Proposal of a Single Sweep Measurement of a Potential Profile in Tokamak Plasmas by High Voltage Heavy Ion Beam Probes

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Abstract
Because of the large error induced by the changes of the injection angles of the secondary beam to the analyzer, the measurement of a potential profile in tokamak plasmas by heavy ion beam probe (HIBP) has been performed through tens of successive plasma discharges under the same discharge conditions, at a rate of a few shots to adjust the entrance angles at each point in the plasma. In this paper, a new method for the potential profile measurement by a single poloidal sweep, is proposed, which will automatically eliminate the error induced by the changes in the injection angles. In addition, new results on the calibration of a HIBP in tokamaks, are presented.

Keywords: potential measurement of plasma, tokamak, heavy ion beam probe.

1. Introduction
The heavy ion beam probe (HIBP) in a magnetic confinement system is particularly useful for the measurement of local electric potential and fluctuations of local plasma density and potential [1]. The first precise measurement of a potential profile of the tokamak plasma, was performed in ST tokamak [2]. Its measurement was, however, conducted at a very low current of about 20kA where the deviation of the secondary beam from one poloidal plane was very small. It means that trajectories of the beam in the analyzer stay nearly in the analyzer plane (plane of symmetry of the analyzer and perpendicular to the plane of analyzer electrode) because of small deflection due to plasma current. In this case, the error in the measurement of total energy of the beam is insignificant, since beam velocity perpendicular to the analyzer plane, is small. In ISX-B tokamak, potential profiles of ohmic plasmas and those of plasmas with co and counter neutral beam injection, were measured by shot-to-shot basis in order to eliminate the error due to the change in entrance angles, caused by the scanning of plasma cross-section [3]. Similar measurements were performed in TM-4 and TEXT tokamaks [4,5]. Nowadays the energies of the beam for HIBP are 0.5 MeV for TEXT and IIPP T-IIU tokamaks and 2 MeV for TEXT upgrade. In these cases, the measurement of plasma potentials about 1 kV is very susceptible to these errors.

The reason for the change in an in-plane entrance angle to an analyzer is illustrated in Fig.
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1. The secondary beam generated in different places in the plasma, has a shape similar to a sheet. The small portion of the sheet, generated at a certain point in the plasma, goes through the input slit of the analyzer and hits the detector. If we sweep an injection angle of the beam at an entrance to the tokamak, we can observe beams generated in different places in the plasma, but the secondary beam goes through the slit with different entrance angles to the analyzer as shown in Fig. 1a.

As for an out-of-plane entrance angle, let’s consider a case of the injection of heavy-ion probing beam into an axisymmetric confinement system, for simplicity. Because of a change in charge state, the secondary beam carries the information of a local plasma potential and a local stream function, where it is ionized, as shown in Fig. 1b, through the conservation of energy and canonical angular momentum. The changes in beam energy ($\Delta E$) and angular momentum ($mrv_\phi + erA_\phi$) are simplified and given by

$$\Delta E = e (\Phi(\mathcal{R}_x) - \Phi(\mathcal{R}_\text{analyzer})),$$  

and

$$mrv_\phi\text{analyzer} + e\mathcal{P}(\mathcal{R}_\text{analyzer}) = e(\mathcal{P}(\mathcal{R}_x) - \mathcal{P}(\mathcal{R}_\text{analyzer})) + mrv_\phi\text{injection} + e\mathcal{P}(\mathcal{R}_\text{injection})$$

where, $r_x$ is the position where ionization of the primary beam by the plasma occurs. $\mathcal{P}(r)$ is a stream function $(rA_\phi)$ and $\Phi(r)$ is an electric potential. Since $v_\phi/(v_\phi^2 + v_z^2)^{0.5} - \Omega$ is approximately an out-of-plane injection angle to the analyzer where $\Omega$ is an angle between the analyzer plane and the injection plane of the beam, the change in the out-of-plane entrance angle during scanning of plasma cross-section is inevitable even in the case of axisymmetric toroidal coils and is significant when plasma current is large.

The error due to the change in an in-plane entrance angle to an analyzer, can be suppressed significantly as long as the in-plane entrance angle is about 30 degrees, because we use an analyzer with focusing up to the second order. Up to now, for scanning plasma cross-section by HIBP, we have to tune, shot by shot at each point in the plasma the direction of the analyzer so that an out-of-plane entrance angle should be zero and the in-plane angle be 30 degrees, to suppress the error. In order to get a precise profile of plasma potential, we have to invent a new method to eliminate the error instead of relying on shot by shot measurements.

Recently energy of the beam for HIBP in tokamaks has been increased to 0.5 MeV in TEXT and JIPP T-IIU tokamaks [6,7]. The development of a new 2 MeV HIBP for TEXT is also under way [8]. The energy of the injected beam itself has the stability of the ripple less than a few volts out of 500 kV in JIPP T-IIU HIBP, since the HIBP usually uses a thermionic ion gun [9], and a highly stabilized high voltage power supply. Accordingly, the error in a potential measurement by HIBP may be determined by the error in an energy analyzer. Since the error due to the energy analyzer is proportional to the beam energy, a new method for the calibration and elimination of the error in an energy analyzer is urgently needed.

The calibration of HIBP system is so far done by an introduction of a primary beam to an energy...
The disadvantage of the calibration is those basic parameters of the tokamak and HIBP, such as toroidal field, beam voltage, analyzer voltage and the trajectory to the analyzer, are entirely different from those under which the secondary beam generated in the vacuum vessel is guided into the analyzer. Accordingly, the calibration of the system is done with many assumptions, the linearity of the voltage of the analyzer and, exact adjustment to changes in both in-plane and out-of-plane entrance angles to the analyzer. A very reliable calibration in the routine measurement is almost impossible. In addition, accurate measurements of the absolute values of an accelerating voltage of the beam (about 500 kV) and an analyzer voltage (100 kV) are difficult and cause additional errors in a measurement of plasma potentials. The relative change of the potentials has been measured up to now. Accordingly, a new systematic way of the calibration of zero potential during scanning of plasma cross-section is also required.

Recently at ATF HIBP experiment, gas ionization of the beam is employed for the calibration of zero potential [10]. It is a great improvement of HIBP in the toroidal machine. It is particularly suited to helical machines, where the beam trajectory does not change appreciably by a low β plasma. But as for a tokamak, the secondary beam due to gas ionization has not been detected since the analyzer is adjusted to the beam with large deflection in the toroidal direction.

In this paper we are going to discuss the possibility to measure a potential profile in a single poloidal sweep across the plasma, by a fast toroidal sweep for the compensation of the error due to the change of an out-of-plane entrance angle, and by a gas ionization method in a tokamak to suppress the error caused by the change of an in-plane entrance angle. In addition we present preliminary results of the first gas ionization experiment in a tokamak for HIBP calibration and discuss the limitation of this method.

2. Error Analysis in the Measurement

Figure 2 shows the arrangement of HIBP system in JIPP T-IIU tokamak [11]. The heavy ion beam from a 500keV electrostatic accelerator is guided by an electrostatic deflector into the tokamak. Two quadrupole electrostatic lenses are installed for beam transport and focusing in the center of tokamak plasmas. Toroidal and poloidal sweepers are installed at the entrance to the tokamak. A poloidal sweeper is used to scan plasma cross-section. A toroidal sweeper is used to compensate the beam displacement in the toroidal direction at an analyzer, which is induced by plasma current. The analyzer used here is parallel plate electrostatic analyzer with entrance angle of 30 degrees and focusing up to the second order [12].

Figure 3a shows a cross-sectional view of trajectories, of primary beams and the secondary beam generated in the plasma during scanning of plasma cross-sections by sweeping the injected beam. The modeling of the toroidal coil must be accurate, since the ripple of the toroidal field affects the beam trajectory significantly. Poloidal fields are calculated using plasma equilibrium code with real poloidal coil parameters.

The secondary ions produced on the dotted line in Figure 3a are allowed to enter the input slit of the energy analyzer. Accordingly, along the dotted lines, a potential profile is measured by a poloidal sweep at the entrance to the tokamak. Inevitably, an entrance angle (in-plane) to the analyzer changes noticeably during the poloidal sweep. Figure 3b shows a plane view (x, y, coordinates, if
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Fig. 3 The beam trajectory of HIBP in JIPP T-IIU, Toroidal field at \( r = 93 \) cm is 3 Tesla. Beam energy is 350 keV. Plasma current is 200 kA. Initial \( v_c \) at the injection into tokamak is zero. (a) Cross-sectional view. (b) Horizontal view.

the symmetry axis of tokamak is taken to be \( z \) axis) of trajectories with the same parameters in Figure 3a.

It is clearly shown that during scanning of the cross-section, an out-of-plane injection angle as well as a horizontal place on the input slit of the analyzer, changes appreciably. In addition, the breaking of the conservation of canonical angular momentum is clearly observed by behaviours of the primary beam in the region far from the plasma. When axisymmetric toroidal coil is assumed in the calculation, trajectories of the primary beam are lines intersecting the axis of symmetry in Figure 3b in the field free region, since the initial injection is radial (\( v_c = 0 \)) as is observed in Figure 3b. In the real case, the ripple of the toroidal field affects the radially injected beam significantly and straight lines of trajectories far from the plasma do not intersect the axis of symmetry as shown in Figure 3b.

There are two types of electrostatic analyzers which have good focusing up to the second order, a plane mirror energy analyzer (parallel plate analyzer) and a cylindrical mirror energy analyzer [13]. Because of a large shift of the entrance point on the input slit in the horizontal direction, the cylindrical mirror analyzer is not used, although the error due to the out-of-plane entrance angle does not exist in it. By this reason, the energy analyzer commonly used in HIBP is a parallel plate electrostatic analyzer with 30 degree injection angle.

The plasma potentials \( (\Phi (r_*)) \) are reduced from the beam energy \( (V_b) \) and the analyzer voltage \( (V_a) \) by the following equations [14],

\[
\Phi_b (r_*) = V_b - V_a (q_b - q_p) G (\theta) (\cos q_b)^{-2},
\]

(3)

where \( \theta, \phi_b \) are in-plane and out-of-plane entrance angles. \( q_s \) and \( q_p \) are charge numbers of the secondary and primary beams respectively. The gain function \( G (\theta) \) is the main characteristics of the analyzer and is the ratio of the beam energy in the analyzer plane to an analyzer voltage when the beam is in the middle of the upper and lower detector plates. It is theoretically given by

\[
G (\theta) = \frac{q_p}{2 H1} \frac{L_t - (h_2 + h_1) \cos \theta}{\sin 2 \theta}
\]

(4)

where \( L_t \) is the distance between the slit and the detector, and \( h_2 \) and \( h_1 \) are distances between the parallel plate and the detector or the slit respectively. \( H1 \) is a distance between upper and lower electrode as is shown in Figure 1a. The \( G (\theta) \) must be determined experimentally, since the theoretical estimate (4) is a little different from the experimental value because the accuracy of the physical size of the analyzer, the separation of the parallel electrodes for example, may not exceed \( 10^{-4} \), while the accuracy of the \( G (\theta) \) is required up to \( 10^{-4} \) or more.

The error due to the change in in-plane and out-of-plane entrance angles is obtained by equation (4) and (3) and is given as follows,

\[
\Delta \Phi_b (r_*) \approx - V_b \phi_b^2 + 32 V_b (\Delta \theta)^2,
\]

(5)
where $\Delta \theta$ is the deviation of $\theta$ from the second-order focus angle of 30 degrees.

As is shown in Fig. 3b, the $v_f/v_b$ can be about 0.1. The error due to the out-of-plane entrance angle is comparable to or larger than an expected plasma potential of a few kilovolts in the tokamak when the 500 keV beam used, if an analyzer is set parallel to the injection plane into the tokamak. In addition, the error due to the deviation of in-plane angle from 30 degrees also becomes significant when the deviation is not small, because of the cubic power of $\Delta \theta$ and the large coefficient of 32. Accordingly, at each measurement of one spatial point, the energy analyzer has been adjusted in two directions, so as to keep an in-plane entrance angle to be 30 degrees and an out-of-plane entrance angle to be zero.

3. Calibration by Neutral Gas

The difficulties of the accurate measurement of the very high accelerating voltages of the beam (about 500 kV) and the analyzer voltage (about 100 kV), cause uncertainties in the experimental determination of zero potential and the gain factor of the analyzer in a very high voltage region. In order to suppress these errors, a calibration of the total HIBP system by the electron stripping by neutral gas is adopted. The cross-section $\sigma_{1.2}$ of electron stripping for Tl$^{+1}$ or Cs$^{+1}$ ion in the hydrogen gas, grows significantly in the energy range from 200 keV to 500 keV as shown in Table 1 [15].

The check of the alignment and calibration by neutral particles is particularly useful, since the almost entire condition is the same with the plasma experiment except the existence of poloidal magnetic field due to plasma current and poloidal field coils. Also the energy loss of the beam by the gas ionization can be estimated to be less than a few volts. In addition, in tokamaks, motions of the beam injected nearly perpendicularly to the tokamak, in the x, z plane in Fig. 3, are mainly determined by the strongest field of toroidal field. The trajectories of those beams are almost the same, as long as $v_f/v_b$ is small. This means that the in-plane entrance angle to the analyzer is almost the same with one without the plasma current even in case of large plasma current. Accordingly, the error due to the change in an in-plane entrance angle during scanning of the plasma cross-section, can be detected by the gas ionization method as a shift of zero potential, and can be compensated.

Figure 4a shows signals of the secondary beam in the analyzer. This is the first observation of the secondary beam generated by neutral gas in the tokamak, since the energy analyzer was so far stationed with an angle of a few degrees to the X-axis to detect the deflected beam by plasma current. In that case it is impossible to detect the secondary beam due to gas ionization which has no toroidal deflection, unless the detector plate is very long. D$_2$ gas is introduced into the vacuum vessel through a fast valve. Cross-sections of ionization or recombination of Tl in D$_2$ and H$_2$ are considered to be nearly equal because the mass number of Tl is much larger than those of D$_2$ and H$_2$. The injected Tl$^{+1}$ current into the tokamak is a few $\mu$A. Since the shape of the secondary beam generated by neutral gas in the vacuum vessel is similar to a sheet or a curtain, as is discussed in the case of the plasma, we can observe the secondary ions, in the different places such as the input slit which is composed of split plates, electrically insulated each other, and pair plates of the detector. In Fig. 4a, the structure of the split-input-slit is shown. The beam is swept toroidally in order to measure the beam size at the slit. Fig. 4b, the expanded view of the traces of Fig. 4a, clearly shows that the beam size at the analyzer is much less than the horizontal opening of the slit (4 cm) of the analyzer and the signal at the detector is not intercepted horizontally by the input slit.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>200</th>
<th>400</th>
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</thead>
<tbody>
<tr>
<td>Reaction</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>$\sigma_{1.0} (10^{-17}/cm^2)$</td>
<td>4.8</td>
<td>5.1</td>
</tr>
<tr>
<td>$\sigma_{0.1} (10^{-16}/cm^2)$</td>
<td>4.3</td>
<td>6.3</td>
</tr>
<tr>
<td>$\sigma_{1.2} (10^{-18}/cm^2)$</td>
<td>1.2</td>
<td>5.1</td>
</tr>
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Table 1 Cross-sections of thallium at 200 keV and 400 keV for electron stripping and capture in the hydrogen gas from I. Alvarez and C. Cisneros, Phys. Rev. 13, 1728 (1976).
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Fig. 4 Signals of the Secondary beam at the split-input slits and at the detector by the D₂ gas puffing. The analyzer voltage is tuned to the doubly ionized particles. Beam energy is 200 keV, 2.5 Tesla. Injected Ti⁺ beam current is a few μA. (a) General characteristics of the signals at the split slit (up, down, right and left) and at the detectors. The slit structure of the analyzer is also shown. (b) Expanded view of the time behaviours of the slit signals. (c) Detector currents with different gas puff rate. The upper figure corresponds to gas puff rate of 1.2 x 10⁻³ torr/50 msec. In lower figure, the gas puff rate is 0.8 x 10⁻³ torr/50 msec.
The detected signals at the split slit and the signals at the detectors of the analyzer show different characteristics in time behaviors. Gas pressure starts to rise linearly after the opening of the gas valve and reaches the value of $1.2 \times 10^{-3}$ torr at 50 msec after the opening. After 120 msec when the valve is closed, the gas pressure decays slowly, because the pumping time constant of the tokamak is about 1 second. The signals of the currents of the split entrance slit are roughly proportional to the gas pressure of the tokamak. Although the primary beam can not arrive at the analyzer slit without any ionization by neutral gas, as is shown in Figure 3a, currents on the split slit can be a mixture of singly ionized (recombined from doubly ionized beam) and doubly ionized beam.

Schematics of the trajectories of singly ionized beams on the analyzer slit are shown in Figure 5a. The currents of the detector in Fig. 4a should be doubly ionized beam because the voltage of the analyzer is tuned to doubly ionized ions. The decrease in signals at the detectors, while the current on the slits is still increasing, may be due to the recombination of doubly ionized ions. The difference in time behaviors is also explained by the fact that the recombination of doubly ionized beam may reduce its contribution to the current on the slit roughly to half, because the recombined singly ionized beam has a shape of a sheet and some part of the sheet can go through the slit. On the contrary, the recombined singly ionized beam can not hit the detector because the analyzer is tuned to doubly ionized particles.

Although the cross-section of the recombination of doubly ionized thallium in the gas, $\sigma_{2,1}$, is not measured [15], the reasonable estimation is that $\sigma_{2,1}$ is a little larger than $\sigma_{1,0}$. At 40 msec after the start of gas puff, the currents on the detector begin to decrease. At this time, the mean free path for $\sigma_{1,0}$ is about 5 meters and is comparable to the experimental dimensions. So it is a reasonable assumption that the recombination of the secondary beam is the reason for the decrease in the detector current. This can also explain the temporal shift of the peak current in the detector at different gas puffing rates as shown in Figure 4c. The peak of the detector signal occurs at the time when the pressure inside the vessel is roughly the same.

Since the signals at the detector are determined by the competition of the ionizing process of the primary beam and the recombination of the doubly ionized beam, the pressures at the peak of the signals under different gas puff rates must be the same as is observed in the experiment and should be dependent only on geometric configuration.

As is mentioned, the time behavior of the signals is explained roughly by the attenuation of the secondary beam. As for quantitative analysis, Monte Carlo analysis of the trajectory to describe effects of the change of state, must be performed to

![Fig. 5 Schematics of the trajectories of the primary and secondary beam affected by complex changes of charge state. X mark shows the point where ionization or recombination of the beam occurs. 5a, the trajectory of a recombined secondary beam to the analyzer slit. 5b, the expansion of the primary beam due to recombination and ionization of primary beam, and the trajectory of doubly ionized particles with different entrance angles to the slit due to multiple ionization and recombination process.](image-url)
understand fully signals on the input slit. In this calculation, the expansion of the gas into the sweepers, deflectors and lens system, must be taken into consideration.

The currents on the detector plates, even tuned to doubly ionized beams, are affected by complex changes of charge state on trajectories. Some examples of trajectories with those changes of ionization states are shown in Figure 5b. One is recombination of singly ionized particles and its subsequent ionization in gas. Because of this effect, the injected primary beam itself forms a current sheet as shown in Figure 5b. The other is recombination and its subsequent ionization of the secondary beam as shown in Fig. 5b. The effects due to these multiple processes are the broadening of entrance angle (in-plane) and the degradation of spatial resolution of the measurement. For the quantitative analysis of this effect, Monte Carlo analysis is necessary. In the limit of low gas puffing, however, heavy ions on the detector are only due to single ionization of the primary beam and are free from the effect due to multiple ionization and recombination processes. Accordingly, currents on the detector at low gas density limit can be used for the calibration of a zero potential and the effect of the change in the in-plane entrance angle.

4. Elimination of Errors due to the Change of the Out-of-plane Entrance Angle

As is discussed, the error due to this change is quite significant in the case of large plasma current. It may be a dominant error when we want to measure the potential profile in a single shot by sweeping the beam through the plasma cross-section. We are going to propose a new idea for the automatic elimination of this effect in this section.

We are going to install plates for fast toroidal sweeping of the secondary beam, in a space between an input slit and a lower parallel plate electrode, where no electric field is applied (method 1). If we apply high voltage sine wave on the sweep plates inside the analyzer, an out-of-plane angle inside the analyzer changes sinusoidally and it crosses zero at some time during one cycle of the sweep if the sweep angle is larger than the entrance angle induced by plasma current. Only when the beam inside the analyzer is parallel to the analyzer plane, the ratio of the detector signals (up and downs plates) indicates the total energy of the beam, the maximum of the energy corresponding to the motion in the analyzer plane. This maximum energy is free from the error due to an out-of-plane entrance angle.

If we trace local maxima, the error due to the non-zero out-of-plane entrance angle, will be automatically eliminated, although the time response of the total system will be reduced by the introduction of a fast toroidal sweep inside the analyzer. In principle, a change in the energy of the beam induced by a fast sweep can be determined by the ratio of swept time to transit time of the beam in the sweeper and the voltage of the sweepers. Since the transit time is small because the energy is high and the sweeper is small, it is expected that the frequency of a toroidal deflection can be to about 100 kHz and the frequency of a poloidal deflection can be up to the order of 1 kHz. The discussion of the error by the fast sweep will be performed in §5.

Difficulties in method 1 will be caused by two factors. The first factor is the problem with respect to the sweeper. The secondary beam hits the analyzer slit with a large displacement in horizontal direction as shown in Fig. 3b. Figure 6a shows contours of the horizontal displacement of the beam at the slit as a function of toroidal and poloidal sweep angles at the entrance to the tokamak. This figure shows clearly that the displacement is a complex function of sweep angles. Also characteristics of this figure change considerably when we change the beam energy. Accordingly, we have to expect a large displacement of the beam in the horizontal direction at the slit. A compact and low-aberration horizontal sweeper with a large opening in the horizontal direction is needed. One of appropriate deflectors is an octupole deflector or a higher-order multipole deflector [16], in order to have very low aberrations in a narrow space. A multipole deflector with electrodes on an ellipsoid instead of a conventional circle, may be the best choice. Another factor is how to obtain homogeneous characteristics of the analyzer along the horizontal opening of the slit and will be discussed later.

An alternative method for the compensation of an out-of-plane entrance angle is fast sweeping in
Fig. 6a Contours of the horizontal displacement (m) of the secondary beam at the analyzer slit as a function of poloidal and toroidal (horizontal) sweep angles at the injection into the tokamak. The sweep point is shown in Figure 3a and parameters of figure 6a and 6d are the same as those of figure 3. In case of figure 6c and 6d the secondary beam is produced by the gas and plasma current is zero.

Fig. 6b Contours of \( f(v_x, v_y) = v_y/(v_x^2 + v_y^2)^{0.5}\) of the secondary beam at the analyzer slit in the plane of poloidal and toroidal (horizontal) sweep angles at the injection into the tokamak JIPP T-IIIU.

Fig. 6c Contours of the horizontal displacement at the slit in case of no plasma current.

Fig. 6d Contours of \( f(v_x, v_y) = v_y/(v_x^2 + v_y^2)^{0.5}\) at the analyzer slit in case of no plasma current.

the toroidal direction at the entrance into the tokamak (method 2). Figure 6b shows contours of \( f(v_x, v_y) = v_y/(v_x^2 + v_y^2)^{0.5}\) at the slit, as a function of toroidal and poloidal sweep angles at the entrance to the tokamak. If we apply a fast sweep in the toroidal direction while we scan plasma cross-section by a slow sweep of a poloidal injection angle as shown in Fig. 3a, the out-of-plane angle can be zero at some moment in the fast sweep since \( f(v_x, v_y)\) is a smooth and one-valued function of the horizontal sweep angle as shown in Fig. 6b. At the time \( f(v_x, v_y) = \sin(\beta)\), where \( \beta \) is the angle between the analyzer plane and the \( z \) plane, the out-of-plane entrance angle is zero. At this time the measured energy becomes locally maximum during a single fast toroidal sweep and is free from the error. The contours in figure 6a, b are dependent on plasma current, position of the plasma center, current profile, and the beam energy. Accordingly, the exact programmed compensation of out-of-plane angle is difficult and the above mentioned method will be the most basic method. Fig. 6b shows also the effect of the ripple of the toroidal field. If we sweep the beam to the direction of positive \( v_y \) at the entrance to the tokamak, then \( v_y \) at the analyzer slit is negative due to the reflection by the ripple of the toroidal field.

In these two methods (method 1 and 2), especially in method 2, we have to use a fairly wide input slit and detector plates in the horizontal direction. In order to suppress the error of the potential to 50 or 5V, the gain function \( G(\theta) \) should be uniform along the horizontal opening of the slit, to the degree of \( 10^{-4} \) or \( 10^{-5} \), as is shown in
equation 3. A usual parallel plate analyzer has guard rings with a chain of resistors to get the uniform electric field. The energy analyzer in the tokamak experiment is, however, irradiated by the very intense visible, UV, VUV, and soft x-ray light from a high temperature plasma. The intense light induces secondary electron emissions and some of those electrons flow into the guard rings, causing the errors in the measurement. The shaped electrode system without guard rings, designed for HIBPs [8,17] on TEXT and JIPP T-IIU is a new approach to eliminate those errors completely and to expand the region of the uniform electric field. Although a general theory for the shaped electrodes is unknown, in order that an analyzer with a realistic width of the electrodes may have the uniformity of 10^{-4} to 10^{-5} in a wide region, we have to optimize shapes of the electrode system. In addition, there are meshes on the lower electrode to permit the entrance of the beam into the region between upper and lower electrodes. The local irregularity of the field deflects the beam in-plane and out-of-plane directions and induces the errors. The extensive computational and experimental studies of those effects are being performed by us and will be reported in a separate paper.

The calibration of the dependence of the horizontal position becomes essential for a precise measurement of the potential profile. For this purpose, it is very important to have two sweepers in the toroidal direction at the entrance to the tokamak and at the analyzer in the gas calibration experiment. By a sweeper at the entrance to the tokamak, we can sweep a horizontal entrance point of the analyzer and by a fast sweep at the analyzer we can measure the beam energy, eliminating the error due to the effect of an out-of-plane entrance angle. By this method we can measure the dependence of zero potential on the horizontal entrance point. In addition, the sensitivity calibration becomes feasible if we slowly change the accelerating voltage.

By fast toroidal scanning at the entrance to the tokamak, it is possible to measure the potential profile and calibrate the analyzer at the same shot, even when the analyzer is set at certain angle to the x axis to detect the deflected beam by the plasma current. Figures 6c and 6d show the horizontal displacement of the beam and $v_y / (v_y^2 + v_x^2)^{0.5}$, at the slit when there is no plasma current and the beam is ionized by the gas. By a small horizontal deflecting at the entrance to the tokamak, we can easily, as is shown in figures 6c and 6d, guide the secondary beam ionized by the gas to the analyzer and adjust an out-of-plane entrance angle to zero even the analyzer is set with a few degrees to the x axis for the plasma measurement. Accordingly, when gas is introduced in the vacuum vessel after the plasma is terminated, the calibration will be performed automatically in a single shot if the input slit is wide and the sweep angle is large enough. The modifications of the energy analyzer and its access port to the tokamak, are now planned to provide a space for the installation of a deflector at the analyzer and in order to have very homogeneous characteristics along the horizontal direction.

5. Discussion

We discuss in this section the assessment of the over-all accuracy of the measured potential by this method. There are many factors which affect the accuracy of the potential measurement in the tokamak plasma. There are errors common to all HIBP measurement in the high temperature plasmas, 1) focusing property of the analyzer even if it is ideal, 2) deflection of the beam into the direction perpendicular to the analyzer plane by local field irregularities near the meshes at the holes in the lower electrode, 3) the change of the analyzer and accelerator voltage due to the photo-current by intense stray plasma light, and 4) the photo-current on the detector due to the stray light. They become more serious problem because we have to detect a small change out of the high beam energy (0.5 MeV in JIPP T-IIU HIBP, for example).

The errors specific to the method with fast toroidal sweeps are, 5) the noise of the detector circuit, 6) the change of the beam energy ($\Delta E_b$) due to the passage through the fast toroidal sweep, 7) the shift of sample volume from one magnetic surface during the toroidal sweep, 8) the error due to the process of a kind of unfolding of the signal to find the true peak of the energy since the change of the energy due to the toroidal sweep is modified by the simultaneous sweep in poloidal direction.
The circuit noise will be the dominant factor of the accuracy of the measurement, because HIBP measurement is performed at the very low secondary current of 1-100 nA and the noise increases at higher frequency. The noise level in the TEXT and JIPP T-IIU HIBP is about 1 nA at 1 MHz bandwidth [6,7].

The rough estimate of the change of the beam energy in the transient electric field may be written by $\Delta E_b < 2\pi / f_s \cdot t_s \cdot V_s$, where $f_s$ is the frequency of the sweep and $t_s$ is the transit time of the beam over the effective length of the sweeper. $V_s$ is the potential applied to the electrode of sweeper. If a potential of 1.4 kV (for 1 degree sweep for 500 keV beam) with the frequency of 100 kHz is applied to the sweepers of the length of 10cm, $\Delta E_b < 120$ V. This means that we may have 12% error if the plasma potential is about 1 kV.

The deviation of one magnetic surface during the toroidal sweep is about a few millimeters, when the toroidal sweep angle is 1 degrees in the case of Fig. 6. This may give small ambiguity of the sample volume and small errors in the potential measurement. It may be possible to compensate partially this error through a kind of the unfolding procedure after a potential profile is obtained without taking this effect. In order to reduce the error due to the simultaneous poloidal and toroidal sweeps, the ratio of the poloidal sweep time to the toroidal sweep time must be large. A ratio of about 100 may be sufficient to reduce this error to less than 1% because we can also partially compensate this error by the unfolding procedure. The overall error of the measurement would be less than 1% if we choose the choice of 20 Hz for poloidal sweep and 5 kHz for toroidal sweep and a wide MCP detector to reduce the noise level.

6. Summary

Since the energy of the HIBP beam is about 0.5 MeV for TEXT and JIPP T-IIU tokamaks, the errors induced by the changes of the in-plane and out-of-plane entrance angle cause a serious problem. In this paper the systematic ways (neutral gas calibrations and fast sweep methods at the energy analyzer and at the entrance to the tokamak) for the error elimination due to these changes, are proposed. By these methods it will be possible to measure a potential profile in the tokamak plasma by a high voltage HIBP in a single scanning of the beam across the plasma. The gas ionization method is found to have a complex character compared to the usual gas box method. It may be due to the fact that since recombination cross-section is comparable to or larger than those of ionization of the primary and secondary beams, the beams experience recombination and ionization on its trajectories to the analyzer when the vacuum vessel of the tokamak is filled with gas. We have to be careful that the measurement is done at low density limit.

Fast toroidal sweeping at the entrance to the tokamak and at the energy analyzer may be useful for the elimination of the error due to the out-of-plane entrance angle, only if the energy analyzer has very homogeneous characteristics for large horizontal displacement of the beam. It means that large area of uniform electric field in the analyzer with shaped electrodes is required. In addition, the precise parallelism among the surfaces of the electrodes, the opening of a long input slit and long detector plates, is also required. As for the horizontal sweeper in the analyzer, its design is itself a challenging task because it should have a large horizontal opening in a narrow space of analyzer. We started a design study for the ellipsoidal multipole deflector. The calibration of the energy analyzer for the horizontal shift of the beam becomes very essential for the elimination of the error. The combination of these two sweepers at the entrance to the tokamak and at the energy analyzer, will be very powerful for the calibration of the analyzer itself and for obtaining a precise one-shot measurement of a potential profile in the tokamak, although the time response deteriorates. It may have the frequency limit roughly to the order of 10 kHz.

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