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HEAVY ION BEAM PROBE

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This article presents a description of the diagnostic complex for plasma probing with Heavy Ion Beams Probs (HIBP). Using this diagnostics, it is possible to determine the radial profile of the plasma density, its fluctuations, as well as the radial distribution and fluctuations of the plasma potential. At the moment, this is the most modern diagnostics in Europe and it is implemented on the TJ-II stellarator in the form of a dual HIBP diagnostic complex consisting of two HIBPs. The dual HIBP diagnostic suite has expanded the range of plasma parameter measurements by adding the ability to measure long-scale correlations (LRC) of data between two HIBP systems.

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INTRODUCTION

In the mid-20th century, intensive development of research in the field of controlled thermonuclear fusion began. To study hot plasma, hot plasma diagnostics was required and it was created as a new branch of plasma physics [1 - 6]. Diagnostics can be conditionally classified as follows: probe, laser, spectroscopic and corpuscular. Probe diagnostics have a significant drawback – their use is limited to the periphery of the plasma. Laser diagnostics – the disadvantage is the low efficiency of lasers. Spectroscopic diagnostics has the disadvantage of a complex connection between the directly measured intensity and the plasma parameters. A special place among diagnostics is occupied by active corpuscular diagnostics HIBP (Heavy Ion Beam Probe). This is a unique diagnostic for plasma study in thermonuclear installations. HIBP diagnostics [7 - 11] allows to measure such important parameters as the radial profile of the plasma density, plasma potential, its fluctuations and poloidal magnetic field. HIBP diagnostic is a very common type of diagnostics. It has been widely used and is used on thermonuclear devices such as stellarators and tokamaks. For example, in Europe (Table): stellarators TJ-I, TJ-II (Spain), Uragan-2M (Ukraine) and tokamak WEGA (Germany). Fig. 1 shows schematically the operating principle of HIBP diagnostics.

The ions of the primary beam move throughout the plasma, constantly colliding with plasma particles along the trajectory of their movement. In doing so, they participate in many atomic processes. These processes include excitation of the electron shells of the ion, ionization of various multiplicities. As a result of this ionization, doubly charged ions are formed at each point of the trajectory. The trajectories of doubly charged ions form a "fan" along the curvature in the magnetic field, which leads to the separation of the trajectories of the doubly charged ions trajectory of the primary beam (see Fig. 1). An energy analyzer is installed at a calculated distance from the plasma in the path of the fan of secondary ions. Thus, particles are separated from the fan of secondary ions and enter the detector diaphragm. Part of the fan of doubly charged ions is the secondary ion beam that enters the collectors. By measuring the parameters of the secondary ion beam and the parameters of the primary one, it is possible to determine the plasma parameters, such as the local plasma potential, plasma density, magnetic field, and their fluctuations. The region, where the secondary ion beam is formed, is the measurement region of the HIBP diagnostics or, so-called, the detector region.

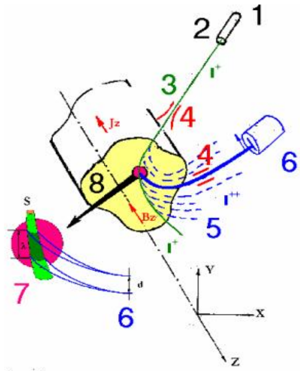

Fig. 1. Block diagram of the principle HIBP diagnostics: 1 – ion source; 2 – accelerating tube; 3 – primary ion beam; 4 – correction plates; 5 – secondary ion beam; 6 – analyzer; 7 – measurement area; S – primary beam cross section; λ – simple volume; 8 – part of the plasma cord; I^+ – singly charged ions; I^{++} – doubly charged ions; Bz – magnetic field

The complex consists of the following parts: a primary ion injector, an electrostatic analyzer, control system, a measurement system, diagnostics parameter control systems, data acquisition and processing systems. In turn, the primary ion beam injector consists of several parts. First, a source of singly charged cesium ions; an accelerator tube; a primary beamline located between the accelerator tube and the inlet of the TJ-II stellarator; a system for controlling the parameters of the diagnostics and a system for capturing and processing data. Secondly, from the high-voltage sources, the accelerating and focusing voltages, the heating unit of the ion source spiral. The ion source is based on a solid-state thermal emitter of cesium ions. Alkali metal ions Cs^+ are emitted when the emitter is heated and an extraction voltage is applied. Such sources have a number of advantages, among which it should be noted: – small spread of ion energy, which is determined by the heating temperature of 900…1250°C and at primary ion beam energies up to 200 keV, it is possible to obtain beams with ion current densities up to 1.5 mA/cm^2 in steady-state operation. One of the most modern HIBP diagnostics is dual HIBP installed on the TJ-II stellarator (Table).

TJ-II stellarator parameters

Parameters	Values
Major radius	1.5 m
Minor radius	0.2 m
Magnetic field	1 T
Plasma pulse	0.35 s
ECRH	2×0.3 MW
NBI	2×0.5 MW
Plasma volume	1 m^3

DUAL HIBP DIAGNOSTICS

Dual HIBP diagnostics consists of two diagnostic complexes HIBP1 and HIBP2. The complexes are installed on the toroidal chamber of the TJ-II stellarator in identical poloidal cross-sections, the distance along the torus between the complexes is about 2.5 m (Fig. 2).

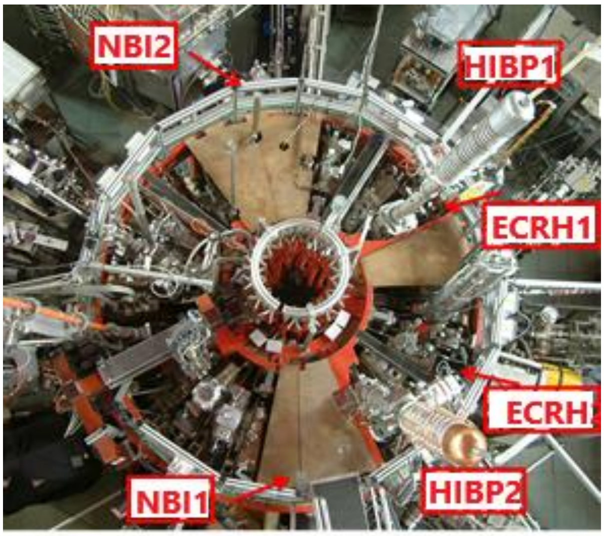

Fig. 2. The placement of HIBP1 and HIBP2 diagnostics on the TJ-II stellarator and plasma heating systems

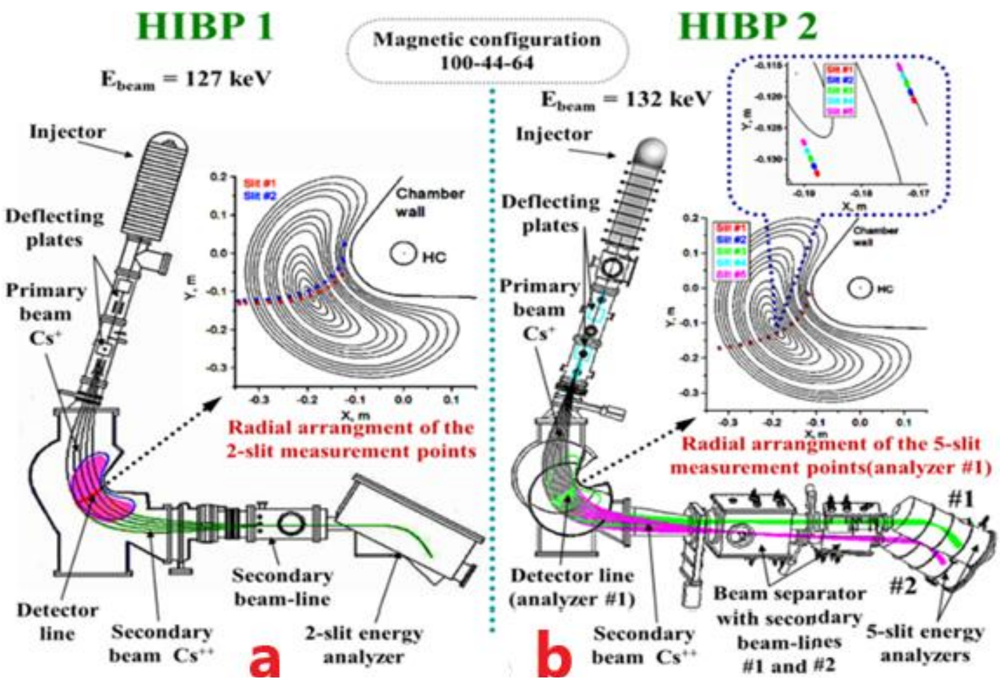

Fig. 3. Complete set of two HIBP diagnostics. HIBP1 diagnostics (a); HIBP2 diagnostics (b)

This arrangement guarantees the same configuration of the magnetic field in the measurement cross-sections of both diagnostic complexes.

The use of dual HIBP (Fig. 3) diagnostics opens the way for the study of long-scale correlations (LRC) electric potential, plasma density profile, poloidal magnetic field, poloidal and toroidal plasma turbulence structure, and various types of instabilities in the central and peripheral plasma. In this dual diagnostic complex, each of the two components is similar in principle, but has some differences.

Firstly, they have different beam energies. In HIBP1 it is 127 keV, and in HIBP2 it is 132 keV. In HIBP1 the energy analyzer has 2 slits (8 collectors), and in HIBP2 has 5 slits (20 collectors). Both have 4 blocks of correcting plates at the primary beam-line, but HIBP1 has 2 blocks at the secondary beam-line, and HIBP2 – 4 blocks.

The dual HIBP diagnostics complex has a wide range of experimental schemes for measuring plasma parameters – this is the operation of both complexes in scan mode; in measurement mode at given points, both at the same and at different ones (along the plasma cross-section in 2D format); in mixed modes – scanning mode on one complex and measurement mode at a given point on the other.

AM AND POTENTIAL FLUCTUATIONS

The dual HIBP [12 - 14] setup allows us to study fluctuations and long-range correlations (LRC) in the plasma. In this chapter, we will present data on plasma potential fluctuations HIBP1 and HIBP2 diagnostics in the region of mixed heating of ECRH and NBI, where the Alfvén mode (AM) occurs. Fig. 4 shows the plasma pulse data, the region light blue color (f) is the localization of AM occurs with frequency 270...210 kHz. The

HIBP2 diagnostics are carried out measurements at point 0.6 from the high field side (HFS). Fig. 4 shows the localization of AM relative to the reduced plasma radius, from the low field side (LFS), ρ from 0.1 to 0.65 and from the HFS side ρ from -0.1 to -0.65. No AM is observed in the peripheral region of the plasma.

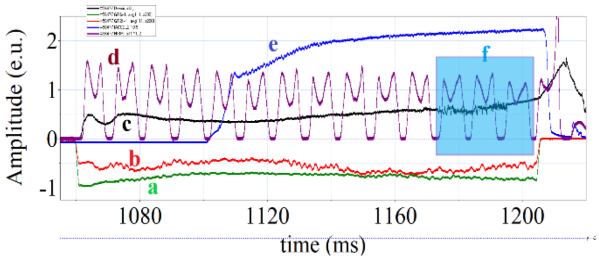

Fig. 4. Plasma pulse parameters: ECRH1, 260 kW (a); ECRH2, 225 kW (b); NBI2, 405 kW (e); plasma density from 0.5 up to 0.75×10^{19}m^{-3} (c); density profiles HIBP1 diagnostic (d)

On Figs. 5 and 6 the data on the power spectral density (PSD) of the signals of the HIBP1 and HIBP2 diagnostic potentials in the region of AM existence are presented (see Fig. 4, f). Fig. 5 shows the localization of AM (scan regime), Fig. 6 shows the type of potential at the point 0.6 HFS during the AM existence time. Radial localization of the AM on profile density HIBP1 system is shown in Fig. 7.

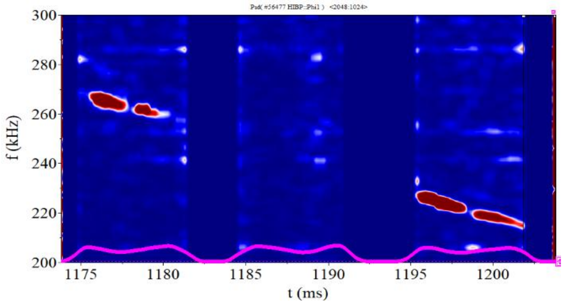

Fig. 5. PSD of HIBP1 potential signal in the AM region (see Fig. 4, f), frequency from 220 kHz (start time point 1175 ms) up to 270 kHz (1202 ms)

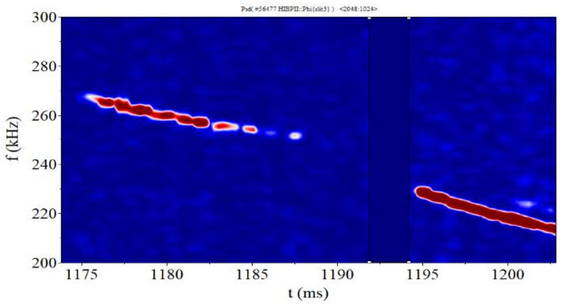

Fig. 6. PSD of HIBP2 potential signal in the AM region (see Fig. 4, f), frequency from 220 kHz (start time point 1175 ms) up to 270 kHz (1202 ms)

As an option for verifying the measurements of plasma potential fluctuations in the AM region by dual HIBP, the PSD of the Mirnov probe signal in the AM region is shown (Fig. 8). As can be seen, plasma fluctuations measured at point 0.6 HFS by HIBP2 diagnostics (see Fig. 6) are visually similar. Similarity both in the frequency range and in locality (absence of turbulence in the region of 1187...1195 ms). The final conclusion about the similarity of the obtained data can be made from Figs. 9 and 10, this is an assessment of the coherence of the signals of the HIBP1 and HIBP2 potential with the Mirnov probe signals. A high level of data coherence up to 0.8 is observed, with absolute similarity of the AM frequency response.

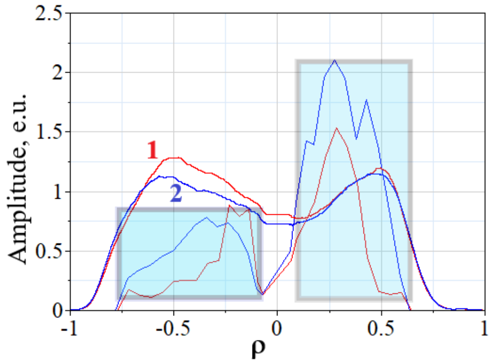

Fig. 7. Radial localization of the AM on profile density HIBP1 system: 1 – first scan; 2 – finish scan (see Fig. 4, f). Zone LFS from 0.1 **ρ** *up to 0.65* **ρ***; zone HFS from -0.1* **ρ** *up to -0.75* **ρ**

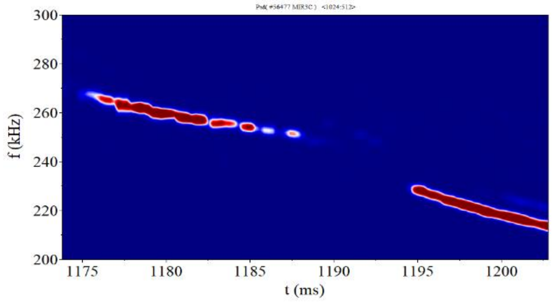

Fig. 8. PSD of Mirnov probe in the AM region

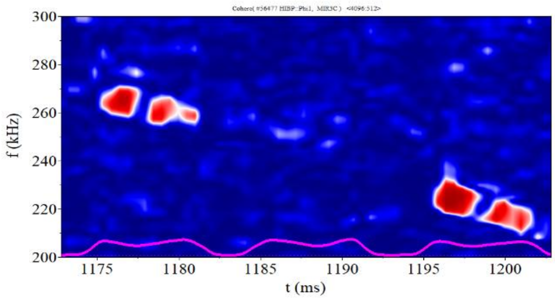

Fig. 9. Coherence between potential signal HIBP1 and Mirnov probe

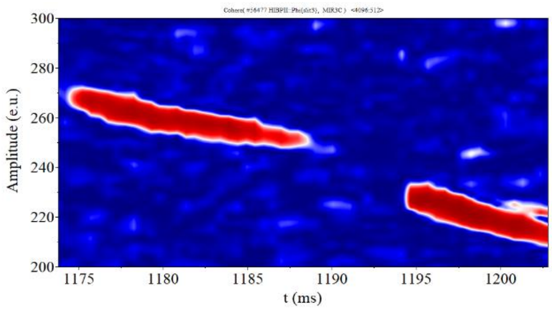

Fig. 10. Coherence between potential signal HIBP2 and Mirnov probe

Fig. 11 shows the long range correlation in plasma potential fluctuations between the HIBP1 diagnostic potential signal in the scanning mode and the HIBP2 potential signal at point 0.6 HFS. The coherence is not less than 0.8 with similarity of localization and AM frequency response.

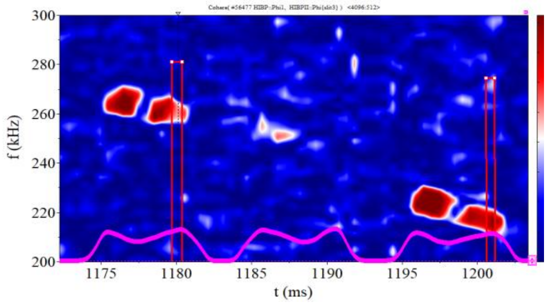

Fig. 11. Coherence between potential signal HIBP1 and HIBP2

This chapter demonstrates the unique capabilities of dual HIBP in measuring plasma potential fluctuations. These are AM localization by plasma radius and long-scale correlations of experimental data in addition to measuring the plasma density and potential profile.

CONCLUSIONS

This paper describes a unique diagnostic on heavy ion beams HIBP. It allows measurements of plasma potential, plasma density profile and their fluctuations, poloidal magnetic field. The dual HIBP diagnostics installed on the TJ-II stellarator additionally allows measuring long-scale correlations. Experimental HIBP data are especially important for correcting calculation programs for plasma turbulence modeling.

The uniqueness of the data obtained justifies the participation of dual HIBP in almost all experimental campaigns and international programs.

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ЗОНДУВАННЯ ПЛАЗМИ ПУЧКОМ ВАЖКИХ ІОНІВ

Л.І. Крупнік, О.С. Козачок, О.Д. Комаров, С.М. Хребтов, О.О. Чмига, Я.В. Матлак

Представлено опис діагностичного комплексу для зондування плазми пучками важких іонів (ЗППВІ). За допомогою цієї діагностики можна визначити радіальний профіль щільності плазми, її коливання, а також радіальний розподіл і коливання потенціалу плазми. На даний момент це найсучасніша діагностика в Європі, і вона реалізована на стелараторі TJ-II у вигляді подвійного діагностичного комплексу ЗППВІ, що складається з двох ЗППВІ. Подвійний діагностичний пакет ЗППВІ розширив діапазон вимірювань параметрів плазми, додавши можливість вимірювати довгомасштабні кореляції даних між двома системами ЗППВІ.