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Steady State Diagnostic Neutral Beam Injector

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Abstract

To provide a beam for active beam emission spectroscopy measurements in large fusion devices a dedicated neutral beam injector was developed. It is operated at energy 50 keV, equivalent beam current (for hydrogen) up to 1 A, pulse duration of up to 4 s. The injector is also capable of providing beam modulation with frequency of up to 500 Hz. In the injector ion source the emitter plasma is produced by an inductively exited RF-discharge. 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. With the grids formed to focus the beam 4 m downstream from the source the integral angular divergence of the beam, measured at 1/e level in the focus, of 10^{-2} rad was obtained. At present two injectors are successfully put into operation at TEXTOR and TCV tokamaks.

The developed injector, in principle, can be operated in steady state regime after several nonprincipal changes in design. The RF-plasma generator allows significantly increased pulse duration without considerable changes. To increase further pulse duration new versions of ion optics system with more intense water cooling are being developed.

Keywords:

plasma diagnostic, neutral beam injector, ion beam, plasma emitter, ion optics system

1. Introduction

Low-divergent, quasi-stationary neutral beams are often applied in modern magnetic fusion devices as a diagnostic tool providing unique information about plasma parameters. The most important requirements to these beams are sufficiently large current and energy of the particles, so that the beam could penetrate to plasma core. At the same time, duration of the beams should be long enough, close to that of a plasma shot, amounting to, at least, a few seconds for large machines. We developed neutral beam injector which is capable of meeting above mentioned requirements. The maximal beam energy is set to 50 kV, the source delivers ion current is up to 2 A, and pulse duration of the beam is up to 4 s. The low divergent beam ($\sim 10^{-2}$ rad) is geometrically focused 4 m downstream from the source. The beam can be modulated with a frequency variable up to 500 Hz. Plasma emitter in the injector is provided by a radio frequency (RF) discharge in hydrogen. The beam parameters were experimentally measured and compared with those predicted by simulations. Possible ways to evolve the developed injector to steady state operation are also considered below in the paper.

2. Injector Description

In the injector the neutral beam is provided by extraction of charged ions from the RF plasma and their acceleration to the desired energy with subsequent neutralization by charge exchange with gas target. General layout of the diagnostic neutral beam injector is presented in Fig. 1. It includes a neutralizer, calorimeters, ion deflection magnet, residual ion dump, pumps and other major components which are housed

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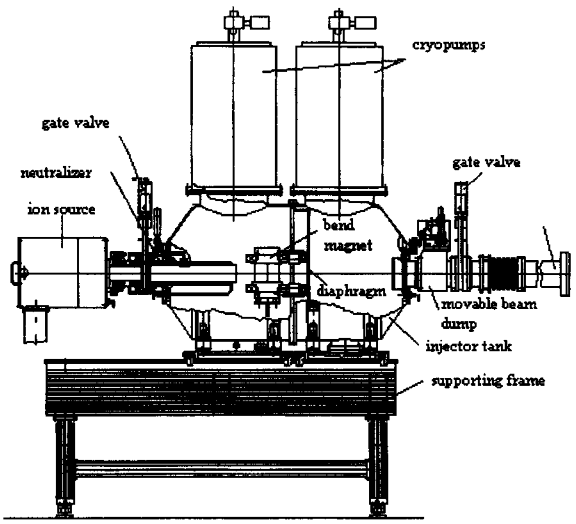

Fig. 1 General view of one of the version of diagnostic neutral beam injector

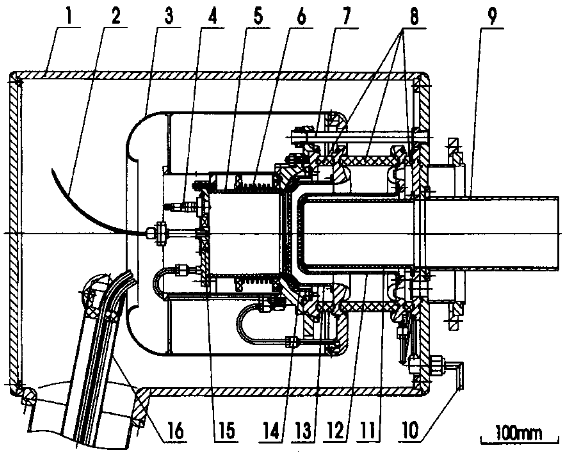

Fig. 2 RF-discharge ion source. 1 – soft metal case, 2 – gas feeding capillary tube, 3 – inner magnetic shield, 4 – trigger, 5 – ceramic wall, 6 – RF-antenna, 7 – pull stud (insulator), 8 – ceramic spacers, 9 – beam duct, 10 – grid cooling manifold, 11 – grounded grid, 12 – accelerating grid, 13 – extracting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

inside or at a cylindrical vacuum tank.

Gas is partly supplied into the beamline neutralization duct by puff from the discharge chamber, the rest amount is puffed into the duct through a manifold by making use of a pulse gas valve. Bending magnet and residual ion dump are placed inside the vacuum vessel at a special servicing platform. Each pump installed on the top of the injector tank has a nominal hydrogen pumping speed of 24×10^3 l/s in molecular flow regime.

3. Plasma Emitter

The injector ion source (Fig. 2) comprises an RF plasma source feeding a multi-aperture ion optics system. The plasma source consists basically of a vacuum-tight cylindrical alumina ceramic chamber and an external coil. For the ion source, the ion current density of 100–130 mA/cm^2 was chosen.

The emitter plasma is produced by an inductively excited RF discharge in hydrogen (or helium). The external RF coil is made of six turns of copper wire wound on a teflon frame. The RF coil is fed by alternating current with a frequency of 4.65 MHz from an amplifier with an output power variable up to 10 kW. Typically, to provide the required current density (130 mA/cm^2) ~2.5 kW of RF-power is to be coupled to the plasma.

The copper backplate of the source vacuum chamber vessel has water channels for active cooling. The ceramic tube is vacuum tighten from both end with indium ring sealings that allow for effective heat conduction to the backplate and front side flange both water cooled. A thermocouple monitored surface temperature of the tube revealed temperature rises at the tube center of less than 50°C under conditions of 10 s operation at maximal power.

The gas is introduced at the backplate by a pulsed gas valve through a flexible capillary tube 0.5 mm in inner diameter and 150 mm long that simultaneously provide electrical insulation of the valve, installed on the grounded flange, from the plasma source. For ~2 A extracted current gas puffing rate for hydrogen was set to 1.5 Torr l/s.

The discharge is initiated by applying a high voltage pulse between the trigger electrode and the discharge chamber rear flange at which the trigger is mounted. To improve the particle confinement in the source, two NdFeB permanent magnets are installed at the backplate. Typical ion current density profile measured at the plane of the first (plasma) grid is shown in Fig. 3. The ion current is homogenious with ±10% accuracy within the plasma grid surface. The emitter current density was found to be changed almost linearly with the RF power coupled to the plasma.

4. Ion Optics System

The ion optics system consists of four molibdenum grids with the 163 apertures 4 mm in diameter forming

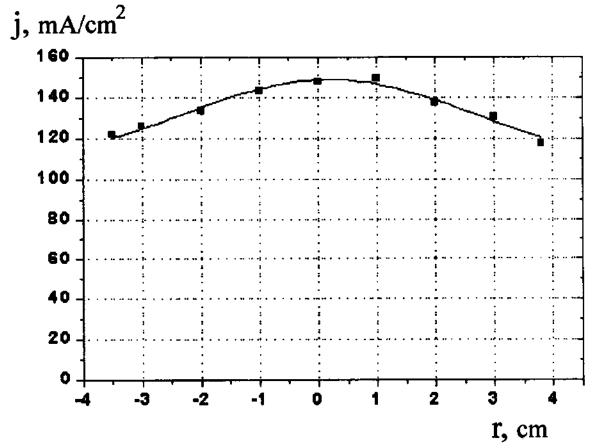

Fig. 3 Typical ion current density profile of RF plasma emitter

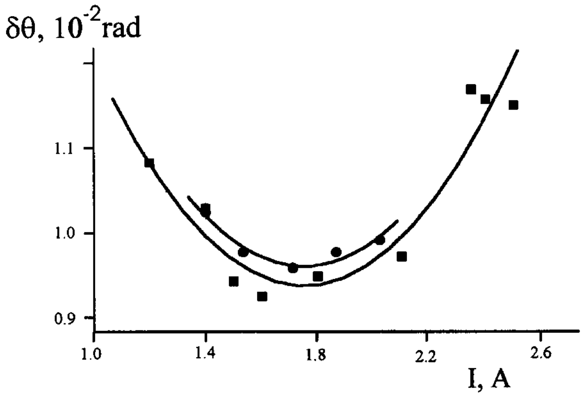

Fig. 4 Beam divergence vs current for the extracting voltage 6.5 kV and 6.75 kV (upper curve)

an hexagonal structure with step of 5 mm. To provide enhanced thermocapacity the extracting, accelerating and ground grids are 4 mm in thickness. Thickness of the plasma grid is 2 mm. Enlarged thickness of the grids required computer simulations of elementary beam formation for optimization of geometry of the elementary cell. The results of the simulations presented in [1] have shown that the angular beam divergence better than 10^{-2} rad can be achieved. According to the simulation the gaps between the plasma and extracting and between extracting and accelerating electrodes are 2.6 mm and 7.4 mm, respectively. Thermal deformations and mechanical stability of the grids at heating by secondary particles have been accessed in [2]. 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.

5. Beam Tests

Beam profiles were measured by making use of an array of secondary emission detectors near the focal plane at distance 4 m downstream from the ion source and, alternatively, by a segmented retractable calorimeter installed 2.2 m from the ion source. The results of these two diagnostics reasonably coincide to each other. The V-shape dependencies of an angular divergence upon the beam current and voltage on the extracting electrode (Fig. 4) have been obtained. The experimental results on the beam divergence and value of optimal extracting voltage are in reasonable agreement with the simulation of the beam formation in elementary cell of ion optics system [1].

Experimental tests indicate that the grids are capable to handle a pulse thermal load when operated at 50 kV and extracted ion current of, at least, 1.7 A for 4 s, with a duty cycle of about 1.5% for cooling.

The species composition has been investigated for 50 keV hydrogen beam. The beam was analyzed by a magnetic mass spectrometer located ~ 4 m from the source. 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 beam of 1.9 A.

6. Steady State Regime

The developed injector, in principle, can be operated in steady state regime after non-significant changes in design. The RF-plasma emitter allows significantly increased pulse duration without considerable changes. The thermal loads to ceramic walls of the plasma generator are moderate and can be removed by the water cooling from the ends in continuous regimes. Estimation of the stationary temperature rise of the ceramic tube is 100°C.

To provide steady state beam formation new versions of intense water cooling of the grids are being developed. In case of use of intense peripheral water cooling the radial profile of stationary temperature rise of grid is expressed by parabolic law $\delta T \approx q(a^2 - r^2)/4\chi h$, where q is thermal load to grid, a is radius of grid, χ is thermal conductivity and h is effective thickness of the grid. Taking $q \approx 24$ W/cm^2 [2] we obtain for grid center $\delta T \approx 300$°C for beam formation without modulation. The next approach is based on use of additional water cooling of the grid central part. In this case the radial profile of the temperature can be written as $\delta T \approx q((a^2 - b^2)\ln(r/a)/\ln(a/b) + a^2 - r^2)/4\chi h$ [3], where b is the radius of grid central part with with cooling. For $a/b = 5$ maximum of temperature rise achieved at $r \approx 2.7\, b$ is $\delta T \approx 100°C$. In version of grid system with more intense cooling water channels are arranged in place of each third row of holes. Maximum of temperature rise for this case is $\delta T \approx 25°C$ but integral grid transparency then decreases from 54% to 36%.

Another parts of the injector such as neutralizer, cryopumps, bending magnet, beam dump can be operated in steady state regimes without significant problems.

7. Conclusions

Experimental tests of the ion source indicate that the ion optical system is capable of handling a pulse thermal load when operated at 50 kV and maximal extracted ion current of 1.7 A for 4 s, with a duty cycle of about 1.5% for cooling. The beam is focused at distance 4 m from the source having ~ 35–40 mm radial extent at the focal point. Simple versions of water cooling of the ion optics system with "thick" grids can be used for evolving the source to steady state regime of operation.

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