Particle-In-Cell Simulations of the Katsumata Probe

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Abstract. Katsumata probe [Katsumata et al., 1996] serves to measure the ion temperature in magnetized plasma. Such a probe typically consists of a collector submerged inside a hollow tube, which is oriented perpendicularly to the magnetic field. According to the basic theory, when the collector is retracted in the tube, electrons with their small Larmor radii should not be able to reach it and the collector becomes sensitive to ions. However, experimental results show, that the electron shielding is in general inefficient, it only works in the case, when the potential of the collector is same as the potential of the inside surface of the tube [Ezumi et al., 2002].

This model was a subject to verification. We have used full 3D Particle-In-Cell cartesian code with fast multigrid Poisson solver. Using this code, we simulated the plasma behavior in the vicinity of a model of the Katsumata probe. Potential structure at the entrance of the tunnel was identified. This structure produced ExB drifts which push electrons into the shielded space. Simulations revealed that electrons can penetrate inside the geometrical shadow in all studied cases but when the potential of the collector is equal to the potential of the tube, they do not reach the collector.

Introduction

The ion temperature $T_i$ is an important plasma quantity, however, difficult to measure in tokamak Scrape-off Layer (SOL), which is a typical domain of probe measurements. It is not possible to deduce $T_i$ from a simple Langmuir probe I-V characteristics due to large electron current. For this reason, Katsumata probe, which shields their collector from electron influx, has been developed [Katsumata et al., 1996] [Ratynskaia et al., 2007]. According to the basic theory [Hutchinson, 2002], the principle of shielding lies in the geometry of the probe and its orientation with respect to the magnetic field. Typical setup of an ion sensitive probe, which has been used at the CASTOR tokamak, is shown in Fig. 1. A cylindrical collector is submerged into a metal tube, which is perpendicular to the magnetic field. Since ions have Larmor radii much larger than electrons, they can penetrate into plasma shadow and reach the collector, while electrons should be screened. The ion temperature is obtained from the fit of the I-V characteristics [Adamek, 2008].

This simple geometrical approach has been falsified by experiment [Adamek, 2008], where the electron shielding was only efficient for the case when the tunnel was biased on the same potential as the collector.

In this paper we present a theoretical study based on computer modelling, which focuses on the problem of electron shielding in the ion sensitive probes. The main aim of our study is to explain the electron behavior in the vicinity of such probe and to verify the experimental technique used to determine $T_i$. 
We have studied a simplified model of the ion sensitive probe by means of self-consistent particle modelling. A full 3D cartesian Particle-In-Cell code SPICE3 has been used for simulations of the probe. This code is an extension of a 2D code SPICE2 [Dejarnac et al., 2009], [Dejarnac et al., 2008]. The PIC code solves the equation of motion of individual particles in a given stationary magnetic field and self-consistent electric field created by plasma space charge. The key element of the code is a solver of Poisson equation. SPICE3 uses a fast multigrid solver based on direct LU decomposition method [Hackbush, 2003] [Davis, 2004]. Full 3D PIC modelling is extremely demanding on the computational time, which is the main constraint of this method. For this reason, the choice of plasma parameters and probe dimensions has been conformed to the feasibility of simulations. SPICE3 was extensively benchmarked with SPICE2 code (simulations of 2D problems), which has been previously benchmarked with experiment [Dejarnac et al., 2008].

Simulation limits

The calculations are restricted by the size of the PIC grid, the current limit is 128x128x128 cells on available computers. The size of the cell has to be equal or smaller than the Debye length in order to avoid numerical instabilities. This creates a window of plasma density/temperature combinations, which can be simulated on accessible hardware. The code can simulate plasma with a range of $T_i/T_e$ ratios between 0.1 and 10, typical for the tokamak SOL conditions. The magnetic field strength, which can be simulated, is restricted by the necessity to resolve the magnetic pre-sheath within the simulation box, which extends several ion Larmor radii into the plasma. This makes strong magnetic fields (smaller ion Larmor radius) easier to simulate, which is an advantage for studies of tokamak plasma. A typical simulation used in this study followed 130 million particles during 2.4 $\mu$s on a grid 64x64x128 cells. The simulation did take 14 days on 8 cores.

Geometry

The setup of the simulations is shown in Fig. 2. The simulation region is of cuboidal shape, with the probe in the lower part. The probe consists of 3 conductors - the top surface, which is biased to floating potential $V_f$, the tube with variable potential $V_T$ and cylindrical collector pointed in direction of the $z$ axis with potential $V_C$. The particles are injected from the top boundary and follow the magnetic field lines, which are inclined at oblique angle with respect to.
Figure 2. Schematics of an ion sensitive probe. 3D view on the left, 2D cut on the right showing the collector position

the top surface. The side boundaries are periodical. The collector is submerged inside the tube by a variable distance \( h \) (distance between the top surface and collector ending). The inner diameter of the tube is 2 mm, while the collector’s diameter is 1 mm. The depth of the tube is 2 mm. The configuration of sources and boundaries is known to produce stable results, however, to allow plasma reaching the electrodes, an artificial misalignment of the magnetic field has to be introduced. This corresponds to common experimental conditions, where the alignment of the magnetic field with respect to the tunnel axis is not perfect. The misalignment used in this study was 10 degrees (in order to speed up the simulations), however control simulations for 5 and 2.5 degrees did show, that the mechanisms of electron transport are insensitive to the misalignment.

Simulation scenario

Probe performance was simulated in plasma with parameters similar to conditions in tokamak SOL. Note that the choice of plasma parameters has great impact on the computational demands, which restricts the range of plasma conditions we were able to simulate. The plasma conditions read:

- Plasma density \( n = 1 \times 10^{18} \text{ m}^{-3} \)
- Ion temperature \( T_i = 70 \text{ eV} \)
- Electron temperature \( T_e = 50 \text{ eV} \)
- Magnetic field magnitude \( B = 1.0 \text{ T} \)
- Magnetic field inclination \( \alpha = 10 \text{ degrees} \)

Electron transport

At first the behavior of electrons in vicinity of the probe has been a subject of interest, therefore a simulation with parameters \( h = 1 \text{ mm}, V_T = -3 kT_e \) (floating potential) and \( V_C = +3 kT_e \) (electron branch of the I-V characteristics) was performed. The aim of the simulation was to see whether electrons can travel inside the tunnel (\( h \) is much larger than the electron Larmor radius) and reach the collector. Indeed, the simulation revealed an electron current flowing to the collector. The ratio of electron and ion collector currents \( R \) has been defined as follows:

\[
R = \frac{I_C}{I_C^*}
\]  \hspace{1cm} (1)

The simulation yields \( R = 700 \), which demonstrates the inefficiency of electron shielding. The mechanism of electron transport is based on the existence self-consistent electric fields. Since
ions can more easily penetrate into the tube than electrons (due to their large Larmor radius), they create a positive space charge near the tube entrance. This results in a potential structure formation and subsequent electric fields apparation, which give rise to an ExB drift driving the electrons inside the tube (as shown in Fig. 4). The presence of electrons inside the tube affects the potential structure, so the system is in self-consistent equilibrium. As a result, there is a narrow stream of electrons flowing along the border of the potential structure (see Fig. 3).

The situation becomes very different when \( V_C \) is changed to \(-3kT_e\), which makes it equal to \( V_T \). The ratio of currents drops to \( R = 0.07 \), while for a regular Langmuir probe at floating potential \( R \) should be close to unity. This is in good agreement with experiment [Ezumi et al., 2002]. Detailed analysis (Fig 5) reveals that electrons are still present in the tube, however they do not flow onto the collector but leave the tube back into the plasma.

**Summary and Conclusions**

A model of the Katsumata probe has been investigated by means of Particle-In-Cell simulations. Electron transport inside the probe tube has been confirmed and its origin attributed to the ExB drift. Electron current suppresion has been observed in case, where the collector and tube potentials are equal. Future studies will focus on probes with dielectric tube (Ball-pen probe). The aim of this research will be to verify the measurements of plasma potential, which has been experimentaly performed by such probe.
Figure 5. Cut of the electric potential (left) and electron flux (right) at the tunnel axis for $V_T = -3kT_e$ and $V_C = -3kT_e$. Surfaces of objects have been highlighted.

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References