ACCURACY OF ELECTROSTATIC ENERGY ANALYZER IN HIBP DIAGNOSTIC

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I. INTRODUCTION

A heavy ion beam probe (HIBP) diagnostic is known as the only tool for the electric potential measurements in hot thermonuclear plasmas. It is obtained by comparison of the initial energy of the primary (single charged) ions with the energy of the secondary (double charged) ions created in collisions with the plasma electrons: the difference exactly equals to the value of the plasma potential inside the ionization (sample) volume. The energy spectrographs used in these measurements present the most delicate part of the HIBP installation due to a very hard requirement to the accuracy of the beam energy determination which must be of the order of $\Delta\varepsilon/\varepsilon \sim 10^{-4}$.

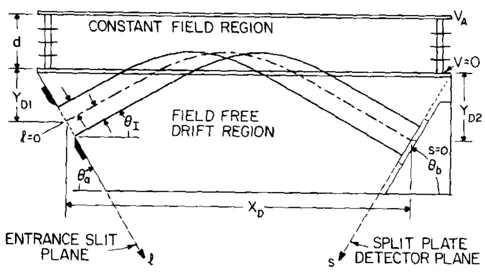

Fig.1. Schematic of a 30º electrostatic energy analyzer.

For the traditional 30º Proca-Green electrostatic energy analyzer, schematically shown in Fig.1, the plasma potential is calculated by the relation [1]:

$$\phi = 2U_a[G_A(\theta,\varphi) - F(\theta,\varphi)\delta i] - U_b, \quad (1)$$

where U_a is the potential applied to the top plate of the analyzer, U_b is the acceleration voltage, $\delta i = (i_U - i_L)/(i_U + i_L)$ is the normalized difference of the secondary beam current on the upper (U) and lower (L) detector plates (split-plates), and $G_A(\theta,\varphi)$ and $F(\theta,\varphi)$ represent the gain and dynamic coefficients of the analyzer which are the functions of the analyzer geometry and the in-plane (mid-plane) and out-plane incident angles of the beam (θ,φ) given by:

$$G_A(\theta,\varphi) = (X_D\tan\theta - Y_D)/4d\sin^2\theta\cos^2\varphi \quad (2)$$

$$F(\theta,\varphi) = w(\sin 30^\circ + \cos 30^\circ\tan\theta)/8d\sin^2\theta\cos^2\varphi \quad (3)$$

$$(Y_D = Y_{D1} + Y_{D2})$$

The effects, generally influencing the accuracy of the measurements, are summarized in Fig.2, and should be taken into account during calculations. This paper presents a short description of some improvements and procedures which have been elaborated and successfully applied in recent HIBP experiments on TJ-II stellarator (Spain), T-10 and TUMAN-3M tokamaks (Russia), and allow minimizing the influence of the most of these effects.

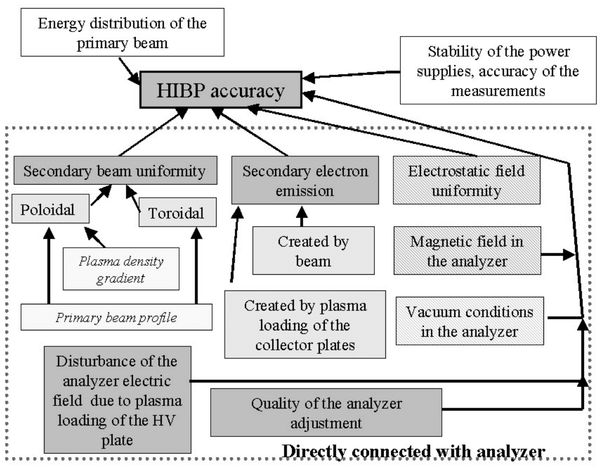

Fig.2. Diagram of the effects, influencing operation of the electrostatic energy analyzer.

II. IMPROVEMENTS IN ANALYZER DESIGN

Because Eq. (1) was derived in the assumption of homogeneous electric field between the analyzer plates, any disturbance will introduce an error in plasma potential determination. Except clear effects of the mechanical accuracies during analyzer manufacturing, the intrinsic edge none-uniformity exists and can strongly influence the measurements if the trajectory of the analyzed particle inclines or shifts out of the mid-plane of the analyzer. In particular, such a situation is usual in HIBP applications on stellarators. In early HIBP experiments it was believed that introducing of the guard rings with externally distributed potential should improve the edge electric field uniformity. However, further experience showed that the problem had still remained due to charging of the guard ring insulators, and not controllable change of the characteristics of the resistive divider in analyzer operational environment (vacuum, plasma loading). Fig.3

shows the photo of the energy analyzer elaborated for the HIBP experiments on TJ-II. The minimal dimension of the uniform electric field (i.e. the minimal width of the analyzer) was estimated by trajectory calculations of the secondary ions in standard regimes of TJ-II operation. Rejection of the guard rings and numerical optimization of the analyzer design by special shaping of the plates allowed obtaining the uniformity $\Delta E/E = 10^{-5}$ inside the region occupied by the trajectories. The additional possibility of the analyzer shift inside vacuum tank in the range of ±10 cm foresees the spreading of the measurements onto the rest of extreme regimes of TJ-II. A smaller version of such an energy analyzer is used in HIBP experiments on TUMAN-3M.

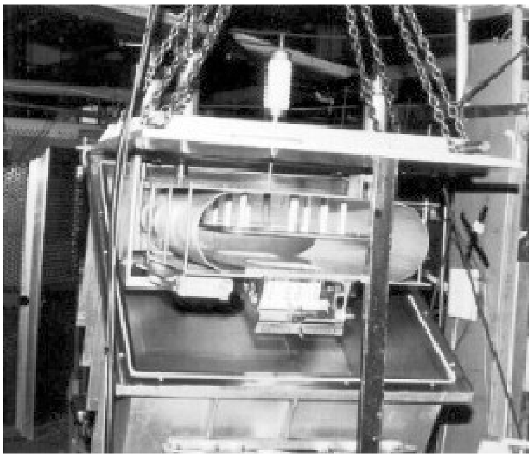

Fig.3. Photo of the electrostatic energy analyzer elaborated for the HIBP experiments on TJ-II.

III. CANCELLATION OF SECONDARY ELECTRON EMISSION EFFECT ON DETECTOR

The actual currents on the split detector are a combination of both the ion and electron currents. The uniform secondary electron emission from the split detector does not influence analyzer operation. However, the different geometry and surface conditions of the split-plates and the asymmetric secondary electron exchange between the plates due to stray magnetic field of a plasma device in the vicinity of the detector break the uniformity of secondary electron flux and can strongly disturb the measurements [2].

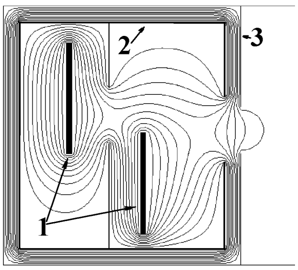

Fig.4. Schematic of the modified split-plate detector and the lines of equal potential.
(1) collector plates;
(2) bias box with extended suppression electrodes;
(3) grounded box.

Fig.4 shows the modified split-plate detector with complete suppression of the secondary electrons. The appropriate bias geometry has been simulated by the SIMION code. In this geometry two collector plates are enclosed inside the bias box, which has two extensions between the plates.

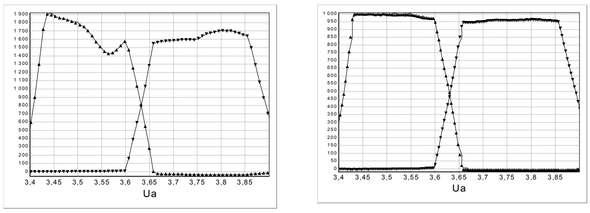

Fig.5. Dynamic curves obtained with usual (left) and modified (right) split-plate detectors.

Fig.5 presents the analyzer dynamic curves obtained on a test facility with the usual (without suppression) and modified (with complete suppression) split-plate detectors. The complete suppression results in the ideal dynamic curve.

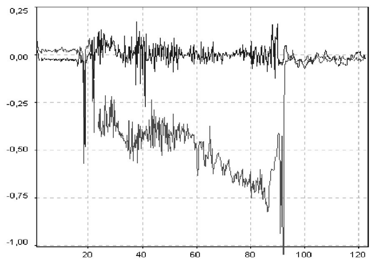

Fig. 6. Suppression of the secondary electrons created by plasma radiation.

Fig.6 demonstrates the effectiveness of the new detector for the suppression of secondary electrons created by plasma radiation on TUMAN-3M.

IV. IMPROVEMENTS IN CALIBRATION PROCEDURE

The calibration of the energy analyzer on a test facility allows obtaining the *G* and *F* functions in a wide range of the incident angles. Comparison with the theoretically predicted ones gives an idea about quality of the analyzer manufacturing. In principal, the obtained data can be used in plasma experiments for the potential calculations by Eq. (1). However, the conditions of the analyzer operation on a test facility and a plasma device are sufficiently different. Therefore, the additional calibration of the energy analyzer in a plasma device real installation is very desirable. The most straightforward way of such *in situ* calibration is the use of a gas puffing into the vacuum vessel of a plasma device and the energy analysis of the secondary ions created in collisions with the gas particles. In a case of stellarators, in which the vacuum magnetic fields are not strongly disturbed by the plasma, this calibration may be considered as an absolute, simplifying the calculations of plasma potential value by the relation:

$$\phi = 2U_aF(\delta i_{gas} - \delta i_{plasma}) \quad (4)$$

In HIBP experiments on TJ-II the additional gas puffing directly after plasma shot is used to suppress the post-generation of the runaway electrons. This procedure significantly facilitates the plasma potential measurements and increases the reliability of the data.

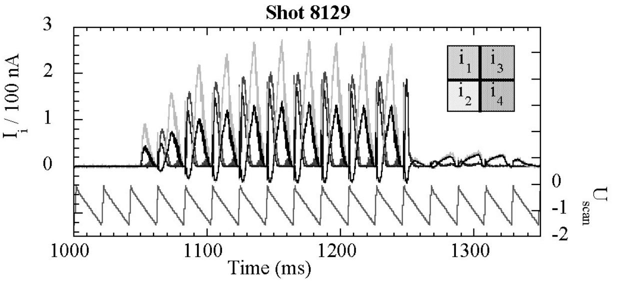

Fig 7. The signal of secondary ions Cs^{2+} created both by plasma electrons and He gas in one operational cycle of TJ-II.

As the illustration, Fig.7 shows the signal of secondary ions Cs^{2+} created both by the plasma electrons and He gas in one operational cycle of TJ-II. Fig.8 presents the profiles of δi_{gas} and δ_{plasma} obtained in experiments on TJ-II.

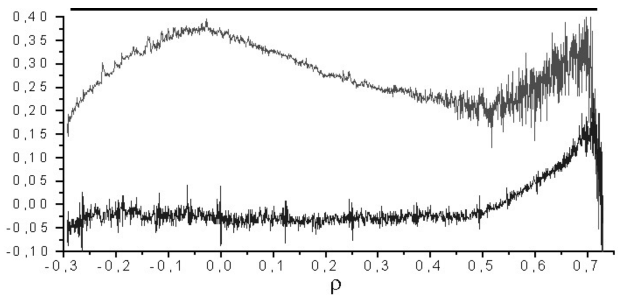

Fig.8. The profiles of δi_{gas} (down) and δ_{plasma} (top).

V. EVALUATION OF THE IN-PLANE INCIDENT ANGLE INTO ELECTROSTATIC ENERGY ANALYZER DIRECTLY DURING PLASMA EXPERIMENT

Contrary to the stellarators, the calibration on a gas target is not so useful in tokamaks due to presence of the magnetic field created by plasma current. This magnetic field influences the beam trajectory and, as a result, changes the incident angles of the beam into energy analyzer. Eqs. (1-3) show that the resolution of the plasma potential measurements is strongly related to the accuracy of the knowledge of the incident angles of the beam θ, φ. The out-plane scanning of the beam by electrostatic plates arranged just before the analyzer entrance slit was proposed as the method to fix the out-plane entrance angle at $\varphi = 0$ [3]. The method for the evaluation of the in-plane incident angle θ directly during plasma experiment has been elaborated recently [4]. This method is based on the addition of a second split-plate detector along a 30° exit axis of the analyzer, and on the comparison of the respective normalized beam currents δi_1, δi_2. The incident angle, θ, is determined by a simple relation:

$$\tan\theta = [(2l/w + \Delta i)/(2l/w - \Delta i)]\tan 30^{\circ}, \qquad (5)$$

where $\Delta i = \delta i_2 - \delta i_1$.

The method has been checked on a test facility with the simplest cutting up of the detector in the mid-plane of the analyzer and shifting of the one part along a 30° axis. The incident angle of the beam was changed externally by mechanical rotation of the analyzer around the entrance slit. For every incident angle the measurements have been performed in the full dynamic range of Δi by changing the beam energy.

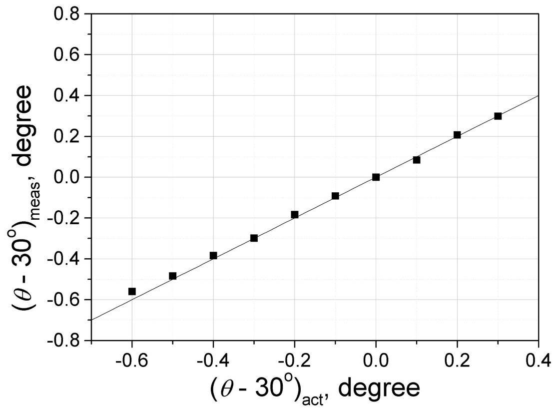

Fig.9. The measured $(\theta - 30^{o})_{meas}$ versus actual $(\theta - 30^{o})_{act}$ obtained during $\theta = 0.1^{o}$ steps rotation of the analyzer near a 30° entrance angle.

Fig. 9 presents the measured $(\theta - 30^{o})_{meas}$ versus actual $(\theta - 30^{o})_{act}$ obtained during $\theta = 0.1^{o}$ steps rotation of the analyzer near a 30° entrance angle, and demonstrates the high accuracy of the method.

VI. CONCLUSIONS

The recently elaborated improvements in the analyzer design, complete suppression of the secondary electron emission from detector, the use of the post-plasma-shot gas puffing for analyzer calibration, and the possibility of the beam incident angles evaluation directly during plasma experiment facilitate the plasma potential measurements by HIBP diagnostic and significantly increase the reliability of the obtained data. These improvements are successfully applied in the current HIBP experiments on TJ-II stellarator and T-10, TUMAN-3M tokamaks.

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