therefore the accelerator could supply tokamak with plasma without additional puffing of working gas. However, alternative scenario of supplying with plasma is also possible at the KTM, since the total number of particles in it ($10^{19}$-$10^{22}$) can exceed the number of particles created by the coaxial accelerator. In this case a pre-puffing of working gas must be performed before breakdown. Both options were tested at Globus-M2 tokamak. We measured dynamics of the growth of plasma current, loop voltage, plasma density and emission of the different line intensities.

3. Results
Investigations of the development of the initial stage of the discharge initiated by plasma jet without additional working gas puffing into Globus-M2 tokamak were made. Figure 3 shows the waveforms of the plasma parameters for the discharge created by the plasma jet — solid curves. The number of injected particles of molecular deuterium was $2\cdot10^{20}$. The voltage at the accelerator electrodes was 4.7 kV. For comparison, similar dependences of the discharge obtained by inductive breakdown of the working gas are shown — discontinuous curves. It is seen that the breakdown voltage in the discharge created by plasma jet decreased in comparison with the voltage during inductive breakdown from 6.1 to 3.1 V (~49%). It can also be seen that the current in the discharge initiated by the jet plasma began to increase by ~ 2 ms earlier compared to increase in current using inductive breakdown. An increase in the radiation intensity of the $D_{α}$ line (by 109–112 ms) corresponded to this current rise. For 112 ms a current drop was observed and only 114 ms did it recover. A similar current drop was not observed in the discharge created by induction gas breakdown. After 115 ms there was further increase in the plasma density and current in both discharges in similar way. The current reached the plateau at 140-
145 ms. The duration of the discharges was ~ 224 ms. A high emission intensity $D_α$ was observed at the start of the discharge created by the induction breakdown of the working gas, compared with the radiation intensity in the discharge produced by the plasma jet. This may be due to ionization of the working gas. The level of emission of carbon line in discharge with plasma jet turned out to be approximately 2 times higher than the level of emission in a discharge created by induction breakdown.

The discharge parameters were repeated with decreasing the voltage at the electrodes of the plasma accelerator. Thus the breakdown voltage increased to 4.8 V with decrease in the voltage at the electrodes to 4 kV. This is 21% less than in the discharge produced by inductive plasma breakdown. The level of carbon emission intensity turned out to be the same as the level observed in the discharge with induction breakdown.

![Figure 3](image-url)

**Figure 3.** Dependences of the parameters of the discharges on time in Globus-M2 tokamak created by induction breakdown of the working gas puffing in the interval 50-68 ms (discontinuous curves #38956) and a plasma jet (solid curves #38967). The dashed lines on the loop voltage graph show how plasma breakdown voltage was calculated.

Studies of the development of the initial stage of the discharge initiated with the help of a plasma jet in combination with preliminary puffing of working gas into the tokamak chamber have been carried out. Figure 4a shows the waveforms of the main plasma parameters for discharge generated by plasma jet — solid curves. Similar dependences of the discharge obtained with the help of plasma jet together with the preliminary puffing of the working gas are shown by discontinuous curves. The voltage at the accelerator electrodes was 4.8 kV. The time dependences of the plasma current during current rise in both discharges were similar to each other. At 112 ms a similar drop in the plasma current was observed, and after 115 ms the current was restored and increased. The behavior of the plasma density in discharges #38957 and #38967 for 113-115 ms turned out to be the same. However the current drop was more noticeable in the discharge without additional gas puffing compared with the discharge with additional gas puffing. The plasma density in the discharge with gas puffing increased sharply compared to the density in discharge without gas puffing. After that the discharge duration sharply decreased and the discharge disrupted for 130 ms. The emission intensities of the $D_α$ and CIII lines increased in discharge with additional gas puffing compared to discharge without additional gas puffing. The increased emission of $D_α$ in discharge #38957 could be due to the ionization of the injected working gas. The time of the most intense emission of CIII coincided with
the time of increase in the plasma density (115-123 ms). High density and high level of emission of the carbon line at the start of the discharge could affect the reduction of the duration of the discharge and lead to disruption of the current. In this case a plasma jet after collision with a 'gas target' could increase the interaction of particles with constructional elements of the chamber (central column). Since plasma jet was fueling into the chamber along major radius from the side of weak magnetic field this effect could be enhanced.

![Graph](image)

**Figure 4.** (a) Dependences of the parameters of the discharges on time in Globus-M2 tokamak created with plasma accelerator in combination with an additional gas puffing for 50-68 ms (discontinuous curves # 38957) and without gas puffing (solid curves # 38967). (b) Video frames of visible radiation of the discharge during startup and the current plateau initiated by plasma jet (# 38960).

The discharges created by plasma accelerator without neutral gas puffing showed their stability after passing through the formation stage. Figure 4b shows the evolution of the discharge visible radiation during startup and the current plateau recorded by video camera with integration time of 125 μs. The location of video-camera is shown in Figure 1a. The discharge was initiated by plasma jet at ~107.5 ms. At stage of increase in the plasma current (115 ms) the most intense visible radiation of the plasma was found near duct through which the jet was injected. Such visible radiation is due to the interaction of tokamak plasma with the gas leaving after the plasma jet. On the current plateau (125 and 153 ms) visible radiation of the discharge was spread out along the cross section of the plasma column.
4. Conclusion
The ability of coaxial plasma jet accelerator for the plasma breakdown and ionization of the working gas at the initial phase of the discharge in Globus-M2 spherical tokamak was studied. The experimental results showed that the current in the discharge, initiated by the plasma of the jet, began to grow earlier by ~ 2 ms compared to the current when using induction breakdown of the working gas. The plasma breakdown voltage decreased from 6.1 to 3.1 V (-49%) with voltage at the accelerator electrodes of 4.7 kV. The emission intensity of the D_α line decreased during the formation of discharge using plasma jet without additional gas puffing. The emission level CIII increased approximately 2 times. At the stage of increase in the plasma current the most intense visible radiation of the plasma was found near duct through which the jet was injected. On the current plateau the visible radiation decreased and spread out over the cross section of the plasma column. The discharge did not disrupt after injection of the jet. Sharp increase in the emission of the D_α line and impurity was observed in discharges produced with plasma jet and with additional gas puffing. Such discharges were not stable for a long time.

The results of research are supposed to be used to develop a technology for breakdown and ionization of gas, as well as to optimize the scenario of the initial phase of the discharge as applied to the parameters of Kazakhstan Tokamak of Materials Science.

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