Technical aspects of the heavy ion beam probing design and operation at the T-10 tokamak

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Abstract. Technical aspects of heavy-ion-beam probe (HIBP) at the T-10 tokamak (National Research Center “Kurchatov Institute”) are discussed. HIBP is a powerful and unique tool for studying electric potential in the core and edge plasmas in the frequency range up to 500 kHz. All the main HIBP elements such as high-voltage power supply, emitter-extractor unit, electrostatic accelerator, both primary and secondary beamlines and energy analyzer are considered. The achieved main HIBP capabilities are discussed.

1. Introduction
Electric field is considered as one of the main candidates for the role of a controlling parameter in the energy and particle transport processes in a fusion plasma [1]. Heavy-ion-beam probe (HIBP) is a unique diagnostics to measure the core electric potential in magnetically confined fusion plasma of both tokamaks and stellarators [2, 3]. For the first time this technique was suggested by Jobes and Hickok in 1970 [4]. Later on it was developed in other machines [5]. Unlike Langmuir probe, HIBP is non-perturbing diagnostics. On top of that, the measurements of plasma potential are direct and local [6]. HIBP allows measuring the core and the edge plasma parameters. Apart from plasma electric potential, HIBP gives information about the electron density and the poloidal magnetic field or plasma current [7, 8]. High time resolution provides the study of the fluctuations of all these quantities [9]. It should be noted that the measurements of all three parameters are simultaneous, which allows a comprehensive analysis of the plasma turbulence [10].

The T-10 tokamak HIBP is capable to operate in the various plasma regimes with high magnetic field \(1.5 \leq B \leq 2.5\) T, various plasma current \(100 \leq I_{\text{pl}} \leq 300\) kA and densities up to \(4 \times 10^{19}\) m\(^{-3}\) using Tl\(^+\) probing ions [11].

However, HIBP has many operational limitations related to its features so technical aspects are crucial for HIBP.

2. HIBP principles of operation and the measurement technique
HIBP uses heavy ions (Tl\(^+\), Cs\(^+\) or Au\(^+\)) as probing particles. The primary probing beam is formed in the emitter-extractor unit and accelerated in the linear accelerator, then it enters plasma and moves along Larmor circle in a toroidal magnetic field of a tokamak (figure 1). The beam energy (from about 100 keV to a few MeV) and the ion mass are selected to get the Larmor radius be higher than the vacuum chamber radius to avoid particle trapping by confining magnetic field of the device.
As the primary beam passes through the plasma, the probing particles are further ionized due to collisions with plasma particles. Doubly charged (secondary) ions continue movement with twice smaller Larmour radius and form a fan of secondary ions. Part of this fan goes into Proca-Green parallel plate energy analyzer so only the particles from a certain ionization point (sample volume—SV) reach a given detector location. SV position can be changed by the beam energy and entrance angle variation. The required entrance angle of the secondary trajectories is set by deflecting plates.

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

$$\phi = (E_1 - E_2)/e, \quad (1)$$

where $E_1$ is the energy of the primary beam and $E_2$ is the energy of a secondary beam.

In T-10, the plasma potential value has a range from several volts at the periphery to several hundred volts in negative near the centre [12, 13], while beam energy is about a thousand times greater. Since plasma potential is measured as a small difference between two large values, both beam injector and energy analyzer voltages must be of a high precision and stability, providing $\Delta E_{1,2}/E_{1,2} \sim 10^{-5}$. 

Figure 1. Scheme of HIBP diagnostics: 1—injector; 2—primary beamline; 3—primary trajectory; 4—fan of secondary trajectories; 5—secondary beamline; 6—energy analyzer; 7—detector.
Multichannel HIBP energy analyzer on T-10 allows observing five SVs simultaneously. The distance between SVs is about 1 cm. Secondary ions from each SV go into the beam detector made of 4 separate plates. The total beam current is a sum of the partial currents:

\[ I = i_1 + j_1 + i_2 + j_2, \]  

(2)

where indexes \(i\) and \(j\) are for left and right detector plates and 1, 2 indexes are for up and down detector plates (figure 2).

Measured plasma potential \(\phi\) is proportional to the vertical displacement of the ion beam on detector plates being calculated as normalized difference \(\delta i\) between up and down currents:

\[ \phi \sim \delta i = ([i_1 + j_1] - [i_2 + j_2])/I. \]

(3)

Measured poloidal magnetic field \(B_{\text{pol}}\) is proportional to the toroidal displacement of the ion beam on detector plates being calculated as normalized difference \(\delta z\) between left and right currents:

\[ \delta z = ([i_1 + i_2] - [j_1 + j_2])/I. \]

(4)

From \(\delta z\) we can calculate poloidal magnetic field induced by plasma current:

\[ \vec{z} = \frac{qe}{mv_r}B_{\text{pol}}. \]

(5)

Electron component concentration \(n_e\) in SV can be found from total beam current \(I\):

\[ I = I_0F_1F_2\sigma_{\text{eff}}ln_e, \]

(6)

where \(I\) is the secondary beam total current, \(I_0\) is the primary beam total current, \(\sigma_{\text{eff}}\) is the effective ionization cross-section, \(l\) is the SV length along the trajectory, \(n_e\) is the electron concentration in SV, \(F_1\) and \(F_2\) are the beam attenuation factors for both primary and secondary beams, defined as

\[ F_j = \exp \left(-\int_{j} \sigma_j n_e dl\right), \]

(7)

where \(j = 1\) for primary and \(j = 2\) for secondary trajectories, \(\sigma_j\) is the ionization cross-section from \(j\) state.

Integrals (7) are calculated along the beam primary and secondary ion trajectories. For low-to-moderate densities, when the beam attenuation factors are not dominating, the density fluctuations are proportional to total current fluctuations:

\[ \frac{\delta n(t)}{n} \sim \frac{\delta I(t)}{I}. \]

(8)
High temporal resolution of HIBP acquisition system is determined by analog to digital converters (adc) and the beam current-to-voltage converters (preamplifiers), which allow to measure fluctuations of plasma potential $\phi$, poloidal magnetic field $B_{pol}$ and electron density $n_e$ up to 500 kHz.

The primary beam current is 10–100 $\mu$A, and the secondary beam current is about 0.1–10 nA so the current signal from split plates is preamplified and converted to voltage with the factor of $10^7$ V/A, then digitized with 1 MHz and stored in the database.

Discussed capabilities of HIBP allow measuring various characteristics of the broadband turbulence and quasicoherent modes. They are Geodesic Acoustic Modes [14, 15], electrostatic quasicoherent modes [16], magneto-hydrodynamic tearing modes [17, 18]. It is worthwhile to mention that the similar HIBP diagnostic system with $E_{beam} < 150$ keV and Cs probing beam became a routine tool to study Alfvén Eigenmodes in the TJ-II stellarator [9, 19–21].

Some of the results of the HIBP operation on T-10 were recently summarized in the review paper [10].

3. HIBP main elements and operation difficulties

As soon as the plasma potential $\phi$ is measured as a small difference between two large values, HIBP measurements are highly sensitive to various factors, affecting the accuracy of the ion beam energies, such as voltage stability of the beam accelerator, energy analyzer and correcting plates, the accuracy of diagnostics elements location, quality of detector electronics, etc. Qualitative measurements requirement brings us to strict limits almost for all aspects of HIBP operation.

3.1. Ion beam injector

Injector provides extracting, focusing and accelerating of primary ion beam before it enters the plasma. At first, solid-state emitter must be carefully heated up to 800–1200 $^\circ$C to create ion current from its surface [22]. Then extractor voltage about several kilovolts takes out thallium ions from emitter surface, and focusing voltage forms the fine-focused beam. Finally, single ended electrostatic accelerator increases the beam energy up to several hundreds kilovolts.

The probing beam emitter (figures 3 and 4) is a replaceable element with a finite lifetime and capacity about 2 mA hours. Before the standard operation of each new emitter it must be degassed through the gradual training heating in the vacuum with pressure control in the emitter-extractor unit. It is crucially important to avoid overheating of the emitter to prevent emitter destruction.

The main problem of the emitter-extraction units design is the placement of the emitter filament heater, extractor electrode and their holders in the way, providing the absence of the electrical breakdown at 10 kV of the extractor voltage. Recently, the emitter-extractor unit was upgraded [23]. Accelerator is equipped by the anti-corona conductor and guard rings are used to decrease the local electric field and to avoid the corona discharge and electrical breakdown.

3.2. Primary beamline

Primary beamline (shown in figure 5) is a beam control device, which allows changing SV location in plasma by changing beam entrance angle. This angle is set up by $\alpha_2$ plates; $\beta$ plates serve for correction of a beam shift induced by plasma current. On T-10 $\alpha_1$ plates serve to correct a little misalignment between injector and primary beamline in the midplane.

Since $\beta_2$, $\beta_3$ and $\alpha_2$, $\alpha_3$ correcting plates are located rather close to plasma, the breakdown probability is higher in comparison with $\alpha_1$ and $\beta_1$ plates due to plasma induced carbon film formation on their working surfaces. To avoid the formation of the films, which are responsible for the breakdowns, plates are heated up to 200 $^\circ$C. Heating is realized via transformers with secondary winding under correcting voltage.
Figure 3. Scheme of the emitter-extractor unit: 1—vacuum vessel; 2—Tl solid-state emitter; 3—extracting electrode.

Wire sensors (shown in figure 6) are used to measure size and position of the beam. Figure 7 displays typical oscillogram obtained in the alignment experiment. Such oscillogram allows calculating beam size on all three wire detectors of the primary beam and, as result, to learn the beam focusing features.

3.3. Energy analyzer

The energy analyzer is the key HIBP element aiming for the measurements of the secondary ion beam energy with a high precision [26]. It has five 2-mm slits which allow making measurements in five different spatial points with a size of less than 1 cm.

The energy analyzer consists of vacuum vessel, entrance aperture, parallel plates, high-voltage feedthrough and split plate detector, as presented in figures 8 and 9. The operating voltage of the energy analyzer is up to 75 kV, while the pressure operating range is from $10^{-6}$ to $10^{-3}$ Pa.

Anode high-voltage plate has a hole in a central zone at the area of the lighting by plasma emission to prevent the reflection of the light to the beam detector, so to avoid the parasitic current caused by secondary electrons. This hole is covered by the wire grid to keep the uniformity of the analyzing electric field.

The cylindrical vacuum vessel of the analyzer must have adequate stiffness to prevent its collapse due to buckling. So the strength calculation should consider not only static case, but also buckling probability.

Entrance aperture slits must have accurate shape and positioning, good enough to form on the detector well shaped beam spot with absence of $z$-$\phi$ dependence. In addition, highly homogeneous electric field is needed in between analyzer plates, so high quality requirements for their design are imposed.

Detector assembly [27, figure 2] must be carried out with high precision as far as the distance between detector plates is only 0.5 mm. Position of the detector assembly is adjusted in order
Figure 4. Scheme of the emitter-extractor unit power supply circuit [23].

Figure 5. Primary beamline: 1—$\alpha_1$ plates; 2—Faraday cup; 3—magnetic relay; 4—$\beta_1$ plates; 5—1st wire sensor; 6—2nd wire sensor; 7—$\beta_2$ plates; 8—$\alpha_2$ plates.

to optimize dependence of calibration coefficients on entrance angle of the secondary beam into analyzer.

Multichannel energy analyzer opens new capabilities to make correlation studies between plasma potentials and densities, measured in neighboring spatial points. The cross-phase between signals provides the poloidal structure of Geodesic Acoustic Modes [28]. Simultaneous measurements of potential in two poloidally separated points and density gives a unique opportunity to retrieve the electrostatic turbulent particle flux [29, 30].
3.4. HIBP power supply system

HIBP power supply system (figure 10) includes two branches of feed up elements—so called high voltage branch and low voltage branch respectively. High voltage branch is at the acceleration potential, placed separately to avoid electrical breakdown and includes next items:

- acceleration voltage generator (up to 400 kV, by Glassman Inc.);
- large capacitor in addition to inner filter of generator;
- 1 GΩ divider for measurements;
- current source for emitter heating—two 12 V 120 A·h batteries;
- two 10 kV voltage sources for three-electrode lens in emitter-extractor unit.
Figure 8. Beam trajectory in the T-10 Proca–Green parallel plate energy analyzer [25]: 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.

Figure 9. Energy analyzer on T-10.

Here, the fourth and the fifth items are placed on high voltage platform.
The main issue in the operation of the high voltage branch (as soon as it has hundreds of kilovolts) essentially is the corona discharge and electrical breakdown. To avoid these unfavorable
Figure 10. High voltage branch of power supply system: 1—high voltage generator for injector (400 kV); 2—additional voltage filter; 3—divider for measurements of injector voltage; 4—high voltage platform with current and voltage sources; 5—injector; 6—high voltage generator for energy analyzer (100 kV); 7—divider for measurements of analyzer voltage; 8—dielectric covering.

events, all components are placed on the top of the T-10 iron core. In addition, all high voltage parts are separated from grounded elements with a distance of at least 1 meter. On top of that, all components have a smooth anti-corona shape to prevent concentration of electric field. At the closest gaps between the high voltage parts and grounded elements the latter were additionally shielded by a thin layer insulator.

Another problem is to control emitter heating and three-electrode lens voltage sources which are at the high voltage. For this, an optical converter is used. There are optical converters on the top and on the bottom of the current source column connected by optical cables to send control and check signals.

Commercial high-voltage generators provide necessary level of stability about $10^{-5}$ for both accelerator (Glassman-400) and energy analyzer (Glassman-100).

4. Conclusions
HIBP diagnostics is set up at the T-10 tokamak and shows stable operation in the experiments. HIBP provides measurements of potential in various T-10 regimes with plasma current from 100 to 300 kA, density from $0.4$ up to $4 \times 10^{19}$ m$^{-3}$ and magnetic field on axis from 1.5 to 2.5 T. HIBP measurements can be carried out both in OH and auxiliary ECRH phase of discharge. Thus, HIBP is reliably operating in the whole range of T-10 parameters and provides the plasma potential mean profile evolution and electrostatic and electromagnetic turbulence characteristics.
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