Advanced Negative Ion Beam Technology to Improve the System Efficiency of Neutral Beam Injectors

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Abstract Technologies producing high current density (>20mA/cm2) negative ions at a low operating gas pressure (<0.3Pa) has been established. Reduction of the gas pressure is efficient to improve the acceleration efficiency of neutral beam injectors. Beam optics in a multi-aperture, multi-stage electrostatic accelerator has been studied using a 400keV negative ion source. It was found that the ion beam tends to expand because of beamlet-beamlet interaction. The effect was confirmed by 3D beam trajectory simulation code. Beam steering technology by aperture displacement has been established to compensate the effect and to focus the beam precisely toward the injection port, which improves the geometrical efficiency of neutral beam injectors. A plasma neutralizer producing a high-density plasma ($1.7x10^{12}$ cm^{-3}) with a high degree of ionization (0.15) has been developed.

1. Introduction

After the successful demonstration of 1MeV acceleration of negative ion beams [1] for ITER and the high current negative ion beam production of 18.5A/6.7MW in JT-60 N-NBI [2], the R&D efforts for NBI at JAERI are focused to improve the reliability and the efficiency of the negative-ion-based NB system.

The overall efficiency of NB system is determined by acceleration efficiency in the ion source, geometrical efficiency depending on the beam divergence and the acceptance of the beamline, neutralization efficiency in the neutralizer cell, and re-ionization loss in drift tube. It is important to improve the efficiency not only for increasing the injection power but also for minimizing the heat load to the beamline components for reliable operation of NB system.

To improve the acceleration efficiency, it is necessary to reduce the operating gas pressure in the negative ion source. This is because the loss in the accelerator is mainly due to the stripping of negative ions by the collision with residual gas molecules. Although the negative ion current tends to decrease at a lower operating gas pressure, the Kamaboko source developed at JAERI [3] has a capability to produce high current negative ion beams even at a low operating gas pressure of less than 0.3 Pa.

Good beam optics is also important to prevent the direct interception of the negative ion beams and to improve both the acceleration efficiency and the geometrical efficiency. Precise focusing of the multiple beamlets extracted from large-area, multi-aperture girds are required to enhance the geometrical efficiency. The development of a plasma neutralizer, which has higher neutralization efficiency than the presently used gas neutralizer, will improve the system efficiency drastically (from 40% to 60%).

In the present paper, progress on the negative ion beam development at JAERI is presented from a viewpoint of improving the NB system efficiency.

2. Negative Ion Production at Low Operating Gas Pressure

The measurement of the heat loading of MeV accelerator [1] revealed that the beam-gas interaction including stripping of the negative ions is the dominant process of the power loss in the accelerator. Therefore, most efficient way to enhance the acceleration efficiency is to reduce the operating gas pressure. However, the negative ion production efficiency tends to decrease at a lower operating gas pressure. To improve the negative ion yield, the negative ion production mechanism has been studied in a cesium seeded volume negative ion source using Laser photoelectron emission measurement [4]. Figure 1 shows the enhancement of the negative ion current when the plasma grid temperature is increased after the cesium seeding. The negative ion current increases by more than a factor of three, which is related to the increase of the photoelectron current indicating that the work function of the plasma grid decreased from 2.2eV to 1.8eV. There was no change in the cesium density and the other plasma parameters. It is concluded that the main mechanism of the negative ion production at a low gas pressure is the conversion of atomic hydrogen at the plasma grid surface that is coated by cesium to have a low work function. Therefore, high negative ion yield is expected by improving the plasma confinement so as to produce ions and dissociated atoms efficiently even at a low operating gas pressure.

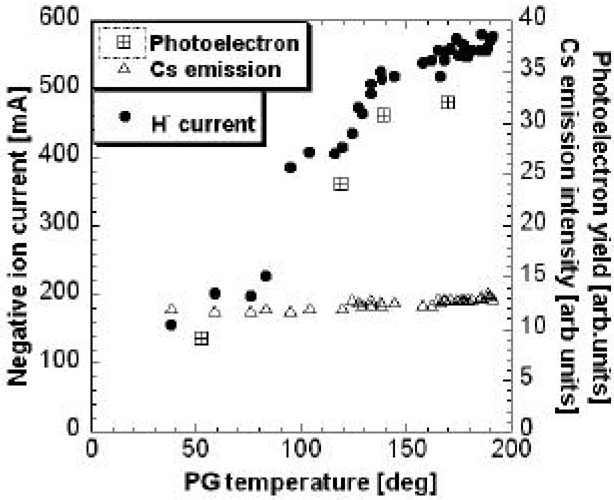

Fig.1 Dependence of the negative ion current, photoelectron current, and the cesium light intensity as a function of the plasma grid temperature.

Table I summarize the various negative ion sources developed at JAERI with typical operating parameters and the operating gas pressures. Although the size of the source differs from 15cm (IS for Linac[5]) to 122cm (JT-60 Source[2]), the negative ion current density can be scaled by the arc discharge power density. Figure 2 shows the negative ion current density as a function of the surface power density, which is defined by the arc discharge power divided by total surface area of the plasma generator. The large negative ion source developed at NIFS for LHD has produced 25A H- ion beam with a current density of 25mA/cm2 [6]. It is also shown in Fig.2, as pointed by “LHD”. Although the highest current density of 80mA/cm2 has been obtained in the “IS for Linac” developed for linear accelerator [5], the operating gas pressure is too high for use in NB system.

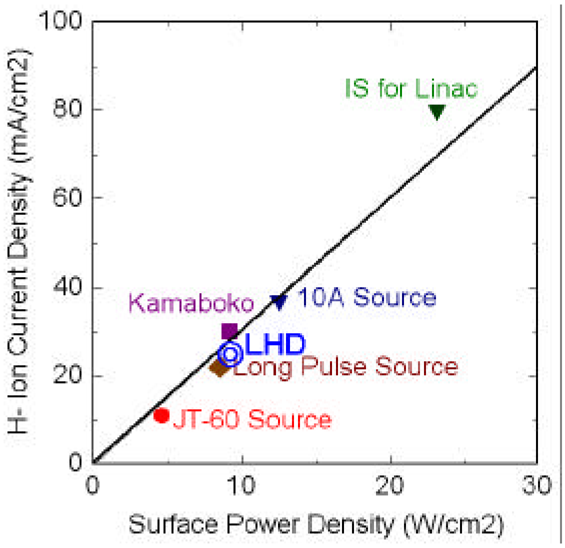

Fig. 2 Scaling of the negative ion sources developed at JAERI and NIFS on the negative ion current density

As discussed, the operating gas pressure tends to decrease by improving the confinement of the plasma generator.

Figure 3 shows the operating gas pressure as a function of the volume/surface ratio (V/S), which is a good index of the plasma confinement. The JT-60 source [2], which is a large Kamaboko source having better plasma confinement, is operated at a lower pressure of 0.15 Pa. The negative ion source for ITER-NBI [7] is designed to have the surface power density of 13W/cm2 and the volume/surface ratio of more than 20. Therefore, the ITER source is expected to produce more than 30mA/cm2 H- (>20mA/cm2 D-) at a low operating gas pressure of less than 0.15 Pa. The stripping loss of the negative ions in the accelerator is reduced to <10 % at 0.15 Pa.

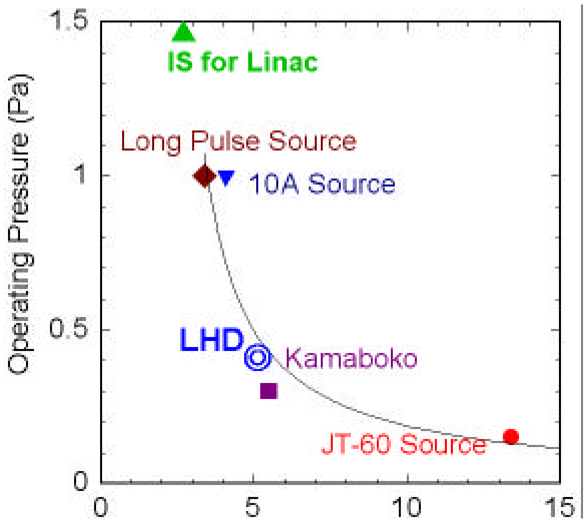

Fig. 3 Scaling of the negative ion sources developed at JAERI and NIFS on the operating gas pressure

Table I High current negative ion sources developed at JAERI

	JT-60 Source	Kamaboko	10A Source	Long Pulse Source	IS for Linac
H- ion beam achieved	18A, 360keV 1s	2.1A,5 0keV 60s	10A, 50keV 1s	0.8A, 50keV CW	0.04A, 70keV 5% CW
Dimension	70cmϕ x 122cm	34cmϕx 34cm	48cmx23c m x 16cm	22cmϕx 18cm	15cmϕx 20cm
Arc Power (kW)	160	50	56	17	30
JH- (mA/cm^2)	11	30	37	22	80
Surface Power Density (W/cm2)	4.64	9.18	12.5	8.49	23.2
V/S (cm)	13.4	5.5	4.1	3.4	2.7
Source Pressure(Pa)	0.15	0.3	1	1	1.5

3. Beam Optics

To improve the geometrical efficiency, the beam optics has been optimized using a 400keV negative ion source. Negative ions are extracted from 25 (5x5) apertures of 14mm in diameter and accelerated in three stage electrostatic accelerator. Figures 4-(a),(b) show the aperture pattern and the accelerated negative ion beams. The beamlet divergence is so small that it is possible to distinguish each beamlet at the target placed 1.5m downstream of the ion source. The contour of the beamlets was measured by an infrared image camera, as shown in Fig.4-(c). The beamlet divergence is as low as 3mrad, which is low enough for use in ITER-NBI. The displacement of the beamlets in horizontal direction is due to the deflection of the negative ions by the magnetic field for the electron suppression in the extractor. It was found that the outermost beamlets are deflected outwards by the negative of

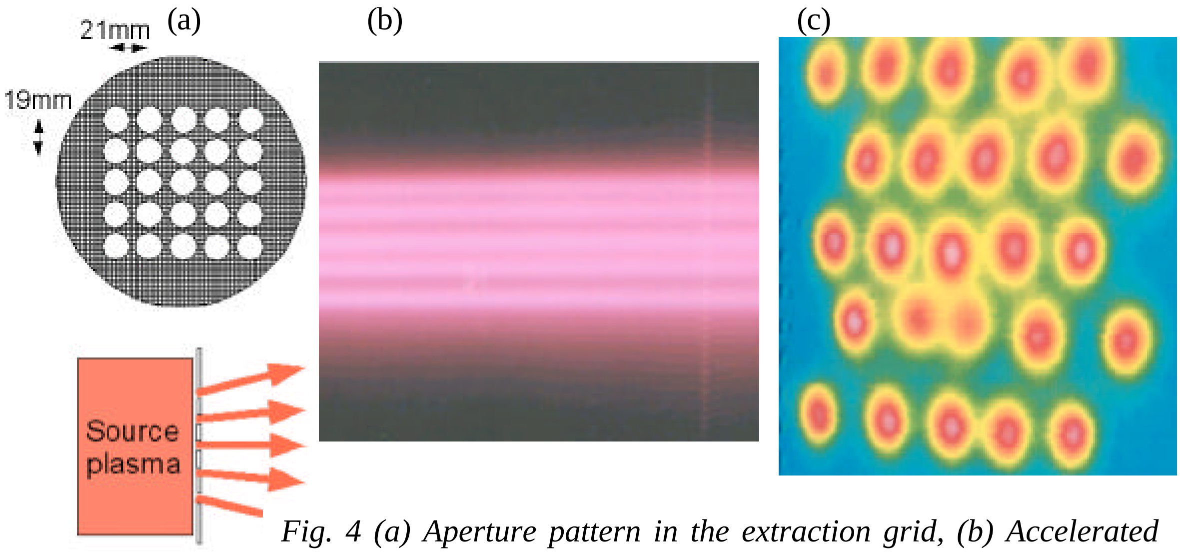

Fig. 4 (a) Aperture pattern in the extraction grid, (b) Accelerated negative ion beam, (c) Infrared image of the beamlets at the target

ion space charge of other beamlets. This is the first observation of the beamlet-beamlet interaction in a negative ion source.

Figure 5 shows an example of emittance diagram of multi-beamlets calculated by 3D ion beam trajectory simulation code (OPERA-3D), where negative ions are extracted from 9 beamlets (3x3) and the distance between the apertures is 22mm. The outer beamlets are shifted by 1mm at the exit of the grounded grid and also deflected by 3mrad because of the beamlet-beamlet interaction. The deflection angle is consistent with the experimental observation.

These effects can be corrected by shaping the acceleration apertures asymmetrically and/or by beamlet steering using the aperture displacement technique, which has been demonstrated experimentally. Figure 6 shows the beamlet steering angle as a function of the aperture displacement distance, where the grounded grid is displaced in the three stage electrostatic accelerator. The steering angle is independent to the beam energy and is agree

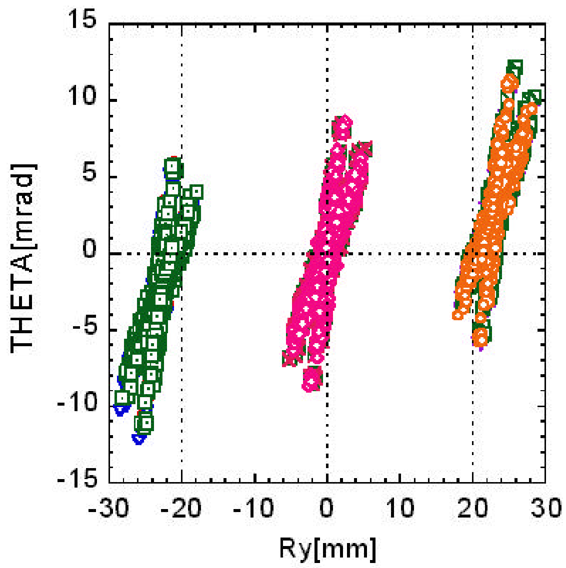

Fig.5 Emittance diagram of multi-beamlets calculated by 3D ion beam trajectory simulation code (OPERA 3D)

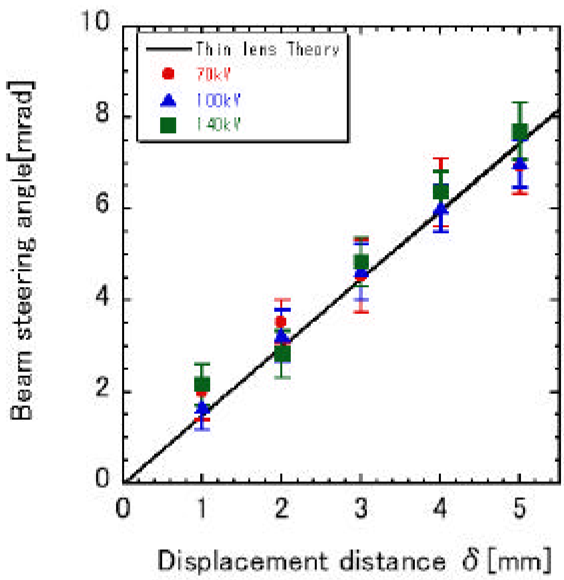

Fig.6 Beam steering angle as a function of aperture displacement distance in three stage electrostatic accelerator.

well with the thin lens theory and the 3D-simulation code. Based on these studies, it becomes possible to focus the multiple beamlets precisely toward the injection port to enhance the geometrical efficiency.

4. Plasma Neutralizer

To improve the system efficiency further, a plasma neutralizer is being developed at JAERI. It consists of a large cylindrical plasma chamber (0.6m in diam, 2m long) and strong magnetic line cusps surrounding the chamber. Plasma is created by arc discharge between filaments and the chamber wall. The operating gas pressure tends to decrease as the plasma confinement is improved. The discharge was stable up to the discharge power of 30kW even at a low gas pressure of 0.01Pa. Good uniformity of <10% was observed in both radial and axial directions within the field-free region, which starts around 7cm from the chamber wall.

The plasma density and the degree of ionization increase as the discharge power increases. The argon plasma density of 1.7×10^{12} cm^{-3} was obtained efficiently at a low operating pressure of 0.05 Pa, resulting in a high degree of ionization of 15% at an arc discharge power of 30kW. The line density is 3.5×10^{15} cm^{-2}. It is expected that the neutralization efficiency is improved from 60% to 70% for 100keV H- ions. The neutralization experiment is planned in a 400keV H- ion beam test facility at JAERI.

5. Conclusion

To minimize the stripping loss in the accelerator, high confinement negative ion source producing high current negative ions at a low operating gas pressure has been developed. Beam steering technology to focus the multiple beamlets has been established to improve the geometrical efficiency. A plasma neutralizer, which produces high density plasma with a high degree of ionization, has been developed. These technologies have possibility to enhance the system efficiency largely in the future negative-ion-based NBI.

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