On Measurement of Plasma Current Profile by Neutral Beam Probe

By

Sadao MASAMUNE, Masayuki FUKAO and Hiroshi NISHIHARA

(Received September 29, 1979)

Abstract

A neutral beam probing method is proposed for measurement of plasma current profile in a tokamak. An emulsion plate is used to detect the secondary ions.

This method is compared with the ion beam probing in which the primary particles are heavy ions. It has been concluded that a neutral beam is superior to an ion beam for the purpose of determining plasma current profile.

From numerical orbit calculations, it has been found that this method is applicable to the tokamak NOVA II, with moderate requirements on the neutral beam source.

1. Introduction

Plasma current distribution has a strong influence on the stability as well as on the power balance of tokamak plasma. The distribution cannot be determined by an electromagnetic measurement from the outside of a current channel. Insertion of a probe electrode into the plasma column is not feasible because of its strong disturbance on the plasma stability. Moreover the electrode will melt down in a moment.

In such circumstances, considerable efforts have been made to find methods for determining the current profile or the poloidal magnetic field distribution. The representative techniques that have been developed are (i) particle beam probing[1)-5)], (ii) detection of harmonic waves with microwave irradiation[6),7)], (iii) measurement of cyclotron splitted spectrum of scattered laser light[8)-10)], and (iv) observation of a change in the polarization of electromagnetic wave propagating through the plasma[11)-14)]. None of them, however, has been established nor can be used routinely.

Hickok and Jobes first tried to determine the plasma current distribution in the ST tokamak[1)] by injecting a singly ionized thallium beam. They were successful in determining the distributions of electron density and space potential, but not in

Department of Nuclear Engineering.

obtaining the current distribution. This method is attractive because of its simplicity and, after adding an energy analyzer, it is applicable to measuring the space potential and plasma density as well. Technical problems are to obtain a very thin probe beam with a sufficient brightness and to make a highly sensitive particle detector with a good spatial resolution.

In the present paper, we propose a method of neutral beam probing with an emulsion plate as the ion detector. We have found that an emulsion plate can detect or record individual tracks of a single helium ion of an energy between 20 and 30 keV, and that the high sensitivity and the excellent spatial resolution greatly reduce the requirement of ideal beam quality. Since the emulsion is not influenced by a magnetic field at all, we can place the detector plate close to the plasma column and make our choice of the species and the energy of neutral particles.

In the next section, the principle of the method proposed and the model used in orbit calculations are described. In Section 3, we compare the neutral beam probing with the ion beam method. In Section 4, we discuss the position of detector plate and the divergence of injected beam. Conclusive remarks follow in Section 5.

2. Principle of Measurement and Model for Calculation

We use the rectangular coordinate system (x, y, z) shown in Fig. 1. The center is at the intersection of the toroidal magnetic axis and a vertical cross section of the torus, positive y-direction is vertically upwards, and positive x-direction radially outwards. The z-axis is chosen to form a right-hand coordinate system.

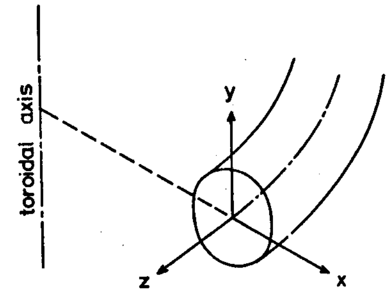

Fig. 1. Coordinate system (x, y, z).

A neutral particle beam for probing is injected into the plasma along the y-axis in the negative direction (downwards). A fraction of the primary beam particles is ionized in the plasma either by a charge exchange with plasma ions or by collisions with electrons.

The secondary ions begin to deviate from the primary beam path (straight line) at their respective points of birth. The individual secondary moves in its curved orbit determined essentially by the strong toroidal magnetic field and the point of ionization. The secondary orbits are approximately in the xy-plane. However, the secondary beam also undergoes a small deflection in the toroidal direction due to the weak poloidal magnetic field (the z-deflection). The intensity distribution of the poloidal field is uniquely determined by the plasma current density distribution. As the points of ionization are continuously distributed along the primary path, the secondary ion orbits form a curved surface. When the detector plate (emulsion plate) is so fixed that it intersects the orbital surface, the curved intersection, which will be called the trace hereafter, is determined by the plasma current distribution. Therefore, the characteristics of the trace can be used to identify the plasma current profile.

The equation of motion of ions in an electromagnetic field is given by

$$M\frac{d\boldsymbol{v}}{dt}=q(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}) \qquad (1)$$

with

$$\frac{d\boldsymbol{r}}{dt}=\boldsymbol{v}, \qquad (2)$$

where M and q are the mass and charge of the ion, respectively. The magnetic field $\boldsymbol{B}$ consists of a strong toroidal component B_t for the confinement of plasma particles, a vertical component B_v for keeping balance with the plasma hoop force, and the poloidal component B_p due to the plasma current. Since the electrostatic potential inside the plasma column is of the order of the magnitude of the electron temperature T_e which is much lower than the beam energy, we can neglect the electric field $\boldsymbol{E}$ of Eq. (1) in orbit calculations. It should be noted, however, that the electrostatic potential is of great importance and can be determined from the difference in the primary and the secondary beam energies. We will not go into this problem here.

The vertical magnetic field B_v gives approximately the same z-deflection to all of the secondary ions, irrespective of the poloidal field distribution. Thus, it merely results in a translation of the trace. Besides, the vertical component is much smaller than the toroidal. Therefore, the vertical field B_v is neglected in the present analysis.

Toroidicity in the toroidal field B_t is taken into account by the relation $B_t=B_0R/(R+x)$, where R is the major radius and B_0 the toroidal field intensity at the minor axis, while the toroidicity in the poloidal field B_p is neglected.

Assuming a cylindrical symmetry, the following four types of current distributions are considered:

(H) hollow distribution $j_z(r) = (2I_p/\pi a^2)(r/a)^2$

(U) uniform distribution $j_z(r) = I_p/\pi a^2$

(PA) parabolic distribution $j_z(r) = (2I_p/\pi a^2)[1-(r/a)^2]$

(PE) peaked distribution $j_z(r) = (4I_p/\pi a^2)[1-(r/a)^2]^3$

where I_p is the total plasma current and a is the minor radius of the plasma column. The orbits of secondary ions are calculated for these distinct current profiles. Calculations are performed assuming typical plasma parameters of the NOVA II tokamak at Kyoto University. The parameters are shown in Table 1.

Table 1. Typical Parameters of NOVA II

major radius	(R_0)	30cm
minor radius	(a)	6cm
toroidal field	(B_t)	10kG
vertical field	(B_v)	0.23kG
plasma current	(I_p)	20kA

3. Comparison between Neutral-Beam and Ion-Beam Probing

A neutral beam of $^4He^0$ atoms of 30 keV and ion beam of $^{40}Ar^+$ ions of 12 keV are comparatively studied as the primary incident beam for plasma probing. The energies are chosen so that the secondary ions $^4He^+$ and $^{40}Ar^{++}$ have the same Larmor radius in the toroidal magnetic field. At the same time, this radius is approximately equal to the plasma radius. Projection of the ion orbits on the xy-plane is shown in Fig. 2. The primary argon ions are injected from the outside in an appropriate direction so that they vertically pass the center of plasma.

Figure 3 shows the displacement in the toroidal direction (z-deflection) for the secondary ion produced at the center of plasma, because the z-deflection becomes the largest in this case. It should be noted that the ordinate is tenfold in Fig. 3. Clearly, the z-deflection is larger and more sensitive to the current profile with a neutral injection than with an ion injection. The reason is that, in the case of an ion injection, the primary ions undergo z-deflection in the opposite direction. Consequently, the primaries' deflection cancels partly the secondaries' displacement. Moreover, the primary ions have to traverse a long path through the strong toroidal magnetic field before reaching the plasma column. Accordingly, for the ion injection technique to be feasible, the Larmor radius of the primary ions in the toroidal field should be so determined that it is much larger than the minor radius. Thus, we are forced to use heavier ions with a higher beam energy. Consequently, the Larmor radius of the secondaries necessarily becomes considerably larger than the radius of the plasma

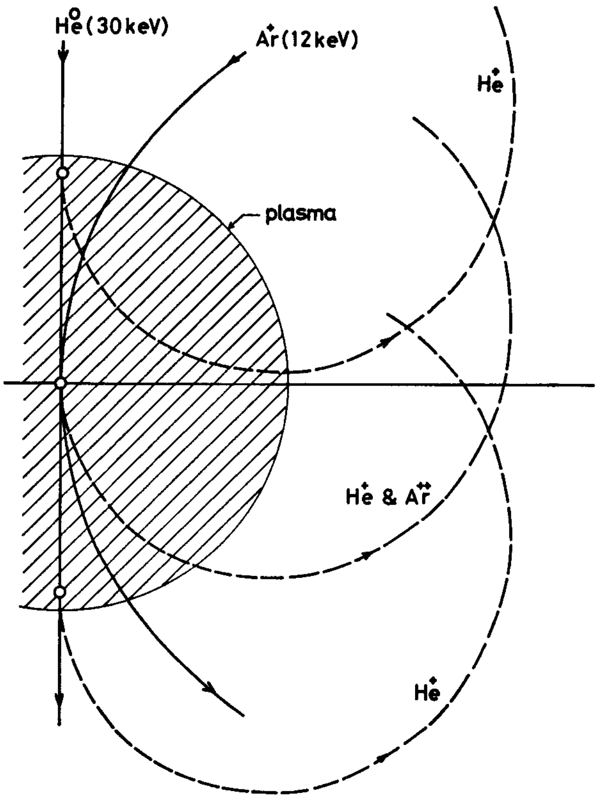

Fig. 2. Representative ion orbits projected on the xy-plane. Projections are determined by the toroidal field B_t.

column.

As the momentum $\boldsymbol{p}$ that a charged particle gains by traversing a path of length L in a magnetic field $\boldsymbol{B}$ is given by the integral

$$\boldsymbol{p}=\int_0^L \frac{dl}{|v|} q(\boldsymbol{v}\times\boldsymbol{B}) \tag{3}$$

and is independent of the velocity of particle, a long flight path is required for the secondary ion to get an appreciable z-deflection after overcoming the reverse deflection of the primary ion. Thus, in a practical arrangement of a tokamak device, both the primary and the secondary ion beam paths will become discouragingly complicated. In contrast with this, for a neutral injection, it is enough to place the neutralizer at the outside of the plasma. Such an arrangement can be made without difficulty.

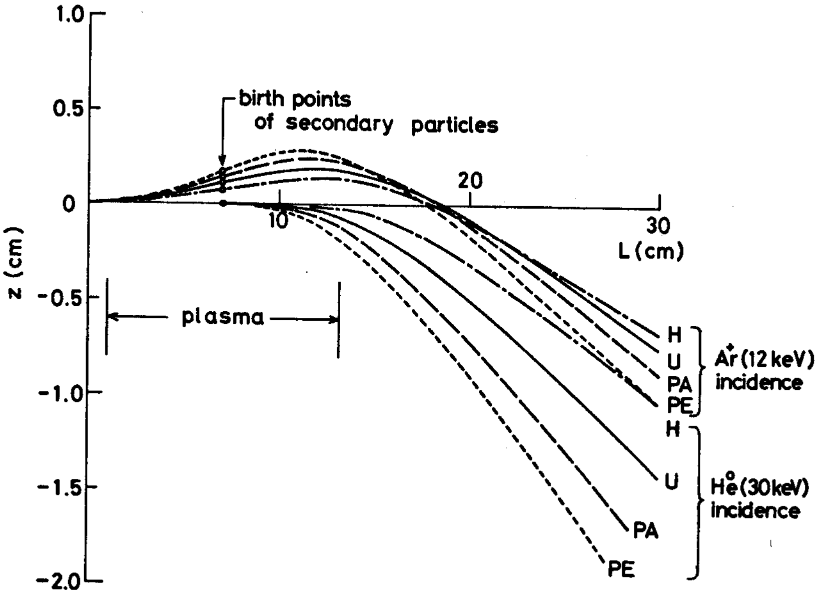

Fig. 3. Comparison of displacement in the toroidal direction for $^4He^0$(30 keV) atom and $^{40}Ar^+$(12 keV) ion incidence. Four types of plasma current profiles (H), (U), (PA) and (PE) are assumed.

4. Detecting Plane and Beam Divergence

Hereafter, we concentrate our attention on the neutral beam probing techniques. Figures 4(a) through 4(c) show the traces of the secondary ions arriving at the detecting planes of the following arrangements:

(a) the detector plate is fixed on the plane $x=6.5$cm and sensitive to the secondaries in the positive x-direction (left to right),

(b) the plate is on the same plane, but sensitive to the secondaries in the negative x-direction (right to left), and

(c) the detector is on the horizontal plane $y=1.5$cm and sensitive to the secondaries in the positive y-direction (upwards).

Each of the figures shows four traces corresponding to the four distinct profiles of the plasma current (H) through (PE) described in section 2.

The numericals on the curves show the points of birth of the secondary ions along the initial beam path. The largest z-displacement as well as the largest difference due to the current profiles appears for the ions born at the center of plasma. The secondary ion born at the point (0, −6, 0) where the primary beam exits the plasma column is entirely insensitive to the current distribution, and its orbit depends only upon the total plasma current. Therefore, its point of detection is fixed on the

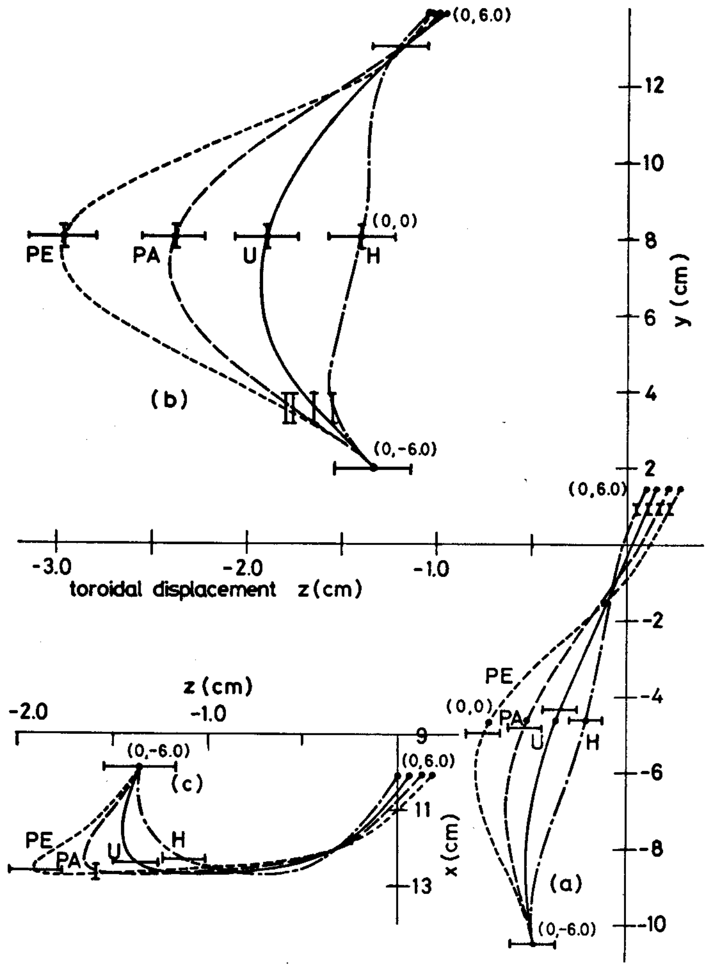

Fig. 4. Traces of secondary ions for four different current profiles (H) through (PE) at three different positions of detection (a), (b) and (c). Primary beam is of $^4He^0$ atoms (30 keV). Decector positions are (a) $x=6.5$cm and ions hit the plate on the plasma-side, (b) $x=6.5$cm but ions hit the oposite side, and (c) $y=1.5$cm. Bars show beam spread brought about by the incident beam divergence of ± 5 mrad in z-direction and ± 20 mrad in y-direction.

detecting plane, irrespective of the current profiles. That is to say, all the traces pass this fixed point. Accordingly, the orbit calculations were started from this point and traced back to the point of ionization.

Requirements on the beam quality are of essential importance in this probing method. By the action of the magnetic lens, which the toroidal field makes up in the xy-plane, divergence of beam due to imperfect collimation is suppressed to a certain extent. The bars shown in Fig. 4 represent the spread of traces on the detecting plane brought about by the initial divergence $v_x = \pm v_y/50$ at the point of beam incidence (0, 7. 5, 0). The figure shows that the focussing effect cannot be expected in the toroidal direction. Consequently, the spread of traces in this direction is equal to the length of the total flight path multiplied by the initial angle of beam divergence. There is a suspicion that this large spread limits the applicability of this method.

A high temperature plasma emits fast neutral particles spontaneously. These particles bring background on the detector plate. Therefore, the detector should not directly face the plasma. In the cases of (b) and (c) in Fig. 4, the detector should be shielded from background sources.

5. Conclusion

A method of neutral beam probing is proposed for determining the profile of plasma current in a tokamak. A neutral beam is superior for this purpose to a heavy ion beam, because the former provides us with a higher sensitivity to the current profile than does the latter. Installation of the equipment is easier with a straight injection of the neutrals rather than with a curved injection of ions. We can choose an optimum beam energy depending upon the plasma parameters, and this involves a mere change of detector position. In order to attain an angle of divergence less than 1/500, it is enough to use a beam collimator consisting of two screens with an aperture of 1mm diameter and separated by a distance of 50cm.

If a neutral beam with an intensity of 1 nA and a diameter of 1mm, both of the conditions being easily realized, 3 to 5% of the neutrals injected will be ionized in NOVA II plasma and 2×10^8 ions will reach the detector per second. Since the detector of the emulsion plate type is not time-resolving, the incident beam has to be pulsed. With a single pulse of 1 ms width, 2×10^5 ions hit the detector. As the secondary ions are distributed along the trace on the plate almost uniformly, we can fix a trace by only one shot.

Numerical orbit calculations with the NOVA II parameters show that discrimination of the uniform distribution (U) from the parabolic distribution (PA) is possible by comparing the traces on the detector plate.

References

1) R. L. Hickok and F. C. Jobes, AFOSR TR-72-0018.
2) J. C. Hosea, F. C. Jobes, R. L. Hickok, and A. N. Dellis, Phys. Rev. Lett. **30** (1973) 839.
3) J. Fujita and K. McCormick, Proc. 6th Europ. Conf. on Controlled Fusion and Plasma Physics, Moscow **1** (1973) 141.
4) K. McCormick, M. Kick, and J. Olivain, Proc. 8th Europ. Conf. on Controlled Fusion and

Plasma Physics, Prague **1** (1977) 140.
5) R. J. Goldston, Phys. Fluids **21** (1978) 2346.
6) R. Cano, C. Etievant, and J. C. Hosea, Phys. Rev. Lett. **29** (1972) 1302.
7) R. Cano, I Fidone, and J. C. Hosea, Phys. Fluids **18** (1975) 1183.
8) F. W. Perkins, MATT-818 (1970).
9) G. Lehner, Z. Physik **232** (1970) 405.
10) J. Sheffield, Plasma Phys. **14** (1972) 385.
11) F. DeMarco and S. E. Segre, Plasma Phys. **14** (1972) 245.
12) A. D. Craig, ibid. **18** (1976) 777.
13) W. Kuntz and G. Dodel, ibid. **20** (1978) 171.
14) S. E. Segre, ibid. **20** (1978) 295.