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DEVELOPMENT OF NEGATIVE-ION-BASED NEUTRAL BEAM INJECTOR FOR THE LARGE HELICAL DEVICE

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Development of negative-ion-based neutral beam injector for the Large Helical Device

Abstract

A high power neutral injection heating system, which is based on the negative ion beam technology, is under construction for the Large Helical Device (LHD). The injection power of 15MW is expected for 10 seconds with 180keV hydrogen. Such high energy is required to inject the beam tangentially in the LHD that the use of negative ions is inevitable. The system consists of two beam lines with four negative ion sources. A large amount of negative ion beam (160A) is required with the high current density (>35mA/cm^2). The design of ion source is carried out on the basis of our R&D in these seven years, where we have succeeded in the high efficient negative ion production and the high quality beam formation. The other components of beam line and the power supplies are designed on the basis of conventional neutral beam technology. Although the NBI system is designed in pulse operation, its duty cycle is rather high (10 seconds in every 5 minutes) because the magnetic field of LHD is generated in steady state. This is a tough condition for the heat removal systems such as the beam dumps.

1. INTRODUCTION

The Large Helical Device (LHD) is the world's biggest super conducting heliotron/torsatron device under construction [1], where the first plasma is expected early in 1998. High power (15MW) neutral beam injection is planned as a main plasma heating tool. In the LHD, the beam should be injected tangentially to avoid being trapped in the helical ripples of the magnetic field [2]. Although the average plasma minor radius is not very large (0.6m), the path of the beam in the plasma is long due to its high aspect ratio (6.2). Then the required beam energy becomes as high as 180keV for hydrogen. With this high energy, the conventional positive ion system is useless, and the negative-ion-based technology must be introduced.

The production of high power negative ion beam is one of the key technology for heating and current drive in the next large tokamak fusion devices such as the ITER, and the R&D of this has been carried out in many laboratories [3]. There are two ways to make high power beams: increasing energy and/or increasing current. For the LHD, the latter is more important because our beam energy is moderate, which is a different case from the request for the ITER. Therefore, we started our own R&D program to develop a high current negative hydrogen ion source in 1990.

Our R&D is successful. We extracted 1.2A of H^- with the current density of 54mA/cm^2 through a small area of the large ion source [4], and then extracted 16A with 45mA/cm^2 through the whole extraction area [5]. We tried to operate the ion source at the low gas pressure, and got 16.2A of H^- at 0.5Pa [6]. The design of our neutral beam injection system is based on our latest R&D results, and will be described in the following sections.

2. DESIGN OF THE NEUTRAL BEAM INJECTION SYSTEM

2.1 Physical requirement for NBI in the LHD

The NBI heating in the LHD has to be satisfied the conditions; 1) the absorbed beams must be passing particles, 2) the deposition profile of the beam is to be peaked at the plasma center, and 3) no net current should be induced. The first condition is to avoid the helical ripple loss of the fast ions, which is essential in the helical system. The second comes from the experimental results that the helical plasma has no profile consistency, and therefore the central heating is important. The last is one of our experimental objectives to study the 'net-current-free' plasma in the LHD.

From the first and the third conditions, the neutral beam lines are designed as tangential balanced injection. The beam energy is determined from the second condition for the high density plasma of $10^{20}m^{-3}$ in average, because the high performance is expected for high density plasmas in the LHD from the empirical scaling [7]. For the hydrogen beams, the energy was chosen to be 180keV taking also the beam shine through at the low density operation into the account. The total port through power of 15MW by two beam lines is planned at the beginning of the experiment. So far, the NBI heating is planned only in a pulse operation up to 10 seconds, although the duty factor is rather high (1/30).

2.2 Design of a negative-ion-based NBI

2.2.1. Arrangement of beam lines

In order to realize the required NBI system, it is necessary to use the negative ions. The design of the system depends on the structure and the performance of negative ion source we use. Here we adopted the cesiated multi-cusp ion source with external magnetic filter, which we have studied in our R&D program. Two ion sources are installed in each beam line. The ion source has a beam extracting area of 0.25m wide and 1.2m high. The H^- current of 40A is expected from this ion source, that is, the current density of over $35mA/cm^2$ must be realized. The design of the ion source will be described in detail later.

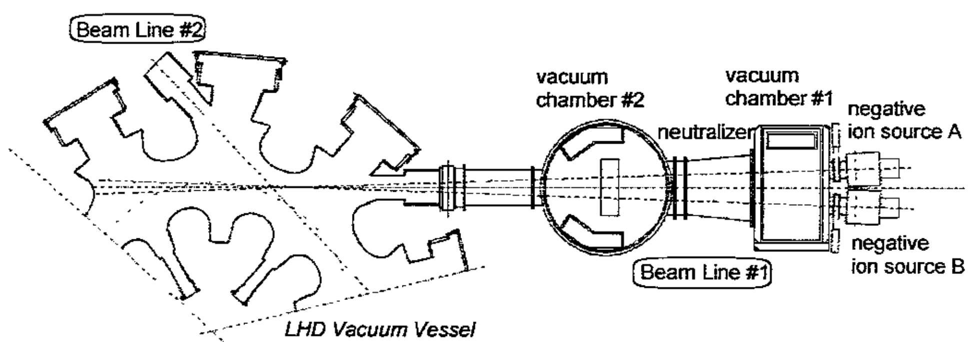

Figure.1 A sectional plan of LHD vacuum vessel and NBI beam line.

Figure 1 shows an equatorial plane view of the LHD vacuum vessel and the beam line of NBI. Two ion sources are installed side by side on the beam line. It should be noted that the cross section of plasma is a twisted ellipsoid in the LHD, and its minimum radius is only 0.4m, which is comparable to the size of the beam.

Because the shape of the vacuum vessel also follows that of plasma, the injection angle is almost uniquely determined to keep the beam away from the wall of LHD vacuum vessel. Fortunately, this angle satisfies the condition that all the injected beams become passing particles. The specification of the NBI system is summarized in Table I with our R&D results that are the design basis for the system.

Table I. Specification of LHD-NBI and the R&D results of negative ion source.

	LHD NBI	*R&D*
Beam Species	H / D	H
Beam energy (keV)	180 / 360	125
Beam extraction area	25cm x 120cm	25cm x 50cm
Beam current (A)	40 / 20	16
Current density (mA/cm^2)	35 / 18	45
Beam divergence (mrad.)	10	9 (multi-holes) 5 (single-hole)
Operating pressure (Pa)	0.4	0.4
Pulse length (sec.)	10	10
Electron content in the beam	10 %	17%
Accelerator	electrostatic (single stage)	electrostatic (single / two-stage)
Focusing	geometrical & beam steering	beam steering

2.2.2. Negative-ion-based beam line

The beam line consists of two vacuum chambers and a long gas neutralizer cell between them. The ion sources are installed on the first chamber that has a cryopump of 360m^3/s and works as an expansion chamber. It is very important to reduce the gas pressure in the accelerator of the ion source to avoid the stripping loss of accelerating negative ions, while the vacuum pressure in this chamber must be as high as to keep the line density for neutralization. We want to reduce the length of the beam line, and therefore the designed pressure is 0.05Pa and the neutralizer cell is 3.5m long. The second chamber consists of a bending magnet, beam dumps, and calorimeters. It also has a cryopump of 1000m^3/s to prevent the reionization loss of the beam not larger than 5%.

We adopted the gas line density for neutralization so that the residual positive and negative ions become equal to reduce the maximum heat flux on the beam dumps. This condition should be kept independently to the operating condition of ion source, although the gas from the ion source is utilized for neutralization. Therefore, we normally feed hydrogen gas into the first chamber to control the gas line density between the ion source and the second chamber.

We use ion bending magnet to separate the ions from the neutrals. We have chosen this active magnetic separation because our beam is so thick to get high current that the electrostatic separation is difficult. The idea of using magnetic leakage field from the LHD cannot be used for the separation because the strength of the field varies among the operating modes and is very weak in some modes. The beam dumps are made by the swirl tube array and the maximum heat flux on them is 16MW/m^2. This value is tolerable for a single shot, but the unknown is the life after many heat cycles. Since the LHD magnetic field operates in steady state, the repetition of the experimental shot depends on the pulsed heating system and the minimum interval is 5 minutes. Then the shot number may exceed 10,000 in a year.

An estimation based on ASME shows that the life is over 10,000 cycles, but the critical condition is not clear. The best way is to reduce the heat load, so that we adopted a reflecting magnet to diverge the ion beam on the beam dumps.

A newly developed large cryosorption pump [8] is adopted as a main vacuum pump. The advantage of this pump is that the operating range of temperature is wide (up to 20 K), and that the cryopanel is directly connected to a refrigerator. Therefore it is stable against the pulsed heat load, and no (power consuming) long cryogenic transfer tube is needed. The pump is composed of several modules (a set of panel and refrigerator). We have used a cryosorption pump of 300m^3/s using small modules for the NBI of JIPP T-IIU tokamak, and the result is satisfactory.

2.2.3. Power Supplies

The power supplies are similar to those of positive ion system; a filament, an arc, and an acceleration DC power supplies. The distinctive power supplies for the negative ion system are the bias power supply and the extraction power supply. The former is needed to reduce the electrons that are accompanied by negative ions from the ion source, and the latter is to prevent the electrons from flowing into the accelerating region. The specification of power supplies are shown in Table II.

Table II. Specification of power supplies.

	Voltage	Current	Pulse width	Features
Filament	14 V	6 kA	30 s	*12 individual outputs*
Arc	100 V	5 kA	20 s	*fast switching circuit*
Bias	10 V	1 kA	20 s	
Extraction	-15 kV	75 A	10 s	*includes electron current*
Acceleration	-170 kV	90 A	10 s	*common for two sources*

The acceleration power supply is common for two ion sources of a beam line, because they are installed so closely that high voltage withstanding between them is not hold. This cannot be helped since two beams must merge at the injection port to pass through it and they should not be separated much in the plasma apart from the port (see Fig.1).

One of the crucial components of the acceleration power supply is the fast switch for breakdowns in the accelerator. We adopted a conventional GTO (Gate Turn Off thyristor) switch in the DC circuit [9], because our beam energy is not very high. Then we can switch the output in less than 1ms. This fast switching is convenient for beam modulation we are planning in the experiments. We also use this GTO switch for the arc power supply. Because its capacity is very large (100V, 5kA), it is very important to detect the abnormal discharge and to switch off the current as soon as possible for protecting the plasma source from the damage.

2.3 Negative hydrogen ion source

2.3.1. High performance negative hydrogen ion source

The ion source is designed based on our latest R&D results. It is a cesiated multi-cusp ion source with a strong external magnetic filter. This ion source does not have plasma loss region in front of plasma grid, and hence can be operated at low gas pressure [10]. There are several performances that are important in designing the ion source: 1) high H^- production efficiency, 2) low operating gas pressure, 3) small electron content in the beam, 4) low beam divergence, 5) good uniformity, and 6) stable operation.

For the high efficient H^- production at the low gas operating pressure, we have already demonstrated 16.2A of H^- with the current density of 31 mA/cm^2 at 0.5Pa. At this pressure, the stripping loss of H^- in the accelerator is below 10%. So far the obtained negative ion current is proportional to the arc power into the ion source, i.e., plasma density. This fact is encouraging to produce high current negative ions; what we have to do is to increase the discharge power density in the ion source. A problem comes from the low gas pressure operation. In order to do that, we have to improve the plasma confinement in the ion source. Usually this can be done by increasing the confining magnetic field strength, which corresponds to the decreasing of the anode area in the arc discharge. In the magnetic multi-cusp ion source, there is a threshold of the ratio of anode to cathode area for the good discharge [11], which means that the cathode area (i.e., number of filaments) must be reduced when the anode area decreased. This condition is opposed to the high power discharge. We have designed the maximum arc current so as not to exceed the current that flows in the direct heated cathode filaments as shown in Table II.

The other important, but not yet well established, technology to improve the H^- production is the cesium adjunct discharge. Cesium enhances the H^- producing efficiency drastically, but the optimization of the amount of cesium in the discharge is so far empirical. Recently, we have found that a long pre-arc discharge of 10 seconds improves the production efficiency by 1.5, which we think that a favorable equilibrium condition is achieved between the cesium in the plasma and on the plasma grid. Actually, in the long pre-arc discharge, the H^- production efficiency does not depend on the temperature of plasma grid much at least in the range of 180 - 300 C, which is different from the result of strong temperature dependence in the short pulse operation. This result is welcomed because the temperature increase of the grid during the discharge cannot be avoid.

2.3.2. High quality beam formation

It is well known that the divergence of H^-/D^- beam is small. We have also shown in the single hole experiment that the minimum divergence of 5mrad. was obtained even at the low energy of 80keV with the high current density of 28mA/cm^2 [12]. This is a good result, but for the multi-hole system there are some problems.

One is the magnetic field in the accelerator, which comes from the magnetic filter and the extraction grid. For the latter, we install magnets between the rows of extraction holes to repel the electrons that are extracted accompanying by H^-. The magnetization of these magnet rows is opposite side by side, and is not canceled perfectly along the ion orbit. Then the ions are deflected and separated. We succeeded to compensate this deviation by beam steering using the grid hole displacement technique [13]. However, these two effects have different dependence on the beam energy, and cannot be compensated in all the conditions.

Another is the inhomogeneity of the ion production over the grid area. Two causes are possible, non-uniform discharge and non-uniform cesium coverage on the grid. As for the discharge, we found that the arc current does not distribute uniformly on the filaments. When the arc current heats up the filament, more emission current can be extracted. This positive feedback enhances the non-uniform discharge, and can be suppressed by adding a variable resistor in the circuit. This stabilization is also necessary for a long pulse operation, and the long pulse operation may improve the cesium condition qualitatively and spatially as we described in the previous section.

3. CONSTRUCTION SCHEDULE

The first beam line is now under construction. Commissioning will start in 1997. The ion sources will be conditioned and tested in the neutral beam test stand where the R&D has been carried out. The first NBI experiment is scheduled in the middle of 1998.

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