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Electron-beam formation and resonances in a symmetric low pressure capacitively coupled plasma

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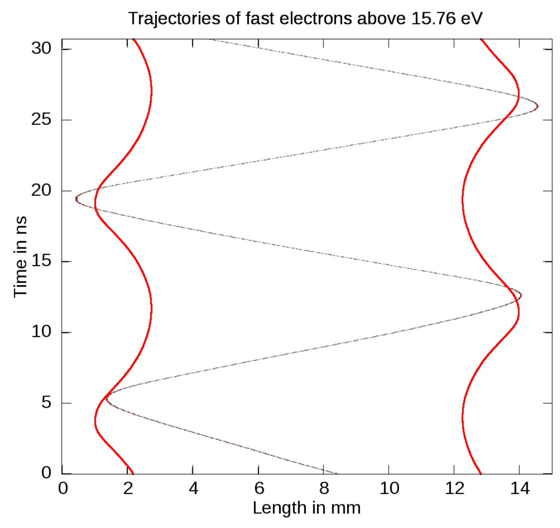
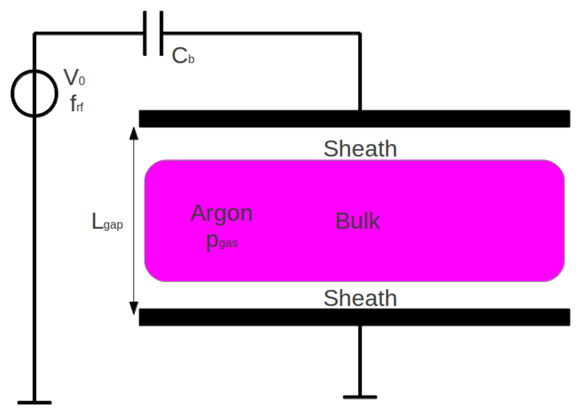
Motivation

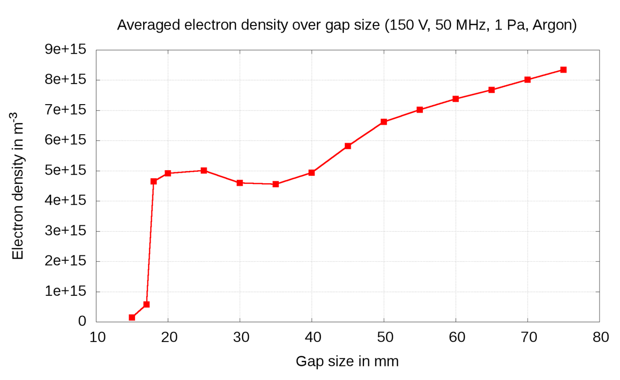
In low pressure capacitively coupled radio-frequency discharges electron heating is dominated by stochastic heating. In this regime electron reflection from the modulated plasma sheaths can produce highly energetic electron beams, which traverse through the plasma bulk, with small probability to undergo a collision and interact with the opposite sheath. By varying the driving frequency and/or the gap size of the discharge, the beams reach the opposite sheath edge at different temporal phases. Electrons can be decelerated if they reach the collapsing phase, they can be accelerated back with higher energies if they impinge the expanding phase or electrons may have enough energy to overcome the sheath potential, thus they will be lost at the electrode. In order to investigate and evaluate the electron beam formation, Particle-In-Cell/Monte-Carlo Collision (PIC/MCC) models have benefits to get self-consistent and accurate solutions of plasma discharges with an acceptable calculation time. For this work the serial 1d3v PIC code *yapic* (benchmarked[1]) is used to study a gap size and frequency variation for a symmetric CCP reactor. An argon chemistry with three electron-neutral and two ion-neutral collisions is considered (JILA database[2]). The dynamics of electron beams can be best visualized by plotting the spatio-temporal distribution of electrons with an energy above 15.76 eV (the ionization threshold of argon). The white lines indicate the plasma sheath edge.



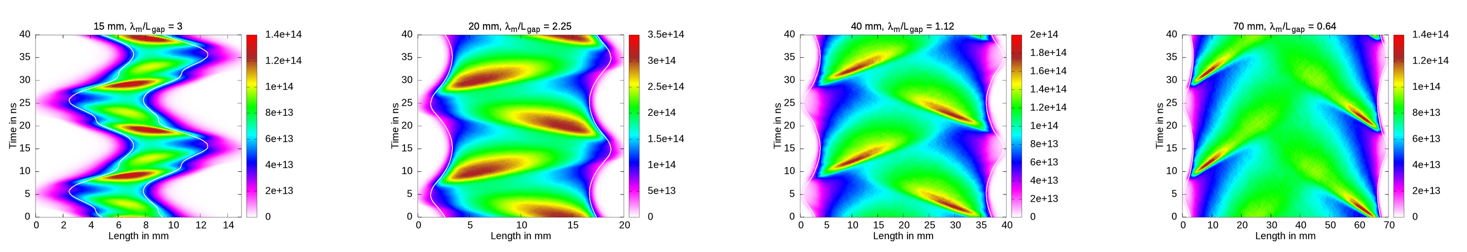


Electron-beam interaction

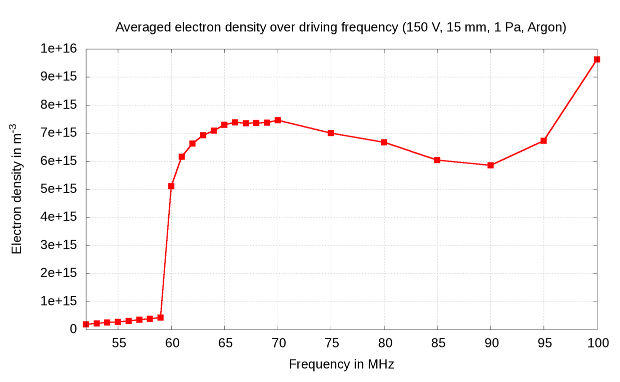
Gap size variation



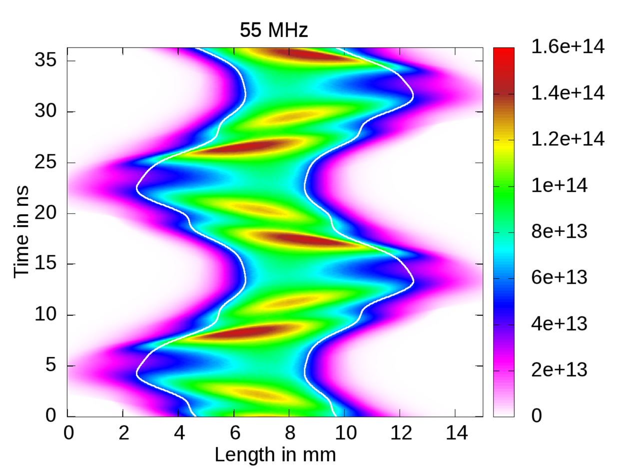
- beam interaction is important for $\lambda_m > L_{gap}$
- with decreasing gap size the impingement phase at the opposite sheath is changing from the expanding to the collapsing phase with a density mode transition
- Bounce-Resonance-Effect[3] occurs around 20 mm
- electron density decreases abruptly at 18 mm



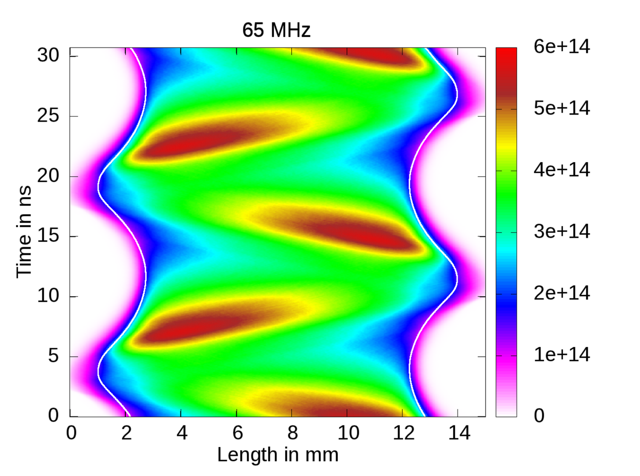
Frequency variation



- $\frac{\lambda_m}{L_{gap}} \approx \frac{45\text{ mm}}{15\text{ mm}} = 3$
- with decreasing frequency the overall periodicity of the discharge and as such the moment of impingement changes
- again, the discharge switches abruptly from a low-density mode to a high density mode
- the transition occurs when the impingement changes from the collapsing to the expanding phase



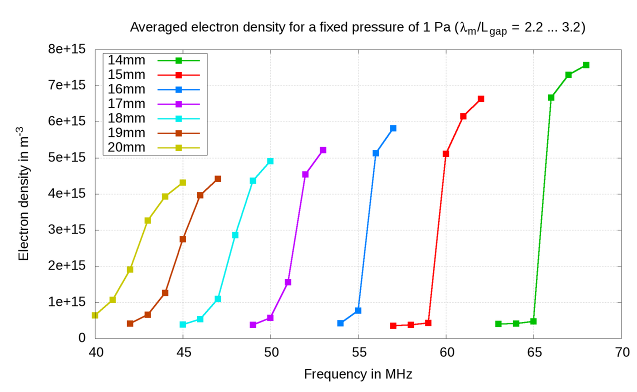
- energy loss mechanism for fast electrons is essential
- deceleration of electrons due to the decreasing sheath potential
- more highly energetic electrons can overcome the electric field potential and lose their energy at the wall

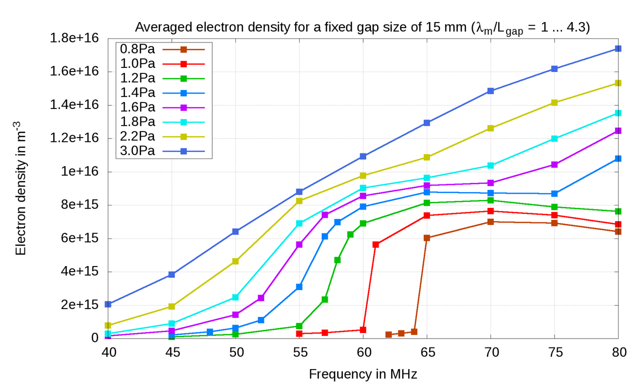


- electrons gain additional energy during the expansion which leads to a significant ionization and excitation enhancement
- better confinement of energetic electrons

Abrupt mode transition

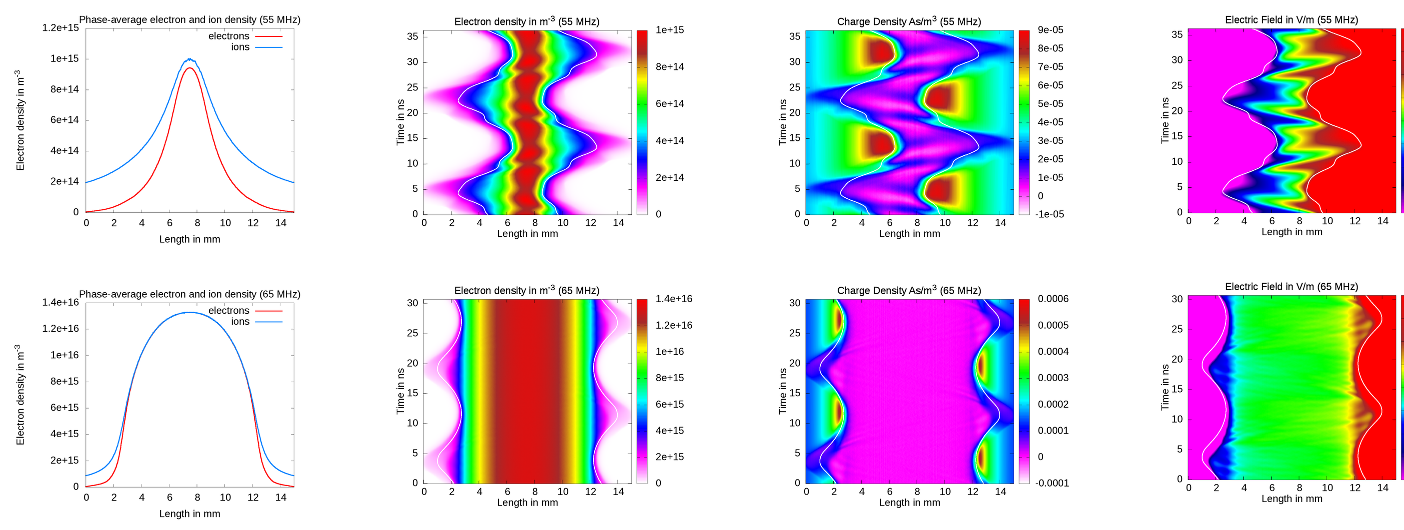
Particularly for a certain combination of gap size, driving frequency and pressure, the electron beams have the characteristic to be practically mono energetic. Therefore, the transition between reaching the collapsing or expanding phase can be very abrupt, if the beam electrons are not scattered. The corresponding factor is the relation between the electron mean free path and the gap size λ_m/L_{gap}. A slight change of the gap size or the pressure affects the electron beam interaction with the neutrals. Thus the beam is more diffuse and the transition will be smoother.





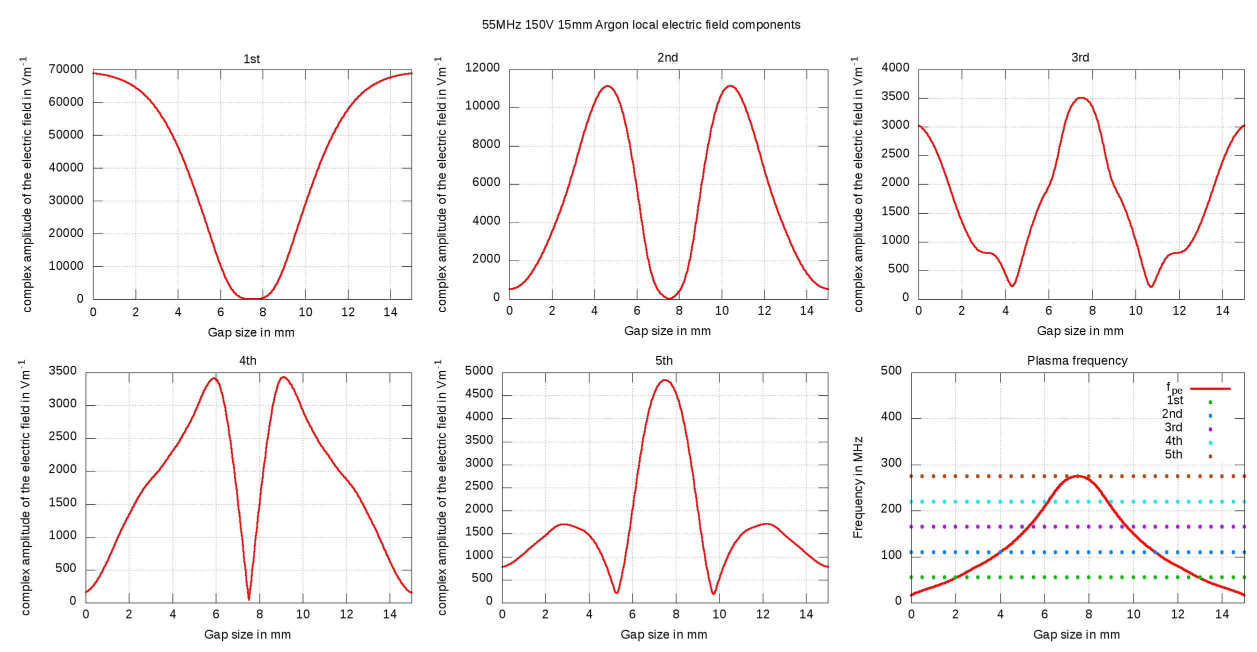
Electron-beam formation

An additional observation is the appearance of a second beam formation, once the plasma density reaches a low value (for example the 55 MHz case from the frequency variation). The acceleration of electron beams causes a perturbation in the center of the discharge. Thus the quasi-neutrality is not satisfied on average. A positive charge density occurs in a temporal cycle between the motion of both electron beams which leads to local electric fields in the plasma bulk. In contrast the high-density mode (65 MHz) indicates just one electron beam formation which does not violate the quasi-neutrality in the plasma bulk.



According to the Fourier spectra of the local electric fields, the amplitudes of the first five harmonics over the gap size are shown. The maxima of the electric field amplitudes are an indication, that the local plasma frequency intersects a higher harmonic of the driving frequency.

$$E(x,t) = \frac{E_0(x,t)}{2} + \sum_{n=1}^{\infty} E_n(x,t)\, e^{-i\varphi_n(x)} e^{in2\pi f_{rf} t}, \qquad f_{pe}(x) = \frac{1}{2\pi}\sqrt{\frac{n_e(x)e^2}{\varepsilon_0 m_e}}$$



References and Acknowledgment

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