ISSN 0915-633X

INTERNATIONAL ATOMIC ENERGY AGENCY

19 th IAEA Fusion Energy Conference
Lyon, France, 14-19 October 2002

IAEA-CN-94/ CT-R6b

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received - Sep. 20, 2002)

NIFS-743 Oct. 2002

RESEARCH REPORT
NIFS Series

TOKI, JAPAN

INTERNATIONAL ATOMIC ENERGY AGENCY

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Abstract. An overview on four-year operation of the negative-ion-based NBI (N–NBI) system for the Large Helical Device (LHD) is presented, and the prospects of negative-ion technology for applying it to future helical fusion reactors are discussed from theses experiences. The N–NBI system was designed and constructed based on the results of R&D at NIFS. Using three beam lines, the total port-through injection power of 9 MW for 2 s has been achieved. Each beam line attained the same performance: 3.5 MW of the port-through power with the beam energy of 165 keV for hydrogen, which corresponds to the averaged negative ion current density of 25mA/cm^2 from ion sources. Also for long pulse injections, 110 s for 0.1 MW by one ion source, and 80 s for 0.5 MW by two ion sources (one beam line) were carried out. These facts show that the negative ion technology has been established to the same power level of conventional positive ion systems. Several technical improvements needed for getting these successful results are described, and the problems that limit the present performance are clarified. Some R&D programs to solve these problems are proposed for further improvement.

1. Introduction

The neutral beam injectors (NBI) for the Large Helical Device (LHD) is the first negative-ion-based NBI (N–NBI) system that was planned as a main plasma heating facility in helical systems [1]. Differing from JT-60U tokamak which also has introduced an N–NBI facility specified for current drive experiments [2], only N–NBI has been adopted in LHD as a beam injection heating and therefore it is requested high reliability as well as available power. The NBI system has three beam lines, and each beam line was designed to deliver 180 keV, 5 MW, 10 s beam by two high efficient cesium seeded negative ion sources with an external magnetic filter. The ion source had been developed at NIFS [3], and the construction of the system was started in 1996 [4].
Through four-year operation from 1998, NBI heating has revealed an excellent performance in LHD as in other helical devices and tokamaks. What is more, the recent studies in LHD have shown that NBI has other potentials than plasma heating, that is, the plasma initiation [5], and the control of rotational transform by its inducing current. Therefore NBI would be the most useful auxiliary device for the helical fusion reactor to initiate, heat and control plasma. Then the key technical issue is the negative-ion-beam technology, because the beam energy required in helical reactors is around 1 MeV for deuterium, which is the same as that of ITER [6]. A perspective for the future development of N–NBI is given.

2. Present Status of LHD-NBI

The neutral beam injection started in 1998 with 2 MW by two beam lines, and their performances have 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. The beam energy increased slowly because the ion sources were reformed in every year for improvement, and the time was insufficient for conditioning. The injection power efficiency (the ratio of the injected port-through power to the input electric power) is around 0.35. The port-through power is evaluated from the heat flux on the armor tile in the LHD vacuum chamber, and therefore it eliminates geometrical and reionization loss in the drift duct tube. The highest averaged negative ion current density is 25 mA/cm^2 over beam extracting area. Pulse length has been extended at low beam power, and the maximum length of 110 s was achieved. In 2001, one more beam line was added and the total port-through power of 9 MW was achieved with a beam energy of 160 keV. It is noted that the new Beam Line 3 (BL-3) revealed the same performance as other two beam lines so quickly after commissioning, which shows that the negative-ion technology of this level has been established.

TABLE I: PROGRESS OF ACHIEVED PORT-THROUGH POWER

	1998	1999	2000	2001
Beam Line 1	2MW / 100keV / 2s	2MW / 133keV / 2s	3MW / 152keV / 2s	3.5MW / 165keV / 2s 1.1MW / 104keV / 10s
Beam Line 2	2MW /100keV / 2s 0.6MW / 66keV / 20s	3.1MW /164keV / 2s 0.5MW / 100keV / 80s	3.6MW /166keV / 2s 0.8MW / 86keV / 64s	⇐ ⇐
Beam Line 3	-	-	-	3.3MW /165keV / 2s 0.1MW* / 81keV / 110s
Total Power	3.7 MW	4.5 MW	5.2 MW	9.0 MW

* *one ion source*

3. Improvements Carried Out for Increasing Performance and Reliability

The key component of the N–NBI system is negative ion source. The original design was based on the preceded R&D results by using 1/3-scaled ion source. It has been modified to increase in output power and to improve reliability. These are summarized as below;

Improvement of Arc Efficiency and Stability

Our plasma source uses an external magnetic filter and has no magnetic field-free region. In order to increase in arc efficiency, careful reform of the magnetic field structure was made to prevent local arc discharge. Especially at the long-side end of plasma source, unexpected field lines that connect directly between the plasma and the grid sometimes exit due to a complex magnetic field configuration, and it was carefully avoided. It should also be noted that the position of cathode filaments is important because the induced magnetic field modifies the magnetic configuration [7].

Control of Cesium Effect to Keep Beam Quality

The amount and quality of negative ion beam is very sensitive to the cesium condition. Trial and error have been done to optimize and to keep the cesium effect. So far, the best way is that the cesium is introduced little by little keeping the temperature of plasma grid as high as 250 degree Celsius. Then the cesium effect on negative ion production becomes reproducible and reliable. There is no problem for continuous feed of cesium even during beam pulse. No deteriorate effect on the voltage withstanding of insulators was observed throughout an experimental campaign (experienced about 30,000 pulses including conditioning shots in five months).

Long Pulse Operation

Another technical improvement was needed for a long pulse operation. After the construction of BL-1, BL-2 and BL-3 were redesigned to be able to operate 30 minutes at low power (~1MW injection). As for a negative ion source, the thermal contact of plasma grid to the water-cooled supporting flange is redesigned and the cooling of ground grid was reinforced [8]. Because we do not control the plasma grid temperature actively, its temperature rises during the beam pulse. In some case it was found that the beam divergence changed during pulse even though the acceleration or extraction current did not change. Therefore a steady state condition should be determined more carefully than the case of short pulse considering the balance between the grid temperature and the amount of cesium supply. It is suggested that the optimum condition of cesium coverage on the plasma grid is determined by the dynamic balance between the supply and the release of cesium from the surface covered by tungsten [9].

Heat Load on the Grids

Reduction of heat load on the grids is a main technical concern. By strengthen the magnetic field on the plasma grid from a magnetic filter and the extracting grid, the amount of extracted electrons associating with negative ions is suppressed sufficiently [10], which is smaller than that of negative ions. However, the heat load on the ground grid still remains (about 10% of the accelerated beam power), which limits the pulse length under high power beam injection. It is considered that both electrons and ions (or neutrals) cause the heat load. The accelerated electron beam is estimated to be several % of the beam power, which is larger than that estimated by stripping of negative ions. The heat load and the X-rays are observed downstream of the ion source, and the protection against their heat load was inevitable for a long pulse operation.

Spatial Non-Uniformity of the Beam

In order to improve the electric efficiency of neutral beam production and to reduce the heat load on the ground grid, the spatial uniformity of the extracted negative ion beam should be improved. The non-uniformity along a long direction of the ion source is usually very large. This is a common problem found in large ion sources [11], and one of the reasons is ascribed to a non-uniform arc discharge. The passive control of arc current distribution was done by inserting series registers in the electric circuit but it was not satisfactory because the current distribution depends on the amount of arc current itself and also on the amount of cesium. In the new BL-3, the filament and arc power supplies have separated twelve outputs (FIG.1) and can control the arc current distribution actively to compensate the non-uniformity. The initial trial showed a favorable result.

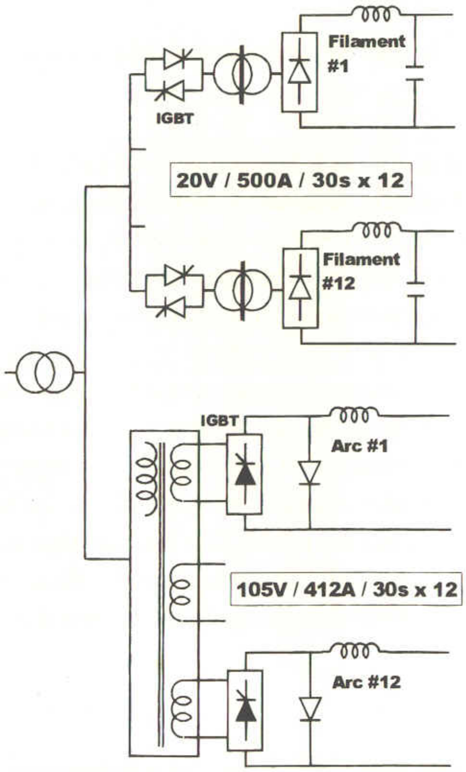

FIG.1. Electric circuit of twelve-output multi filament and arc power supplies.

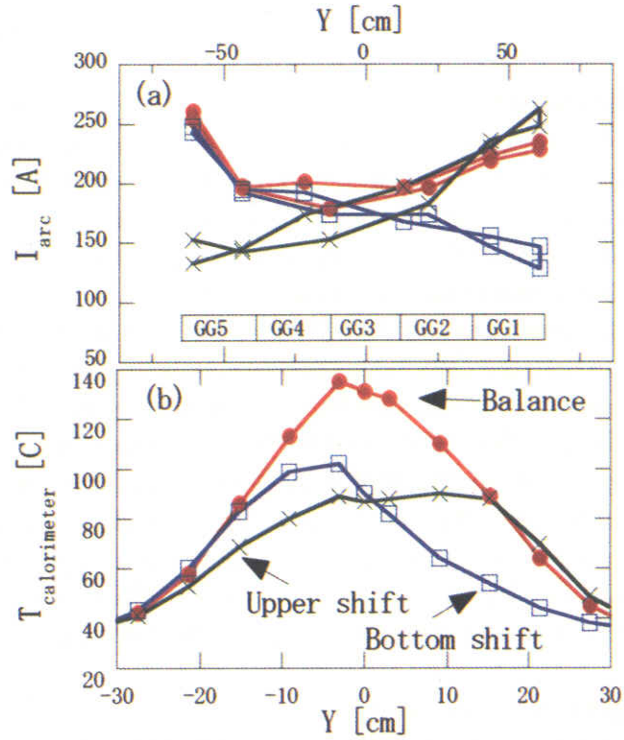

FIG.2. Arc current distribution (a), and the corresponding beam profile measured at the calorimeter. GG1 to 5 indicate the position of separated ground grids.

Figure 2 shows an example of the control of beam profile by adjusting the distribution of arc currents of each pair of filament cathodes (twenty four filaments are usually used in our ion source).

4. Prospects of negative ion technology

Performance of N–NBI

The neutral beam converted from negative ions shows a great performance and the many fruitful experimental results have been obtained in LHD [12]. From four-year experiences in operating LHD-NBI, the handling of cesium seeded negative ion sources has been established, and the stability or reliability has been improved. As a result, a wide range of operation became possible from high power short pulse to low power long pulse injection. Figure 3 shows the operational results of NBI in the latest LHD experimental campaign. It can be concluded that the negative ion source is acceptable, and as a injection system N–NBI has reached the same level of conventional positive-ion system, that is, a 100 keV, 10 MW injection system becomes available for plasma experiments.

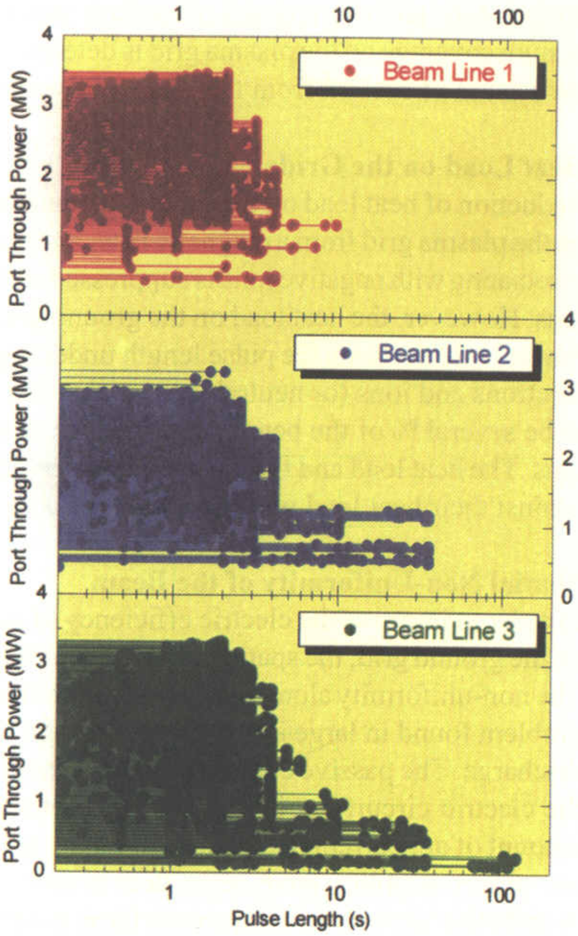

FIG.3. History of all injection shots during the 5^{th} LHD experimental campaign.

Maintainability

So far, we have not succeeded to realize the specified values of each beam line (180 keV, 5 MW). One of the reasons is the short life of cathode. In LHD, plasma is generated in every three minutes, typically. Therefore about 10,000 plasma shots were required during an experimental campaign, and 30,000 shots including conditioning shots were needed. On the other hand, typical lifetime of directly heated tungsten filament cathode, is 10,000 beam shots under the operating condition of producing H^- more than 20 mA/cm^2 (arc discharge time is 10 s in a typical shot). We have to exchange the cathode at least twice during an experimental campaign and it takes weeks for ion sources to recover their best performances after opening them to the air. Although the lifetime of cathode is not determined by the evaporation loss but abnormal arc, it is noted that the measured weight loss of filament is large at the center of plasma source, which corresponds to the beam profile rather than arc current distribution [13]. It should also be noted that the damage of the filament is seen at the position where the back streaming ions hit the cathode directly. From these facts, the development of cathode-less (RF) ion source or other (tough) cathode material should be developed for future stable steady state operation.

Aging of Accelerator

It usually takes a long time to condition the ion source to its specified energy. Breakdowns occurs more frequently when the beam energy is getting close to the maximum value. For the negative ion sources the breakdowns may occur when the electrons, ions or neutrals deposit on the grid locally to outgas. In order to reduce the chance of breakdowns, it is considered that the area of interference between the beam and the grid should be minimized. We have introduced a newly designed accelerator for the next LHD experimental campaign, where the ground grid has a multi-slit structure other than multi-hole. As a result, conditioning has been done so quickly as shown in FIG.4, and specified beam energy of 180 keV has been achieved only by five days.

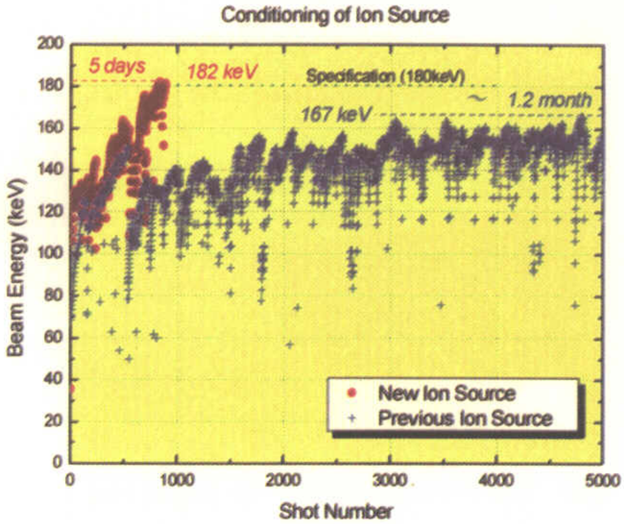

FIG. 4. Comparison of history of conditioning

5. Conclusion

From four-year experience of high power operation of LHD N–NBI, it is prospected that the performance of cesium seeded volume production negative ion source is acceptable for future use, which can cover a wide range of operation. The reliability is being improved and will be improved more when a long lived cathode is developed, and the multi-slit grid will help to shorten the time of aging process. As for the spatial non-uniformity of the beam, which is considered as a main cause of heat load of the accelerating (and ground) grid, an active control of arc discharge current distribution by using separate power supplies works well.

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