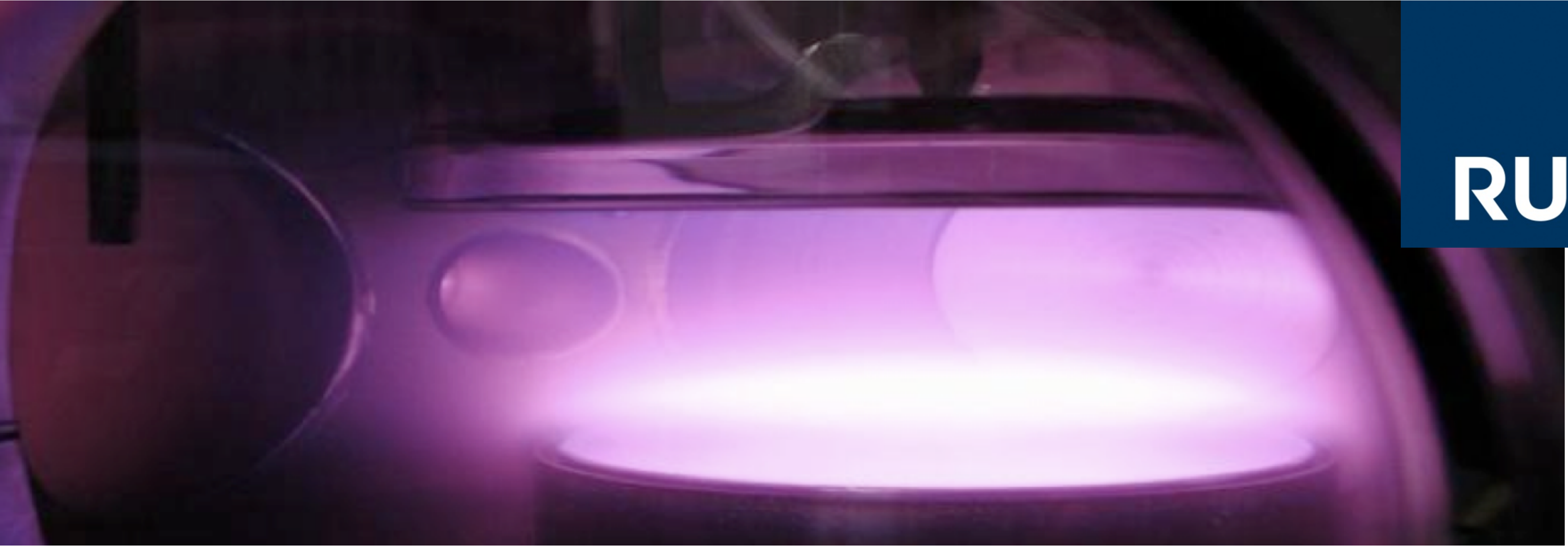

Analyse der Dynamik von RF-modulierten Elektronenbeams in kapazitiv gekoppelten Plasmen

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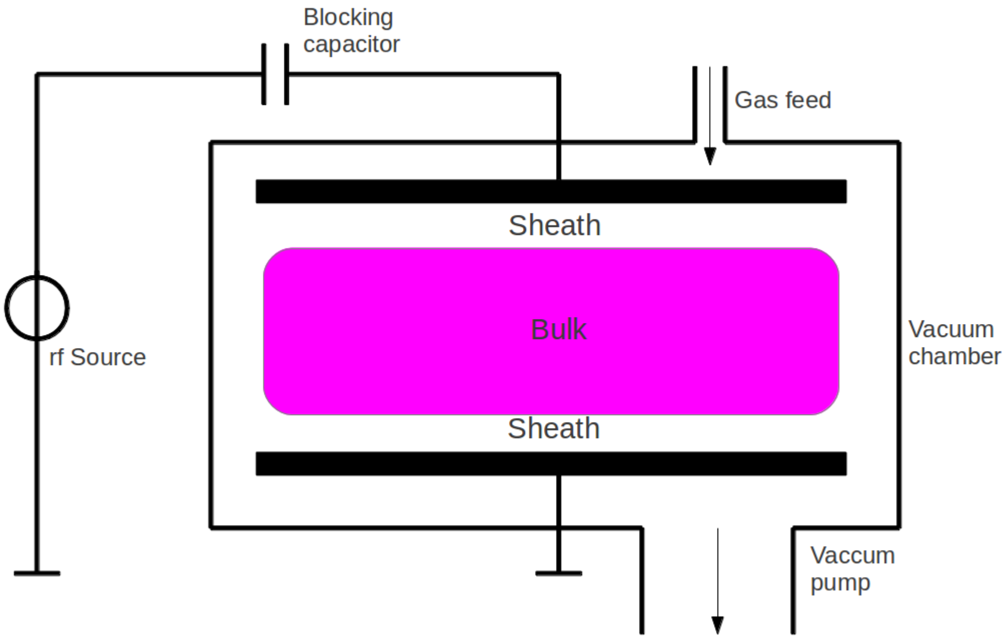
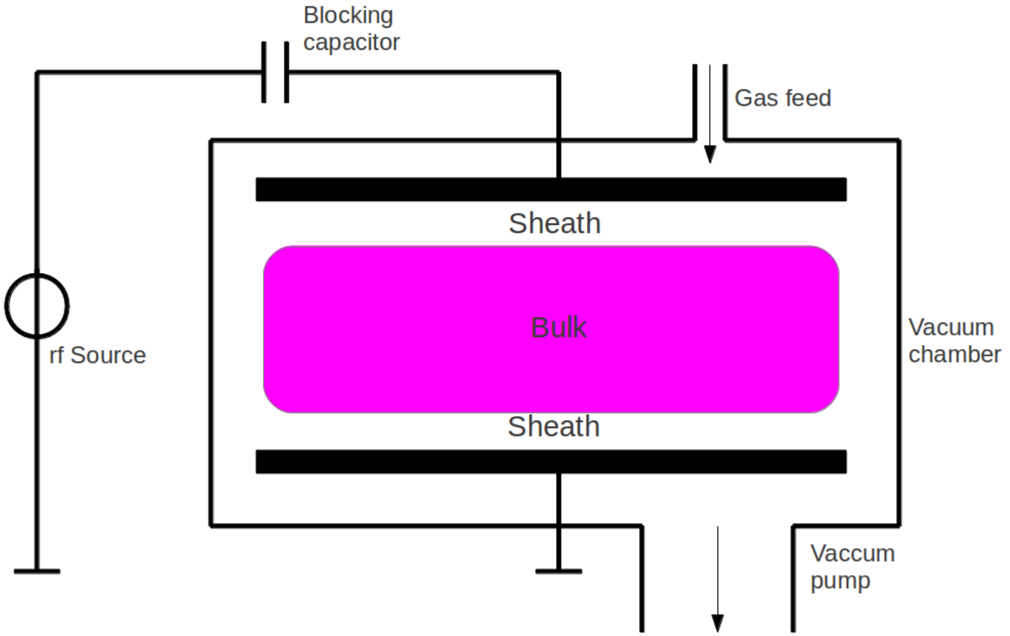
[1]Ruhr-University Bochum
[2]West Virginia University
[2]Wigner Research Centre for Physics

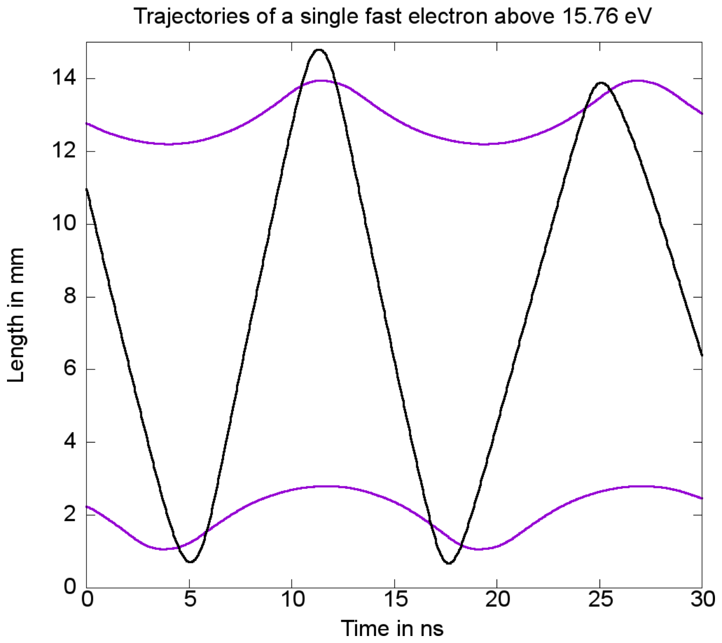
Electron heating in ccrf discharges



- classical capacitively coupled radio frequency discharge
- typical process parameters: pressure, gas, input power, driving frequency, reactor geometry, gap size
- in low-pressures ($p < 10$ Pa) stochastische heating is dominant

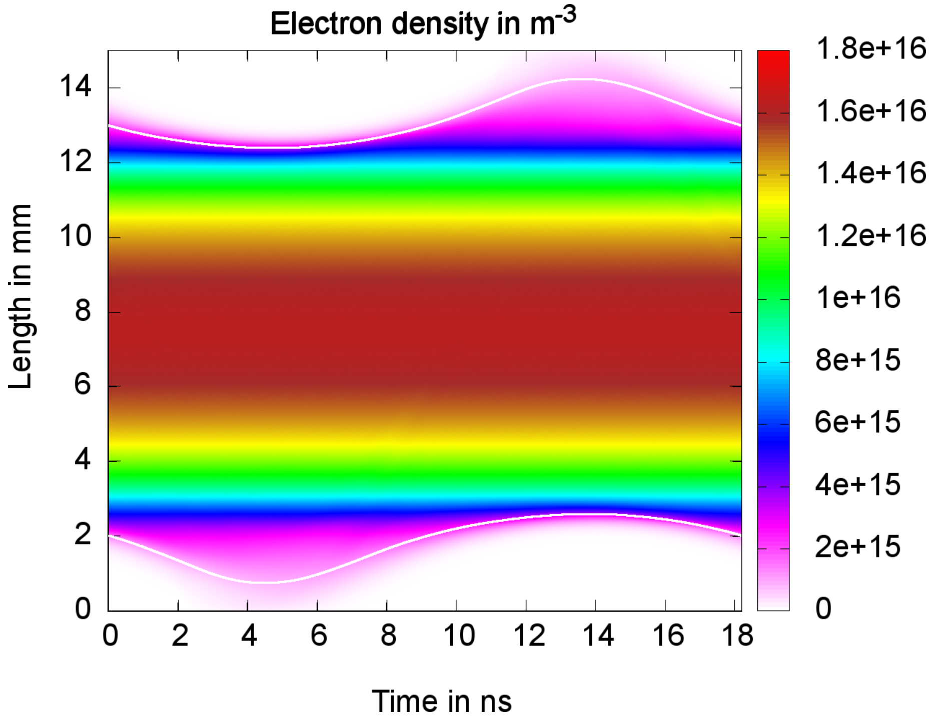
Electron heating in ccrf discharges





- electron interaction/reflection at the rf-modulated boundary sheaths
- **Which process parameters influence the electron dynamics?**
- focus on: pressure, driving frequency, gap size

Spatio-temporal distribution of the electron density



- 3 Pa argon, 15 mm gap size, 150 V, 55 MHz ($\approx 4 \cdot 13.56$ MHz)
- 1d3v Particle-In-Cell Simulation[1]
- homogeneous electron density in the plasma bulk
- electrons modulated in the plasma sheath

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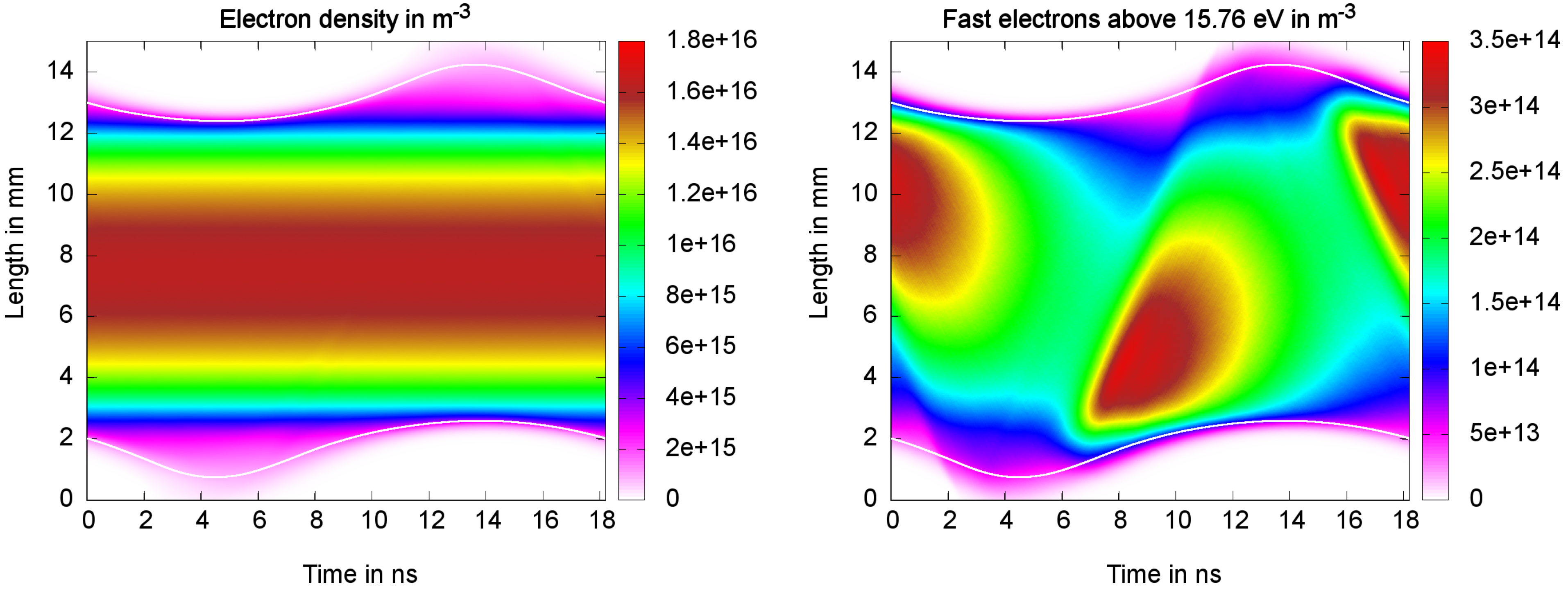
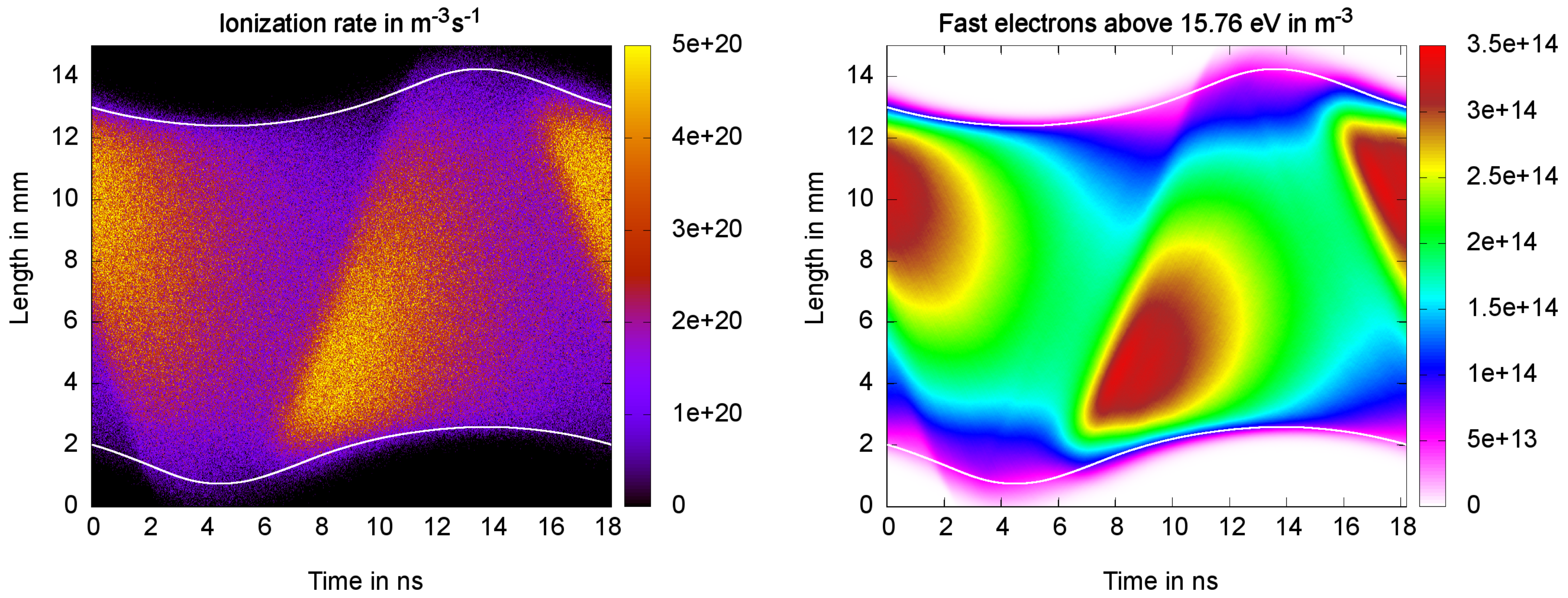
[1] M.M. Turner et. al, Phys. Plasmas 20, 013507 (2013)

Spatio-temporal distribution of fast electrons (ε > 15.76 eV)



- 3 Pa argon, 15 mm gap size, 150 V, 55 MHz ($\approx 4 \cdot 13.56$ MHz)
- extract all electrons above 15.76 eV (ionization threshold of argon)
- sheath expansion accelerates energetic electrons
- directed acceleration $\Longrightarrow$ beam-character

Spatio-temporal distribution of the ionization rate



- 3 Pa argon, 15 mm gap size, 150 V, 55 MHz ($\approx 4 \cdot 13.56$ MHz)
- responsible for the ionization process (sustain the plasma)
- influences the plasma density as well as the EEPF
- experimental measurement with PROES[2]

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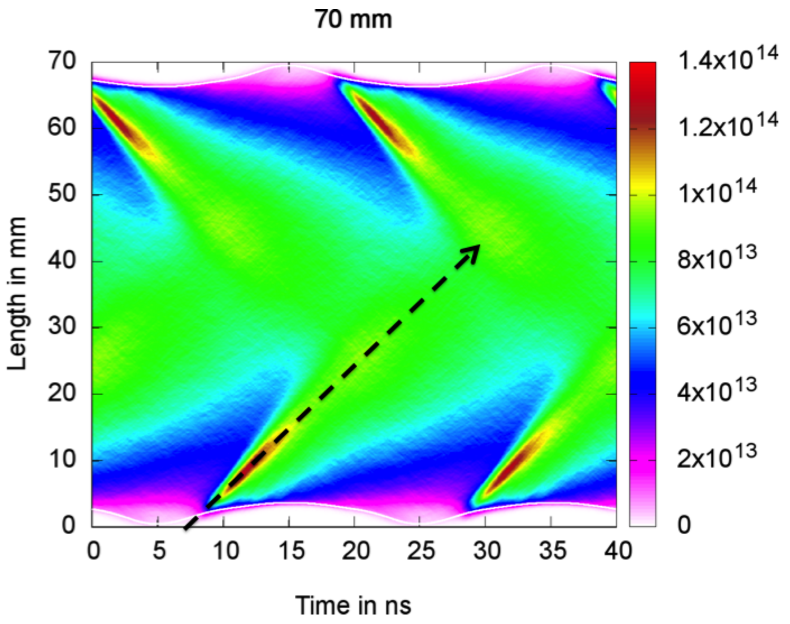
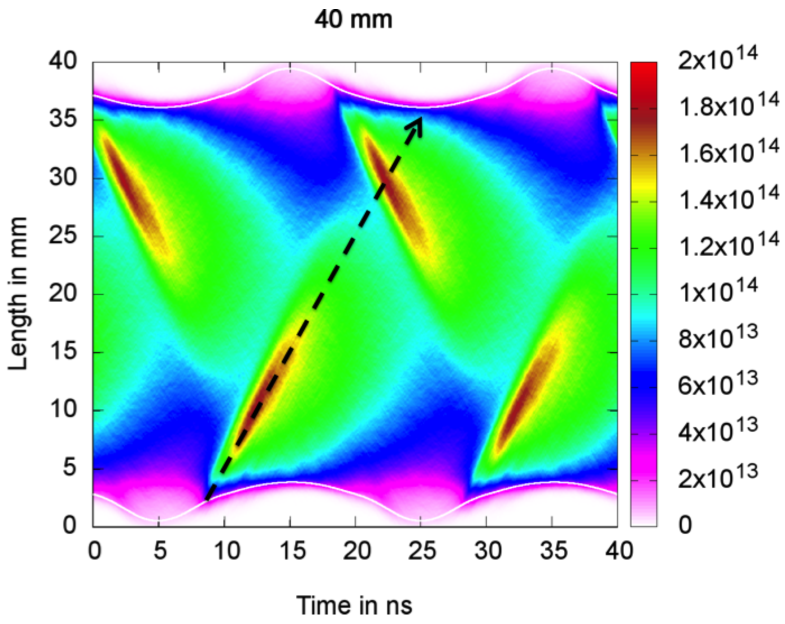
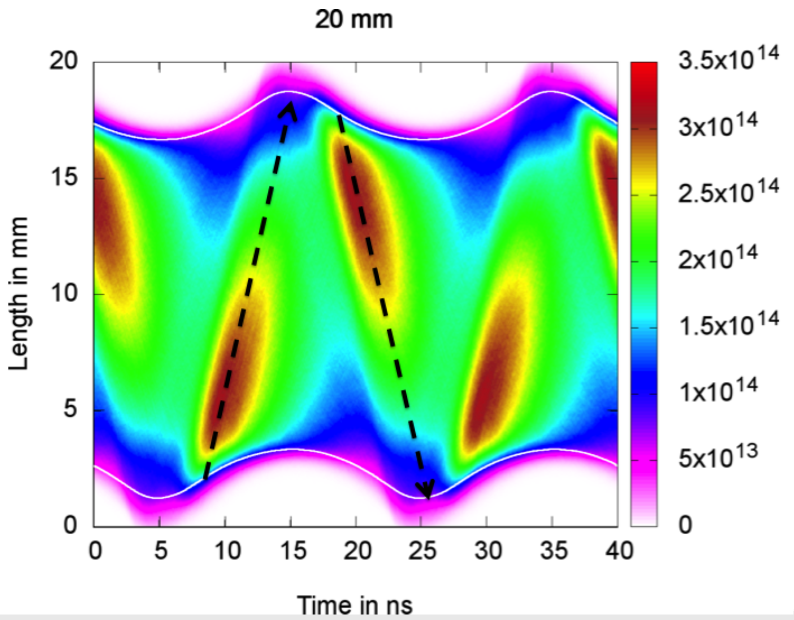
[2] J. Schulze et al., J. Phys. D: Appl. Phys. 41, 042003 (2008)

Influence of gap size and gas pressure

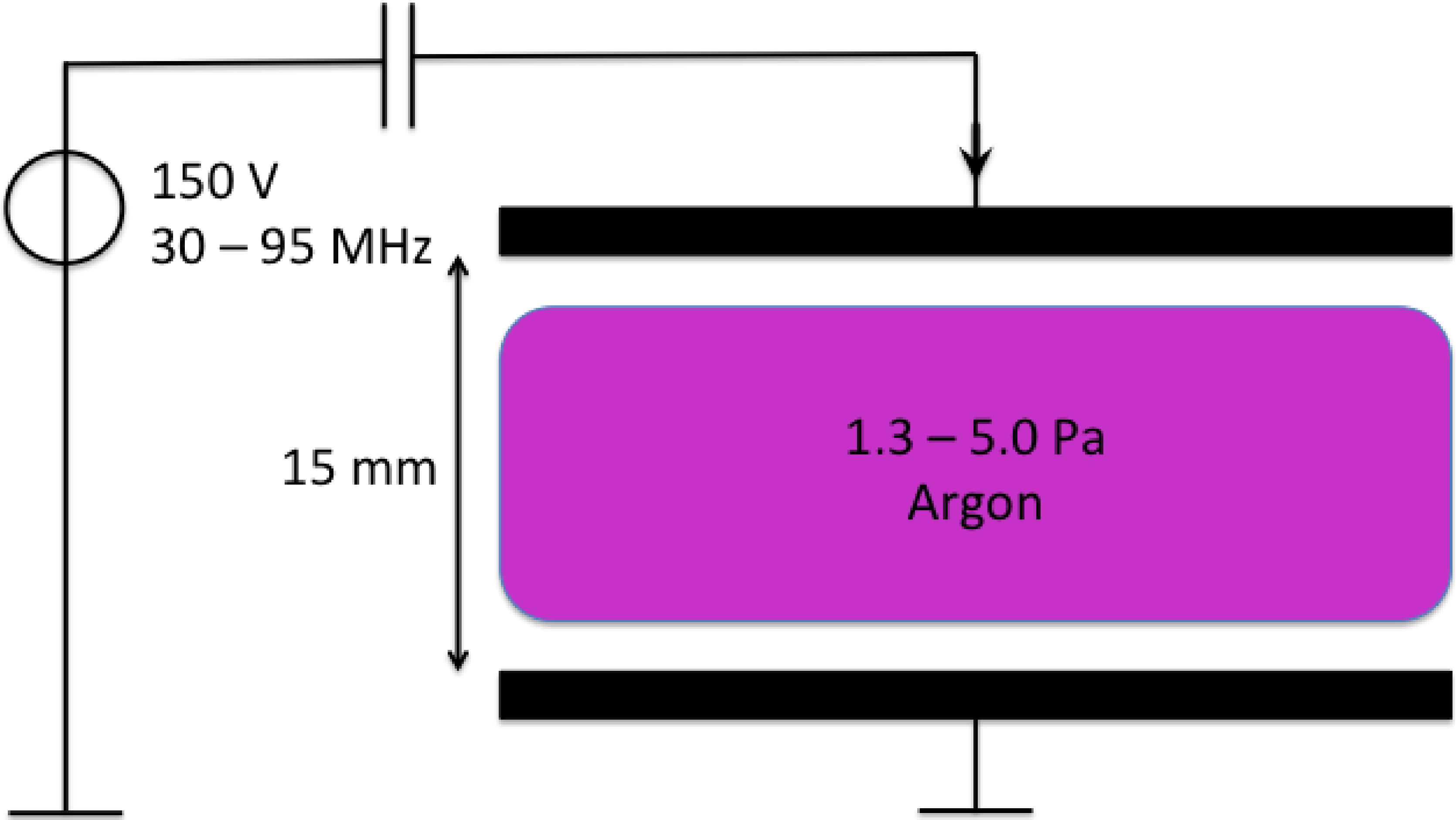






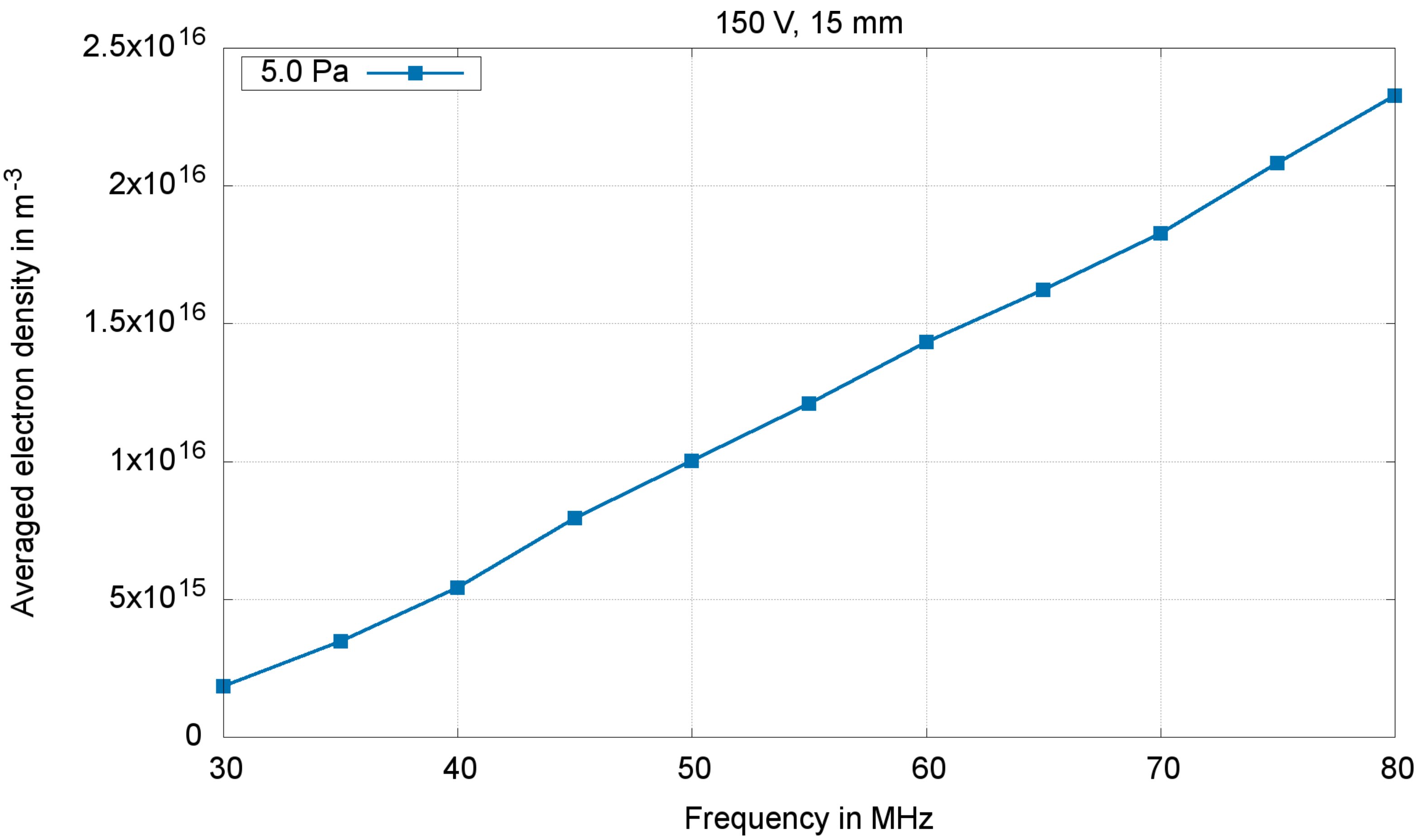
- 150 V, 50 MHz
- 1 Pa argon $\Longrightarrow \lambda_m \approx 45$ mm
- 70 mm: $\frac{\lambda_m}{L_{gap}} \approx \frac{45mm}{70mm} = 0.64 < 1$
- 40 mm: $\frac{\lambda_m}{L_{gap}} \approx \frac{45mm}{40mm} = 1.12 \geq 1$
- 20 mm: $\frac{\lambda_m}{L_{gap}} \approx \frac{45mm}{20mm} = 2.25 > 1$

Variation of the driving frequency



- What is the influence of changing the frequency regarding the beam dynamics?
- experimental quite challenging!

Frequency variation (different pressures)



- $\frac{\lambda_m}{L_{gap}} < 1$ interaction with the oppsing sheath is not important
- linear/quadratic[3] trend of the electron density over the driving frequency ($n_e \sim f^2$)

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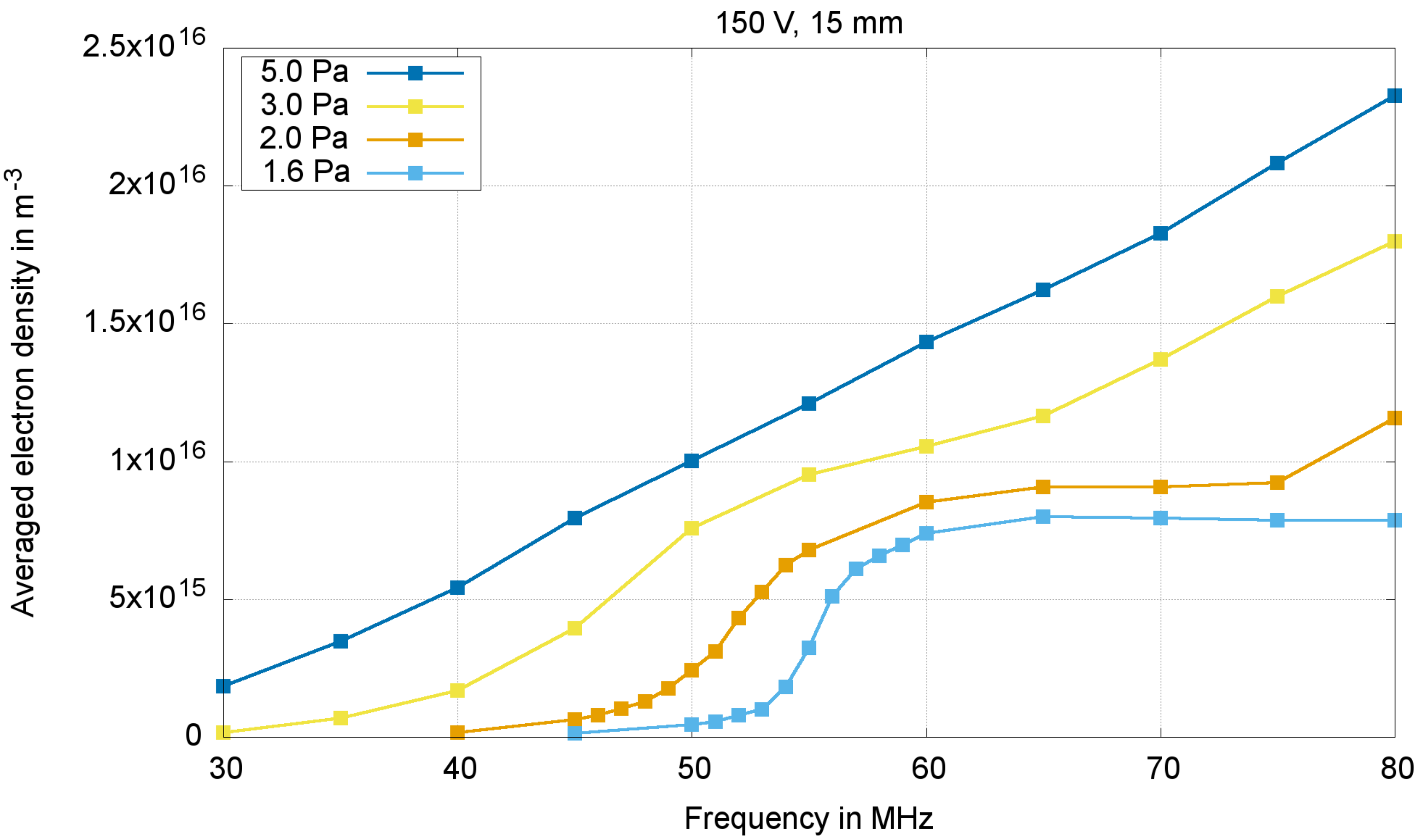
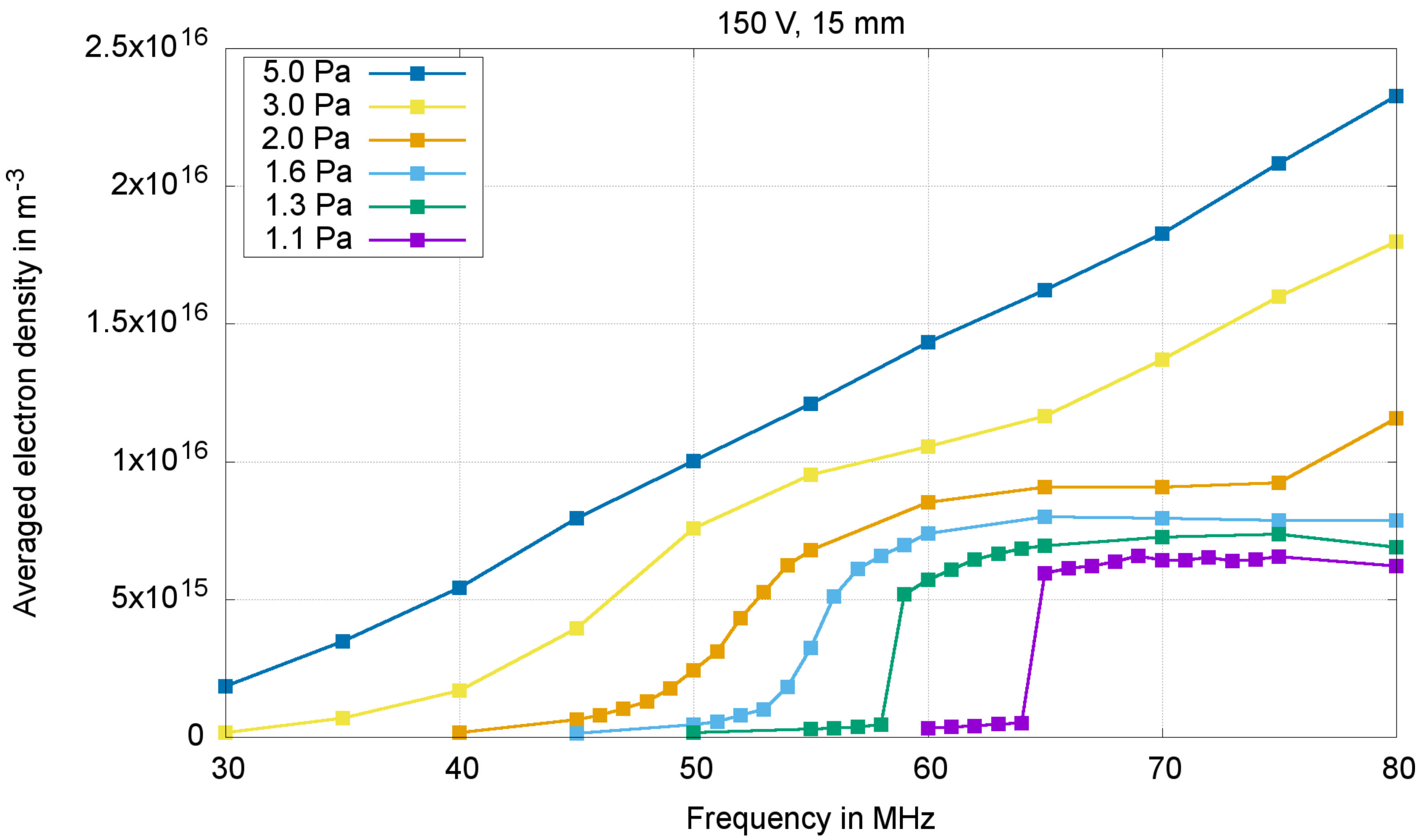
[3] M. A. Liebermann and A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing (2005)

Frequency variation (different pressures)



- $\frac{\lambda_m}{L_{gap}} \geq 1$ interaction with the opposing sheath becomes important
- density over frequency becomes non-quadratic

Frequency variation[4] (different pressures)



- $\frac{\lambda_m}{L_{gap}} > 1$ beam interaction is significant
- abrupt mode-transition (step-like increase (factor of 13))

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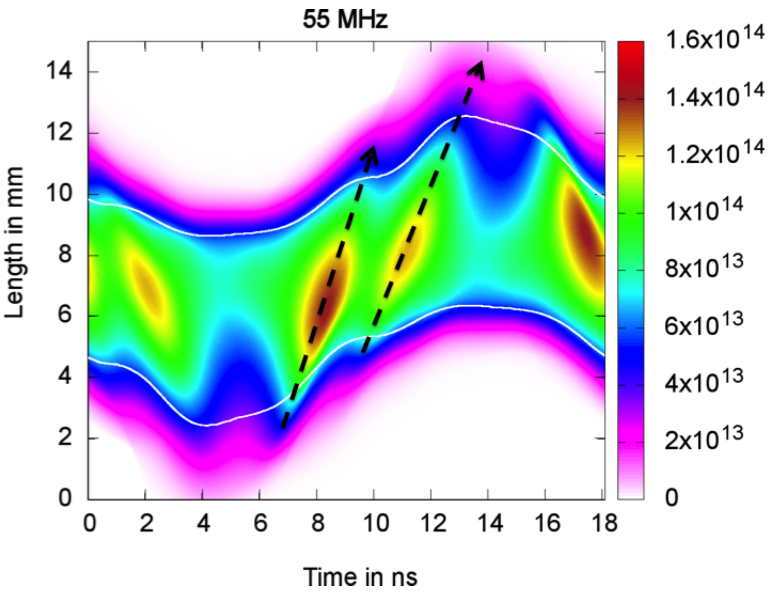
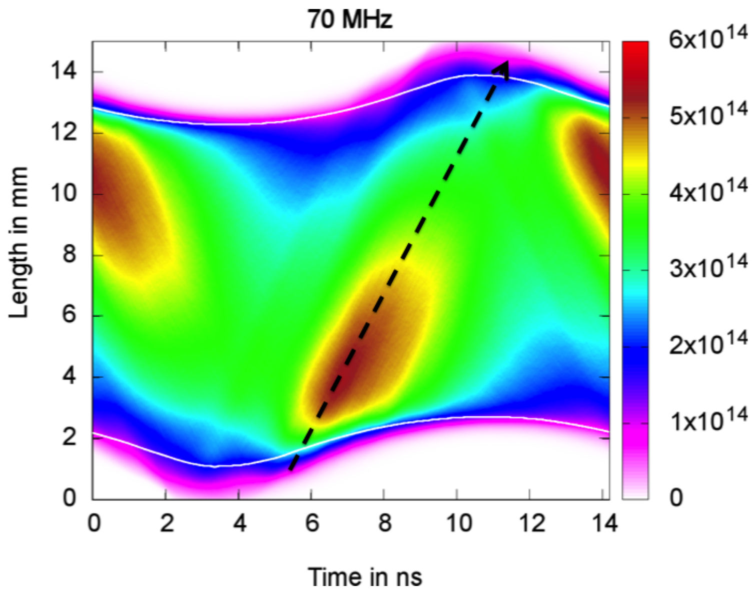
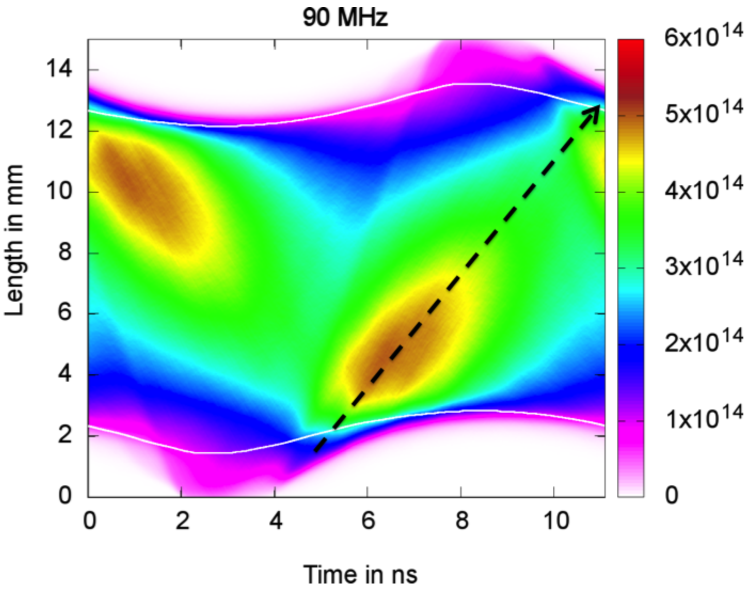
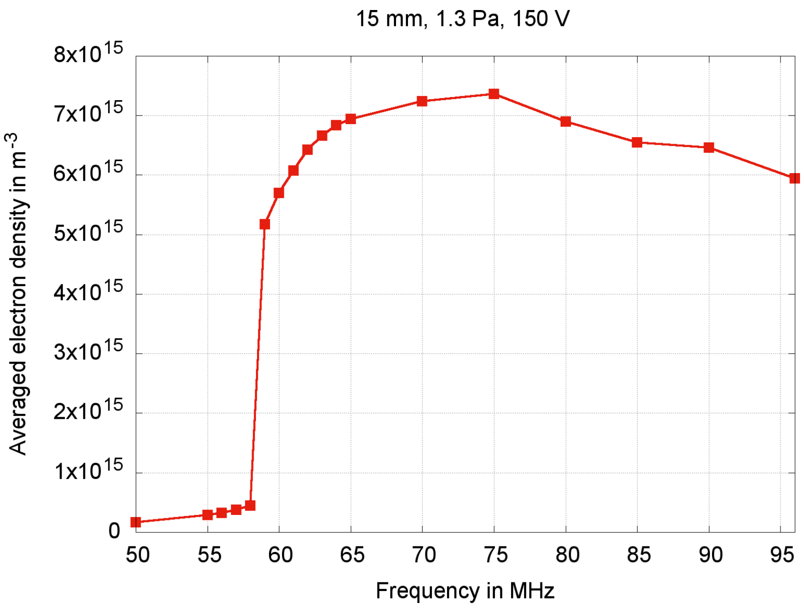
[4] S. Wilczek et. al, Plasma Sources Sci. Technol. 24, 024002 (2015)

Frequency variation: Impingement phase (1.3 Pa, 15mm)

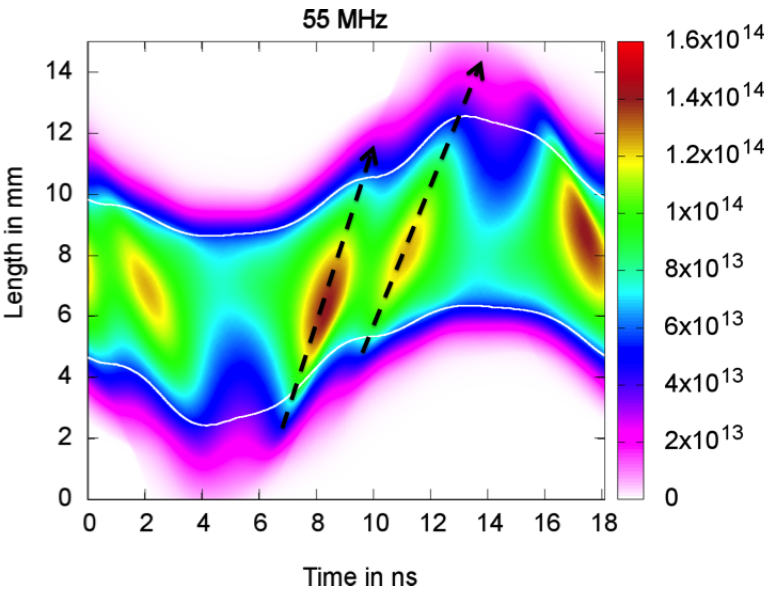

55 MHz

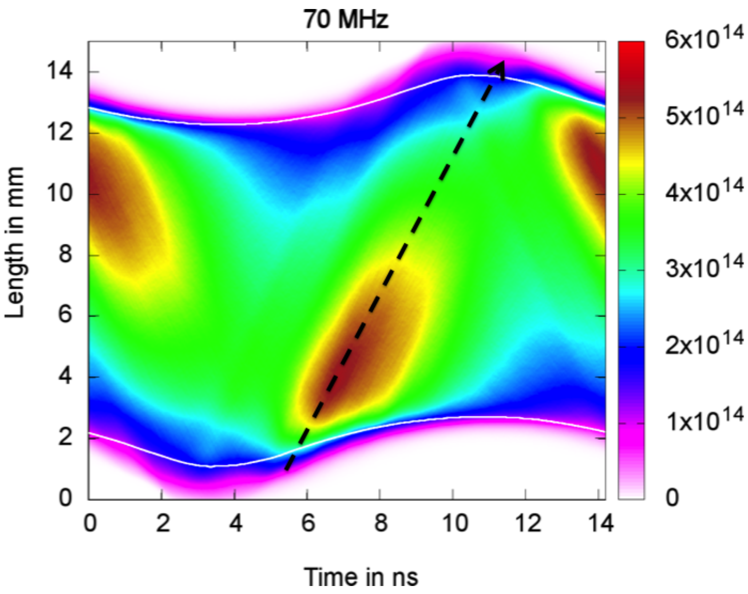

70 MHz

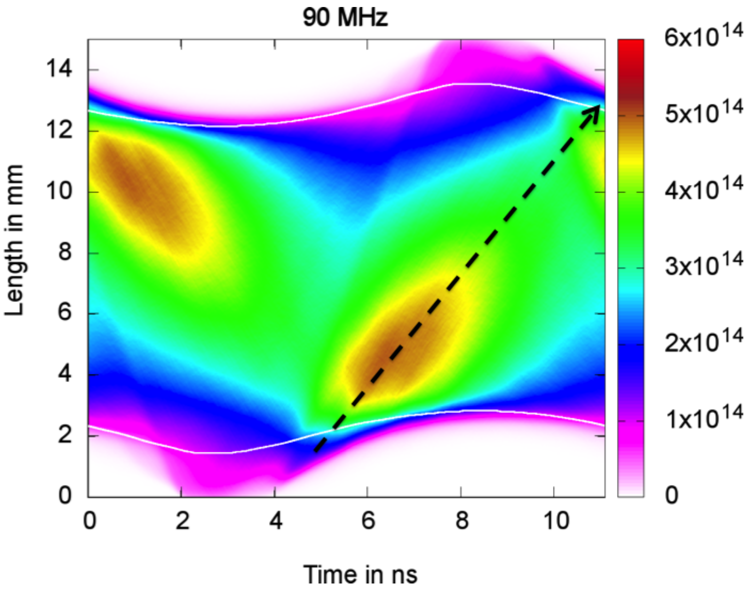

90 MHz

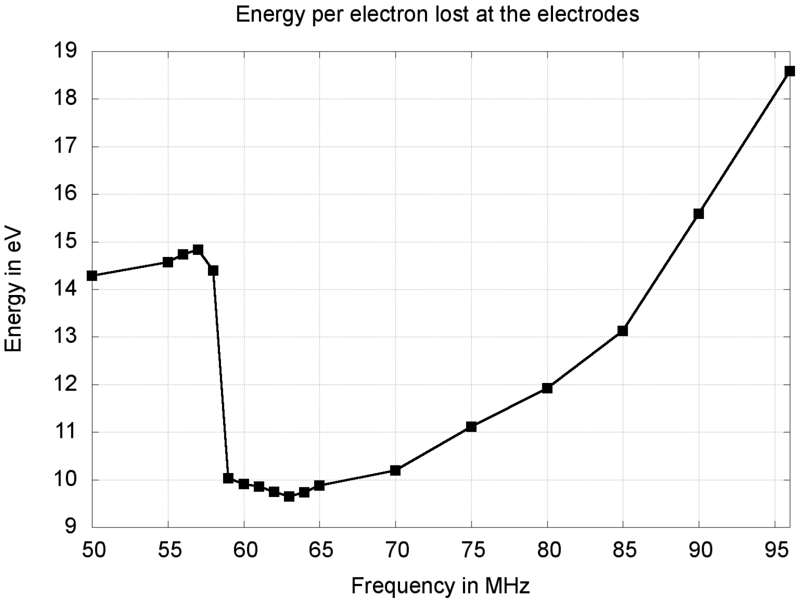

15 mm, 1.3 Pa, 150 V

Frequency variation: Energy loss (1.3 Pa, 15mm)

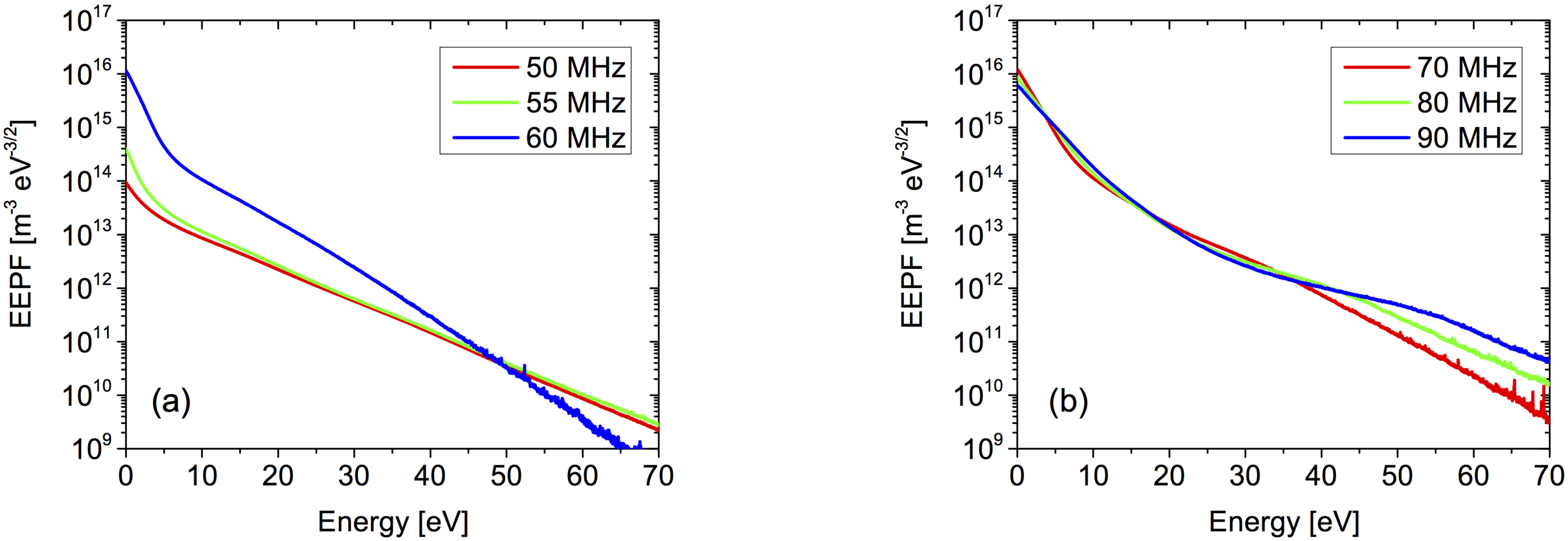

55 MHz


70 MHz

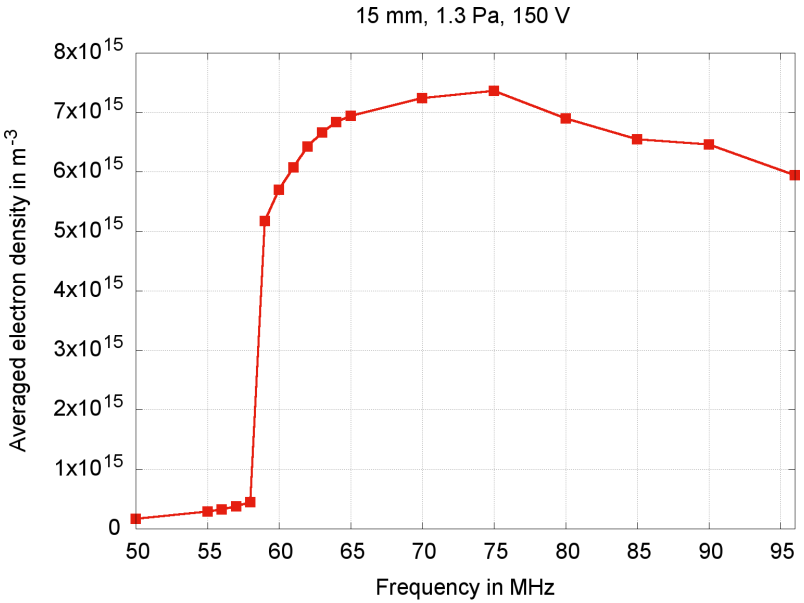

90 MHz


Energy per electron lost at the electrodes

EEPF as a function of the driving frequency



- control of the EEPF
- bi- and tri-Maxwellian
- influences the tail (high energetic particles)
- allows us to get a better control of the plasma process



Conclusion

- control of the electron beam regarding the impingement phase at the opposing sheath
- relation of pressure and gap size is important ($\frac{\lambda_m}{L_{gap}} > 1$)
- driving frequency also changes the impingement phase
- the dependence of the plasma density on the driving frequency is not found to be quadratic
- instead a step-like increase is observed
- energetic electrons hit the sheath minimum, overcome the sheath potential and can be lost at the electrode
- second electron beam is generated due to beam bulk interaction
- bulk electrons are attracted back to the expanding sheath edge and generates the second electron beam[5]

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[5] S. Wilczek et. al, in preparation, arXiv:1507.05505 (2016)