# TOF METHOD IN PLASMA POTENTIAL MEASUREMENTS BY HIBD

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The heavy ion beam diagnostic (HIBD) developed for the tokamak ISTTOK (R = 0.46 m, a = 0.085 m, B = 0.5 T, I = 6-9 kA) is based on a multiple cell array detector (MCAD), which collects simultaneously a "fan" of secondary ions originated along a primary beam trajectory in collisions with the plasma electrons and separated by the magnetic field of the tokamak. Utilization of the traditional electrostatic energy spectrographs for the plasma potential measurements in experiments with MCAD is very complicated. This paper presents the current results of adaptation and mastering of the alternative time-of-flight (TOF) technique. Three schemes of the measurements are considered: i) "integral" scheme of the average plasma potential measurements by a pulsed primary beam, ii) "quasi-local" scheme of the measurements of plasma potential drop between neighbouring sample volumes, and iii) "local" scheme of plasma potential profile measurements. The electronics used in TOF energy analyzer (TOFEA) consist of charge sensitive and fast shaping amplifiers, constant fraction discriminator and time-to-amplitude converter with resolution $\Delta t/t = 10^{-4}$. The TOFEA resolution $\Delta t/t = 3\times10^{-4}$ has been achieved in mastering experiments with a pulsed (250 ns) primary beam carried out to the primary detector in magnetic field of the tokamak. With plasma the resolution is reduced 2.5 times due to decreasing of signal-to-noise ratio caused by plasma loading of MCAD. The changes of the average plasma potential during discharges with minor disruptions have been obtained by TOF energy analysis. The results of this experiment allow to conclude the reliability of TOF technique in plasma potential measurements by HIBD with MCAD. On the base of the obtained data and experience a four-channel TOFEA for the plasma potential profile measurements has been elaborated.
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## I. INTRODUCTION

The heavy ion beam diagnostic (HIBD) is known as the only tool for direct measurement of the electric potential in hot plasmas. These measurements are realized by energy analysis of the secondary ions, which arose in collisions with the plasma electrons. In HIBD with a multiple cell array detector (MCAD) [1], which collects a "fan" of secondary ions originated along a primary beam trajectory inside the plasma, utilization of traditional electrostatic energy spectrographs for plasma potential measurements is very complicated. The alternative can be the time-of-flight (TOF) energy analysis [2].

This paper presents the current results of adaptation and mastering of TOF technique for the plasma potential measurements by HIBD on the tokamak ISTTOK [3]. The structure of the paper is as follows. The principle of TOF method is reminded in Section II. Three schemes of plasma potential measurements by TOF energy analysis are considered in Section III. TOF electronics and influence of plasma loading effect are characterized in Section IV. The current results of the TOF measurements with HIBD on ISTTOK are presented in Section V. The four-channel TOF energy analyzer elaborated recently is shortly described in Section VI. Conclusion is formulated in Section VII.

## II. PRINCIPLE OF TOF METHOD

In TOF method the energy dispersion is created in time, hence, a modulated incident beam must be used with a detection system capable of determining the time-of-flight of the injected particles over a known distance (TOF path). The detector at the entrance of the TOF path creates "start" (reference) signal, while "stop" signal is obtained on the detector at the exit of the TOF path. TOF energy analysis can be generally realized by direct measurements of "start"-"stop" time delay ($t_{TOF}$) in a case of discrete modulated beam ("conventional" TOF), or by measurements of "start"-"stop" phase-shift ($\varphi_{TOF}$) accumulated along TOF path by continuously (sinusoid) modulated beam ("phase-shift" TOF). Resolution of the measurements is given by:

$$|\Delta E/E_0| = 2\Delta t/t_{TOF} = 2\Delta\varphi/\varphi_{TOF}, \qquad (1)$$

The simplest beam modulation technique consists of the fast scanning of the beam across the slit. However, in the case of continuous modulation the higher harmonics appear in the signal due to convolution of the beam profile and slit shape [4], thus resulting in a strong degradation of resolution. In discrete modulation the effect of beam energy perturbation during modulation process can take place when the width of the modulation pulse is comparable with the time-of-flight of the ion between the plates. The easy control of the last effect determines a choosing of the "conventional" TOF for the implementation in HIBD.

## III. TOF PLASMA POTENTIAL MEASUREMENTS

The TOF measurements of plasma potential by HIBD with MCAD can be generally realized by three schemes schematically shown in Fig.1.

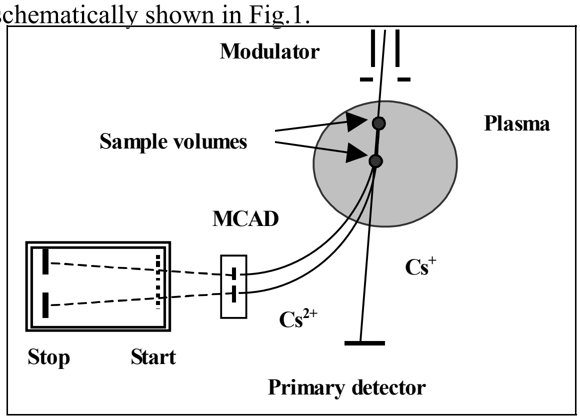


*Fig.1. Schematic of TOF measurements*

The simplest "integral" scheme is the measurement of average plasma potential by primary ion beam. In this scheme the time-of-flight of the ion across the volume with some distributed along beam trajectory ($l_{tr}$) electrostatic potential ($\Phi(l_{tr}/L_{pl})$) is given by the path integral:

$$t_{TOF}=t_{TOFmd}(\Phi=0)(L_{pl}/L_{TOFmd})\{(1/2)\times \times\int[q\Phi(l_{tr}/L_{pl})/E_0]\mathrm{d}(l_{tr}/L_{pl})+1\},\quad (E_0>>q\Phi_{max}), \qquad (2)$$

where $t_{TOFmd}$ is the time-of-flight from modulator to detector, $L_{pl}$ is the plasma dimension, $E_0$ is the initial energy and $q$ is the charge of the ion.

In the second "quasi-local" scheme the potential drop ($\Delta\Phi(\Delta l_{tr})$) between neighbouring sample volumes inside the plasma can be obtained by measuring the relative time-of-flight of the secondary ions between the respective ("start"-"stop") cells of MCAD. The relation is:

$$\Delta t_{TOF}=t_{TOFsd}(\Phi=0)\{(1/2)[q\Delta\Phi(\Delta l_{tr})/E_0]+1\}+\Delta t_{tint},\quad (E_0>>q\Delta\Phi), \qquad (3)$$

where $t_{TOFsd}$ is the time-of-flight of a secondary ion from the sample volume to MCAD constituted the effective TOF path. The term $\Delta t_{tint}$ is some path integral, which for ISTTOK HIBD geometry can be as low as 10%, depending on the achievable resolution of the measurements.

The third "local" scheme presents the conventional HIBD measurements of plasma potential ($\Phi(l_{tr})$) given by:

$$t_{TOF}=t_{TOFss}(\Phi=0)\{(1/2)[\Phi(l_{tr})/E_0]+1\},\quad (E_0>>q\Phi), \qquad (4)$$

where $t_{TOFss}$ is the time-of-flight between "start" and "stop" detectors arranged along secondary ion trajectories outside the plasma.

Notice that the calibration of time-of-flight along the TOF paths without plasma for all schemes is necessary.

## IV. TOF ELECTRONICS AND PLASMA LOADING EFFECT

A routine application of TOF method in mass and nuclear spectroscopy naturally determines the use of the already elaborated approaches and acquisition electronics. The one-channel TOF energy analyzer (TOFEA) currently tested in HIBD TOF measurements on ISTTOK is shown in Fig.2 [4]. It consists of primary beam modulator, detector, conditioning electronics and a time-to-amplitude converter (TAC).

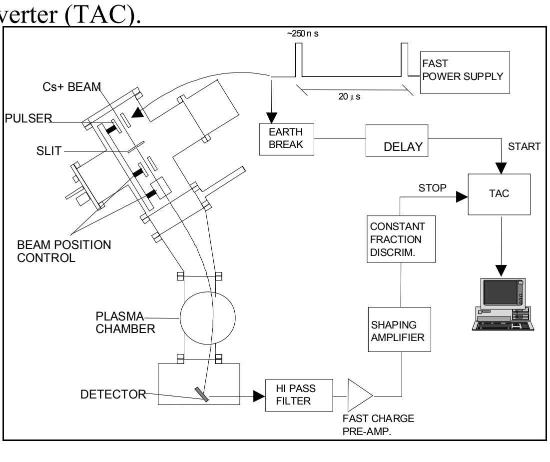


*Fig.2. One-channel TOFEA*

Primary beam modulator constitutes of a pair of electrostatic plates (8 cm length and 0.8 cm separation), powered by DEI HV1000 pulser (55 ns - 10µs range), and the following 2 mm slit. Conditioning electronics are conventional ORTEC products and include a charge sensitive preamplifier, a fast shaping amplifier, and a constant fraction discriminator. A relatively large (of the order of the beam pulse width) effective collection time of detector (copper plate) determines the use of a charge sensitive preamplifier, which is well suited in this condition of operation [5]. The sensitivity of the ORTEC142A charge sensitive preamplifier is 45 mV/MeV. The following fast shaping amplifier (ORTEC474) and constant fraction discriminator (ORTEC455) allow to optimize the resolution of the measurements by choosing of the appropriate time-shaping constants and discrimination levels. The TAC creates a pulse with amplitude proportional to the time-of-flight of the primary beam pulse from the modulator to the primary detector. The time resolution of TAC (ORTEC457) is $(\Delta t/t)_{\mathrm{TAC}}=10^{-4}$. The TAC output is acquired by a multichannel analyzer (LeCroy3001), or by a 1 µs analog-to-digital converter (ADC) with data storage in 64 kilobite buffer memory. The time-delay module allows fast and simple calibration of TOFEA electronics.

The loading of detector by plasma radiation presents the main problem of TOF method implementation in experiments with HIBD. The created current is caused by photo-electron emission from detector surface. Generally, it can be considered as an effective leakage current similar to semiconductor detectors of nuclear spectroscopy with the same consequences. Usually, this current presents a pulse of plasma shot duration (20-40 ms in the case of ISTTOK) with amplitude depending on discharge conditions and geometry of detector arrangement as to the plasma vision. In standard ISTTOK discharges and with the present arrangement of MCAD the value of loading current is high enough to put preamplifier into saturation.

## V. CURRENT RESULTS OF TOF MEASUREMENTS

In the experiments described below the HIBD operated with 1.5 (0.8) µA of steady $Cs^+$ ($Xe^+$) beam extracted from the plasma ion source and accelerated up to 22 keV. Parameters of the modulator and TOFEA were optimized in the experiments with a pulsed primary beam carried out to the primary detector in toroidal magnetic field of tokamak. Particularly, a width of the beam pulse of 250 ns is the compromise between limitations imposed by the beam intensity, detector capacitance and resolution of the measurements.

Fig.3 presents two TOF spectra obtained in these experiments and externally delayed by 2 ns. The full width on half maximum (FWHM) of the spectra is FWHM~20 ns, and mainly contributed by the electrically coupled and electromagnetic interference noise (the signal-to-noise ratio (SNR) is SNR~8). Distinguishing of 2 ns of the delay in spectra demonstrates the TOFEA capability of resolution $\Delta t/t_{TOF}$~$3\times10^{-4}$ ($t_{TOF}$ = 7.2 µs). The saturation of preamplifier during plasma shot has been avoided with inductive high-pass filtration introduced between the detector and preamplifier. However, the level of the noise increases 2.5 times reducing the TOFEA resolution to $\Delta t/t_{TOF}$~$7.5\times10^{-4}$, or $\Delta E/E_0$~$1.5\times10^{-3}$.

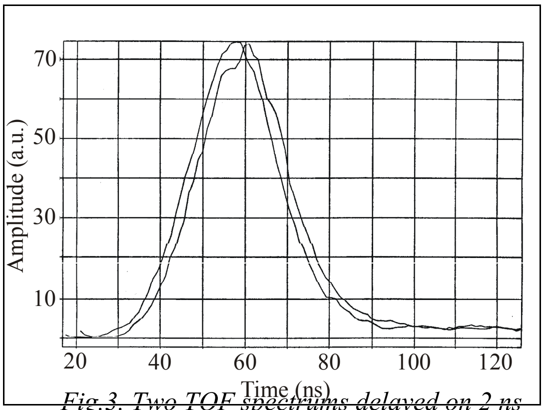


*Fig.3. Two TOF spectrums delayed on 2 ns*

Changes on the average plasma potential in discharges with minor disruptions have been observed by TOF energy analysis in experiments with a pulsed primary beam crossing the plasma [6]. The TOF (TAC) signal and plasma parameters time evolutions are presented in Fig.4. The relative change of the average plasma potential is described by Eq.(2) derived for two moments ($t$) and ($t+\delta t$) of discharge. The resolution of the measurements is given by $\Delta\Phi/E_0 \cong (\Delta E/E_0)(L_{pl}/L_{TOFmd})^{-1} = 1.1\times10^{-2}$, or $\Delta\Phi \cong$ 240 V of the absolute value. Temporal resolution of the measurements is 20 μs restricted by TAC acquisition (busy) time.

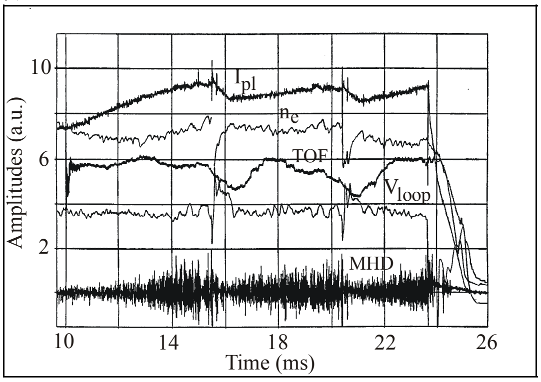


*Fig.4. The TOF signal and plasma parameters time evolutions in disruptive discharges of ISTTOK*

Immediate analysis of TOF signal indicates the drop of plasma potential to a relatively more negative value during disruption. The HIBD observations of minor disruptions on the tokamaks RENTOR [7] and ISX-B [8] show the drop of plasma potential to zero due to the shortening of radial electric field when plasma moves and dumps on the wall of tokamak chamber. Exploitation of this fact allows to estimate the plasma potential value of the order of ~(+450) V. Positive electric potential opposite to the prediction of neoclassic theory was observed on a number of small tokamaks (in particular on RENTOR [7]) with reduced plasma parameters, and is attributed to the fluctuations in the magnetic field which cause the field lines to stochastically wander out to the chamber wall, permitting electrons to escape along the field lines. As a result a positive ambipolar potential is built up until the electron and ion losses are equal. However, the estimated value of plasma potential is higher, than predicted by theory. The presence of runaway electrons in low-density discharge of ISTTOK may be an explanation.

## VI. FOUR CHANNEL TOFEA

The initial experiments with time-of-flight measurements of the plasma potential drop between neighbouring sample volumes have shown that, though the primary beam intensity has been increased 5 times with a new beam injection system [9], the SNR for the secondary beam is still remained too low due to plasma loading effect. Fig.5 presents the schematic of the four-channel TOFEA with cylindrical electrostatic steering plates. Such a design is minimally influenced by plasma loading and suited to strong mechanical constrains of the ISTTOK diagnostic port. The conventional electrostatic plates are foreseen for the careful beam alignment. The "start" (mesh) and "stop" (plate) detectors of TOFEA are arranged inside double-shielded box to minimize the electrically coupled and electromagnetic interference noise.

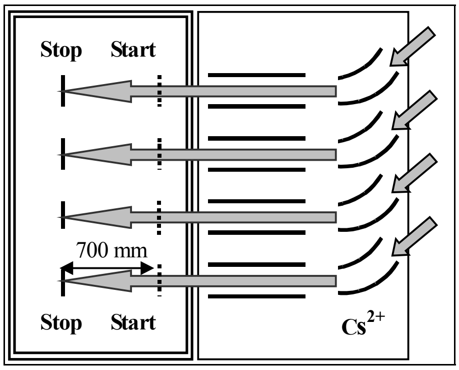


*Fig.5. Four-channel TOFEA*

## VII. CONCLUSION

The presented results demonstrate the reliability of TOF technique in plasma potential measurements by HIBD with MCAD. Resolving of the plasma loading problem with a new TOFEA should allow to improve sufficiently the signal-to-noise ratio and to perform the measurements of the plasma potential profile.

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