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The spatial profile of density in electron beam generated plasmas ☆

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ABSTRACT

In electron beam generated plasmas, plasma generation is confined to the beam volume and is largely independent of reactor geometry. When the beam is magnetically confined, these plasmas exhibit excellent uniformity along the axis of beam propagation but have highly non-uniform charged particle density profiles normal to the beam axis. The structure of this spatial profile is driven by plasma chemistry and diffusion. This article explores the spatial variation of plasma density in different gas backgrounds as a means to separate the role of diffusion from electron/ion recombination in these systems. Small relative concentrations of molecular gas (H_2/CH_4) added to noble gas backgrounds are found to dramatically affect the spatial plasma density profile due to the effect of electron/ion recombination. Diffusion in different noble gases is treated in detail, with attention paid to the role of ion mass and electron temperature. Changes in ion mass affect the spatial plasma density profile by altering the ion mass term of the ambipolar diffusion coefficient. In addition spatial variation in electron temperature also strongly influences the ambipolar diffusion coefficient by changing the electron/neutral collision frequency.

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1. Introduction

Electron beam-generated plasmas are characterized by a low electron temperature (kT_e < 1 eV), high plasma density (n_e ~ 10^{10}-10^{12} cm^{-3}), and low ion kinetic energies (3–5 eV) [1] at adjacent surfaces. These characteristics are relevant to a number of plasma processing applications, such as atomic layer etching [2], plasma processing of thin polymeric films [3,4], and carbon films [5–8]. The inherently low kT_e in electron beam generated plasmas and their resulting low ion kinetic energies have been discussed in a number of works [9–12]. There are however, other aspects of these plasmas that provide enhanced flexibility in processing applications. For example the localized ionization source provided by the electron beam gives the user the ability to control the flux density and species ratios by varying the distance between the workpiece and the beam [13,14]. In this work we utilize a versatile steady state electron beam source to examine the spatial variation of plasma density profiles using Langmuir probes and RF based probes. Attention will be paid to the relative effects of diffusion and electron–ion recombination in shaping the spatial profile of electron beam generated plasmas, and in the case of diffusion, the effects of varying ion mass and electron temperature on the diffusion rate will be explored.

2. Experimental setup

2.1. Diagnostics chamber

To avoid the time-dependencies associated with the plasma parameters in pulsed e-beam systems, a continuous wave (CW) system has been constructed. The measurements obtained in this system are considered analogous to the steady-state phase of the pulsed e-beam system at comparable anode voltage, beam current, and chamber pressure. The CW source measurements here were performed in a stainless steel vacuum vessel enclosed by magnetic field coils that produce a uniform axial magnetic field within the chamber. The vacuum chamber houses a hollow-cathode electron beam source, a termination anode for the electron beam, a Langmuir probe, and RF based probe diagnostics consisting of a wave-cutoff probe [15] and an LC resonance probe [16]. All probes are mounted on linear motion feed-throughs. The electron beam source consists of a hollow-cathode discharge held a few hundred volts negative with respect to a semi-transparent anode screen. The screen has a relatively high optical transparency of 30%, allowing about 25% of the hollow cathode current to enter an acceleration region in the form of an electron beam. The anode screen is biased negatively with respect to a slotted grounded anode so that electrons extracted from the hollow cathode discharge are accelerated to high energy. Importantly, this configuration allows the beam current to be varied independent of the background pressure and the acceleration voltage, because the hollow-cathode voltage independently controls the beam current. Electron sources with both circular and linear slot exit apertures have been constructed to produce electron beams with either cylindrical or slab geometry respectively. A diagram of the experimental

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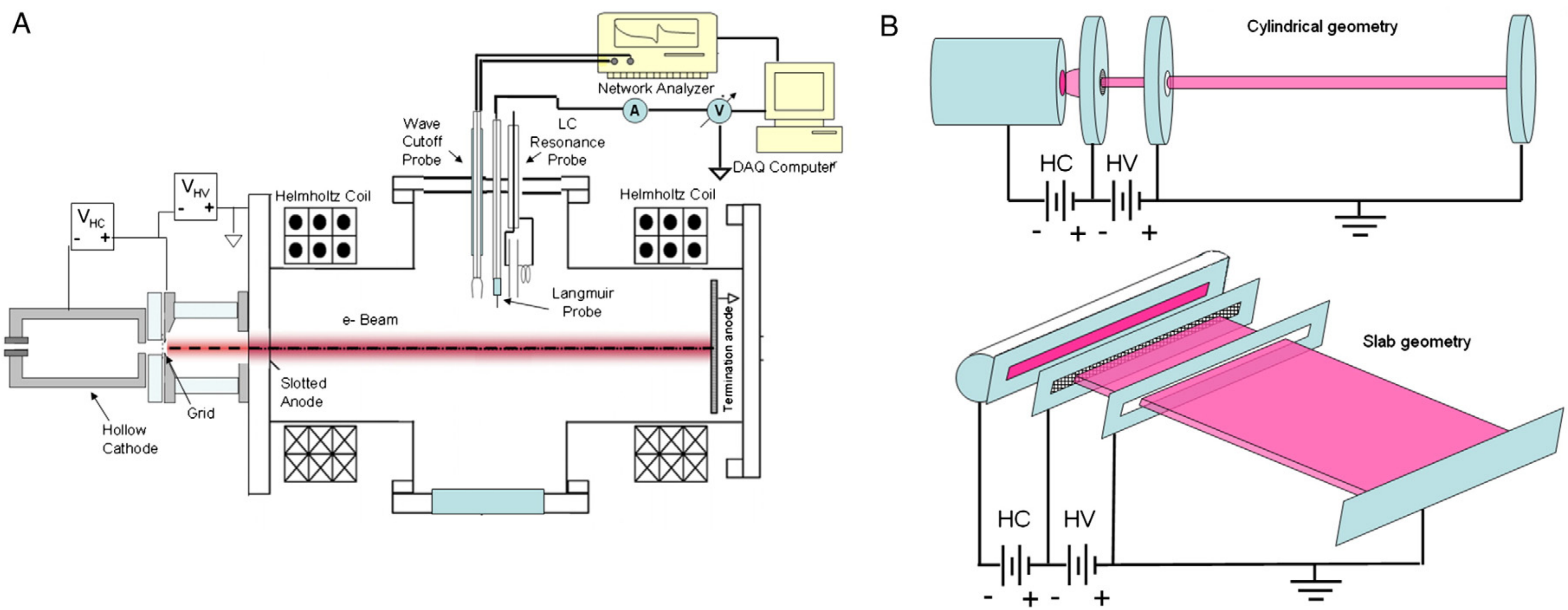

Fig. 1. Experimental setup (A) for the CW electron beam system and diagnostics. Illustrations of the electrode configurations for cylindrical (B — top right) and slab (B — bottom right) geometry.