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Physical Origin of Non-Linear Resonant Excitation in Capacitively Coupled Plasmas

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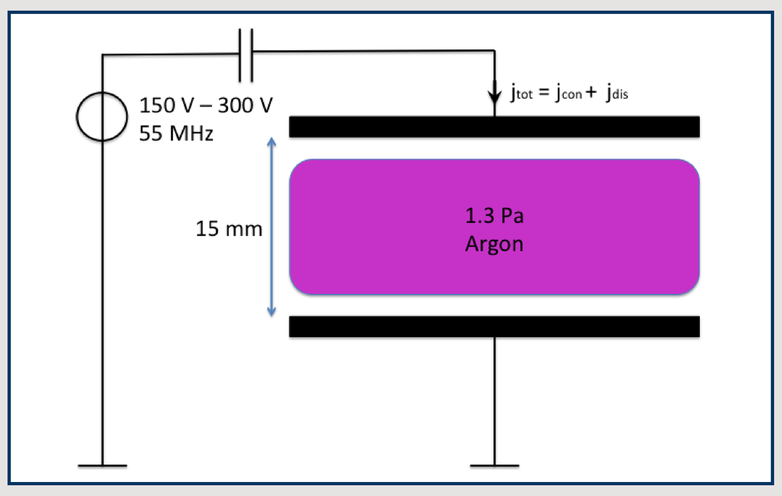
Motivation

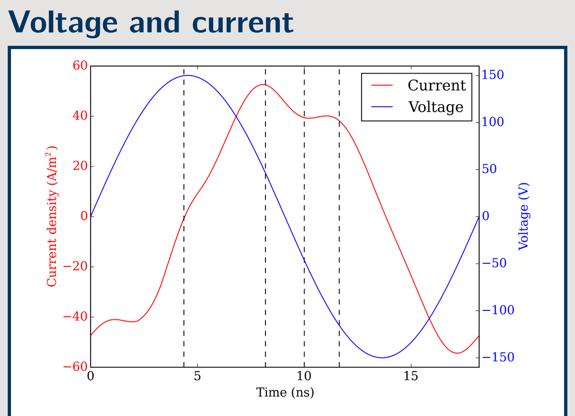
In low-pressure capacitively coupled radio frequency (RF) discharges, non-linear electron resonance heating is still not fully understood. In order to explain the exact mechanism of the excitation of higher harmonics in the RF-current a detailed kinetic description of the electron dynamics must be developed. In this work, the analysis of the spatio-temporal electron velocity distribution function using Particle-in-Cell/Monte Carlo Collisions simulations is presented. A single-frequency capacitively coupled discharge operated in argon at a pressure of 1.3 Pa is characterized. At this low pressure, the plasma sheaths accelerate energetic electron beams. These traverse through the plasma bulk almost collisionlessly and leave behind a positive space charge close to the sheath edge which generates a corresponding electric field. At this position the electric field attracts cold electrons from the plasma towards the expanding sheath. For a short time interval slow bulk electrons and energetic beam electrons move into opposite directions. Subsequently, these cold bulk electrons, which can only react on the timescale of the local plasma frequency, are repelled back into the bulk during the phase of sheath expansion forming a new energetic electron beam. This cycle continues until the end of the sheath expansion.



The effect then can lead to the generation of multiple electron beams during one RF period. Since the electron beams form the major part of the conduction current, this effect explains the excitation of higher harmonics in the rf-current. Furthermore, the conduction current appears only locally in space and time. In this context, the terminology of the Plasma Series Resonance (PSR) as well as the Plasma Parallel Resonance (PPR) can be understood within the frame of a kinetic picture.

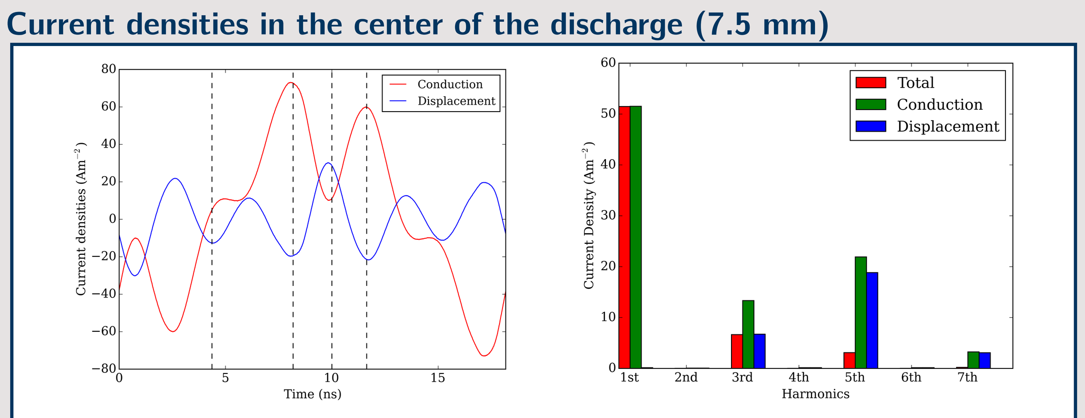
Case 1: 150 V

Voltage and current



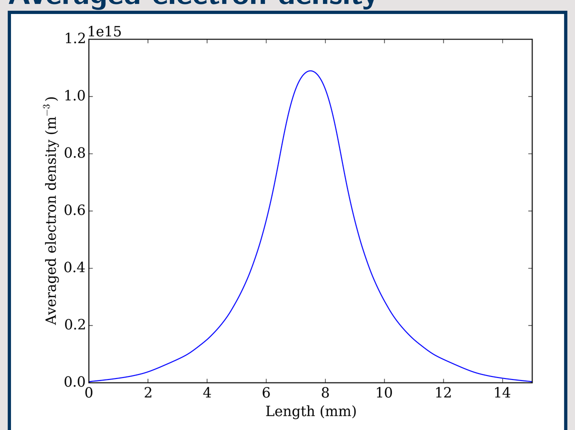
- applied sinusoidal voltage
- 90° phase shifted non-sinusoidal current

Current densities in the center of the discharge (7.5 mm)



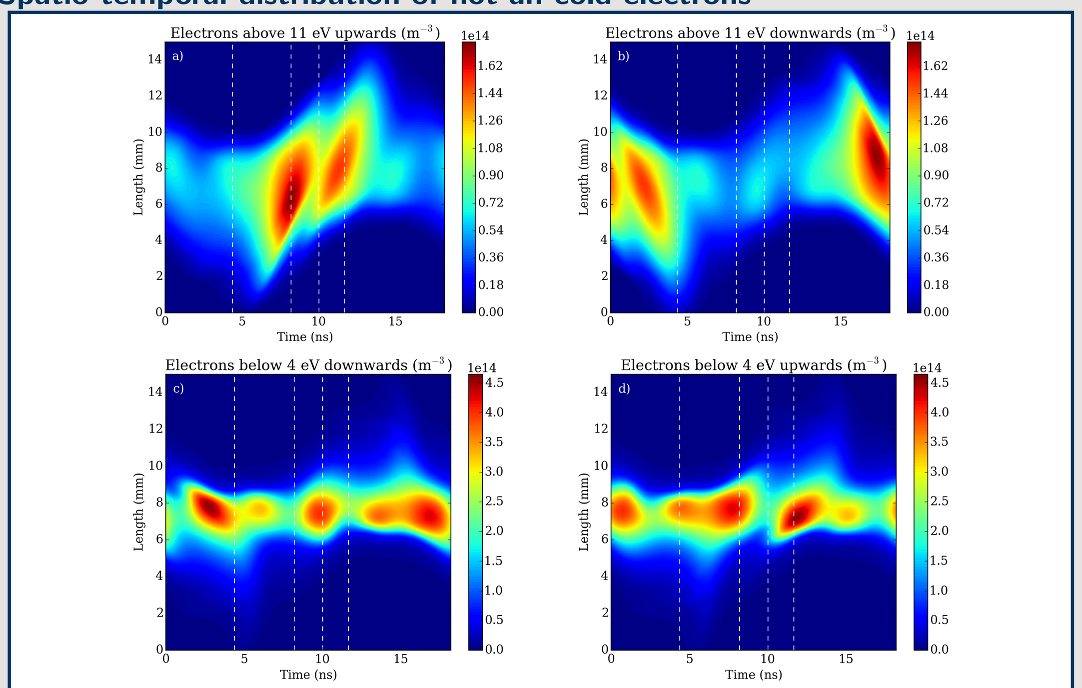
- local displacement current is shifted 180° out of phase with respect to the conduction current and compensates the conduction current
- compensation leads to harmonics in the total current

Averaged electron density



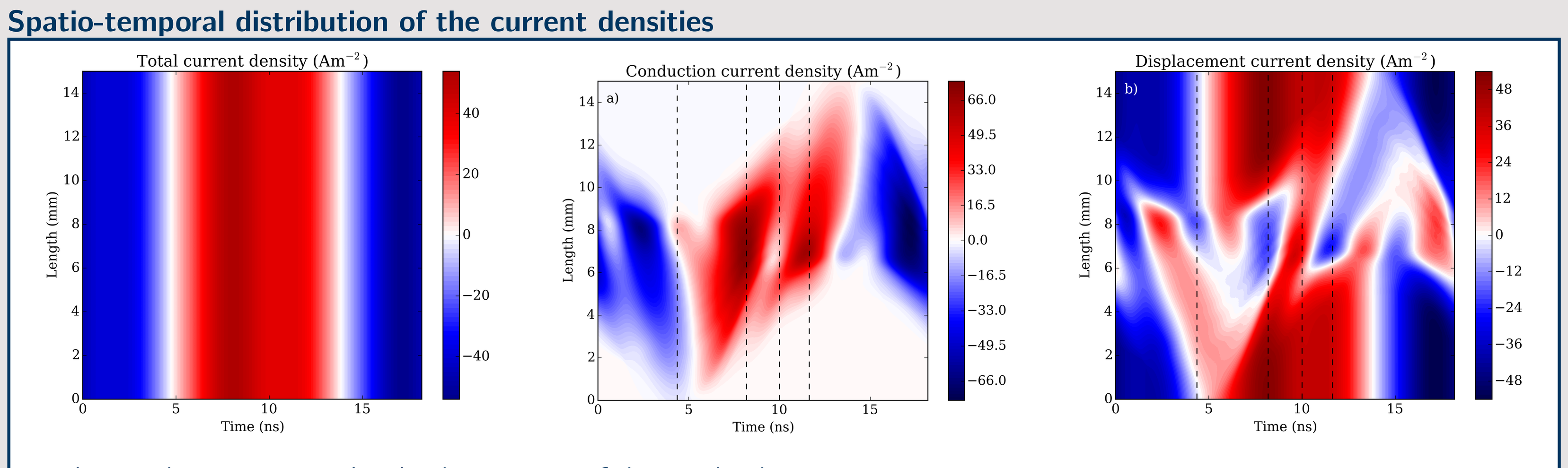
- low plasma density
- bulk density $\approx 10^{15}$ m^{-3}
- $\omega_{pe}(x) = \sqrt{\frac{n_e(x)e^2}{\varepsilon_0 m_e}} \approx 2\pi \cdot 280$ MHz
- $\omega_{pe}(x) \approx 5 \cdot \omega_{rf}$
- electrons respond on the timescale of the local plasma frequency $\tau \approx 2\pi/\omega_{pe} \approx 3.5$ ns

Spatio-temporal distribution of hot an cold electrons



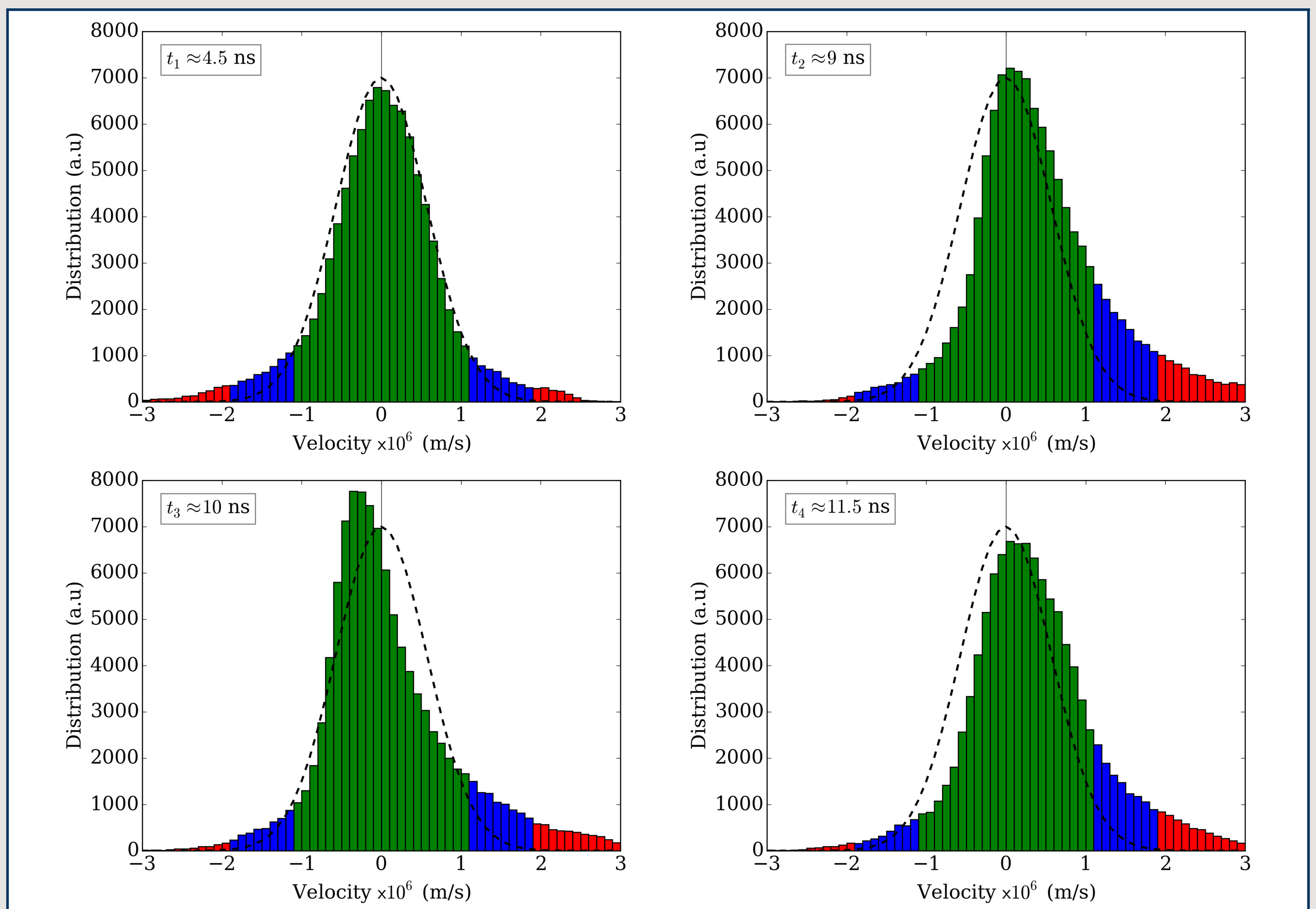
- separate the dynamic of cold ($\epsilon < 4$ eV) and hot ($\epsilon > 11$ eV) electrons
- electron beams are accelerated by the expanding plasma sheath
- bulk electrons are modulated by the local plasma frequency

Spatio-temporal distribution of the current densities



- electron beam causes a local enhancement of the conduction current
- perturbation must be compensated locally by the displacement current: $\nabla \cdot j_{tot} = \nabla \cdot (j_{con} + j_{dis}) = 0$

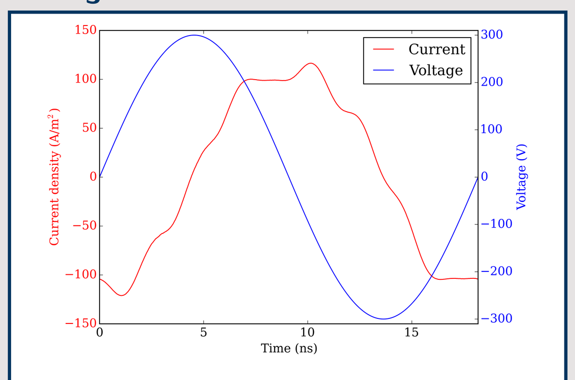
Momentary EVDF (Plasma Bulk)



- detailed kinetic description by a momentary Electron Velocity Distribution Function at the given characteristic reference times spatially averaged over the plasma bulk [6 mm $\leq x \leq$ 9 mm]
- dashed lines correspond to a fitted Maxwellian distribution
- the bars represent energy intervals: red: ϵ >11 eV, blue: 4 eV< ϵ < 11 eV, green: ϵ < 4 eV
- t_1: total current is zero and EVDF is approximately Maxwellian, t_2: first electron beam is accelerated and the EVDF becomes anisotropic, t_3: first electron beam leaves a positiv space charge behind, which attracts cold bulk electrons towards the sheath edge, t_4: these bulk electrons interact with the expanding sheath and are reflected back forming a second beam formation

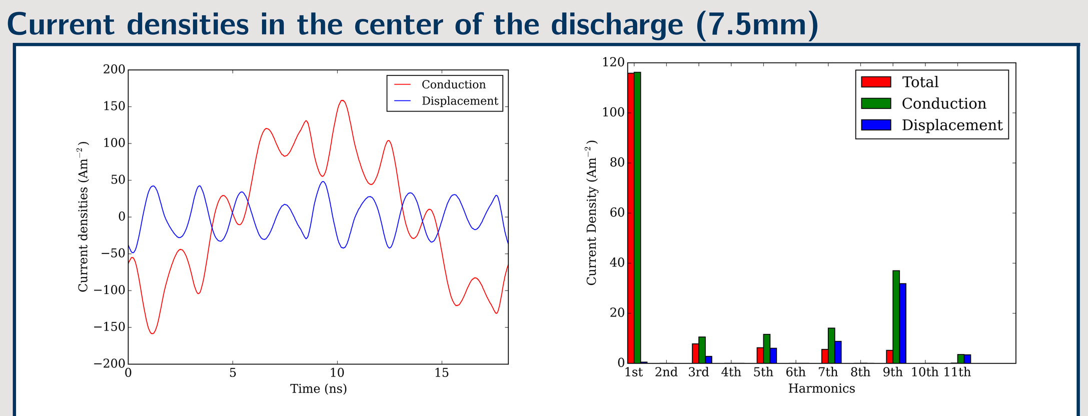
Case 2: 300 V

Voltage and Current

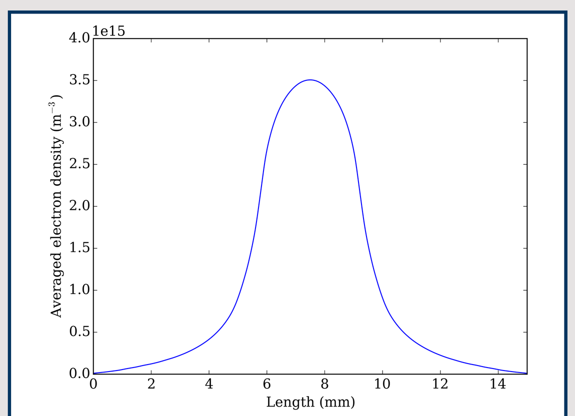


- higher voltage leads to more ionization
- current indicates higher harmonics

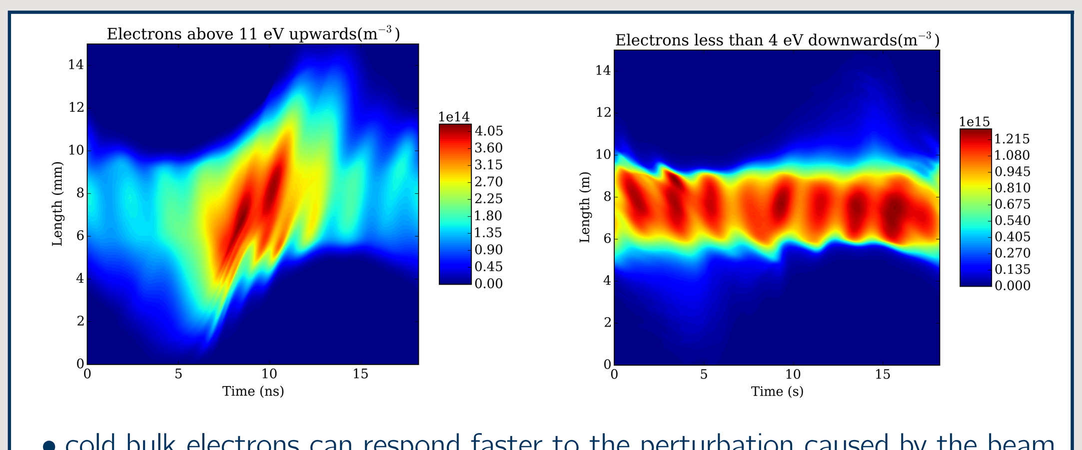
Current densities in the center of the discharge (7.5mm)



- excitation of the 9th harmonic in the current densities is presented
- displacement current tries to compensate the conduction current



- more ionization $\Rightarrow$ higher density
- $\omega_{pe}(x) \approx 2\pi \cdot 500$ MHz
- electrons respond on a faster timescale ($\tau \approx 2$ ns)



- cold bulk electrons can respond faster to the perturbation caused by the beam electrons
- the process can be repeated more often during one phase of sheath expansion
- leads to a generation of multiple electron beams and, thus, higher harmonics in the total current

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