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# Origin of beam non-uniformity in a large Cs-seeded negative ion source

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Origin of the longitudinal beam non-uniformity, that is one of the key issues in large Cs-seeded negative ion sources for fusion application, was experimentally investigated in the JAERI 10 A negative ion source. After a sufficient caesium of ~0.3 g was seeded in the negative ion source to enhance the negative ion production, the longitudinal distribution of the beam intensity was measured. The distribution of the beam intensity was non-uniform, and was absolutely different from that without Cs. From the correlation between the beam intensity and the plasma parameters, it was found that the beam non-uniformity was due to the localization of the plasma caused by B x  $\nabla$ B drift of the fast electron from filaments. Here, B is the magnetic field near the filaments whose strength is the sum of the magnetic filter field and the confinement magnetic filed around the negative ion source.

To improve the beam non-uniformity, the B x  $\nabla$ B drift of the fast electrons from filaments was suppressed by modifying the filament configuration. The beam non-uniformity was dramatically improved. The root-mean-square deviation of the beam intensity from the averaged value deceased to a half of that before the modification while the beam intensity integrated along the longitudinal direction was kept to be constant. Thus it was experimentally confirmed that the beam non-uniformity was improved by suppressing the B x  $\nabla$ B drift of the fast electrons from the filaments.

## I. INTRODUCTION

In the JT-60 negative ion source, high current negative ion beams of >20A have been already produced through a large extraction area of 45cm x 120cm [1,2]. However, the beam pulse length at high current operation is limited to be < 1s by high power loadings on acceleration grids and on beamline components. One of the reasons for the high power loadings are due to the poor beam divergence angle that is caused by a longitudinal nonuniformity of the negative ion density. Therefore, the improvement of the beam nonuniformity is the critical issue for expanding the beam pulse length.

A basic study for investigating the cause of the beam non-uniformity has not sufficiently been carried out and drastic improvements have not been achieved so far [3-5]. In a pure volume production source, the beam non-uniformity was due to a local destruction of the negative ions caused by collisions with high-temperature electrons [6]. In the caesium (Cs)-seeded negative ion source for JT-60U and ITER where H<sup>+</sup> ions and/or H<sup>0</sup> atoms capture the electrons from the caesiated PG surface, the production process of the negative ions is absolutely different from that in the pure volume production source. In addition, it is also considered that the destruction process of the negative ions produced on the PG surface in the Cs-seeded negative ion source are accelerated with the space potential (typically  $2\sim3 V$ ) of the plasma so that the temperature of the negative ions is higher than that in the pure volume production source. Therefore, it is considered that the cause of the beam non-uniformity in the pure volume production source is not applicable to the case in the Cs-seeded negative ion source.

A purpose of the present paper is to clarify the origin of the beam non-uniformity in the Cs-seeded negative ion source. The JAERI 10A negative ion source [7] was used. By measuring the correlations between the beam intensity, the work function of the PG, and plasma parameters, the origins of the beam non-uniformity were examined. Electron trajectories were also calculated by 3D ELEORBIT [8] to understand the behaviour of the high-energy electrons from the filaments. In this paper, an experimental apparatus will be described, and the origin of the beam non-uniformity in the Cs-seeded negative ion source will be discussed.

#### II. EXPERIMENTAL APPARATUS

Figure 1 shows the horizontal and longitudinal schematic diagrams of the JAERI 10A negative ion source. Cartesian coordinate is also shown in this figure. The origin of Z-

axis is at the surface of a plasma grid (PG). The JAERI 10A negative ion source is composed of a plasma chamber and an extractor. The dimensions of the plasma chamber are 240mm in width, 480mm in height and 203 mm in depth. The plasma chamber is the same type as the JT-60 and ITER negative ion sources, namely, a Cs-seeded volume type with a magnetic filter. The plasma chamber wall was fully surrounded by five bar magnets on sidewalls, four bar magnets on the upper and lower walls, and six bar magnets on the back-plate. The magnetic cusp lines on the sidewalls, the upper and lower walls are named as 1st, 2nd, 3rd, 4th, and 5th cusp lines from the PG. The polarities of the magnetic fields on the upper and lower walls were reversed at X=0, where the transverse magnetic fields are created. A pair of the magnets (filter magnets) was placed at X=  $\pm$  124mm and Z=14 mm to decrease the temperature of the electrons near the PG. The filter field was strengthened by the 1st cusp line magnets whose polarities were the same as those of the filter magnets.

Four pairs of tungsten filaments were longitudinally placed between the 2nd and the 3rd cusp lines. The longitudinal positions of #1&5, #2&6, #3&7, #4&8 filaments were at Y=162, 54, -54 and -162 mm, respectively. To fire the discharges, the plasma chamber wall and the filaments were served as an anode and a cathode, respectively. The negative ion source was operated at 0.3 Pa, that is the design value of the JT-60 and ITER negative ion sources.

To enhance the negative ion production, a sufficient amount caesium of ~0.3g was seeded in the negative ion source from a caesium oven installed on the back-plate. The work function of the PG surface was measured by irradiating the  $Ar^+$  ion laser beams with four different wavelengths of 458, 488, 514 and 633nm. By extrapolating the photoelectron currents emitted from the PG surface according to Fowler equations [9], the work functions of the PG surface were estimated. The plasma density and the electron temperature were measured by Langmuir probe.

The H<sup>-</sup> ions were extracted from an ion extraction area of 140mm x 340mm by four grids at the energy of 20-40 keV. The longitudinal length of the ion extraction area is about 1/3 of the JT-60 U negative ion source. The extraction voltage was optimised so as to extract the ions at an emission limit condition. The longitudinal distribution of the beam intensity was measured by a multi-channel calorimeter placed at 0.8m downstream from the grounded grid of the negative ion source.

#### III. DISTIBUTION OF THE BEAM INTENSITY WITH AND WITHOUT Cs

The longitudinal distribution of the beam intensity with Cs was measured and compared with that without Cs. When the negative ion source was seeded with Cs, the PG temperature was kept at 240 °C to enhance the negative ion production. At this temperature, the total beam current increased by a factor of 4 at an arc power of 10 kW. This shows that the negative ions were produced mainly via the surface production process by seeding the caesium.

Figure 2 shows the longitudinal distributions of the beam intensity with and without Cs. Without Cs, the beam intensity was relatively low in the region of Y > 50 mm since the electron temperature was higher than 1 eV [6]. On the contrary, the beam intensity with Cs was relatively high in the same region of Y>50mm. The beam intensity distribution with Cs was absolutely different from that without Cs.

# IV. CORRELATION WITH THE WORK FUNCTION ON THE PLASMA GRID

In the Cs-seeded negative ion source, the negative ions are considered to be produced via the surface production process on the PG surface whose work function is lowered. Since the negative ion production is strongly dependent on the work function of the PG surface [10,11], it was considered that one of the possible beam uniformity was due to the non-uniformity of the work function. Before the measurement of the work function distribution, the PG temperature ( $T_{PG}$ ) was measured because the work function is dependent on the  $T_{PG}$  when caesium is sufficiently seeded in the negative ion source. The longitudinal distribution of the  $T_{PG}$  was uniform within  $\pm 5^{\circ}$ C during the discharge. This is considered to be due that the PG was heated uniformly by the radiation from the filaments.

Figure 3 and 4 show the longitudinal distributions of the work function and the beam intensity for  $T_{PG}$ =60 °C to 200 °C, respectively. As shown in Fig.3, the work functions were longitudinally uniform over the ion extraction region of -170<Y<170mm at both PG temperatures. However, the beam intensity was relatively high in the region of Y> 50mm at both PG temperatures as shown in Fig.4. There was still beam non-uniformity even for the uniform work function on the PG surface. This indicates that main reason of the beam non-uniformity was not due to the distribution of the work function in this experiment.

### V. CORRELATION WITH THE PLASMA PARAMETERS

Since the negative ions are considered to be produced from the  $H^+$  ions and/or the  $H^0$  atoms in the Cs-seeded negative ion source [12], it was considered that one of the possible

beam non-uniformity was due to the plasma non-uniformity. The distributions of the plasma density and the electron temperature near the PG were measured. Figure 5 shows the longitudinal distribution of the electron temperature with and without Cs at Z=14mm. There was no significant difference between the electron temperature distributions with and without Cs. In the present experiment, no electron cooling by Cs seeding was observed. This small variation of the electron temperature was due that the caesium amount in the negative ion source was very small as observed also in the KAMABOKO source [13].

Both of the electron temperatures with and without Cs were relatively high locally in the region of Y> 50mm, where the plasma density was also high. These non-uniformities of the electron temperature and the plasma density show that the plasma was localized in the region of Y> 50mm. As shown in Fig.1, the beam intensity with Cs was relatively high in this region although the electron temperature was high enough to destroy the negative ions produced in the pure volume source.

The local high beam intensity is considered to be due that the surface production of the negative ions was locally enhanced since the plasma was localized. It is also considered to be due that the negative ions via surface production process were extracted without the significant destruction by collisions with the high-temperature electrons because the mean free path for the negative ion destruction is four times longer than Larmor radius of the negative ions.

#### VI. CAUSE OF THE PLASMA NON-UNIFROMITY

To investigate the localization of the plasma in the region of Y>50mm, the magnetic field and the electron trajectory were calculated using a 3D electron trajectory code, ELEORBIT [8] where electron cooling processes by collisions with particles were neglected.

Figure 6-A and B show the contour map of the magnetic field of Y-Z plane at X=0 and the vector diagram of magnetic field of X-Z plane at Y=0, respectively. The transverse magnetic field penetrates deeply into the discharge chamber. Even in the driver region of Z=120mm, the relatively strong transverse magnetic field of 10-30 Gauss is created. At 10 Gauss, the Larmor radius of the electron at 60eV, equivalent to the arc voltage, is as short as 24mm. This short Larmor radius means that electron motion is restrained whole in the plasma chamber.

The unexpected magnetic field is created near sidewalls. A part of the strong filter field links with the fourth cusp magnets placed at Z=132 mm, consequently, the relatively strong magnetic fields of >100 Gauss are created near the both sidewalls where the filaments

are placed. As shown in electron trajectories in Fig.6-B, some of the high-energy electrons are trapped in this field. Since the gradient of this field in X direction is sufficiently large, the trapped electrons move upward by B x  $\nabla$ B drift as shown in Fig.7. This calculated upward drift of the fast electrons was observed also in the experiment [6]. Therefore, it is concluded that the plasma non-uniformity was due mainly to the B x  $\nabla$ B drift of the fast electron from filaments.

#### VII. IMPROVEMENT OF THE NEGATIVE ION UNIFORMITY

To suppress B x  $\nabla$ B drift causing the beam non-uniformity, the filaments was modified. The original filament was bent to the back-plate as shown in Fig.6-B. The filaments were entirely immersed in the cusp magnetic field that drives the fast electrons upward. To suppress the upward drift of the electrons, the filament was bent to the PG side as shown in Fig.8. Although a part of the filament near the sidewall is still immersed in the cusp magnetic field, the front edge of the filament is in the transverse filter field that drives the electrons downward. It was confirmed in the calculation that the drift of the electrons to the upper region was suppressed by this filament modification

Figure 9 shows that the measured longitudinal distribution of the before and after the filament modification. By the filament modification, the beam intensities decreased slightly in the upper half region of Y>0, and increased largely in the region of Y< 0. As the result, the beam non-uniformity was dramatically improved. The root-mean-square deviation of the beam intensity from the averaged value was improved to be a half of that before the modification while the beam intensity integrated along the longitudinal direction was kept to be constant. It was experimentally confirmed that beam non-uniformity was improved by suppressing the B x  $\nabla$ B drift of the fast electrons from the filaments.

## VIII. SUMMARY

Origin of the beam non-uniformity in large Cs-seeded negative ion sources was experimentally investigated in the JAERI 10 A negative ion source. The longitudinal distribution of the beam intensity was non-uniform and absolutely different from that without Cs. It was found that the beam non-uniformity was due to a localization of the plasma caused by the drift of the fast electron from filaments. To improve the beam non-uniformity, the B x  $\nabla B$  drift of the fast electron from filaments was suppressed by modifying the filament

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configuration. The beam non-uniformity was dramatically improved. Thus, it was confirmed that the beam non-uniformity was improved by suppressing the B x  $\nabla$ B drift of the fast electrons from the filaments.

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Figure 1 Horizontal and longitudinal schematic diagrams of the JAERI 10 A negative ion source



Figure 2 Longitudinal distributions of the beam intensities with and without Cs.



Figure 3 Longitudinal distributions of the work functions for  $T_{PG} = 60$  °C and 200 °C.



Figure 4 Longitudinal distributions of the beam intensities for  $T_{PG} = 60$  °C and 200 °C.



Figure 5 Longitudinal distributions of the electron temperatures with and without Cs at Z=14mm.



Figure 6-A Contour map of the magnetic field of Y-Z plane at X=0 and electron trajectories near the upper wall.



Figure 6-B Vector diagram of the magnetic field of X-Z plane at Y=0 and electron trajectories near the sidewall.



Figure 7 Trajectory of the electrons from the filament.

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Figure 8 Schematic diagram of the filament modification



Figure 9 Longitudinal distributions of the beam intensity after and before filament modification.