Characteristics of High-Power-Density and Focused Neutral Beam System

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1. Introduction

Neutral beam injection (NBI) systems have been widely used for heating, current drive, momentum injection and diagnostics in magnetically confined nuclear fusion plasmas. In reversed-field pinch (RFP) plasmas, topics such as current drive to suppress the dynamo electric field, and plasma heating for beta limitation study are important issues. However, a highly focused beam with a diameter less than 100 mm is required in several cases, particularly the RFP device where NBI must be performed through a very narrow aperture in the vacuum vessel [1]. To prevent particle orbit loss and beam shine through, beam energy is limited to less than ~30 keV. For beam focusing and high power injection, an NBI system using concave electrodes of large area is designed and fabricated. In the present paper, the superior focusing characteristics of this NBI system are described.

2. Experimental setups

Three concave-type electrodes, acceleration, deceleration and grounded electrodes, are used, wherein the designed focal length is 1860 mm and effective diameter of the extraction region is 345 mm. The extraction aperture diameter of the concave acceleration electrode with a meniscus structure is 4.0 mm at the ion-source side [2,3]. The transparency of each electrode is ~50 %. The distance between the acceleration and deceleration electrodes is 5.5 mm, and that between the deceleration and grounded electrodes is 2.0 mm. The thickness of all electrodes is 2.0 mm. Hydrogen plasma is produced using a bucket ion source whose inside surface is covered by a copper sheet 2.0 mm thick to prevent accidental arc erosion. Cusped magnetic field is

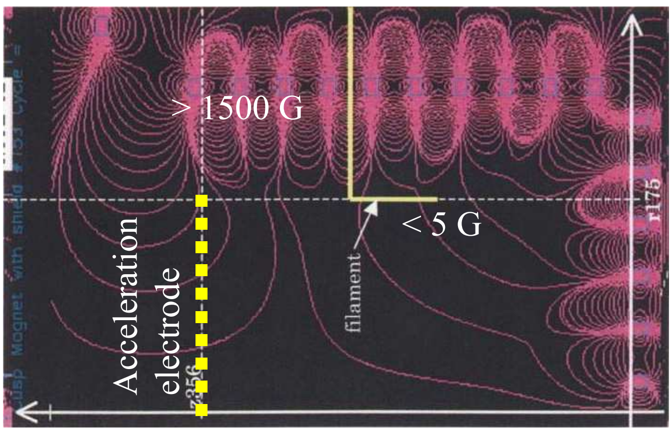

Fig. 1. Contour plot of the calculated magnetic field.

larger than 1500 G at the inside surface of the chamber, and residual magnetic field in the plasma is smaller than 5 G, as shown in Fig. 1. The analyzed magnetic field almost coincides with that measured using a gauss meter.

A power supply (PS) system with capacitor banks is adopted. Specifications of PSs are 30 kV and 50 A with voltage ripples less than 5% for the acceleration PS, -5 kV and 6 A for the deceleration PS, and 300 V and 1 kA for the arc PS. The filament PS of DC operation (30 s) has the specifications of 20 V and 2700 A (= 180 A x 15 sets of filaments), and constant-voltage control is programmed with the setting accuracy of 0.1%. Narrow hairpin tungsten filaments of ϕ2 mm are adopted as cathodes. The designed beam duration is 30 ms.

3. Experimental results

Figure 2 shows the shot history with time evolution of the ion beam power, P_{beam} (= I_{ext} x V_{acc}). Here, I_{ext} indicates extracted beam current, which is defined as the difference between the drain current and the current flowing to the deceleration electrode. V_{acc} indicates the acceleration voltage. They are measured at the line between the electrode and the PS. At the initial stage of beam extraction experiments, the breakdown between acceleration and deceleration electrodes takes place even in the case of low acceleration voltage (black line in Fig. 2). If a breakdown is induced, the switches of acceleration, deceleration and ark PS systems are designed to be open such that the voltages become zero. After that, voltages are applied again with an interval of several ms to repeat the discharge. This repetition of restart during one shot is very effective for the aging (cleaning) of both electrodes and the ion source. As a result, constant beam extraction during the discharge with the designed specifications is obtained (yellow line in Fig. 2). Here, in order to keep V_{acc} (as a result, P_{beam}) constant, one of the resistances in the circuit is bypassed utilizing IGBT switches. Six resistances of 16.7 ohm each are installed in series in the circuit and hence, the six-step recovery of V_{acc} is possible.

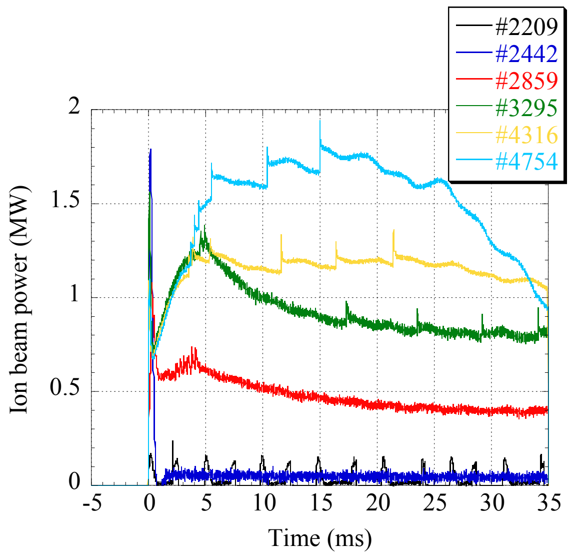

Fig. 2. Shot history with time evolution of P_{beam}.

At present, P_{beam} of ~1.8 MW and I_{ext} of ~75 A are achieved (sky-blue line in Fig. 2), which is ~50% higher than the designed value. The reduction of P_{beam} after t~20 ms is due to the capacitor limitation of the acceleration and arc PSs.

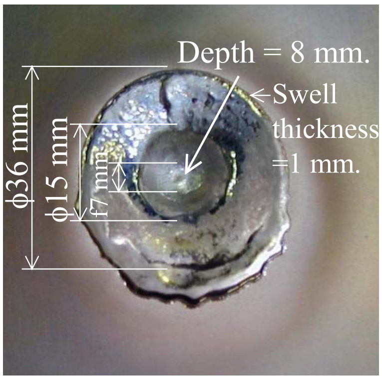

Fig. 3. Beam trace of the melted copper target plate.

The beam profiles are measured using a thermocouple probe with ϕ10 mm aperture and a melted pattern of the target plate, which are installed in the target chamber. The movable probes can be swept in X, Y (horizontal) and Z (vertical) directions. Figure 3 shows the beam trace of the melted copper target plate at X= 1383 mm from the electrode (X=0 mm). The beam diameter is measured as the spot size of the beam trace to be ϕ~36 mm. Figure 4(a) shows the beam profile measured by the thermocouple at X=1680 mm in the case of V_{acc}~24 kV and I_{ext}~55 A. The beam spreads are estimated as the half width at 1/e of the peak values. We can see that the beam has a ground-shaped profile. The shape coincides with the shape of the beam trace of the melted stainless-steel target plate. It is inferred that the acceleration electrode is locally deformed by heat radiation of the filaments during the shot. Figure 4(b) shows the beam profile measured by the thermocouple at X=2150 mm. The beam spreads become broader, and temperature increments become smaller than those in Fig. 4(a), respectively.

As shown in Fig. 5, beam trajectory is estimated by fitting the beam profile data. This gives the beam divergence angle of about ±0.8 deg and the focal length becomes approximately ~1400 mm from the electrode, which is shorter than the designed value. This

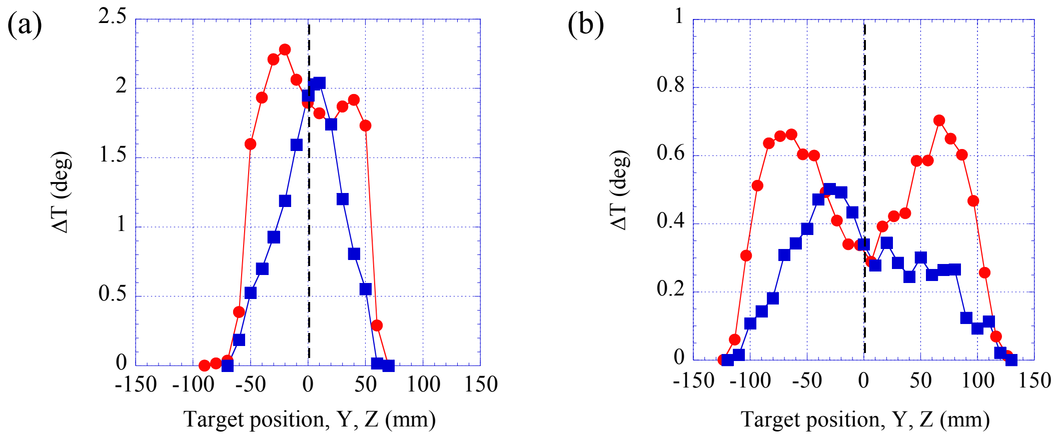

Fig. 4. Beam profiles measured by the thermocouple in the case of V_{acc}~24 kV and I_{ext}~55 A, (a) at X=1680 mm, and (b) at X=2040 mm. Red and blue symbols indicate horizontal and vertical scanning data, respectively.

might also be due to the deformation of the acceleration electrode. The beam power (1.24 – 1.69 MW) estimated from the beam profile data is in the range of 69 - 94% of P_{beam} measured on the electrode side. Nevertheless, the maximum beam power obtained in the case of I_{ext}~75 A is higher than the designed value. It is considered that the beam component extracted from one part of the deformed electrode probably diverges to the inner wall of the neutralization gas cell. As a result, power density as high as ~1 GW/m^2 is attained at the focal point of the neutral beam in the case of I_{ext}~75 A.

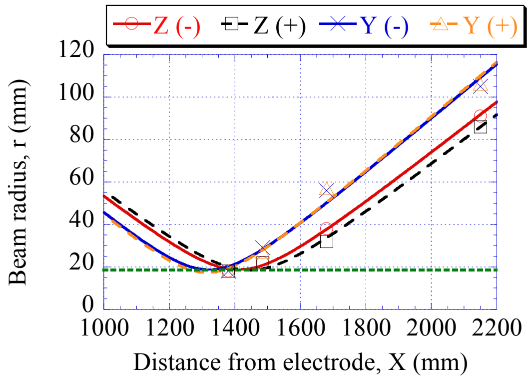

Fig. 5. Beam trajectory estimated by fitting the beam profile data of Y- and Z-axis scanning.

4. Summary

A strongly focused high-power-density neutral beam system with large-area concave electrodes is successfully developed. The obtained beam performance is estimated to be 1.24 – 1.69 MW at maximum, which is higher than the designed value. It is estimated that a beam with a diameter of 345 mm at the electrode is focused to a diameter of ~36 mm at the focal point with the divergence angle of about ±0.8 deg. As a result, a power density as high as ~1 GW/m^2 is attained at the focal point of the neutral beam.

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