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Generation of high-intensity nano ion beams using plasma sheath nonlinearity and micro-glass capillary guiding

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Recent studies underscore the critical role of the plasma sheath near the ion extraction aperture in enhancing the performance of plasma-based focused ion beams (FIBs) [1,2]. The sheath electric fields govern the shape of the ion emission surface, and their penetration through the extraction aperture induces a nonlinear demagnification factor in plasma-based FIBs [2]. Consequently, understanding the mechanisms of electric field penetration through the extraction aperture is essential for optimizing the efficiency of the FIBs and for generation of sub-micron ion beams.

To further reduce the beam size, micro-glass capillaries can serve as a promising tool for guiding and focusing ion beams [3]. These capillaries are crucial for the lossless guiding and focusing of ion beams, with the key mechanism based on the distribution of charged patches on the capillary inner wall induced by the incident beam [3,4]. However, when focusing intense ion beams through micro-glass capillaries, the space charge force surpasses the self-focusing force, imposing a self-focusing limit [4]. Overcoming this limit is challenging.

In this work, we (i) experimentally measured the penetration of sheath electric fields through grounded micro apertures of varying sizes (30 to 500 microns), and (ii) demonstrated a novel method in capillary guiding where externally applied electric fields control the dynamics of charge patches, allowing the beam to focus beyond its self-focusing limit and achieve high-intensity nano beams.

In the experimental system, continuous mode microwaves (frequency 2.45 GHz) are employed to ignite Ar plasma in an octupole magnetic multicusp configuration, as shown in Fig. 1 [1]. Operating pressure ranges from 0.25 to 0.8 mTorr, with microwave power between 150 and 350 W. A plasma sheath is formed on the plasma-facing side of the plasma electrode (PLE). The axial distribution of penetrated sheath fields through the PLE was measured using a custom-designed, and calibrated electric field probe, as shown in Fig. 1. It is observed that electric field penetration through the PLE aperture increases nonlinearly as the aperture size decreases below the Debye length (~100 microns). The strength of electric field penetration depends on the aperture size, as confirmed by numerical simulations that reasonably agree with the experimental findings.

In the capillary guiding experiment, two sets of glass capillaries, straight (SC) and tapered (TC), were employed, as shown in Figures 2(a) and (b). Two electrodes (el_1 and el_2) were attached to the outer surface of the capillaries using silver paste. The capillaries were attached to the ion beam system using a Perspex holder (Figure 1(c)). The transmitted beam current was measured by a Faraday cup, and the output beam size was determined by taking the beam impression on a polymethyl methacrylate (PMMA) thin film. It was found that adjusting the bias voltage generated high-intensity ($J_{out} \approx 3.05\times10^5$ Am^{-2}) nano beams (~160 nm) [5]. A Particle-In-Cell (PIC) simulation was developed to explain the findings. This approach will aid in designing an ion source for matter wave diffraction experiments. The detailed results will be presented at the conference.

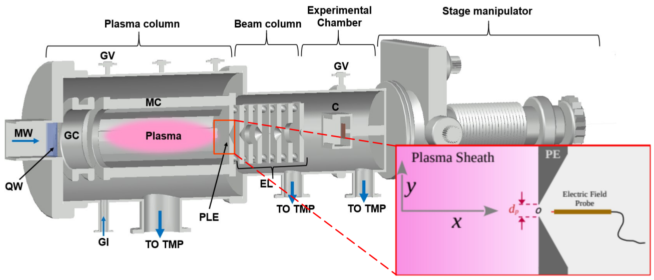

Figure 1: Schematic diagram for measuring penetrated sheath electric fields in a microwave plasma-based ion beam system [1].

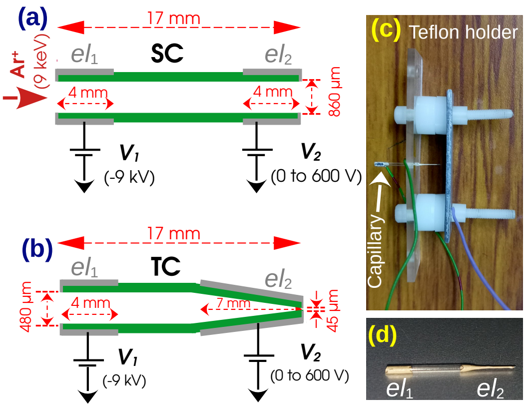

Figure 2: Schematic diagram of (a) straight (SC) and (b) tapered (TC) capillaries. (c) Digital image of the capillary attachment system. (d) Digital image of a tapered capillary.

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