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SCATTERING OF THE FAST ATOMS BY A PROBING ION BEAM AS A DIAGNOSTIC TECHNIQUE TO DETERMINE THE SPACE POTENTIAL OF A PLASMA

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Introduction

The spatially and temporally resolved measurement of the plasma potential has not yet become routine in fusion-oriented experiments. The most prominent technique to determine the space potential is heavy ion beam probing, having been applied to several experiments [1-3]. Unfortunately, a good spatial resolution is difficult since the magnetic field distribution with finite plasma beta must be known. Further-more, the possibility for full in-sity system calibration is absent. There are some other difficulties for this technique too.

The aim of this work is the attempt to find proper diagnostic technique for a plasma space potential measurement that would be free from these difficulties.

Diagnostic technique

A schematic representation of the proposed diagnostic technique is given in Fig. 1. The theory of small-angle particle scattering is well-established. Energy and momentum conservation determines the energy spectrum of the elastically scattered neutrals. We shall only give a brief summary of the main results.

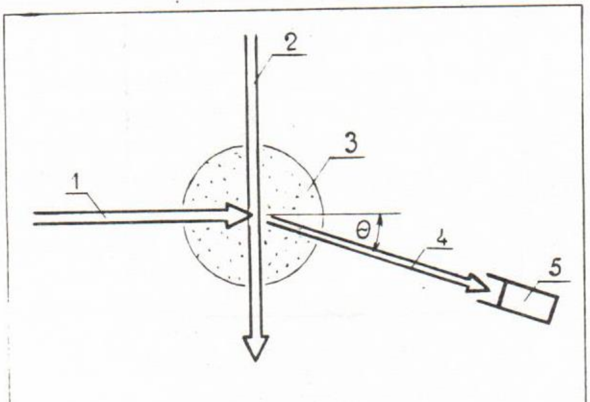

Fig. 1. Schematic representation of the proposed diagnostic technique: (1) scattering neutral beam; (2) probing ion beam; (3) plasma; (4) scattered neutral particles; (5) energy analyzer.

When a beam 1 of monoenergetic neutrals collides with a probing ion beam 2, the energy distribution of particles scattered within a fixed angle by a probing beam ions reflects the energy distribution of the probing beam and hence the plasma potential at an unique volume element within the plasma. The energy shift of the scattering distribution with respect to primary energy E_0 is given by

$$\delta E = E_1 - E_0 = E_0\Big[\Big\{\gamma\cos\theta + \sqrt{\gamma E_2^*/E_0}\,\sin\theta + \Big(1 - \gamma^2\sin^2\theta + \gamma\sin^2\theta\, E_2^*/E_0 + \gamma\sin 2\theta\sqrt{\gamma E_2^*/E_0}\Big)^{1/2}\Big\}(1+\gamma) - 1\Big], \qquad (1)$$

with E_1, the maximum of the energy distribution of the detected neutrals; $\gamma = m_1/m_2$, the mass ratio of neutral beam and ion beam particles; θ, the scattering angle; $E_2^* = E_2 - \varphi$, the energy of the probing ions at "observation point"; E_2, the primary energy of the probing beam; φ, the plasma potential.

For $\sin\theta \ll 1$, $\gamma\sin\theta \ll 1$, $\gamma\sin\theta\cdot E_2^*/E_0 \ll 1$ and $\varphi/E_2 \ll 1$ a simple expression for the plasma potential φ can be obtained. Equation (1) yields

$$\delta E \approx 2\theta\sqrt{\gamma E_2 E_0} - \varphi\theta\sqrt{\gamma E_0/E_2} - \gamma\theta^2 E_0\,, \qquad (2)$$

and it can be rewritten as

$$\varphi \approx \frac{2\theta\sqrt{\gamma E_2 E_0} - \gamma\theta^2 E_0 - \delta E}{\theta\sqrt{\gamma E_0/E_2}}$$

Thus the energy shift between the spectra of particles scattered by probing ions and particles scattered by plasma impurity ions (or by neutral component of the probing beam) gives the possibility to determine the plasma potential at the scattering volume. Profile measurements can be performed on a shot-to-shot basis by shifting the ion source or by changing its injection angle with adjusting the line-of-sight of the analyzer.

The flux of scattered neutral particles

The current I registered by the analyzer/detector combination can be written as

$$I = k\, j_1\, n_2\, V \left(d\sigma/d\Omega\right)_{lab} \cdot d\Omega \qquad (3)$$

with k, the combined attenuation due to charge-exchange and ionization processes and the efficiency of the detector; j_1, the "current" density of the neutral beam; n_2, the probing ion density; V, the scattering volume; $(d\sigma/d\Omega)_{lab}$, the differential scattering cross section; $d\Omega$, the solid angle.

The scattering cross section in laboratory frames is given in our case by

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \left[\frac{Z_1 Z_2}{E_0 + \gamma E_2^*} \; \frac{1+\gamma}{2}\right]^2 \frac{R}{\sin^4(\chi/2)} \qquad (4)$$

where Z_1, Z_2 are the nuclear-charge numbers of projectile and target particles, γ is the scattering angle in the center-of-mass frame, $R(\chi, \gamma, E_0, E_2^*) \sim 1$.

For availabel to us ion and neutral beam sources [4] the maximum current density is $j \backsim E^{3/2}/\sqrt{m}$. Thus, $j_1 \backsim E_0^{3/2}/\sqrt{m_1}$, $n_2 \backsim E_2$. This and (3), (4) lead to

$$I \backsim k \frac{E_0}{E_2} \sqrt{\frac{E_0}{m_1}} \left(\frac{Z_1 Z_2 (1+\gamma)}{E_0/E_2 + \gamma}\right)^2 \frac{1}{\sin^4(\chi/2)} \qquad (5)$$

To chose the beam species, the beam energies and the scattering angle, it is necessary to attain both a sufficient sensitivity of the potential measurement and a large enough flux of scattered particles for recording the spectra. Furthermore, it is necessary too that the probing ion gyroradius would be much more than the characteristic size of the magnetic field region. In order that we do not have the problems with background flux of particles scattered by the main plasma component, it is desirable that the corresponding limitary scattering angle would be less then our scattering angle Θ.

It can be concluded from the careful consideration of these conditions that the pairs of particles $N^0 \rightarrow Ar^+$ or $Ne^0 \rightarrow Kr^+$ would be more favourable for us. For the scattering of N^0 by Ar^+ one has γ =0,35. Let us assume, that the beam energies E_0 = $=10^4$ eV, E_2 $=4\cdot10^3$ eV and Θ $=10°$. Then the equation (2) yields $E_1 \approx 10{,}7\cdot10^3$ eV $- 0{,}2\,\varphi$, where φ in volts. Thus, the average energy of a detected neutrals is larger then the primary energy roughly at 700eV that allows to eliminate the double-charge-exchange background.

The available density of a probing ions Ar^+ is $n_2(\backsim E_2) \approx (1{+}5)\cdot10^9$ cm^{-3}. This density is approximately on the four order of magnitude smaller than the characteristic plasma density in the ion-temperature measurements, based on the similar Rutherford-scattering technique [5,6]. Nevertheless, the scattering cross section (4) for pair $\vec{N^0} \rightarrow Ar^+$ is larger in this case on the same four order, that might eliminate this difference in the density of targets. However, our experimental study of scattering in this range of parameters [7] shows that the measured cross section for this pair is approximately on the one order smaller than one predicted by formula (4). This deviation between the measured and calculated data is explained by the screening of Coulomb interaction by the large number of electrons present. Thus, the intensity of the scattered neutrals can be the same as for the Rutherford-scattering diagnostic to ion temperature measurements for the plasma density $n_i \approx (1{+}5)\cdot10^{12}$ cm^{-3}, that appears to be a possible task, taking into account the absence of the background problems.

Summary

The diagnostic technique proposed in this work corresponds to the intended aims. First, we do not need in the knowledges of the magnetic field distribution with finite plasma beta for a good spatial resolution, since the point of scattering in our case is determined by the intersection of the neutral beam trajectory with the line-of-sight of the analyzer. Second, we have the possibility for full in-situ system calibration. Furthermore, the minimum availabel plasma density for the plasma potential measurements is determined by the probing ion density.

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