Status of Negative-Ion-Based Neutral Beam Injectors in LHD

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Recent progress in LHD N-NBI system is described. The system was designed to provide 15 MW of port-through beam power by three beam lines (BL-1 to BL-3) with 180 keV hydrogen for 10 sec. However, starting from 3.2 MW injection by two beam lines, the performance has not satisfied all its specifications at the same time yet. This is because several difficulties were found in large negative ion sources although the specifications were determined based on the R&D results of small ion sources. Hence, the continuous efforts have been done to improve the performance of negative ion source, and the injection power has been increased year by year, and in the latest LHD experimental campaign total port-through power of 13.1 MW was achieved, where R&D on the ion source of BL-1 has been succeeded. Two improvements have been done on the ion source of BL-1. One is the optimization of magnetic cusp structure by modifying the shape of plasma source, which increased the negative ion current. The other is the adoption of multi-slot aperture for the grounded grid, which reduces the conditioning time of the accelerator dramatically. As a result, the specifications of beam energy and port-through power were satisfied in BL-1. The remaining problem is a pulse length which is still limited due to high heat load on the grounded grid.

1. INTRODUCTION

The neutral beam injector (NBI) for the Large Helical Device (LHD) is the first negative-ion-based NBI (N–NBI) system that was constructed as a main plasma heating facility in helical systems [1]. Because tangential beam injection is necessary and the required beam energy is so high as 180 keV for hydrogen that it is possible to construct a system only by using negative ions. No conventional positive-ion based NBI has been adopted in LHD. Therefore high reliability is required as well as available power for N-NBI system in LHD, although negative ion technology has not been matured yet. Since LHD is designed to confine net current free plasma, more than one beam line is required to balance the direction of beam to compensate the induced current. Actually in LHD, an interlock system is constructed to quit the beam injection when the plasma current exceeds an upper limit. It is the difference from JT-60U tokamak which also has introduced an N–NBI facility specified for prince of proof experiments on beam induced current drive [2]. The NBI system in LHD has three beam lines, and each beam line was designed to deliver 180 keV, 5 MW, 10 s neutral beam into LHD by two high efficient cesium seeded negative ion sources with an external magnetic filter. This negative ion source had been developed at NIFS [3]. The construction of the injection system began in 1996 [4], and the injection experiments started in 1998.

Although the high energy NBI heats mostly plasma electrons, it has revealed an excellent heating performance in LHD as in other small helical devices where about half of beam power goes to ions directly from the beam [5]. In LHD, NBI has also shown its other potentials than plasma heating, that is, the plasma initiation [6], and the control of rotational transform by its inducing current [7]. Among them, the beam plasma production is a unique and a very reliable method in LHD. It works even under the low confining magnetic field strength, and high beta plasma studies has been made remarkable progress owing to this method [8]. Therefore tangential high energy NBI now becomes the most useful auxiliary tool to initiate, heat and control plasma in LHD.

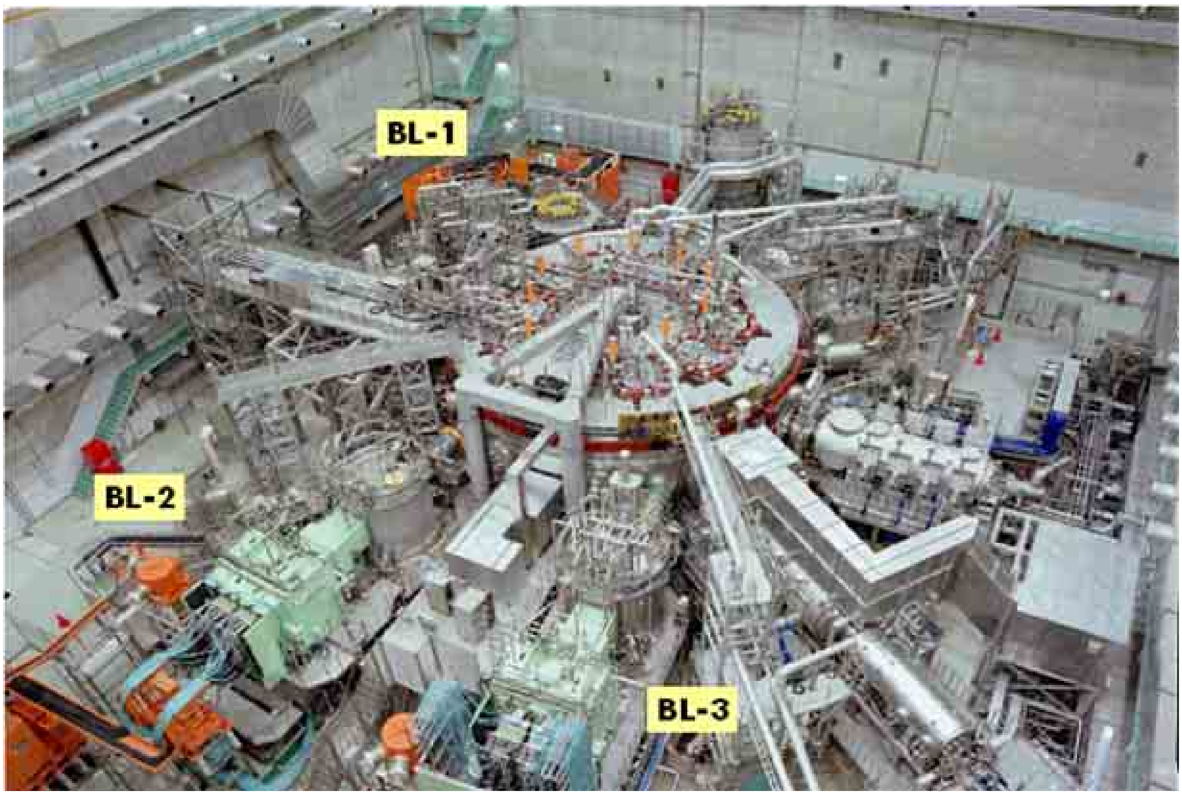


Fig. 1 A bird's-eye view of LHD experimental hall. Three tangential beam lines are installed.

2. **PRESENT STATUS OF LHD N-NBI**

The neutral beam injection experiments started in 1998 with 2 MW of port-through power by two ion sources with beam energy of 100 keV. Because the operation of large ion source still had several technical problems, the achieved injection power was far from its design value. Therefore, the efforts of improving the performance of negative ion source have been carried out even after the beam injection experiments started. LHD usually has a six-month-long experimental campaign in every year, and the improvement of negative ion sources and other components were carried out during the off-machine time. As a result, the performance of NBI has been improved year by year. The progress of the total injected port-through power and those achieved in each beam line are summarized in Table I. It can be said that negative ion beam technology has been established at the same level of conventional positive ion technology such as handling 100keV, 10MW beam [9]. A big achievement in the latest experimental campaign is that one of the specifications (port-through power) has been achieved at the beam line #1. Here, the port-through power is evaluated based on the measurement of heat load on the armor plate located in the vacuum vessel of LHD. The measurements are done in the presence of magnetic field of LHD, and therefore both the geometrical loss and the re-ionization loss of the beam in the drift duct are expelled from the evaluation. We believe that the evaluation of port-through power in LHD is most accurate among other NBI systems in the world [10 The injection power efficiency (the ratio of the injected port-through power to the input electric power) is around 0.35. The highest averaged negative ion current density is 30 mA/cm^2 over beam extracting area. Although the specific pulse length is 10 seconds, it is able to be extended at low beam power. Stable long pulse discharges were obtained by NBI in LHD [11. So far the maximum length of 110 s was achieved, which was limited by other reason. Long pulse discharge

Table I Progress of achieved port-through power

Year	Beam line #1	Beam line #2	Beam line #3	Maximum Total Power
1998	2MW / 100keV / 2s	2MW /100keV / 2s 0.6MW / 66keV / 20s	-	3.7 MW
1999	2MW / 133keV / 2s	3.1MW /164keV / 2s 0.5MW / 100keV / 80s	-	4.5 MW
2000	3MW / 152keV / 2s	3.6MW /166keV / 2s 0.8MW / 86keV / 64s	-	5.2 MW
2001	3.5MW / 165keV / 2s 1.1MW / 104keV / 10s	3.6MW /166keV / 2s 0.8MW / 86keV / 64s	3.3MW /165keV / 2s 0.1MW* / 81keV / 110s	9.0 MW
2002	4.4MW / 180keV / 2s	2.9MW /162keV / 2s	3.7MW /165keV / 2s	10.3 MW
2003	5.7MW / 183keV / 1.6s	4.1MW /181keV / 1s	3.9MW /174keV / 1s	13.1 MW

* *one ion source*

Figure 2 shows a history of injected port-through power for three beam lines in the latest experimental campaign. Although the beam conditioning precedes the LHD experiment, the beam pulse length is limited by the calorimeter and is not long enough for plasma experiments. Therefore the long pulse beam conditioning is only possible by using LHD plasma as a target. This is why the port through power increases gradually as the beam shot seen in the figure. It is noted that the beam is injected in every three minutes in LHD, which is possible because LHD is super conducting machine and the duty of plasma shot is determined by heating devices. This interval (3 min) is good for operating negative ion source because the temperature of plasma grid should be kept high for efficient negative ion production, and the arc discharge power is utilized to rise the grid temperature in our ion source. On the other hand, a large amount of shots of this high repetitive operation is hard for cathode life. Due to high current arc discharge of the ion source, the filament cathode does not last throughout the experimental campaign. Then the arc chamber must be open to air for exchanging cathodes during the campaign. This opening affects the high voltage withstanding of grids, and the additional beam conditioning will be needed. This is the reason why the maximum injection power is usually attained at the last phase of the experimental campaign.

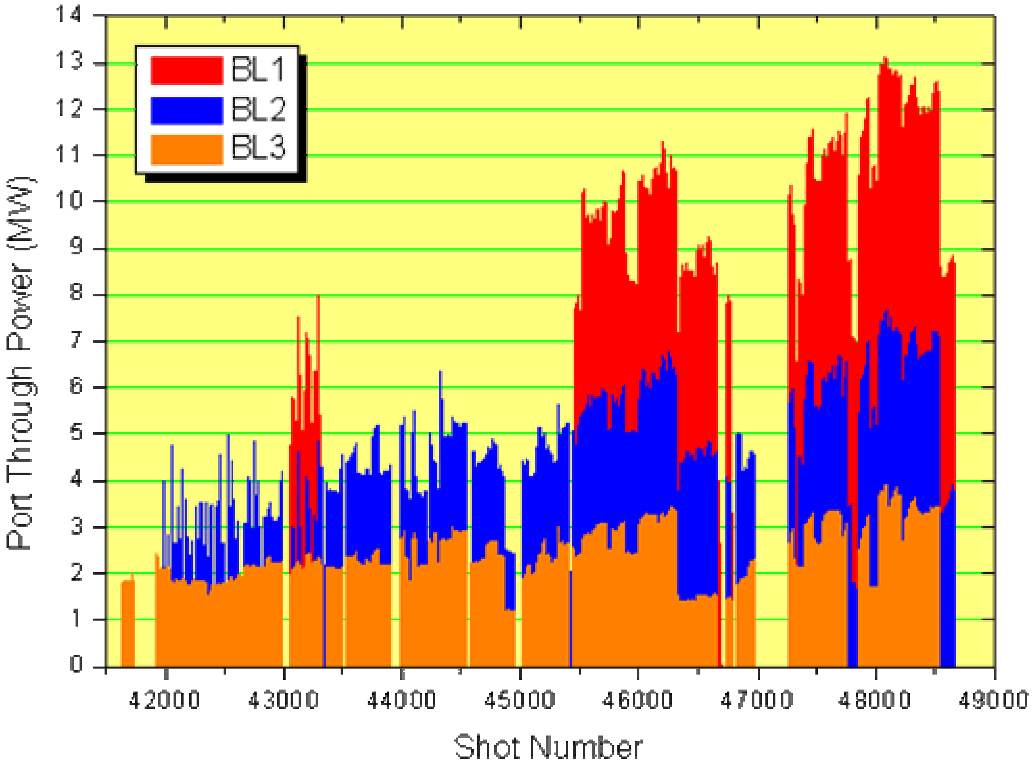


Fig.2 History of injected port-through power in the seventh experimental campaign of LHD. The distribution of three beam lines is shown by different colors.

Unfortunately, the beam line #1 suffered several troubles in this campaign, and the operation period was short compared with other two beam lines. Nevertheless the highest performance was achieved successfully in this beam line as can be seen in fig.3 (a), because a large modification had been done in the ion sources of this beam line, the detail of which will be described in the next section. There are two reasons for achieving high power. One is to attain the specific beam energy (180 keV) quickly and to maintain its level stably (fig. 3(b)). Usually it takes long time (many shots) to increase the beam energy by conditioning. The new ion source of beam line #1 has solved this problem by adopting a new accelerator grid system. The other is to get high negative ion current (fig. 3 (c)). The new ion source has also succeeded to improve the efficiency of negative ion production.

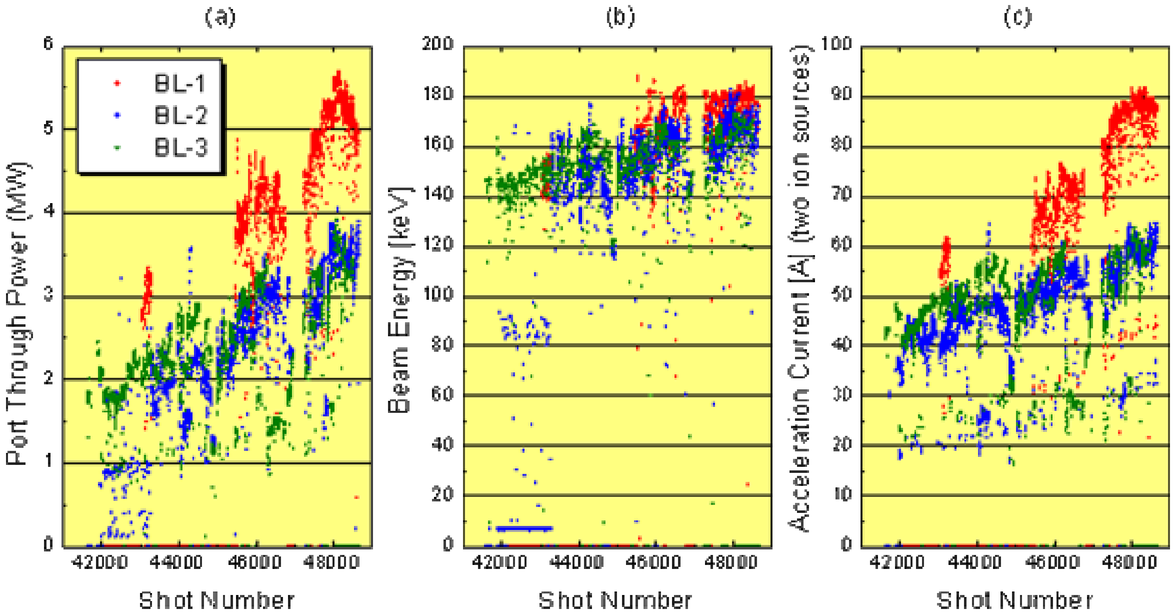


Fig.3 History of injected port-through power, beam energy and acceleration current of each beam line. Two ion sources are operated by single acceleration power supply in each beam line.

Although the designed value is 10 seconds, the practical pulse length is limited by the heat load on the grounded grid. So far, the extracted electrons are suppressed well by the magnetic filter and the electron suppression magnet in the extraction grids. The amount of extracted electrons is smaller than that of negative ions, and the heat load on the extraction grid is in the tolerable level. On the other hand, the heat load on the grounded grid is about 15% of acceleration power, which is very high. We limited the pulse length by monitoring the temperature increase of outlet cooling water of grounded grid, and the typical pulse length is 2 s for maximum beam power (5 MW / ion source) and therefore 10 s for 1 MW / ion source. (see fig. 4) When the beam power is reduced to 0.5 MW, the cooling capacity becomes higher than input power and the ion source can be operated in steady state. The power supplies and the cryo-sorption pumps of NBI can operate 30 minutes continuously at this low beam power, but the remaining problem for long pulse beam injection is that the cooling capacity of the inner wall protector of drift tube is small. As a fact, the temperature of this molybdenum protector plates continued increasing during a beam injection.

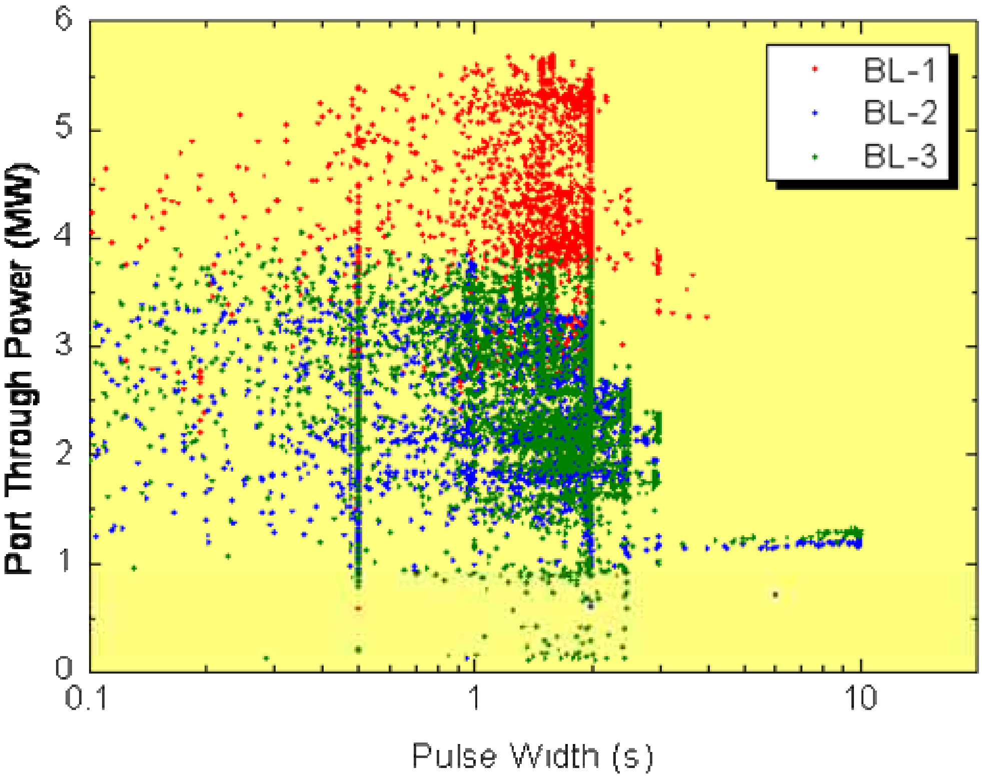


Fig. 4 Port-through power vs. Pulse length for each beam line in the last campaign. Typical pulse length is 2 s. The maximum pulse length is limited by power, which comes from the heat load on the grounded grid, hence it depends on the injection power.

3. IMPROVEMENT OF NEGATIVE ION SOURCE

3.1. HIGH ENERGY BEAM ACCELERATION

Usually the voltage withstanding of the accelerator of ion source increases only after suffering many break downs during beam acceleration. It takes more times when the beam energy becomes high. Although the current density of negative ion source is much lower than that of positive ion source, it still needs many shots for conditioning. One reason is considered that the number of beam extraction halls is large. Our ion source has a beam extraction area of 25 cm by 125 cm, and has about 900 extraction holes. If the break down occurs due to the interference of the beam with the peripheral of grid hole, the more conditioning shots is required when the number of holes increases, because the beam is ceased very quickly when the interlock of power supply finds voltage break down at even one hole. Considering that break down itself conditions the surface of the peripheral of the hole, other holes are not conditioned in this shot. The other reason of occurrence of many break downs may attribute to the spatial non-uniformity of negative ion current density over the grid, because the optimum perveance does not much all over the beam extracting area in this case.

Then the two ways to shorten the conditioning process are considered; one is to reduce the area of interference between the beam and the grid, and the other is to improve the spatial uniformity of the negative ion production. The latter is also important to increase the total beam current. In the design of new accelerator of beam line #1, the former was considered, and the conclusion was to adopt multi-slot rather than multi-holes for grounded grid (fig. 5). It was also expected to reduce the heat load on the grounded grid by the beam (electrons, ions and neutrals). The result was remarkable. The conditioning time reduced much, and the designed beam energy was obtained very quickly even though it was the first achievement of designed beam energy [12]. It is also noted that the heat load on the grounded grid reduced to about a half of multi-aperture grid, which is consistent with the increase of transparency of the grid aperture.

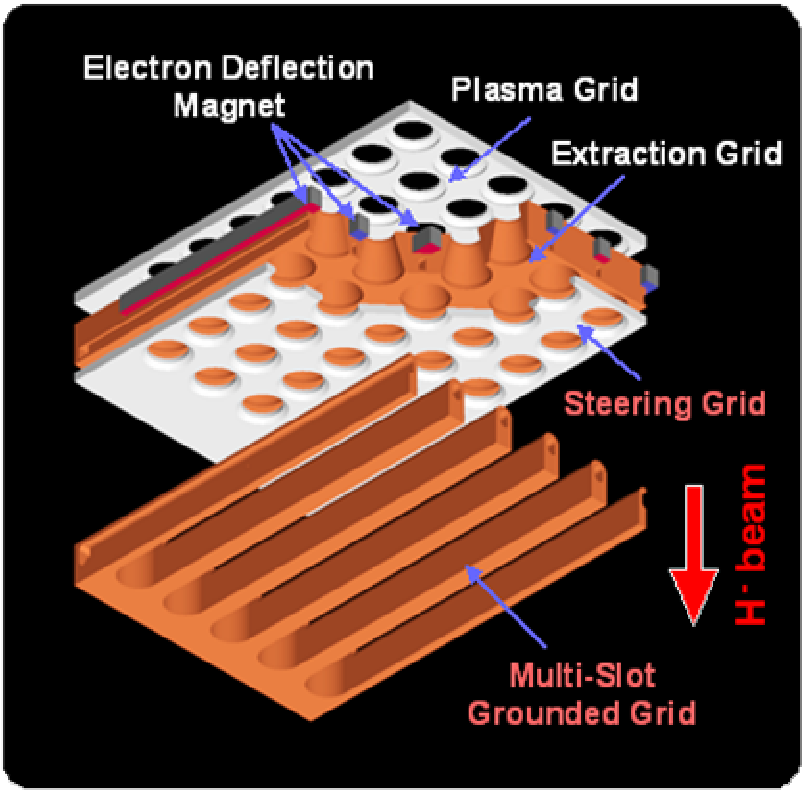
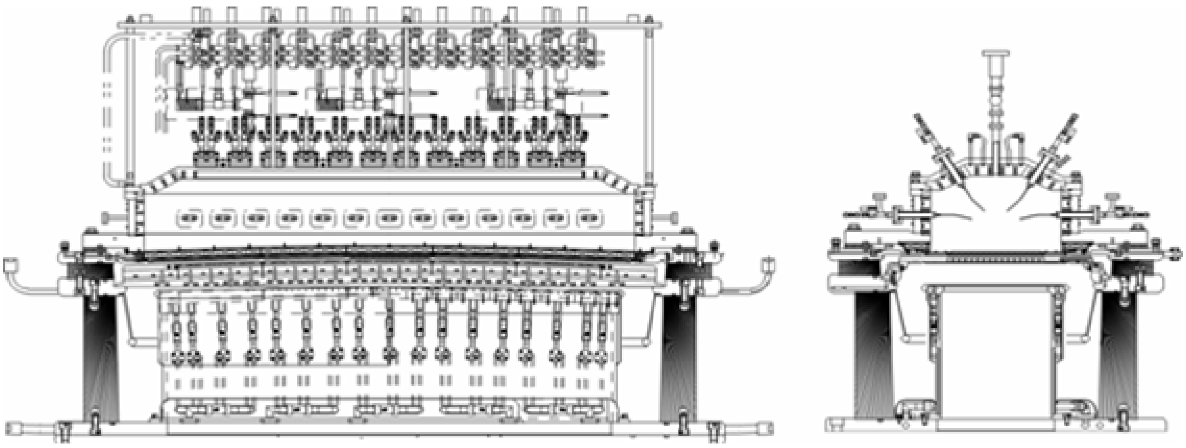


Fig. 5 A schematic drawing of new grid system with multi-slot grounded grid.

The other interesting experimental result was observed recently in the beam line #2. We are carrying out different R&D's in different beam lines. In the beam line #2, new plasma grids were introduced, which were designed to cool the grid more firmly and uniformly. The objective of these grids is to keep grid temperature at the optimum value during a long pulse operation. When these new plasma grids were installed and started testing, an unexpected result was obtained that the conditioning time was apparently reduced. It is considered that the distributed cooling channel becomes a reservoir of cesium which helps to improve the spatial uniformity of negative ion production. A uniform negative ion density makes the optical condition good widely over the beam extracting area.

3.2. HIGH EFFICIENT NEGATIVE ION PRODUCTION

The efficient negative ion production depends on the cesium condition in the arc discharge. The amount of cesium and the temperature of plasma grid are the key issues of controlling the efficiency. In our ion sources, the injection of cesium is done slowly even during arc discharge. The total consumption of cesium is 9 g for one ion source throughout an experimental campaign where about 20,000 shots are operated including conditioning shots. The plasma grid temperature is also important. The optimum temperature is around 250 C at the corner of the grid. In our ion source, the plasma grids are heated by using the power of arc discharge, and the temperature is kept by insulating the grids from the water cooled support structure. The level of thermal insulation is delicate to determine the grid temperature because it should be as high as to raise the grid temperature during arc discharge, and should be as low as to be cooled between the shots. This method is not appropriate to the long pulse operation because the grid temperature increases during arc discharge and exceeds the optimum value. As for increasing the total ion current, the improvement of spatial non-uniformity is another issue. The arc chamber of beam line #1 was designed to fit the shape of its confining magnetic cusp structure to the magnetic filter field as shown in fig. 6, where the corners of the arc chamber were cut. However there still a thin plasma region at both ends of long direction. Two more filament cathodes were added in this direction and adjust arc current distribution. Then the total current increased about 15%, which directly contributed to increase the injection power.



(a) (b)

Fig.6 Cross sectional views of negative ion source of the beam line #1. The size of the arc chamber is 140 cm (L) x 35 cm (W) x 24 cm (H). The filaments at the back plates are spares. The accelerator adopted single stage acceleration, and the grid is divided into five segments along the long direction. Each segment is inclined toward the focal point 13 m downstream of the ion source.

3.3. BEAM DIVERGENCE

Good optics of negative ion beam can compensate the disadvantages of N-NBI such as its long beam line and needs of large ion source. In our negative ion source, beam divergence is around 10 mrad which assures a favorite port through efficiency of the beam. As described in the previous section, a new accelerator of the beam line #1 with multi-slot grounded grid has shown an excellent performance from the view point of beam conditioning and the heat load on the grid. However, an issue remains on beam optics.

In the conventional multi-aperture grid system, the holes of grounded grid are displaced systematically for beamlet steering and focusing, but it is not possible for the multi-slot grid to focus the beamlets in the direction parallel to the slot. In order to steer the beamlets in this direction, an extra grid was added downstream side of the extraction grid as shown in fig. 5. The electric potential of this extra grid (steering grid) is the same as that of extraction grid, and the holes of which are systematically displaced. Although the steering angle becomes more sensitive to the shift of hole at the steering grid compared with that at the grounded grid, that is, the more accuracy of manufacturing and assembling is required for steering grid, this technique works well.

Another problem is still remained. It is well known that the beam divergence depends on the current density, the extraction electric field strength and the acceleration electric field strength. After the optimum condition between the current density and the extraction field is determined and fixed, the beam divergence depends on the acceleration field and usually an optimum value exists. The problem is that the optimum optical conditions are different between the parallel and perpendicular directions along slot. The electric potential near the slot makes a strong fringe field across the direction of perpendicular to the slot and the electrostatic lens is formed. However, it is almost flat along the slot and no lens is formed in the direction parallel to the slot. Therefore the dependence on the acceleration field strength is considered to be weak in this direction. This situation is shown in fig.7. In the figure, the horizontal axis shows the ratio of the electric field of acceleration region to that of extraction region. The vertical axis shows the width of the beam profile measured at the calorimeter. The horizontal width indicated in the figure corresponds to the direction parallel to the slot of the grounded grid. It should be noted that the calorimeter is located at a half of the beam focal length, and the measured profile still reflects the size of the ion source. Therefore a large vertical width does not always mean that the beam divergence is large, although it is considered to be really large from the observation of heat load inside the drift tube. This caused the reduction of port through efficiency and the increased heat load damaged the drift duct in the last campaign.

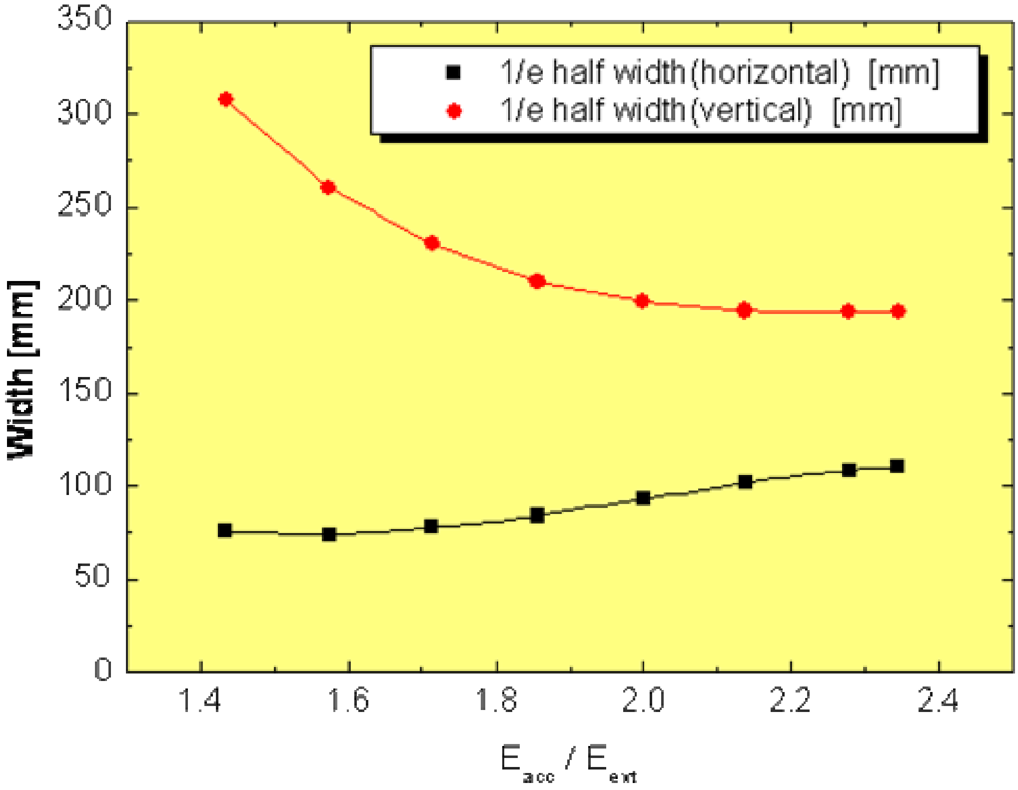


Fig. 7 Dependence of the width of measured beam profile on the calorimeter on the extraction and acceleration electric field ratio. The slots of grounded grid are lined up in the vertical direction.

4. FOR FURTHER IMPROVEMENT

The efforts on improving the performance of negative ion source still continue for the next experimental campaign which will start in September 2004. The mismatch of optimum electric field ratio owing to the multi-slot structure will be improved by modifying the shape of holes of beam steering grid. The availability of this method was confirmed using a 1/3 scale ion source at the test stand, and it is applied for full size ion sources of the beam line #1. If this method worked well in the next campaign, high power beam would be injected longer than 2 s, because the heat load on the grounded grid is small for the multi-slot structure. After confirming that the beam optics is improved, we will adopt a multi-slot grounded grid for other two beam lines.

A new plasma grid will also be applied for the ion sources of the beam line #2, the cooling of which has been reinforced for long pulse operation. As described in the previous section, more spatially uniform negative ion production is considered to be realized on the plasma grid. We expect that the best accelerator can be made by the combination of this plasma grid with cooling channel, the steering grid with deformed aperture, and the multi-slot grounded grid.

REFERENCES

[1] Mutoh, T., et al., "HEATING SYSTEMS OF LARGE SUPERCONDUCTING HELICAL DEVICE" Fusion Technology 1988, (1989) 552.

[2] Kuriyama, M., et al., "Development of Negative-Ion Based NBI System for JT-60U" J. of Nucl. Science and Technol., 35 (1998) 739.

[3] Takeiri, Y., et al., "Negative hydrogen ion source development for Large Helical Device neutral beam injector" Rev. Sci. Instrum. 71 (2000) 1225.

[4] Kaneko, O., et al., "Negative-Ion-Based neutral Beam Injector for the large helical Device" Fusion Energy 1996, (1997) 539.

[5] Komori, A., et al., “Recent results from the Large Helical Device”, Plasma Phys. Control. Fusion **45** (2003) 671.

[6] Keneko, O., et al., "Plasma startup by neutral beam injection in the large Helical Device", Nucl. Fusion 39 (1999) 1087.

[7] Ohyabu, N., et al., “Influence of Beam Flow on the Electron Transport in Low Density LHD Discharges”, 30th EPS Conference on Controlled Fusion and Plasma Physics, St.Ptetrsburg (2003).

[8] Sakakibara, S., et al., “Effect of MHD activities on pressure profile in high-beta plasmas of LHD”, Plasma Phys. Control. Fusion **44** (2002) A271.

[9] Kaneko, O., et al., “Engineering prospects of negative-ion-based neutral beam injection system from high power operation for the large helical device”, Nucl. Fusion **43** (2003) 692.

[10] Osakabe, M., et al., "In situ calibration of neutral beam port-through power and estimation of neutral beam deposition on LHD," Rev. Sci. Instrum., **72**, (2001) 590.

[11] Takeiri, Y., et al., “Plasma characteristics of long-pulse discharges heated by neutral beam injection in the Large Helical Device,” Plasma Phys. Control. Fusion, **42** (2000) 147.

[12] Tsumori, K., et.al., "High power beam injection using an improved negative ion source for the large helical device", Rev. Sci. Instrum **75** (2004) 1847.