Probing ion trajectory simulations for the HIBP diagnostics at the T-15MD tokamak

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Abstract. The paper presents the results of preliminary simulations of the Tl⁺ ion trajectories and detector grids for Heavy Ion Beam Probe (HIBP) diagnostics at the T-15MD tokamak. For these calculations, authors have developed the HIBP SOLVER software package using the Runge-Kutta method of the 4th order for solving the motion equation for the probing particles. Simulations have shown that the HIBP diagnostics at the T-15MD tokamak will allow measuring the entire radial profile of the plasma potential during one shot, including both the core and edge regions. The detector grid covers the most area of the vertical plasma cross section, so the two-dimensional potential distribution can be recovered. In the start regime (1 T, 1 MA), the beam energy will be below 300 keV, and in the standard regime (2 T, 2 MA), the beam energy will amount to 1000 keV.

1. Introduction

Heavy Ion Beam Probe (HIBP) diagnostics is an advanced multi-purpose non-disturbing diagnostics used to study magnetically confined plasmas [1]. It allows measuring directly the plasma electric potential distribution by changing the probing beam energy. In addition, the beam current and the beam toroidal shift provide data on the plasma density \( n_e \), and the poloidal magnetic field \( B_{pol} \). The multichannel HIBP diagnostics can be also used for measuring the poloidal electric field and the turbulent particle flux, as well as for studying the broadband turbulence and the quasi-coherent modes such as the geodesic acoustic mode [2, 3] and the Alfvén eigenmodes [4].

The HIBP diagnostics is based on the injection of singly charged heavy ions such as Tl⁺ (or Cs⁺) transversely to the magnetic field \( B_t \) confining plasma, (this beam is called the “primary beam”), and the analysis of the ”secondary” ions Tl²⁺ (or Cs²⁺) produced as a result of ionization by plasma electrons. The entrance aperture of the energy analyzer cuts out the secondary beam from the fan of the secondary trajectories, and selects the sample volume (SV), which will be analyzed [5].

The HIBP diagnostics has been successfully operated at the middle-sized tokamaks (the TEXT, JIPPT-2U, and JFT-2M), and at the CHS stellarator. Now the HIBP diagnostics is operating at the TUMAN-3M and the ISSTOK tokamaks, the MST reversed field pinch and the LHD stellarator. The upgraded HIBP diagnostics operated till recently at the T-10 tokamak (\( a = 0.3 \) m, \( R = 1.5 \) m, \( B_t = 1.5–2.5 \) T, \( I_p = 140–330 \) kA, \( P_{ECRH} < 2.2 \) MW, Tl⁺ probing ions), and it operates now at the TJ-II stellarator (\( a = 0.22 \) m, \( R = 1.5 \) m, \( B_t = 1 \) T, \( P_{ECRH} < 0.6 \) MW, \( P_{NBI} < 1 \) MW, Cs⁺ probing ions). If optimally
installed and precisely calibrated, the HIBP diagnostics allows studying time evolution of the radial profiles and/or local values of the plasma parameters both from the high field side (HFS) and the low field side (LFS) (at the TJ-II: $-1 < \rho < 1$, Cs$^+$ ion energy was 125 keV, measurements in a single shot; in the T-10: LFS (+0.2 < \rho < 1), Tl$^+$ ions energy was 300 keV) [1]. Currently, the HIBP diagnostics is being designed for the T-15MD tokamak ($a = 0.67$ m, $R = 1.5$ m, $B_t < 2$ T, $I_p < 2$ MA, probing ions: Tl$^+$) [6].

The HIBP diagnostics installation at the T-15MD requires preliminary calculations of the probing ions trajectories and detector grids in order to determine the optimal location of the injection point and the injection angle of the primary beam, as well as the location of the detection point for the secondary ions. For this purpose, authors developed the HIBP SOLVER software package written in the Python programming language.

The paper is organized as follows. Section 2 describes the principles of operation of the HIBP diagnostics and the HIBP SOLVER package. Section 3 presents the simulation results for the T-15MD tokamak, while Section 4 briefly summarizes the results.

2. HIBP diagnostics: principles of operation

2.1. HIBP diagnostics

Let’s discuss the HIBP diagnostics principles of operation by the example of the T-10 HIBP diagnostics, which is a prototype for the T-15MD HIBP diagnostics; the T-15MD tokamak is now under construction. Figure 1 shows the primary beam of Tl$^+$ ions accelerated by the long-focus ion-optical system [7], and injected into the tokamak chamber [8].

Tl$^+$ ions move along the curved trajectory, collide with plasma electrons, become ionized and produce the secondary Tl$^{++}$ ions. Due to an increase in the charge number $q = +2$, the secondary ions acquire the twice smaller Larmor radius and form a fan of the secondary ion trajectories, as shown in figure 2 in red.

During the secondary ionization in plasma, heavy Tl$^+$ ions with the $E_b$ energy lose electrons having the potential energy $U = -e\phi_SV$ (SV is the sample volume), where $\phi_SV$ is the local plasma potential in the SV. The kinetic energy of Tl$^{++}$ ions, which have left the plasma, is $E_d = E_b + e\phi_SV$ and, thus, the plasma potential in the sample volume is equal to $\phi_SV = (E_d - E_b)/e$.

By varying the injection angle of the primary beam (the voltage on the deflecting plates) one can vary the SV location and, in this way, scan the plasma cross-section. This provides measuring the spatial profile of the plasma potential along the detector line. Variation of the beam energy allows shifting the detector line and forming the 2D detector grid.

Figure 1. HIBP principle of operation by the example of the T-10 tokamak HIBP diagnostics
2.2. **HIBP SOLVER: a software package for probing ion trajectory calculations**

2.2.1. **Magnetic field.** The magnetic field of a tokamak consists of three main components: the toroidal field $B_t$ confining plasma, the vertical poloidal field of the control coils and the poloidal field of the plasma current. At first, the calculation domain and the shape of the toroidal and poloidal coils are specified. Then each coil is divided into a set of filaments. HIBP SOLVER calculates the total magnetic field by solving the Biot-Savart-Laplace equation for each filament and summing up the contributions of each coil. The same principle is applied to the magnetic field of the plasma current. The plasma current profile is taken from the equilibrium calculations performed using the TOKAMEQ code [9].

2.2.2. **Electric field of deflecting plates.** One of the deflecting plates is grounded and the constant voltage is applied to another plate. The HIBP SOLVER uses the iterative method for solving the Laplace equation ($\Delta \phi = 0$ outside the plate with applied voltage). The iteration process terminates, when the difference in potentials in two successive iterations reaches the specified accuracy.

2.2.3. **Trajectory calculations.** Using the calculated magnetic and electric fields, the HIBP SOLVER solves the motion equation:

$$m\ddot{v} = q(E + [V \times B])$$  \hspace{1cm} (1)

using the Runge-Kutta method of the 4th order. At first, the program calculates the primary beam trajectory, starting from the injection point, which usually is at the output of the beam accelerator. The trajectory is curved by the deflecting parallel plates and becomes twisted in accordance with the Larmor orbit of ions in the tokamak magnetic field. The primary trajectory is calculated until it leaves the plasma.

The HIBP SOLVER generates the secondary trajectories from each point of the primary trajectory until one of them hits the detection point (it is usually set to be at the input of the energy analyzer). After that the program saves the resulting set of the primary and secondary trajectories that hit the detection point and the SV coordinates.

Then the HIBP SOLVER repeats the SV calculations with changed voltage on the primary deflecting plates. Performing the cyclic calculations, the HIBP SOLVER produces a set of SVs, which forms the detector line. We can change the detector line location by changing the $E_b$ energy and form the detector grid as a set of detector lines.

3. **Calculation results**

First, let us consider the start operating regime with $B_t = 1$ T and $I_p = 1$ MA. For this regime, figure 2 presents the Tl$^+$ primary trajectory, started from the injection point E, and a fan of the Tl$^{++}$ secondary trajectories, originated at the primary trajectory. Figure 3 shows the formation of the detector line for the ion beams with equal $E_b$ energy. Figure 4 shows the detector grid.

In both figures 4 and 5, solid lines are the detector lines of equal energy, and dashed lines are the detector lines of equal entrance angle (deflecting voltage $UA2$).

4. **Summary and outlook**

Calculations have shown that the HIBP diagnostics at the T-15MD tokamak allows measuring the plasma potential distribution over the radius from the plasma center to the edge. By varying the injection angle we can obtain the entire radial profile from the center to the edge in one shot. The detector grid can cover the most area of the vertical cross section, so the two-dimensional potential distribution can be recovered. In the start regime (1 T, 1 MA), the beam energy will be below 300 keV, and in the standard regime (2 T, 2 MA), the beam energy will amount to 1000 keV.
Figure 2. Primary and secondary trajectories for $E_0 = 160$ keV.

Figure 3. Detector line for $E_0 = 200$ keV.

Figure 4. Detector grid for $B_t = 1$ T, $I_{pl}$. 
In the next stage, the further optimization is necessary aiming for the reduction of the energy range and the trajectories’ entrance angle of the energy analyzer. In addition, for the multichannel HIBP diagnostics intended to measure the poloidal plasma rotation [10] and turbulent particle flux [11], the poloidal orientation of the SVs should be achieved.

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