ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received - Nov. 26, 1996)

NIFS-471 Dec. 1996

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

Effects of Horizontal Injection Angle Displacements on Energy Measurements with Parallel Plate Energy Analyzer

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Abstract

A formula including correction due to change of beam injection angle is derived for measurements of beam energy using parallel plate energy analyzers. The formula is mainly aimed for potential measurements in high temperature plasma with heavy ion beam probes.

Keywords; Parallel Plate Energy Analyzer, Horizontal Injection Angle, Correction, Heavy Ion Beam Probe

The 30° parallel plate energy analyzer (PGA), which was proposed by Proca and Green[1, 2], has an excellent capabilities, (i) wide acceptance angle up to second order focusing in vertical injection angle θ, and (ii) high energy resolution. A schematic view of PGA is shown in Fig. 1. According to these advantages, PGA is often used as an energy analyzer for heavy ion beam probes, which are a unique method to measure space potential in the interior of magnetically confined plasmas[3-5]. In this application, injection angles of measured beam particles may not be kept constant, and hence a certain correction is required. In this note, we will describe the effect of holizontal injection angle φ, mainly for the HIBP application.

In this analyzer, particle energy is determined from horizontal range of beam particles L. The relationship between the particle energy and the horizontal range is given by

$$K = \frac{qV_{\rm p}(L - h/\tan\theta)}{2d\sin 2\theta} \ , \tag{1}$$

where $h = h_1 + h_2$. Figure 1 demonstrates all coordinates and variables used in the following derivation. The horizontal range is obtained from the position of the beam particle on the detector plane(see Fig. 1c), and is written as

$$L\cos\varphi = L_0 + \Delta_{\rm y} \ , \tag{2}$$

where the reference horizontal range L_0 is defined as

$$L_0 = \frac{h}{\tan\theta_0} + \frac{2}{q}G_{\rm q}d\sin 2\theta_0 \ . \tag{3}$$

Note that $\theta_0 = 30°$ for the Proca and Green analyzer. When the energy analyzer has a first order focusing, the condition of $h = G_{\rm q}d/2q$ is satisfied, and $L_0 = 3\sqrt{3}h = 3\sqrt{3}G_{\rm q}d/2q$ for $\theta_0 = 30°$, where $G_{\rm q}$ is a gain factor for the charge of beam q; $G_{\rm q}/q \equiv G_1$. The distance η on the detector plane in Fig. 1c is related to the displacement on the horizontal plane.

$$\eta = \frac{\Delta_{\rm y}\sin\theta}{\cos\theta\sin\theta_{\rm d}\cos\varphi + \sin\theta\cos\theta_{\rm d}} \ . \tag{4}$$

This parameter η is the variable to be measured. A derivation of this relation is described at the end of this note.

Substituting Eqs. (2) and (4) into Eq. (1), we obtain the following formula,

$$K = qV_{\rm p}F(\theta,\ \varphi)\left(\frac{\eta}{d}\right) + qV_{\rm p}G(\theta,\ \varphi) \ , \tag{5}$$

where functions F and G are defined as

$$F(\theta,\ \varphi) = \frac{\sin\theta_{\rm d}\cos\theta\cos\varphi + \cos\theta_{\rm d}\sin\theta}{2\sin 2\theta\sin\theta\cos\varphi}\ .$$

$$G(\theta,\ \varphi) = \frac{L_0\tan\theta - h\cos\varphi}{2d\sin 2\theta\tan\theta\cos\varphi} = \frac{G_1\left(3\sqrt{3}\tan\theta - \cos\varphi\right)}{4\sin 2\theta\tan\theta\cos\varphi}\ . \tag{6}$$

Here, the functions F and G are termed as sensitivity and gain, respectively. Figure 2 shows F and G as a function of θ for several horizontal injection angles, and here the function G is normalized by G_1. The gain curve $G(\theta,\ \phi)$ indicates a flat region around $\theta = 30°$, and moves upwards as φ increases. On the other hand, the sensitivity function F is more dependent on the vertical injection angle θ than the horizontal one φ. This fact should be kept in mind.

In the actual use of PGA for HIBP measurements, a split plate detector is used [5,6] to determine the beam position on the detector plane. Approximate horizontal position $\Delta_{\rm x}$ can be also monitored with the split plate detector. The injection angle φ, therefore, is known from a relation $\cos^2\varphi \simeq 1 - (\Delta_{\rm x}/L_0)^2$. Substitution of this estimated φ value into Eq. (6) allows us to correct an error in beam energy measurements[4], and we obtain

$$F(\theta,\ \varphi) \simeq \frac{\sin(\theta_{\rm d}+\theta)}{2\sin 2\theta\sin\theta} + \frac{\cos\theta_{\rm d}}{4\sin 2\theta}\left(\frac{\Delta_{\rm x}}{L_0}\right)^2 \equiv F_0(\theta) + \Delta F(\theta)\left(\frac{\Delta_{\rm x}}{L_0}\right)^2$$

$$G(\theta,\ \varphi) \simeq \frac{G_1(3\sqrt{3}\tan\theta - 1)}{4\sin 2\theta\tan\theta} + \frac{3\sqrt{3}G_1}{8\sin 2\theta}\left(\frac{\Delta_{\rm x}}{L_0}\right)^2 \equiv G_0(\theta) + \Delta G(\theta)\left(\frac{\Delta_{\rm x}}{L_0}\right)^2\ . \tag{7}$$

Finally, the correction due to change of the horizontal injection angle φ is given by

$$K_{\rm corr} = qV_{\rm p}\left(\frac{\Delta_{\rm x}}{L_0}\right)^2\left(\Delta F_0(\theta)\left(\frac{\eta}{d}\right) + \Delta G_{\rm q}(\theta)\right)\ . \tag{8}$$

The second term will be more dominant than the first term. This expression will be helpful for practical use of HIBP measurements.

Acknowledgements

The authors would like to thank the reviewer for her/his critical and careful reading.

Appdendix - Derivation of Eq. (4)

In Fig. 1c, the vector normal to the detector surface is $\vec{n} = (0, -\sin\theta_{\rm d}, \cos\theta_{\rm d})$, and the equation of the detector plane is represented by

$$-y\sin\theta_{\rm d} + z\cos\theta_{\rm d} = 0 \ .$$

The equation of trajectory line in the drift space is also written as

$$\begin{aligned} x &= \Delta_{\rm x} + t\cos\theta\sin\varphi \\ y &= \Delta_{\rm y} + t\cos\theta\cos\varphi \\ z &= -t\sin\theta \end{aligned} \quad ,$$

where $\Delta_{\rm x}$ and $\Delta_{\rm y}$ represent the displacements on the horizontal plane. The cross point between the line and the detector plane is obtained as

$$\begin{aligned} y &= \frac{\Delta_{\rm y}\sin\theta\cos\theta_{\rm d}}{\cos\theta\sin\theta_{\rm d}\cos\varphi + \sin\theta\cos\theta_{\rm d}} \\ z &= \frac{\Delta_{\rm y}\sin\theta\sin\theta_{\rm d}}{\cos\theta\sin\theta_{\rm d}\cos\varphi + \sin\theta\cos\theta_{\rm d}} \end{aligned} \quad .$$

Using a relation, $\eta = \sqrt{y^2 + z^2}$, we obtain Eq. (4).

References

1) T. S. Green and G. A. Proca. Rev. Sci. Instrum. **41**. 1409(1970).

2) G. A. Proca and T. S. Green, Rev. Sci. Instrum. **41**. 1778(1970).

3) F. C. Jobes and R. L. Hickok, Nucl. Fusion, **10**, 195(1970).

4) A. Fujisawa, H. Iguchi, S. Lee *et al.*, Rev. Sci. Instrum.**67**, 3099(1996).

5) L. Solensten and K. A. Connor. Rev. Sci. Instrum. **58**, 516(1987).

6) A. Fujisawa, H. Iguchi, Y. Hamda, Rev. Sci, Instrum. **65** 1580(1994).

Figure Captions

Fig. 1: (a) A side view of a parallel plate energy analyzer. (b) A top view of a parallel plate energy analyzer. (c) Definitions of coordinates and parameters in detector and horizontal planes.

Fig. 2: (a) Sensitivity curves $F(\theta,\ \varphi)$ as a function of vertical injection angle θ with respect to two horizontal angles $\varphi = 0°, 10°$. The parameter $\theta_{\rm d} = 60°$ is assumed. (b)Gain curves $G(\theta,\ \varphi)$ normalized by G_1 as a function of vertical injection angle θ with respect to several horizontal angles $\varphi = 0°, 1°, 2°, 3°, 4°, 5°$.

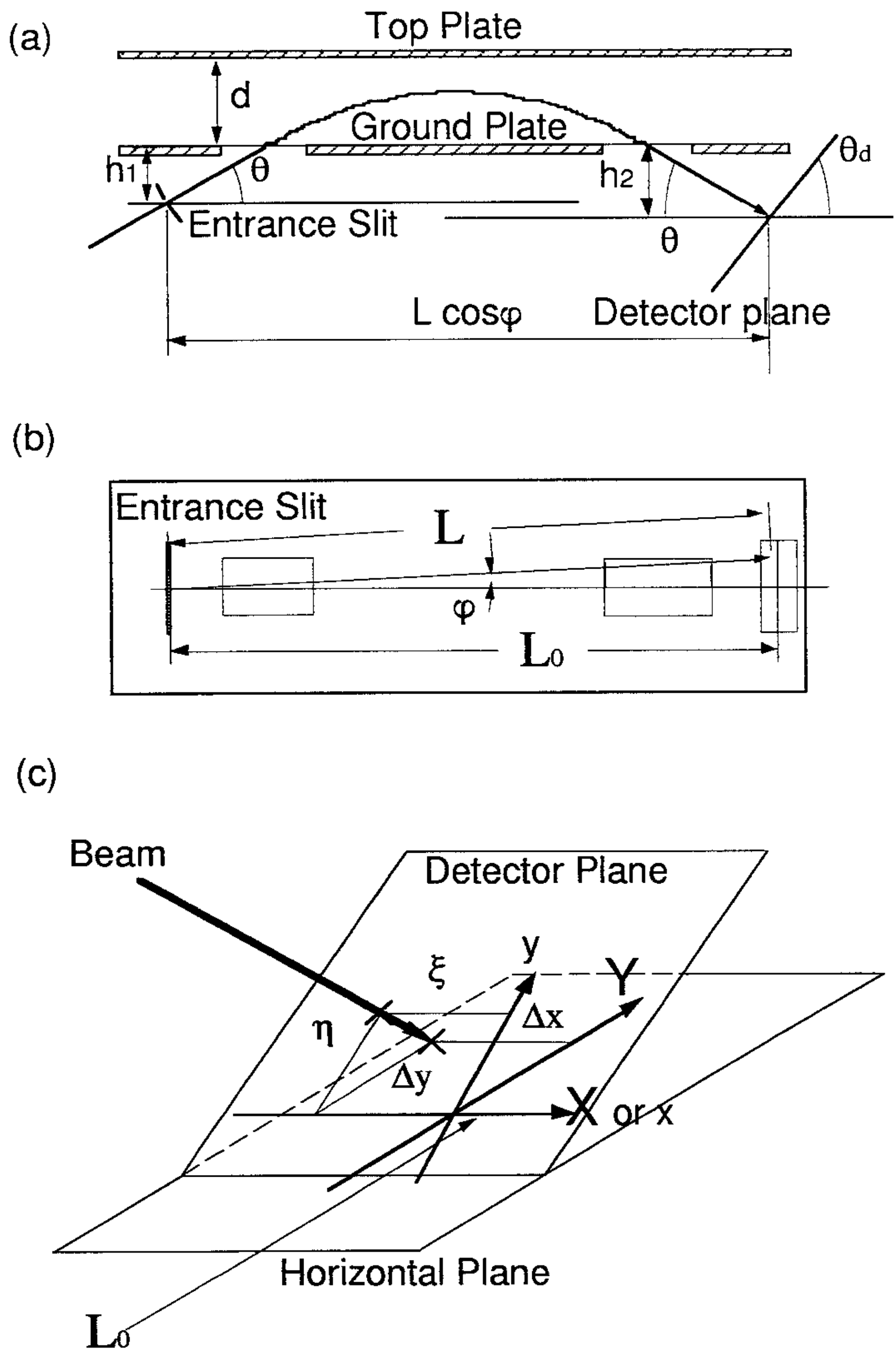

Figure 1 A. Fujisawa, et al.

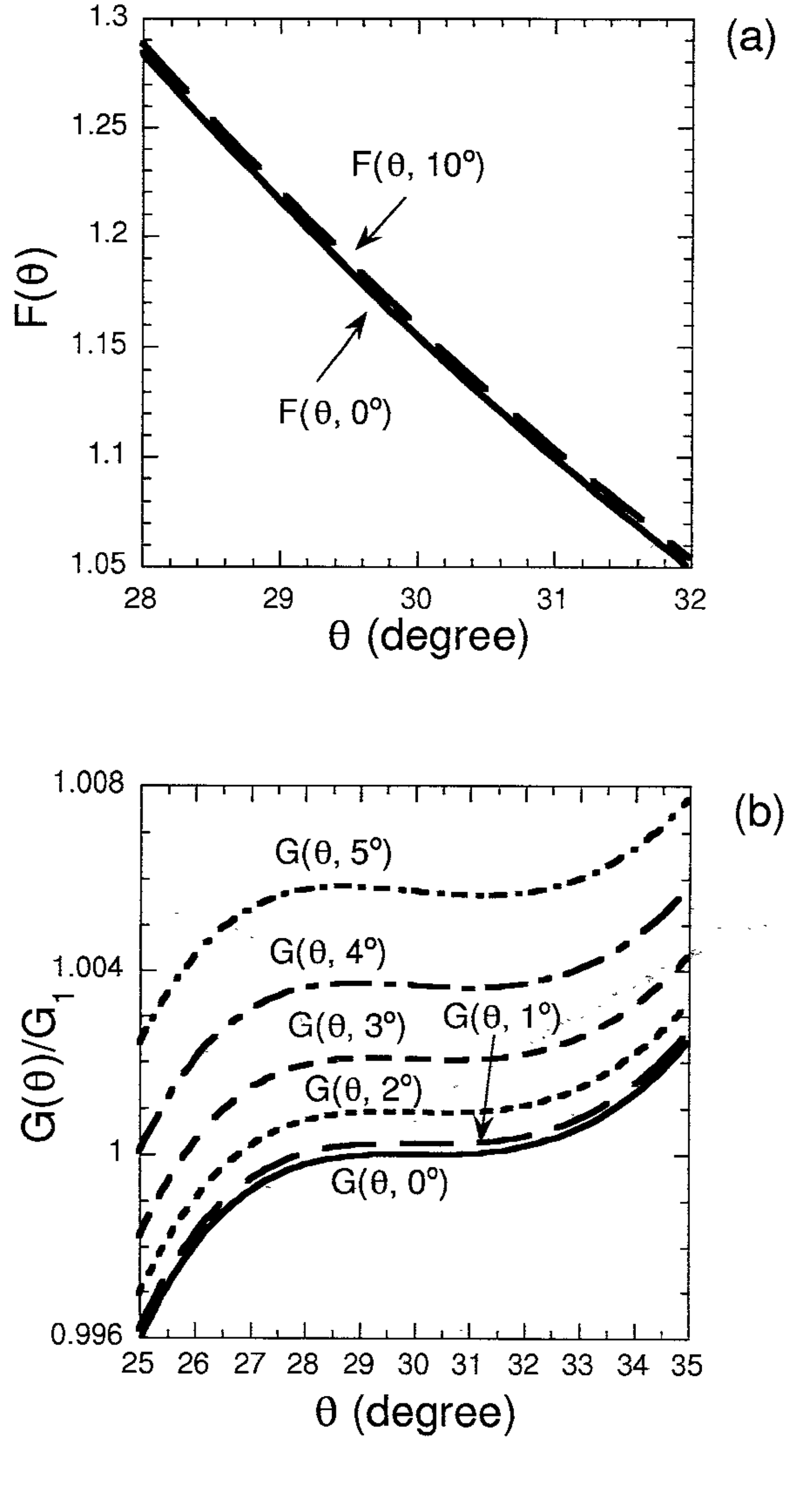

Figure 2 A. Fujisawa, et al.

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