Diagnostic Neutral Beams for Plasma Studies in Magnetic Fusion Devices

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Abstract: Nowadays, low-divergent, quasi-stationary neutral beams are widely used in magnetic fusion devices as a diagnostic tool providing unique information about plasma parameters. Essentially, a diagnostic determines the requirements for the beams, which in many cases consist in sufficiently large current density and energy of the particles so that the beam can penetrate to the plasma core. At the same time, the duration of the beams should overlap that of a plasma shot (~10 s or longer for large machines). We have developed a number of diagnostic hydrogen beams with a maximum beam energy of 55kV, extracted ion current varying up to 6 A, and pulse duration from several milliseconds to 10 s. The beams are formed by a four electrode ion optical system which makes it possible to provide a low divergent (0.5-0.7°) beam. Additionally, a beam can be focused onto a desired point by proper choice of the curvature radius of the grids. The beams can be modulated with a frequency variable up to 500 Hz. The plasma emitter in the injector is provided by a radiofrequency discharge in hydrogen (deuterium) for long duration beams and, alternatively, by an arc-discharge plasma box for the beams with a duration of up to ~0.5 s. The arc discharge plasma box provides a higher proton fraction (~90%) than the RF discharge version (~60%). The parameters for the different beams developed are presented.

1. Introduction

Diagnostic neutral beams have become extremely valuable tools in fusion plasma diagnostics. By studying the interaction of the beam with the plasma, various plasma parameters can be deduced. In particular, spectroscopy of neutral beam induced radiation is widely used to measure density and temperature profiles, parameters of plasma turbulence, and cross field transport as well as spatial profiles of highly ionized impurities [1,2,3]. The required beam parameters are determined by the diagnostic for which the beam is used and the parameters of plasma under study. For instance, a hydrogen beam energy of 50 keV, which is about at the maximum of the charge exchange cross section for the 7-8 transition of C^{5+} ions, is of particular interest for many cases. At the same time this energy provides reasonable beam penetration into the plasma interior in the modern plasma physics experiments with a minor plasma radius of 0.5-1 m and average density of ~ 10^{14} cm^{-3}. The estimates suggest that the equivalent beam current incident on the plasma should be about 1 A or higher to provide reasonable signals in the detection system [1,2,3]. However, the beam power density should be small enough to prevent significant local heating up of the plasma under investigation. In some experiments, a significant increase of the ion temperature measured with neutral particle analysis has been observed for a beam power of ~50 kW. In the Budker Institute, Novosibirsk, a diagnostic neutral beam injector has been developed, which although quite simple in design, is capable of meeting the above mentioned requirements. The ion source developed has two modifications in which a radiofrequency (RF) and an arc-discharge based plasma box are alternatively applied, and both have similar four electrode ion optical systems. Several versions of the source have been developed for different plasma physics experiments. For producing beams with a pulse duration exceeding 0.5 s, the modification with the RF-discharge plasma box is more appropriate [4,5]. For shorter pulse operation, the arc-discharge modification provides the advantage of higher full energy species in the beam [6].

2. Diagnostic beams with an RF plasma box version

The source with the RF plasma box has several versions with different extracted current, particle energy and pulse duration. The 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. The diagnostic neutral beam injector, which incorporates all systems required for the beam control and measurements, is shown in Fig. 1. 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. For short pulses, the diagnostic beam comprises only an ion source and a neutralizer.
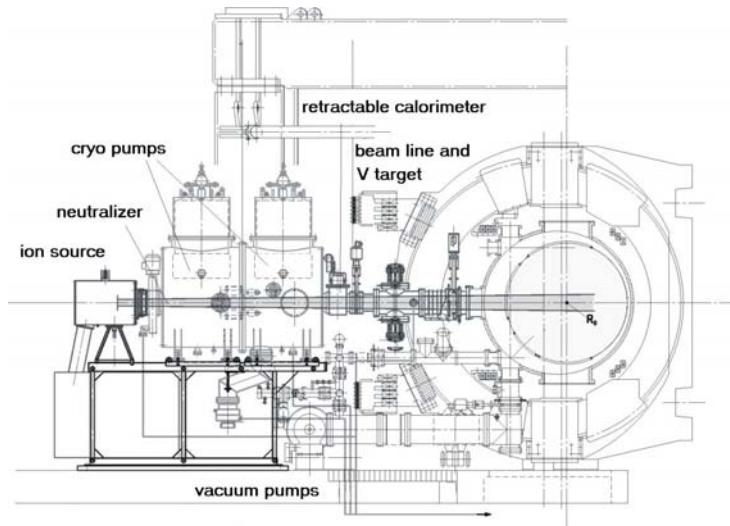

FIG. 1. Diagnostic neutral beam injector setup at TEXTOR.

The vacuum system consists of two liquid-helium cryogenic pumps and one turbomolecular pump, which is used for initial pump-down of the injector vessel and during cryogenic pump regeneration. Each cryopump installed 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.
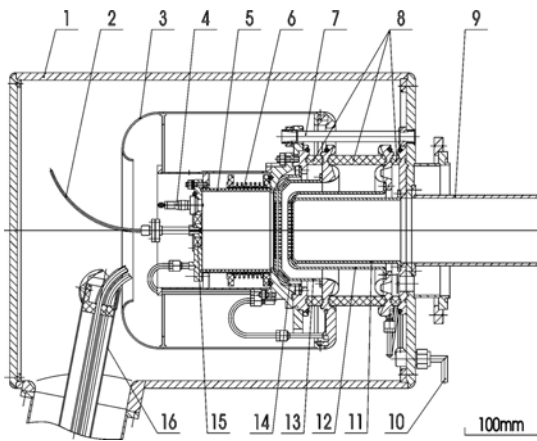

FIG. 2. RF ion source: 1 soft metal case; 2 gas feeding capillary tube; 3 inner magnetic shield; 4 trigger; 5 ceramic wall; 6 RF coil; 7 pull stud (insulator); 8 ceramic spacers; 9 beam duct; 10 water inlet manifold; 11 grounded grid; 12 accelerating grid; 13 extracting grid; 14 plasma grid; 15 magnets;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

The injector ion source shown in Fig. 2 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 grids with circular apertures configured in a hexagonal pattern. A distinctive feature of the ion source is that a thermal inertia-type ion optical system with "thick" electrodes is used. To limit

the temperature rise of the grids to a tolerable value, the extracting, accelerating and ground grids are made of thick molybdenum plates. The grids are mounted on the water-cooled flanges, making possible full heat removal from pulse to pulse as well as partial heat removal during the injection pulse [5]. In order to focus the beam on to the desired point inside the plasma, the grids are formed to be spherical segments with the desired curvature radius (4 m for the TEXTOR beam).
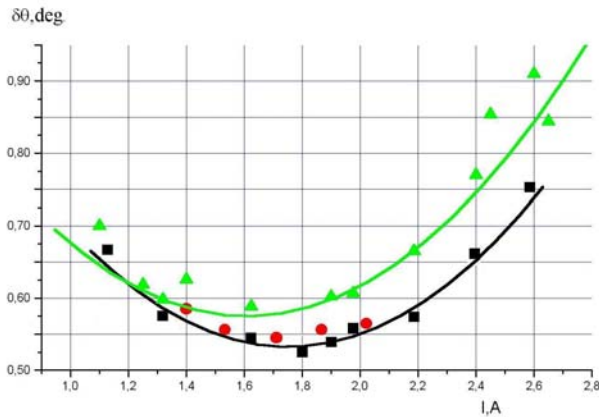

FIG. 3. Beam divergence vs. current for the extracting voltage 6.5 and 6.75 kV (upper curve). Circles stand for calorimetric data, triangles and rectangles stand for SED data.

The geometry of the elementary cell was optimized by using the 2D computer code AXCEL [5] 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. As a matter of 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.

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 [5] (see Fig. 3). 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 [7].

3. Diagnostic beams with an arc-discharge plasma box

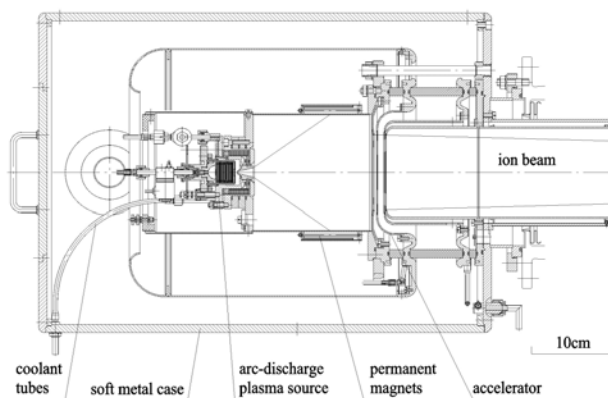The ion source with the arc-discharge modification of plasma box (Fig. 4) is capable of

FIG. 4. Schematic view of ion source with an arc-discharge plasma box.

producing a higher proton fraction in the 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 [6]. To withstand high power loads in longer pulses, it is equipped with an augmented cooling of the components. The version shown in Fig. 4 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.

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 lower cost and 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.

TABLE I: LIST OF DNBI PARAMETERS.

	TEXTOR DNBI (RF) [4]	TCV DNBI (RF)	RFX DNBI (arc-discharge)	MST DNBI [8] (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

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.

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