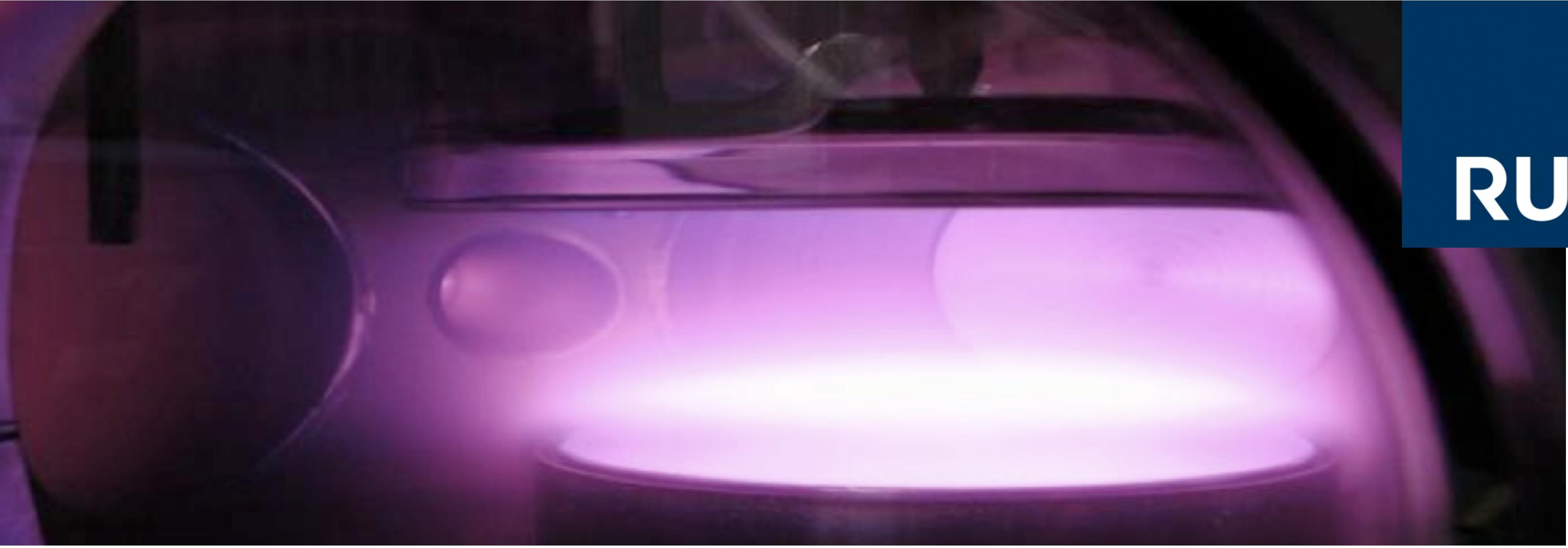

RUB

Generation of highly energetic electrons through interaction with modulated plasma sheaths

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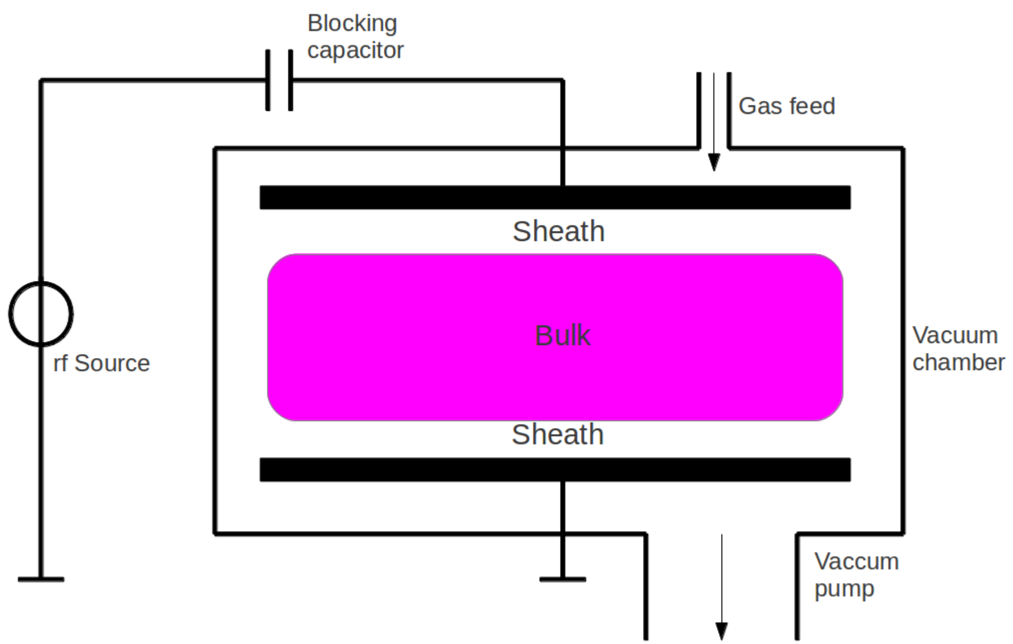
Outline

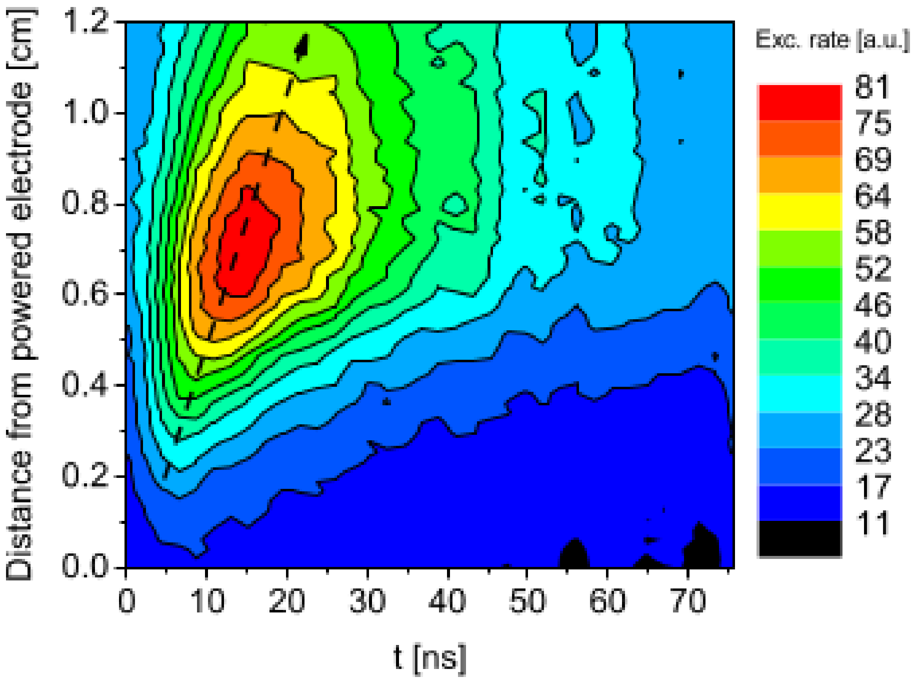
- **Motivation**
  - Electron heating in CCRF discharges
  - Highly energetic beam-like electrons
- **Particle-In-Cell simulation**
- **Results**
  - Acceleration of electron beams (3 Pa and 1.3 Pa)
  - Local resonance phenomena
- **Conclusion**

Electron heating in ccrf discharges at low pressures



- highly relevant for industrial applications
- stochastic heating is dominant (few Pascal)
- non-local and collisionless regime
- acceleration of highly energetic electron beams is very important

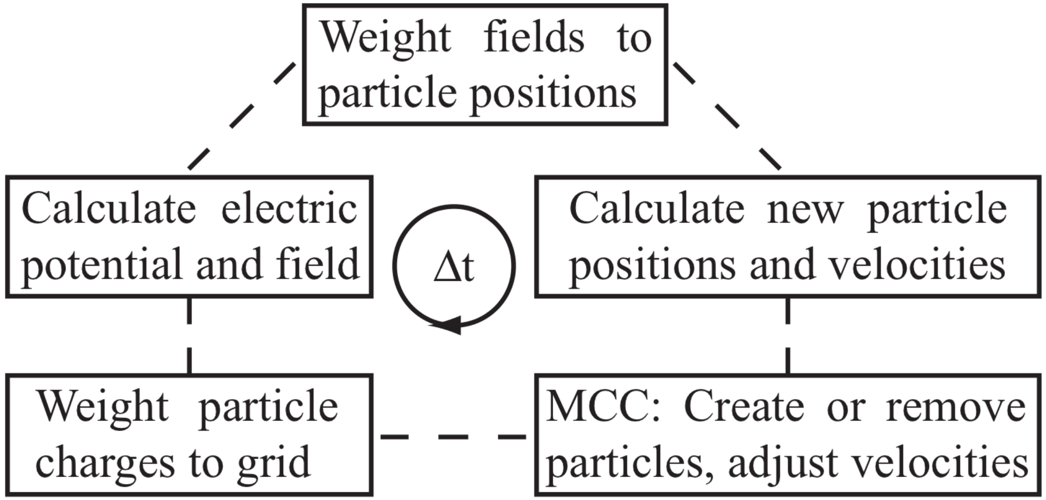
Experimental measurements with PROES



- Phase Resolved Optical Emission Spectroscopy (PROES)[1]
- spatio-temporal plot of excitation into Kr2p_5 (758.7 nm)
- 10 Pa, 8 W, 13.56 MHz
- excitation caused by beam-like highly energetic electrons

[1] J. Schulze et al., J. Phys. D: Appl. Phys. 41, 195212 (2008)

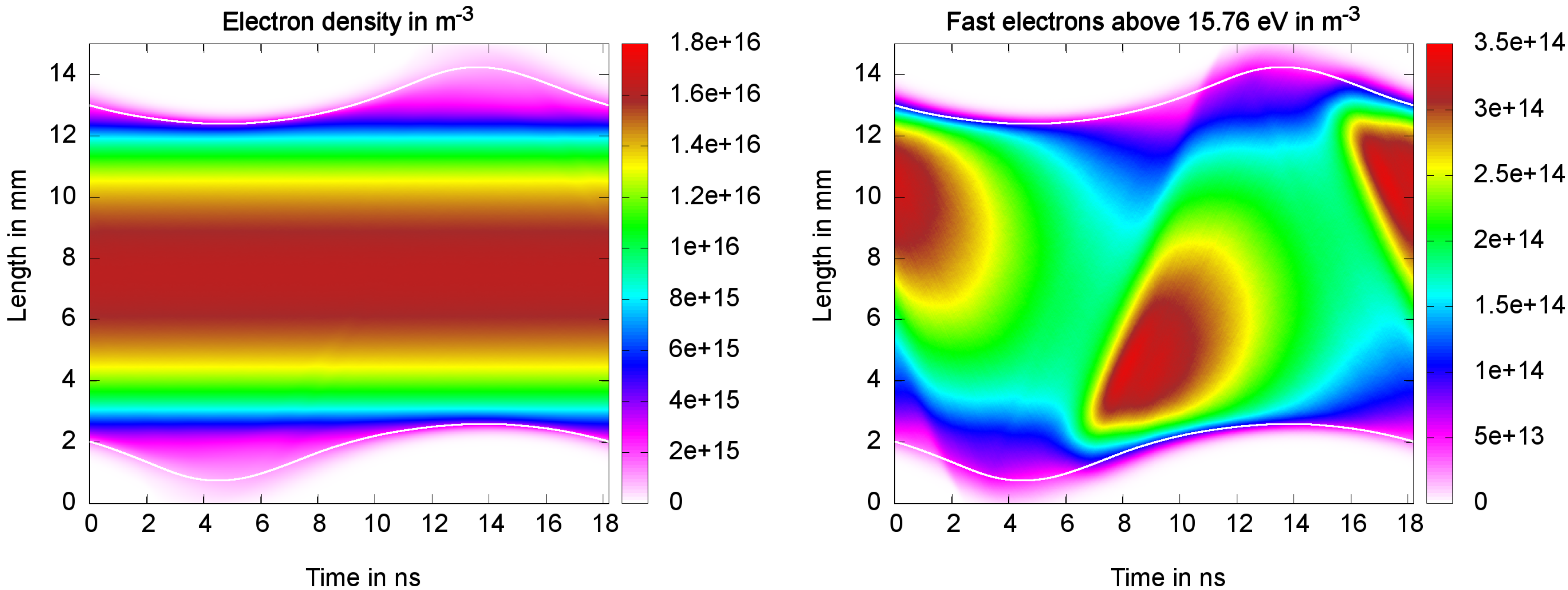
Particle-In-Cell simulation



- self-consistent and accurate description of the particle dynamic
- serial 1d3v PIC code *yapic*
- benchmarked against different PIC implementations[2]
- no reflection of particles at the electrodes and no secondary electrons
- small gap size of 15 mm, high driving frequency of 55 MHz
- 1.3 and 3 Pa Argon (10 and 22 mTorr)

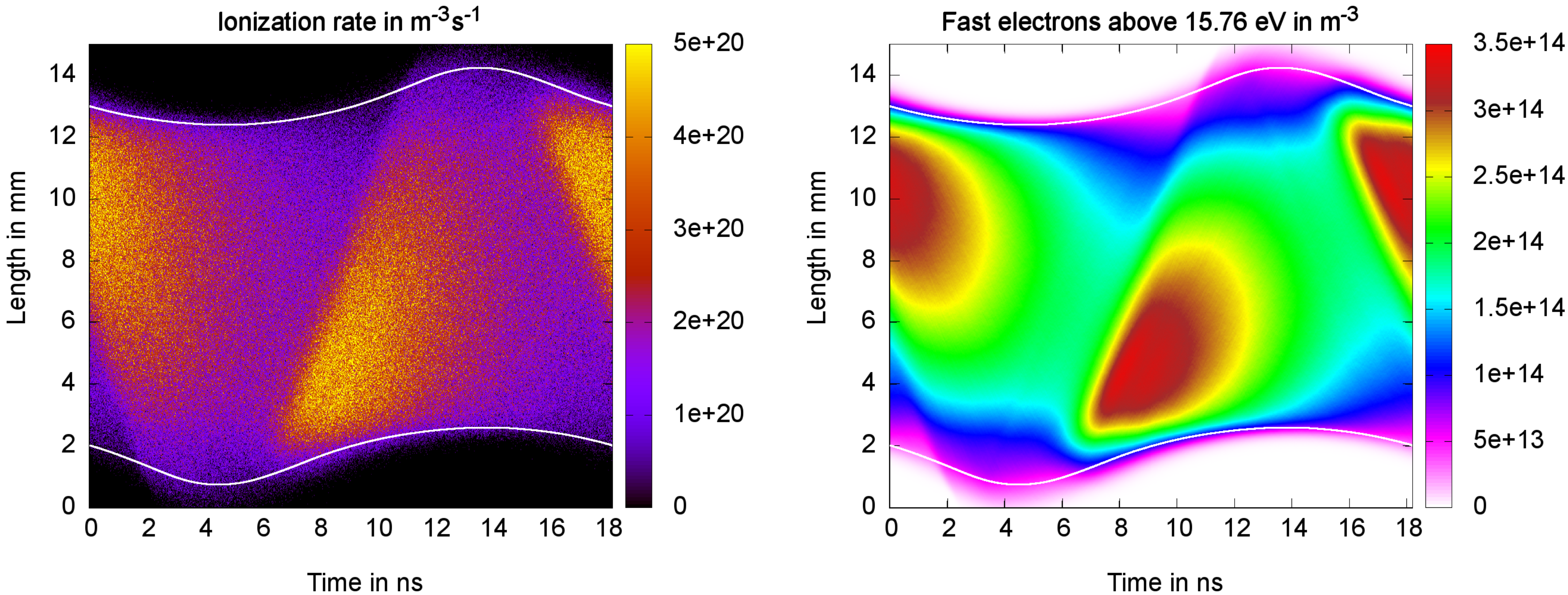
[2] M.M. Turner et. al, Phys. Plasmas 20, 013507 (2013)

Density of fast electrons above 15.76 eV (3 Pa)



- 15 mm gap size, 150 V, 55 MHz, 3 Pa Argon
- electron density is not modulated in the bulk region (left)
- spatio-temporal distribution of fast electron above 15.76 eV (right)
- beam-like behavior, due to the expanding sheath

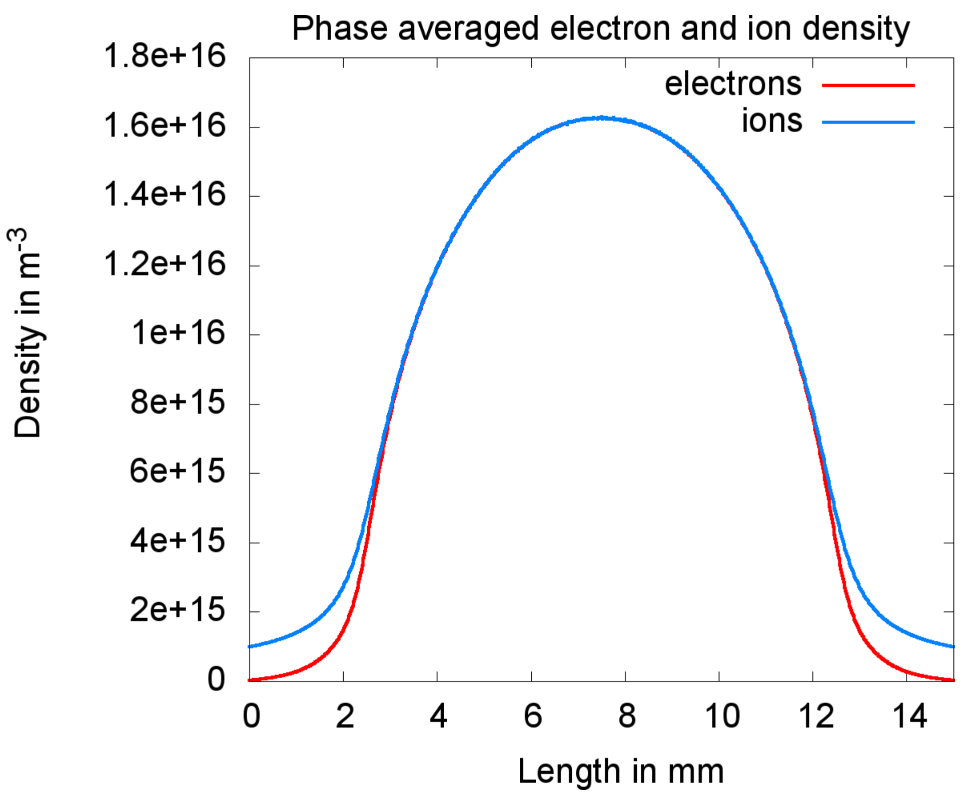
Density of fast electrons above 15.76 eV (3 Pa)



- 15 mm gap size, 150 V, 55 MHz, 3 Pa Argon
- expanding sheaths accelarte electron beams[3]
- energy is higher than the ionization threshold
- significant to sustain the plasma

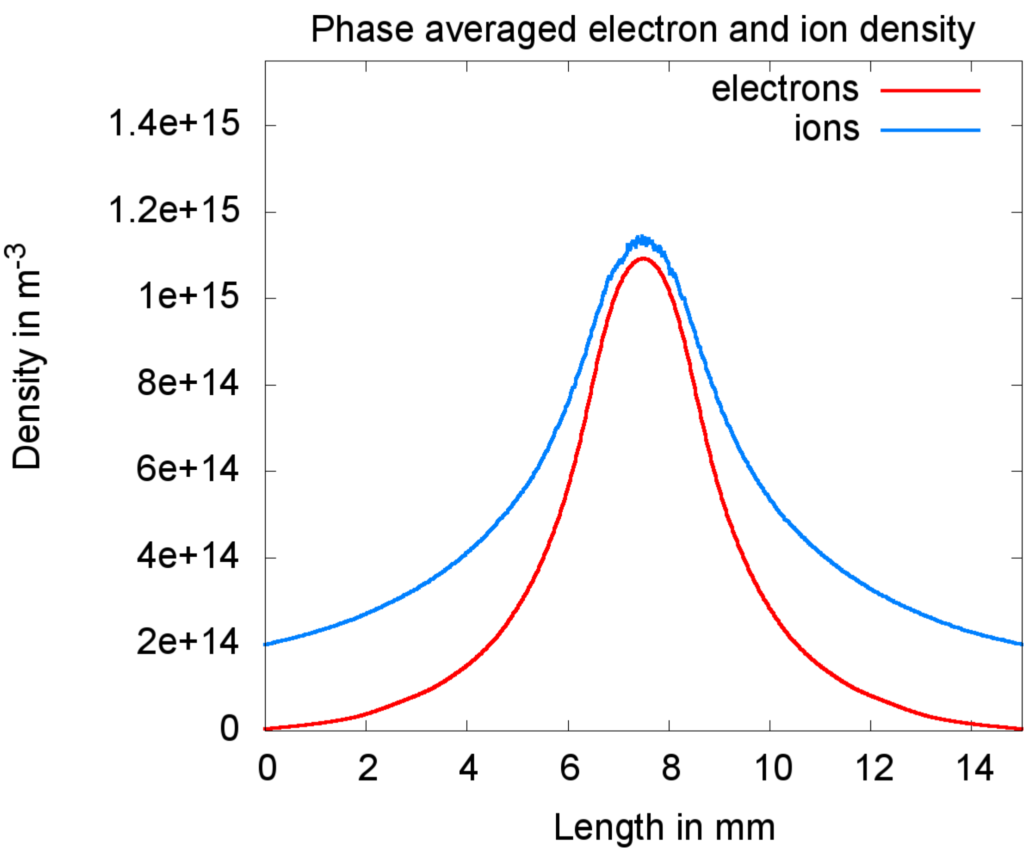
[3] J. Schulze et al., J. Phys. D: Appl. Phys. 41, 042003 (2008)

Phase-averaged electron and ion density (3Pa)



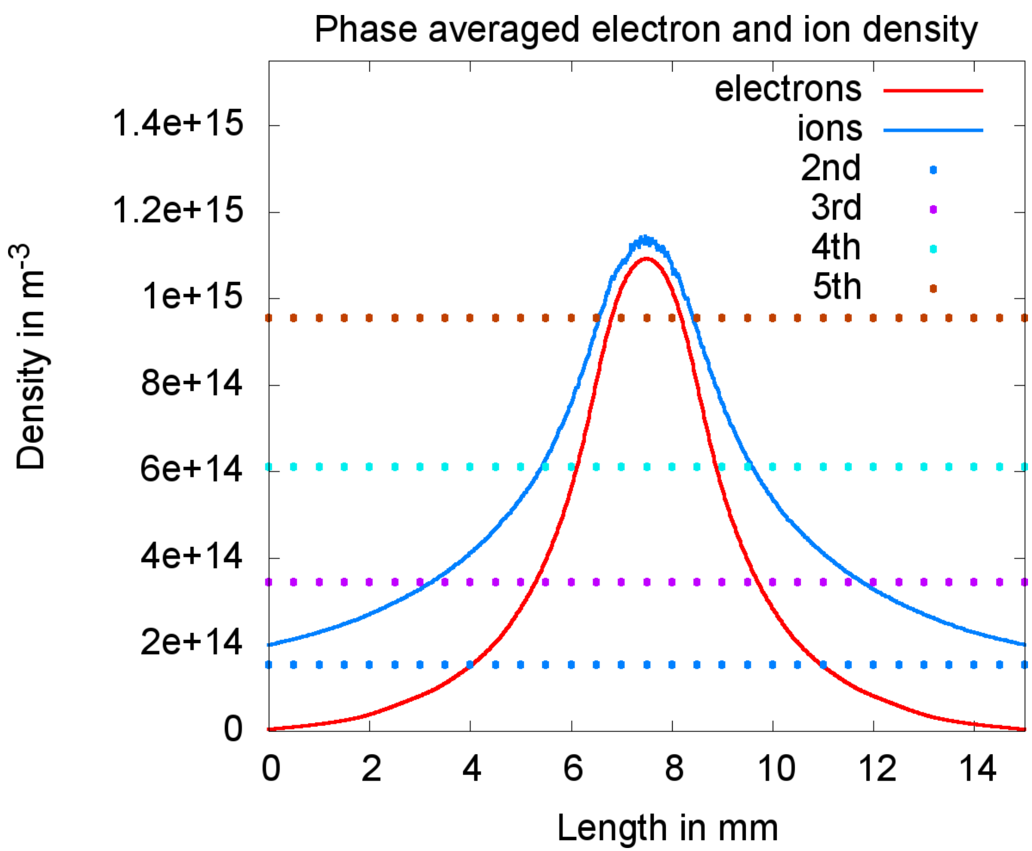
- 15 mm gap size, 150 V, 55 MHz, 3 Pa Argon
- electron beam ($n_{e,beam} \approx 3 \cdot 10^{14}$ m^{-3}) just a fraction of the plasma density
- electron beam and bulk plasma are not disturbed

Lower electron and ion density (1.3Pa)



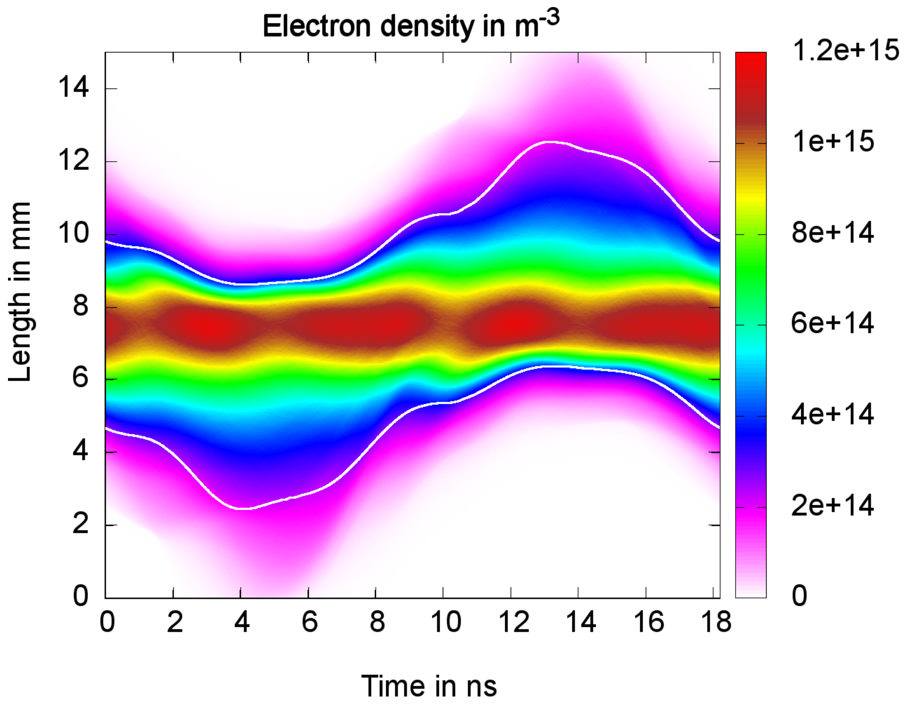
- 15 mm, 150 V, 55 MHz, 1.3 Pa Argon
- How do the bulk electrons interact with the electron beam?
- Is there any connection to local resonance phenomena?

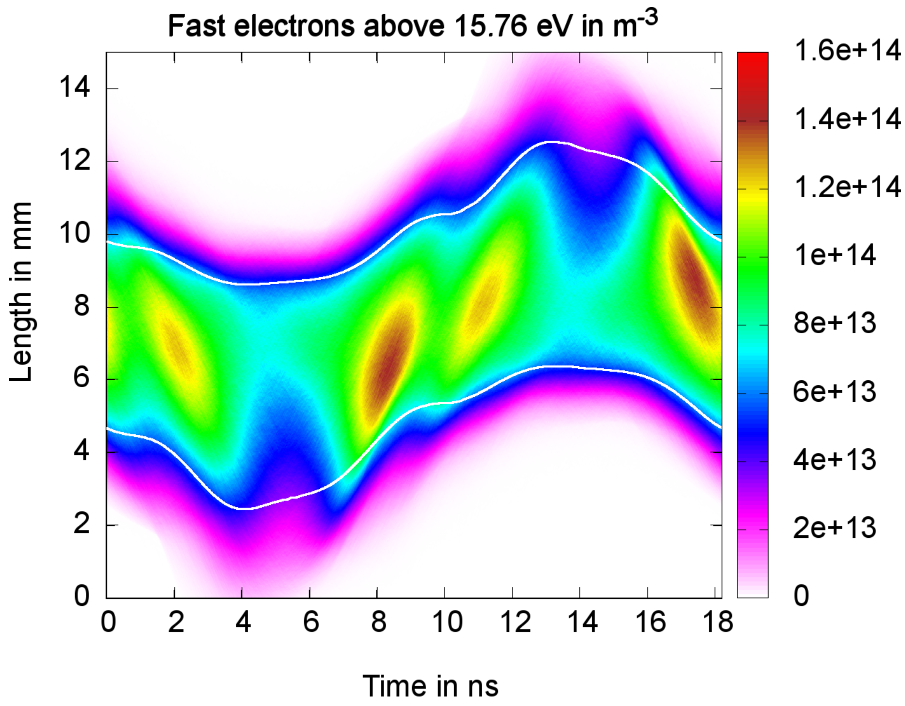
Lower electron and ion density (1.3Pa)



- 15 mm, 150 V, 55 MHz, 1.3 Pa Argon
- local plasma frequency intersects higher harmonics of the driving frequency
- $\omega_{pe}(x) = \sqrt{\frac{n_e(x)e^2}{\varepsilon_0 m_e}} = N \cdot \omega_{rf}$

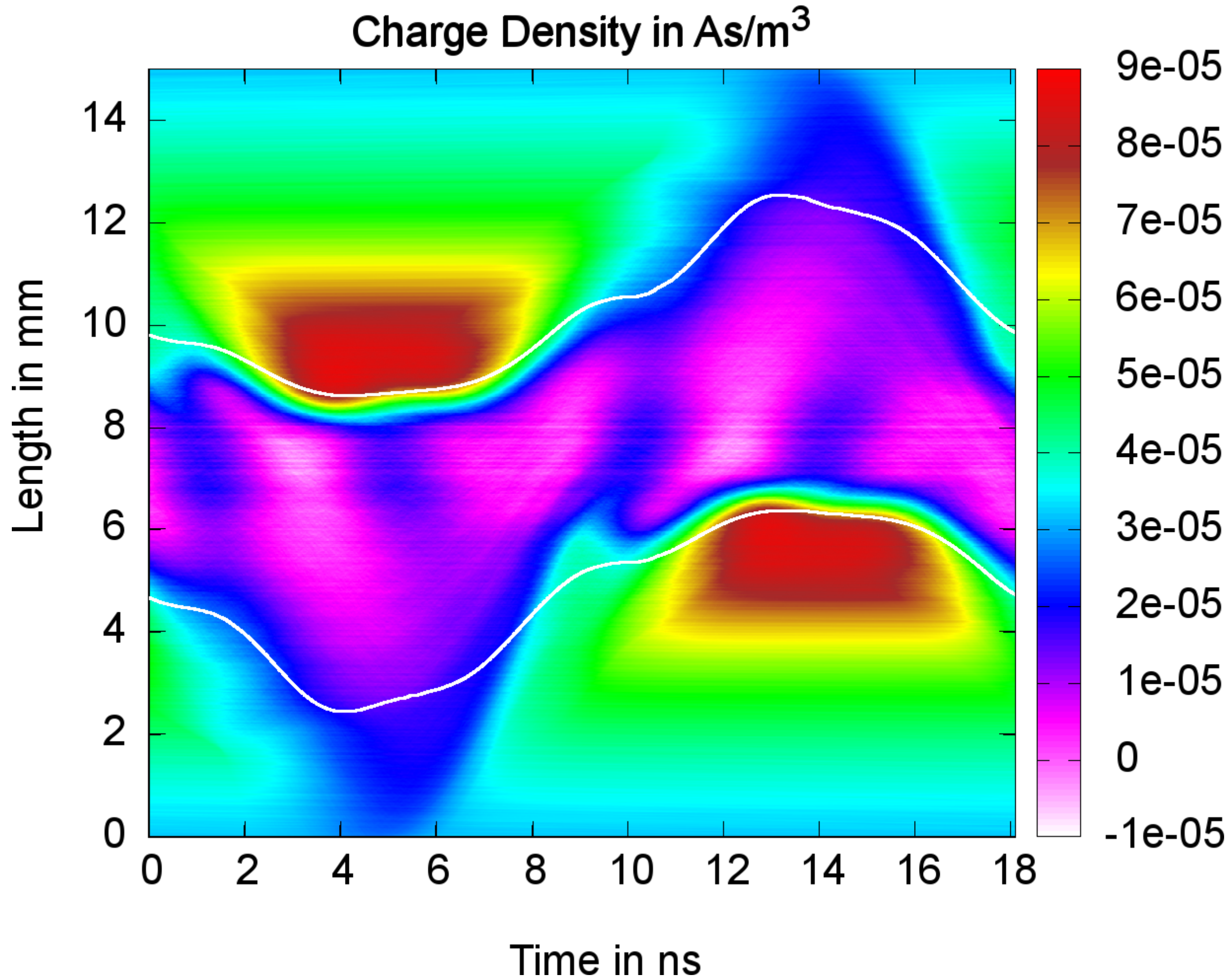
Electrons: 15 mm, 150 V, 55 MHz, 1.3 Pa Argon





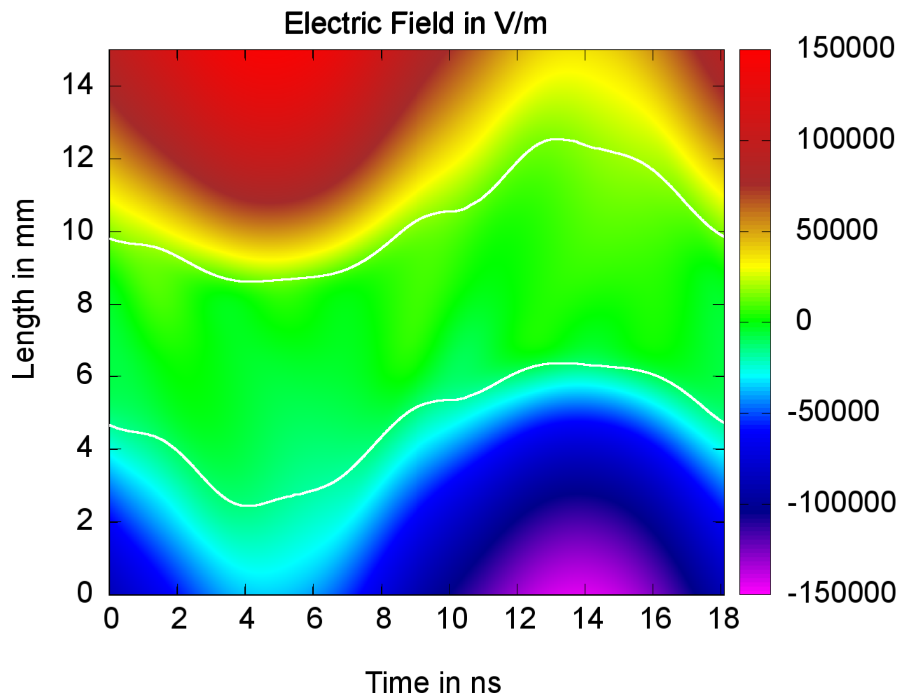
- central plasma density is disturbed
- hardly noticeable bulk region
- double beam formation
- beam formation is disturbed

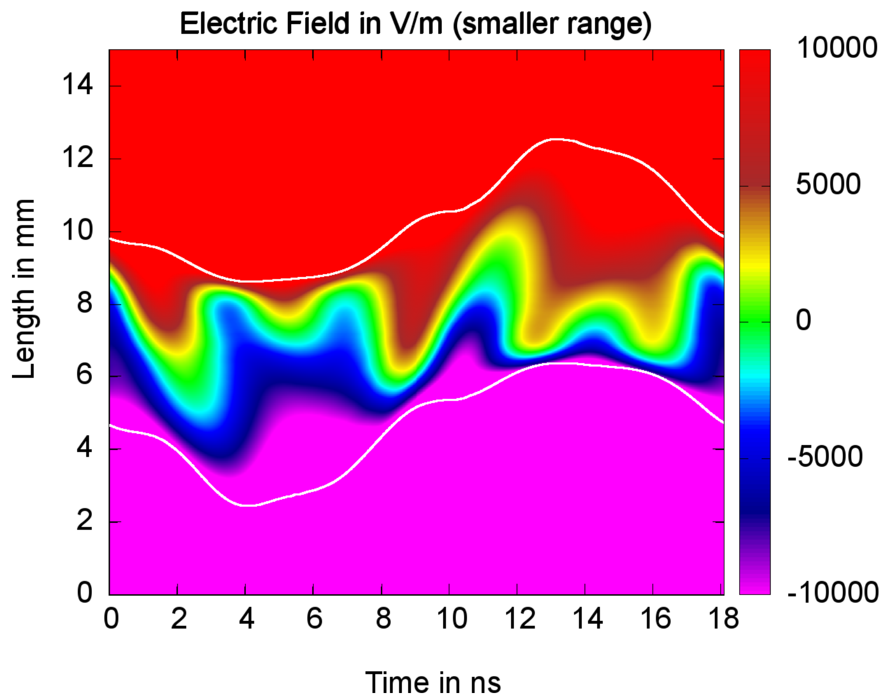
Charge Density: 15 mm, 150 V, 55 MHz, 1.3 Pa Argon



- 15 mm, 150 V, 55 MHz, 1.3 Pa Argon
- significant charge densities in the center of the discharge

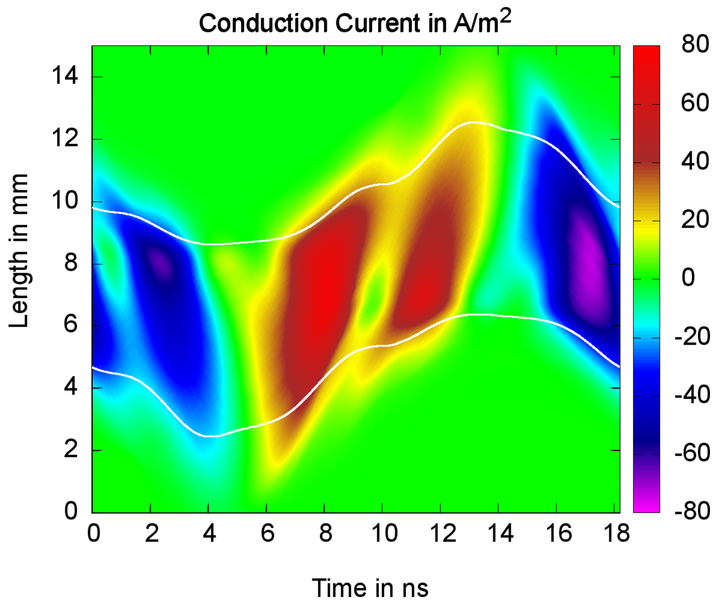
Electric Field: 15 mm, 150 V, 55 MHz, 1.3 Pa Argon

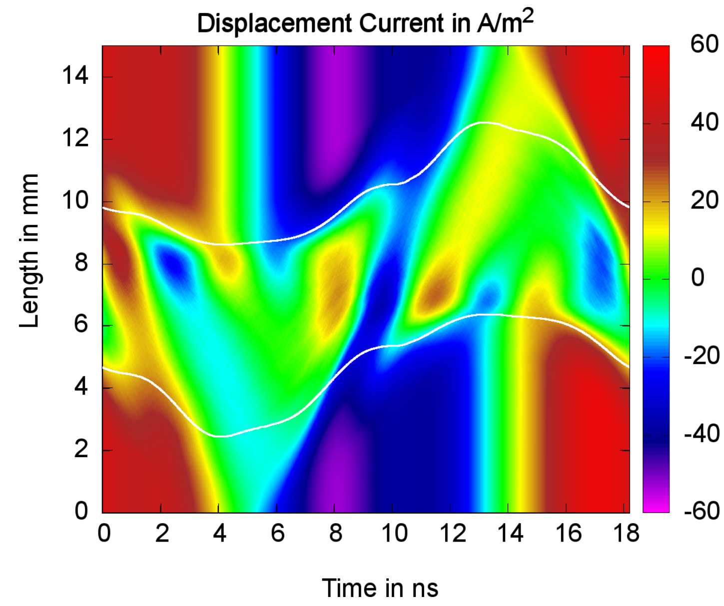


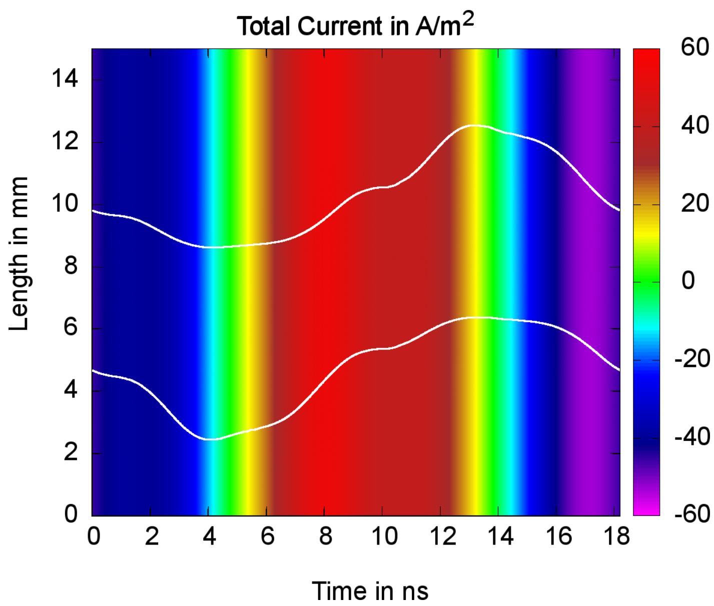


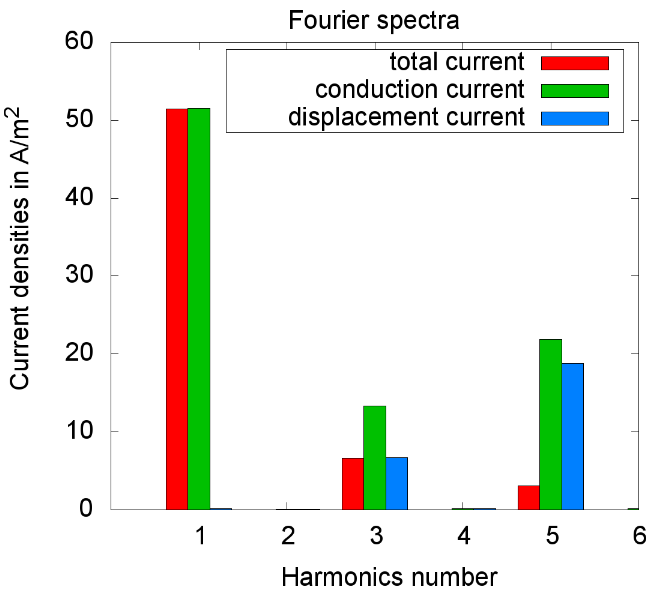
- sinusoidal oscillation of the electric field
- field in the center approximately zero?
- significant electric fields in the center ($\omega_{pe}(x) \approx 5\omega_{rf}$)
- higher harmonics (5th harmonic)

Current densities: 15 mm, 150 V, 55 MHz, 1.3 Pa Argon

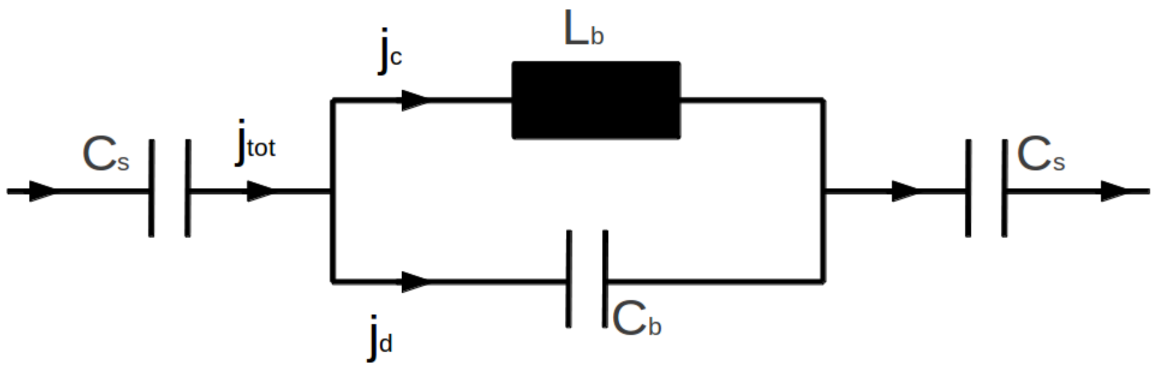








Series and parallel resonance



$$C_s = \varepsilon_0 \frac{A}{l_s}$$

$$C_b = \varepsilon_0 \frac{A}{l_b}$$

$$L_b = \frac{m_e l_b}{n_e e^2 A}$$

<u>Series resonance</u>

$$Z = \frac{2}{j\omega C_s} + \frac{1}{\frac{1}{j\omega L_b} + j\omega C_b}$$

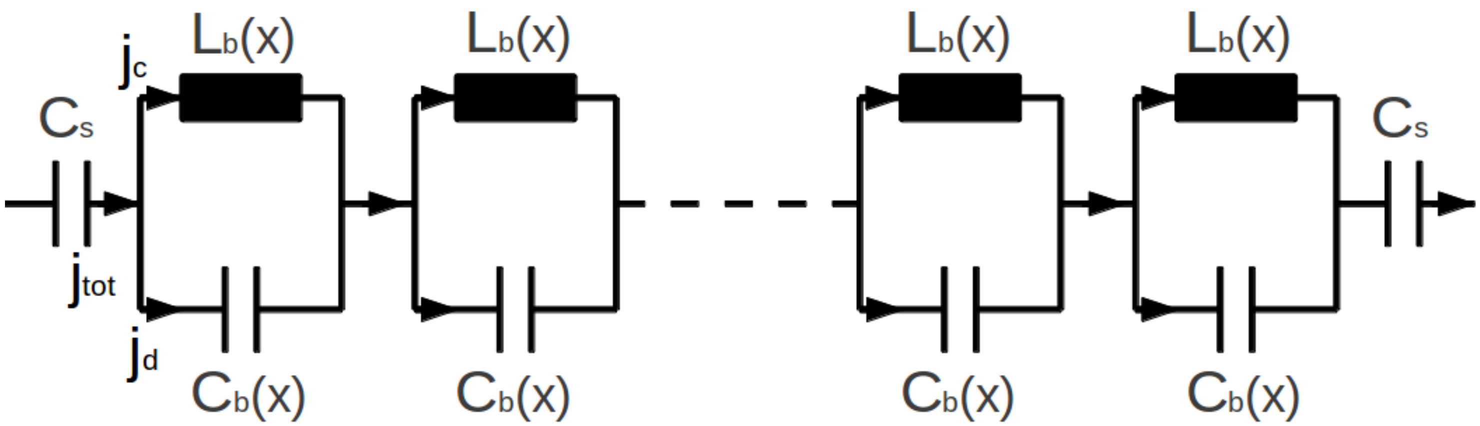
$$\omega_{psr} = \omega_{pe} \sqrt{\frac{2l_s}{l_{gap}}}.$$

<u>Parallel resonance</u>

$$Y = j\omega C_b + \frac{1}{j\omega L_p}$$

$$\omega_{ppr} = \omega_{pe}$$

Nonuniform plasma model[4]

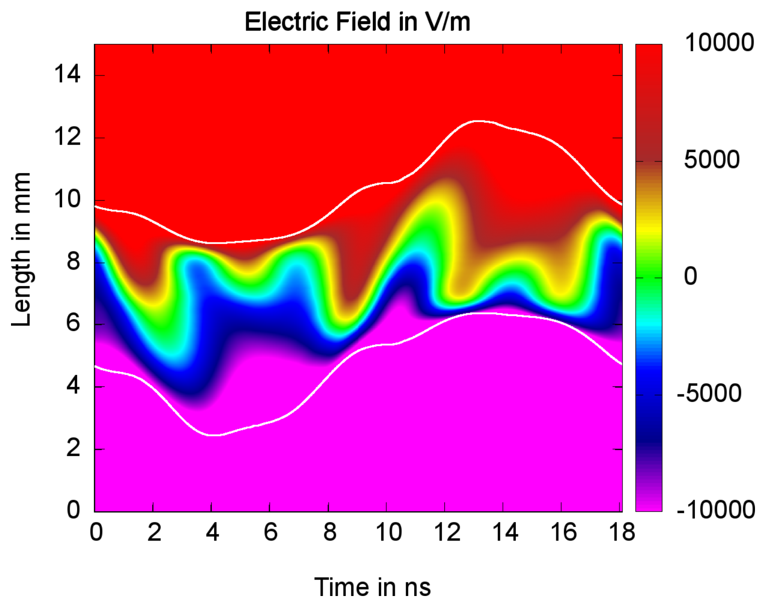


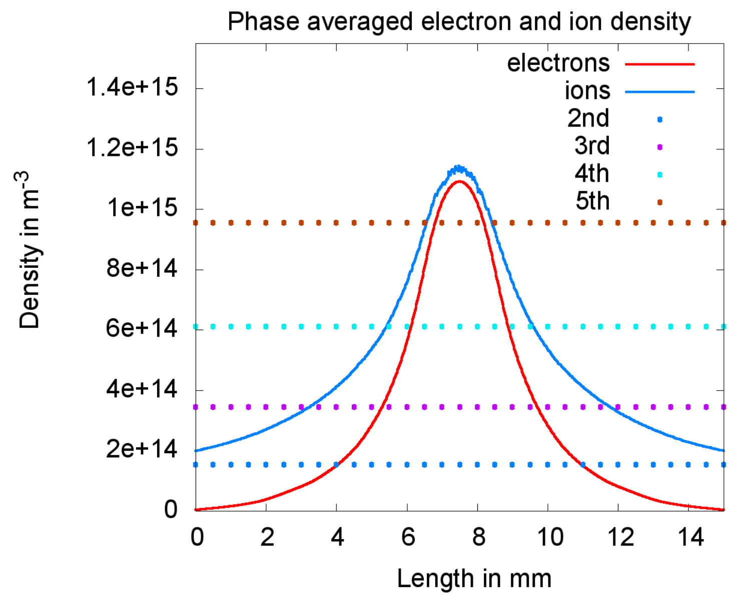
$$\omega_{ppr}(x) = \sqrt{\frac{1}{L_b(x)C_b(x)}} = \omega_{pe}(x)$$

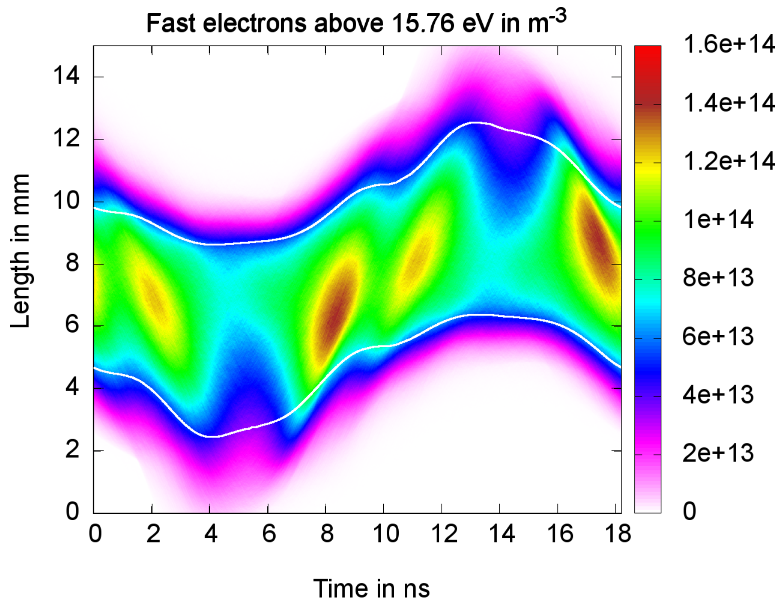
- cold plasma model (collisionless)
- bulk as infinity numbers of parallel circuits
- excitation of a local parallel resonance (current resonance)

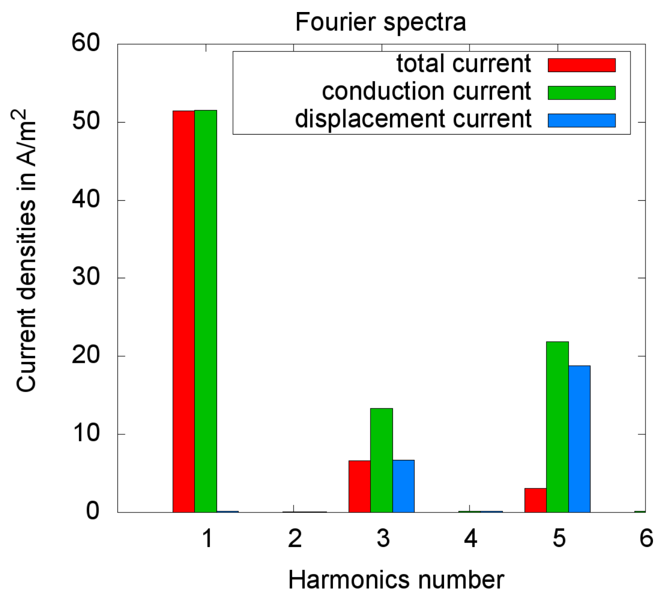
[4] V Ku et al., J. Appl. Phys. 84, 6536 (1998)

Summary: 15 mm, 150 V, 55 MHz, 1.3 Pa Argon

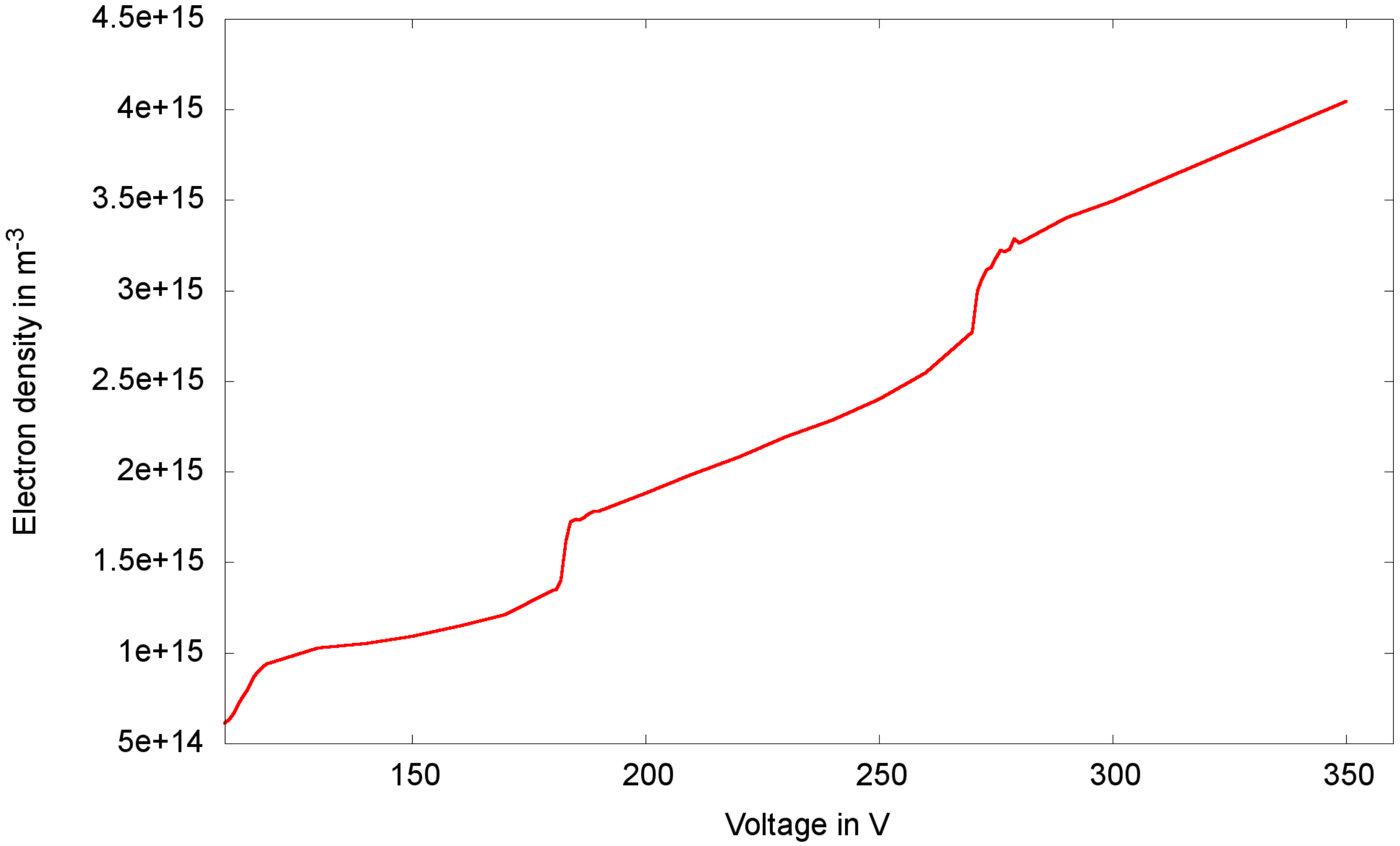






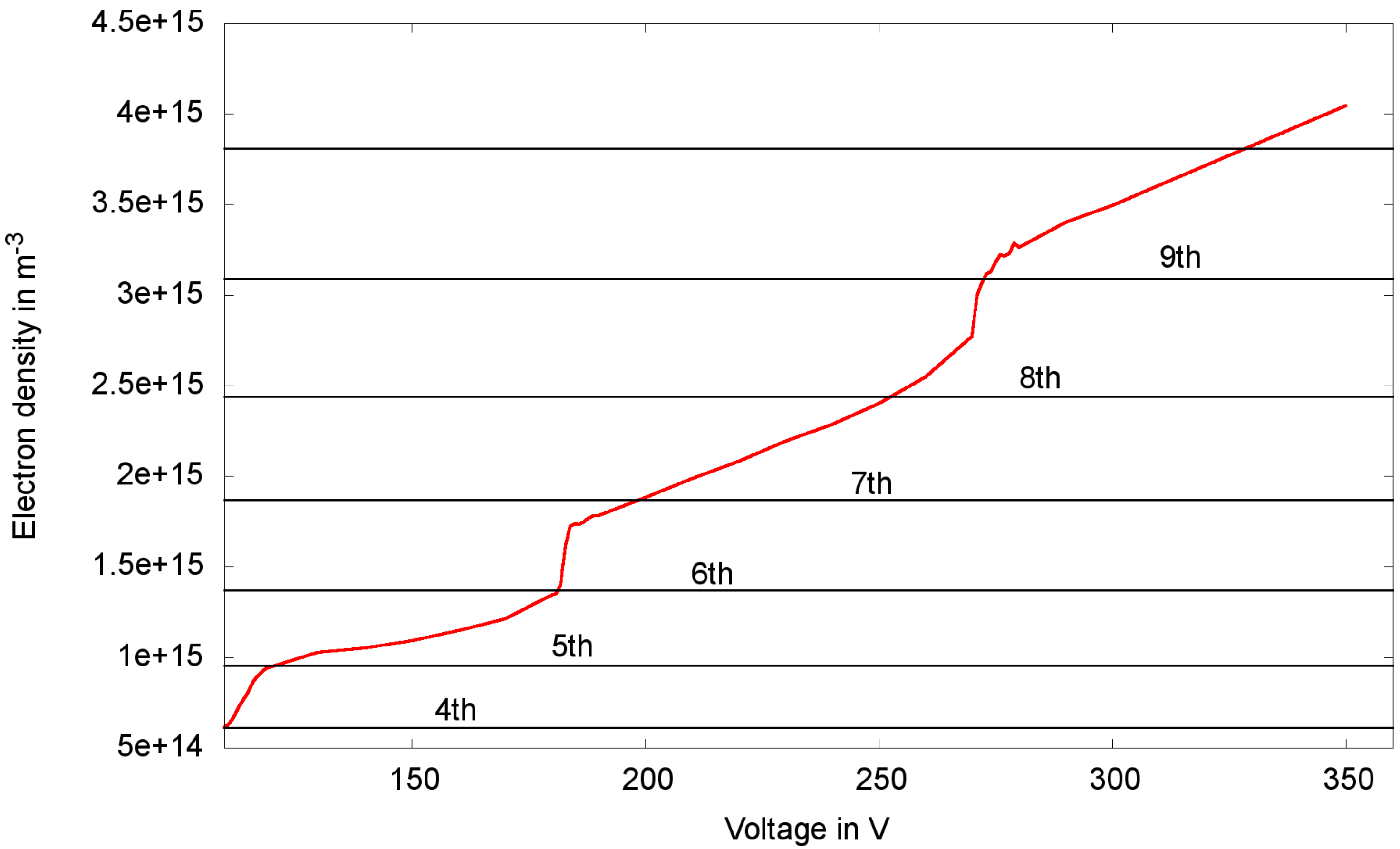


Voltage Variation: Argon 1.3 Pa, 55 MHz, 15 mm



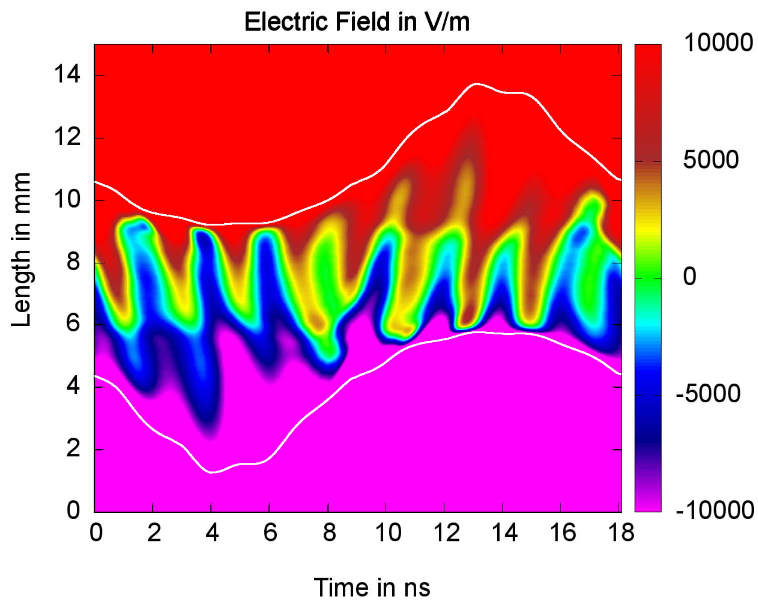
- What happens if higher harmonics are excited?
- increase voltage ⇒ more ionization ⇒ higher density

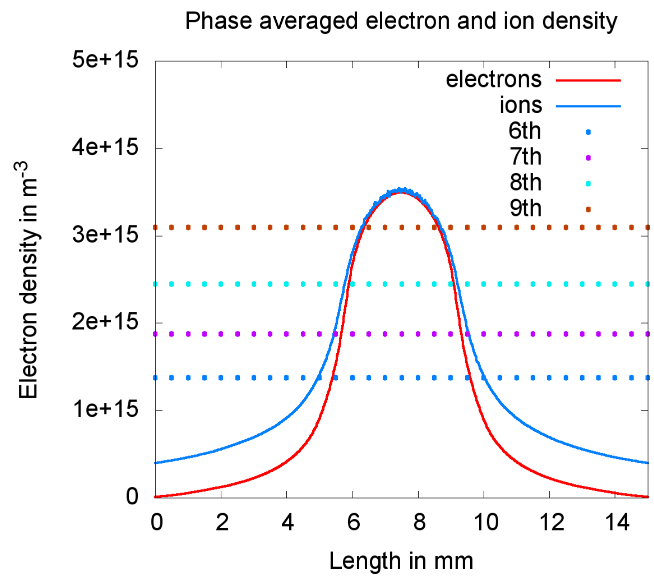
Voltage Variation: Argon 1.3 Pa, 55 MHz, 15 mm

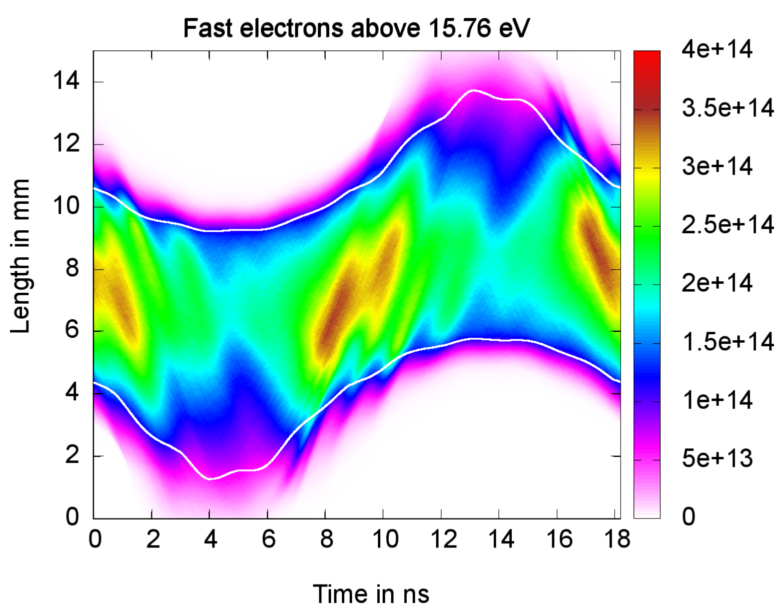


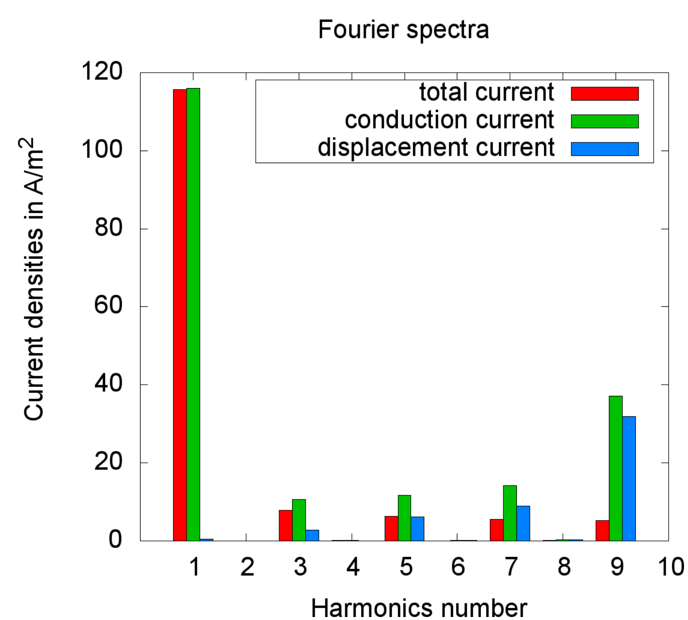
- increasing voltage ⇒ more ionization ⇒ higher density
- $\omega_{pe}(x)$ reaches higher harmonics of the driving frequency
- example: 300 V

15 mm, 300 V, 55 MHz, 1.3 Pa Argon









Conclusion

- electron beam formation as well as the plasma bulk are disturbed at low plasma densities
- in such a regime higher harmonics of the driving frequency intersect the local plasma frequency (especially in the center)
- local resonance phenomena (excitation of a local parallel resonance)
- higher harmonics of the conduction and displacement current increase significantly at this location but compensate each other, thus the total current is conserved
- electric field oscillates with higher harmonics
- effect is also shown with different discharge setups (Helium, Neon, larger gap sizes, lower frequencies, current source)