Beamlet divergence of research and development negative ion source with RF mode at NIFS

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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 radio frequency-driven (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 filament-driven arc (FA) negative ion source for the NBI on the Large Helical Device (LHD). Recently, an upgraded Research and development Negative Ion Source at the National Institute for Fusion Science (NIFS-RNIS) demonstrated 7 mrad even at low beam energy of 50 keV in RF mode using cesium (Cs) seeding. With higher beam energy like the HNB and DNB, the beam divergence should satisfy the ITER requirement of less than 7 mrad. Experimentally getting optimal perveance, which is a parameter of the balance between negative beam current affected by negative ion density and extraction voltage, as well as optimal beam focusing condition with respect to the ratio of the acceleration and extraction voltages, a beamlet divergence of less than 7 mrad should be achievable. Thus, a promising outlook for meeting the beamlet divergence requirement for the ITER project has emerged.

The NIFS-RNIS is an FA negative ion source of the same type as a giant negative ion source for operating NBI on LHD with a beamlet divergence of lower than 7 mrad and has been upgraded to FA and RF negative ion source by a collaboration with NIFS, ITER organization (IO) and Max Plank Institute for Plasma Physics (IPP). Direct performance and physics comparisons are possible with the upgraded NIFS-RNIS installed on a neutral beam test stand (NIFS-NBTS). At the FEC29, our collaboration confirmed that the NIFS-RNIS with RF mode could be successfully operated.

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 operates at optimal extraction and acceleration voltages. After the 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. The Cavity Ring-Down technique (CRD) was implemented to measure negative ion density, a crucial parameter for confirming the increase in negative ion density due to Cs seeding, and to compare the FA and RF sources. 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 temperature of the plasma grid (PG), which is the ion source plasma-facing and the first grid electrode of the accelerator, is vital because negative ions are produced on the low work function surface of the PG. With operation across a two-minute period, the negative ion density rose to 1.2×10^{17} m^{-3} after approximately 100 shots (Fig. 1), 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 but similar to those of the developing RF negative ion sources for the ITER project. This marks the first negative ion density enhancement observation 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. We have not fully understood the characteristics of the upgraded NIFS-RNIS in RF mode, still, this density is less than that of the well-Cs-conditioned original FA NIFS-RNIS, where the density was $2.5 - 3 \times 10^{17}$ m^{-3}.

The beamlet divergence of the NIFS-RNIS with RF mode was investigated with the Beamlet Monitor (BM). The BM consists of a carbon fiber-reinforced carbon composite (CFC) tile with the carbon fiber aligning the beam direction and an Infrared thermography camera (IR camera). The beamlets hit and heat the CFC tile, and the IR camera measures the temperature profiles on the backstream surface of the CFC tile (Fig. 2). 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. The IR camera views the CFC tile from a diagonal behind. The beamlet profile elongates vertically due to not only the line of sight of the IR camera but also the vertically and horizontally asymmetric accelerator grid electrode system of the NIFS RNIS. Figure 3 shows the beamlet divergence variation of the beamlet indicated in a circle in Fig. 2 for the extraction voltage. A ratio of acceleration to extraction voltages changes around the empirical optimum ratio at 14. 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 in the order of 10^{17} m^{-3} near the PG. The beamlet divergence decreased with a lower extraction voltage, reaching the ITER requirement of 7 mrad in the horizontal direction at an extraction voltage of 3 kV, which is the minimum voltage at the NIFS-NBTS. Here, as other RF negative ion source facilities use, the beamlet diameter at the grounded grid (GG) of the NIFS-RNIS is assumed to be 5 mm. Although the beamlet divergence should increase if the extraction voltage is too low, the bottom of the beamlet divergence does not appear in Fig. 3. This suggests that a smaller beamlet divergence than 7 mrad can be achievable in the current NIFS-RNIS configuration by using an extraction voltage lower than 3 kV or a lower negative ion density, i.e., by optimizing the perveance, a parameter relating to the balance between negative ion density and extraction voltage.

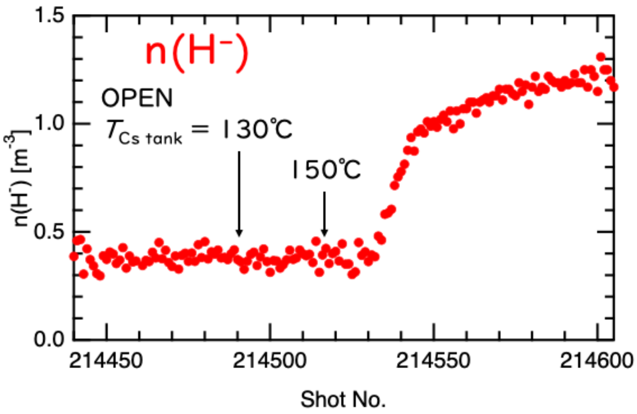

Figure 1. Shot trend of negative ion density before and after cesium seeding start

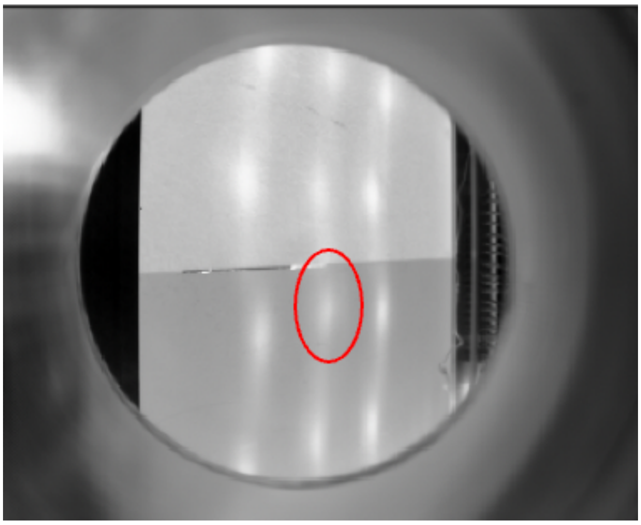

Figure 2. Beamlets profile image obtained by IR-camera using CFC tiles

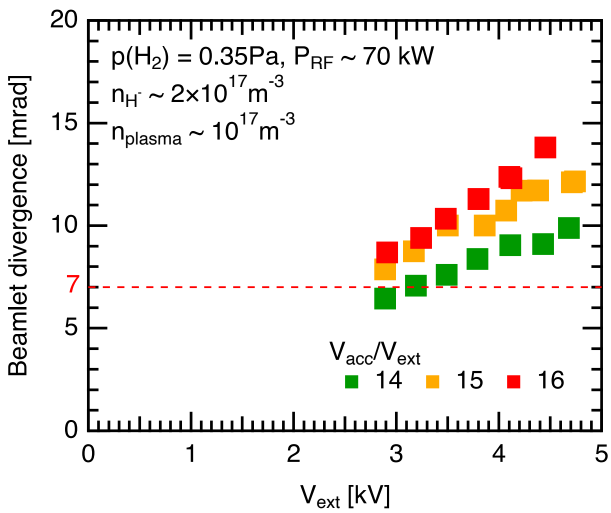

Figure 3. Beamlet divergence variation of the beamlet in a red circle in Fig. 2 for beam extraction voltage. Beamlet diameter at the grounded grid is 5 mm.