Development of radial neutral beam injection system on LHD

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A radial Neutral Beam Injector (NBI) is newly installed on the Large Helical Device (LHD). The aims of the NBI are its usage as a diagnostic NB for charge exchange recombination spectroscopic measurement and using the NB as a heating source for ions in plasmas. A new positive-ion source was developed for this NBI at NIFS. The structure of the cusp field of the source was determined by the numerical code and its performances were verified by experiments. The performances of the developed source fulfill its specification. Especially, the maximum beam current of 102[A] exceeds the requirement of 75[A] about 33[%].

Keywords: NBI, large positive ion sources, radial beam injection

1. Introduction

A positive-ion based Neutral Beam Injector (NBI) is newly installed on the Large Helical Device (LHD). The major purposes of installing this NB on LHD are; (1) to provide a tool for ion temperature profile measurement and for electric field profile measurement by using this NB as a diagnostic beam for Charge eXchange Recombination Spectroscopic (CXRS) measurement, (2) to achieve the high ion temperature regime on LHD by producing peaked density profiles with central beam fueling and by an intensive ion heating with low energy and high power beam, and (3) to use this NB as a probe beam for investigating the confinement property of perpendicular fast ions on LHD.

In this article, we will show our research and development results for the new positive ion-source for the radial NBI. In designing the ion-source, the thickness of a plasma-electrode, which is an electrode facing to the ion-source plasma, was the most important issue since it significantly affects the optics of extracted ion-beam. Considering the beam-optics, the thickness of the electrode is preferred to be as thin as possible. But, in the actual case, the electrode needs to have finite, i.e., non-zero, thickness so that it can have enough strength to avoid the distortion by the gravity and by thermal heat loads. The required thickness depends on the heat loads onto the electrode, and also on the material and cooling structure of it.

The arc-efficiency is also an important parameter of ion-sources, where the efficiency is defined by the ratio of extracted beam current to the required arc-power in sustaining ions-source plasmas. Since the heat load onto a plasma electrode can be considered to be proportional to the arc-power, the increase of the arc-efficiency will reduce the heat load onto the electrode. Thus, achievement of high arc-efficiency will help to reduce the thickness of a plasma electrode.

The specification of the radial-NBI on LHD and its ion-sources are briefly discussed in Sec.2. The design of cusp-field configuration for the ion-source is shown in Sec.3. The determination of its plasma-electrode thickness is shown in Sec.4. The operation of the source at the NBI are shown in Sec.5. The section 6 is a summary.

2. Specification of the radial-NBI and its ion-sources

Figure 1 shows the schematic drawing of the radial-NBI on LHD. Its specifications are shown in Table 1. As shown in this table, the required performances on the ion-source is almost comparable to those of the giant positive ion sources for NBI [1-3].

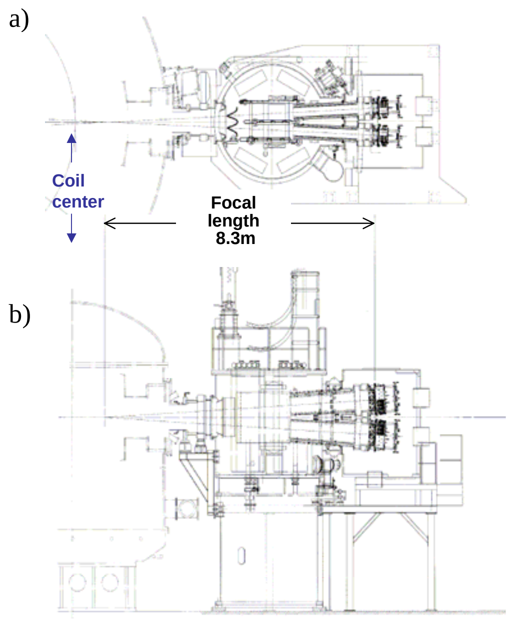

Fig.1 Schematic drawing of the radial-NBI on LHD. (a) Top-view and (b) side –view.

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Table 1 Specification of LHD radial-NBI

Beam species	Hydrogen
Injection energy	40 [keV]
Total Injection power	6 [MW]
Beam pulse duration	10 [s]
Injection port-size	ϕ 0.8[m]
Size of NB-protection armor at the injection counter wall	(W)1[m] x (H)1 [m]
Focal length and pivot length of ion-sources	8.3[m]
Type of ion source	Positive ion-source
Electrode system	Accele-decel-ground electrodes system.
Number of ion sources	4
Beam current required for single ion source	75[A]
Beam extraction area	(W)0.21[m] x (H)0.5 [m]
Transparency of the electrode	35[%]

The injection energy was chosen to be 40-keV with Hydrogen beam ion species. This energy was determined by the requirement of CXRS measurement. To have enough penetration of NB into the core-region of LHD plasmas, the beam was injected radially to the LHD torus, thus the injected fast ions has its kinetic energy mostly on the perpendicular direction to the magnetic-field lines.

One of the largest limitations in designing a radial-NB injector on LHD is the small-protection area of its injection counter wall and the limitation on the size of injection-port. The former limitation comes from the fact that there is no enough space left in the inboard side of LHD vacuum vessel to install protection armor tiles

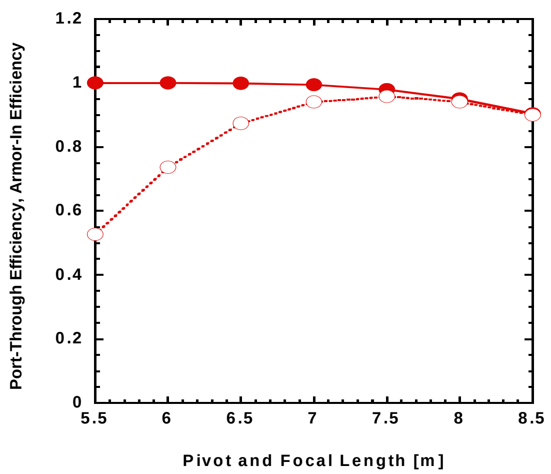

Fig.2 Calculated port-through efficiency (solid lines with closed circles) and armor-in efficiency (dashed lines with open circles)of the radial-NB.

with cooling structures at the toroidal section where plasmas are vertically elongated. At this location, the vacuum vessel walls, which cover the helical coils, significantly project to the LHD-plasma. Therefore, it is very important to consider the injectors's configuration which maximize the armor-in efficiency as well as port-through efficiency. Here, armor-in efficiency is defined by the ratio of the beam power which goes into the inside of the protection armor plates to the total neutral beam power. The pivot-length and focal-length of the ion-sources were determined to maximize the armor-in efficiencies and to minimize the difference of these two efficiencies, simultaneously. It was found that the focal length is better to be equal to the pivot length of the ion-sources to maximize the armor-in efficiency. From Fig.2, the pivot and focal length of 8[m] is determined to be the best, but they were set to 8.3[m] at the final design to avoid the interference with the diagnostic ports for CXRS-measurements.

3. Design of an arc-chamber of the ion-source for the radial-NBI

Several structures of cusp magnetic-field were surveyed for the ion-source of the radial-NBI using a code developed by Tsumori. *et.al.*[4,5]. Among them, two of the configurations were chosen as candidates for the ion-source. The calculated distributions of cusp field lines and those of primary electrons from filaments are shown in Fig.3. The calculation shows that type-A configuration has better confinement than type-B, i.e., the 63% of electrons launched from filament locations are confined for type-A, while only 15% are confined for type-B. On the other hand, type-B configuration has more electrons in the region close to the plasma electrode and better uniformity in this region than type-A as shown in Fig.3(c) and (d).

A series of experiments to compare the arc-efficiencies of these two configurations was performed at NIFS-NBI test-stand since it was very difficult to determine which cusp configurations are better in the efficiency just from the simple orbit calculations. The arc-efficiency of 0.44[A/kW] were obtained for type-A configuration, while that of 0.35[A/kW] are for type-B as shown in Fig.4. We must note that the half of the plasma-electrode was masked to limit the beam current in these experiments since the acceleration power supply at the test-stand can only handle the beam current of 40[A]. Thus, the arc-efficiencies in the test-stand experiment became about a half of those for non-masked configuration. No significant differences were observed on beam-profiles between the two cusp configurations. It was confirmed by experiments that the confinement of primary electrons was more important than the uniformity and the numbers

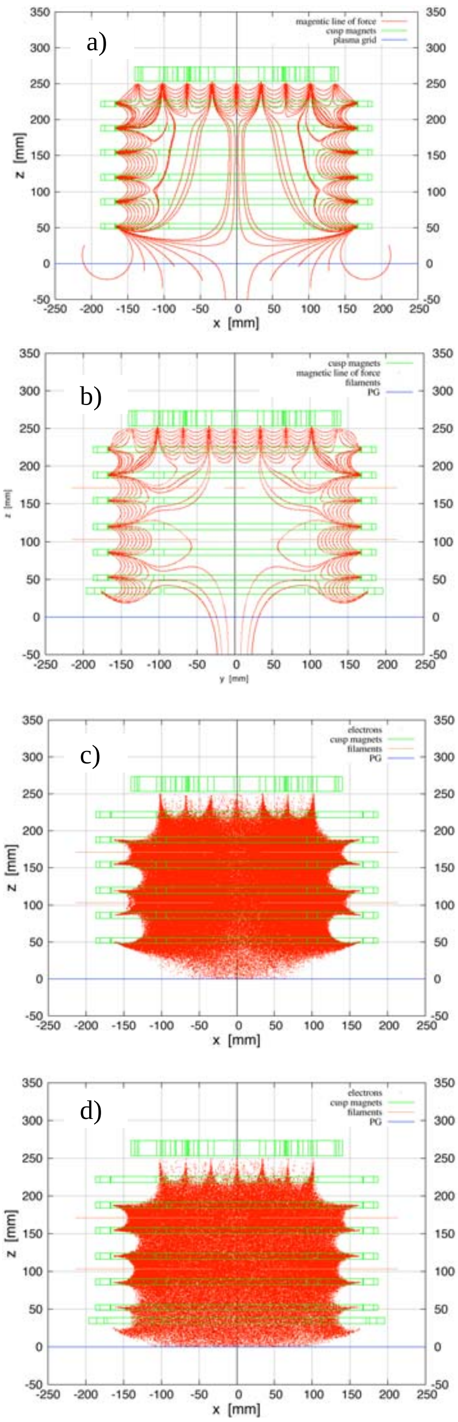

Fig. 3 Calculated magnetic filed lines for (a)type-A and (b)type-B cusp configurations. Magnetic field lines are shown by red lines and the location of permanent magnets are by green lines in these figures. Primary electron distribution are shown by red-dots in (c)type-A and (d)type-B. The z=0 lines show the location of plasma electrode.

of them in the region near plasma electrode by the experiment. Thus, the type-A configuration is adopted as the cusp configuration of the ion sources for the radial NBI.

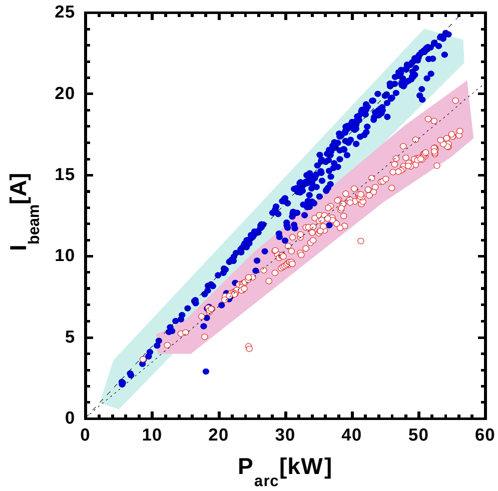

Fig.4 The comparison of arc-efficiency for type-A (closed-blue-circles) and type-B (open-red-circles) cusp configurations.

4. Determination of plasma electrode thickness of the ion-source for the radial-NBI

As a plasma electrode of the ion-source, we have adopted a oxygen-free copper electrode with water-cooling channels which is placed to each raw of beam extraction holes. The thickness of the electrode is required to be greater than 4-mm from the view point of mechanical strength and heat load handling, while this is to be less than 3.3-mm from the view point of beam-optics. To overcome the conflict, experiments of beam extraction using electrodes of both thicknesses were also performed at the NBI test-stand. For these two electrodes, the perveances, which express the beam currents normalized by acceleration voltages according to

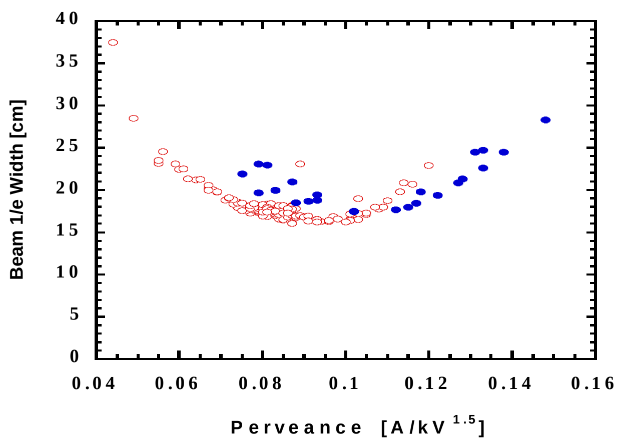

Fig.5 Perveance dependence of beam profile width. The beam widths for a 4-mm thick plasma-electrode are shown by the open-red-circles, while those for a 3.3-mm thick electrode are by closed-blue-circles.

the Child-Langmuir law, were scanned to find their optimum value where the beam widths have their minimum in the experiments (Fig.5). The distance of the gap between a plasma-electrode and a decel-electrode was 6.5[mm] at the experiments for the 3.3[mm] thick electrode, and was 6[mm] at those for 4[mm] thick one. As shown in Fig.5, the optimum perveance for the electrode of 3.3[mm] thickness is larger than that for the 4[mm] thickness. Thus, the electrode of 3.3[mm] thickness has preferable feature, as is expected. Taking the gap(d_{gap}) dependence of the Child-Langmuir law, where the beam current is proportional to d_{gap}^{-2}, into an account, this tendency becomes more significant.

The distortion of plasma-electrode by the heat loads can be evaluated by the change of beam profile with the heat loads. The dependence of beam widths on the heat loads of the plasma electrode are shown for the 3.3[mm] thick electrode in Fig.6. The heat loads were measured by a water calorie-metric method using the cooling water of the electrode. Scan of the heat loads are done by changing the duration time of arc-discharges preceding with the beam extraction. These heat loads in the figure correspond to the beam duration time of 0.3[s] to 4[s]. To minimize the dependence of beam widths on perveances, beams are extracted at around the optimum perveance condition. As shown in Fig.6, the dependence of beam widths on the heat loads are almost negligible. Therefore, it was concluded from these experiments that the 3.3[mm] is thick enough as a plasma-electrode of the ion-source.

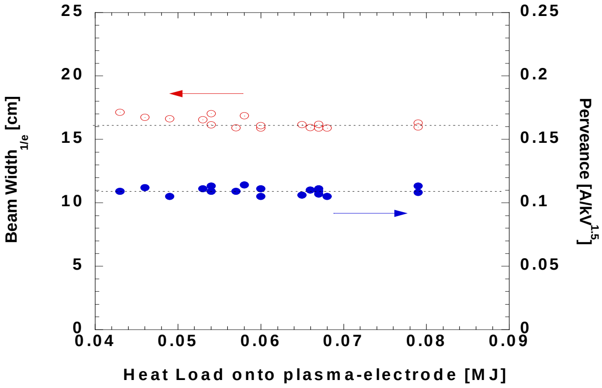

Fig.6 Dependence of beam widths on the heat loads of plasma-electrode. The beam widths are shown by open-red-circles, the perveances of the beam are also shown by closed-blue-circles.

5. Operation of ion-source at the radial-NBI

The acceleration power supply of the radial-NBI is designed to operate two ion-sources with single power supply. With the operatin of single ion-source with this power supply, the maximum beam current can be evaluated (Fig.7). The arc-efficiency of the source was 0.78[A/kW] in thses experiments. The maximum beam current of 102[A] was achieved at the acceleration voltage of 40[kV]. The averaged current density exceeds 250[mA/cm^2] with this maximum beam current. The maximum of the current was limited by the operational limit of arc-discharge, i.e., arc-discharges of the ion-source became unstable when the arc-power exceeded 120[kW]. The optimum perveance was examined using the calorie-meter array in the injector. It was 0.28[A/kV$^{1.5}$] when the gap distance (d_{gap}) was set to 5.5[mm]. The total injection power of 7.2[MW] was achieved with simultaneous four ion-sources operation.

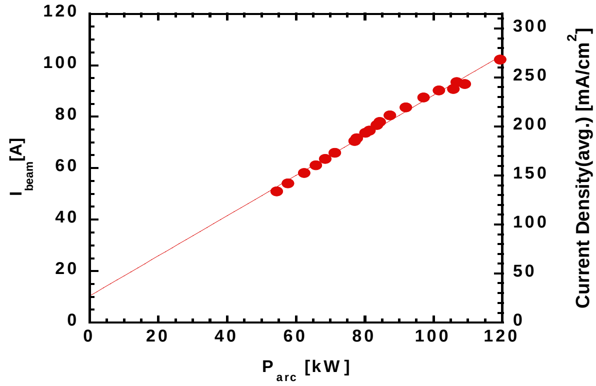

Fig.7 Arc-discharge power dependence of extracted beam current of the source at the radial-NBI.

6. Summary

A radial-NBI using positive ion-sources was installed and is successfully operated on LHD. To fulfill the specifications of the NBI, a giant positive ion source was newly developed at NIFS. The performances of the developed source fulfill its specification. Especially, the maximum beam current of 102[A] exceeds the requirement of 75[A] about 33[%].

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