Experimental and Numerical Investigation of Plasma Sheath Electric Field Penetration Through a Micro-aperture

Sushanta Barman[1], Ashutosh Nayak[2], and Sudeep Bhattacharjee [1]
[1] Department of Physics, Indian Institute of Technology Kanpur, India
[2] School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
e-mail (speaker): sushanta@iitk.ac.in

The plasma sheath has been the subject of extensive investigation over the years; however, its comprehensive understanding remains an ongoing challenge. Therefore, it attracts the attention of researchers to investigate the properties of plasma sheaths under various conditions, not only for its implications in fundamental physics but also for its practical applications. The plasma sheath governs a range of fundamental processes at the interface between plasma and surfaces, including electrical coupling, surface chemical properties, and bidirectional mass transport [1]. Consequently, it significantly impacts various plasma applications, including surface modification, electromagnetic wave excitation, plasma immersion ion deposition, plasma etching, and, more importantly, the performance of plasma-based focused ion beam (FIB) systems [2]. Therefore, investigation of the penetration of plasma sheath fields through micro-aperture, which governs the shape of the ion emission surface, becomes imperative for enhancing the efficiency of plasma-based FIBs.

In this study, we have performed experiments to investigate the penetration of sheath electric fields through a grounded micro aperture (plasma electrode) of variable sizes d_P = 20 to 500 μm. In the experiment, continuous mode microwaves of frequency 2.45 GHz are used to ignite Ar plasma and the plasma is confined in an octupole magnetic multicusp [3,4]. The operating pressure and microwave power are varied in the range of 0.1 to 1 mTorr and 100 to 400 W, respectively. A plasma sheath is formed on the plasma-facing side of the plasma electrode (Fig. 1(a)), allowing the electric fields of the sheath to penetrate through its aperture (O) into the extraction side. An electric field probe has been designed and fabricated to measure the axial distribution of the penetrated sheath electric field, as shown in Fig. 1 (a).

The experimental results show that as the size of the plasma electrode (PE) aperture (d_P) decreases to below the Debye length (~100 microns), the penetration of the electric field through the aperture increases nonlinearly. Furthermore, the strength of electric field penetration is observed to be dependent on d_P and experimental operating conditions, such as pressure and microwave power. This observation is further confirmed by numerical simulations, where Poisson's equation was solved numerically using the successive over-relaxation method to calculate the distribution of electric potentials and fields near the PE aperture. The results indicate that when d_P is smaller than the plasma Debye length, the increased electric field at the center of the plasma electrode (PE) aperture arises due to inadequate shielding of electric fields within the Debye sphere in the sheath region. Detailed experimental and simulation results will be presented at the conference.

This study will help to understand the effect of plasma sheaths on the performance of plasma-based FIBs. More importantly, it helps to focus high-current plasma ion beams to sub-micron regimes using the phenomenon of nonlinear magnification of plasma-based FIBs [2,3], which originates from nonlinearity in sheath electric field penetration.

References

[1] P. Vanraesa and A. Bogaerts, Journal of Applied Physics 129, 220901 (2021).
[2] S. Barman, S. K. Maurya, and S. Bhattacharjee, Plasma Research Express 4, 025003 (2022).
[3] S. K. Maurya, S. Barman, N. Pan, S. Bhattacharjee, Physics of Plasmas 26, 063103 (2019).
[4] S. K. Maurya, S. Barman, S. Paul, and S. Bhattacharjee, Journal of Physics D: Applied Physics 52, 055205 (2018).

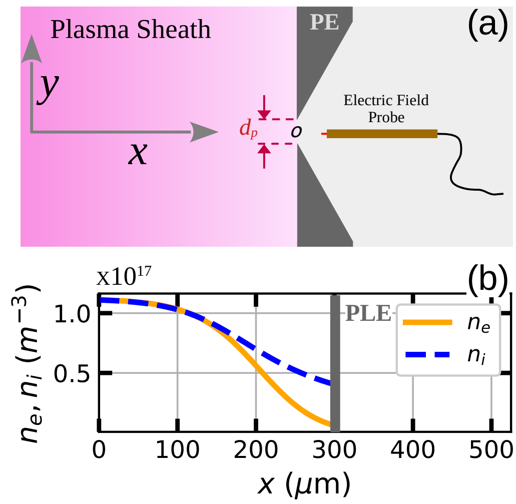

Figure 1. (a) The plasma sheath region and electric field probe. (b) Variation of ion density (n_i) and electron density (n_e) with the axial distance (x) in the plasma sheath region