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Nonlinear Electron Resonance Heating in Asymmetric Capacitive Discharges

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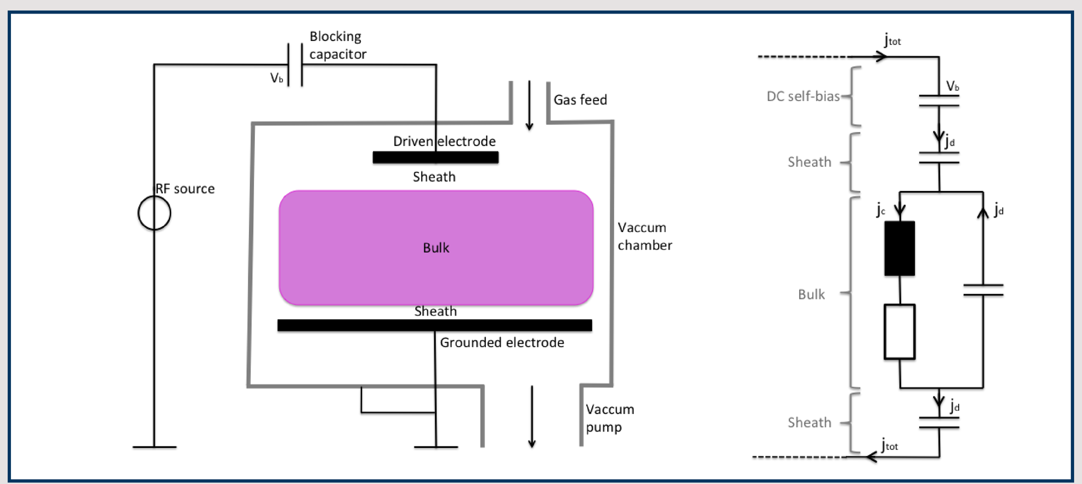
Abstract: In low-pressure capacitive discharges the concept of Nonlinear Electron Resonance Heating (NERH) becomes important to enhance Ohmic dissipation. Particularly in geometrically asymmetric capacitive discharges (generation of a DC self-bias), the nonlinearities of the boundary plasma sheaths lead to a strongly non-sinusoidal radio frequency current. The Fourier spectra of such a current can indicate harmonics which are in resonance with the Plasma Series Resonance (PSR). The scenario of PSR was investigated by different models (e.g. zero-dimensional, spatially resolved), which assume that the bulk current is carried by the electron current and the sheath current by the displacement current. Although these models are able to resolve the nonlinear behavior between bulk and sheath a detailed kinetic picture is missing. In this work, we discuss the particle dynamics in the regime of NERH on a nanosecond timescale by means of a self-consistent kinetic simulation. We use a 1d3v spherical Particle-In-Cell code in order to simulate an asymmetric discharge. It is shown that the excitation of harmonics is connected to the generation of multiple electron beams accelerated by the expanding plasma sheath. Furthermore, the interaction of these beams with bulk electrons leads to significant plasma oscillations and thus, to a moderate displacement current in the center of the discharge. These kinetic effects should be taken into account for future models in order to understand the comprehensive electron heating in capacitive discharges.

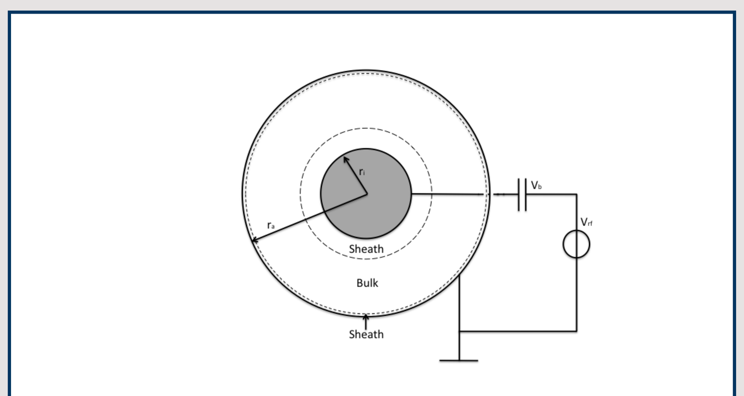
Asymmetric CCRF Discharge

- larger grounded electrode (reactor wall naturally grounded)
- dc self bias generation
- series and parallel resonances [1,2]
- $\omega_{psr} = \omega_{pe}\sqrt{\frac{2s}{L}}$
- $\omega_{ppr} = \omega_{pe}$
- Non-linear Electron Resonance Heating (NERH)[3]

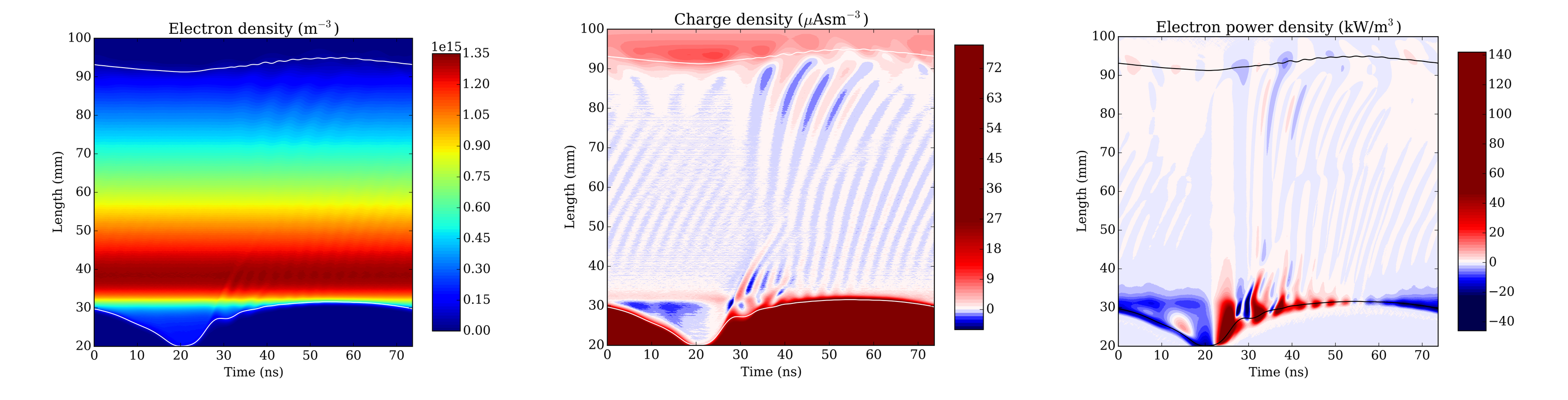


Particle-In-Cell Simulation

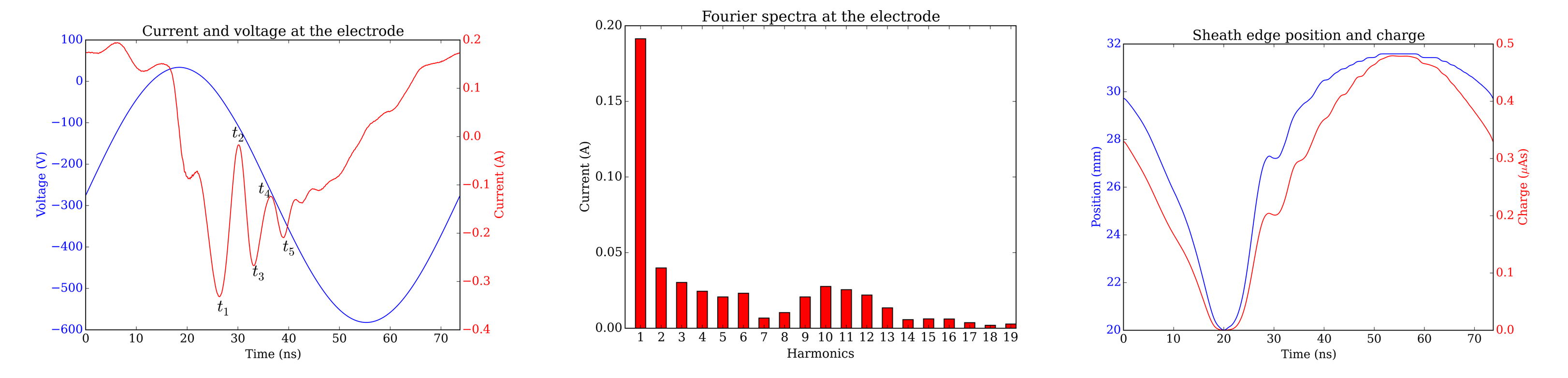
- 1d3v PIC simulation, spherical shell model[2][4]
- argon chemistry: 3 electron-neutral (elastic, excitation, ionization) and 2 ion-neutral (isotropic, backward elastic scattering) collisions
- base case setup:
  - V_{rf} = 300 V, $\omega_{rf} = 2\pi \cdot 13.56$ MHz , p = 1 Pa = 7.5 mTorr
  - r_i = 20 mm, r_a = 100 mm, r_a - r_i = 80 mm gap size
  - electrode area ratio $A_a/A_i \approx 25.01$, C_b = 0.3 nF



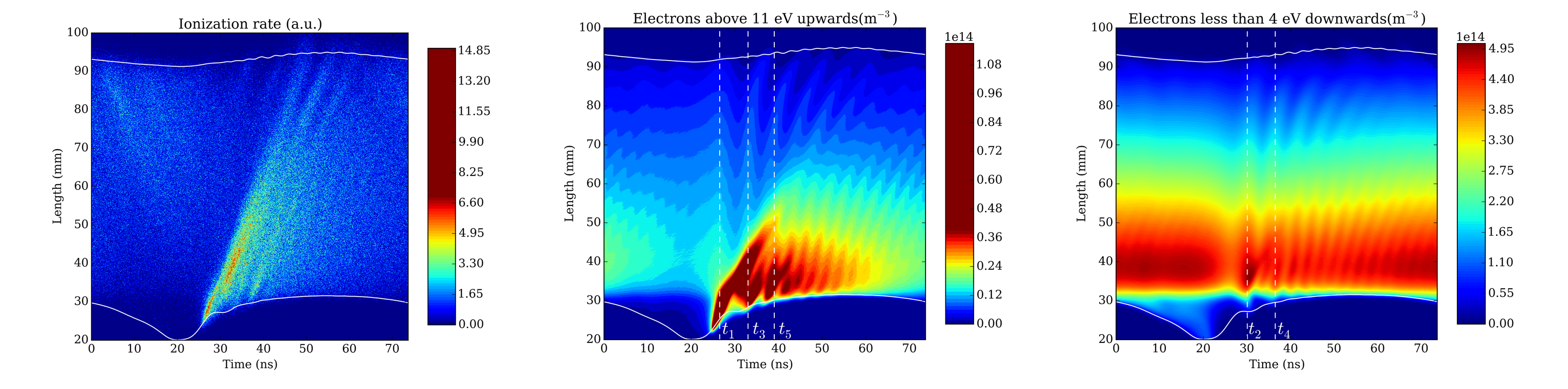
Base Case



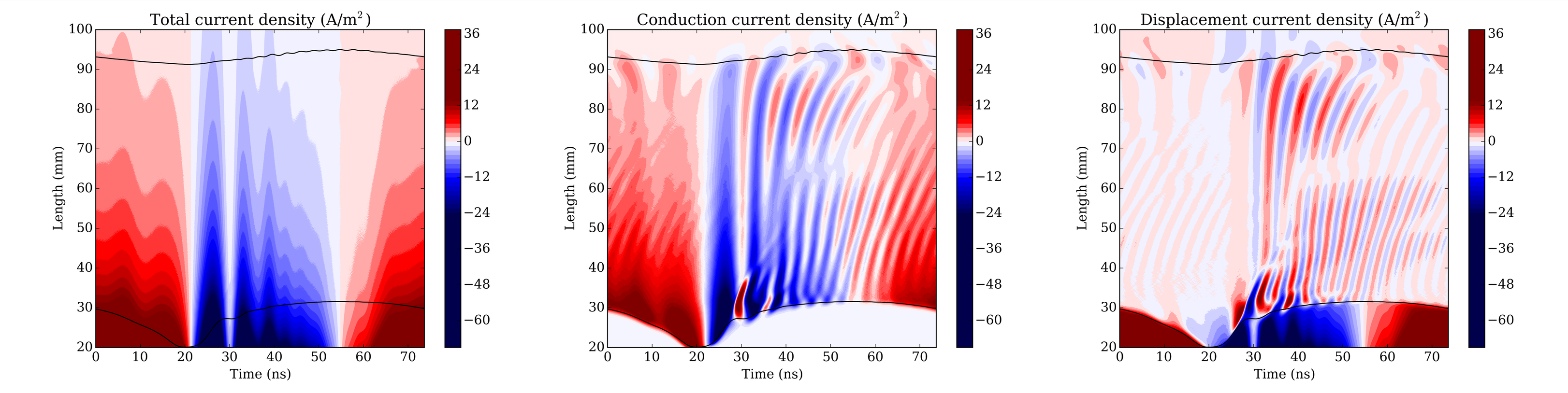
- significant charge densities in the bulk due to electron modulation (ions constant over time)



- harmonic oscillation in the rf current $\Longrightarrow$ excitation of plasma series resonance



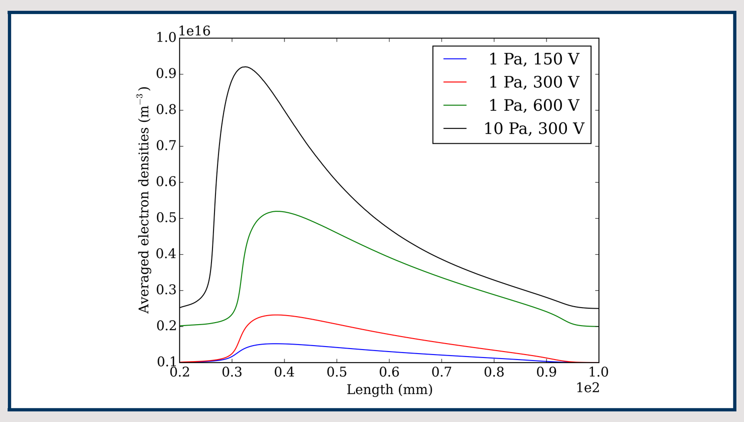
- electron beam penetrates into the bulk and cold bulk electrons are accelerated back to the expanding sheath



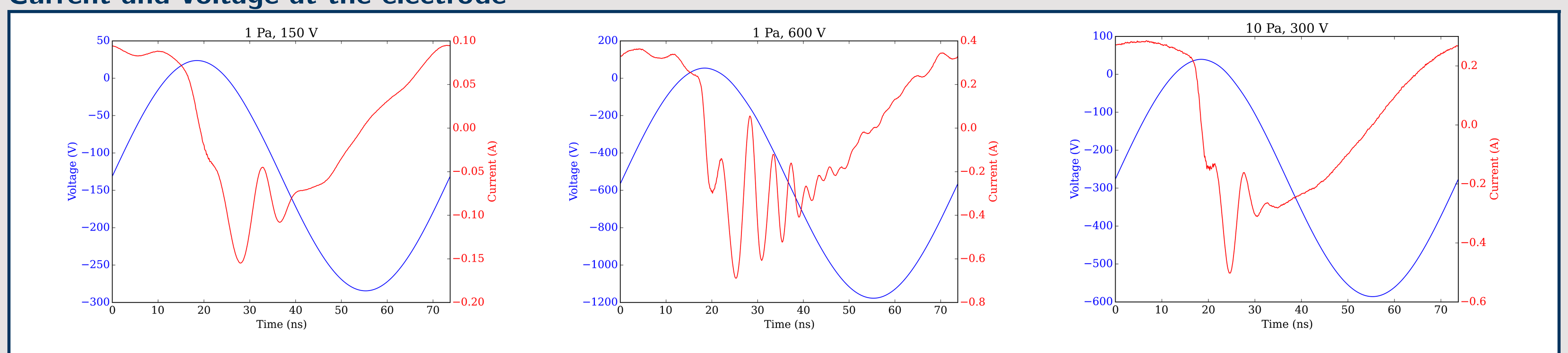
- current conservation must be ensured $\nabla \cdot j_{tot} = \nabla \cdot (j_c + j_d) = 0$

Parameter Variation

- ↑ voltage ⇒ ↑ ionization ⇒ ↑ n_e ⇒ ↑ ω_{pe} ⇒ ↓ $\tau_{pe} = 2\pi/\omega_{pe}$
- electrons respond to local perturbations on faster timescales
- excitation of higher harmonics is possible
- higher pressure damps the nonlinear excitation
- sheath edge criterion [5]: $\int_0^{s(t)} n_i(x)dx = \int_{s(t)}^{\infty} (n_i(x) - n_e(x))dx$

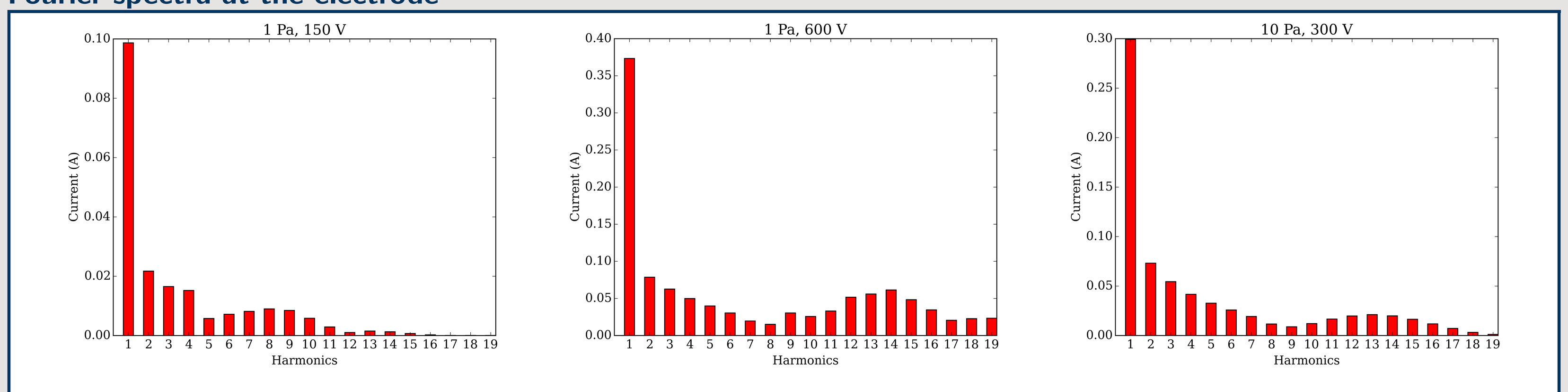


Current and voltage at the electrode



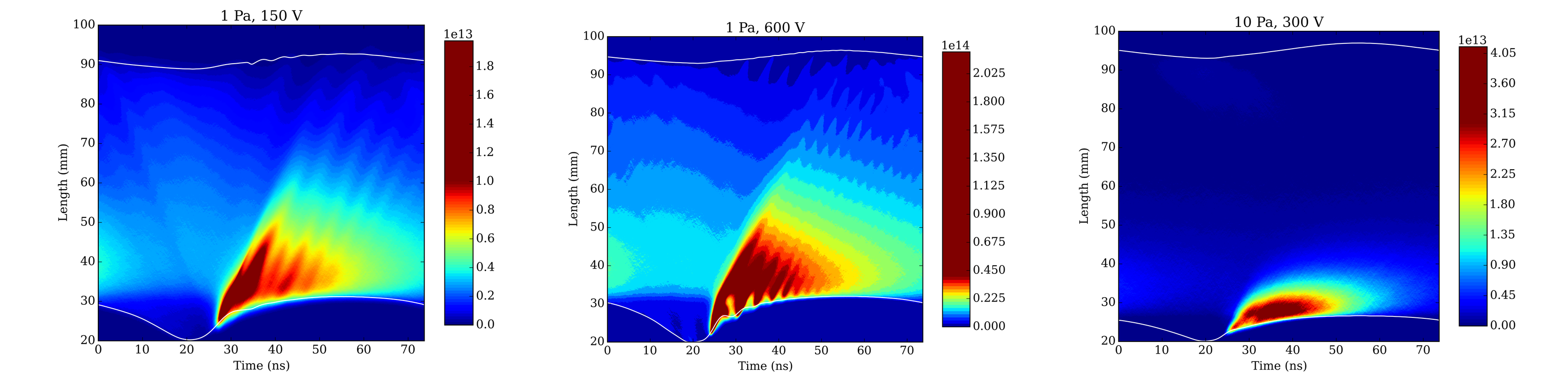
- stronger oscillation for higher voltages, oscillations are damped for higher pressures

Fourier spectra at the electrode



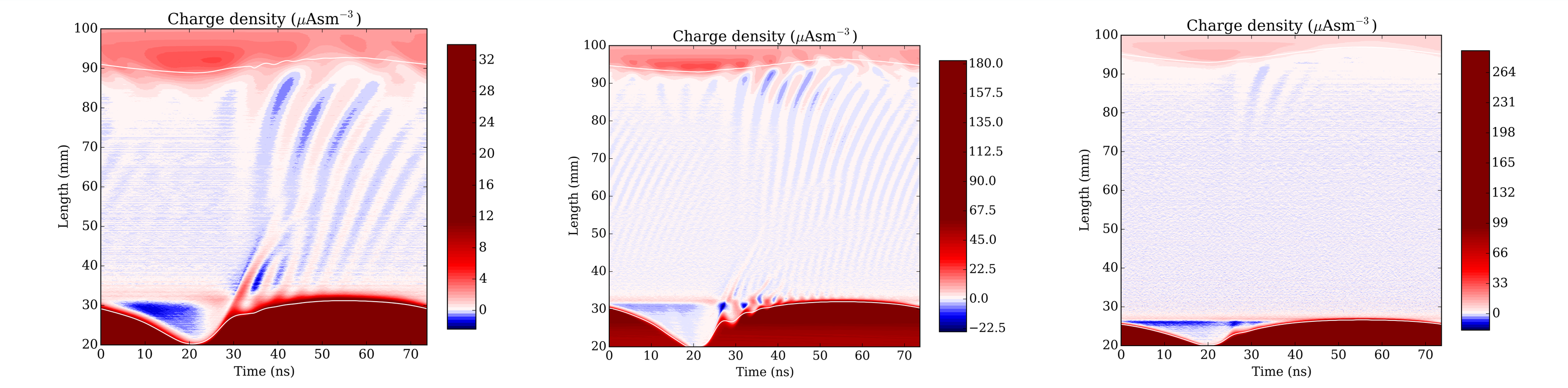
- series resonance is shifted and damped for higher pressures

Electrons above 15.76 eV in m^{-3}



- number of electron beams changes

Charge density in μAsm^{-3}



- charge density in the bulk region vanishes for higher pressures

Conclusion

- kinetic analysis is required in order to understand local kinetic phenomena which lead to resonance effects
- local interaction between energetic beam electrons and cold bulk electrons $\Longrightarrow$ (bulk) electron-sheath interaction [6]
- displacement current in the bulk region exist due to this interaction

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