# ESTIMATIONS OF PLASMA POTENTIAL AND DENSITY BY THE HEAVY ION BEAM PROBING DIAGNOSTICS ON THE URAGAN-2M TORSATRON

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First estimations of plasma electric potential and density in URAGAN -2M (U-2M) torsatron were done by the Heavy Ion Beam Probing Diagnostic (HIBP). The estimated plasma potential has the negative potential value of -(80…195) V. The experimental values of the secondary ion beam current are well correlated with average plasma density measured by radio-interferometer – (1.25… 2.5)×$10^{12}$ $cm^{-3}$. Notable oscillations of the secondary beam current were observed, which were caused by fluctuations of the torsatron magnetic field.

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## INTRODUCTION

HIBP diagnostic system has been launched for the first time in Ukraine on U-2M torsatron. Cesium ion beam with energy $E_b$ = (17…120) keV and primary ion current $I_{p.ion}$= (10…150) µA was used in the first experiment ([1]), in which probing beam was traced trough torsatron magnetic field $B_0$ = (0.3…0.4) T. Secondary ion currents $I_{s.ion}$ were measured by the "target" plates (these plates have the same dimensions 8 mm width as the detector plates), placed in front of the analyzer entrance slit and analyzer detector plates. Measurements were made with ionization of probing beam by plasma and by neutral hydrogen without plasma. The measurements were conducted with torsatron magnetic field $B_T$ = 0.39 T, probing beam energy $E_b$ = 70 keV and beam current $I_b$ = (55…65) µA. The following currents in torsatron coils were used: in helical coil $I_{hc}$= 14.1 kA, in toroidal coils $I_{tc}$ = 5.7 kA and in correcting coils $I_{cc}$ = 100 A in, Kφ = 0.336. Probing ion beam trajectories are illustrated by Fig. 1.

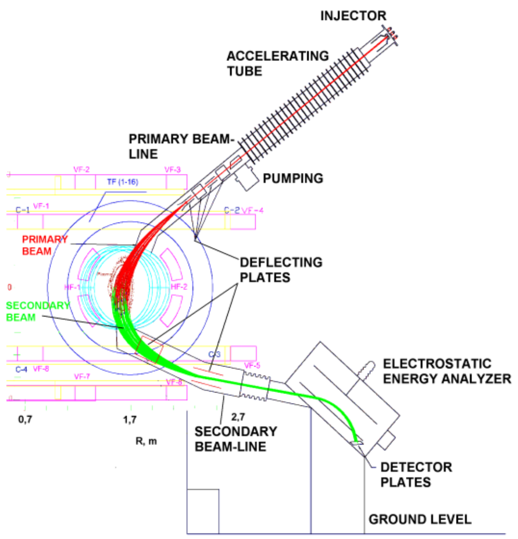


*Fig. 1. Probing ion beam trajectories in U-2M torsatron*

## EXPERIMENTAL RESULTS

Fig. 2 illustrates the current of analyzer detector plates ($I_{s.ion}$ ) without plasma.

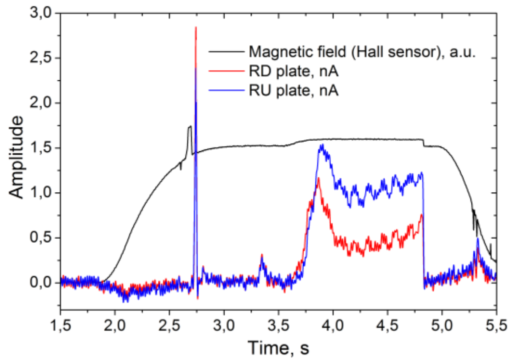


*Fig. 2. The secondary beam signals from analyzer detector plates without plasma. $I_{s.ion}$ = (5…6) nA, hydrogen gas pressure is 4.2x$10^{-6}$ Torr. $E_b$ = 70 keV, $I_b$ =60 µA, $U_a$ = 16.25 kV. Shot # 108, 28.04.2015*

The probing beam reaches analyzer only at certain value of U-2M magnetic field, duration of this event is approximately 1.5 s. The sharp break of the signal is caused by the beam shutdown. Fig. 3 shows the current of analyzer detector plates ($I_{s.ion}$ ) with plasma.

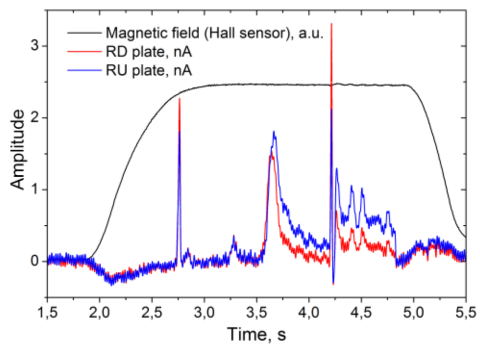


*Fig. 3. The secondary beam signals from analyzer detector plates with and without plasma: $I_{s.ion}$ = (5…6) nA, hydrogen gas pressure is 4.2×$10^{-6}$ Torr. $E_b$ = 70 keV, $I_{p.ion}$ = 60 µA, $U_a$ =16.5 kV. Shot # 109, 28.04.2015*

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During this pulse the analyzer voltage ($U_a$) was increased to 16.5 kV. Calculations were performed with the assumption that the potential of the neutral gas $\varphi_{ng}$ is 0. For usual $30^0$ Proca-Green electrostatic analyzer

$$\varphi_{ng} = 2U_a(G + F\delta_i) - U_b = 0, \text{ where}$$

$$\delta_i = (I_{RU} - I_{RD}) / (I_{RU} + I_{RD}),$$

G = 2.119 – analyzer gain ratio, calculated for maximal current from right up (RU) and right down (RD) detector plates without plasma; F = 0.025 – dynamic coefficient, assumed from previous analyzer calibration; $I_{RU}$ – current from upper right analyzer detector plates; $I_{RD}$ – current from lower right analyzer detector plates; $U_b$ – primary beam voltage.

The plasma potential values for first maximum of signal equaled $\varphi$ = -195 V, for the second maximum – $\varphi$ = -80 V (Fig. 4.).

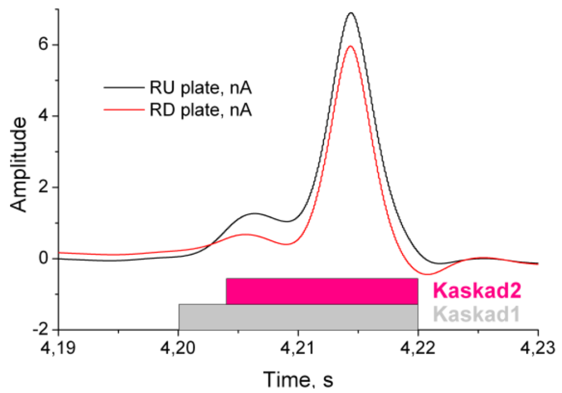


*Fig. 4. Shot # 109, 28.04.2015. The secondary beam signals from analyzer detector plates $I_{s.ion}$ with plasma. Time scale is increased compared with Fig. 3*

Plasma was created by 2 RF generators “Kaskad 1” and “Kaskad 2” (frequency – 5.3…5.6 MHz, power – 0.5 MW each). “Kaskad 1” switched on at 4.2 s and operated during 20 ms. “Kaskad 2” was operated during 16 ms an switched off simultaneously with “Kaskad 1”. So, the overall time of plasma ion cyclotron RF heating was only 20 ms at the flat “table” of the magnetic field. The soft X-ray radiation from plasma was observed during 5 ms after switching on the “Kaskad 2” generator (Fig. 5.). The electron temperature, obtained from these signals , equaled (35…40) eV (Fig. 6).

Unfortunately, the temporal resolution of probing beam scanning along the plasma small radii does not exceed 15 ms. So, the spatial profile of potential can not be measured during one U-2M shot because of small lifetime of the plasma. However, we can see the temporal evolution of potential of one particular plasma sample volume over a one shot period.

The plasma parameters measurements by Langmuir probe, placed at the distance of 3.5 cm from plasma axis also give the negative plasma potential of -80 V, (Figs. 7, 8). So, the HIBP plasma potential measurements in U-2M have a good correlation with corresponding Langmuir probes measurement of plasma negative floating potential.

This potential value is significantly different from positive plasma potential at TJ-II heliac with ECRH plasma heating with rather small density. But the negative plasma potential was also registered at TJ-II when NBI plasma heating was used [2]. In the U-2M torsatron plasma is created by ion cyclotron RF heating, i.e. the main RF energy is absorbed by hydrogen ions. Electron temperature $T_e$ is very low. In such a case, the ion confinement time must be less than electron one and plasma potential should be negative.

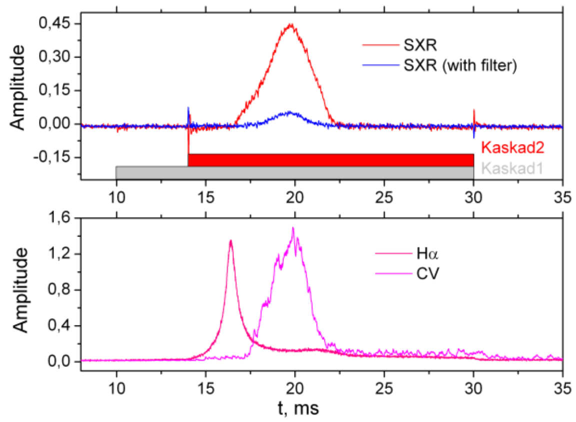


*Fig. 5. Electron temperature measurements on 27.04.2015, shot # 143 in the same mode of U-2M operations, as on Fig. 4. Bottom graph is Hα and CV radiation from plasma. HIBP potential measurements points are marked with green lines*

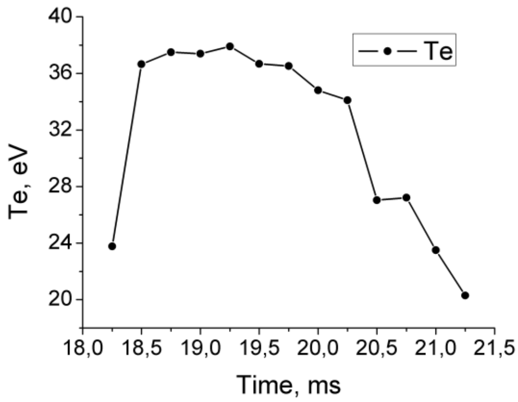


*Fig. 6. Electron temperature calculations, 27.04.2015, #143*

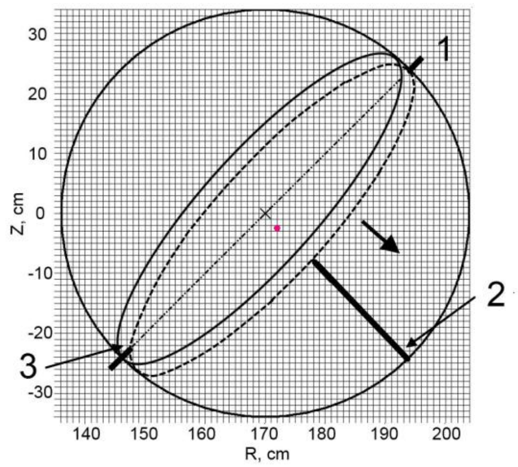


*Fig. 7. The Langmuir probes are positioned in the adjacent cross section of diagnostic port. Red point is the probe location*

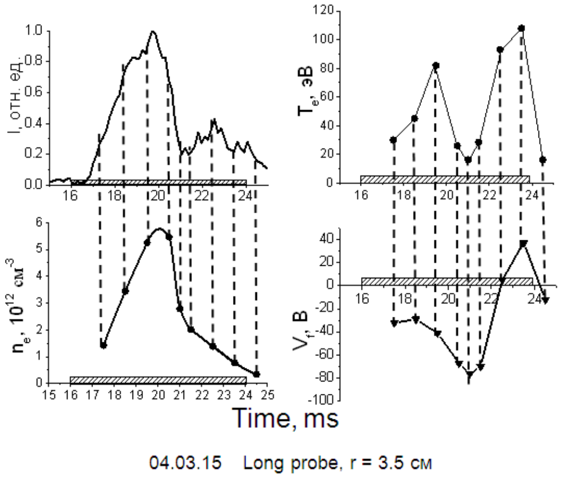


*Fig. 8. Langmuir probe measurements during "Kaskad 2" operation*

At the analyzer detector plates we can clearly see the amplification of secondary beam current oscillations, immediately after shutdown of "Kaskad" generators. These oscillations have the same phase and period (150…180 ms), as the toroidal magnetic field measured by Hall detector. The magnetic field oscillations have approximately 6 % of amplitude of the U-2M magnetic field (0.39 T) – about 230 Gs (Fig. 9).

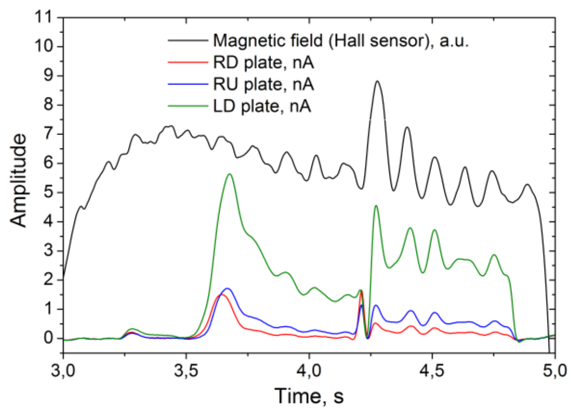


*Fig. 9. The oscillations of toroidal magnetic field and secondary ion currents. Shot #109, 28.04.2015*

The difference of the toroidal magnetic field between the best time for probing beam propagation and the time point of "Kaskads" switching on is 2.5% of $B_T$=100 Gs.

The preliminary estimations of plasma density in the HIBP sample volume were done by the measurements of secondary beam current on the "target" plates. These plates have the same dimensions as the detector plates (8 mm width). The calculations of the secondary beam current were done by Lotz formula

$$j_S \sim \sigma_{(i^+ - i^{++})}(T_e) \cdot n_e,$$

$$j_s = \gamma_e \sigma_{(i \to S)} n_e l_{SV} F_i F_S j_i \, q_s / q_i \; ,$$

where $n_e$ – plasma density; $\gamma_e$ – ion-electron secondary emission rate from analyzer plates; $l_{SV}$ – dimension of sample volume; $F_i$ , $F_S$ – primary and secondary beams attenuation rates ; $\sigma_{(i^+ - i^{++})}$ – ionization cross-section; $j_i$ – primary beam current; $j_s$ – secondary beam current.

In our case $T_e$ = 40 eV (see Fig. 4), $n_e$ = $(3.5\times10^{11}$ – $3.5\times10^{12})$ cm$^{-3}$, $j_i$ = 100 µA, sample volume dimension – 1 cm, secondary emission rate is 2. For plasma densities, used in the experiment, the beam attenuation rates were neglected. Ionisation cross-section was taken from [3] ( Fig. 10).

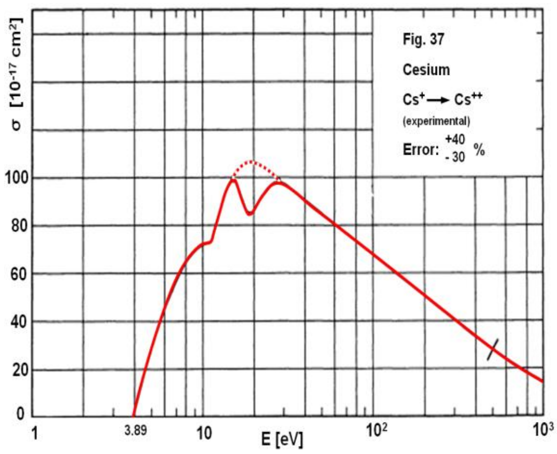


*Fig. 10. Ionisation cross-section [3]*

The result is illustrated by Fig. 11. Experimental points were taken from the pulses with different plasma densities, #90, 09. 04. 2015 and #109, 28. 04. 2015.

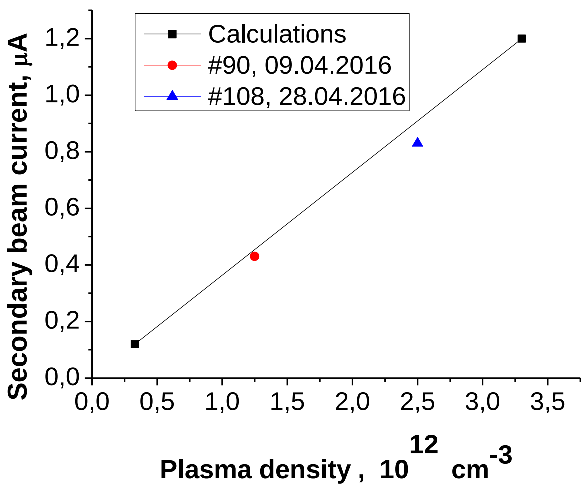


*Fig. 11. The secondary beam current vs plasma density (calculations and experimental points), #109, 28.04.15 and #90, 09.04.15*

Therefore with a sufficient degree of certainty we can say that in this case plasma density measured by HIBP is well correlated with average plasma density measured by radio-interferometer n =(1.25…2.5)×$10^{12}$ cm$^{-3}$. It means that the HIBP sample volume is situated not exactly at plasma center, but anywhere in the region of $\rho \le 0.5$.

## CONCLUSIONS

Preliminary estimations of plasma electric potential and density on U-2M torsatron were made using HIBP diagnostics.

HIBP results have a good correlation with Langmuir probes measurement of plasma floating potential and with average plasma density measured by radio-interferometer ($1.25\text{-}2.5\times10^{12}$ cm$^{-3}$).

The HIBP measurements of the plasma density in the area of vision is approximately the same as average density, and therefore, the area of vision is located closer to the periphery of the plasma radius, $\rho\geq0.5$.

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### ОЦЕНКИ ПОТЕНЦИАЛА И ПЛОТНОСТИ ПЛАЗМЫ С ПОМОЩЬЮ ДИАГНОСТИЧЕСКОГО КОМПЛЕКСА ЗОНДИРОВАНИЯ ПЛАЗМЫ ПУЧКОМ ТЯЖЕЛЫХ ИОНОВ НА ТОРСАТРОНЕ УРАГАН-2М

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С помощью диагностического комплекса зондирования плазмы пучком тяжёлых ионов (ЗППТИ) на торсатроне УРАГАН-2М проведена предварительная оценка потенциала и плотности плазмы. Оценка дала значение отрицательного потенциала на уровне -(80…195) В. Полученные экспериментальные значения плотности плазмы достаточно хорошо соответствуют измерениям средней плотности плазмы с помощью интерферометра – $(1.25…2.5)\text{x}10^{12}$ см$^{-3}$. Зарегистрированы колебания тока вторичных ионов, обусловленные флуктуациями магнитного поля торсатрона.

### ОЦІНКИ ПОТЕНЦІАЛУ ТА ГУСТИНИ ПЛАЗМИ ЗА ДОПОМОГОЮ ДІАГНОСТИЧНОГО КОМПЛЕКСУ ЗОНДУВАННЯ ПЛАЗМИ ПУЧКОМ ВАЖКИХ ІОНІВ НА ТОРСАТРОНІ УРАГАН-2М

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За допомогою діагностичного комплексу зондування плазми пучком важких іонів (ЗППВІ) на торсатроні УРАГАН-2М були проведені попередні оцінки потенціалу та густини плазми. Оцінка дала значення негативного потенціалу на рівні -(80…195) В. Одержані експериментальні значення густини плазми збігаються з вимірюванням середньої густини плазми за допомогою інтерферометра – $(1.25…2.5)\text{x}10^{-12}$см$^{-3}$. Зареєстровані коливання струму вторинних іонів, які обумовлені флуктуаціями магнітного поля торсатрону.