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BEAMLET DIVERGENCE OF RESEARCH AND DEVELOPMENT NEGATIVE ION SOURCE WITH RF-MODE AT NIFS

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Abstract

A key challenge in the neutral beam injectors (NBI) for the ITER project with a beam energy of 1 MeV for heating and current drive (HNB) and 100 keV for diagnostics (DNB), is achieving a beamlet divergence from a giant negative ion source of less than 7 mrad in order to obtain nominal injection power. So far, the beamlet divergence of the developing radiofrequency-driven (RF) negative ion sources for ITER with an energy of less than 100 keV has been more than 11 mrad, assuming a beamlet diameter of 5 mm at the grounded grid electrode (GG). Direct beamlet divergence angle comparison of a filament-driven arc (FA) and RF negative ion sources has been investigated using FA/RF hybrid negative ion source for NBI at the National Institute for Fusion Science (FA/RF hybrid NIFS-RNIS). In the RF-mode of the FA/RF hybrid NIFS-RNIS, firstly, the increase of the negative ion density by cesium seeding was observed, which is one of the conditions to obtain the minimum beamlet divergence angle in a cesium-seeded negative ion source for NBI. In the well cesium-seeded condition, assuming the point beamlet at the GG, the beamlet divergence angle of 9 mrad was obtained. This angle corresponds to 7 mrad in the 5 mm diameter assumption.

1. INTRODUCTION

A Neutral Beam Injector (NBI) is utilized for plasma heating and current drive in magnetic confinement fusion plasmas, including tokamaks, helical configurations, field-reversed configurations, and mirror configurations. The neutral beam is formed by neutralization of hydrogen isotopes (hydrogen, deuterium, and tritium) ion beams. The beam energy ranges from sub-MeV to 1 MeV. In such beam energy, since neutralization efficiency from positive ions comes to zero, primary ions, which are accelerated by the desired beam energy, must be negative ions.

Negative ion based NBIs was operated on JT-60U at Japan Atomic Energy Agency (JAEA) (National Institutes for Quantum Science and Technology (QST) in present) [1], is operated on Large Helical Device (LHD) at National Institute for Fusion Science (NIFS) [2], and will be operated on JT-60SA at QST from Japanese fiscal year of 2026 [3]. These negative ion-based NBIs, whose beam duration is less than 100 seconds, adopt a Filament-driven Arc (FA) negative ion source. Toward future operating machines, such as ITER, CFETR, and JA-DEMO, the development of the negative ion-based NBI has been conducted [4-8]. These NBIs utilize RadioFrequency driven (RF) negative ion sources, which are planned to extract a 1-hour beam or a continuous beam. The distance from the negative ion source and beam injection port is a few tens of meters to install beam line components, such as neutralizer, residual ion beam dump, and vacuum pump, to ensure the beam passing length in the equipment concerning the confinement magnet of fusion plasma, and to protect the negative ion source itself from radiation caused by the fusion reaction. Therefore, the beam divergence angle from the negative ion source should be low to transport the beam over such a long length. For the ITER, the beam divergence angle requirement is 7 mrad with beam energy of 0.87 MeV negative hydrogen ion beam and 1 MeV negative deuterium ion beam for heating and current drive NBI, and 100 keV negative hydrogen ion beam for diagnostic NBI. So far, the beamlet divergence of the developing RF negative ion sources for the ITER with less than 100 keV has been more than 11 mrad, although an under 7 mrad beamlet divergence has been achieved by the FA negative ion source for the NBI on the Large Helical Device (LHD) [9]. To directly compare the beamlet divergence angle of the FA and RF negative ion sources, recently, Research and development Negative Ion Source at NIFS (NIFS-RNIS), which is half the size of the same type as the negative ion source for LHD-NBI, has been upgraded to the FA/RF hybrid negative ion source by a collaboration with NIFS, ITER organization (IO), and Max-Planck Institute for Plasma Physics (IPP) [10]. The paper presents the beamlet divergence angle as well as the ion source plasma in NIFS-RNIS installed on a Neutral Beam Test Stand (NIFS-NBTS).

2. EXPERIMENTAL SETUP

A schematic view of the FA/RF hybrid NIFS-RNIS and NIFS-NBTS is shown in FIG. 1. The difference from the original NIFS-RNIS is the newly designed RF backplate funded by IO. The RF driver was imported from IPP by IO and consists of the copper coil surrounding the alumina tube at the center of the RF backplate. There are two cesium (Cs) seeding ports at the upper and lower sides of the RF driver. Twelve filaments are equipped on the side wall of the discharge chamber, the same as the original NIFS-RNIS. Therefore, FA and RF plasma can be produced in the same configuration. A self-oscillated RF generator (HIMME, HGL 120/1), which had been utilized for MANITU negative ion source at IPP [11] was imported to NIFS by the IO. Nominal RF power is 120 kW, the frequency range is 0.9 – 1.1 MHz, and the pulse duration is 10 seconds every 3 minutes. The RF power is transmitted via a coaxial cable (Fujikura Dia Cable, WF-H50-13S) with a length of approximately 30 m to the matching circuit located near the NIFS-RNIS. A high-voltage insulation transformer imported from IPP is in the matching circuit box. The plasma grid electrode (PG), which is the ion source plasma-facing and the first grid electrode of the accelerator, is made of molybdenum, and the PG mask made of copper is set on the upstream of the PG to make isolated beamlets for estimating the beamlet divergence angle without beamlet-beamlet interaction. An accelerator consists of the PG with multiple holes, the extraction grid electrode (EG) with multiple holes, the Steering Grid electrode (SG) with multiple racetrack grids, and the Grounded Grid electrode (GG) with multiple slot grids from upstream. The grids of SG and GG are long horizontally.

Plasma parameters in the vicinity of the PG can be measured with various plasma diagnostics installed on the bias insulation flange between the discharge chamber and the PG flange. Local plasma density, plasma space potential, and electron temperature are evaluated with an RF-compensated Langmuir probe. Line-averaged negative ion density is evaluated using the Cavity RingDown technique, where the measurement line length is defined as 180 mm instead of 350 mm, which is the discharge chamber length, because of the full-width half-maximum of the plasma density profile.

Beam diagnostics are installed in the NIFS-NBTS. Whole beam profile and whole beam divergence are evaluated using cross-shape beam calorimeters embedded upstream and downstream of the neutralizer. Beamlet diagnostics are installed approximately 1 m from the GG of NIFS-RNIS: Beamlet Monitor (BM), beam emission spectroscopy, pepper-pot type emittance meter, and fast beam monitor [12]. The BM consists of a carbon fiber-reinforced carbon composite (CFC) tile with the carbon fiber aligned in the beam direction and an Infrared thermography camera (IR camera). The beamlets inject and heat the upstream surface of the CFC tile. The heat transfers to the backstream surface of the CFC. The IR camera views the CFC tile from a diagonal behind. After the perspective transformation is applied to the IR image, the temperature profiles on the backstream surface of the CFC tile are obtained. The beamlet divergence is evaluated from the distance from the ion source to the CFC tile, which is 0.86 m, and the e-folding half-width of the temperature peaks of the CFC tile.

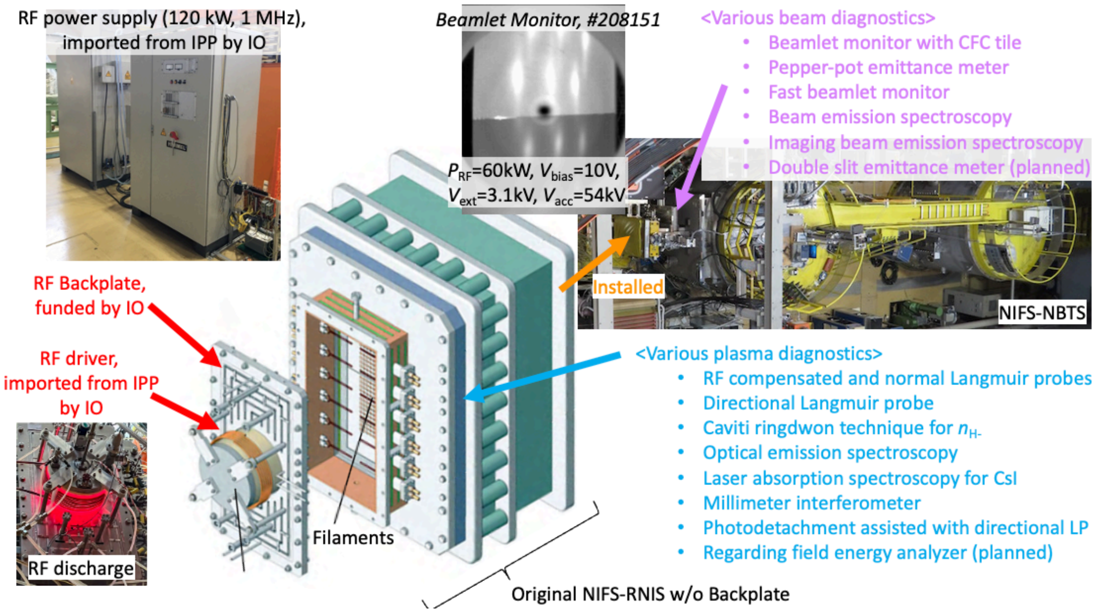

FIG. 1. FA/RF hybrid NIFS-RNIS, RF generator, and NIFS-NBTS [10].

3. ENHANCEMENT OF NEGATIVE ION DENSITY BY CESIUM SEEDING

The minimum beam divergence is achieved under optimal conditions where the negative ion density in the ion source plasma and beam current increase with Cs seeding, and the accelerator is operated at optimal extraction and acceleration voltages. After the 29th IAEA-Fusion Energy Conference (FEC29), the NIFS-RNIS underwent servicing to achieve these optimal conditions, including cleaning and reassembling the discharge chamber and Cs seeding system, reinforcing the withstand voltage of the feeder connecting the impedance matching box and RF driver coil, and enhancing diagnostics for operation in the RF-mode, among other improvements.

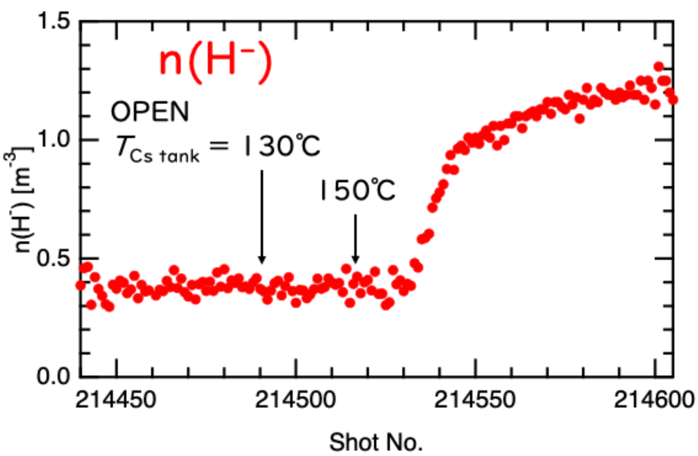

FIG. 2. Shot trend of negative ion density before and after the Cs seeding starts

The negative ion density, with and without Cs seeding, is one of the critical parameters for comparing the FA and RF negative ion sources. FIG. 2 shows the shot trend of the negative density before and after the Cs seeding starts. The duration of the ion source plasma is 10 seconds every two minutes. The negative ion density without Cs seeding in RF-mode reached 0.4×10^{17} m^{-3} at an output power of 60 kW from the RF generator. This density was equivalent to or slightly below the density of the original FA NIFS-RNIS. The temperature of the Cs reserve tank regulates the Cs seeding rate. Moreover, the PG temperature is vital because negative ions are produced on the low work function surface of the PG. The negative ion density rose to 1.2×10^{17} m^{-3} after approximately 100 shots, facilitated by Cs seeding with the Cs reserve tank temperature set at 150 degrees Celsius and the PG temperature at 70 to 90 degrees Celsius. These temperatures are lower than those of the original FA NIFS-RNIS operation (180 to 190 degrees Celsius and approximately 280 degrees Celsius, respectively), but similar to those of the developing RF negative ion sources for the ITER project. This marks the first observation of negative ion density enhancement through Cs seeding at the NIFS-RNIFS in RF-mode. After conditioning for a week, the negative ion density attained 2×10^{17} m^{-3} at an output power of 70 kW from the RF generator. The characteristics of the FA/RF hybrid NIFS-RNIS in RF-mode have not been fully understood; however, this density is less than that of the well-conditioned original FA NIFS-RNIS, which had a density of $2.5 - 3 \times 10^{17}$ m^{-3}.

4. BEAMLET DIVERGENCE IN RF-MODE

The beamlet divergence angle was analysed for central beamlets as shown in the red circle in FIG. 3. After perspective transformation, the beamlet profile elongates vertically due to the vertically (y-direction) and horizontally (x-direction) asymmetric accelerator grid electrode system of the NIFS-RNIS. Here, horizontal beamlet divergence is focused on.

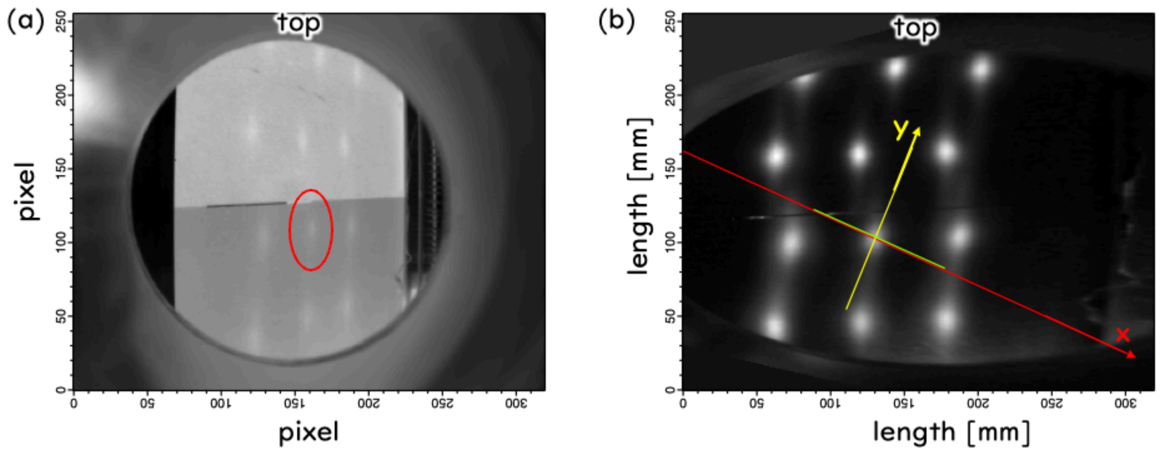

FIG. 3. (a) IR image of the downstream surface of the CFC tile. A beamlet in the red circle is analysed. (b) Image after subtracting the background and using the perspective transform.

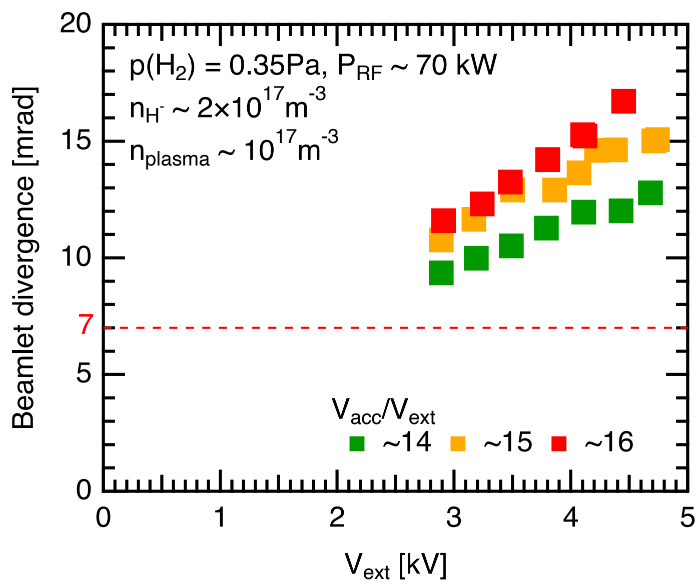

FIG. 4. Beamlet divergence variation of the beamlet in the red circle in FIG. 5 for the beam extraction voltage. Point beamlet is assumed at the GG.

FIG. 6. shows the beamlet divergence angle variation for the extraction voltage. A ratio of acceleration to extraction voltages changes around the empirical optimum ratio at 14. A point beamlet at the GG is assumed. This assumption leads to an overestimation of the beamlet divergence angle. The filling hydrogen pressure without discharge is 0.35 Pa, and the output power of the RF generator is 70 kW. The negative ion density is 2×10^{17} m^{-3}, and the plasma density is the order of 10^{17} m^{-3} near the PG. The beamlet divergence decreased with a lower

extraction voltage, reaching 9 mrad in the horizontal direction at an extraction voltage of 3 kV, which is the minimum voltage at the NIFS-NBTS. Although the actual beamlet size is unknown, if the 5 mm beam diameter at GG is adopted as the other RF negative ion source development facilities for the ITER-NBI, the beamlet divergence angle of 9 mrad in the point beamlet assumption becomes 7 mrad, which meets the ITER requirement. Although the beamlet divergence should increase if the extraction voltage is too low, the bottom of the beamlet divergence angle does not appear here. This suggests that a smaller beamlet divergence angle than 7 mrad can be achieved in the FA/RF hybrid NIFS-RNIS in RF-mode by using an extraction voltage lower than 3 kV, i.e., by optimizing the perveance, a parameter that relates to the balance between negative ion density and extraction voltage.

5. CONCLUDION

The FA/RF hybrid NIFS-RNIS underwent servicing to explore the minimum beamlet divergence angle with negative ion density enhancement by the Cs seeding. The negative ion density increased from 0.4×10^{17} m^{-3} to 2×10^{17} m^{-3} by the Cs seeding at the RF generator output power of 70 kW. The beamlet divergence angle of 9 mrad in the point beam assumption at GG was observed, and that of the ITER requirement of 7 mrad has been evaluated in the assumption of a diameter of 5 mm at the GG. A prospect of a smaller beamlet divergence angle was obtained by optimizing the negative ion density and the perveance condition.

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