FIRST RESULTS FROM THE HEAVY ION BEAM PROBE DIAGNOSTIC ON THE TUMAN-3M TOKAMAK

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Many existing facilities and the ITER tokamak-reactor under design have tight aspect ratio. The tokamak Tuman-3M with small aspect ratio is the next step in this direction. The Heavy Ion Beam - Probe (HIBP) diagnostics could be very useful there [1].

Motivation of the spherical tokamak - HIBP alliance is the following.

The spherical tokamaks are oriented to researches in support of the tokamak-reactor and to the investigation of main tokamak problems such as disruptions and β increase. The economically-beneficial reactor should operate with a high plasma confinement (H-mode). An important role in the L-H transition, which was obtained in all tight aspect ratio tokamaks, is played by the radial electric field $E_r = d\Phi/dr$ (Φ is the plasma potential). Therefore Φ measurements by HIBP could be very important for understanding the physical nature of this effect.

HIBP is a non-perturbative local multipurpose diagnostics that allows us to monitor the temporal evolution of 2D distributions of several plasma parameters, such as the electric potential Φ, the density n, the poloidal field B_p and the electron temperature T_e. HIBP allows us to measure the fluctuations Φ, B_p and n, which may cause the anomalous transport. The investigation of the plasma electric potential can be provided by HIBP only.

Tight aspect ratio tokamaks have a set of additional coils for the plasma shaping. Therefore the inner part of the torus is often not seen by traditional chord diagnostics. HIBP is convenient for spherical tokamaks, where the space is limited, because it needs curvilinear access routes.

Up to now the HIBP was used in tokamaks with high aspect ratio (ST, TM-4, T-10, TEXT, RENTOR, JIPPT-IIU, ISTTOK, TJ-1, JFT-2M).

The basics of the HIBP diagnostics are as follows. The underlying principle of the plasma potential measurement is conservation of ion's energy when it passes through the plasma. When the probing beam's ions are additionally ionized by the plasma electrons, their potential energy decreases by Φ_{pl}, where Φ_{pl} is the plasma potential at the ionization point. Then, the doubly ionized ion's energy conserves again (neglecting the possibility of triple ionization) during the rest of the trajectory, until a detector unit collects them. The plasma potential is obtained by measurements of energy of the secondary ions when the leave the plasma. The probing ion beam must have the energy large enough to penetrate through the toroidal magnetic field of the device. The secondary beam trajectory has a curvature radius two times smaller than primary one, therefore the secondary beam gets detached from the primary, so the detector located outside the plasma receives the secondary ions only from a short part of the primary beam trajectory. To know the spatial location and size of sample volume, one should calculate both the primary and secondary trajectories, taking into account all the real magnetic field structure.

The HIBP for Tuman-3M has been developed for simultaneous measurements of plasma electric potential and density profiles and their fluctuations. Conventional composition of this equipment consists in two parts: injector of the primary probing beams and the analyzer of secondary particles. The general scheme of the HIBP installation is shown in Fig.1. Location of all the parts was chosen on the basis of optimization calculations. HIBP diagnostic equipment consists of three main systems: injection, detection, control and data acquisition.

Relatively low toroidal magnetic field ($B_T \leq 1T$) and small size of the Tuman-3M (a=0.25m, R=0.53m) allow the probing K^+ ion energy to be no more then 100 keV. On the other hand, plasma current in the Tuman-3M may be as high as 150 kA, thus leading to strong toroidal shift of the ion trajectories due to the $\mathbf{B_p}$ **x** $\mathbf{V_r}$ force. Here V_r is the radial projection of the ion's velocity. As for the poloidal magnetic field component B_p, at different spatial locations different sources of it are important. In the central part of the plasma B_p is mainly caused by the plasma current itself. However, when the secondary K^{++} ions leave the vacuum vessel of the Tuman-3M tokamak on their way to an energy analyzer, their trajectory goes in close proximity to the control field coil bearing up to the 70-80 kA of current opposite in direction to the plasma current. As a result, the secondary and primary ion trajectories form a complicated 3D curve, which must by guided through the existing vacuum ports of the tokamak. In principle, the secondary ions could be directed to the energy analyzer entrance port using one ore more pair of deflector plates with appropriate (and varying in time) voltages applied. The energy analyzer (a 30° Proca-Green type [2]) is located rather close to the plasma volume, and its entrance slit faces the. tokamak plasma. As a result, the UV radiation coming from the tokamak discharge causes surface photo-effect on the metallic elements of the analyzer's construction, giving rise to stray currents to the detector (Fig.2a, curve 1). These stray currents are many times stronger than secondary beam current. To suppress them, the detector unit was equipped with electrostatic shield and additional electrodes negatively biased (Fig.2b). This design have been firstly used in HIBP diagnostic on Tuman-3M tokamak. It allowed the suppression of stray currents below the secondary current level (Fig2a, curve 2) [3].

Specific features of Tuman-3M are that all magnetic fields, and in particular the toroidal magnetic field, are not constant - they decay with time constant of ~150ms (Fig.3a). It results in movement of the sample volume through the plasma cross-section, thus giving the possibility to perform "naturally" the radial scan of the plasma potential (Fig.3b).

The plasma potential measurement is one of the most difficult problems to HIBP. Required resolution is provided by the separated measurements of the secondary beam intensities on the split plates detector. Relation for the plasma potential extraction is: $\Phi_{pl} = 2U_a(\delta iF(\theta) + G(\theta)) - U_b$ where U_a and U_b are accelerator and analyzer voltages, $\delta i = (i_t - i_b)/(i_t + i_b)$ is the normalized difference of the currents on the top (i_t) and bottom (i_b) detector plates, G and F are the functions of the analyzer geometry and the beam entrance angles. For the Tuman-3M tipical parameters U_b=100keV, U_a=17keV, Φ_{pl} = 1keV (2G=4.66), it implies that for 10% accuracy of the potential measurements it is necessary to provide minimum 2.5 10^{-4} accuracy of high voltage registration and setting.

First plasma potential measurements by HIBP on Tuman-3M have been directed to the investigation of the regimes with L-H transition. Plasma potential in all regimes of the Tuman-3M operation is strongly negative. Fig.5 show time evolution of D_α emission, plasma density and electric potential in the shots with H and L regimes. We can summarize some features of the plasma potential behavior during process of the edge transport barrier formation (L-H transition): - the local plasma potential in the inner points correlates with D_α intensity, both drop down simultaneously; - increasing of plasma density and decreasing of plasma potential start at the same time, absolute value of plasma potential during transition changes approximately on 100eV. It was perceived strong changes in the plasma current radial gradient during the L-H transition. Fig.6 show time evolution of the secondary beam displacement in horizontal place (toroidal direction) during transition ($i_2 + i_3 = i_t$). Nature of the toroidal displacement of probing beam is its interaction with poloidal magnetic field, i.e. plasma current in tokamaks.

Finally, we propose the HIBP project for Spherical Torus GLOBUS-M to establish the systematic researches of the radial electric field E_r structure and temporal evolution as an idea to investigate both the reactor-related physics (H-mode), and the basic plasma physics (nature of the anomalous transport).

The trajectories of probing particles are calculated by a numerical solution of the motion equation in the full magnetic field of the tokamak. The calculation was made for the standard Globus-M regime (I_pi = 300 kA and BO = 0.6 T) with Cs$^+$ as primary beam ions. Three possible probing schemes for GLOBUS-M were found. The first one is presented in Fig.7 (probing trajectories and detector grid in vertical projection). Here we have used the traditional HIBP scheme. The upper x-point port is used for injection and the horizontal port is used for the detection.

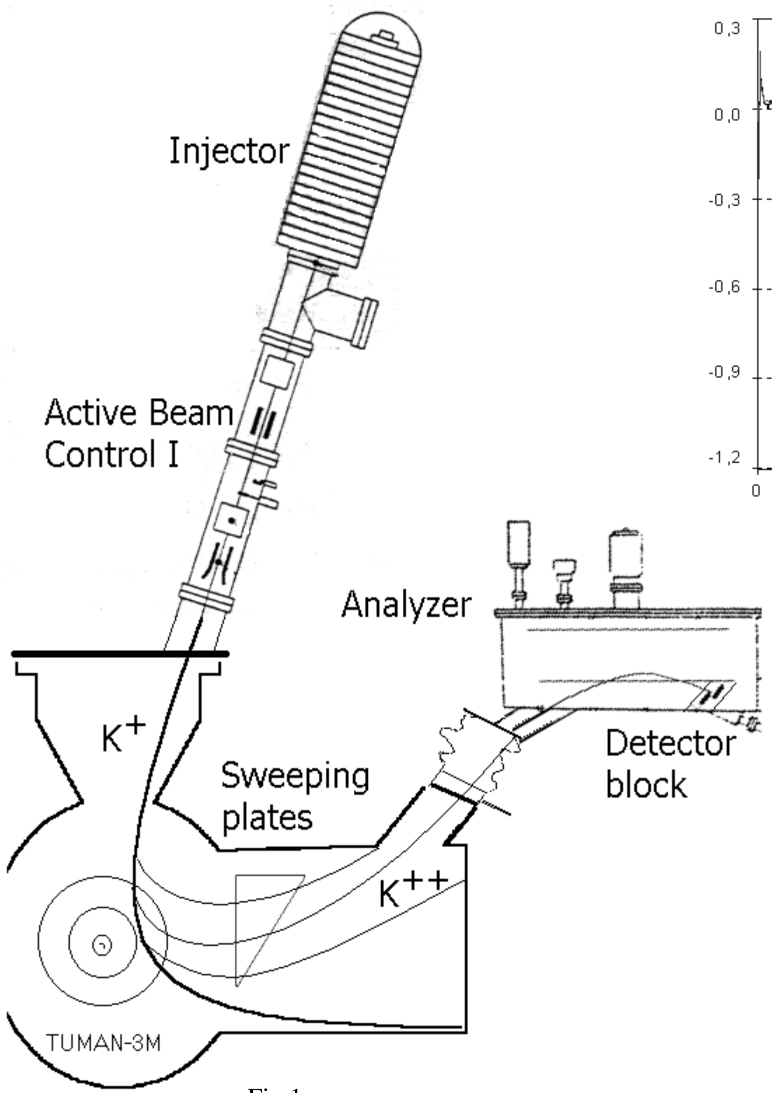

Fig.1

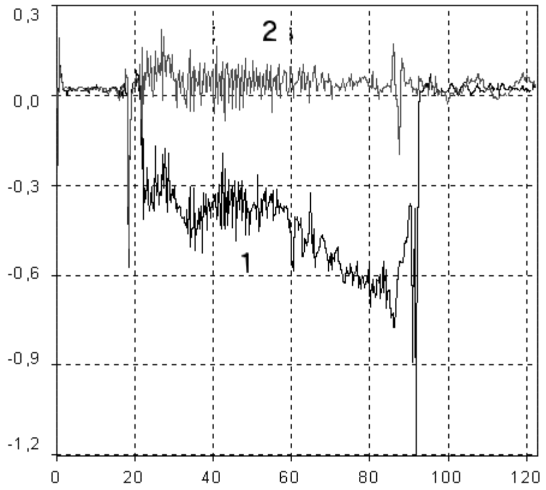

Fig.2 a

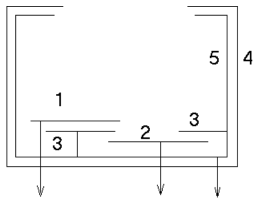

Fig.2 b

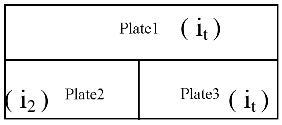

Fig.2 c

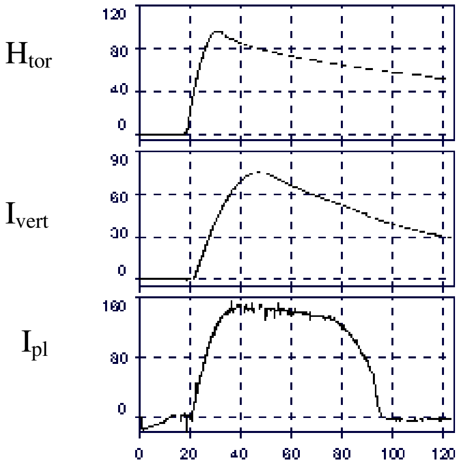

Fig.3

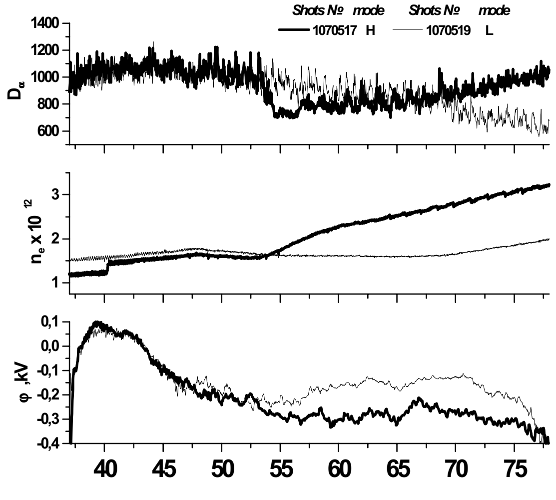

Fig.5

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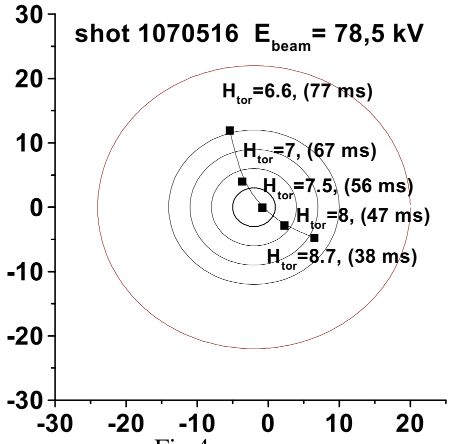

Fig.4

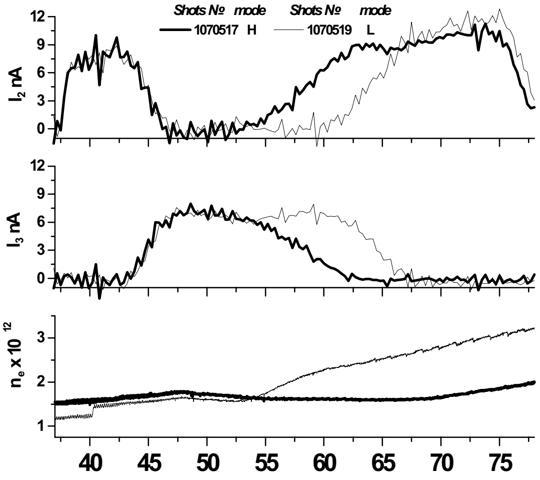

Fig.6

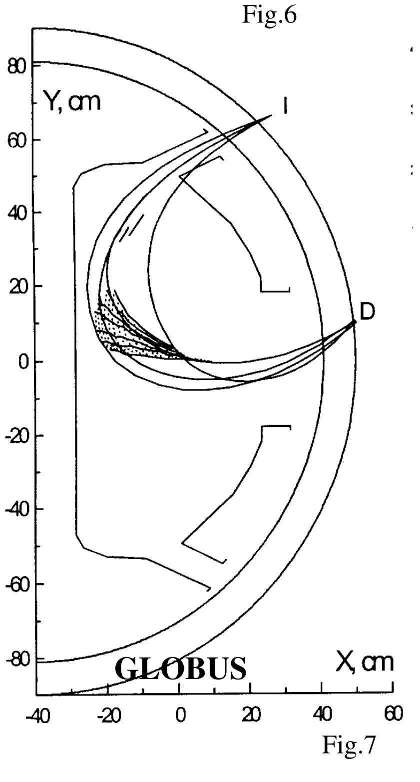

Fig.7