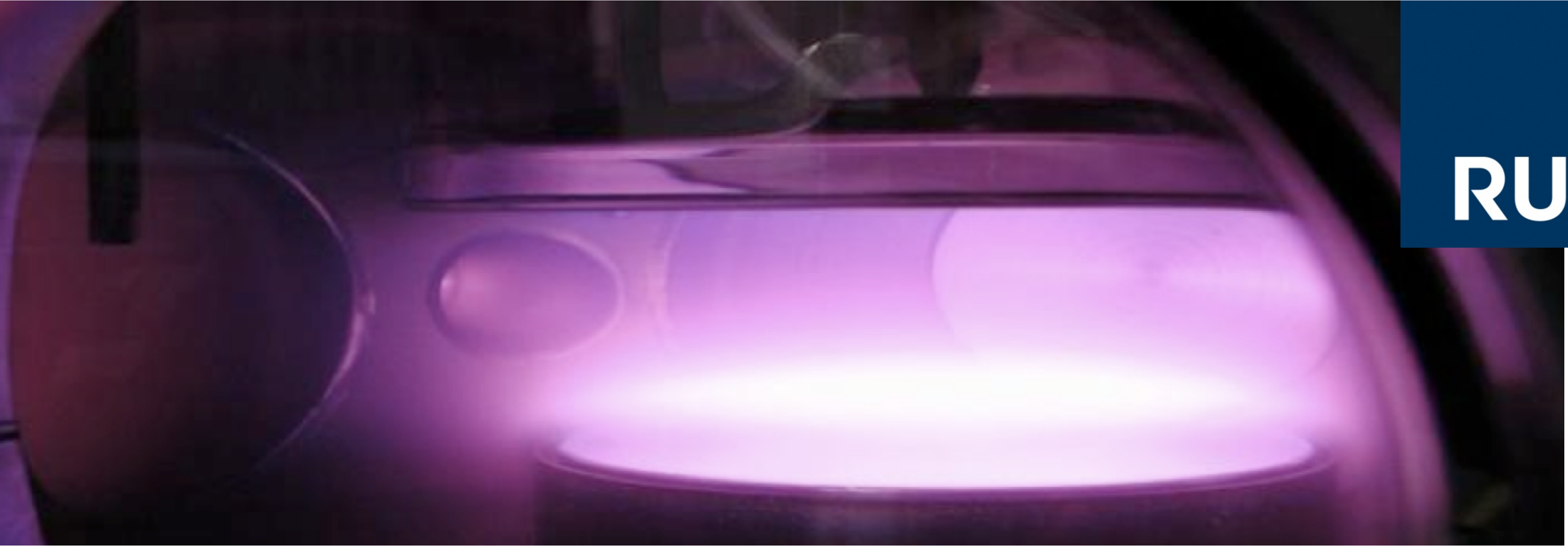

Kinetic simulation of low pressure capacitively coupled plasmas: Analysis of an abrupt mode transition

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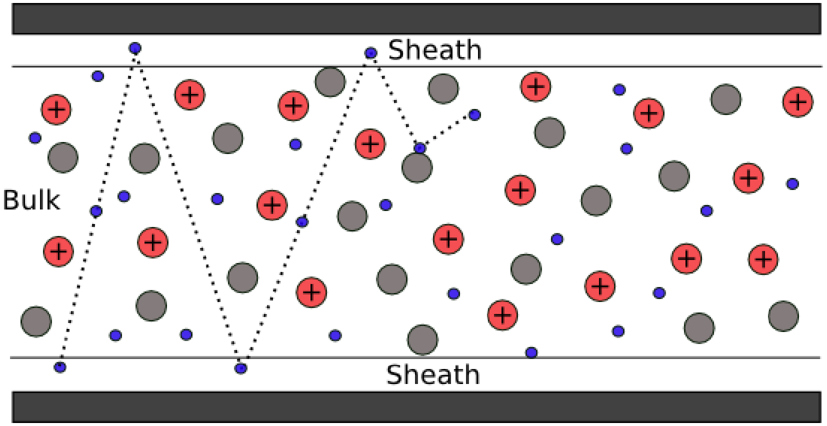
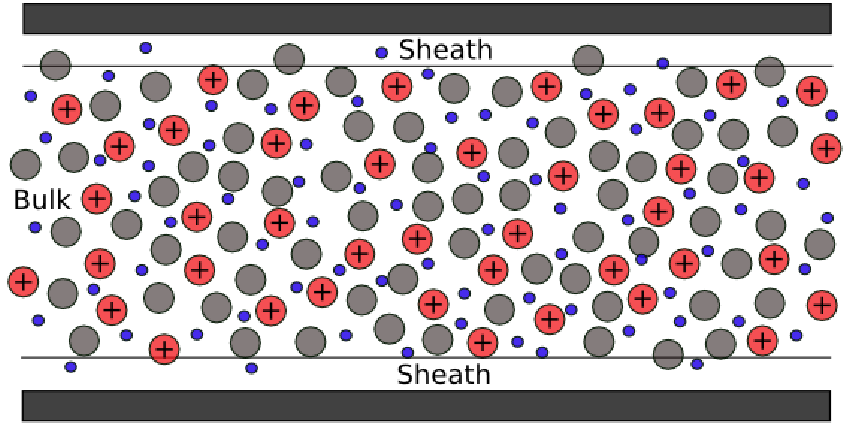
Pressure regime



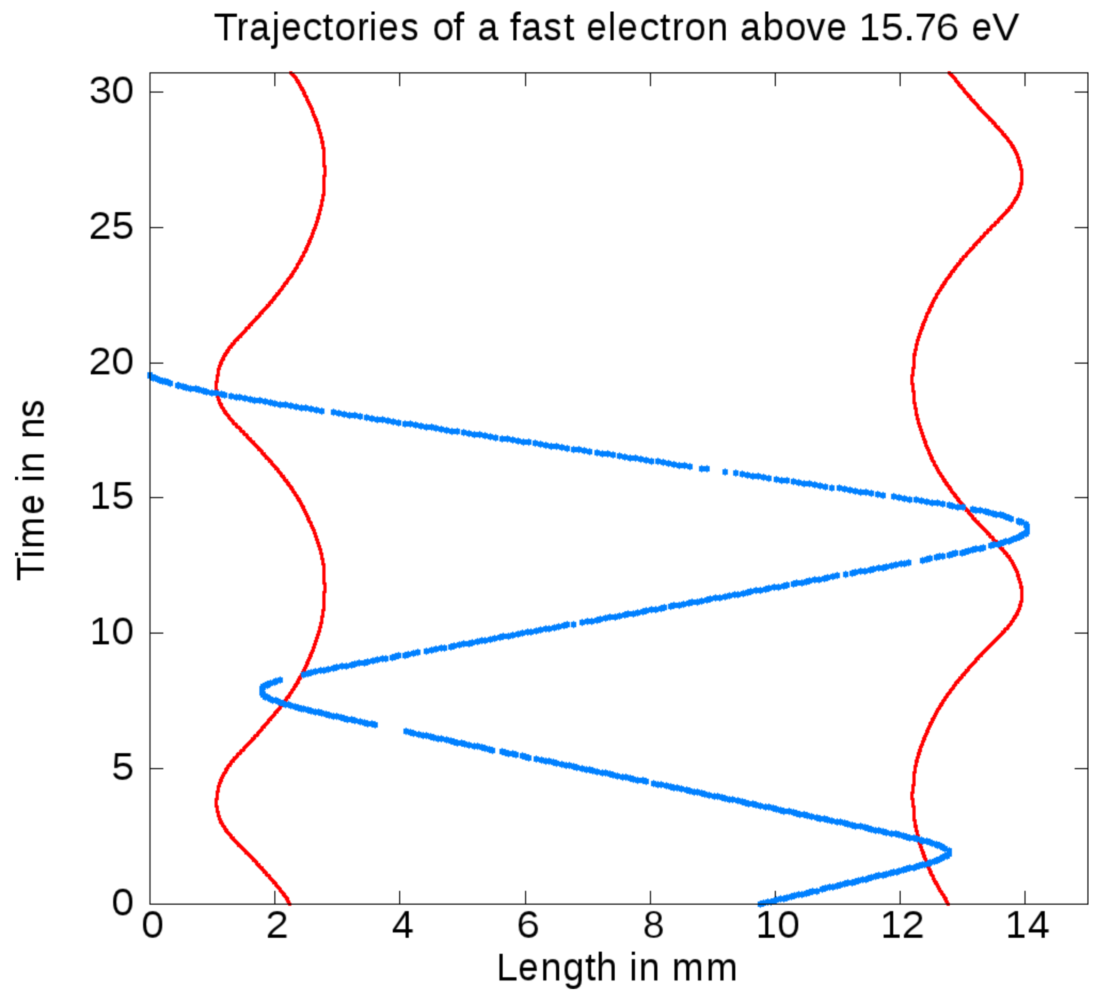


- low pressure
  - stochastic heating
  - interaction with the sheath
  - gap size smaller than the mean free path of electrons
  - bounce resonance effect[1]
- high pressure
  - ohmic heating
  - electron-neutral collision

[1] Liu et al., Phys. Rev. Lett. 107, 055002 (2011)

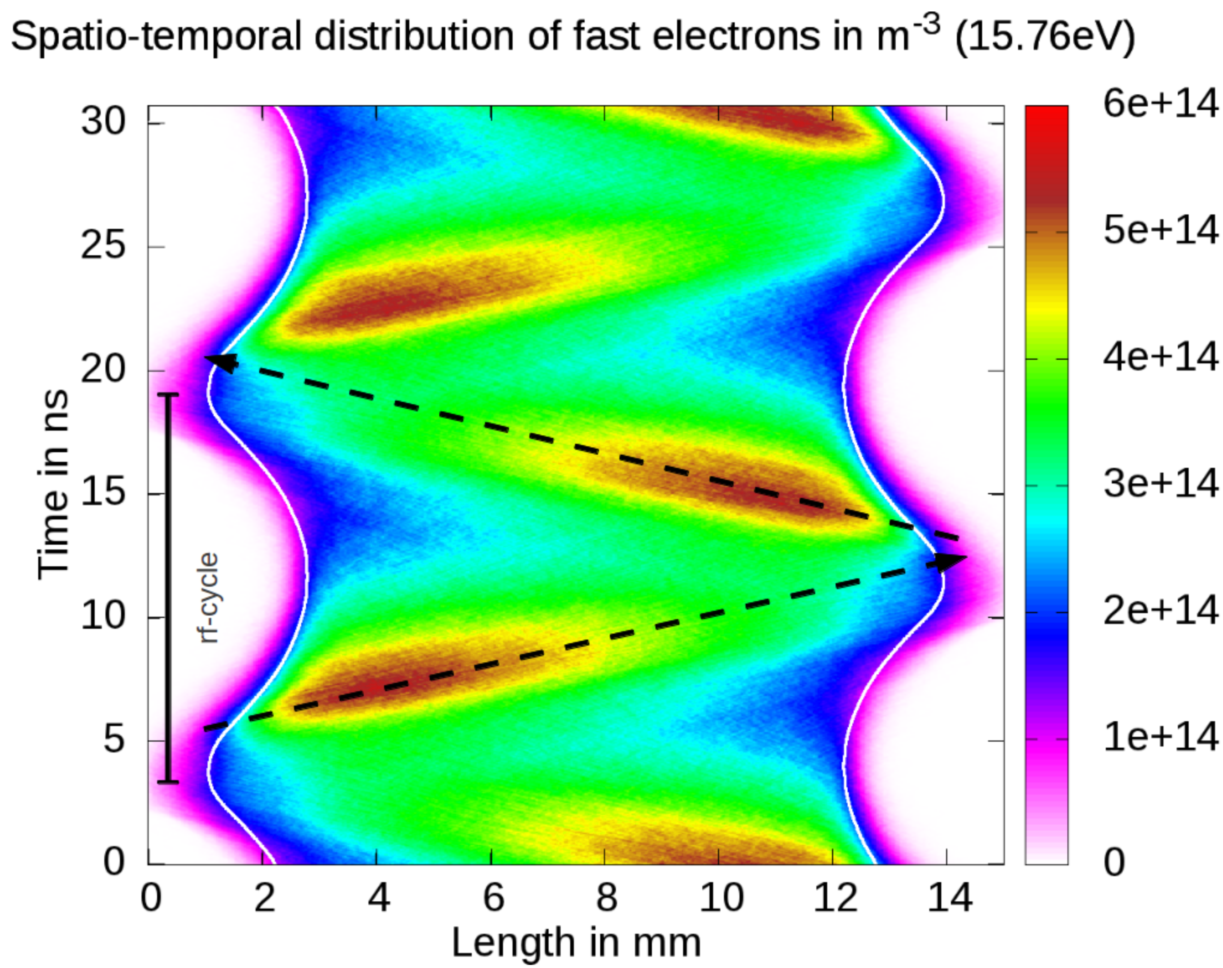
Trajectory of fast electrons

- trajectory of a highly energetic electron in a PIC-simulation
- small gap size (15mm) and a high frequency (65MHz), Argon (1Pa)
- traverses more then 3 times through the bulk due to reflection at the expanding sheath
- can gain enough energy to overcome the sheath potential



Impingement phase of fast electrons

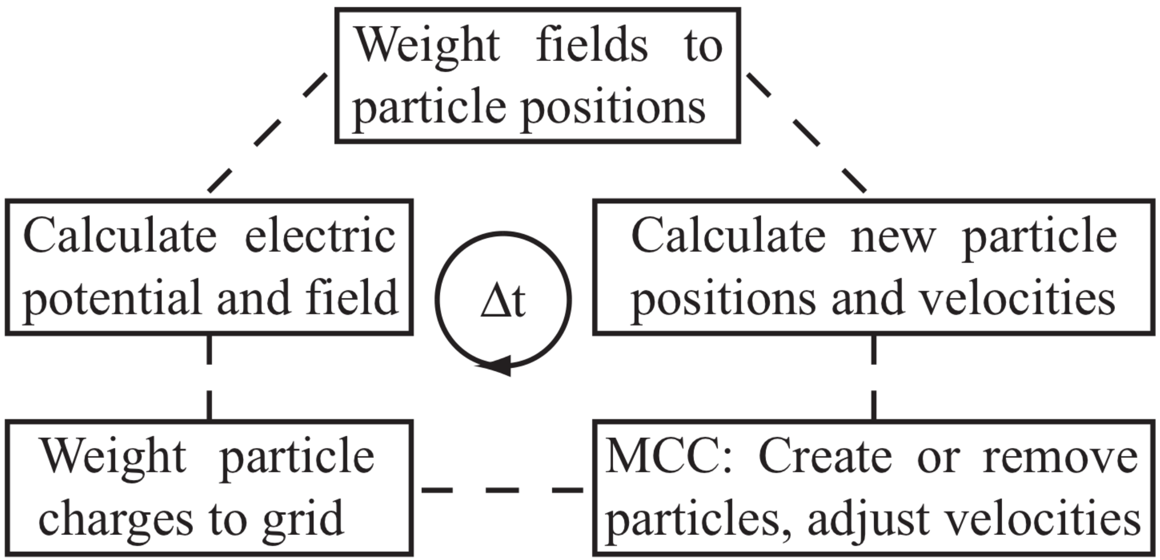
- expanding sheaths[2] produce fast electrons
- phase of the impingement is important
- electrons lose their energy on the wall or can be reflected during the expansion
- gap size and frequency variation change the impingement phase



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

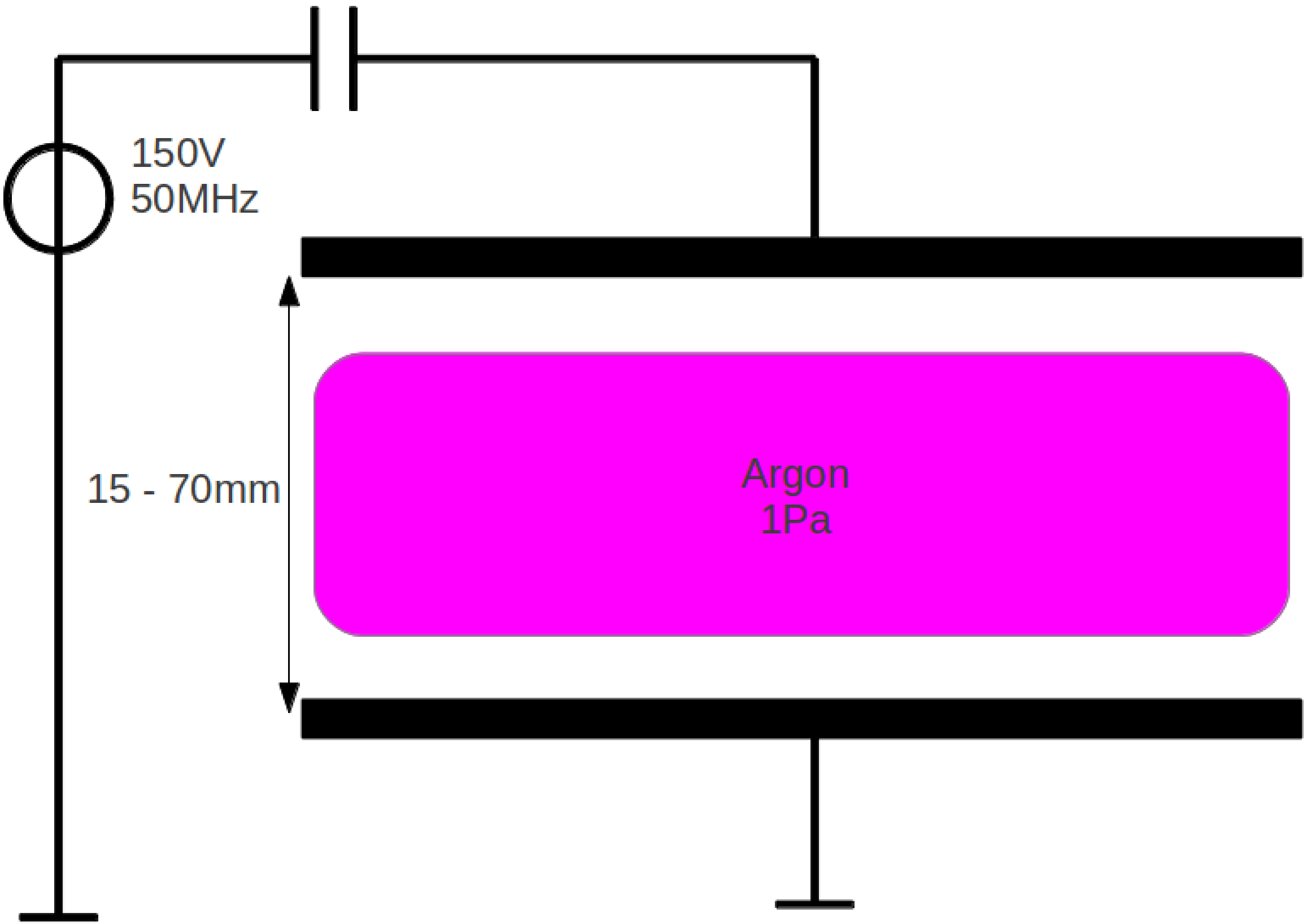
PIC/MCC Simulation

- serial Particle-In-Cell code *yapic*
- explicit 1d3v code, electrostatic approximation
- benchmarked against different PIC implementations[3]
- Monte-Carlo method with a null-collision scheme
- no reflection of particles at the electrodes and no secondary electrons

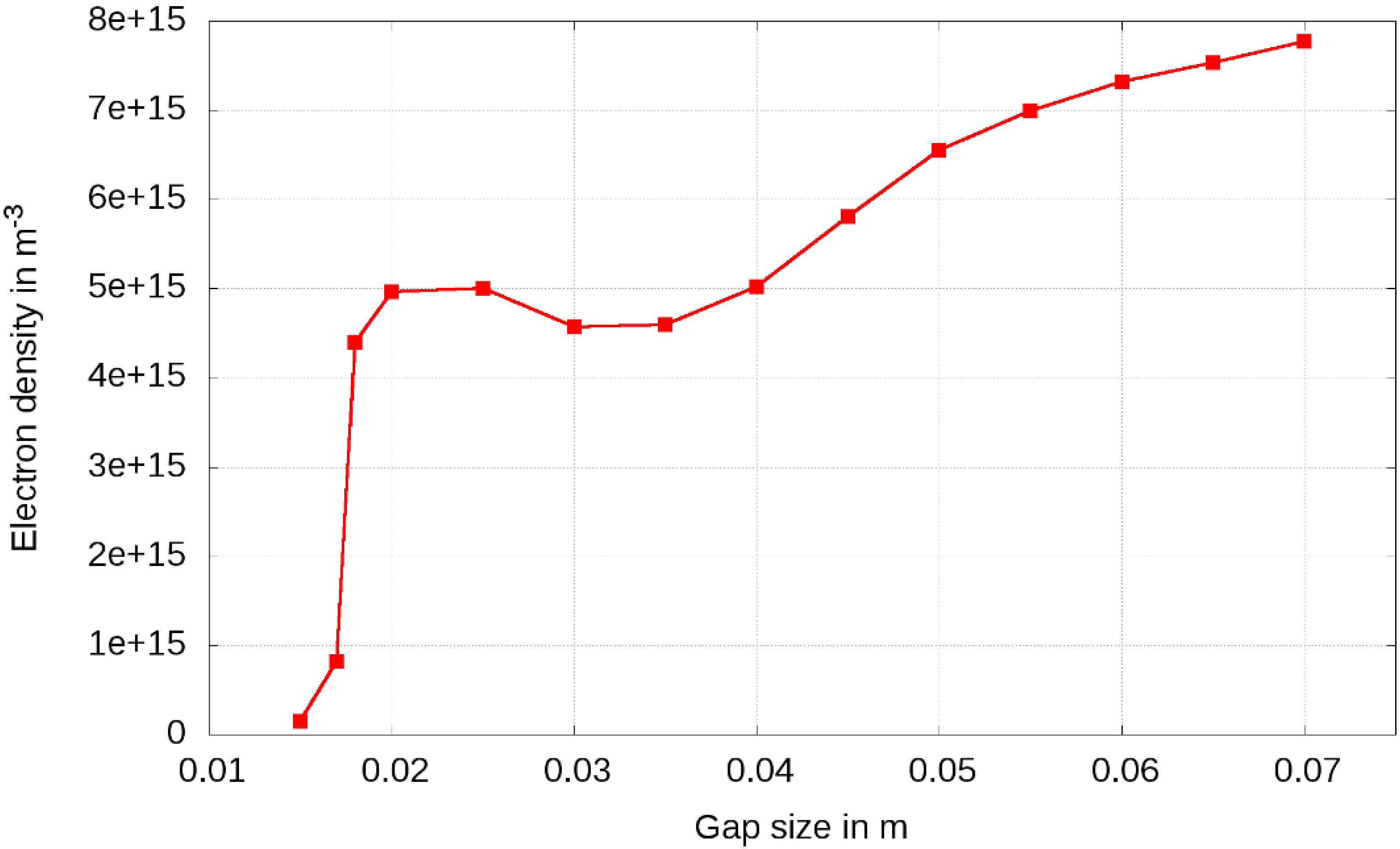


[3] M.M. Turner et. al, Phys. Plasmas 20, 013507 (2013)

Gap size variation

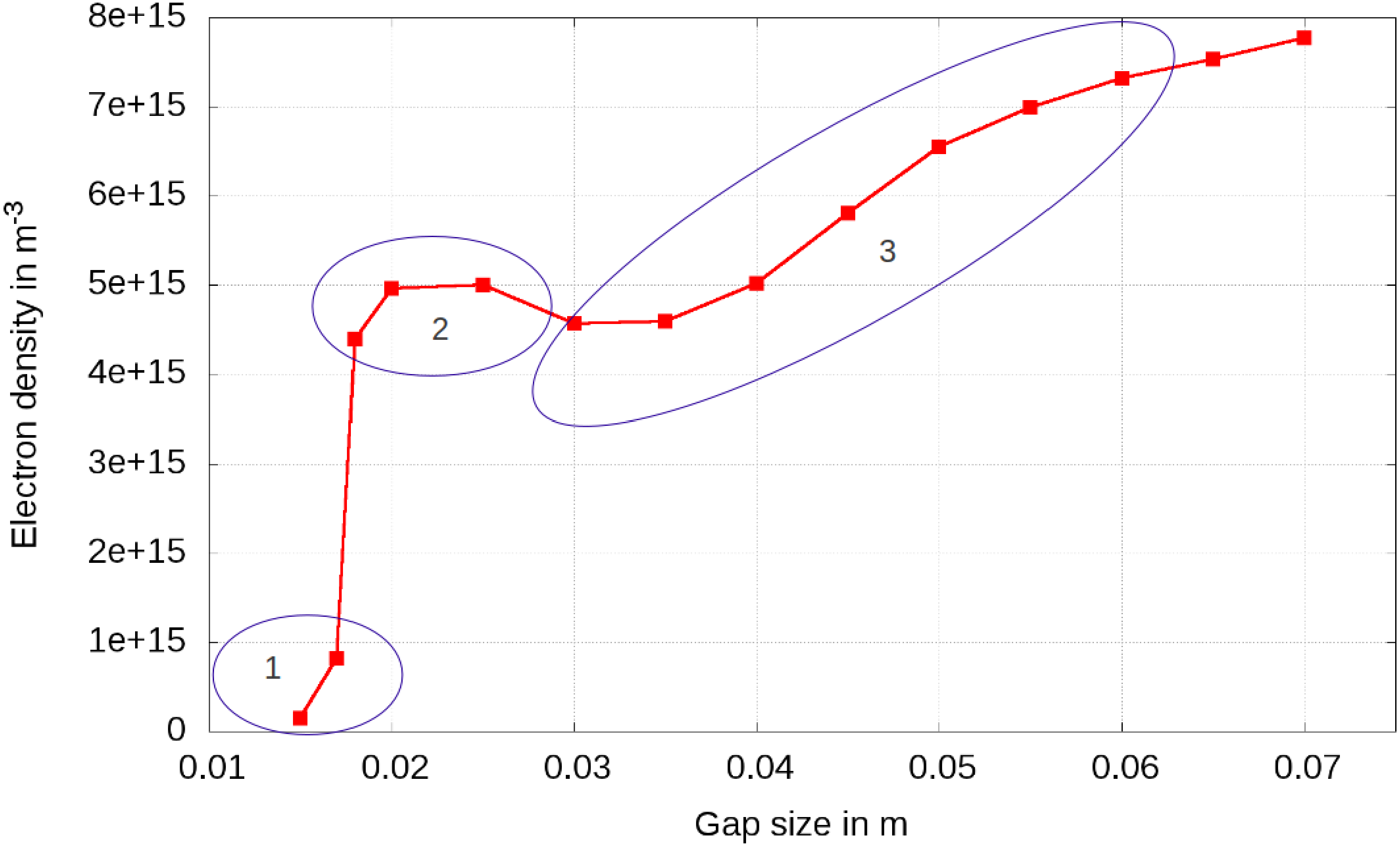


Averaged electron density over the gap size

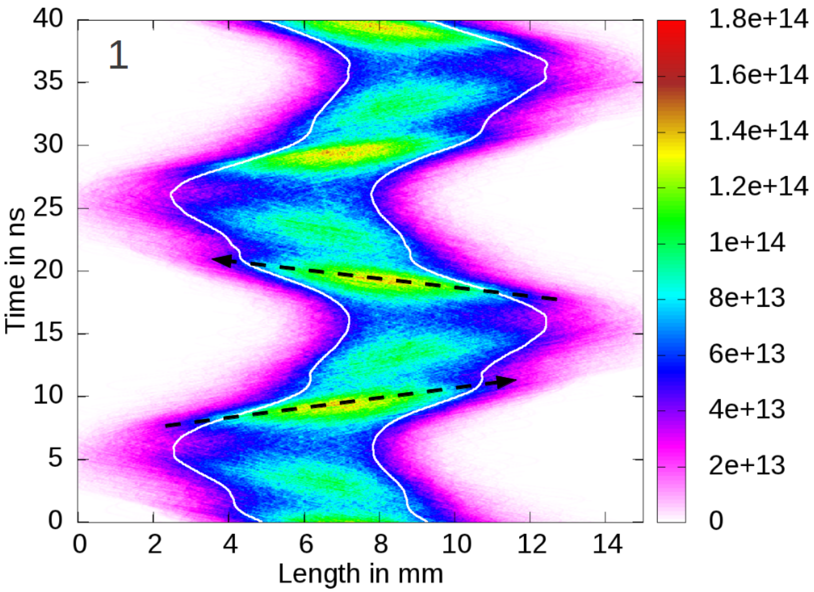


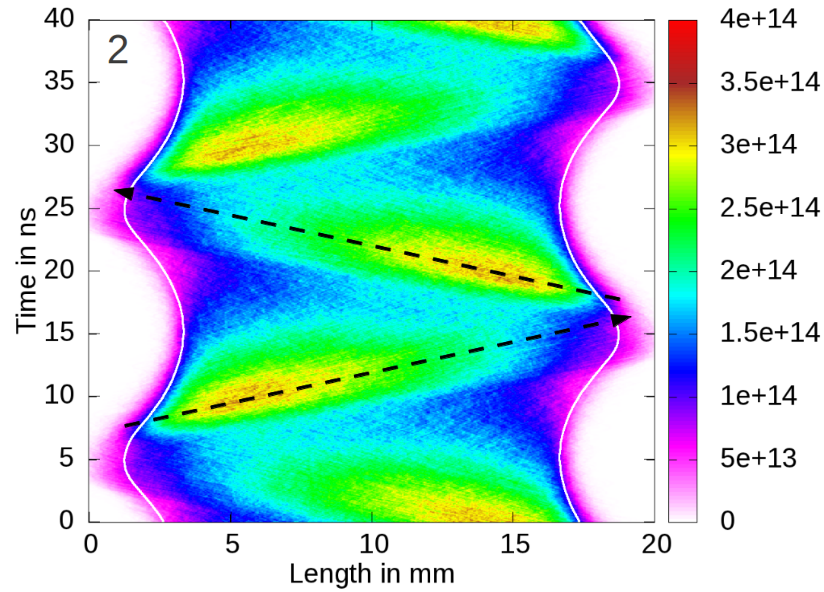
Averaged electron density over the gap size

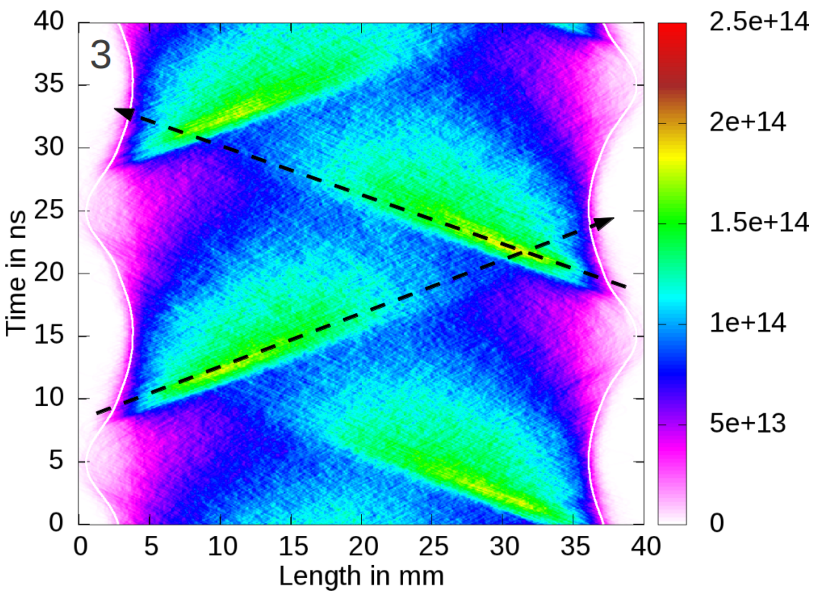
RUB

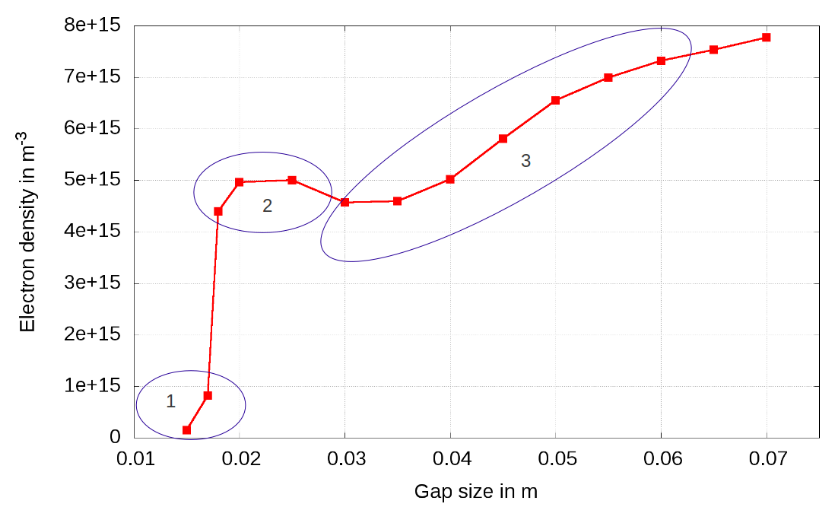


Spatio-temporal distribution of fast electrons in m^{-3}

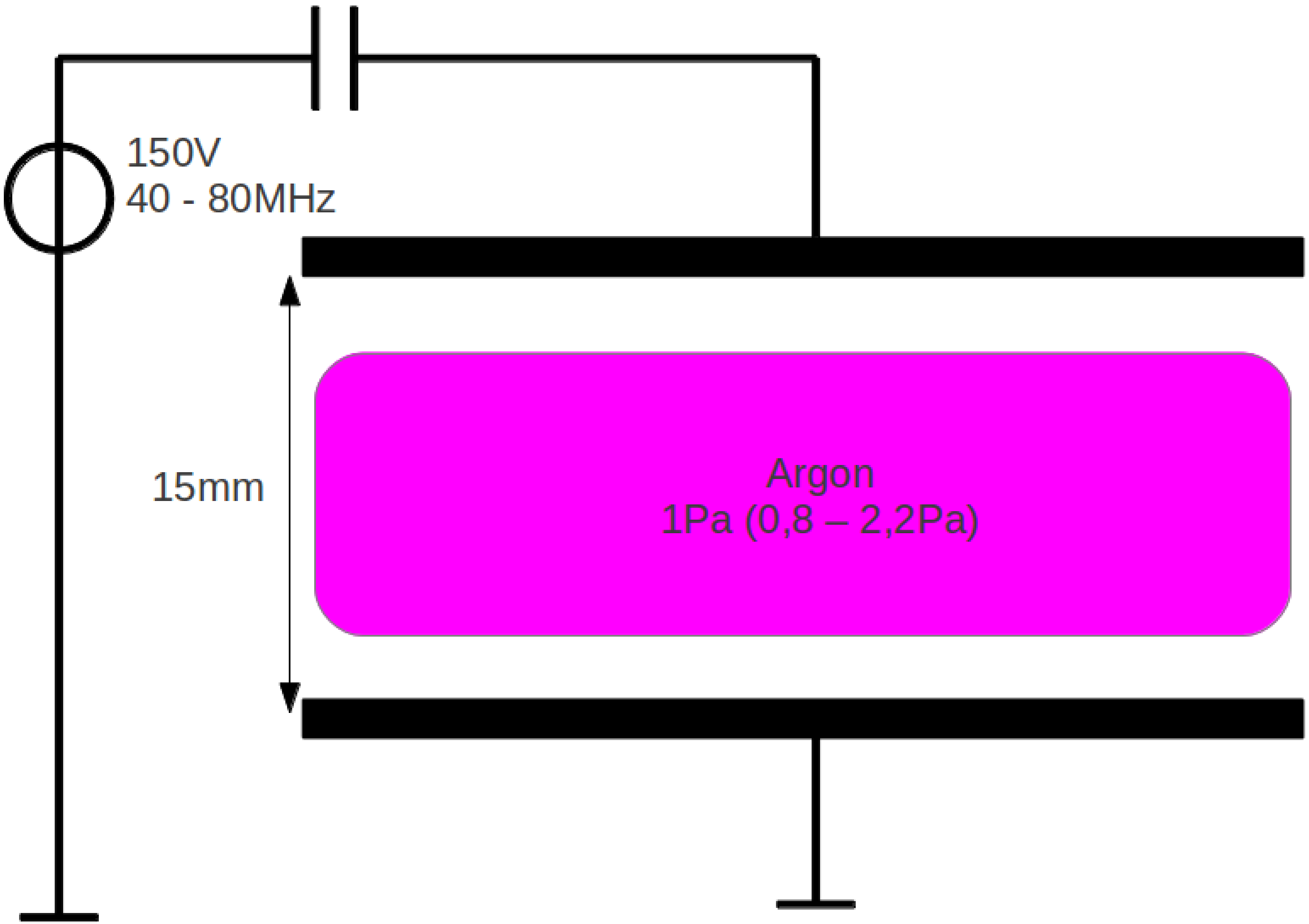




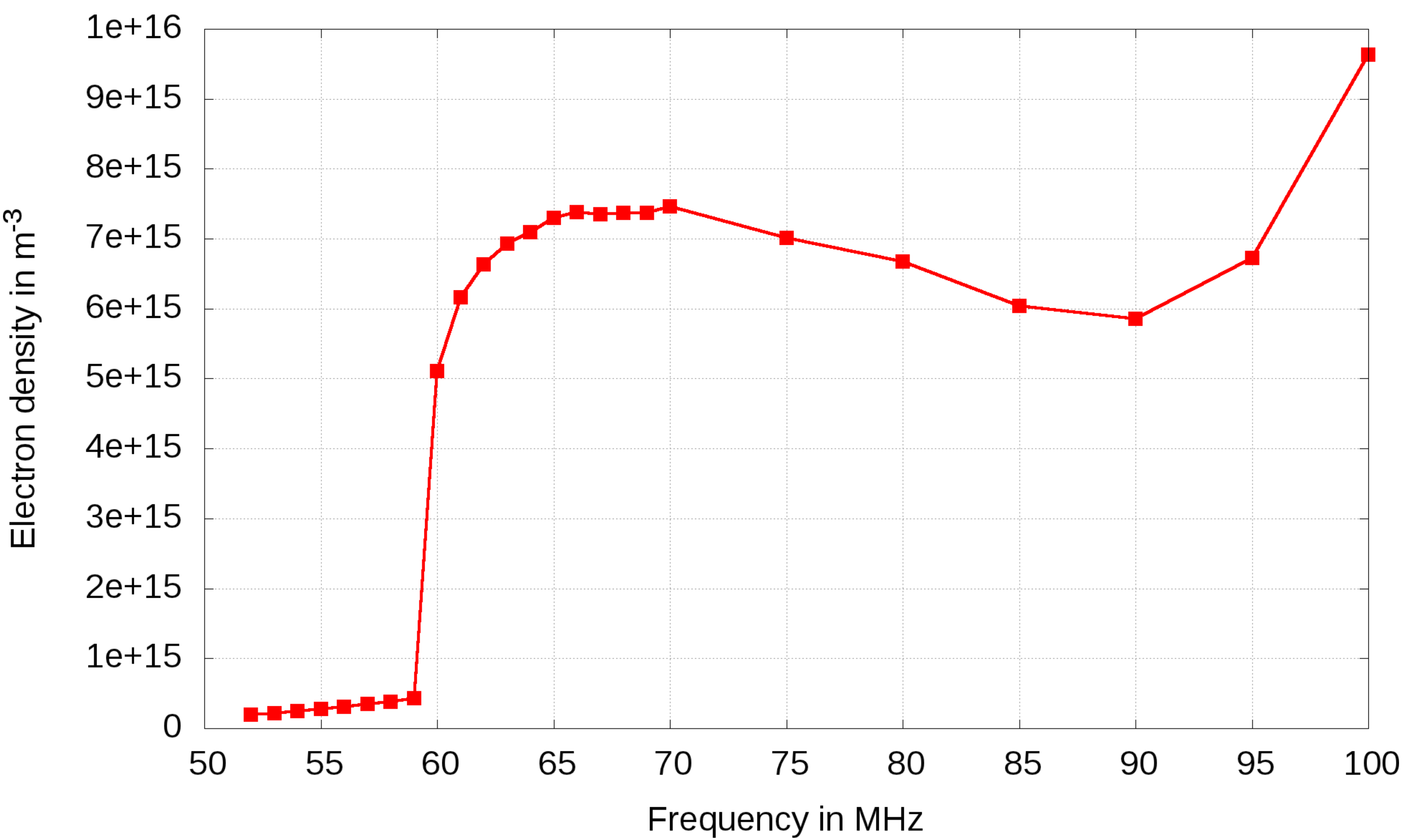




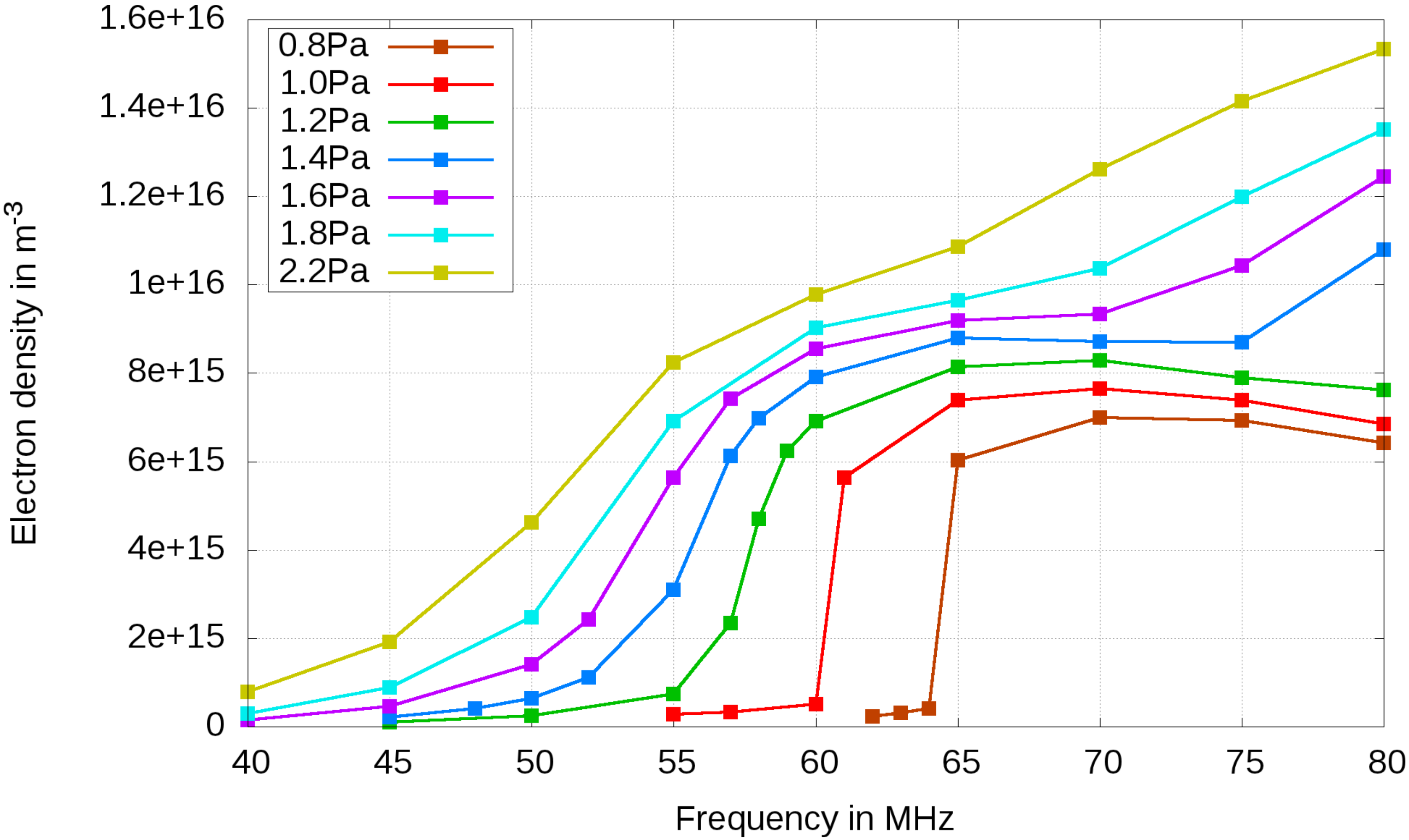
Frequency variation (different pressures)



Averaged electron density over the driving frequency (1Pa)

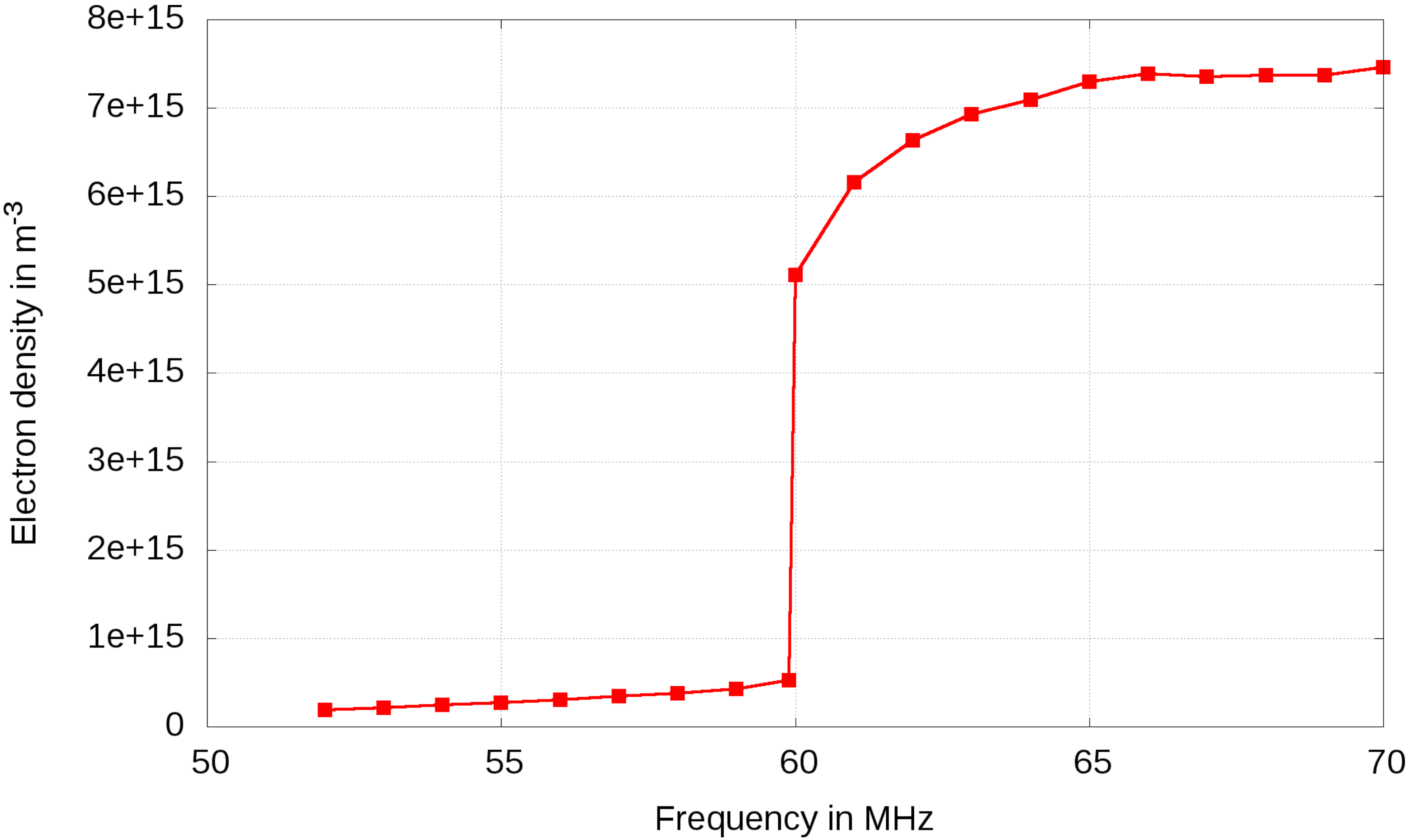


Pressure variation



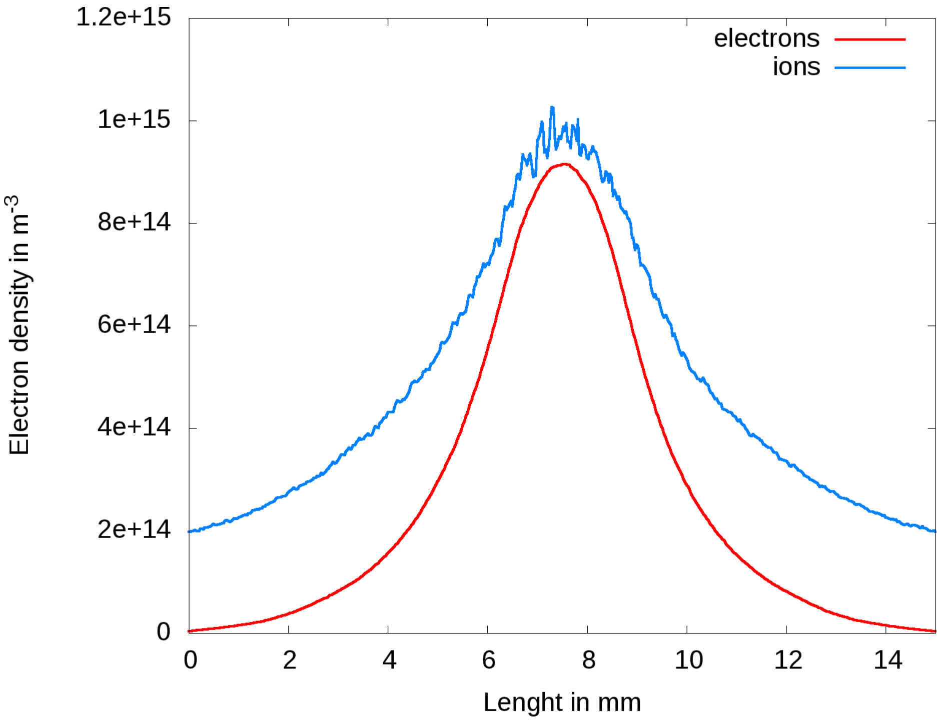
- abrupt transition disappears for higher pressures
- low pressure effect

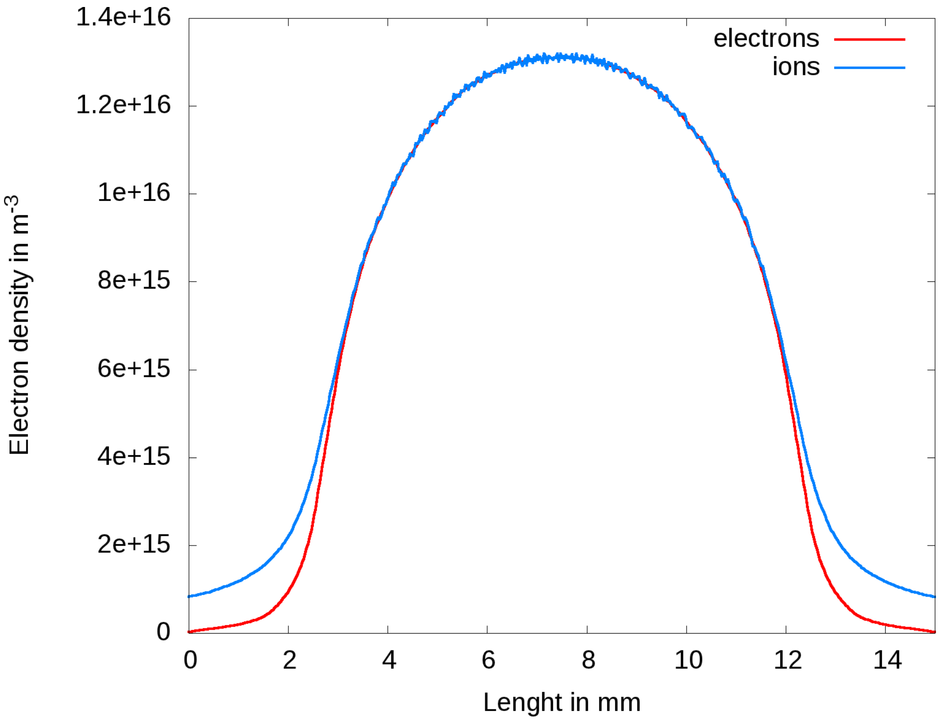
Averaged electron density over the driving frequency



- abrupt transition by changing the frequency from 59MHz to 60MHz
- compare the plasma characteristics of 55MHz (lower density mode) and 65MHz (higher density mode)

Phase-averaged electron and ion density

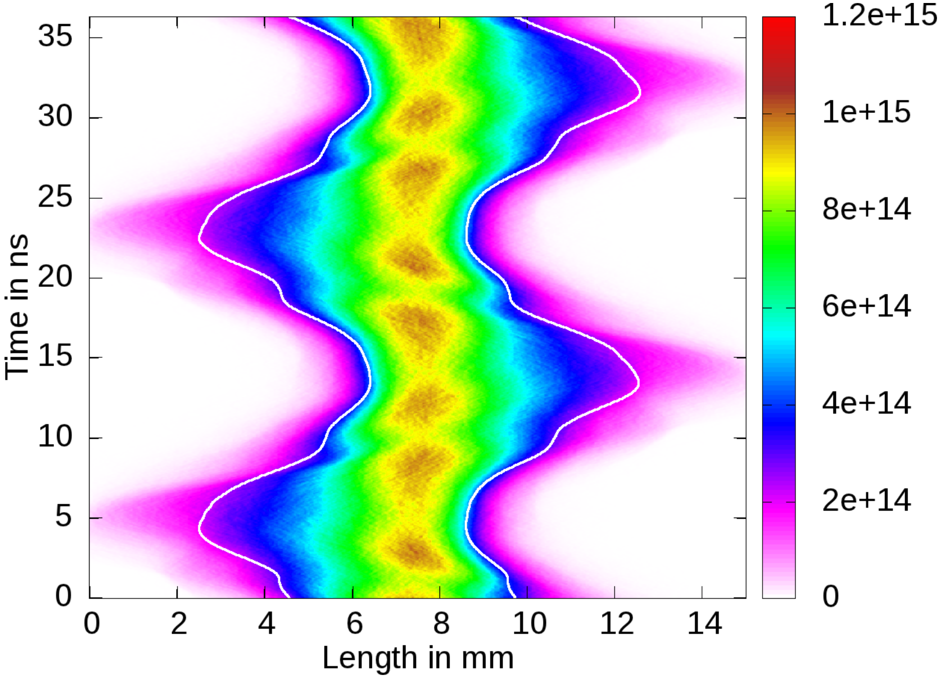


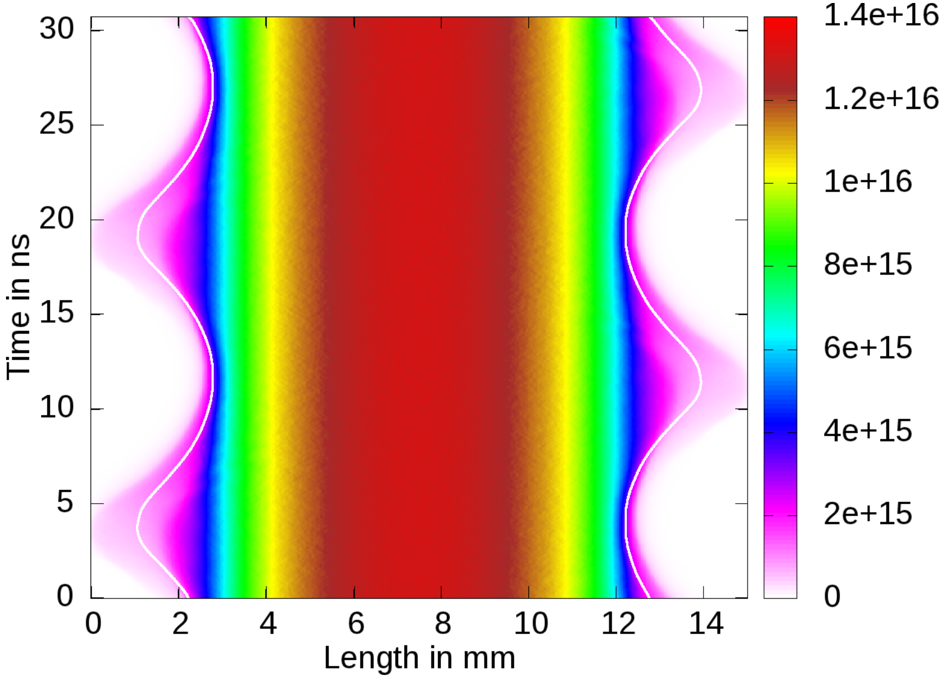


- 55 MHz (lower density mode)
- large plasma sheath
- quasineutrality is not satisfied (on average)

- 65 MHz (higher density mode)
- small plasma sheath
- plasma bulk is quasineutral

Spatio-temporal distribution of electrons in m^{-3}

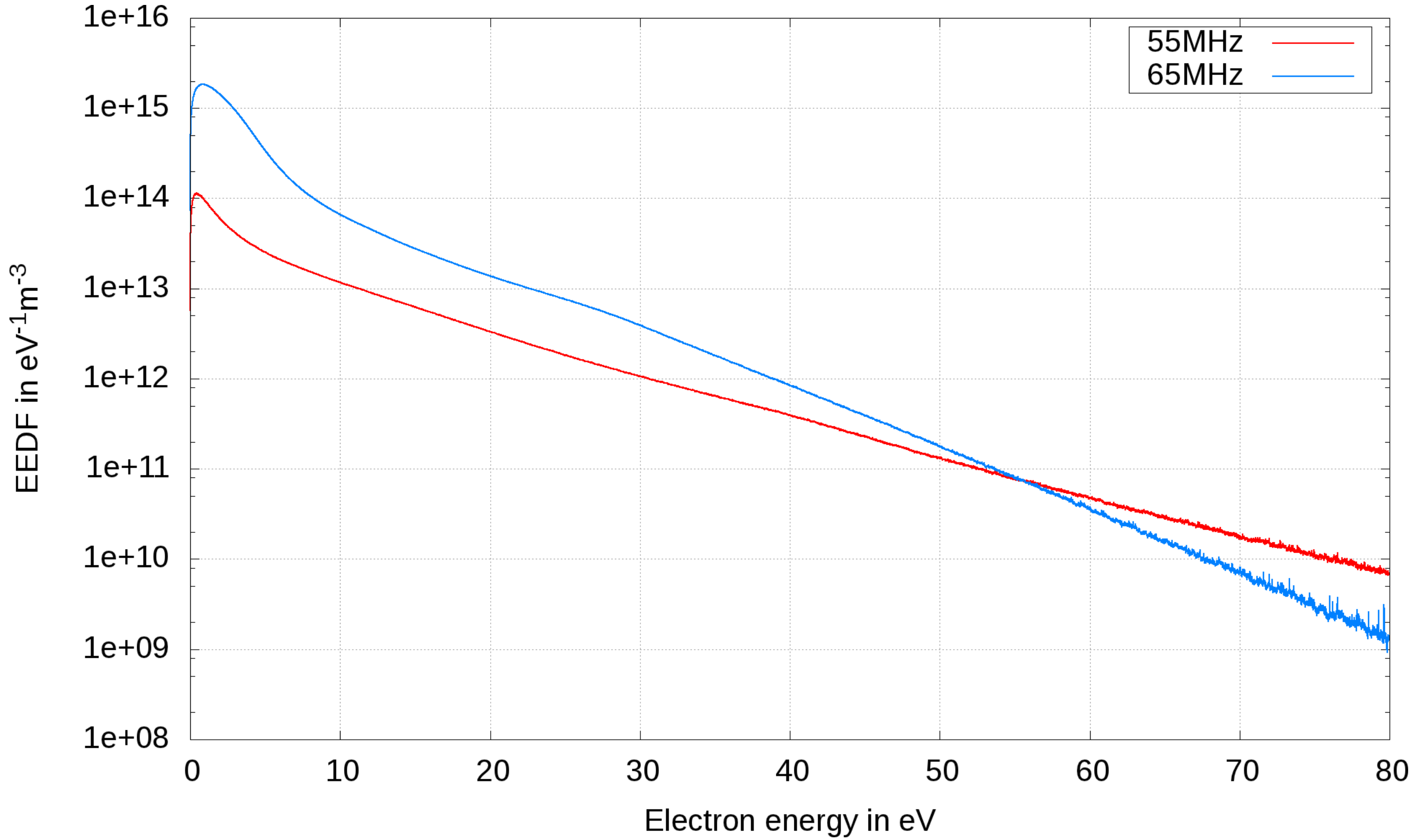




- 55 MHz (lower density mode)
- fast sheath expansion
- bend during the expanding and collapsing phase
- non-uniform distribution of electrons in the center of the discharge

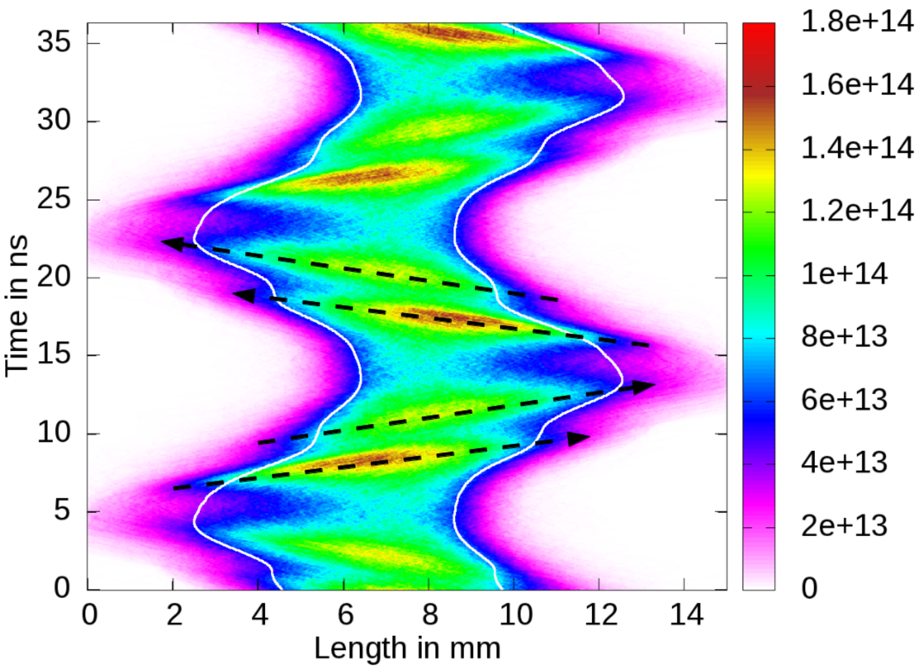
- 65 MHz (higher density mode)
- slow sheath expansion
- sinusoidal sheath movement
- uniform distribution

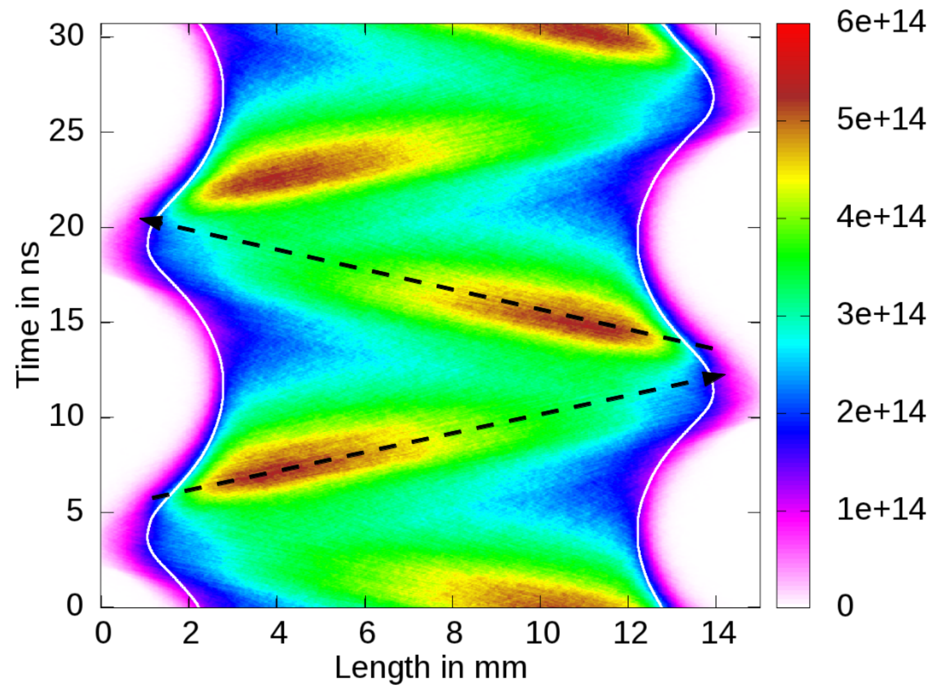
Electron Energy Distribution Function (EEDF)



- more highly energetic electrons (<60eV) for 55MHz
- accelerated by the large plasma sheath

Spatio-temporal distribution of fast electrons in m^{-3}



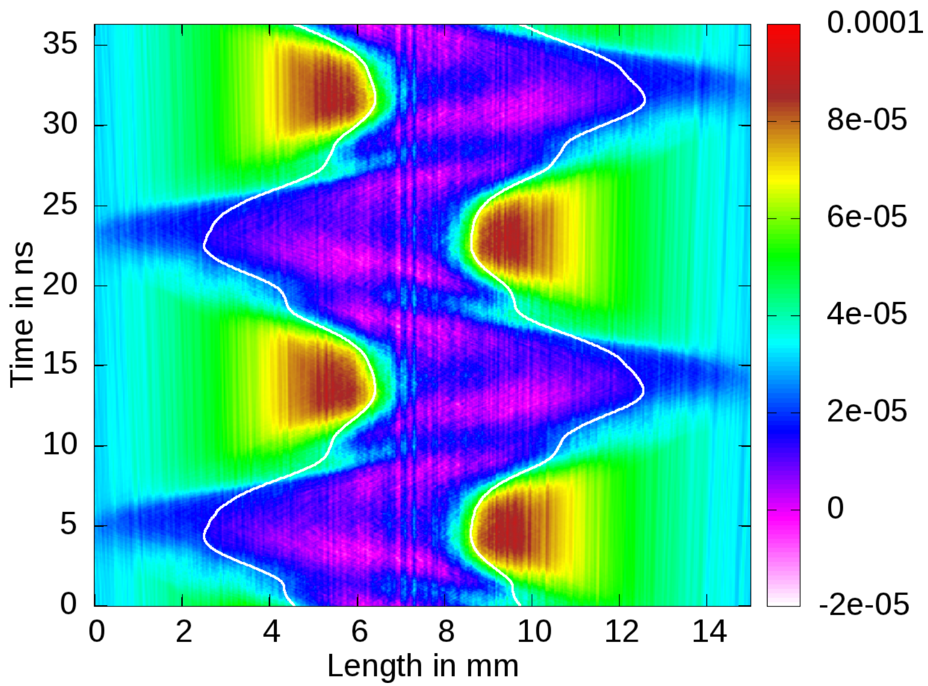


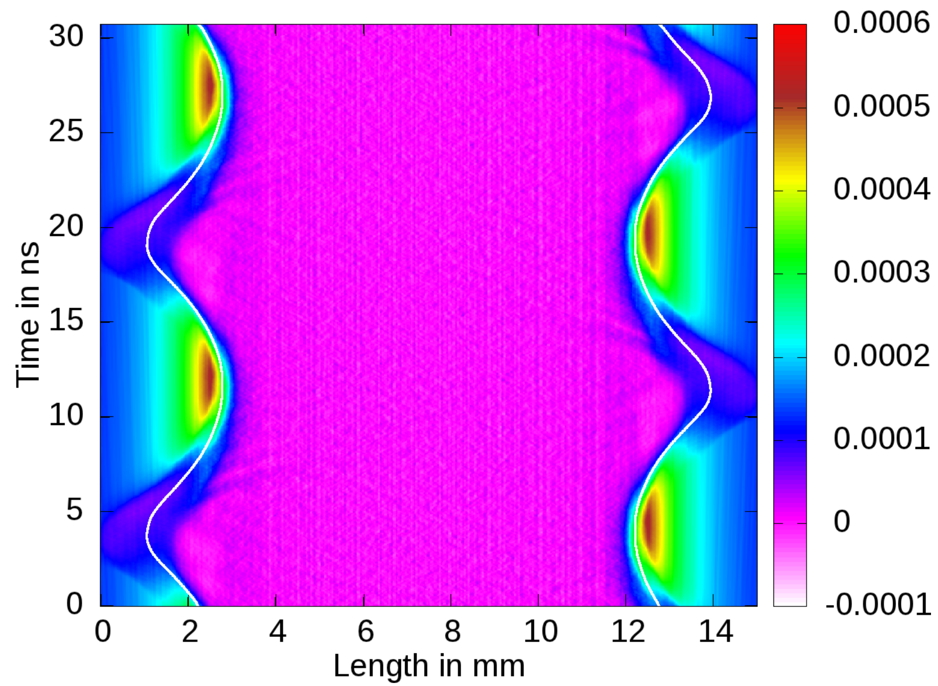
- 55 MHz (lower density mode)
- two-beam structures
- electron energy lost at the electrodes: 29eV

- 65 MHz (higher density mode)
- just one-beam structure
- electron energy lost at the electrodes: 19eV

Spatio-temporal distribution of the charge density in $\frac{\mathrm{As}}{\mathrm{m}^3}$

RUB

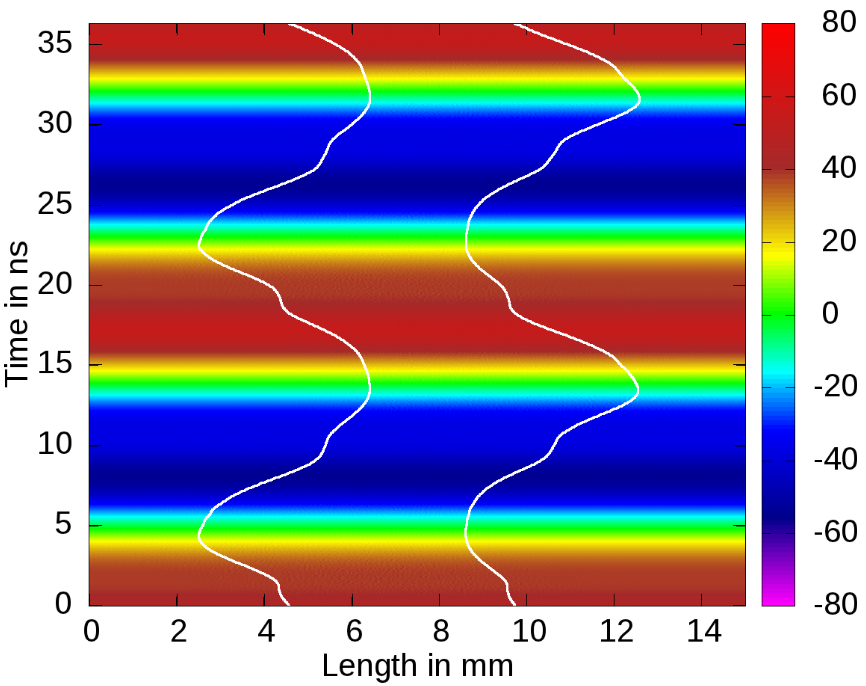


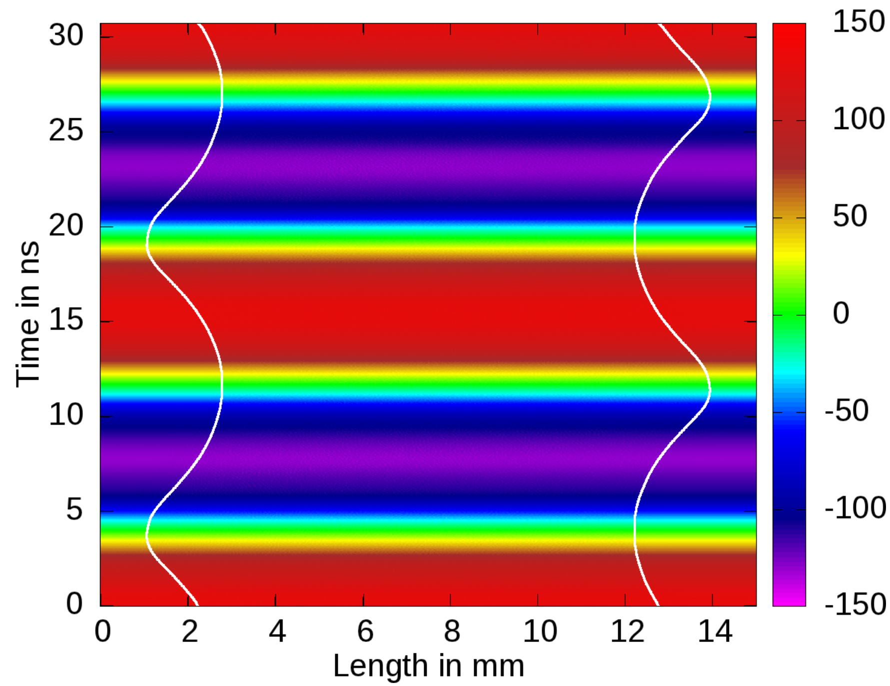


- 55 MHz (lower density mode)
- no quasi neutrality
- high electric fields in the bulk
- displacement current

- 65 MHz (higher density mode)
- quasi neutrality

Spatio-temporal distribution of the total current in $\frac{\mathbf{A}}{\mathbf{m}^2}$

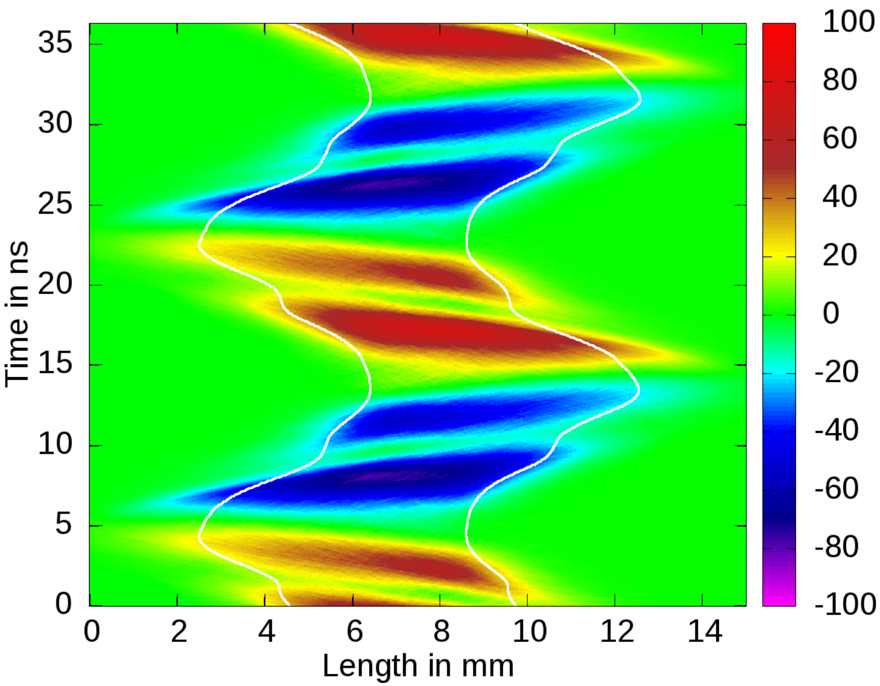


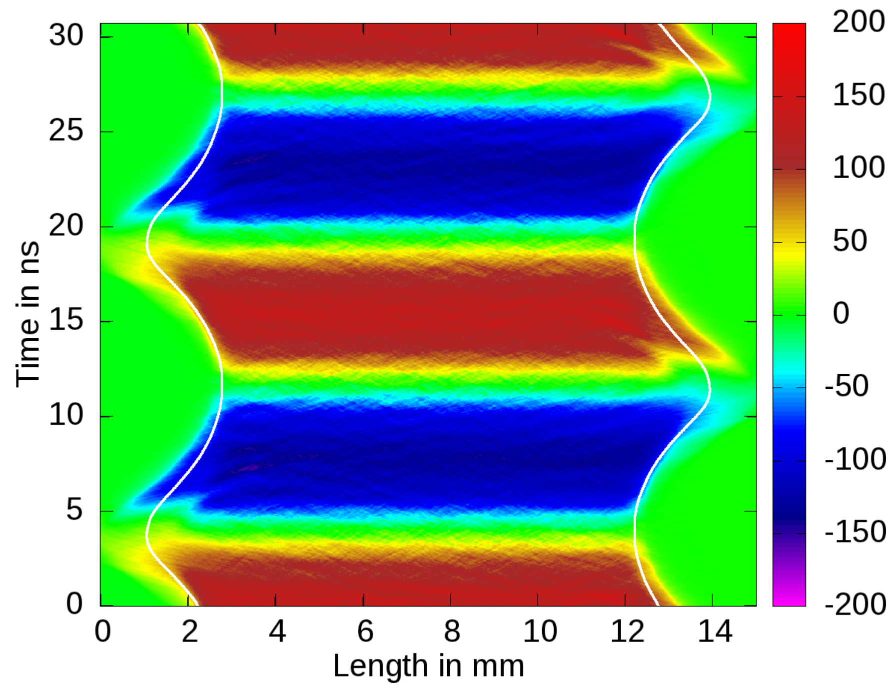


- 55 MHz (lower density mode)
- 65 MHz (higher density mode)

- total current is homogeneous over space
- conduction current: $j_c = e(\Gamma_i - \Gamma_e)$
- displacement current: $j_d = \varepsilon_0 \frac{dE}{dt}$
- total current: $j_t = j_c + j_d$

Spatio-temporal distribution of the conduction current in $\frac{\text{A}}{\text{m}^2}$



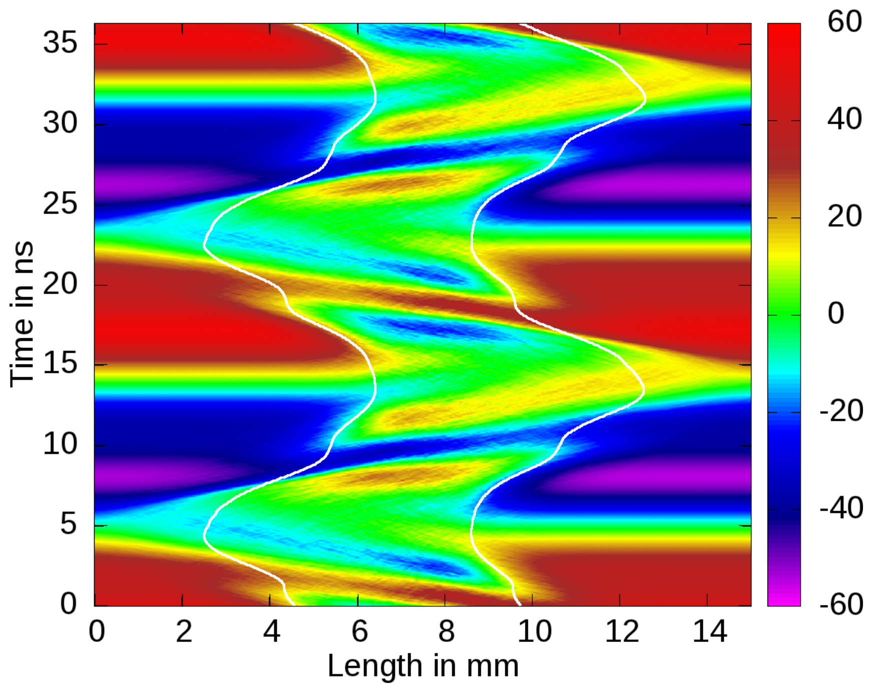


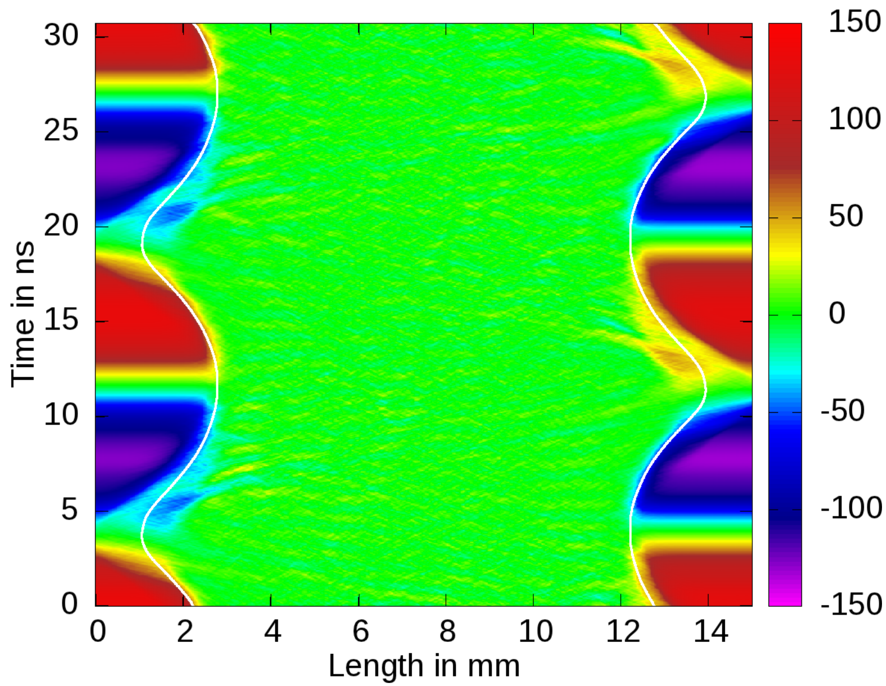
- 55 MHz (lower density mode)
- modulated by the 2 electron beams
- no conduction current between the beam formation and in the plasma sheath

- 65 MHz (higher density mode)
- uniformly distributed
- no cunduction current in the plasma sheath

Spatio-temporal distribution of the displacement current in $\frac{\mathrm{A}}{\mathrm{m}^2}$

RUB

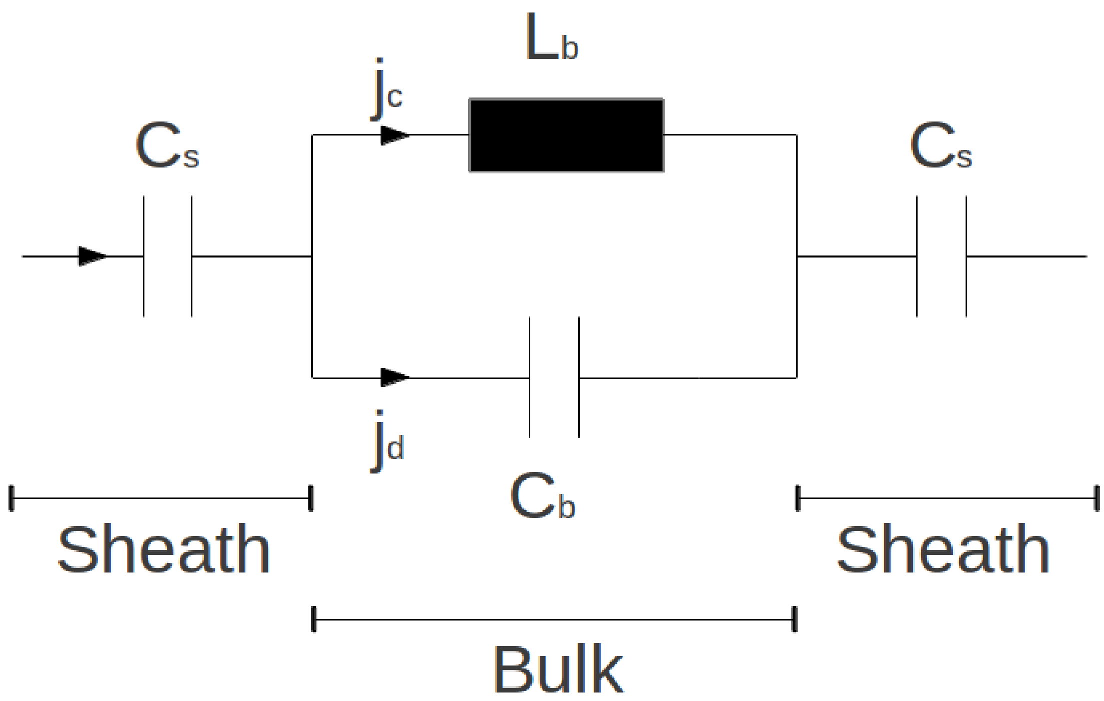




- 55 MHz (lower density mode)
- displacement current in the center of the discharge
- interplay between the displacement and conduction current

- 65 MHz (higher density mode)
- classical behaviour
- displacement current in the plasma sheath
- conduction current in the plasma bulk

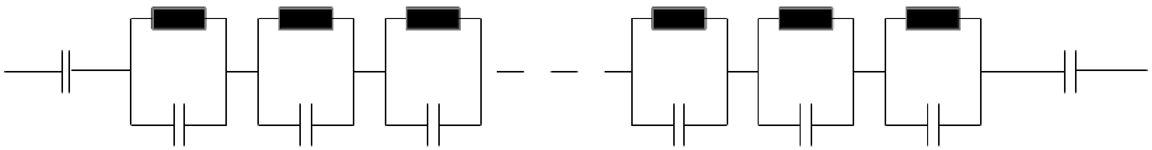
Parallel resonance

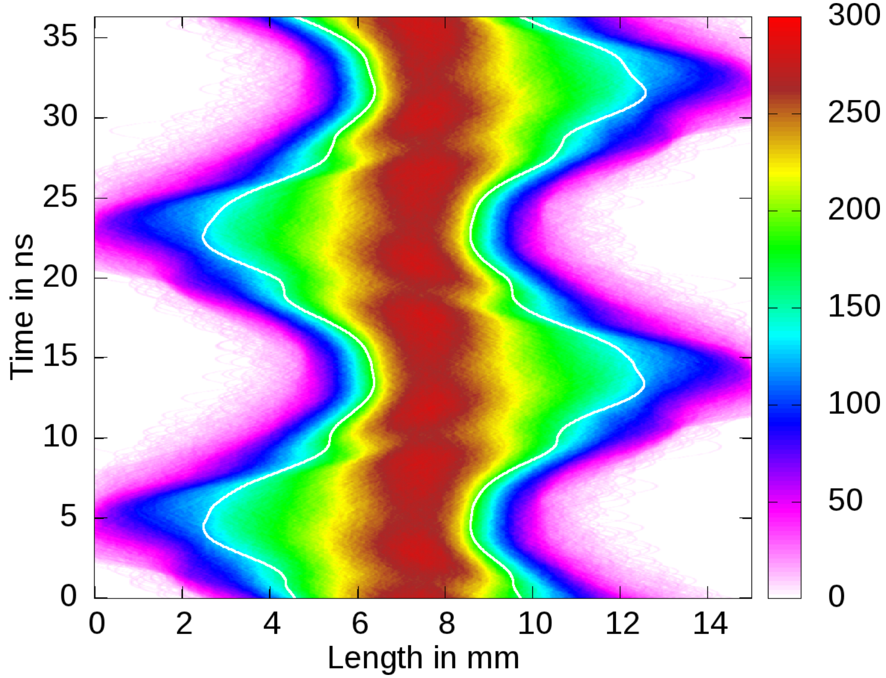


$$Y = j\omega C_b + \frac{1}{j\omega L_p}$$

$$\omega_R = \sqrt{\frac{1}{C_p \cdot L_p}} = \sqrt{\frac{1}{\frac{\epsilon_0 A}{s} \cdot \frac{m_e s}{n_e e^2 A}}} = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}} = \omega_{pe}$$

Excitation of local resonances (local plasmafrequency)





Spatio-temporal distribution of the plasmafrequency in MHz

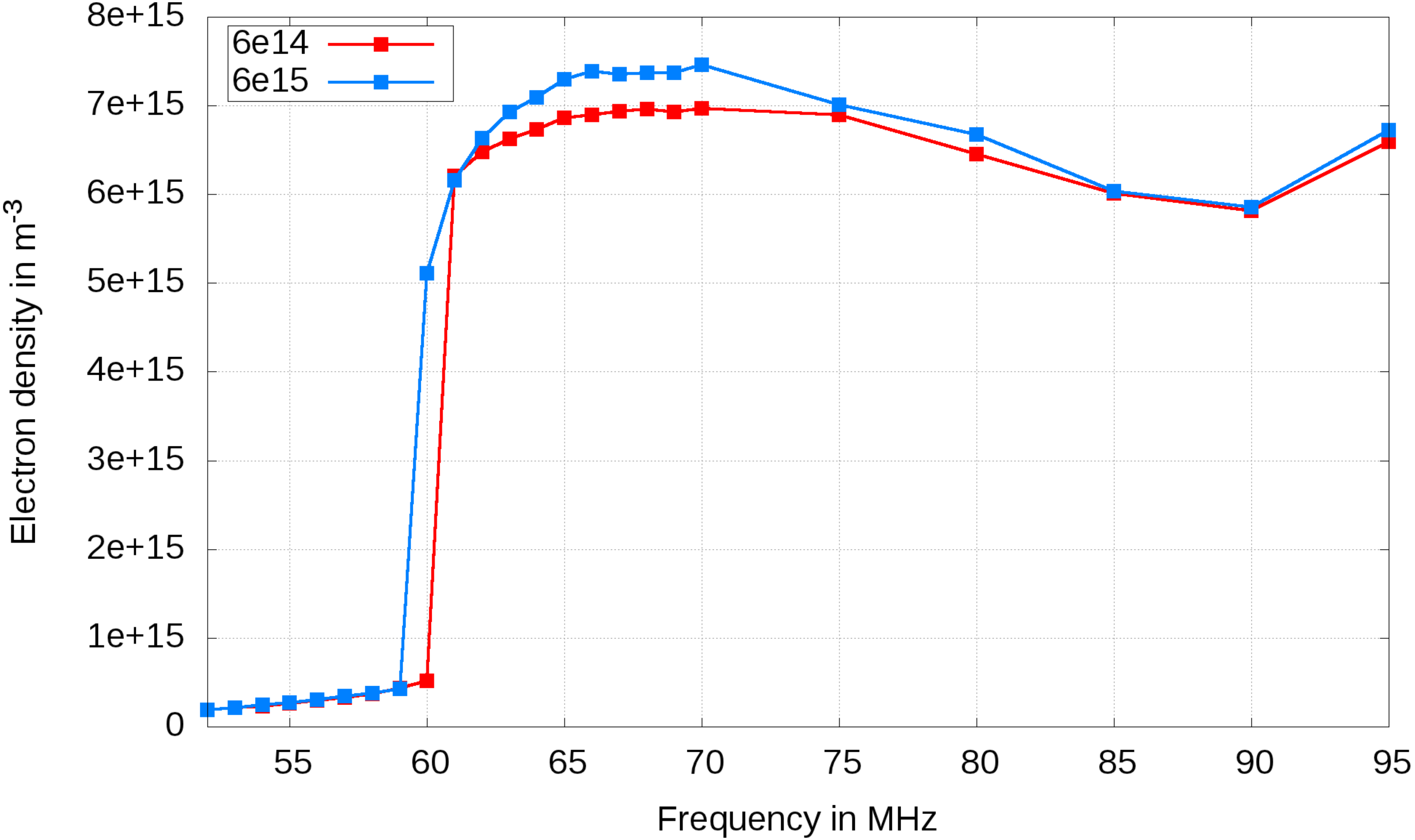
- non-uniform plasma model[4]
- infinite number of elementary cells each one constituted by an inductor an a capacitor in parallel
- consider a local plasmafrequency
- $\omega_{pe}(x) = \sqrt{\frac{n_e(x)e^2}{m_e\epsilon_0}}$

[4]Victor P.T. Ku et al., J. Appl. Phys. 84, 6536 (1998) Plasma-sheath resonances and energy absorption in ccrf plasmas

Conclusion

- with decreasing gap size or frequency the impingement phase of fast electrons is changing from the expanding to the collapsing phase
- abrupt transition between the impingement of the collapsing and expanding phase
- appearance of a two-beam structure
- excitation of local resonances, which could be responsible for the second beam formation
- Outlook
  - more information about resonance effects
  - transition is complimented by the appearance of a hysteresis
  - beam formation in large-area ccps in conjunction to electromagnetic effects (2d Darwin-PIC)

Outlook: Hysteresis



Outlook: Currents (55MHz) with FT of the discharge center