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**Abstract.** It is a touchstone for the success of ITER and future fusion reactor whether the present high performance negative-ion-based NBI (N-NBI) heating systems work properly. The LHD and JT-60U are only two facilities where N-NBI systems are working for high power plasma heating / current drive in the world. Because handling of negative hydrogen / deuterium ions was amateur technology, it has taken a long time to improve its skill. In LHD, we succeeded in improving the performance of one of three beam lines dramatically in 2003 by adopting a multi-slot grounded grid for the accelerator of ion source. The effort on improving the performance was also done in other beam lines with conventional ion sources in parallel. The guidelines of improving are optimization of magnetic multi-cusp configuration for efficient negative ion production, and increasing the transparency of the grounded grid for reduction of heat load on it. As a result the available beam power has been increased, that is, successive injection power level more than 10MW became possible throughout four-month long experimental campaign, although the maximum injection power has been almost the same. The averaged negative ion beam current density at the exit of ion source, which was evaluated from the port-through injected power, was achieved up to 350A/m$^2$ which is larger than the required value of ITER NBI in hydrogen beam operation. Pulse length at high beam power level has also been extended owing to the reduction of heat load on the grounded grid. These results (increase in available power and pulse length) have contributed to expand the operation region of LHD. By continuous R&D, we also have found the way of solving an associated problem of multi-slot grounded grid system, that is, mismatched conditions of optimum beam optics in vertical and horizontal directions. According to this result, better beam divergence can be realized, and the increase in the total injection power is expected in the next experimental campaign.

## 1. Introduction

The successes of heating plasma by injecting high energy atomic beams and developing high power positive-ion-based NBI have led the recent evolution of magnetic fusion research. In order to use this reliable method in larger fusion devices, it is necessary to use negative ions in spite of positive ions due to their good neutralization efficiency. Therefore the effort has been concentrated on the development of high current negative hydrogen / deuterium ion source, and fortunately it was found to be feasible to extract order of ten ampere negative ions from the plasma source that was converted from the conventional positive ion source. Then the negative-ion-based neutral beam injector (N-NBI) has become one of key technologies for heating and current drive in ITER and fusion reactor. In order to judge its viability, it should be demonstrated that 10 MW scale N-NBI system is operating reliably.

The Large Helical Device (LHD) is the worlds' largest superconducting helical system, major and minor radii of which are 3.75m and 0.6m, respectively. The role of NBI in LHD is main heating power source of 15MW because NBI is the only successful method of producing high performance plasma in other helical systems and tokamaks. It must be N-NBI because the required beam energy is so high as 180 keV for hydrogen that an efficient system is only possible by using negative ions [1]. As a result, N-NBI of LHD has become one of two facilities that are serving for heating and/or driving current in the present working fusion experiment devices (LHD and JT-60U). Because N-NBI is main heating power source, the LHD cannot carry out experiments without it. Therefore high reliability is required as well as available power for N-NBI in LHD, although negative ion technology has not been matured yet. It is in different situation from N–NBI of JT-60U where the main power source is positive-ion-based NBI and N-NBI is specified for principle of proof experiments on current drive by using high energy (500 keV) beam injection [2]. Both systems had technological problems at first, and some of them were common in spite of different design. Through the working experiences, most of them have been solved and the performance of N-NBI system has been improved remarkably, although there still remain a few problems.

## 2. N-NBI of LHD

The N-NBI system in LHD has three beam lines, and each beam line is designed to deliver 180 keV, 5 MW, 10 sec hydrogen 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 through seven-year R&D [3]. The construction of the first beam line started in 1996 [4], and the beam injection experiments began in 1998. Since LHD is a superconducting device, the confining magnetic field exists throughout a day time. Then the repetition time of plasma shot is determined by NBI because its operating electric power is supplied by Fly-Wheel Motor Generator, and it is typically three minutes. Therefore the performance of NBI is required to be kept constant throughout 200 plasma shots in a day (note that there is no Ohmic heating coil in LHD).

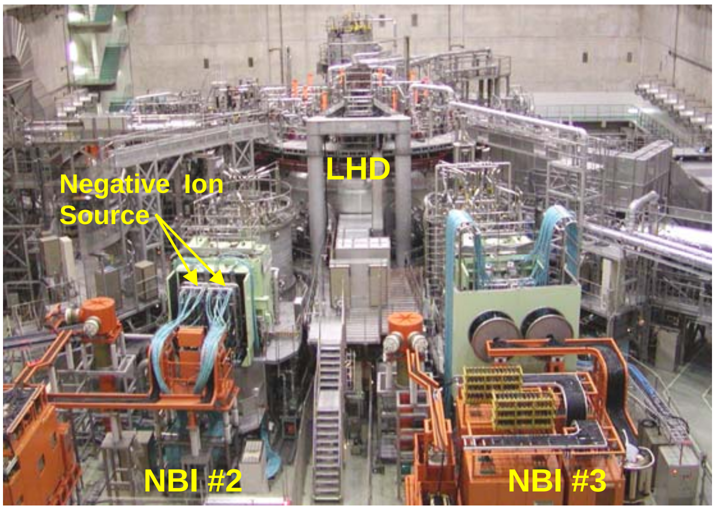



*FIG.1 Photo of N-NBI's of LHD. Green boxes are magnetic and X-ray shield for ion sources, and orange boxes are power supplies of plasma sources. NBI #1 is located behind LHD.*

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 a half of beam power goes to ions directly. In addition to this, NBI can initiate plasma [5], and beam induced current is utilized for changing rotational transform. Among these roles of NBI, the beam plasma production is a unique and a reliable method in LHD. It works even under the low confining magnetic field strength, and high beta plasma studies have been made remarkable progress owing to this method. Therefore tangential high energy NBI now becomes the most useful auxiliary tool to initiate, to heat and to control plasma in LHD. Then again, the reliability of NBI became more important. An experimental campaign of LHD usually starts in October and ends in February. About 10,000 shots are injected during this period, and it is not easy to keep the best condition of three beam lines. So far, all the designed values of NBI have not yet achieved at the same time, and therefore the ion source is continued to be modified during the maintenance period (March to September) to improve its performance after the experiences of operating in the latest campaign. Actually these efforts are rewarded by increase in the injection power. In FIG.2, The trends of injection power (port through power into LHD) and achieved beam energy are shown for three beam lines. The power of beam line #1 (BL-1) is higher than other two beam lines because it adopted new type ion sources. It is noted that beam line #3 (BL-3) was added in 2001.

### 3. Successive High Power Injection

Figure 2 shows the history of achieved input power and beam energy during each experimental campaign after the NB injection started in LHD. Here, the injection power is evaluated as "port-through" power by measuring the distribution of heat load on the beam armor plate inside the vacuum chamber of LHD in the case of injection beam into vacuum [6]. It should be noted that the confining magnetic field always exists, and the re-ionization loss is excluded also in this measurement. In the figure, it is seen that the injection power of BL-1 increased significantly in 2003, and attended beyond its specific power of 5MW. This success was attributed to the two technical improvements. One is the adoption of multi-slot grounded grid (MSGG) in the accelerator, and the other is the modification of magnetic cusp geometry of the plasma source. The former enables quick conditioning of the accelerator to the specific beam energy (180 keV) [7], and the latter improves the arc efficiency. The arc efficiency itself becomes large by strengthening magnetic multi-cusp field, but it makes the discharge unstable at high current, and accordingly the extractable current density does not increase. In our plasma source, the shape of chamber was modified to avoid the discharge from localizing in the corner of chamber [8]. Then the arc discharge becomes stable, and the current density of negative ion at the exit of ion source was increased up to 350 A/m$^2$ which is larger than the required value of ITER NBI [9]. Accordingly, the total injection power was attained to be 13 MW [8].

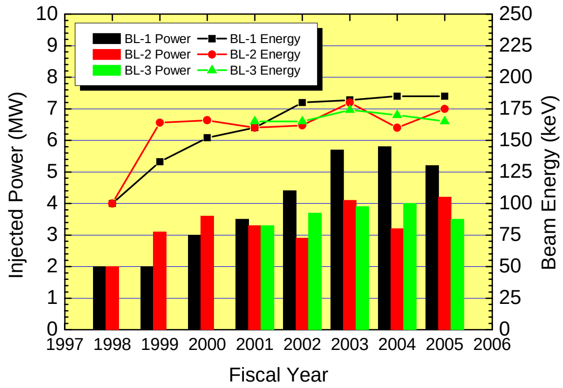



*FIG.2. Trends of maximum beam energy and port-through injection power of three beam lines. The maximum total input power in these three years is 12-13MW.*

Although the maximum total injection power has been almost the same for these three years, the available power level has been increased. In FIG.3, summaries of injected port through power throughout experimental campaign are shown for the fiscal year of 2003 and 2005. In 2003, the injection powers were low at the beginning of the experiment, and the power increased as the beam conditioning progressed as the plasma experiment carried on. However

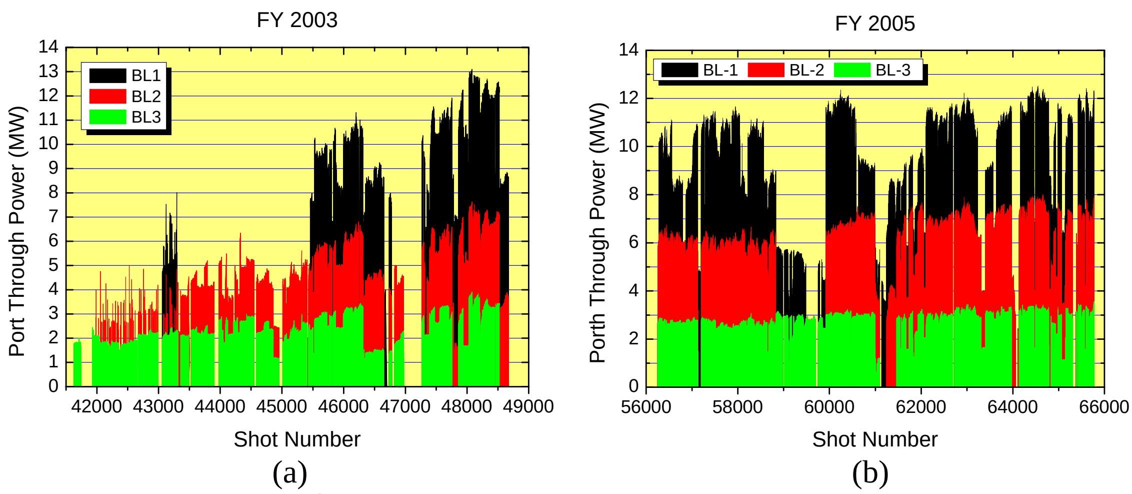
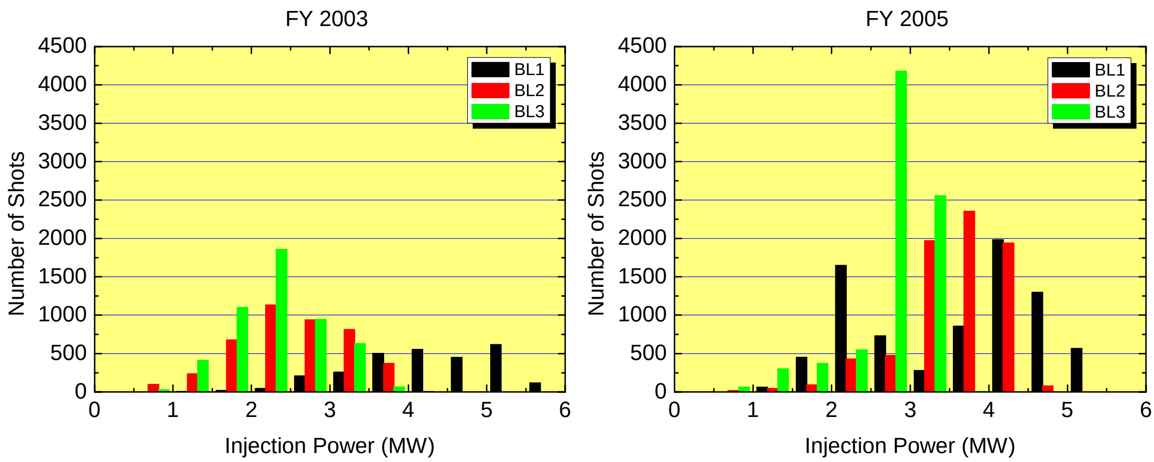



*FIG.3. Summaries of injection power throughout experimental campaign in 2003 and 2005. Three beam lines are distinguished by colors. In 2003, BL-1 had troubles in new type ion sources, but in the latter it showed remarkable performance.*

this good condition reverted to the starting condition when the ion sources were opened to the air for exchanging tungsten filament cathodes that were damaged after many high current arc discharges. This situation is clearly seen in FIG. 3 (a) at around shot number 46700. On the contrary, after the optimization of operational conditions had been studied, the status of each beam line was improved in 2005 as shown in FIG. 3 (b) where the injection power was kept almost at the same level throughout experimental campaign, although the maximum total injection power was a little bit smaller than that of 2003. This fact shows the difficulty to keep the condition of three beam lines high at the same time.

The improvement of operating status can be seen more clearly from the histogram shown in FIG.4 where the numbers of shot are counted in every 0.5MW for three beam lines throughout experimental campaigns in the year 2003 and 2005. It is clearly seen from the figure that the most available injection power level increased clearly from 2003 to 2005 in all three beam lines. In these cases, the pulse length of the beam is set by two seconds at around maximum power level. The power level of less than 2 MW was chosen for longer pulse operations such as 10 s and longer. It is noted that the peak at 2.5 MW of BL-1 in 2005 comes from one-lung operation, that is, the operation with one ion source due to a trouble of the other ion source. We will discuss the limitation of pulse length later.




(a) (b)

*FIG.4. Histogram of injection power of each beam line during the 7th and 9th experimental campaign. Injection shots are counted in the interval of every 0.5MW.*

It is seen from FIG. 2 and FIG. 4 that the performance of BL-1 is superior to other two beam lines (BL-2&3). This is attributed to the new type ion source of BL-1. However, the new ion source had a problem that the beam divergence was not good. Then the injection efficiency (port through power / electric power for beam acceleration) became worse, and the heat load at the injection port increased due to geometrical loss of the beam. During the experimental campaign of 2004, an air leak occurred at the drift tube of BL-1 due to this high heat load. Therefore, the injection power of BL-1 was suppressed in 2005, which is the reason why the maximum power of 2005 became small as shown in FIG.2. By this reason, MSGG has not been applied to BL-2&3 yet, and their injection power stays low around 4MW (FIG. 2).

## 4. Reformation of Conventional Ion Source

Although BL-2 and 3 use conventional type ion sources, they were also modified to improve their performances. In the latest campaign (2005), the configuration of magnetic multi-cusp was changed in BL-2 ion sources. This configuration has a symmetric arrangement of magnetic cusp lines as shown in the left development in FIG. 5, which was known as high efficient one but the operational window for stable high current discharge was narrow. Hence we had adopted "checkered" configuration (indicated in the right of FIG. 5) to stabilize discharges although the efficiency of negative ions is low. However, since we had paid many dues on operating ion sources we tried again this high efficient configuration. The result is shown in the center graph in FIG. 5. The acceleration current which is proportional to the negative ion current has increased 10% at the same arc current as expected. The reliable operation was also possible throughout experimental campaign as can be seen from FIG. 3.

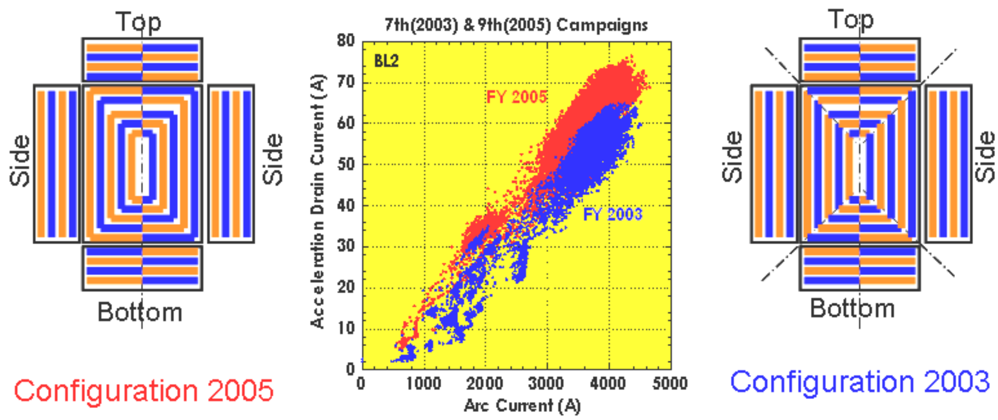



*FIG.5. Comparison of negative ion production efficiencies between two types of magnetic multi-cusp configurations. Red and blue bars in the developments of arc chamber show magnetic cusp lines of different polarities.*

Another modification was to enlarge the aperture of grounded grid. Because the MSGG showed a large effect to reduce the heat load on it, this had been done to expect reduction of heat load by increasing the transparency of the grounded grid. The result is shown in FIG. 6 where the strong dependence on the transparency can be seen. It is a dilemma that the space for cooling water channels in the grid becomes small when the transparency becomes large, and the change from round to slot is a good way from this point of view.

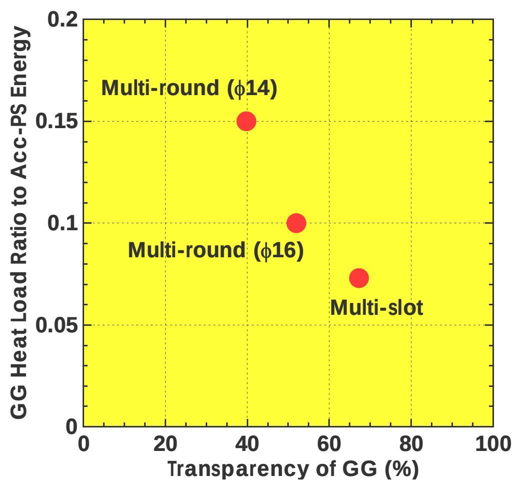



*FIG.6. Heat load on the grounded grid reduces as the transparency increases.*

## 5. Extension of Pulse Length

Pulse length at high output beam power has been increased because the heat load on the ground grid is reduced to be almost a half by adopting MSGG (FIG. 6). However it is still limited to be 2 sec at the highest beam power since the power also increased (FIG. 7). The integrated beam power (totally injected kinetic energy) can be used as a measure of operation limit as shown in the figure. It is interesting that the results of JT60U N-NBI are also fit this limit [10]. When the beam power decreases, pulse length can be extended longer than this limit because active water cooling of the grid becomes effective. At the operation longer than 100s, cesium condition becomes other parameters to be controlled, which are the balance of cesium supply and consumption, and the temperature of plasma grid [11].

It is important to reduce the heat load not only for extending beam pulse but also for improving injection power efficiency. The injection efficiency is 0.3 to 0.35 which has not been improved very much through our long-term R&D. Judging from the dependence shown in FIG. 6, it is considered that the cause of high heat load on the grid is the accelerated electrons produced in the accelerator or diverged ion / neutral beam components. In fact, the strong X-ray emission is observed downstream the ion source. But we do not have clear evidence of existing halo ion beam, so far. Therefore, more efficient electron suppression method should be developed.

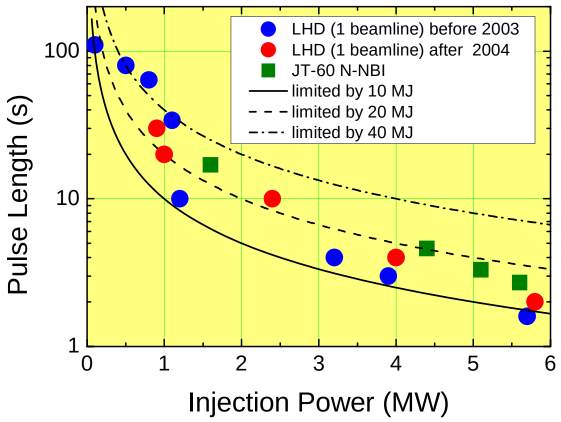



*FIG.7. Pulse length vs. injection power. Black lines show the ones of constant integrated beam power.*

## 6. R&D on Correction of Beam Optics of New Ion Source

The injection power of BL-1 would become larger and reliable if the beam optics could be improved. Therefore it is important to correct it. The worse beam divergence comes from the mismatched condition of optimizing beam optics between vertical and horizontal directions. This is a natural result of adopting MSGG in the multi-circular aperture grid system, because the cylindrical symmetry of multi-circular aperture grid system is violated by axisymmetric multi-slot. When cylindrical beamlets pass through the grounded grid, they suffer electrostatic lens force across the slots while there is no force along the slot. Therefore the shape of beamlet is deformed from the circular cross section. Figure 8 shows the structure of new grid system with MSGG. An extra multi-aperture grid called steering grid, which is electrically at the same potential as extraction grid, is added to the exit of extraction grid to converge beamlets along the direction of slot by using aperture displacement technique. In order to match the optical condition, the aperture of this steering grid was deformed from circle to racetrack to compress the beamlet in the direction parallel to the slot [12]. This method was examined by using one of the five sectors of a new ion source in BL-1, and the results are shown in FIG. 9.

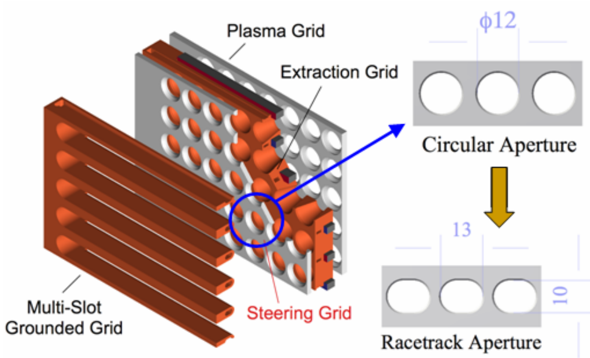



*FIG.8. Grid system using multi-slot grounded grid. Other grids remain multi-circular. Steering grid is added to converge beamlets in the direction parallel to the slot by aperture displacement.*

Figure 9 (a) shows the 1/e folding half width of the beam profile measured on the calorimeter as a function of the voltage ratio of accelerating voltage to extraction voltage ($R_v$) in the case of circular aperture. This type had been used till the latest experimental campaign (FY 2005). As can be seen from the figure, the optimum condition (minimum width) in horizontal direction appears at different $R_v$ from vertical direction. It is 14.5 in horizontal direction while it is 21 in vertical direction. It is also noted that the vertical width is larger than horizontal width (more than twice at the narrowest width) in spite of beam extraction area is almost square like. In this configuration, horizontal direction is the direction parallel to the slot. Figure 9 (b) shows the case of racetrack aperture. As can be seen from figure, the optimum conditions for both directions concur well. What is more, the narrowest beam widths in both directions become close.

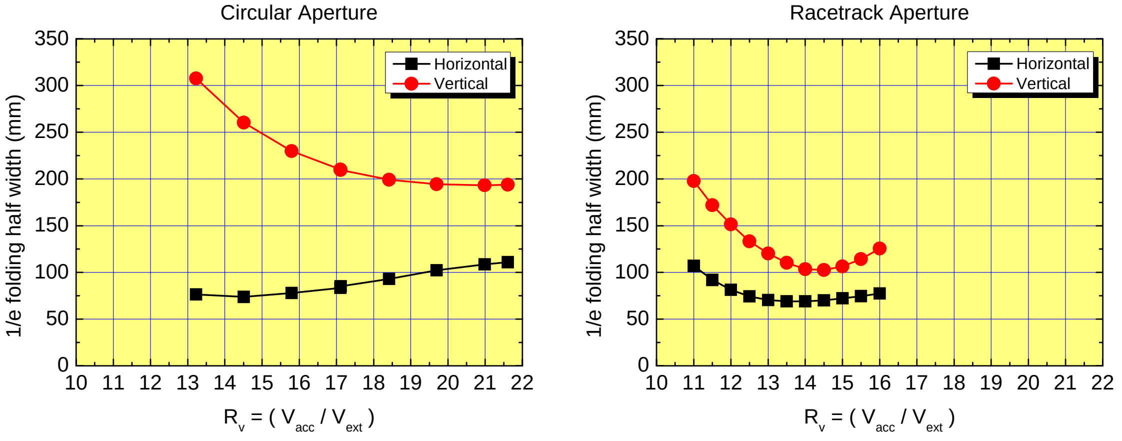
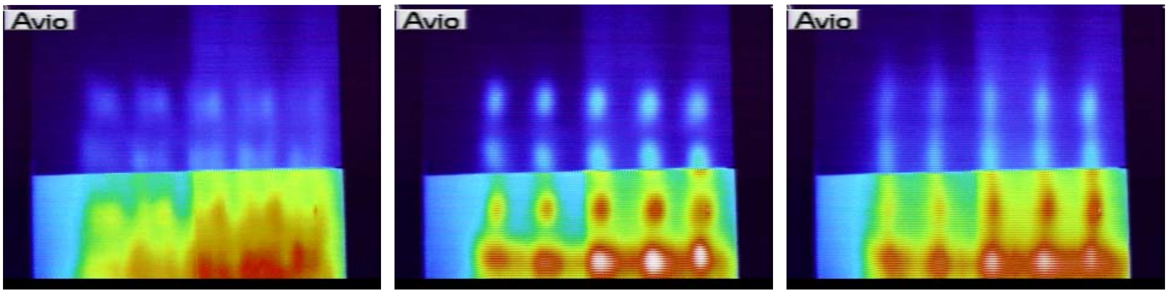



*FIG..9. Dependence of beam width on the ratio of acceleration to extraction voltage in vertical and horizontal directions in the case of circular aperture (a), and racetrack (b). The extraction voltage was fixed at 7.5keV (a) and 8keV (b).*

In order to see the behavior of beamlets more precisely, the burn pattern of beamlets on the graphite plate, which is located 282cm downstream from the ion source, was monitored by the IR camera. Figure 10 shows three cases of the optimum ( (a): $R_v$ =14.0) and two unsuitable voltage ratios ( (b): $R_v$ =12.5, and (c): $R_v$ =15.5) for comparison. From FIG. 6 (b), one can see that even at the optimum condition the shape of each beamlet is not circular but elongated about 1.5 times longer in the vertical direction. This is consistent with the observed beam profile on the calorimeter where the vertical width is also 1.5 times wider than the horizontal width. Apart from the optimum condition, the pattern of each beamlet becomes blurred, which shows that the beam divergence becomes large. Also from the figure, one can see that at the larger $R_v$ than the optimum value, the divergence of the beamlet becomes large in vertical direction, and each column of beamlets looks sticking together (FIG. 10 (c)). At smaller $R_v$, beamlet looks expanded in vertical direction, but it is expanded also in horizontal direction and becomes even hollow. This tendency is consistent with the beam profile shown in FIG. 9 (b). At the optimum condition, the beam divergence angle is evaluated as 4 mrad in horizontal and 6 mrad in vertical direction. It should be noted that these result support the design of ITER NBI, where multi-beamlet will be merged at the last stage of acceleration [8].




(a) (b) (c)

*FIG.10. Image of burning pattern of beamlets from the ion source at different acceleration to extraction voltage ratio $R_v$; (a) $R_v$ =12.5, (b) $R_v$ =14.0 and (c) $R_v$ =15.5 in the case of racetrack steering grid corresponding to the result of FIG. 6 (b).*

## 7. Summary and Future Perspective

The performance of N-NBI in LHD had been improved in its maximum injection power until FY 2003, and in its reliability for these three years. The main reason of this improvement is attributed to the optimization of magnetic multi-cusp structure of plasma source and to the high transparent beam acceleration system. According to the recent R&D, the injection power is expected to be increased more when we will correct the beam optics of the ion source of BL-1 in the next experimental campaign. After the improvement is confirmed from the injection result, we will adopt the new multi-slot ground grid to BL-2&3. We hope that the injection power more than specification (15MW) would be achieved reliably. The biggest remaining issue is the extension of pulse length at the highest power that is limited by heat load on the grounded grid.

## Acknowledgement

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