Focused Neutral Beam With Low Chaotic Divergence For Plasma Heating And Diagnostics in Magnetic Fusion Devices

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Abstract:

A series of neutral beam injectors has been developed in the Budker Institute of Nuclear Physics, Novosibirsk for plasma heating and diagnostics in modern fusion devices. Ion optical system of these injectors is optimized to produce ion beams with low angular divergence. In order to provide beam focusing, the grids are formed as spherical segments. Such geometrically focused beams are neutralized in a gas target and subsequently are used to heat or diagnose plasma. For diagnostic purposes these beams are advantageous when high spatial resolution is necessary. In many cases such focused beam with small divergence are also necessary for plasma heating in the machines with narrow ports through which only small size, high power density beams can be transported.

1. Introduction

In recent years, neutral beams dedicated for plasma diagnostics have become widely used in magnetic fusion experiments [1-3]. Note that even though the number of diagnostics based on neutral beam injection is already quite large, nevertheless new promising ideas continue to emerge.

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. In particular, in spectroscopy of neutral beam induced radiation[1,3] for impurity studies, hydrogen beams with an energy of 50-60 keV, about at the maximum of cross section of the charge exchange cross section for excitation of the 7-8 transition of C^{5+} ions, are of particular interest. This energy also provides reasonable beam penetration into the plasma interior in modern plasma physics experiments with minor plasma radius of 0.5-1 m and average density of ~ $10^{20}m^{-3}$. Estimates suggest that the equivalent beam current incident on a plasma about 1 A or higher provide reasonable signals in the spectroscopic detection system[1,6]. At the same time, the beam power density should be small enough to prevent significant local heating of the plasma. This is important for the investigation of Ohmic, ICRH and ECRH heated plasmas. This requirement is generally consistent with the requirement of having sufficient signal in the detection system if the beam current is limited to several equivalent amperes. It is worthwhile to note that the parameters of beams for plasma diagnostics generally are different from those typical for the beams for plasma heating. Therefore, a number of dedicated diagnostic neutral beams have been developed for application in plasma physics experiments[4].

Development of neutral beam injectors for plasma physics experiments was started in the Budker Institute of Nuclear Physics, Novosibirsk, several decades ago. Initially, the developed beams had a pulse duration 0.1–0.2 ms and beam energy of 10–25 keV, which was consistent with the characteristic plasma parameters achieved at that time in toroidal systems and magnetic mirrors. These short pulse beams were provided by extracting ions from a plasma jet expanding from the anode orifice of high current arc discharge. Specific mechanism of plasma cooling during jet expansion makes feasible to form ion beams with transverse temperature as low as ~0.2eV[13].

Later on, a series of diagnostic hydrogen (or helium) beams, which are based on unified basic elements, i.e. plasma box and ion optical system, were developed for experiments on modern plasma devices. The required beam current can be provided by changing the size of the plasma box and the grids. The distinguishing feature of the developed beams is that the grids of the ion optical system are inertially cooled, i.e. have no channels for water cooling inside, as is always necessary for high power long pulse ion sources. Due to the limited pulse duration (2-10 s) and long enough intervals between the pulses in present day magnetic fusion facilities, the average thermal power loads on the grids appear to be rather moderate. Therefore heat capacity of the grids can be made high enough to limit its temperature rise during the pulse. Subsequently, the heat can be removed from the grids by water cooling from the periphery because of the very moderate time-averaged heat loads. This approach allows avoidance of significant thermo-mechanical deformations of the precisely machined and carefully aligned grids in long pulse operation [5-8]. At the same time, such arrangement of the grids enables to form them as spherical segments thus providing geometrical focusing of extracted and accelerated ion beam. Note that this approach is hardly applicable when the grids have internal cooling channels.

The developed ion sources are based on an RF-discharge plasma box[4-6], and, alternatively, on an arc-discharge plasma box [7,8]. As a matter of fact, the RF-version appears to be more appropriate for generating beams with a pulse duration exceeding 1s. Experimental tests showed that this version of plasma box has a reasonable lifetime exceeding 50,000 shots of multiple second duration. The arc-discharge version is used for relatively shorter beams. Its advantage, in comparison to the RF-version, is a higher proton fraction in the extracted beam (typically 80-90% by current)[9].

Injection of low-divergent, focused neutral beam of higher power is also necessary to heat plasma in machines in which access to plasma is provided through narrow ports, like compact tokamaks, stellarators, RFCs, magnetic mirrors, etc. For that purpose a beam with extraction grid system similar to that used in the diagnostic beams but of larger diameter was developed. Correspondingly, larger diameter RF-discharge plasma box was employed. In the paper, the characteristics of the long pulse diagnostic beams are presented. In the following sections the description of the RF and the arc discharge based ion sources is given together with a brief description of the general layout of the diagnostic neutral beam injector that incorporates the ion source. In the last section, description of developed focused heating beam is given.

1. **Diagnostic beams with cold cathode arc-discharge plasma box**

The ion source with the arc-discharge modification of plasma box (Fig. 1) is capable of producing a higher proton fraction in the beam. A cold cathode arc discharge plasma generator produces highly ionized plasma jet. As a result of its collisionless expansion from anode orifice, the ion current density falls to an optimal value that required for precise 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[8]. To withstand high power loads in longer pulses, it is equipped with an augmented cooling of the components. The version shown in Fig. 1 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

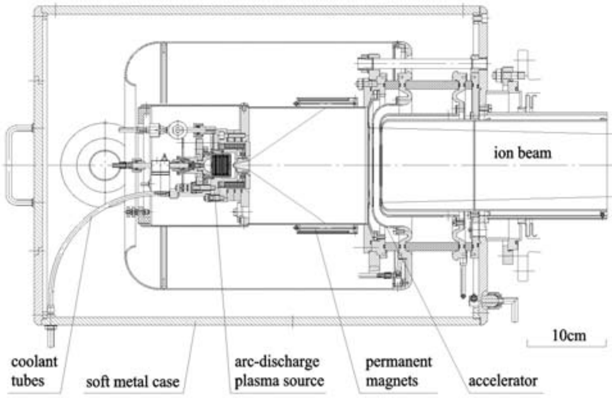

FIG. 1. Schematic view of ion source with an arc-discharge plasma box.

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 and 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 ion current density of 100-140mA/cm^2 has been obtained with a discharge current of 350- 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.

2. Diagnostic beams with an RF and hot cathode arc discharge plasma box

The source with the RF plasma box was developed in modifications with different extracted current, particle energy and pulse duration. In all the modifications neutral beam is provided by extraction of charged ions from the RF-driven plasma, and their acceleration to the desired energy with subsequent neutralization by charge exchange in a gas target. Typical arrangement of the diagnostic neutral beam injector, which incorporates all systems required for the beam control and measurements, is shown in Fig. 2. This particular version has been developed for the TEXTOR-94 tokamak[5]. For shorter pulses, the diagnostic beam injector actually comprises only an ion source and a neutralizer.

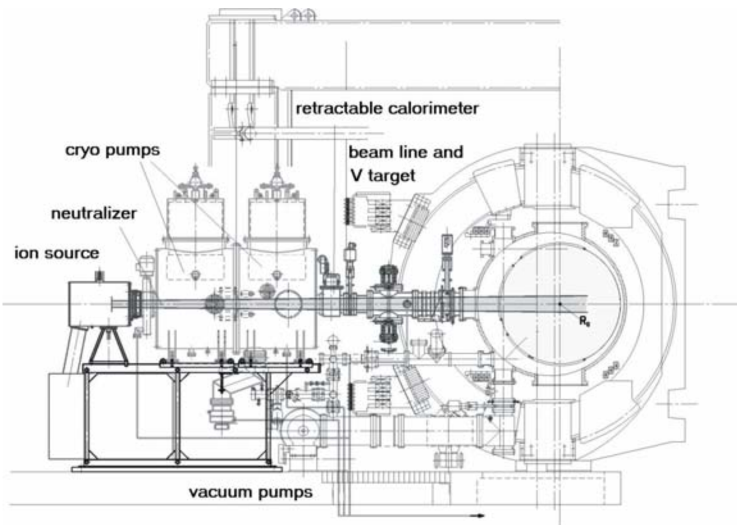

FIG. 2. Diagnostic neutral beam injector setup at TEXTOR.

The vacuum system consists of two cryogenic pumps and turbomolecular pump, which is used for initial pump-down of the injector vessel and during cryogenic pump regeneration. For the beam installed at Textor-94 each cryopump has a nominal hydrogen pumping speed of 24 m^3/s in molecular flow regime for a beam current of ~1 eq. A and up to 90 m^3/s for correspondingly higher beam current. .

To meet the requirements of the diagnostics at Textor-94, 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.

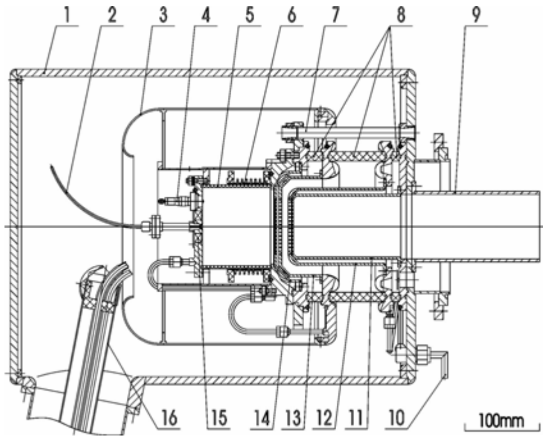

FIG. 3. RF ion source: 1 soft metal case; 2 gas feeding capillary tube; 3 inner magnetic shield; 4 trigger; 5 ceramic wall; 6 RF coil; 7 pull stud (insulator); 8 ceramic spacers; 9 beam duct; 10 water inlet manifold; 11 grounded grid; 12 accelerating grid; 13 extracting grid; 14 plasma grid; 15 magnets;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

The injector ion source shown in Fig. 3 comprises an RF plasma source feeding a multi-aperture electrostatic accelerator. The plasma source 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, an array of NdFeB permanent magnets is installed at the back plate. In the accelerator, there is a set of four nested molybdenum grids with circular apertures which are configured in a hexagonal pattern. The grids have curvature radius of 4m to focus the beam at desired position inside TEXTOR plasma.

The geometry of the elementary cell was optimized by using the 2D computer code AXCEL[6] to obtain small angular divergence of the beam. It is worthwhile to note that the ion optical system with thick electrodes benefits from smaller admissible negative biasing of the accelerating grid. In fact, a negative potential barrier for back-streaming electrons is established on the axis of the holes in the accelerating grid for a voltage on the grid as small as –200 V.

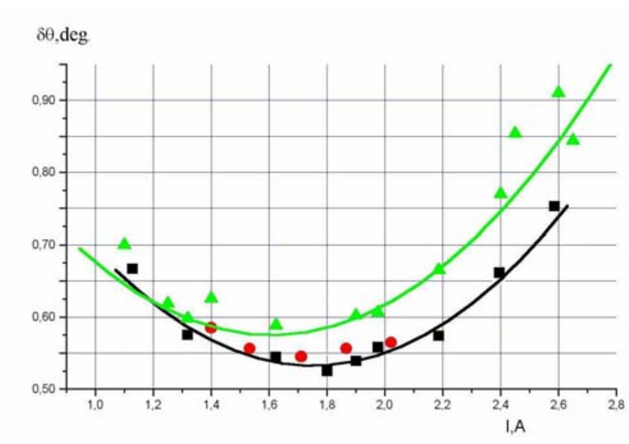

FIG. 4. Beam divergence vs. current for the extracting voltage 6.5 and 6.75 kV (upper curve). Circles stand for calorimetric data, triangles and

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[4,5] (see Fig. 4). Mass analysis of ion beam constituents indicates that H^+, H_2^+, and H_3^+ percentages are 71.5%, 13%, and 15.5% , respectively, when the ion source is operating with a beam of 1.9 A. Similar results were obtained with spectrometric measurements of the beam species[9].

Alternatively**,** an arc discharge plasma box (see Fig.5) can be applied to improve full energy fraction of the beam[8]. For pulse duration of up to 4s, a cylindrical electron emitter 5 was introduced into cathode cylindrical cavity. The emitter is composed of LaB_6 discs alternated by flexible washers made of thermo-extended graphite. To heat the stack, a current flows over it so that the ohmic power mainly releases in the graphite spacers, which essentially are used as a heaters. Each LaB_6 disc is 17 mm in diameter and 2 mm thick, the number of the discs was varied from 5 to 10 depending upon required discharge current. Working temperature of the emitter is 1600-1650C.

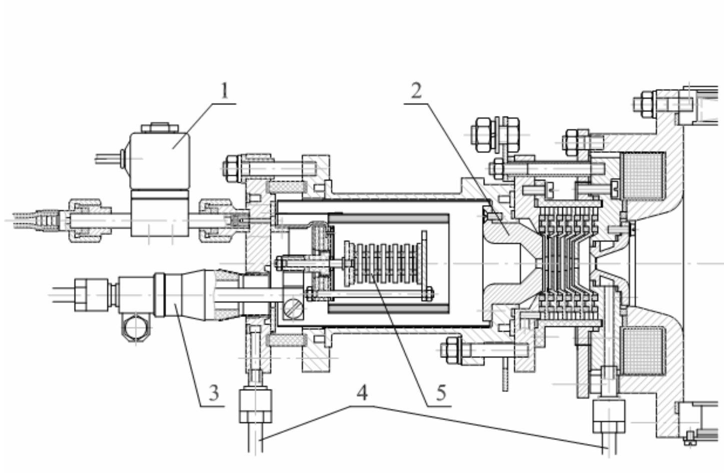

Fig. 5 General view of cathode assembly and electron emitter: 1 – cathode gas valve; 2 – cathode insert; 3 – heater feedthrough; 4 – water manifolds; 5 – electron emitter.

Such a design of the heater has several advantages against traditionally used heaters made of refractory metals or graphite in which the electron emitter is heated by radiation of the heater. The developed electron emitter with ten LaB_6 discs was used in arc-discharge source of hydrogen plasma, which was operated in pulses with duration upto 4s with arc current upto 700A. A version with smaller number of LaB_6 discs in the electron emitter was used in the TEXTOR-94 diagnostic beam with upto 370A current with 50%/50% modulation. This arc discharge plasma box with larger number of the LaB_6 discs and correspondingly higher arc current and plasma output was applied in the ion source of diagnostic beam injector which is now operated in AlcatorC-mod tokamak[4,8]. The ion source also has larger grid diameter and size of the plasma expansion chamber providing beam current of upto 8A in 3s pulses and beam energy of 55 keV energy .

3. Heating beam with geometrical focusing

A modification of the ion source with higher current of upto 40A, particle energy of 40keV and pulse duration 1s was developed for plasma heating.

The overall configuration of the ion source with the RF-plasma box is shown in Fig. 6. The nominal current density of 360 mA/cm^2 was chosen for the ion source. Plasma emitter in the ion source is produced by an inductively exited RF-discharge in a cylindrical ceramic tube (see Fig.6.). Non-homogeneous magnetic field inside the plasma box is produced by an array of permanent magnets located at the end flange. The multi-turn antenna (4) couples to the plasma up to 50kW of RF power at ~ 4MHz frequency. With 45kW of RF-power absorbed in the plasma, the source delivers an ion current of 45A (hydrogen).

In the accelerator, there is a set of three nested grids with circular apertures 4 mm in diameter. 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 geometry of the elementary cell was optimized to obtain appropriate angular divergence of the beam. Calculated ion trajectories and equipotentials are shown in Fig.7

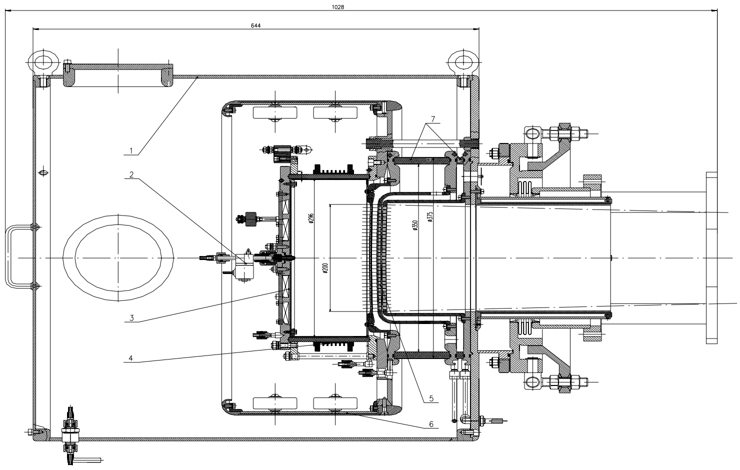

Fig.6. Ion source with an RF-discharge plasma box: 1- metal case, 2 – pulse gas valve and trigger unit, 3 – RF-plasma box, 4 – RF-coil, 5 – grids, 6 – internal magnetic and electrostatic shield, 7 – ceramic insulator.

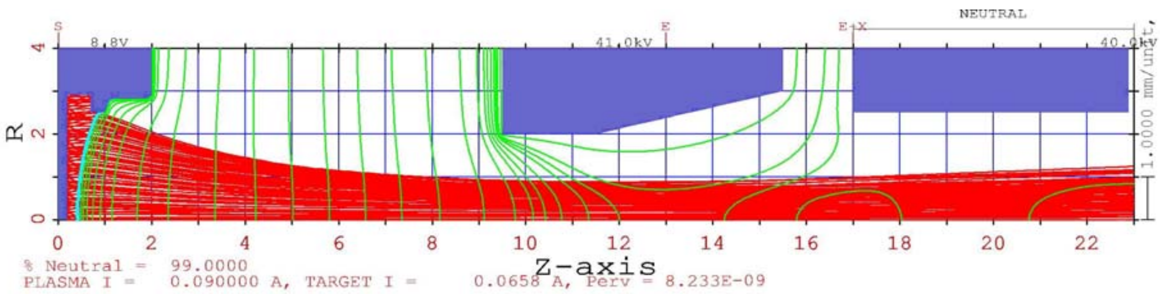

Fig.7 Plot of ion trajectories and equipotentials in elementary cell.

Experimentally, the beam divergence was inferred from the beam density profile on the calorimeter 2m downstream from the source taking into account that its axial position is by 900mm closer to the ion source than the focal plane of the beam.

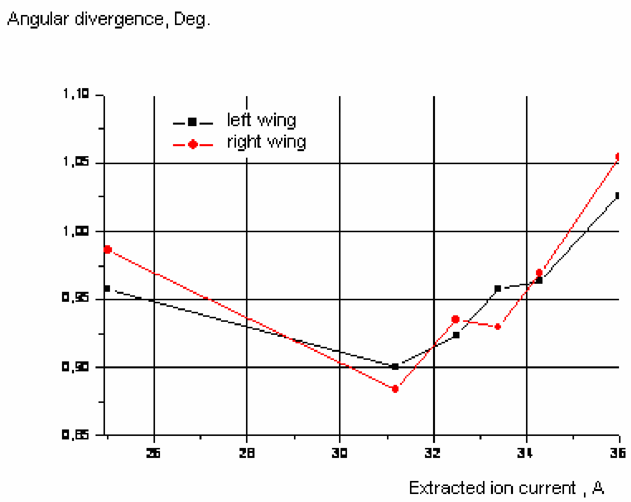

Fig.8 Bam divergence inferred from the beam power density profile measured on calorimeter wings

The beamlets on the periphery of the grids have no neighboring ones from one side which results in non-compensated radial electric fields. These fields produce some tilting of the elementary beams and leads to appearance of a beam halo with increased divergence. Special Pierce-like trim is introduced at the periphery of the plasma grid to compensate the radial fields generated by the space charge[10].

4. Conclusions

A number of diagnostic beams have been developed in the Budker Institute, Novosibirsk for different plasma physics experiments (see Table I). A distinctive feature of the ion sources as an application of an ion optical system with thick electrodes which have no internal cooling channels. In this case, the temperature rise of the grids during a pulse is limited by their thermal inertia and complete heat removal takes place between the pulses. Besides relatively simpler fabrication, the grid design adopted has several advantages as compared to designs with internal cooling channels. Namely, it provides higher grid transparency and possibility of using a molybdenum grid with higher electrical strength. Additionally, the freedom from developing a water leak in the grids is also a quite important issue contributing a lot to the overall reliability of an ion source. The developed DNBIs have plasma boxes of two modifications based on RF or arc discharge. The former has a proton fraction approaching ~90% (by current). At the moment, several DNBIs are routinely operated in different plasma physics laboratories throughout the world and have shown sufficiently high reliability. A beam with geometrical focusing with higher current was developed for plasma heating.

TABLE I: LIST OF DNBI PARAMETERS.

	TEXTOR DNBI (RF)[5]	TCV DNBI (RF)	AlcatorC-mod (ARC)	RFX DNBI (ARC)	MST DNBI [7] (ARC)
Beam energy, keV	20-50	20-55	55	20-55	30 (20 for He beam)
Max. extracted current, A	2	3	7	5.5	4
Duration, s	10	2	3	0.05	0.0035
Modulation	500 Hz + external	external	external	External	No
Ion species, % (by current)	60/20/20	-	-	90/5/5	90/5/5
Diagnostic served	CHERS	CHERS	MSE, CHERS	MSE, BES, CHERS	Rutherford scattering, MSE, CHERS

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