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Optimization of negative ion sources for a heavy-ion-beam probe

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The development of plasma-sputter-type negative ion sources is underway for the heavy-ion-beam probe system as plasma diagnostic beams of the large helical device (LHD) for potential and fluctuation field measurements. Our purpose is to increase the doubly charged exchanged Au^+ beam intensity to enhance the detection signal after passing through the plasmas of the LHD. For this purpose, the characterization of the Au^- ion source and the beam optics has been carried out both experimentally and numerically. Based on these results, a new plasma-sputter-type negative ion source is designed and tested. © 2006 American Institute of Physics. [DOI: 10.1063/1.2170094]

I. INTRODUCTION

A heavy-ion-beam probe (HIBP) system has been installed in the large helical device (LHD) to measure the local plasma potential and the fluctuations.¹ It consists of a sputter-type Au^- ion source,² a tandem accelerator, beam steering electrodes, and an energy analyzer. The accelerated Au^- beam undergoes double charge exchange and the resulting Au^+ beam (primary beam), which normally reaches up to 6 MeV, is injected into the LHD plasma. The secondary beam of Au^{2+} produced from the primary beam by electron stripping in the LHD plasma is detected by the energy analyzer. The energy difference between the primary and the secondary beam corresponds to the value of the local plasma potential.

The plasma-sputter negative ion source installed in the present HIBP system produces the mass-separated dc Au^- beam with 10 μA current and 10 keV mean energy. In the experimental campaign of the LHD in 2004, the secondary beam was successfully detected with an adequate signal-to-noise (S/N) ratio for an operational regime with the plasma density lower than 10^{19} cm^{-3} . However, it is predicted that a more intense beam of Au^+ should be injected to realize enough S/N ratio, when the LHD is operated in a regime with the density higher than 10^{19} cm^{-3} . To produce Au^+ primary beam of enough intensity for diagnostics of high density and temperature plasmas, the Au^- beam current of the order of 100 μA is required.

To enhance the Au^+ primary beam current, a negative ion source having larger sputtering target and plasma volume has been designed. For the scale up of the negative ion source, the characteristics of the plasma-sputter negative ion source are investigated at a separate test bench. The computer code, PBGUNS,³ is used to study the properties of Au^- beam extracted from the ion source. Preliminary experimental results of the new ion source are described in this article.

II. EXPERIMENTAL SETUP

Figure 1 shows the Au^- plasma-sputter ion source and the extraction system. The size of the cylindrical ion source is 8 cm in diameter and 9 cm in length. The gold target of 14 mm diameter for sputtering is inserted into the ion source. The electrostatic extraction system consists of an electrode with the 5-mm-diam hole. A pair of permanent magnets is located near the extraction hole to produce the dipole transverse field as an electron suppressor. The tungsten filament the LaB_6 cathode are tested. The argon or xenon plasmas are maintained at the discharge current up to 5 A at the gas pressure of 2×10^{-6} Torr in the beam line of the ion source downstream. By adding cesium vapor into the ion source, the discharge voltage decreases to roughly 20 V. The cesium vapor is supplied continuously during the beam extraction. The Au^- beam current is measured by a Faraday cup located at approximately 50 cm downstream from the extraction electrode. The Einzel lens voltage, V_L , is adjusted to maximize the beam current at the Faraday cup.

FIG. 1. Plasma-sputter-type negative ion source and extraction system.

FIG. 2. Au[−] beam current as a function of target voltage. The discharge current is 5 A with a stable cesium vapor introduction.

III. EXPERIMENTAL RESULTS

A. Dependence on the target voltage

There are two important problems in Au[−] source development suitable for Au⁺ primary beam for LHD-HIBP. One is the optimization of the target voltage, which is deeply related with not only the sputtering rate of Au, but also the beam optics. To increase the sputtering rate, the positive ion density must be increased, and the sufficient high voltage must be applied to the Au target. From the theoretical aspect of the Thompson-Sigmund formula,⁴ however, higher target voltage is considered to cause the growth of the energy spread of Au[−] and the short life of the Au target. Because the higher target voltage and the target lifetime have the opposite aspect, the target voltage is to be kept as low as possible, if the Au[−] beam current is adequate. As shown in Fig. 2, as the target voltage is raised higher, the Au[−] beam current increases. It seems possible to increase the Au[−] beam current even higher by applying the target voltage higher than 500 V.

The other issue is maintaining a low work-function surface of the Au target by the cesium adsorption. The optimum coverage of cesium atoms on the Au target is considered to be around one monolayer. Although it is difficult to accurately monitor this condition, the amount of cesium vapor is controlled by adjusting the heater temperature of the cesium oven in the range from 150 to 180 °C to realize a stable beam output. The Au[−] ion source yielded the Au[−] beam current of 39 μA at the target voltage $V_t = -500$ V and the beam energy of 10.5 keV. However we could not maintain a stable discharge with the Au[−] beam current larger than 10 μA. The stable beam output would depend on the supply of cesium vapor on the Au target surface.

B. Lifetime of filaments and target

The endurance test of filaments and target is performed to choose a filament diameter and an Au target thickness

FIG. 3. (a) 3 MeV Au[−] beam current as a function of the magnetic field of the sector magnet. (b) Au⁺ beam current and other multicharged positive ion current as a function of the electric field of the charge separator.

properly. A tungsten filament with the diameter of 0.7 mm is used to emit thermionic electrons to produce the plasmas. The integrated 140 h could be operated without any apparent fatal damage during the injection to the tandem accelerator. No clear difference was observed by a LaB₆ cathode discharge.

The Au target of 16 mm diameter and 2 mm thickness is attached on the Cu substrate by electron-beam welding. The lifetime of an Au target was approximately 200 h, and the Cu[−] beam due to the substrate material of the target holder appeared toward the end of the experiment. During 1.5 month operation, the mean maximum Au[−] beam current of 3.7 μA was injected into the tandem accelerator.

C. Conversion of Au[−] to Au⁺ beams

Typical beam signals of the LHD-HIBP system are shown in Fig. 3(a) at the low-energy side and Fig. 3(b) at the high-energy side. In Fig. 3(a), the Au[−] beam current of 2.4 μA is extracted stably with the acceleration voltage of 3 MV. The sector magnet located before the injection port of the tandem accelerator separates the pure Au[−] beam from the impurity beams. While the Au[−] beam is injected into the tandem accelerator, the voltage of the sector magnet corresponding to the dipole magnetic field is set to the value at the maximum of Au[−] beam current. Through the gas cell in the tandem accelerator multicharged positive ions are mixed in Au⁺ beams, as shown in Fig. 3(b). These impurity ions are removed by the electrostatic deflector at the downstream of

TABLE I. Comparison between present and new ion sources at the similar discharge conditions.

	Plasma volume (cm ³)	Target size diameter ϕ (cm)	Extraction hole diameter ϕ (cm)	Au [−] current (μA)	Target voltage and current
Present source	346	ϕ1.4	ϕ0.5	6.75 at 9.8 keV	300 V, 15 mA
New source	1057	ϕ2.0	ϕ2.0	65 at 14 keV	600 V, 10 mA

FIG. 4. Beam optics of Au^- ion source calculated by PBGUNS. From the left, the Au target inside the ion source cylinder, the extraction electrode, and the Einzel lens are drawn with the Au^- beam with the energy of 10.5 keV. The equipotential lines are overlaid.

the exit aperture of the tandem accelerator. The deflector voltage is swept at the frequency of 0.05 Hz in this case to detect the Au^+ beam. The Au^+ beam current of approximately $0.15 \mu\text{A}$ is injected into the LHD vacuum vessel successfully with the energy of 6 MeV through beam transport tubes. The conversion efficiency from Au^- to Au^+ is found to be more than 0.1 at the optimum gas pressure of the gas cell.

D. Beam transport

The characteristics of the ion source and beam optics are studied by the computer simulation code, PBGUNS, to enhance the beam intensity. The optimized Au^- beam trajectories are shown in Fig. 4. The beam is well focused to our desired size by adjusting the Einzel lens voltage. Even with our maximum beam intensity, the beam loss due to the space charge was not effective.

E. Scale up of ion source

For the high current and stable dc operation, a new plasma-sputter-type negative ion source, shown in Fig. 5, has been manufactured. The new ion source has 16 Samarium Cobalt magnets to produce the multicusp magnetic fields for plasma confinement, and its volume is three times larger than that of the present ion source. To tolerate high input power

operation, the ion source body and the target rod are cooled by water. The characteristics of two ion sources are summarized in Table I. At the discharge current of approximately 4 A, the Au^- beam current of $65 \mu\text{A}$ could be extracted with the energy of 14 kV from the ion source. The Au^- beam current enhances by a factor of 4–10, compared with the present ion source, although, in front of the Au target, the positive ion density for the new ion source is three times lower than that for the present one. We can expect the higher beam intensity by means of the enhancement of the filament and the discharge power supplies for the creation of higher plasma density for the sputtering of the gold target.

We consider two possibilities for a stable discharge and a high beam output of the new ion source. Owing to the scale up of the ion source, the plasma volume of the new ion source becomes larger than that of the present ion source. It would lead to the enhancement of the uniformity and the stability of plasmas in front of the gold target for sputtering. Another possibility is the following; the temperature of the gold target has to be kept properly because of the optimum adsorption of the cesium atoms. However, for the present ion source the heating by the radiation from the filaments is much stronger than the heat removal. Therefore the scale up causes the temperature decrease of the gold target. It follows the large amount of cesium adsorption on the gold target surface. This is a better condition for the gold negative ion production, because the negative ions require the low work-function surface. The optimizations of the target temperature and electrode shapes will be continued for higher beam currents.

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FIG. 5. New plasma-sputter-type negative ion source.

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³PBGUNS, Thunderbird Simulations, <http://www.thunderbirdsimulations.com>

⁴M. W. Thompson, Philos. Mag. **18**, 377 (1968).