DEVELOPMENT OF FOCUSED NEUTRAL BEAMS WITH SMALL ANGULAR DIVERGENCE FOR PLASMA HEATING AND DIAGNOSTICS

V.I. Davydenko[1,2], A.A. Ivanov[1,2], P.P. Deichuli[1,2], V.P. Belov[1], A.I.Gorbovsky[1], V.V. Mishagin[1], I.V. Shikhovtsev[1,2],
A.V. Sorokin[1,2], A.V. Stupishin[1,2], G.I. Shulzhenko[1], G.Fiksel[3], B. Schweer[4]

[1]*Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia, V.I.Davydenko@inp.nsk.su*
[2]*Novosibirsk State University, 630090, Novosibirsk, Russia*
[3]*University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[4]*Trilateral Euregio Cluster, Institut fuer Energieforschung-Plasmaphysik,*
Forschungszentrum Juelich GmbH, Association EURATOM-FZJ, 52425 Juelich, Germany

A series of neutral beam injectors for plasma heating and diagnostics in modern magnetic fusion devices has been developed in the Budker Institute of Nuclear Physics. In ion sources of these injectors arc discharge or RF plasma boxes are used. Ion optical systems are optimized to produce ion beams with a low enough angular divergence. In order to provide beam focusing, the grids are formed as spherical segments. Such ballistically focused beams are further neutralized in a gas target and subsequently are used to heat or diagnose plasma. Obtained diagnostic neutral beams with precise focusing are widely used to measure plasma parameters by beam emission spectroscopy methods in tokamaks, stellarators, reversed field pinches and open traps. High power focused beams with small divergence are also necessary for heating of localized regions of plasma and in the devices with narrow access ports through which only small size, high power density beams can be transported. Transition to steady state operation regime of the injectors is discussed.

I. INTRODUCTION

Diagnostic neutral beams have become an extremely valuable tool in fusion plasma diagnostic[1,2]. 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 composition and energy of particles are also determined by the diagnostic in which the beam is used.

Within the last fifteen years more than ten diagnostic neutral beam injectors have been developed and produced in the Budker Institute for different plasma physics experiments[3]. For medium size machines such as mirror traps, reversed field pinches and stellarators short pulse diagnostic neutral beam injectors with pulse duration from 3 ms to 20 ms and beam energy from 20keV to 40 keV have been developed. To support beam emission spectroscopy in large tokamaks, dedicated neutral beams have been developed. In this case, the maximum beam energy is 55 kV, the ion current is up to 7 A, and the pulse duration of the beam is up to 10 s. A distinctive feature of the ion sources with the long pulse duration is use of ion optical systems with thick electrodes which have no internal cooling channels. In this case, the temperature rise of the electrodes during a pulse is limited by their thermal inertia while complete heat removal takes place between the pulses.

Injection of high-power, low-divergent, focused neutral beam of higher power is also necessary for plasma heating in machines in which access to plasma is provided through narrow ports, like compact tokamaks, stellarators, RFPs, FRCs, magnetic mirrors, etc. In the paper, a description of developed focused neutral beam with 1 MW power and 1 s pulse duration for plasma heating is given.

II. DIAGNOSTIC NEUTRAL BEAMS

The ion sources in the developed diagnostic neutral beam injectors usually operate with a relatively small emission ion current density ~110-130 mA/cm^2. For such emission current density the gaps between the grids of ion optical system are large enough, the aberrations of the elementary beams are small and the angular divergence of a formed ion beam at a level of 0.5-0.6 degree can be achieved. Two varieties of plasma boxes based on either

RF or on arc discharge are used[3,4]. The ion source of the arc-discharge variety (Fig.1) is capable of producing a higher proton fraction in the beam. A cold cathode arc discharge plasma generator produces a highly ionized plasma jet. As a result of its collisionless expansion from the anode orifice, the ion current density falls to an optimal value that is 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. To withstand higher power loads in longer pulses, it is equipped with an auxiliary 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 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. To obtain homogeneous ion current density at the plasma emission surface, the plasma stream expands from the anode orifice into a cylindrical volume the outer surface of which is covered by multi-pole array of Nd-Fe-B permanent magnets. The ion current density of 100-140 mA/cm^2 has been obtained with a discharge current of 350-500 A. Measurements of beam species for the ion source with the arc-discharge indicate the proton fraction as high as ~90% depending upon the beam current.

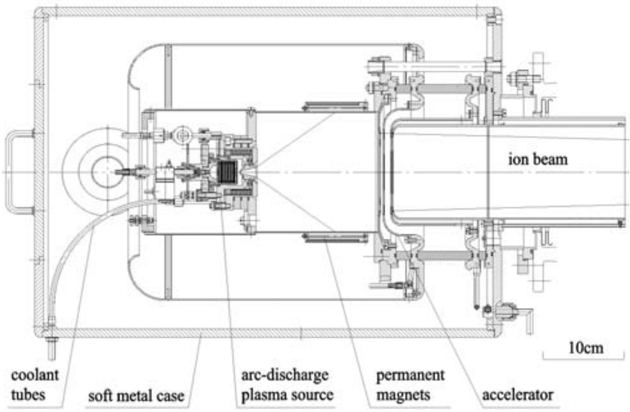

Fig. 1. Schematic view of an ion source with an arc-discharge plasma box.

For short pulse ion beam formation, four-electrode ion optical systems with round apertures[5] are used. The grids are made of 0.5 mm thick pure molybdenum. Photo-etching technology is used for formation of the holes in the grids. Then, the grids are spherically formed and re-crystallized at high-temperature in vacuum.

For pulse duration of up to 4 s, a cylindrical electron emitter shown in Fig.2 was introduced into a cylindrical cavity in cathode. The emitter is composed of LaB$_6$ discs alternated by flexible washers made of thermo-extended graphite. The stack is heated resistively by driving electric current through it so that the ohmic power is mainly released in the graphite spacers. Working temperature of the emitter is 1600-1650 °C.

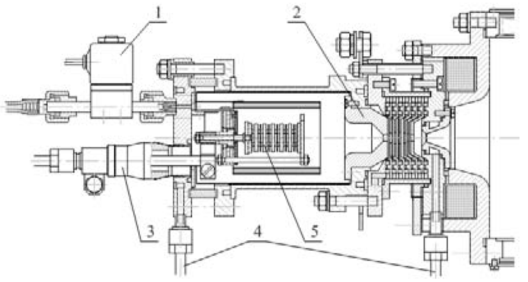

Fig. 2. General view of the cathode assembly and electron emitter: 1 – cathode gas valve, 2 – cathode insert, 3 – heater feedthrough, 4 – water manifolds, 5 – electron emitter.

For long pulse operation an RF-version of the injector ion source shown in Fig. 3 was developed. In the plasma box, plasma is produced inside a vacuum-tight cylindrical alumina ceramic chamber by using 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 the 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.

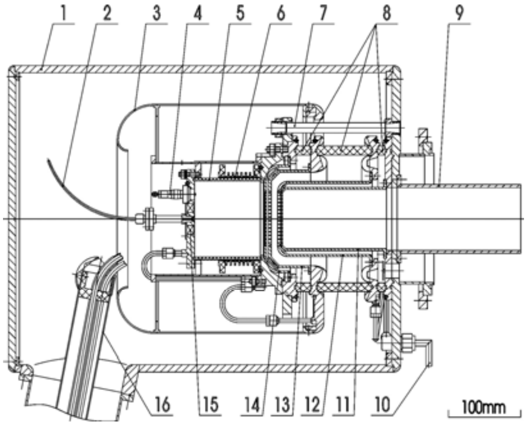

Fig. 3. RF ion source: 1 – soft steel case, 2 – gas feeding capillary tube, 3 – inner magnetic shield, 4 – trigger, 5 – ceramic wall, 6 – RF coil, 7 – pull stud (insulator), 8 – ceramic spacers, 9 – beam duct, 10 – water inlet manifold, 11– grounded grid, 12 – accelerating grid, 13 – extracting grid,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

The geometry of an elementary cell with thick electrodes was optimized by using the 2D computer code AXCEL to obtain small enough angular divergence of the beam. It is worthwhile to note that increased thickness of accelerating electrode reduces negative biasing applied to the electrode required to repel the back streaming electrons.

The experimental results on the beam divergence and value of the 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. 4). Mass analysis of the 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 1.9 A beam. Similar results were obtained with spectrometric measurements of the beam species.

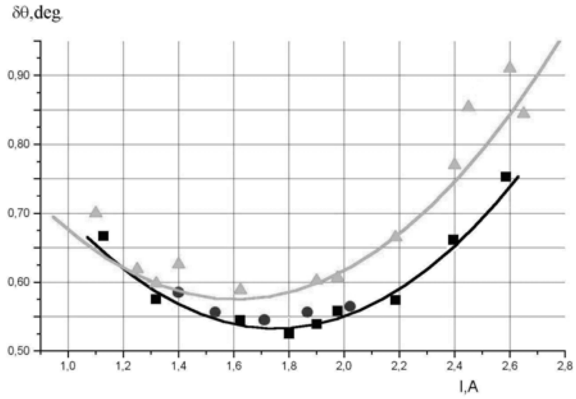

Fig. 4. Beam divergence vs. current for the extracting voltage 6.5 and 6.75 kV (upper curve). Circles represent calorimetric data, triangles and rectangles represent secondary emission detectors data

To provide a beam for active beam emission spectroscopy measurements in large stellarator W-7X the diagnostic neutral beam injector RUDI-X is being developed. The RUDI-X beam will have an energy 60 keV, equivalent beam current (for hydrogen) up to 5 A, and pulse duration of up to 10 s. In the RUDI-X ion source the plasma emitter is produced by RF-discharge and the ion beam with 190 mm initial diameter is formed by four-electrode multi-slit ion optical system[6] with beam focusing. Use of slit-like apertures provides lower angular divergence in the direction along the slits because in this direction there are no electric field components that may contribute to the increase of beam angular spread due to aberrations. Among other advantages of the slit electrode geometry are higher transparency and simpler arrangement of the water cooling channels. Each grid of the ion optical system consists of three plates made of Cu-Cr alloy and is intensively cooled by water flowing through channels located at both sides of the plates. The slit apertures in the plates are 60 mm long and 4 mm wide. The slits are arranged with 5 mm step. Ends of the slits are rounded with 2 mm radius. In experimental studies of beam formation in single slit ion optical system angular beam divergences of 0.53 degree across the slit and 0.35 degree along it were measured. The experimental results on beam formation are in agreement with 3D simulations by the KOBRA-INP code. Presently, experimental tests of ion beam formation by the RUDI-X ion source are conducted.

III. HEATING FOCUSED NEUTRAL BEAM

As it was previously mentioned, application of focused neutral beams for plasma heating is very attractive. It allows to inject higher beam power through narrow ports and/or provides a highly localized power deposition in plasma. For this purpose, injector of focused neutral beam[7] with power appropriate for plasma heating was developed. The injector beamline is shown in Fig.1. It includes a neutralizer, calorimeters, an ion deflection magnet, residual ion dumps, pumps, and beam diagnostics, all of it housed inside a rectangular vacuum tank. A beamline neutralization duct serves to convert the primary ion beam into the atomic one. The neutralizing gas is partly supplied into the duct from the discharge chamber, the rest amount is puffed into the duct through a manifold by a separate pulse gas valve. Each vaccum cryo-pump installed on the top of the injector tank has a nominal hydrogen pumping speed of $80 \cdot 10^3$ l/s in molecular flow regime. The injector was designed to be operated at an energy up to 40 keV, equivalent beam current (for hydrogen) of up to 40 A, and pulse duration of up to 1 s.

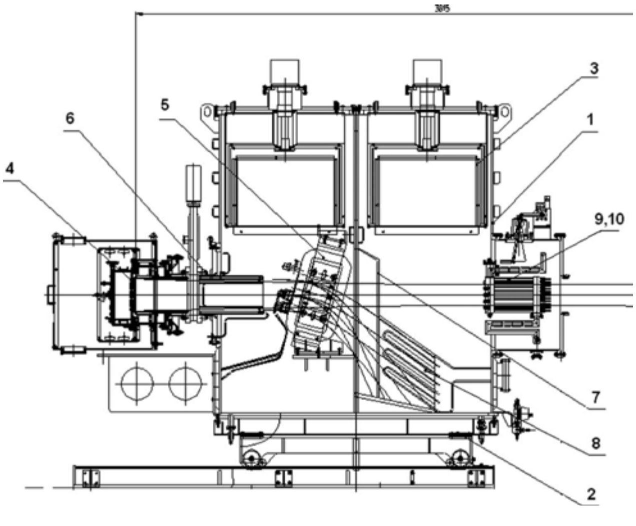

Fig. 5. General view of the neutral beam injector: 1 – rectangular vacuum tank, 2 – beam supporting block, 3 – cryopump, 4 – ion source, 5 – ion deflecting magnet, 6 – neutralizer, 7 – diaphragm, 8 – residual ion dump, 9 and 10 – aiming device, moveable calorimeter.

The nominal current density of 360 mA/cm^2 was chosen for the ion source. The plasma emitter in the ion source is produced by an inductively excited RF-discharge with external antenna. The multi-turn antenna couples up to 50 kW of RF power to the plasma at 4.6 MHz frequency. With 45 kW of RF-power absorbed in the plasma, the source delivers an ion current of 45A (hydrogen).

In the ion optical system, there is a set of three nested grids with circular apertures. In order to focus the beam on to the desired point inside the plasma, the grids are formed to be spherical segments. Each grid has its own curvature radius, so that the gaps between the grids vary with radius in order to compensate the radial plasma non-uniformity in the plasma box. The focal length of the ion optical system is 3.4 m. The accelerating and grounding grids are made of copper. The plasma grid is made of molybdenum and has special cuts at periphery to decrease thermomechanical tensions during beam formation. The geometry of the elementary cell was optimized to obtain appropriate angular divergence of the beam. Calculated ion trajectories and equipotential lines are shown in Fig. 6. Special Pierce-like trim is introduced at the periphery of the plasma grid to compensate the radial fields generated by the space charge.

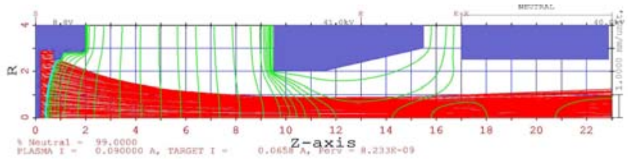

Fig. 6. Plot of ion trajectories and equipotential lines in elementary cell.

The ion species content of the RF plasma source was measured by Doppler shift spectroscopy of shifted H_α line (Fig. 7). Typical ion species mix consists of 70%, 20%, and 10% for ions H^+, H_2^{+} $^+$, and H_3^+ respectively. Special vacuum procedures allow decreasing heavy impurities, generally CH and OH, down to 0.3% by current.

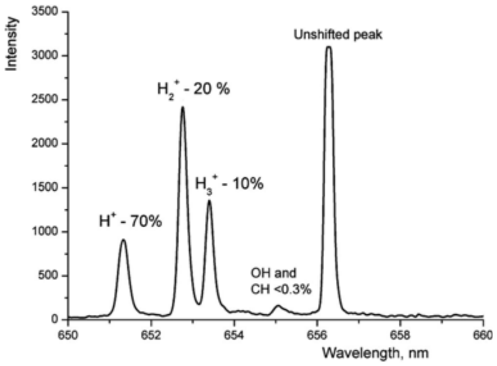

Fig. 7. Doppler shifted H_α peaks for 40 kV neutral beam.

IV. STEADY STATE REGIME

The developed injectors, in principle, can be operated in steady state regime after some modifications in the design. The RF-plasma boxes allow to significantly increase the pulse duration without considerable changes. The thermal loads to walls of the plasma boxes are moderate and can be removed by edge cooling in continuous regimes. A version of the washer-stack discharge channel of the arc plasma generator for operation in extended pulse regime is developed. The washers are soldered to ceramic spacers thus forming a unit with intensive water cooling of the washers at periphery. The beam duration is now limited by overheating of the grids of the ion optical system. Introduction of the cooling channels into the grid body can significantly mitigate this problem. Other components of the injectors such as neutralizer, cryo-pumps, bending magnets, beam dumps can be operated in steady state regime without significant problems.

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