

## New powerful ion source for Globus-M2 spherical tokamak injector

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Neutral Beam Injection (NBI) is one of the main methods for auxiliary heating of tokamak plasma. In Globus-M2 spherical tokamak, toroidal magnetic field and plasma current will more than double [1] providing an opportunity for a significant increase in plasma density. Thereby, in order to ensure the optimal depth of atomic beam penetration into the plasma before beam ionization, it is necessary to increase the energy of injected particles. For this purpose, we developed a new three-electrode ion source with peripheral magnetic field (ISPM-1M). While ISPM-1M retains the advantages of an arc discharge plasma emitter, the design of its high-voltage insulator assembly and slit ion-optical system is different from its analogues ISPM-1 and ISPM-2 [2].

NBI complex of Globus-M2 spherical tokamak consists of a neutral beam injector and systems which ensure its operation: vacuum pumping system, gas puffing system, power supply system, water cooling system, and control and data acquisition system. An ion source and body with integrated cryosorption pump and ion separator constitute the main components of the injector. The principle of fast atomic beam generation is based on electrostatic acceleration and the focusing of a positive ion beam in an ion source with subsequent recharging of this beam on a gas target into a beam of atoms. Part of ion current drawn from plasma emitter surface, along with atomic ions  $H^+$  ( $D^+$ ), is made up of molecular ions  $H_2^+$  ( $D_2^+$ ) and  $H_3^+$  ( $D_3^+$ ), which after recharging on the gas target and dissociation are converted into atoms with the energy of 1/2 and 1/3 of the main beam component energy. In turn, the main components of the ion source are an arc discharge chamber (ADC), high-voltage insulator assembly (HVIA) and ion optical system (IOS). ADC is a stainless steel casing (serves as an anode of the arc discharge) with isolated cathodic "filaments." HVIA is designed for holding IOS electrodes. The extraction and formation of the ion beam is provided by a multi-slot IOS which consists of three electrodes: emission (EE), negative (NE) and grounded (GE). IOS also ensures the general focusing of a beam in two directions. The structure of ISPM-1M is schematically shown in Fig. 1.

The main characteristics of ISPM-1M are as follows:

- maximum ion beam power – 2 MW;
- maximum accelerating voltage – 40 kV;
- maximum ion beam current – 50 A;
- emission surface area – 115 cm<sup>2</sup>;
- number of electrode grids – 4 pcs.;
- cathode heating voltage – 10.5 V;
- cathode heating current – 1300 A;
- discharge voltage – up to 70 V;
- discharge current – up to 1300 A.

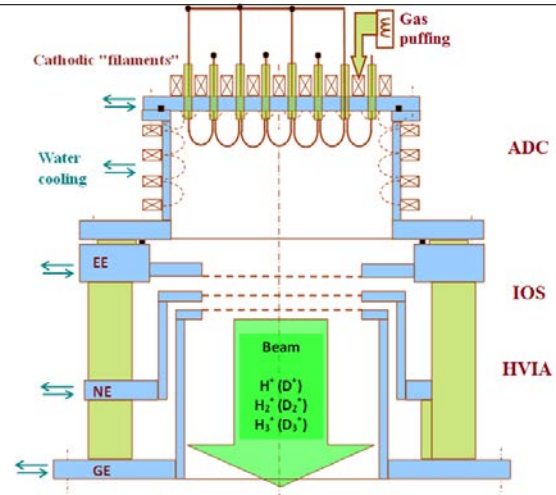


Fig. 1 Ion source with a peripheral magnetic field

ISPM-1M was prepared for experiments on auxiliary heating of Globus-M2 tokamak plasma. For this purpose, elements of ADC, HVIA and IOS were manufactured followed by the development of an aligning technique of three-electrode IOS and assembly of ADC with IOS installed inside the HVIA. After that, we mounted a new ion source on the injector, achieved the required  $\sim 10^{-6}$  Torr vacuum level in the source, ensured water cooling of heat-stressed components, and performed the components' hydraulic tests and high-voltage tests of the ISPM-1M junctions.

ADC preparation was performed by gradually increasing the discharge current from 250 A to approximately 1300 A (the nominal value), with the volt-ampere characteristic of the arc discharge shown in Fig. 2. The EE power supply was upgraded, and a step-up autotransformer was added into the circuit of the system [3]. The optimal program of gas puffing, i.e. the duration and volume of the puffed working gas, was selected to ensure the perfect ISPM-1M emitting capability and the optimal neutralization efficiency of the ion beam [4].

After the assembly of a new ion source and the completion of all preparations, we proceeded to obtain a fast particle beam. We succeeded in achieving stable generation of a beam with particle energy of 22 keV. Typical waveforms of the ISPM-1M basic electrical parameters are shown in Fig. 3. For this shot, we determined the neutralization coefficient of the ion beam  $\eta_{io}$  and its power  $P_i$  and used them to calculate the atomic beam power  $P_{nb}$ :

$P_i \approx U_{EE} (I_{EE} - 1/2 I_{NE}) = 300$  kW and  $P_{nb} = \eta_{io} \eta_{tr} P_i = 220$  kW, where  $U_{EE}$  is the applied

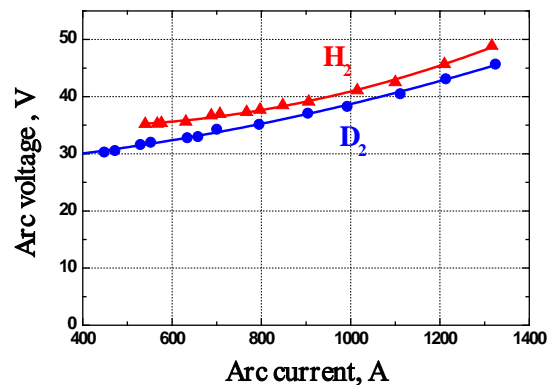


Fig. 2 Volt-ampere characteristic of ISPM-1M arc discharge

accelerating voltage;  
 $I_{EE}$ ,  $I_{NE}$  – load current of  
 the EE and NE,  
 respectively; and  $\eta_{tr}$  –  
 transportation losses.

With the help of  
 movable beam collector  
 [2], we measured the  
 power distribution,  
 cross sectional  
 dimensions ( $\Delta X_{I/e} = 4.0$   
 cm horizontally;

$\Delta Y_{I/e} = 15.7$  cm vertically) and displacement of the atomic beam. We applied beam energy composition diagnostics to measure the emission spectrum of the atomic beam shown in Fig. 4. Analysis of the obtained spectrum showed the following beam component composition:  
 $D(E):D(E/2):D(E/3) = 0.42:0.40:0.18$ , and  
 power distribution by beam components:  
 $P(E):P(E/2):P(E/3) = 0.71:0.23:0.06$ ,  
 where  $E = eU_{EE}$  is the energy of the main beam component. The generation of a beam with energy exceeding 22 keV is prevented by NE breakdowns.

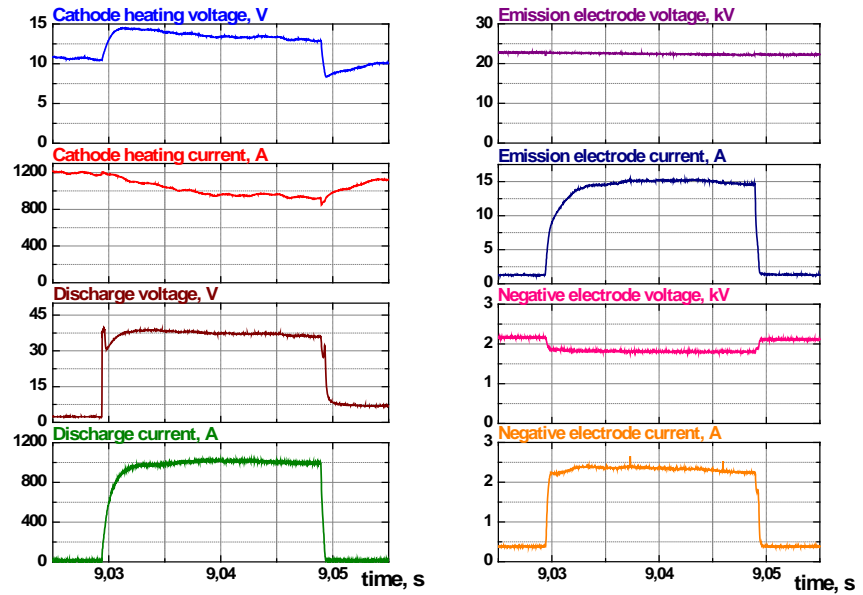


Fig. 3 Dynamics of current and voltage waveforms  
 in the power supply system during ISPM-1M beam generation

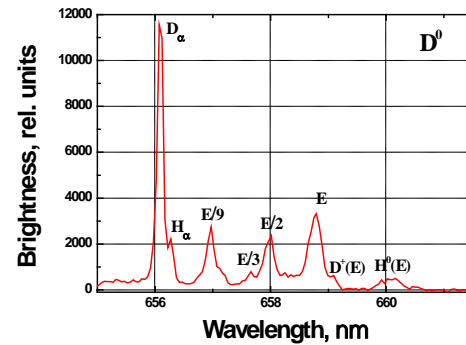


Fig. 4 The emission spectrum of deuterium atomic  
 beam  $E \approx 22$  keV, exposition time 10 ms

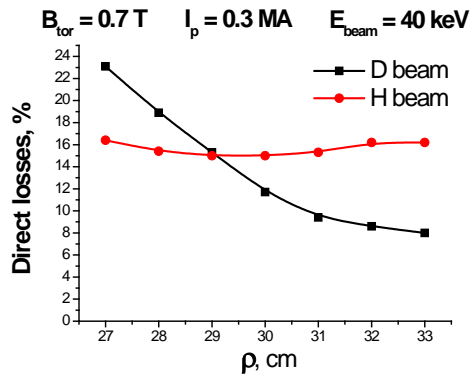


Fig. 5 Dependence of direct losses of fast  
 particles on possible impact parameter values

For 40 keV atomic beam, we performed calculations of fast particle losses for available values of the beam line impact parameter (27-33 cm) in Globus-M2 plasmas during NBI using a full 3D fast ion tracking algorithm [5]. Calculations were carried out with  $B_{tor} = 0.7$  T and  $I_p = 0.3$  MA for  $7.5 \times 10^{19} \text{ m}^{-3}$  volume averaged density. The results of this analysis are shown in Fig. 5, which represents the

dependence of direct losses of fast particles for deuterium and hydrogen beams on available values of impact parameter.

These simulations provided the foundation for predictive modeling of heating and current drive created by the neutral beam for Globus-M2 discharges. Predictive modeling of main plasma parameters for Globus-M2 discharges ( $I_p = 0.3$  MA,  $B_{tor} = 0.7$  T) was performed with the help of the ASTRA code [6] in the  $2.5 \times 10^{19} - 15.0 \times 10^{19} \text{ m}^{-3}$  range of volume averaged electron density. Effective plasma charge value  $Z_{eff}$  was assumed at 2.5. To calculate ion concentration, we assumed carbon as the main impurity. Thermal energy confinement time was predicted by ITER H-mode scaling  $\tau_E^{IPB98}$  [7]. Heat balance equations were solved in the model both for electron and ion components. Ion heat diffusivity  $\chi_i$  was supposed to be equal to electron one  $\chi_e$ , but higher than neoclassical heat diffusivity (estimated using NCLASS). Particle diffusion coefficient  $D = 0.5\chi_e$  and Ware convection velocity were used to evaluate the electron density profile taking neutral particle influx as a free parameter.

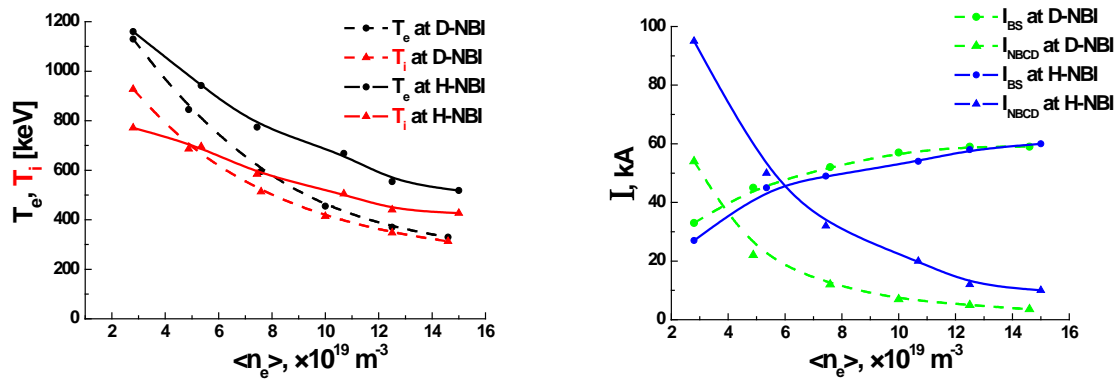


Fig. 6 Dependencies of central electron and ion temperatures and non-inductive currents on volume average density in Globus-M2 discharges with H-NBI and D-NBI

$I_{BS}$  – bootstrap current,  $I_{NBCD}$  – beam driven current

The results of these calculations are shown in Fig. 6. Numerical simulations indicate the achievement of conditions for better NBCD efficiency, higher fast particle confinement, and overall plasma performance. The total fraction of non-inductive current is found to be from 20 to 40% depending on plasma density.

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