Heavy ion beam probe for studying potential and turbulence on MAST

A.V. Melnikov[1], S.V. Perfilov[1], S.E. Sharapov[2]

[1]*Institute of Tokamak Physics, RRC "Kurchatov Institute", Moscow 123182, Russia*
[2]*EURATOM /CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*

1. Introduction

The observed anomalous transport in tokamaks is usually explained by turbulent microinstabilities driven by density and temperature gradients [1]. The fluctuating electric fields associated with this turbulence cause a convection of plasma across the toroidal magnetic surfaces, while turbulent magnetic field fluctuations perturb the toroidal surfaces, so heat flow may be transported away along the destroyed magnetic field lines at a rapid rate. Direct measurements of both the electric and magnetic perturbed fields associated with the plasma turbulence, as well as the density fluctuations and the turbulent particle flux $\Gamma_r = \langle \delta n_e \cdot \delta V_r \rangle = \langle \delta n_e \cdot \delta E / B \rangle$, are required for assessing theoretical models explaining the anomalous transport caused by the turbulence [2]. For the next-step burning plasma experiments with significant populations of fusion alpha-particles and super-Alfvénic NBI-produced energetic ions, high-frequency (100-500 kHz) Alfvén instabilities may play an important role in the transport of the energetic ions [3]. Such instabilities are often observed in present-day experiments, and their interaction with the energetic particles also requires an accurate measurement of the perturbed plasma quantities similar to the ones required for thermal plasma turbulence.

2. The physics of HIBP diagnostics

Measurements of the perturbed quantities described above represents a major challenge for modern diagnostics. One of the promising avenues in this area is a heavy ion beam probe (HIBP) multipurpose diagnostics based on injection of heavy beam ions, and capable to produce simultaneous information about the local plasma potential φ from the beam energy, plasma density n_e from the beam current I_t, and poloidal magnetic field B_{pol} from the toroidal beam shift ζ [4-6]. Initially designed and used on several tokamaks and stellarators for measuring the electrostatic potential, HIBP was recently expanded in the frequency bandwidth (up to several hundreds of kHz) and applied for studying the potential oscillations, broadband turbulence and quasi-coherent modes like Alfvén Eigenmodes (AE) in NBI heating plasmas of the TJ-II stellarator [7], and geodesic acoustic modes in OH and ECRH plasmas of the T-10 tokamak [6, 8]. The conventional HIBP provides time (1 μs) and spatially (< 1 cm) resolved information on the plasma potential profile and fluctuations of plasma potential, density and perturbed poloidal magnetic field. A novel multi-channel HIBP with poloidally oriented sample volumes (*SV*) can also provide measurements of fluctuating poloidal electric field and the turbulent particle flux Γ_r [7].

The basic principle of the measurement of the electric potential is the energy conservation. The probing beam enters the plasma with an initial energy E_b. As the particles pass through the plasma, the total energy is conserved. At the ionization point, which is the HIBP sample volume, electrons with potential energy of $-e\varphi_{pl}^{SV}$ are stripped off, here e is the electron charge, and φ_{pl}^{SV} is the local electrostatic potential at *SV*. The total energy of the secondary ions leaving the plasma is $E_d = E_b - e\varphi_{pl}^{SV}$. Therefore, the plasma potential at the sample volume equals to the energy difference: $\varphi_{pl}^{SV} = (E_d - E_b)/e$. Since E_b is constant, the oscillatory component of potential is proportional to the energy of the secondary beam. A conventional parallel plate energy analyzer is used in HIBP diagnostic. Fluctuating plasma density is obtained from measuring the beam current. The beam current I_t measured by the analyzer is directly proportional to the density in the sample volume n_e^{SV} with some attenuation factor depending on the density along the beam path, its length and cross-section of beam ionization. The energy of the beam and the type of the heavy ions depend on the machine size and the magnetic field. In present-day machines, Tl^+ ions (m=205) are used on T-10 (B=2.5 T, a = 30 cm) and Cs^+ ions (m=133) are used on the TJ-II (B=1 T, a=22 cm).

3. Modelling of HIBP on MAST

In this work, we assess possibility of employing the HIBP diagnostic on the Spherical Tokamak MAST [9] (R=0.85 m, a=0.65 m, B= 0.4-0.6 T, I_{pl} = 1 MA). Although development of such diagnostic tool for MAST is not being considered at the moment, the concept of employing HIBP on spherical tokamaks with relatively low magnetic fields is of great interest, and the MAST machine is a good example for such study. Modelling should clarify, is it possible to measure the potential and the fluctuations over the whole radius and in the scrape-of-layer of MAST. For the typical magnetic field on MAST, Cs^+ ions are suitable, and the problems to solve are the geometry and the energy of the beam required for the measurements. The upper location of the HIBP is considered as the most conventional, although it is also possible to mount the beam injector at the bottom. For the upper location of HIBP, toroidal field direction has to be such that the ion grad-*B* drift is upwards.

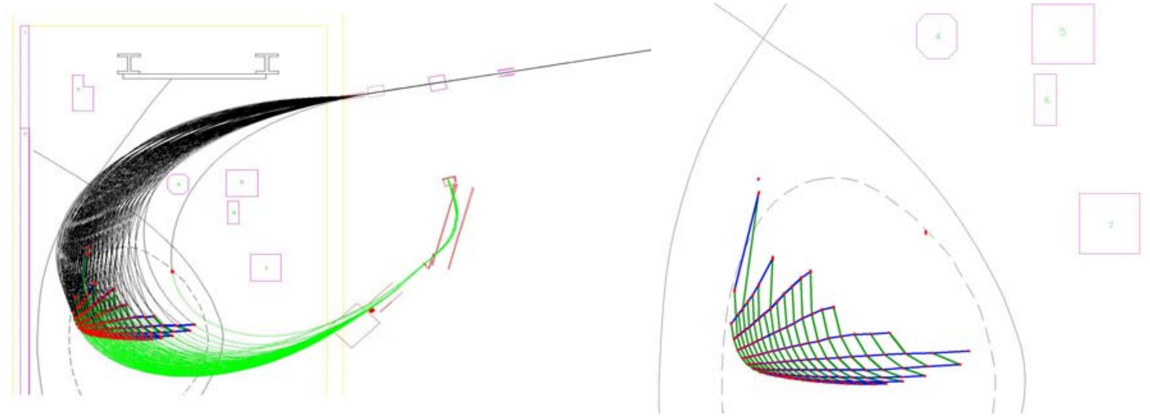

Figure 1. Left: Simulated beam trajectories on MAST aiming at measurements of the central plasma region. Right: Zoom showing the detector grid covering the central region of the plasma. The beam energy covers the range E_b= 50- 250 keV, the blue lines drawn with 10 keV step in the energy, green lines – with 1 kV step in the sweeping voltage.

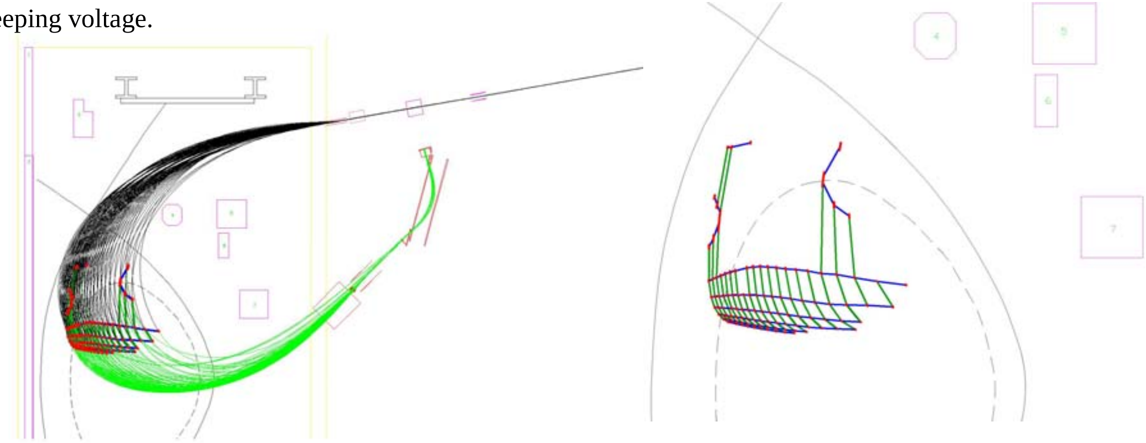

Figure 2. Left: Simulated beam trajectories on MAST aiming at measuring the up-shifted region of the central plasma. Right: Zoom showing the detector grid covering the up-shifted region of the plasma. The beam energy covers the range E_b= 50- 250 keV.

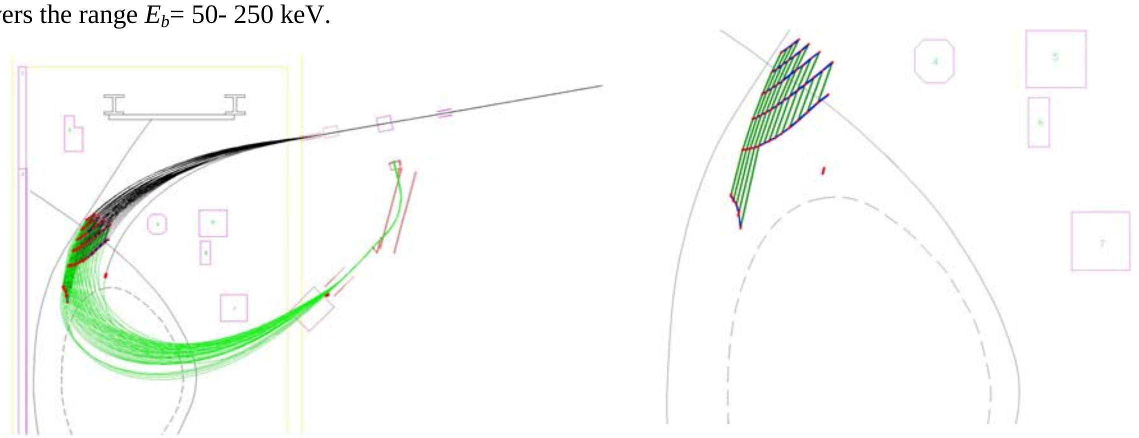

Figure 3. Left: Simulated beam trajectories on MAST aiming at measuring plasma edge and scrape-of-layer region near the upper X-point. Right: Zoom showing the detector grid covering edge and SOL regions.

Results of the HIBP modelling are presented in Figures 1-3, which show the HIBP trajectories required for the full coverage of the plasma volume from the centre to the very edge and SOL. It is found that the beam energy required for HIBP diagnostics based on Cs^+ ions is 100- 250 keV, which is in the range of the compact commercial high voltage equipment [10, 11].

3. Conclusions

Our calculations show that HIBP may provide measurements of the potential and the plasma fluctuations over the whole radial interval on MAST with the fine spatial resolution ~ 1 cm. The HIBP Cs^+ beam energy required for such coverage is found to be $E_b < 250$ keV, and one can use the compact commercial high voltage equipment for such beam. The HIBP diagnostics seems to be feasible for the present-day MAST machine, although additional assessment of the HIBP will be required for the MAST-Upgrade.

Acknowledgements

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