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DEVELOPMENT OF NEGATIVE HEAVY ION SOURCES FOR PLASMA POTENTIAL MEASUREMENT

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ABSTRACT

A plasma sputter negative ion source was studied for its applicability to the potential measurement of a fusion plasma. Both the beam current density and the beam energy spread are key issues. Energy spectra of a self extracted Au^- beam from the source were measured under the condition of a constant work function of the production surface. The FWHM increases from 3 eV to 9 eV monotonically as the target voltage increases from 50 V to 300 V, independently from the target surface work function of 2.2 - 3 eV.

Key Words

Au^-, negative ion source, plasma potential, Heavy ion beam probe, energy spread, work function

Introduction

The formation of a plasma potential and its correlation to the plasma confinement have been studied as fundamental problems in plasma physics. Recently, the potential and the density fluctuations are considered to be important on the particle transport in toroidal plasma devices for the nuclear fusion. A heavy ion beam probe (HIBP) has been used as a reliable method to determine the plasma potential, and to study the potential and plasma density fluctuations[1,2]. However, the required beam energy increases up to several MeV for recent big fusion devices, such as a Large Helical Device(LHD, $a \sim 0.6m$, $B_H \sim 3T$)[3]. A HIBP based on a negative heavy ion source is attractive because of the possibility of tandem beam acceleration, and that of neutral beam injection.

In a HIBP diagnostic, a high energy beam of either neutral or charged particles, A^q q=-1,0,1,2,etc., is injected into a magnetically confined plasma. Most of the injected beam particles loose electrons by collisions in the plasma (a secondary beam).

$$A^q \longrightarrow A^{q+1} + e, \ldots, A^{q+i} + i\,e, \quad \text{etc.} \qquad (1)$$

When the primary beam is injected into a plasma, it is post-decelerated (or accelerated) by $q\phi$, where ϕ is the plasma potential, and the secondary beam is accelerated(or decelerated) by $(q+i)\phi$ when it comes out of the plasma. The plasma potential can be obtained from the energy difference between the two beams.

In several experiments on toroidal systems, potential formations of order of the ion temperature were observed. The levels of potential fluctuations in the TEXT experiments were reported to be one to several tens percents, depending on the radial position[2].

In the case of LHD, the ion temperature is expected to be one to several keV. Energy spread of less than 0.1 keV is demanded as a primary beam for the potential measurement, and that of order of 10 eV is desirable to study the fluctuations of the local plasma potential and the density. Considering the helical field strength of 3T, and the practical configuration of the beam trajectories, the energy of 5.6 MeV is required for a singly charged heavy ion beam of mass 200 [4] .

We have measured the longitudinal energy spectra of a self extracted Au^- beam from a plasma sputter negative ion source. The work function of the negative ion production surface was simultaneously monitored. Some relevant physics on negative ion formation process obtained from those measurements are also discussed in this paper.

1. A plasma sputter negative ion source

Negative ions of heavy elements are often produced by sputtering processes on a metal surface of low work function.
Various types of negative ion sources on the sputter principle are reviewed by Alton[5]. Among them, we have studied a plasma sputter negative ion source because of its high-brightness and stable operation. In this source, the target surface is sputtered by plasma ions with relatively low energy.

The probability of negative ion formation has been known, experimentally and theoretically, to be dependent on the surface work function, ϕ, the electron affinity of the ejected particle, ε_A, and its escaping velocity normal to the surface, v_n. The general form can be given by

$$P^-(v_n) = 2/\pi \exp\{-c_1(\phi - \varepsilon_A + V_i)/v_n\}, \quad (2)$$

where the parameters of c_1 and V_i are assumed constant[5].
Negative ion spectrum expected from a plasma sputter negative ion source with the target voltage of V_t is then

$$I^-(E) = 2/\pi\, I^+ Y_s(eV_t) \int f(E_2, \theta)\, P^-(E_2, \theta)\, d\Omega \quad (3a)$$

$$E = eV_t + M v_n^2/2 = eV_t + E_2 \cos^2\theta \quad , \quad (3b)$$

where I^+ and $Y_s(eV_t)$ are the incident target current and the sputtering yield at the energy eV_t. The negative ion formation probability $P^-(E_2,\theta)$ is related to $P^-(v_n)$ in Eq.(2) by $v_n = \sqrt{2E_2/M}\cos\theta$, where E_2 and θ are the ejection energy and its polar angle. Following the theory developed by Thompson[6], the ejected particle spectrum $f(E_2,\theta)$ can be expressed by

$$f(E_2,\theta) \propto E_2\ (E_2+U_0)^{-3}\cos\theta\ , \qquad (3c)$$

and gives a maximum at $U_0/2$, where U_0 is the surface binding energy of the particle. In eq.(3a), the integral on the solid angle $d\Omega$ depends on the target shape, the target bias, and the beam transport geometry.

In Table 1, the comparison of various parameters which are influential on negative ion yields and their spectra is given for stable elements of mass > 150. The minimum work function ϕ_{min} is calculated by the semi-empirical relation proposed by Alton[5]. High production probability of negative ions are expected for Ir, Pt and Au because of their negative values of $(\phi_{min}-\varepsilon_A)$. Sputtering yields of Pt and Au are also large[7]. On the other hand, the energy spreads of Au, Tl and Pb are expected to be small. Thus we have studied the production of Au^- and its energy spectrum for a plasma sputter source operated with argon.

2. Energy spectra of Au^-

Negative ion spectra are generally related to the work function of the production surface through Eq.(2). We have measured the energy spectra of Au^- under the condition of a constant target work function.

The source was a medium sized (d=10.8 cm, l=12 cm) multi-cusp magnetic field plasma container with a gold plate target at the center. The target was biased negatively with respect to the source chamber (the anode), and cesium vapor from an oven was introduced onto its surface. The target work function was simultaneously monitored by a photo-electron detection system at two wave lengths(488nm, 633nm). The longitudinal energy spectrum of the Au^- beam self-extracted from the source was measured by a retarding potential type electrostatic energy analyzer. The details of the source, the work function monitoring system and the energy analyzer are described in Ref. 9,10,11.

In Fig. 1 are shown the energy spectra at different values of negative ion yields *Yn* (the ratio of Au^- to the target current). The position of the zero energy has an ambiguity of 1 eV. The work function of case 1 and that of case 3 were estimated to be 2.2 eV and 2.4 eV from the photoelectric current induced by an Ar+ laser based on the Fowler's theory[11]. Comparing *Yn*, it was conjectured that the work function of case 2 and that of case 4 were around 2.3 eV and ~ 3 eV. The four spectra agree well up to more than 10 eV, in spite of the one order of difference in *Yn*.

In Fig. 2 the full width of half maximum (FWHM) of the spectrum is plotted as a function of the target voltage, which corresponds to the argon sputtering energy. The FWHM increases monotonically as the target voltage increases, independently from the target surface work function.

3. Discussions and Conclusions

The energy spectrum of sputtered particles calculated by Thompson's formula, Eq. 3c, predicts the FWHM of about 7.3 eV, while those observed in present work and in Ref. 10 are less than that when $V_t < 250$ V. One of the reasons is that negative ions are accelerated through the sheath at the target in a plasma sputter source and the beam consists from ejected particles with the polar angle to some extent in Eq. 3a. However, the target voltage dependence of FWHM cannot be explained by this. Possible reason is that the sputtered particle energy distribution depends on the incident energy E_i, and its high energy tail falls off faster when E_i is relatively small. Similar tendency has been observed in the energy spectra of neutral Cu atoms sputtered by an argon beam in the same energy region[12].

The work function dependence was not obvious in the present experiments, and the weak dependence of the negative ion production process on the work function can be anticipated in case of $\phi \sim \varepsilon_A$. The dependence of the total beam intensity of Au^- was also reported to be weak at $\phi < \varepsilon_A$[9].

The measured FWHM's were less than 10 eV at the target voltage less than 300 V. The sputtering yield $Y_s(eV_t)$ and thus the Au^- beam intensity do not increase drastically at higher voltage. The Au^- beam from a plasma sputter source with the target voltage less than 300 V seems to be feasible for the application to the HIBP of the potential measurement in a fusion device.

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Element	Ta	W	Re	Os	Ir	Pt	Au	Tl	Pb	Bi
Mass	181	184,186 182,183	187,185	192,190 189,188	193,192	195,194 196	197	205,203	208,207 206	209
ε_A	0.8	0.5	0.15	1.4	2.0	2.13	2.31	0.5	1.2	1.0
$\phi_{min}{}^*$	1. 72	1.62	1.51	1.58	1.58	1.39	1.43	1.82	1.75	1.65
Ys(0.2)	~0.3	~0.3	....	....	....	~0.6	~1	....	....	....
U_0	8.1	8.8	8.1	8.1	6.9	5.8	3.8	1.9	2.0	2.3

Table 1

Comparison of the electron affinity, ε_A [8], the empirical minimum work function, $\phi_{min}{}^*$, the sputtering yield by an argon beam at 0.2 keV, $Y_S(0.2)$ [7], and the the surface binding energy for various stable heavy elements. The ε_A 's, $\phi_{min}{}^*$'s and U_0's are in eV.

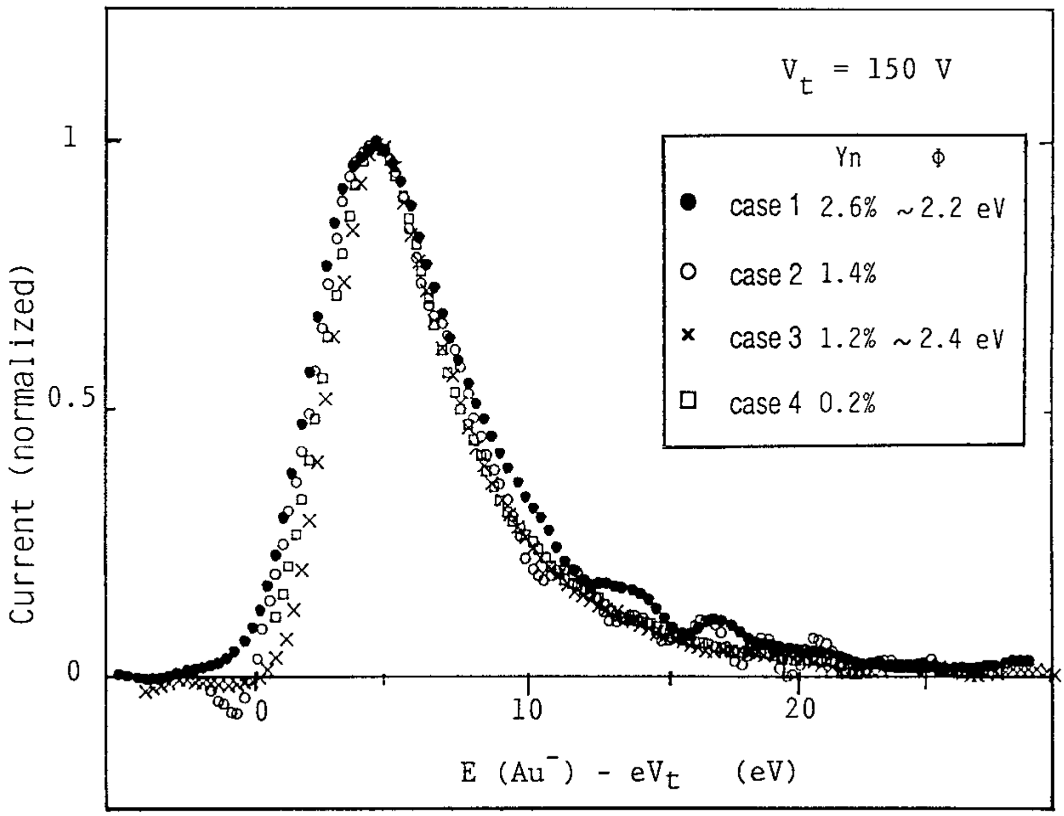

Fig. 1 The energy spectra at different levels of negative ion yields *Yn* . The spectra are normalized to one at the peak. Notches in the spectra of case 1 and 2 are due to electric noises.

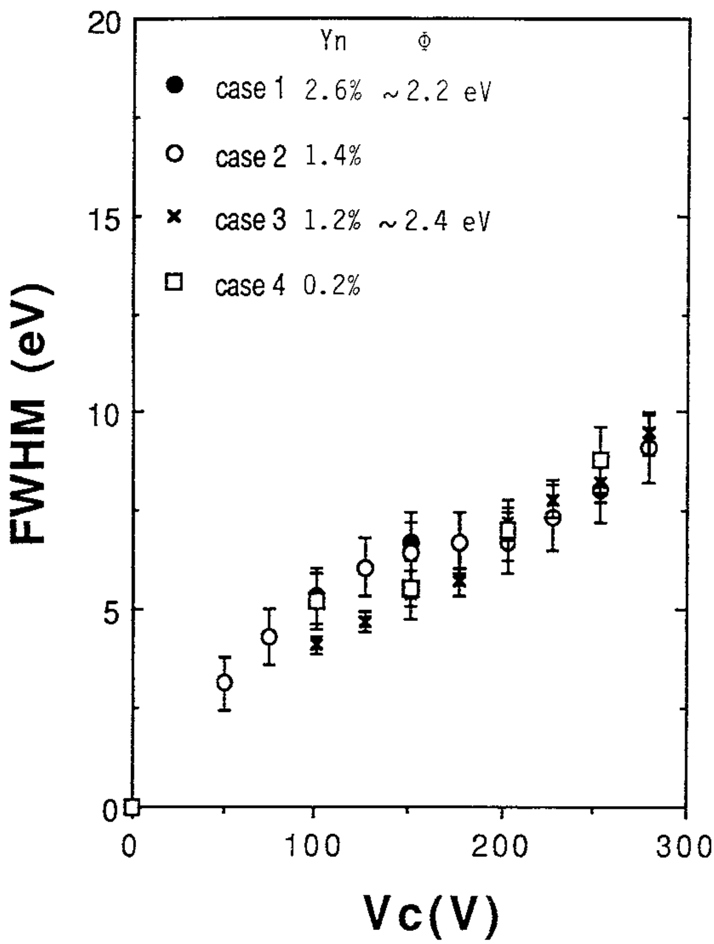

Fig. 2 The target voltage dependence of FWHM of a Au^- beam at various levels of production rate.

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