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Development of neutral beam injectors for plasma diagnostic in Budker Institute of Nuclear Physics (invited)

V. I. Davydenko[a)] and A. A. Ivanov
Budker Institute of Nuclear Physics, Novosibirsk, 630090, Russia

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A number of hydrogen beam injectors have been developed in Budker Institute of Nuclear Physics, Novosibirsk, for plasma diagnostic in magnetic fusion devices. The developed neutral beams have an energy ranging from 20 to 55 keV, equivalent beam current of 1–4 A, angular beam divergence of $\sim 10^{-2}$ rad, and pulse duration 10^{-2}–10 s. For the beam with a duration of less than 1 s, an arc-discharge plasma box is used in which a low transverse ion temperature plasma is produced by expanding plasma jet. A radio frequency discharge is used for long duration beams. The beams are formed by a four electrode ion optical system. The electrodes are formed as spherical segments in order to provide geometrical focusing of the beam. For better use of the nonuniform plasma emitter, a version of the ion optical system has been developed in which the gaps extend with the radius. This ensures optimal beam formation from an enlarged surface. To provide a beam for active beam emission spectroscopy measurements in large fusion devices, the injector was developed with beam energy up to 55 keV, equivalent beam current (for hydrogen) up to 1.4 A, and pulse duration of up to 10 s. The injector is capable of providing modulated beam with frequency of up to 500 Hz. A distinctive feature of the ion source is that in order to simplify injector design, a thermal inertia-type ion optics system with "thick" electrodes is used.
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I. INTRODUCTION

Diagnostic neutral beams have become an extremely valuable tool in fusion plasma diagnostic. By studying the interaction of the beam with the plasma, various plasma parameters can be deduced. The required beam parameters are determined by the diagnostic and the parameters of the plasma under study. Generally, the beam intensity should be high enough to provide a desirable signal-to-noise ratio, especially for fluctuation studies where a good time resolution is required. The beam size must be small enough to provide a good spatial resolution. The beam specie and energy of particles are also determined by the diagnostic in which the beam is used.

A number of diagnostic neutral beams injectors have been developed in the Budker Institute, Novosibirsk, for different plasma physics experiments. The parameters of the beams are listed in Table I. For middle size machines such as mirror traps, reversed field pinches and stellarators short pulse diagnostic neutral beam injectors with a pulse duration 3–20 ms and beam energy of 20–30 keV has been developed. To support the beam emission spectroscopy in large tokamaks,[1] dedicated neutral beams have been developed. In this case, the maximal beam energy is set to 55 kV, ion current is up to 3 A, and pulse duration of the beam is up to 10 s. The results of the experimental study of the developed neutral beams are presented in the article.

[a)]Electronic mail: davydenko@inp.nsk.su

II. SHORT PULSE DIAGNOSTIC NEUTRAL BEAM INJECTOR

A short pulse diagnostic neutral beam injector comprises an ion source and neutralizer. The ion source and neutralizer are mounted inside a cylindrical soft-iron magnetic screen, which reduces stray magnetic field to a tolerable value. Figure 1 shows a schematic view of the injector ion source. A specific approach to formation of high brightness focused ion beam is used in the ion source. A cold cathode arc-discharge plasma generator produces a highly ionized plasma jet. Expansion of this jet onto the grids is collisionless and transverse ion temperature in a diverging stream is therefore reduced from initial $\sim$3–5 eV down to $\sim$0.2 eV.[2] The ion beam is formed by a multiaperture four-electrode ion optics system with geometrical focusing. The beam focusing is achieved by spherical forming of the electrodes. The gaps between the electrodes extend with the radius providing optimal beam extraction from the enlarged surface of the nonuniform plasma emitter. The bell-like radial distribution of the proton current density in plasma jet can be approximated by the expression[3] $j(r)=I/\pi^2 z^2(l+r^2/z^2)$, where I—total proton current in jet and z—axial distance to generator. For optimal formation of the proton beam, in agreement with the Child–Langmuir law, the following increase of the gaps of ion optical system with radius is required: $d(r)=d_0(1+r^2/z^2)$, where d_0 is the on-axis value of the gap.

The multiaperture ion optical system comprises four spherically formed electrodes. The curvature radii of the first three electrodes—plasma, extracting, and accelerating are different. Accordingly, the gaps increase with radius for earlier mentioned reason. The curvature radius of the fourth

TABLE I. List of DNBI parameters.

	TEXTOR DNBI (rf)	TCV DNBI (rf)	RFX DNBI (arc-discharge)	MST DNBI (arc-discharge)
Beam energy (keV)	20–50	20–55	20–55	30 (20 for He beam)
Max. extracted current (A)	2	3	5.5	4
Duration (s)	10	2	0.05	0.0035
Modulation	500 Hz+ external	External	External	No
Ion species, % (by current)	60/20/20	⋯	90/5/5	90/5/5
Diagnostic served	CHERS	CHERS	MSE, BES, CHERS	Rutherford scattering, MSE, CHERS

grounded electrode coincides with the radius of curvature of the accelerating electrode.

To determine a focal length at a given geometry of the ion optical system, several factors have to be taken into account. Namely, these factors are a difference in radii of electrodes, position of plasma boundary in elementary cell, initial velocity of ions in the plasma emitter, compression of elementary beam, etc. The problem has been comprehensively analyzed by three-dimensional numerical calculations of elementary beam formation by Whealton.[4] The results of these calculations were used for refinement of the focal distance.

An ion beam formation in the diagnostic neutral beam injector[5] for MST reversed field pinch is executed by 547 apertures 2.5 mm in diameter, which are arranged in hexagonal structure with a step of 3.2 mm. An outer diameter of the grids is 8 cm. The grids were made of 0.5-mm-thick pure molybdenum. Photoetching technology was used for formation of the holes in the grids. Then, the grids were spherically formed and recrystallized at high-temperature in vacuum. The curvature radius varies from 1.5 m for the inner plasma electrode, to 0.5 m for the outer, grounded electrode. The calculated focal distance of the optical system is 130 cm.

Characteristics of the formed hydrogen beam were studied at an experimental test stand. Beam profiles were measured at several distances downstream from the grids with an array of secondary emission detectors and a movable miniature calorimeter. Figure 2 shows profile of hydrogen beam intensity measured at distance of 1.6 m that is close to beam focus. The measured profile can be approximated by Gaussian $-j=j_{\max}\exp(-r^2/r_0^2)$. The deduced value of r_0 is ≈ 2.6 cm that corresponds to integral angular divergence of focused beam of $\delta\alpha\approx 1.6\times 10^{-2}$ rad.

The beam composition has been measured with a magnetic mass-analyzer equipped with a stripping He target. Figure 3 shows the results of the measurements at the beam energy of 30 keV. The measured fraction of hydrogen atoms at full energy exceeds 90%. This is attributed to a high electron temperature and high plasma density in the plasma source, which ensures full ionization of the plasma and a low concentration of molecular ions.

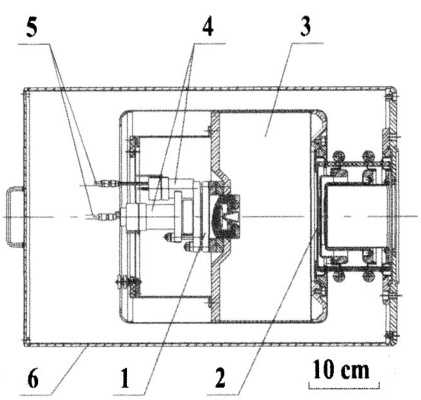

FIG. 1. Schematic of the short pulse ion source: (1) plasma generator, (2) electrodes of the ion optical system, (3) plasma expansion volume, (4) gas puffing valves, (5) HV feedthrough, and (6) magnetic screen.

III. AN INJECTOR WITH A RADIO FREQUENCY-PLASMA EMITTER FOR BEAM EMISSION SPECTROSCOPY

The neutral beam is provided by extraction of charged ions from a plasma driven by radio-frequency (rf) fields, and their acceleration to the desired energy with subsequent neutralization by charge exchange in a gas target. The diagnostic neutral beam injector, which incorporates all systems required for the beam control and measurements, is shown in Fig. 4. This particular version has been developed for the TEXTOR tokamak and its general layout is essentially typical for the developed diagnostic beams with long pulses. The vacuum system consists of a tank equipped with two liquid-helium cryogenic pumps. There is a turbomolecular pump, which is used for the initial pump-down of the injector vessel and during cryogenic pump regeneration. Each cryopump in-

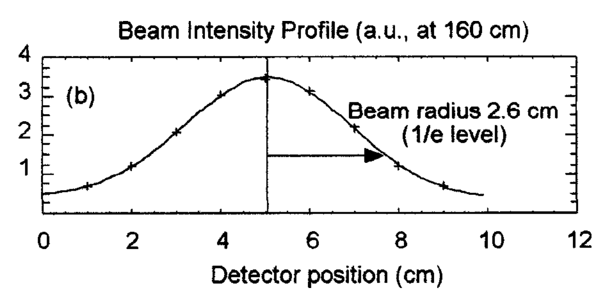

FIG. 2. Current density profile of hydrogen beam at 160 cm from the plasma electrode.

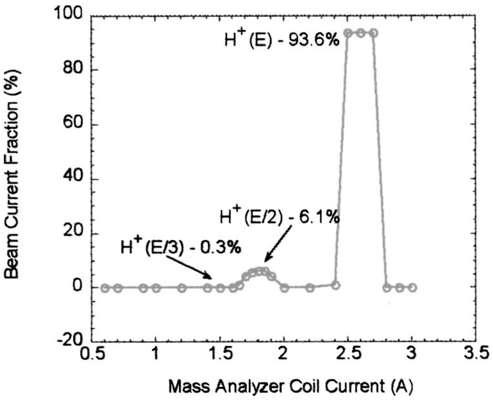

FIG. 3. Beam species in the hydrogen beam.

stalled on the top of the injector tank has a nominal hydrogen pumping speed of 24 m^3/s in molecular flow regime (for a beam current of ~1 eq. A).

To meet the requirements of the diagnostics at TEXTOR, the injector was designed to be rated at an energy of up to 50 keV, an equivalent atomic beam current (for hydrogen) of up to 1 A and a pulse duration of up to 10 s with 500 Hz modulation.

The injector ion source shown in Fig. 5 comprises a rf plasma box feeding a multiaperture electrostatic accelerator. The plasma box consists basically of a vacuum-tight cylindrical alumina ceramic chamber and an external rf coil. Typically, to provide the required current density (130 mA/cm^2), about 2.5 kW of rf power is to be coupled to the plasma. The discharge is initiated by applying a high voltage pulse to the trigger electrode mounted at a rear flange of the plasma box. To improve the particle confinement in the plasma box and efficiency of the discharge, an array of NdFeB permanent magnets is installed at the backplate.

The ion optical system consists of four molybdenum grids with the 163 apertures 4 mm in diameter forming a hexagonal structure with a step of 5.2 mm. To provide enhanced thermal capacity the extracting, accelerating, and ground grids, they are made of 4-mm-thick plates. The thickness of the plasma grid is 2 mm. Enlarged thickness of the grids required careful computer simulations of elementary beam formation to optimize geometry of the electrodes. The results of the simulations presented in Ref. 6 have shown that angular beam divergence better than 10^{-2} rad can be achieved. According to the simulation, the gaps between the

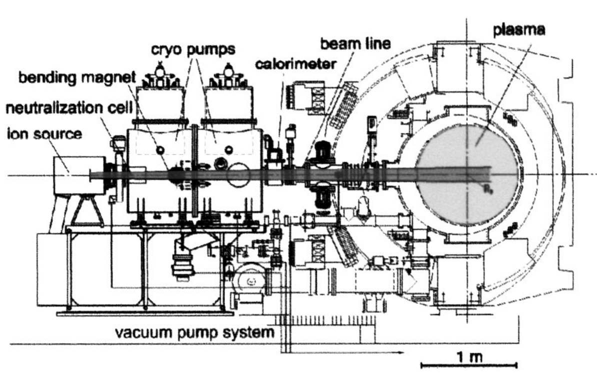

FIG. 4. Diagnostic neutral beam injector setup at TEXTOR.

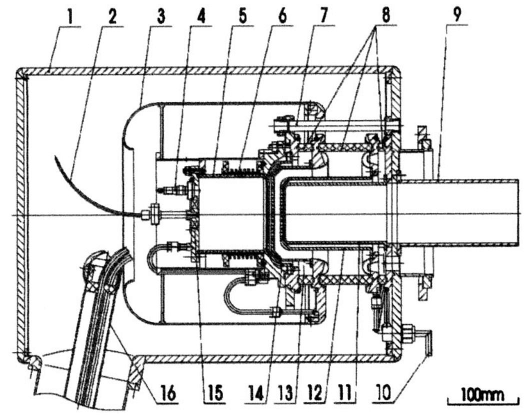

FIG. 5. rf ion source: (1) soft metal case, (2) gas feeding capillary tube, (3) inner magnetic shield, (4) trigger, (5) ceramic wall, (6) rf coil, (7) pull stud (insulator), (8) ceramic spacers, (9) beam duct, (10) water inlet manifold, (11) grounded grid, (12) accelerating grid, (13) extracting grid, (14) plasma grid, (15) magnets, and (16) coaxial feed through.

plasma grid, extracting grid, and accelerating grid were chosen to be 2.6 and 7.4 mm, respectively. Thermal deformations and mechanical stability of the grids under heat loads have been assessed in Ref. 7. The grids are mounted on the water-cooled flanges enabling the full heat removal from pulse to pulse as well as partial heat removal during the injection pulse. In order to focus the beam on to the desired point inside the plasma, the grids are formed to be spherical segments with the required curvature radius of 4 m.

The experimental results on the beam divergence and value of optimal extracting voltage were found to be in reasonable agreement with the simulation of the beam formation in the elementary cells of the ion optical system (see Fig. 6). Mass analysis of ion beam constituents indicates that H^+, H_2^+, and H_3^+ percentages are 71.5%, 13%, and 15.5% by current, respectively, when the ion source is operating with a current of 1.9 A. Similar results were obtained with spectrometric measurements of the beam species.[8]

IV. ION SOURCE WITH AN ARC-DISCHARGE PLASMA BOX

The ion source with the arc-discharge plasma box (Fig. 7) is capable of producing a higher proton fraction in the

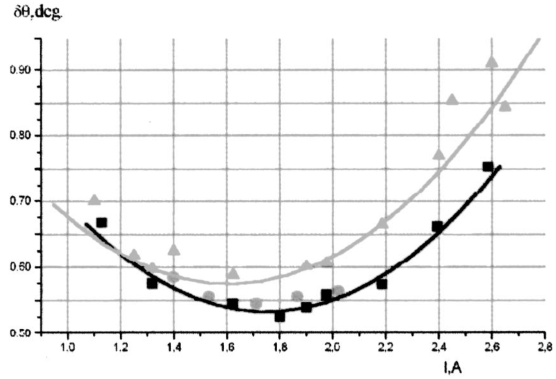

FIG. 6. Beam divergence vs current for the extracting voltage 6.5 and 6.75 kV (upper curve). Circles stand for calorimetric data, triangles, and rectangles stand for secondary emission detector data.

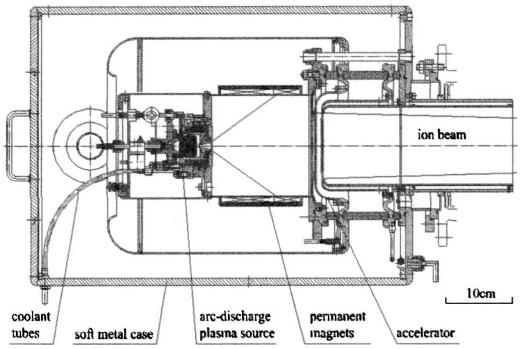

FIG. 7. Schematic of ion source with an arc-discharge plasma box.

beam. A cold cathode arc-discharge plasma generator produces a highly ionized plasma stream. As a result of collisionless expansion, the ion current density falls to that required for optimal beam extraction. At the same time, the transverse ion temperature in the diverging plasma decreases, which results in a small beam divergence. For a pulse duration limited to ~0.1 s and long enough intervals between the pulses, this modification does not require intense cooling. To withstand high power loads in longer pulses, it is equipped with an augmented cooling of the components. The version shown in Fig. 7 has been designed for a pulse duration of up to 0.1 s. The flanges at which the cathode and the anode are mounted have water coolant channels inside. The copper cathode has a spherical cavity and is separated from the anode by a stack of electrically floated washers. For longer pulses, the coolant channels are located directly at the surface of the cathode and the anode. In addition, the washers are also cooled from their edges by water flow. The gas is supplied through the gap between the cathode and the nearest washer or through a hole at the center of the cathode. The discharge is initiated by applying a high voltage pulse to a special trigger electrode inside the cathode. To obtain homogeneous ion current density at the plasma grid, the plasma stream expands from the anode orifice into a cylindrical volume the outer surface of which is covered by an array of Nd–Fe–B permanent magnets. The magnetic field strength at the inner wall of the expander is 0.2 T and falls down radially to less than 0.01 T at 2 cm distance. The current density required to extract a 4.5 A ion beam has been obtained with a discharge current of about 500 A. The measurements of the beam species for the ion source with the arc-discharge indicate a proton fraction as high as ~90% depending upon the beam current.

V. ARC PLASMA GENERATOR WITH HOLLOW LaB_6 CATHODE

Experience of the arc plasma generator operation has shown that the most critical part of the generator is the cold cathode. Intense cathode arc sputtering leads to electrical contact between the cathode and the nearest washer that breaks operation of the generator. To increase the lifetime of the plasma generator a version with a hollow LaB_6 cathode is developed. General layout of the plasma generator is shown in Fig. 8. It consists of an anode, discharge channel,

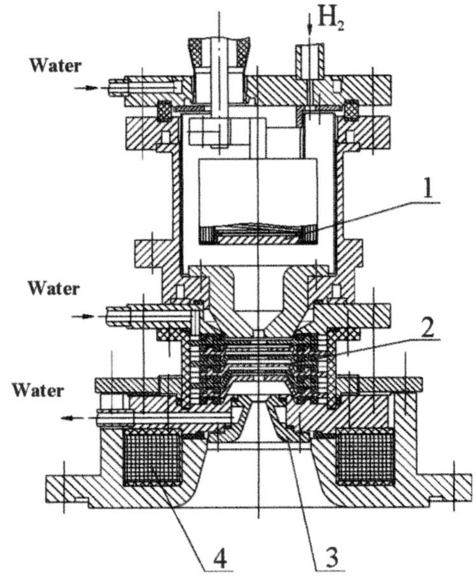

FIG. 8. Schematic of the arc plasma generator with LaB_6 cathode 1—LaB_6 tablet, 2—discharge channel, 3—anode, and 4—magnetic coil.

cathode assembly, magnetic coil, and a cooling system. The gas discharge is sustained between a copper anode and a hollow cathode with an internal LaB_6 electron emitter. The discharge channel is formed by a stack of isolated molybdenum washers with the internal diameter varying from 5 to 7 mm. The plasma production is increased by the application of a longitudinal magnetic field of about 0.1 T in the anode region, which is formed by the coil. The gas (hydrogen) is supplied through a gap between the anode and the nearest washer, and into the cathode cavity. The washers, cathode, and anode have intensive water cooling.

Lanthanum hexaboride has a high emission electron current up to 20–40 A/cm^2 at rather moderate temperatures. We have introduced a LaB_6 electron emitter into the hollow cathode to increase efficiency of plasma production. The LaB_6 tablet is supported by graphite rings and is heated by radiation of tungsten heater. The discharge is initiated by applying a 20–50 V voltage between the tablet and cathode body. At discharge current of ~270 A, a 2 A ion beam was extracted. The typical value of the heating power of the tablet was 650 W. A temperature required for stable operation was found to be about 1700 °C.

As it was already mentioned, the lifetime is a critical parameter for the arc-discharge plasma generator. By now, more than 1000 shots have been made with a pulse duration 1 s without noticeable damages to the generator components. Several 2 s shots also were made without critical damages to the generator.

[1] E. Hintz and B. Schweer, Plasma Phys. Controlled Fusion **37**, A87 (1995).
[2] V. I. Davydenko, Nucl. Instrum. Methods Phys. Res. A **427**, 230 (1999).
[3] V. I. Davydenko *et al.*, Zh. Tekh. Fiz. **53**, 258 (1983).
[4] J. H. Whealton, R. W. McGaffey, and P. S. Mezaros, J. Comput. Phys. **63**, 20 (1986).
[5] G. F. Abdrashitov *et al.*, Rev. Sci. Instrum. **72**, 594 (2001).
[6] V. I. Davydenko *et al.*, Rev. Sci. Instrum. **68**, 1418 (1997).
[7] A. D. Beklemishev *et al.*, Rev. Sci. Instrum. **69**, 2007 (1998).
[8] P. P. Deichuli *et al.*, Rev. Sci. Instrum. these proceedings.