The upgraded heavy ion beam probe diagnostics on the T-10 tokamak

M A Drabinskii1,2,6, P O Khabanov1,3, A V Melnikov1,4, L I Krupnik5, A S Kozachek5, A D Komarov5 and A I Zhezhera5

1 National Research Centre ‘Kurchatov Institute’, 1, Akademika Kurchatova pl., Moscow, 123182, Russian Federation
2 Bauman Moscow State Technical University, 5, ul. Baumanskaya 2-ya, Moscow, 105005, Russian Federation
3 Moscow Institute of Physics and Technology, 9, Institutskiy per., Dolgoprudny, Moscow Region, 141700, Russian Federation
4 National Research Nuclear University MEPhI, 31, Kashirskoe highway, Moscow, 115409, Russian Federation
5 National Science Center Kharkov Institute of Physics and Technology, 1, Akademicheskaya St., Kharkov, 61108, Ukraine

E-mail: drabinskii91@yandex.ru

Abstract. The upgraded Heavy Ion Beam Probe (HIBP) diagnostics on the T-10 tokamak (National Research Center ‘Kurchatov Institute’) is presented. HIBP is a powerful tool to study electric potential in the core and edge plasmas along with broadband turbulence and quasicoherent modes such as Geodesic Acoustic Mode (GAM) and Alfven Eigenmode (AE). To study broadband turbulence and AEs, which can be driven by fast electrons in regimes with auxiliary Electron Cyclotron Resonance Heating the frequency range of about several hundred kHz is needed. The upgrade is focused on the extension of the frequency range of HIBP signals up to 500 kHz, and on increasing of density operating limit up to 5·10^{19} m^{-3}. It becomes possible due to a newly designed emitter-extractor unit of HIBP accelerator aiming to provide the primary beam with the current of 300 μA at the energy of 300 keV and diameter of 7-10 mm. The new in-vessel elements of a primary beamline – wire sensor and Faraday cup – were upgraded accordingly to be able to deliver the probing beam with advanced parameters to the plasma.

1. Introduction

Heavy Ion Beam Probe (HIBP) is instrumental to study magnetically confined plasmas. It is the only diagnostic to measure the electric potential in hot plasma of toroidal fusion devices, both tokamaks and stellarators [1, 2]. For the first time in tokamaks this technique was implemented by Jobes and Hickok in 1970 [3]. Unlike electric probes, HIBP does not disturb the plasma and the measurements are direct and local, taking place in both core and the edge plasmas. Moreover, along with electric potential, HIBP gives information on the electron density and the poloidal magnetic field or plasma current [4]. High time resolution provides the study of the fluctuations of all these quantities [5].

6 To whom any correspondence should be addressed.
Remarkably, the measurements of all three HIBP quantities take place simultaneously, which gives an important contribution to comprehensive analysis of the plasma turbulence.

HIBP has started to operate on T-10 tokamak with Cs⁺ probing ions since late 1980s [4, 6] in the regimes with low density ohmic plasmas and low magnetic field B = 1.5 T. Then HIBP was upgraded several times to be able finally to operate in the ohmic and auxiliary Electron Cyclotron Resonance heated regimes with high magnetic field B ≤ 2.5 T and densities up to 4×10¹⁹ m⁻³ using Tl⁺ probing ions [7]. The recent research with HIBP on T-10 is focused on studying of broadband plasma turbulence [8] and quasicoherent modes of plasma oscillations such as Geodesic Acoustic Mode (GAM) [9, 10, 11, 12] and Magneto Hydro Dynamic (MHD) tearing modes [13, 14]. GAM is a high-frequency type of zonal flows which is supposed to be a mechanism of turbulence self-regulation [15, 16]. It has been shown recently that GAM can interact with broadband turbulence at the ion drift wave frequencies (200-300 kHz) [17, 18], so the investigation of these processes in depth is important for understanding the mechanisms of the turbulent energy and particle transport. Interaction between fast ions, alpha-particles or fast electrons with a bulk plasmas can drive Alfvén Eigenmodes (AE), which theoretically can have a considerable influence on fast particle transport [19]. Therefore, studies of AE can make a significant contribution to fusion reactor physics. Recently the Neutral Beam Injection induced AE were intensively studied with HIBP on the TJ-II stellarator [20, 21, 22, 23]. On top of that, the fast electron induced modes were found on TJ-II [24]. In T-10 it is expected to find AE driven by fast electrons at frequencies up to 500 kHz.

The modernization, described in the present paper aims to expand the observation area towards the plasma core (with densities up to 5×10¹⁹ m⁻³) and to broaden the frequency range of studied fluctuations to 500 kHz in order to provide the study of the broadband turbulence, GAMs, MHD modes and AEs.

2. Principles of operation and the measurement technique

HIBP is a test particle experiment using heavy ions as test particles. Commonly, singly charged ions of Na⁺, K⁺, Cs⁺, Tl⁺ or Au⁺ are used as particles of a probing beam (the heavyweight Tl⁺ is used now on T-10). The probing (primary) beam after being formed in the emitter-extractor unit and accelerated in the injector enters plasma and moves along Larmour circle in a toroidal magnetic field of a tokamak (see figure 1 (a)). As the primary beam passes through plasma, its particles are further ionized due to the collisions with plasma electrons. Doubly charged (secondary) ions move along the trajectories with twice smaller Larmour radius and form a fan of secondary ions. Proca-Green parallel plate energy analyzer is set on the way of these secondary ions. The aperture of the analyzer cuts out a secondary beam from the fan so only the particles from a given ionization point (sample volume - SV) reach a given detector location.

At the SV the primary ion loses an electron with an energy of \(-e\Phi\), where \(e\) is an electron charge and \(\Phi\) is the value of plasma electric potential at the SV. Thus, \(\Phi\) can be calculated as

\[\Phi = (W_1 - W_2) / e,\]

where \(W_1\) is the energy of the primary beam and \(W_2\) is the energy of a secondary beam.

As far as plasma potential is measured as a small difference between two large values, both beam injector and energy analyzer are the instruments of a high precision and stability, providing \(\Delta W_1 / W_1 \sim 10^{-5}\). On T-10 the value of plasma potential has a range from several dozen Volts at the periphery to several hundred Volts near the centre, as measured with primary beam energy up to 300 keV.

T-10 energy analyzer has five entrance slits, so five SV are observed simultaneously. The beam from each SV enters to split plate detector (see figure 1 (b)). The primary beam current is 10-100 μA, and the secondary beam current is about 0.1-10 nA so the current signal from split plates is pre-amplified and converted to voltage with the factor of 10⁷ V/A, then digitized and stored in the database.
Figure 1. (a) basic principle of HIBP diagnostic; (b) Proca-Green parallel plate energy analyzer on T-10 (B – secondary beam, 5-S – five entrance slits, GP – ground plate, HVP – high voltage plate, G – wire grid, W – window, D – 5 channels split plate detector assembly).

Total secondary beam current I on the detector plates is linked with electron density \( n_e \) at SV as

\[
I \sim I_0 F_1 F_2 \sigma_{\text{eff}} n_e l
\]

where \( I_0 \) is the primary beam current, \( F_{1,2} \) are attenuation factors for primary and secondary beams, \( \sigma_{\text{eff}} \) is an effective cross-section of ionization, \( l \) is the length of the SV.

\[
F_j = \exp(- \int \sigma_j n_e \, dl) \ ; j=1,2
\]

\( \sigma_j \) is the ionization cross-section from \( j \)-state, the integration is carried over the entire path of the primary/secondary beam. For low-to-moderate densities, when factors \( F_{1,2} \) are not dominating, the density fluctuations are proportional to total current fluctuations:

\[
\frac{\delta n(t)}{n} = \frac{\delta I(t)}{I}
\]
3. Key features of the modernization

There are two reasons to increase the primary beam current. As soon as the attenuation factors $F_{1,2}$ increase with the electron density, at high densities ($n_e > 4 \times 10^{19} \text{ m}^{-3}$) the secondary beam current becomes comparable to the noise level. So, for measurements at higher densities a higher value of primary beam current density is required. In addition, the necessity to study plasma fluctuations claims the continuous particle flow, not the particle counting character of the signal. The frequency resolution is limited by the number of particles per oscillation period. So higher frequency resolution claims the higher value of primary beam current density. Finally, to expand the frequency range of potential and density fluctuations up to 500 kHz and to increase the density operating range up to $5 \times 10^{19} \text{ m}^{-3}$, it was targeted to increase primary beam current to 300 μA at the beam diameter at the SV of 7-10 mm and beam energy of 300 keV.

3.1. Emitter-extractor unit

To solve this task a new emitter-extractor unit was designed and prepared for assembly. The 3D-model of the new unit is shown in figure 2 (a). A three-electrode lens configuration was chosen: the first one is the emitter tablet holder, the second one is the extraction electrode and the third one is the focusing electrode (the first ring of the accelerator tube) – see figure 2 (a) and (b). Calculations using Simion 3D code showed that this configuration will maintain the aimed values of primary beam current. Figure 2 (b) shows the scheme and the circuit for the unit. It includes two batteries of high capacity (120 A×hour each) and two 10 kV voltage sources.

![Figure 2](image)

**Figure 2.** (a) New design of the emitter-extractor unit; (b) emitter-extractor unit power system circuit; red marker shows thallium emitter covered by Pierce electrode with 6 mm hole.

3.2. Primary beamline

Since the primary beam current grows from 100 μA to 300 μA, its diameter at the beamline may also increase. To avoid the beam contact with elements of the primary beamline, the in-vessel elements were also upgraded, as presented in figure 3. The distance between first correcting plates in a vertical direction ($\alpha$-plates) was increased to 50 mm, and the Faraday cup diameter was increased to 56 mm. Faraday cup has movable bottom driven by traction relay. It is open during the steady state phase of the tokamak discharge to provide the beam pass into the plasma and then into the energy analyzer.
Figure 3. Primary beamline. Faraday cup bottom is open.

Figure 4. (a) Faraday cup (bottom closed); (b) the 1st wire sensor (front view, red lines show wires); (c) typical current signals from two wire sensors, black and green are signals from the 1st sensor, blue and red – from the 2nd one; the beam is focused on the 1st wire sensor, extraction voltage is 2.58 kV.

It is closed between tokamak discharges to provide primary beam current measurements and/or to prevent the beam interaction with chamber wall or residual working gas. The secondary electrons generated due to this interaction may be accelerated during the ramp up of the toroidal field and cause hard X-ray emission entering the chamber well. To avoid this harmful effect the movable bottom opens after the start of the plasma current. Photo of the new Faraday cup is shown in figure 4 (a). Wire sensors are aimed to measure the primary beam profile and position. Combination of two beam positions gives us the beam entrance angle to the plasma. Both upgraded 1st and 2nd wire sensors have similar design with 2 horizontal and 2 vertical wires. The minimal possible number of wires was chosen to minimize their influence on the beam. Front view of the 1st sensor is shown in figure 4 (b), wires are painted in red. By changing the voltage on α- or β-plates, orthogonal to α- we move the beam across the vertical or horizontal wires, thus measuring the beam profile and position by the wire currents. The typical currents from two wires from two sensors for α-scan are shown on figure 4 (c). In the present case the beam is focused on the 1st sensor with extraction voltage 2.58 kV.

4. Conclusion
The main physical aim of HIBP upgrade on the T-10 tokamak is to expand the diagnostic capabilities to study the Geodesic Acoustic Modes interaction with broadband turbulence to 500 kHz in the extended density operating range up to $5 \times 10^{19}$ m$^{-3}$. This requires the growth of the primary beam.
current to 300 μA. To achieve this value the new emitter-extractor unit was designed and the elements of the primary beamline were upgraded.

Acknowledgements
The work was carried out by Russian Science Foundation, project 14-22-00193.

References
[1] Fujisawa A, Ido T, Shimizu A et al. 2007 Experimental progress on zonal flow physics in toroidal plasmas Nucl. Fusion 47 S718
[2] Melnikov A V, Hidalgo C, Eliseev L G et al. 2011 Plasma potential and turbulence dynamics in toroidal devices (survey of T-10 and TJ-II experiments) Nucl. Fusion 51 083043
[3] Jobes F C and Hickok R L 1970 A direct measurement of plasma space potential Nucl. Fusion 10 195-197.
[4] Dnestrovskij Yu N, Melnikov A V, Krupnik I and Nedzelskij I S 1994 Development of Heavy Ion Beam Probe Diagnostics IEEE Trans. Plasma Sci. 22 (4) 310-331
[5] Melnikov A V, Eliseev L G, Jiménez-Gómez R et al. 2010 Internal measurements of Alfvén eigenmodes with heavy ion beam probing in toroidal plasmas Nucl. Fusion 50 084023
[6] Melnikov A V, Bondarenko I S, Efremov S L et al. 1995 HIBP diagnostics on T-10 Rev. Sci. Instrum 66 317
[7] Melnikov A V, Andreev V F, Grashin S A et al. 2006 Investigation of geodesic acoustic mode oscillations in the T-10 tokamak Plasma Phys. Control. Fusion 48 S87-S110
[8] Vershkov V A, Shelukhin D A, Subbotin G F et al. 2015 Density fluctuations as an intrinsic mechanism of pressure profile formation Nucl. Fusion 55 063014
[9] Melnikov A V, Eliseev L G, Gudozhnik A V et al. 2005 Investigation of the plasma potential oscillations in the range of geodesic acoustic mode frequencies by heavy ion beam probing in tokamaks Czech. J. Phys. 55 349-360
[10] Melnikov A V, Vershkov V A, Eliseev L G et al. 2006 Investigation of geodesic acoustic mode oscillations in the T-10 tokamak Plasma Phys. Control. Fusion 48 S87-S110
[11] Zenin V N, Eliseev L G, Kozachek A S et al. 2014 Study of poloidal structure of geodesic acoustic modes in the T-10 tokamak with heavy ion beam probing, Problems Atomic Sci. Techn. Series: Plasma Physics 6 (94) 269
[12] Melnikov A V, Eliseev L G, Perfilov S V et al. 2015 The features of the global GAM in OH and ECRH plasmas in the T-10 tokamak Nucl. Fusion 55 063001
[13] Eliseev L G, Ivanov N V, Kakurin A M, Melnikov A V and Perfilov S V 2015 Magnetic island and plasma rotation under external resonant magnetic perturbation in the T-10 tokamak Phys. Plasmas 22 052504
[14] Eliseev L G, Ivanov N V, Kakurin A M et al. 2015 Study of the large-scale MHD mode and its effect on GAM in the T-10 tokamak 42-nd EPS Conf. on Plasma Physics. Lisbon, Portugal, 22nd−26th June Rep. P5.159 http://ocs.ciemat.es/EPS2015PAP/html/
[15] Winsor N, Johnson J L and Dawson J M 1968 Geodesic acoustic waves in hydromagnetic systems Phys. Fluids 11 2448
[16] Diamond P H, Itoh S-I, Itoh K and Hahm T S 2005 Zonal flows in plasma - a review Plasma Phys. Control. Fusion 47 R35
[17] Nakashima Y, Hoshino K, Ejiri A et al. 2005 Observation of Nonlinear Coupling between Small-Poloidal Wave-Number Potential Fluctuations and Turbulent Potential Fluctuations in Ohmically Heated Plasmas in the JFT-2M Tokamak Phys. Rev. Lett. 95 095002
[18] Ido T, Miura Y, Kamiya K et al. 2006 Geodesic–acoustic-mode in JFT-2M tokamak plasmas Plasma Phys. Control. Fusion 48 S41
[19] Heidbrink W W 2008 Basic physics of Alfvén instabilities driven by energetic particles in toroidally confined plasmas Phys. Plasmas 15 055501
[20] Melnikov A V, Eliseev L G, Jiménez-Gómez R et al. 2010 Study of Alfvén Eigenmodes in the
TJ-II stellarator Plasma and Fusion Research. 5 S2019

[21] Jiménez-Gómez R, Könies A, Ascasibar E et al. 2011 Alfvén eigenmodes measured in the TJ-II stellarator Nucl. Fusion 51 033001

[22] Melnikov A V, Eliseev L G, Ascasibar E et al. 2012 Alfvén eigenmode properties and dynamics in the TJ-II stellarator Nucl. Fusion 52 123004

[23] Melnikov A V, Ochando M, Ascasibar E et al. 2014 Effect of magnetic configuration on frequency of NBI-driven Alfvén modes in TJ-II Nucl. Fusion 54 123002

[24] Melnikov A V, Hidalgo C, Ido T et al. 2012 Plasma Potential in Toroidal Devices: T-10, TJ-II, CHS and LHD Plasma and Fusion Research 7 2402114