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Bandwidth Structure of Growth Rate of Two-Stream Instability of An Electron Beam Propagating In A Bounded Plasma

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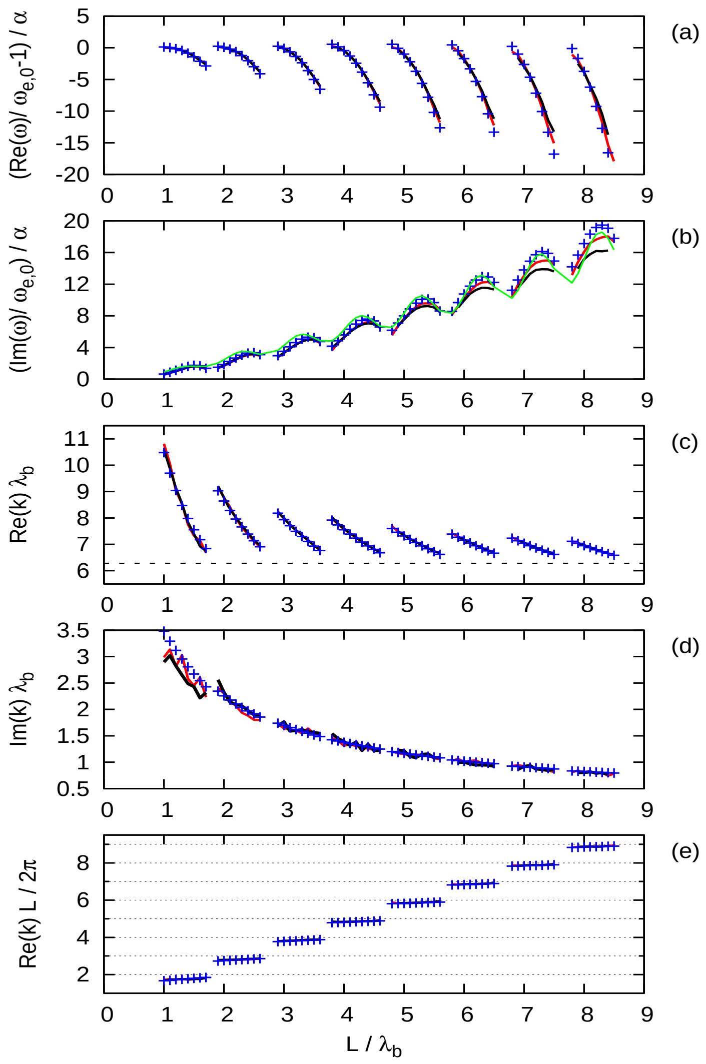

Figure 1 – (a) Frequency, (b) growth rate, (c) wavenumber, (d) spatial growth rate, and (e) the number of wave periods per system length versus the length of the system. Blue crosses are analytical solution. Solid red and black curves are (red) n_b/n_p= 0.00015 and (black) n_b/n_p = 0.0006 (black). In (b), the solid green curve is the fitting formula. In Fig. (c), the black dashed line is the resonant wavenumber.

The two-stream instability of an electron beam propagating in finite-size plasma placed between two electrodes was studied analytically and numerically using PIC simulations. We found that the growth rate of the instability in such a system smaller than that in infinite plasma or finite size plasma with periodic boundary conditions. Even if the width of the plasma matches the resonance condition for standing waves, standing waves do not develop. Instead, the wave transforms into spatially growing wave, whose growth rate is small compared to that of a standing wave in a system with periodic boundary conditions. This growth rate is approximately described by

$$g \approx \frac{w_{pe} n_b L}{13 n_p v_b} \ln\left(\frac{L w_{pe}}{v_b}\right),$$

where w_{pe} is the electron plasma frequency, n_b and n_p are beam and plasma densities, v_b is the beam velocity and L is the plasma width. The frequency and growth rate as a function of plasma width form a bandwidth structure. The parameters of the instability are in Fig. 1 and are very different from a conventional infinite or periodic system.

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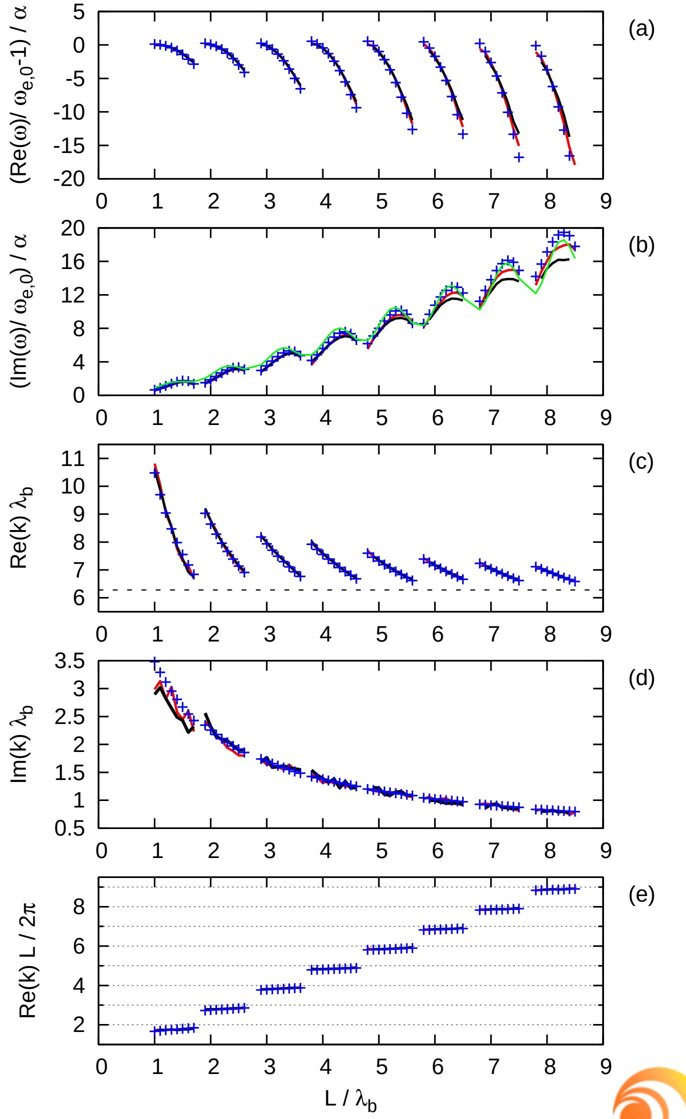
TWO-STREAM INSTABILITY OF AN ELECTRON BEAM PROPAGATING IN A BOUNDED PLASMA



- **Electron beams propagating in a bounded plasma excite a two-stream instability. An analytical model was developed to predict instability growth rates. (Invited talk, 2015 APS-DPP Meeting)**
- **Comparisons were made to PIC simulations of injected e-beam into bounded systems.**
- **Instabilities in bounded systems have slower growth rates and do not develop standing waves.**
- **Figure shows (a) frequency, (b) growth rate, (c) wavenumber, (d) spatial growth rate, and (e) wave periods per system length vs length of the system.**
- **+ = analytical solution, — = n_b/n_p= 0.00015 — = n_b/n_p= 0.0006, — fitting formula, Fig. (c), --- resonant wavenumber.**

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DC Particle-in-cell (PIC) Simulations of Atmospheric Pressure Argon Discharges

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Atmospheric pressure plasma discharges in contact with liquid surfaces are of increasing interest, especially in the bio-medical field. Our computational investigation of these devices is motivated by the experimental results of Rumbach et al. (2015) [1] who reported the presence of hydrated electrons just below the surface of water acting as anode to an atmospheric pressure argon dc discharge. The gas phase plasma in this study was modeled using 1D3v Particle-in-cell (PIC) simulations. To match the experiments by Rumbach, the plasma was assumed to be pure argon, operated at atmospheric pressure (760 Torr) and 300 K. The discharge length was 2 mm, a negative dc current of magnitude $J = 4 \times 10^4$ A/m^2 was applied at the cathode (LHS electrode at x = 0), and we assumed an ion induced secondary electron emission coefficient of 0.15. We neglected any effects the liquid electrolyte has on the plasma and treated the plasma-water boundary as a grounded anode (RHS electrode at x = 2 mm). In this case, the PIC results show that a peak in positive ion density occurs near the cathode and that the plasma density is $\approx 2 \times 10^{19}$ m^{-3} for most of the domain. The cathode fall voltage is about 300 V, and the electric field in the bulk plasma region is nearly independent of position at about 1.5×10^5 V/m. The electric field is larger at the water anode surface ($\approx 6.5 \times 10^5$ V/m) and accelerates electrons to the surface. Results from the PIC simulation for the electric field at the water anode surface are shown in Fig. 1a as a function of input current density J. For larger currents ($J > 1000$ A/m^2), electron diffusion alone cannot satisfy current continuity under atmospheric pressure conditions, and an electric field develops to accelerate electrons into the surface. The electron energy distribution at the surface for $J = 4 \times 10^4$ A/m^2 is shown in Fig. 1b. Most electrons impact the water surface with energies between 5 and 12 eV due to the accelerating electric field. The relatively high electron energy suggests that there are few if any energetic barriers for electrons to enter the water and become solvated.

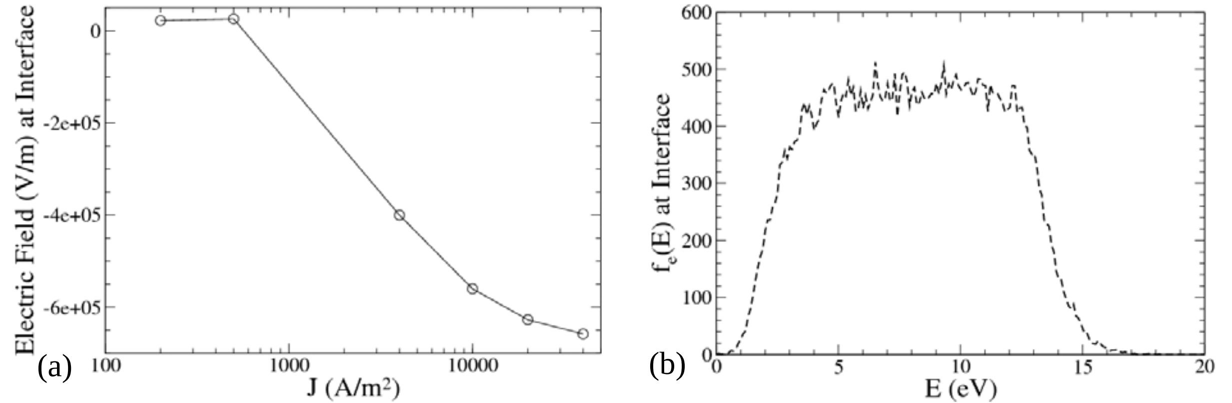

Fig. 1 – (a) E field at interface vs. J. (b) Electron energy distribution at interface for $J = 40{,}000$ A/m^2.

References

[1] P. Rumbach, D.M. Bartels, R.M. Sankaran, and D.B. Go, Nat. Commun, **6**, 7248 (2015).

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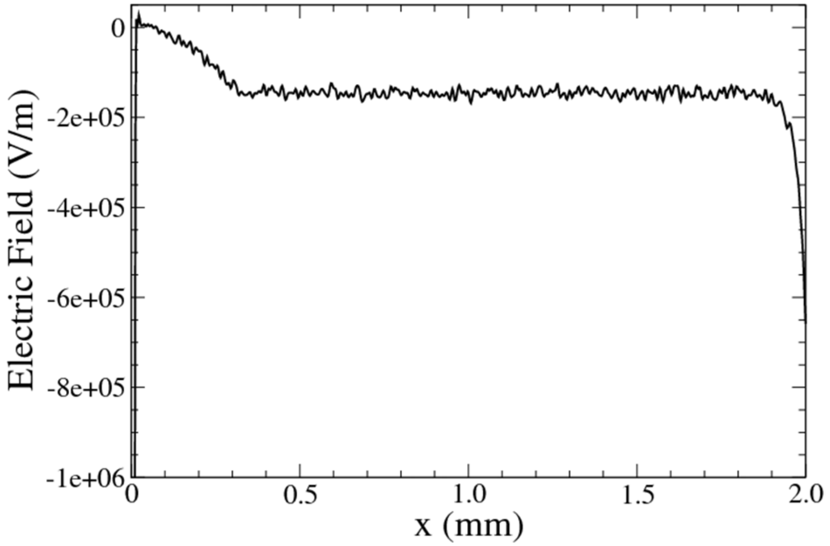
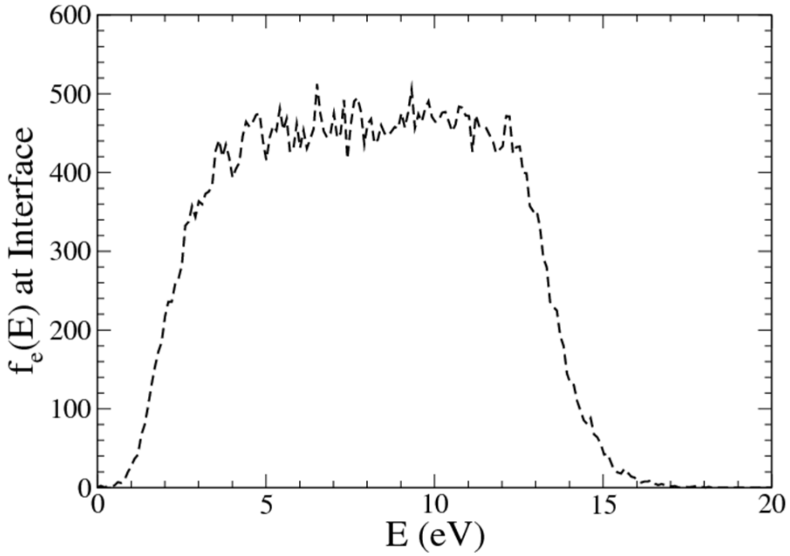
PIC SIMULATIONS OF DC ATMOSPHERIC PRESSURE ARGON DISCHARGES: WATER BOUNDARIES



- Electric field



- Electron energy to water/anode surface

- **A 760 Torr, 300 K argon discharge, 2 mm gap, was modeled using 1D3v PIC simulations. A dc current of -40 kA/m^2 was applied at the cathode (x=0). The plasma-water boundary is treated as a grounded anode (x=2 mm).**
- **Electron diffusion is insufficient to satisfy current continuity at 1 atm. An electric field forms to accelerate electrons to the anode water surface.**
- **The relatively high electron impact energy onto water suggests there are few if any energetic barriers for electrons to enter the water and become solvated.**

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