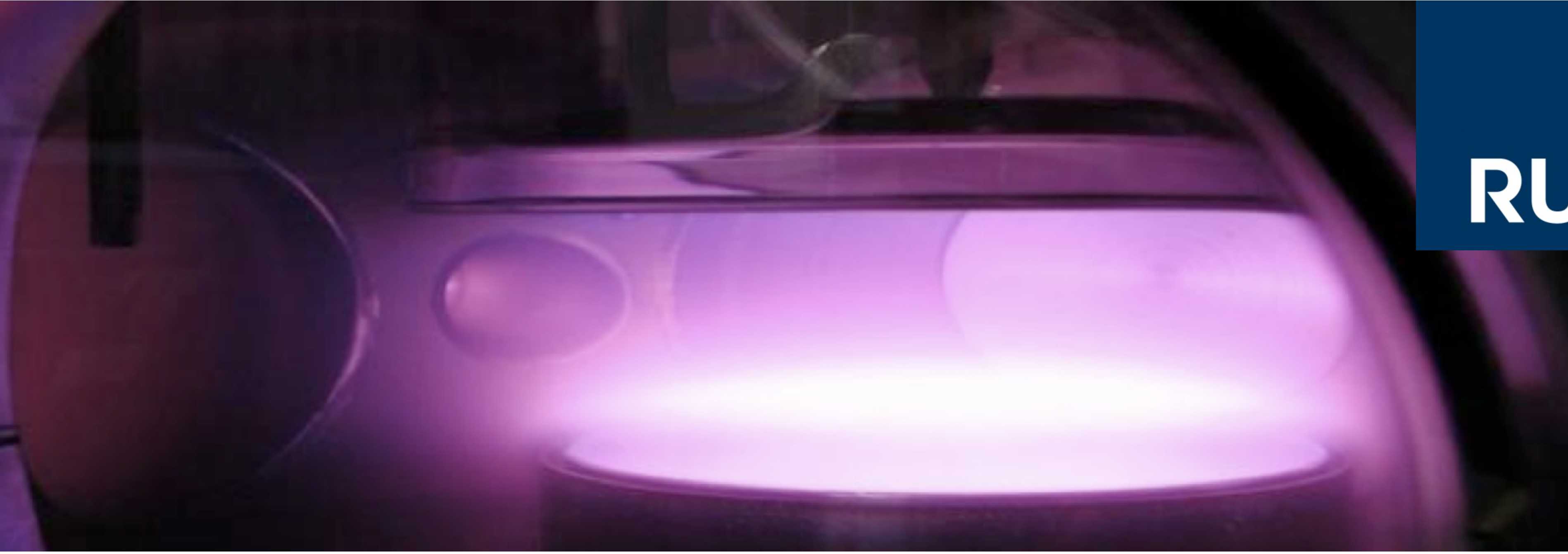


Plasma Oscillation and Local Perturbation in Low Pressure Capacitively Coupled Plasmas

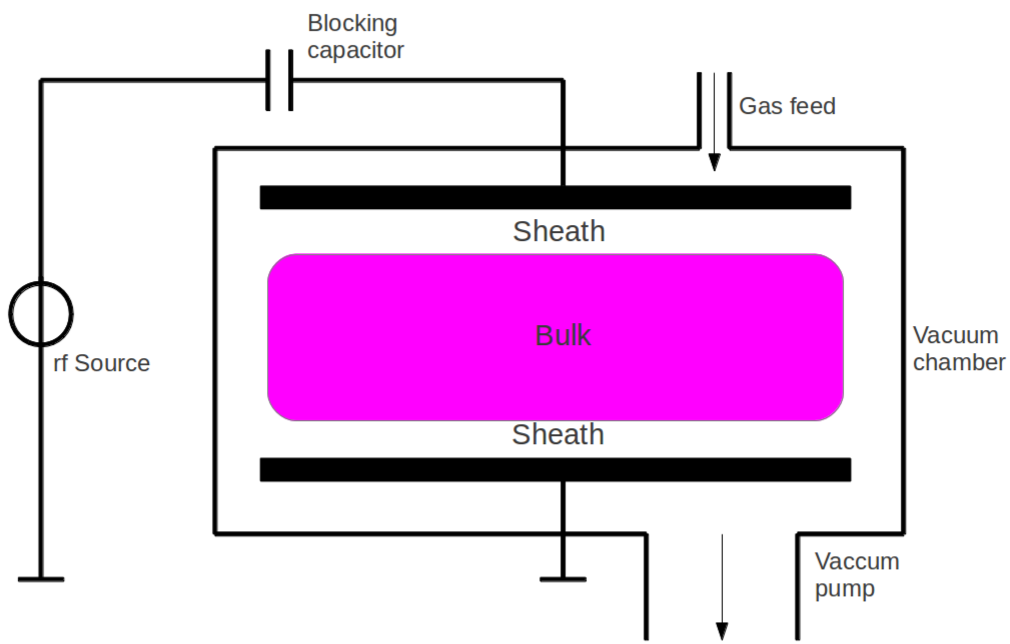
S. Wilczek[1], J. Trieschmann[1], R. P. Brinkmann[1], T. Mussenbrock[1], E. Schüngel[2], J. Schulze[2], A. Derzsi[3], I. Korolov[3], Z. Donkó[3]

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

Outline

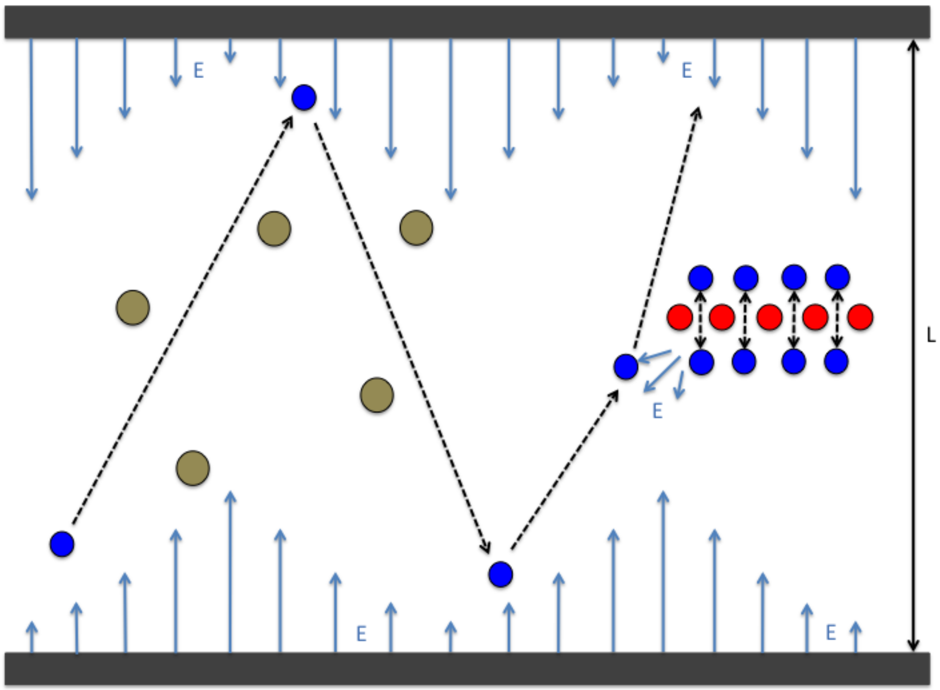
- **Motivation**
  - Electron heating in low pressure CCRF discharges
  - Non-local and collisionless regime
  - Plasma oscillation and highly energetic electron beams
- **Particle-In-Cell simulation**
- **Results**
  - Interaction of low energetic bulk electrons with high energetic beam electrons
- **Conclusion**
- **Outlook: Electron Series Resonance**

Electron heating in ccrf discharges at low pressures



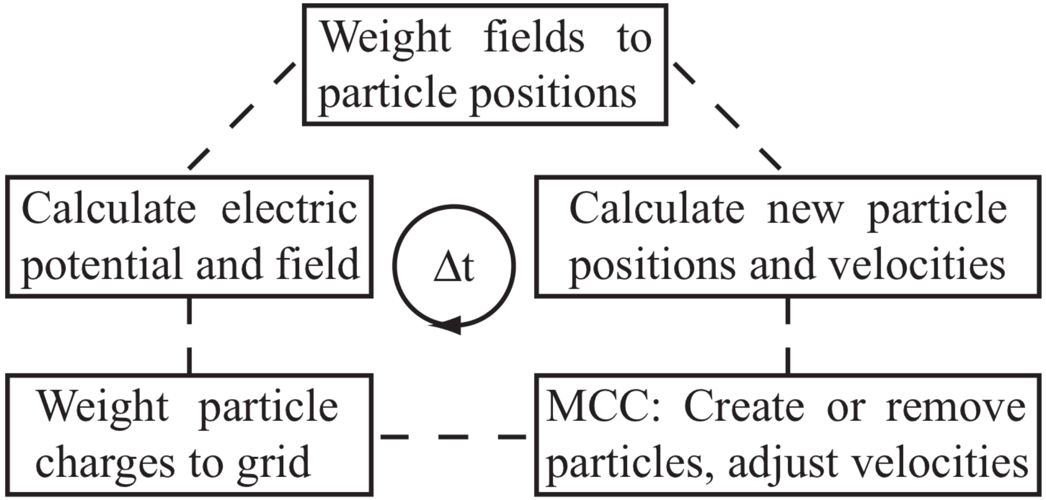
- highly relevant for industrial applications
- stochastic heating is dominant (few Pascal)
- non-local and collisionless regime
- How do the bulk electrons interact with highly energetic electrons?

Non-local and collisionless regime



- electrons move through the bulk, without experiencing a collision: $\lambda_m > L_{gap}$
- electron dynamic can be influenced by electric fields at every location
- oscillation of electrons in front of the not modulated ion background (ω_{pe})
- leads to significant fields in the bulk region

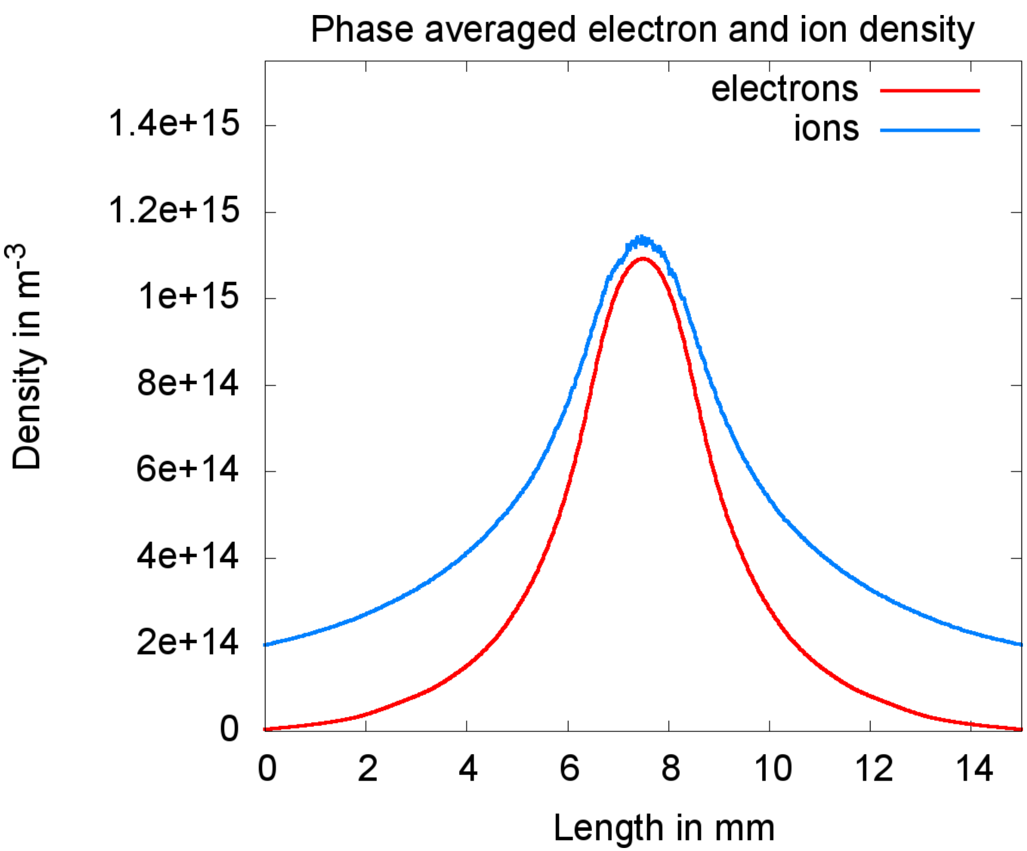
Particle-In-Cell simulation



- self-consistent and accurate description of the particle dynamic
- serial 1d3v PIC code *yapic*
- benchmarked against different PIC implementations[1]
- three electron-neutral and two ion-neutral collisions
- 1.3 Pa Argon (10 mTorr)
- small gap size of 15 mm, high driving frequency of 55 MHz, 150 V

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

Electron and ion density profile

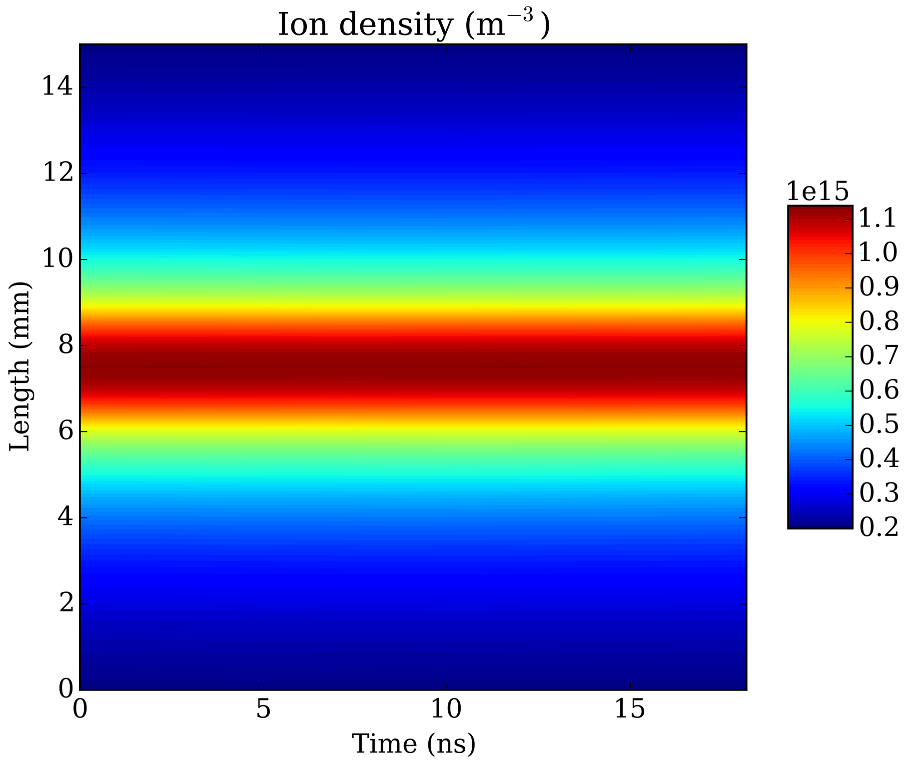


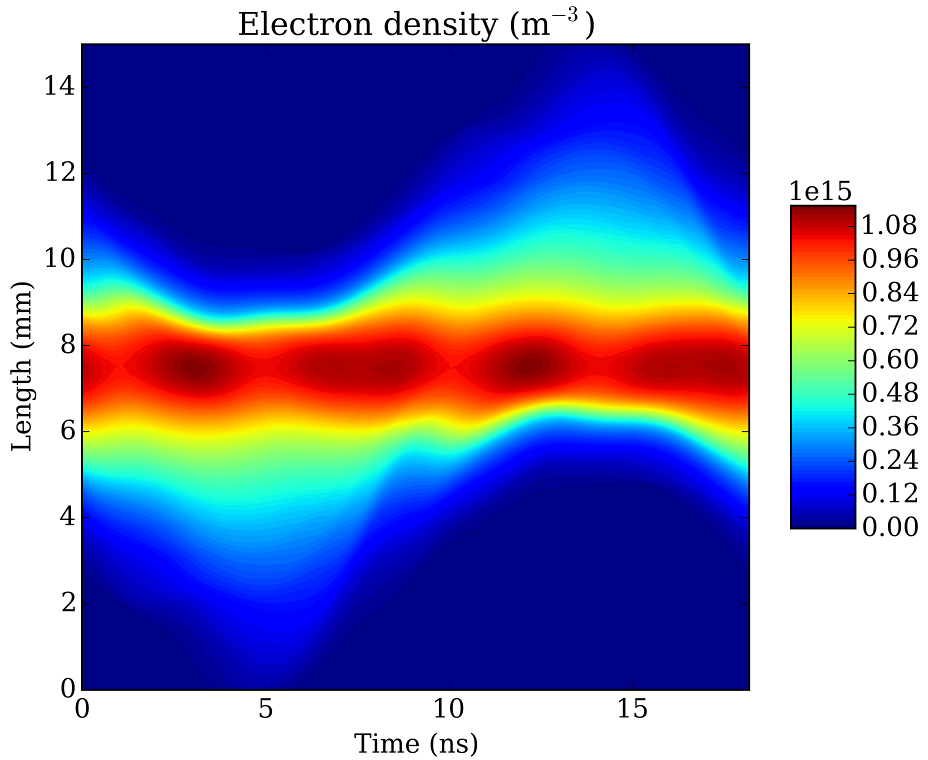
- 15 mm, 150 V, 55 MHz, 1.3 Pa Argon
- low plasma density
- plasma frequency in a range of driving frequency ($f_{pe} \approx 280$ MHz $\Rightarrow f_{pe} \approx 5 \cdot f_{rf}$)

Video

- VIDEO: Averaged Ion and Electron Density

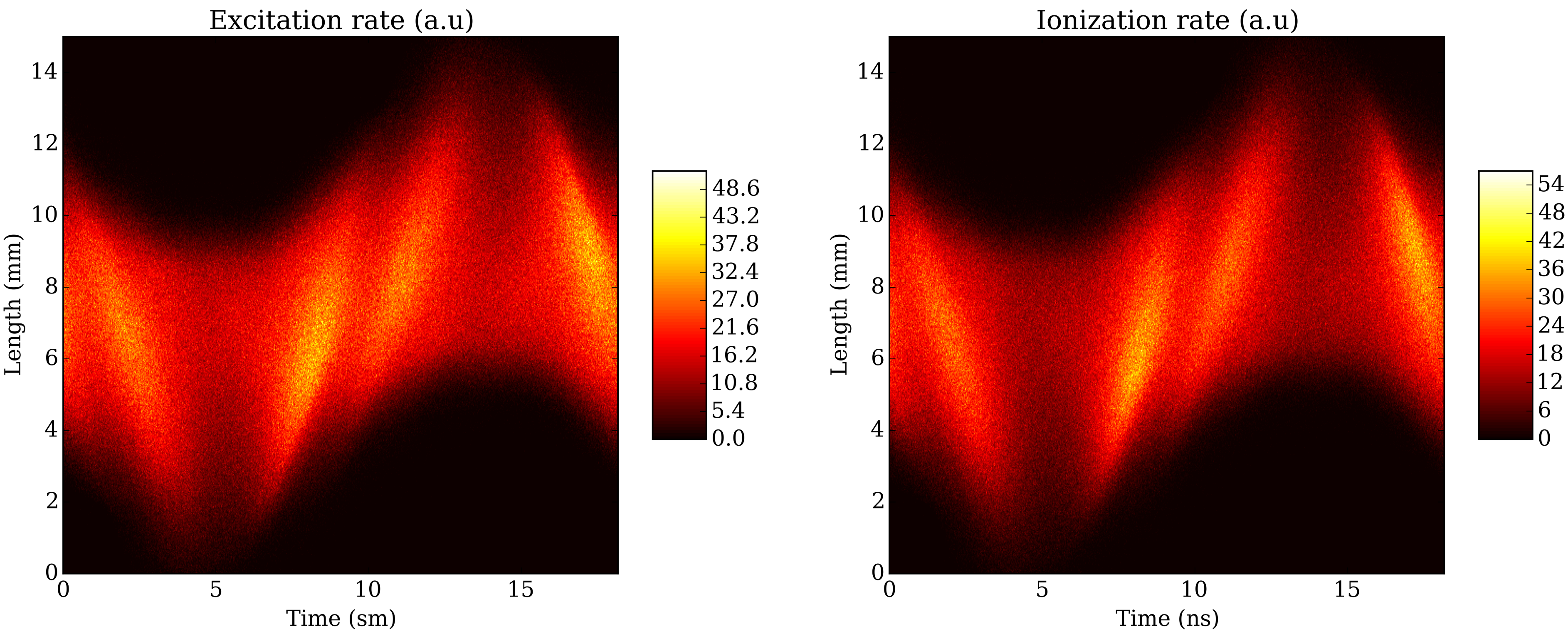
Spatio-temporal distribution of ions and electrons





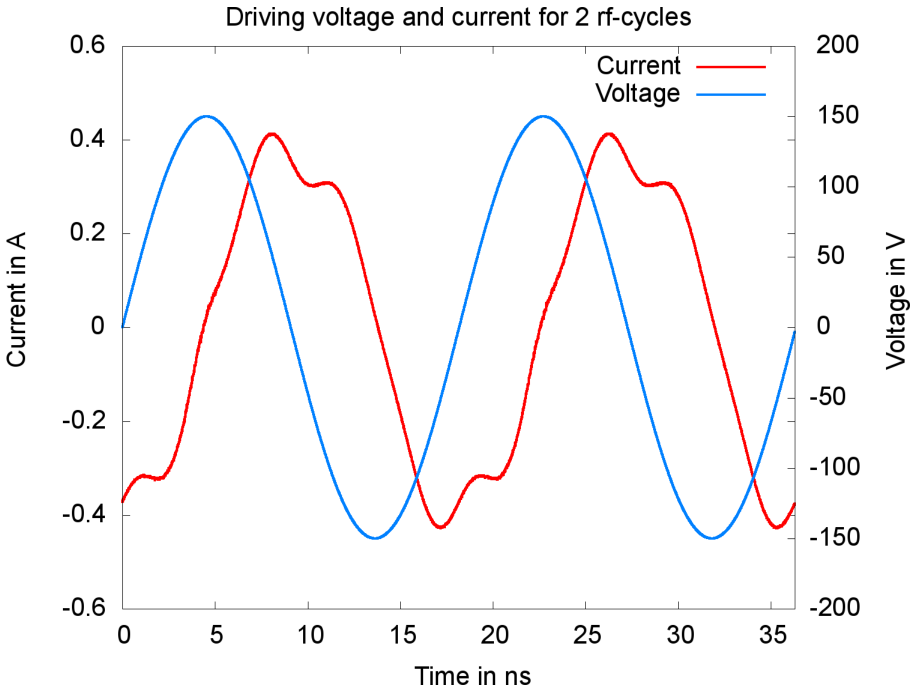
- 15 mm gap size, 150 V, 55 MHz, 1.3 Pa Argon
- ions only see the time averaged potential and do not follow the rf field
- electrons are modulated (even in the bulk region) and follow the electric field potential ($f_{pe} \approx 280$ MHz $\Rightarrow f_{pe} \approx 5 \cdot f_{rf}$)

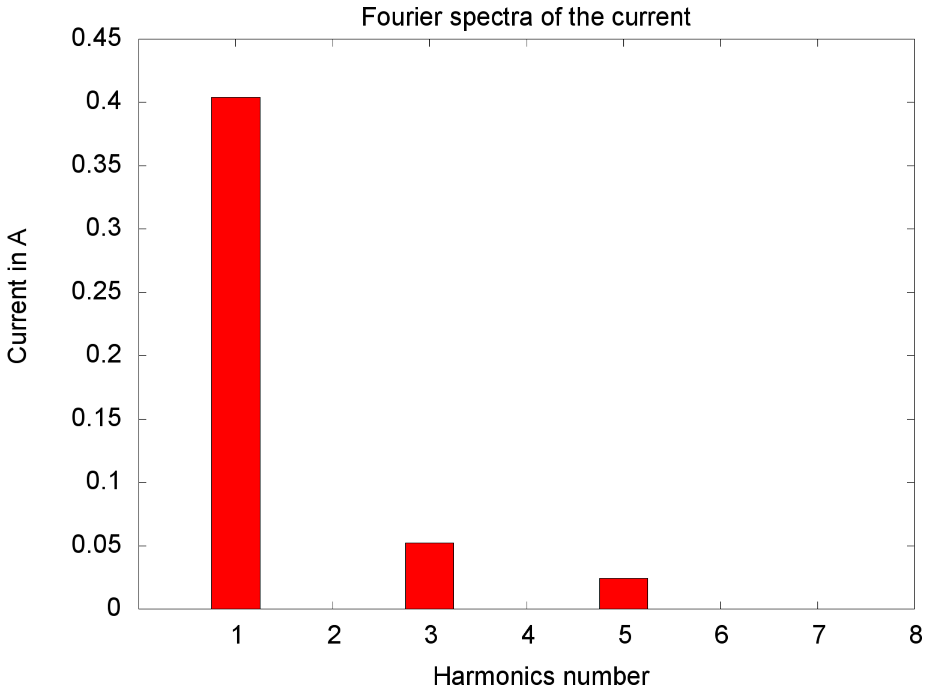
Excitation and ionization processes



- Excitation threshold: 11.5 eV and ionization threshold 15.7 eV
- highly energetic electrons are accelerated from the modulated plasma sheath and lead to significant excitation and ionization processes
- important to sustain the plasma

Current and voltage at the electrode



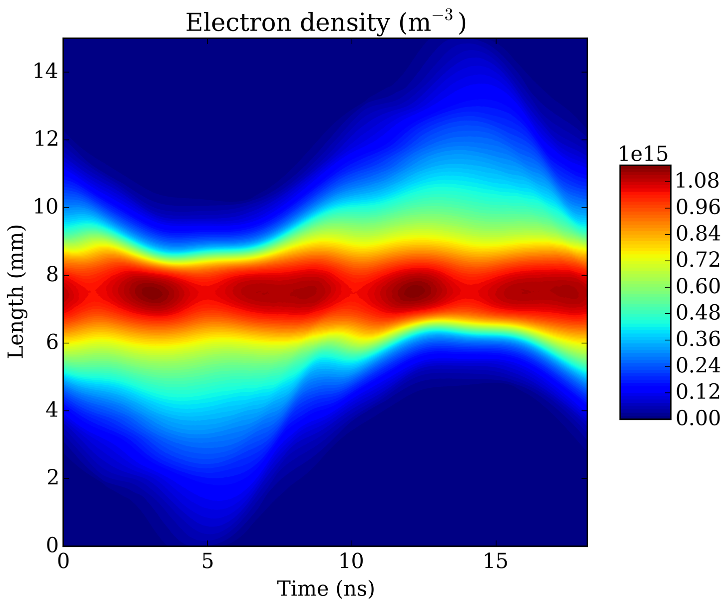


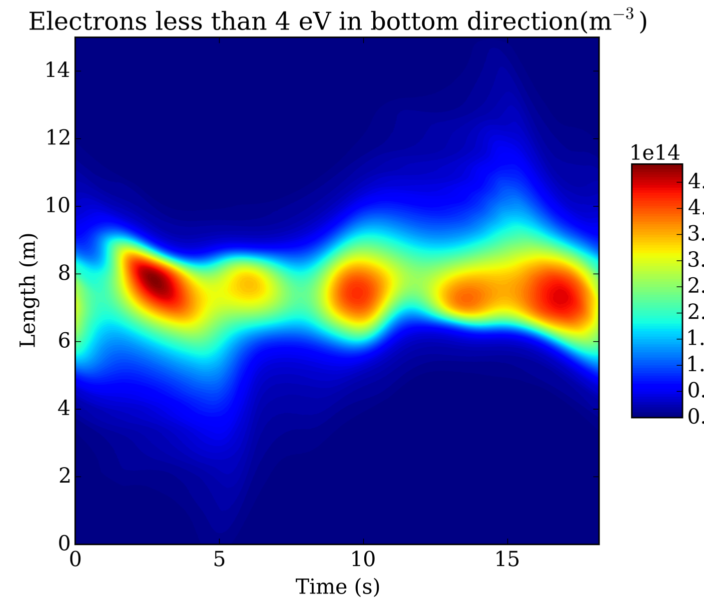
- non-linear system
- sinusoidal voltage source with 150 V
- current indicates higher harmonics
- dynamics of fast electrons influence the electron current ($j_e = en_eu_e$)

Video

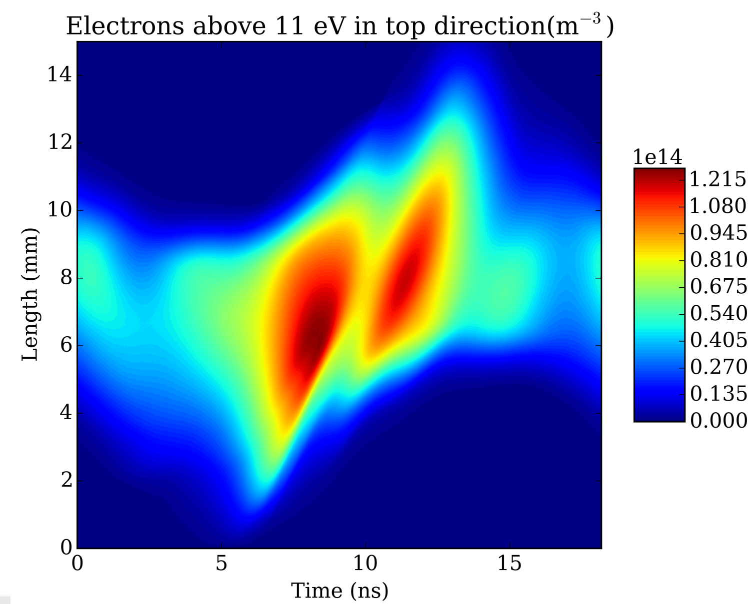
- Video Phase Space

Bulk electrons vs. energetic electrons

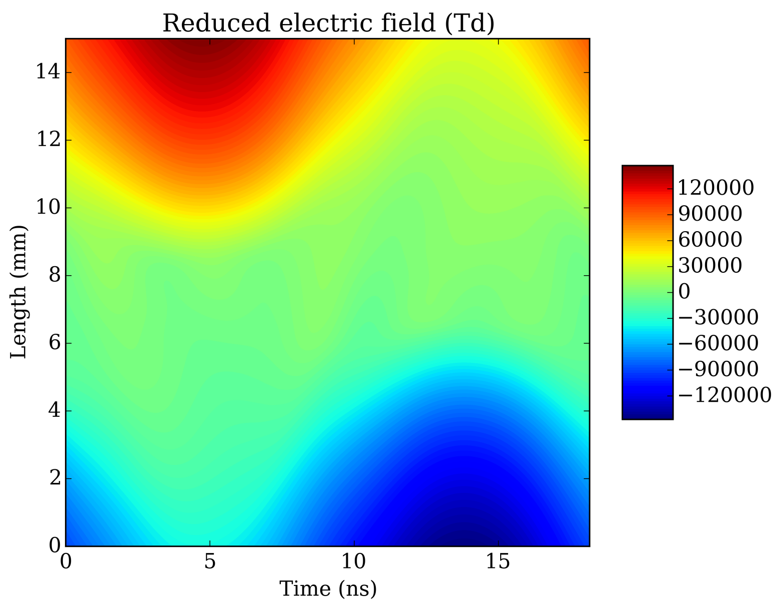


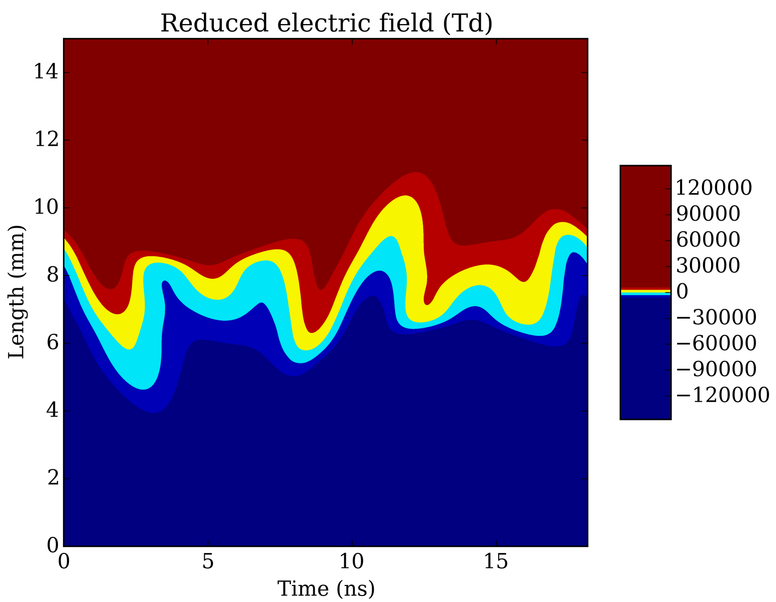


- extract the velocity information from the phase-space
- low energetic bulk electrons are modulated due to the plasma oscillation ($f_{pe} \approx 5 \cdot f_{rf}$)
- high energetic electrons are modulated by the oscillating plasma sheath



Electric field

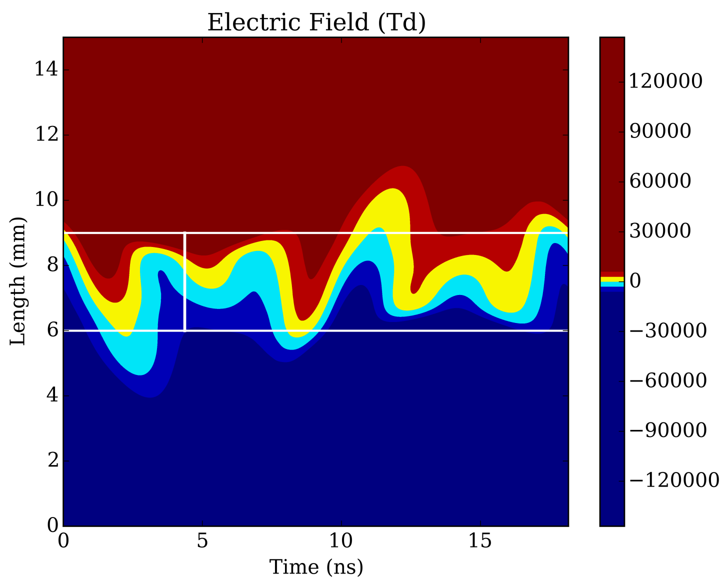


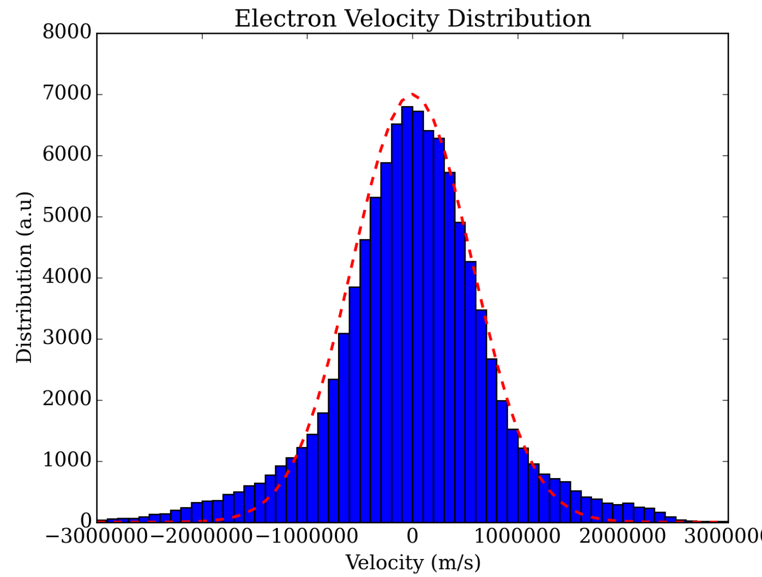


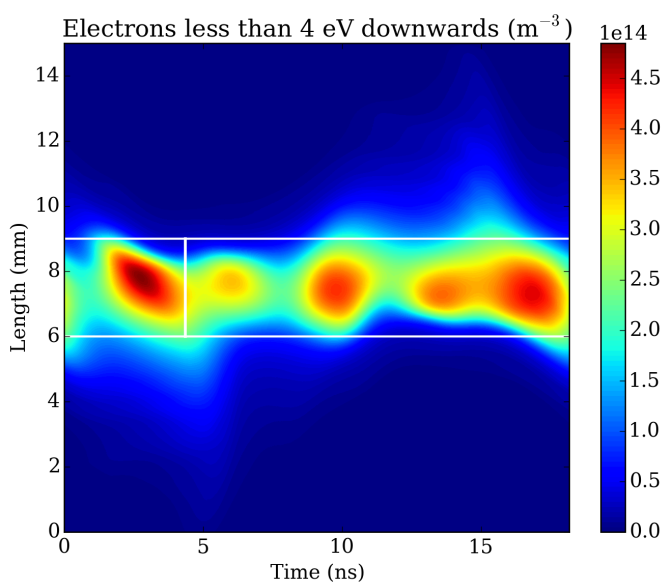
- sinusoidal oscillation of the electric field in the sheath
- acceleration of energetic electrons

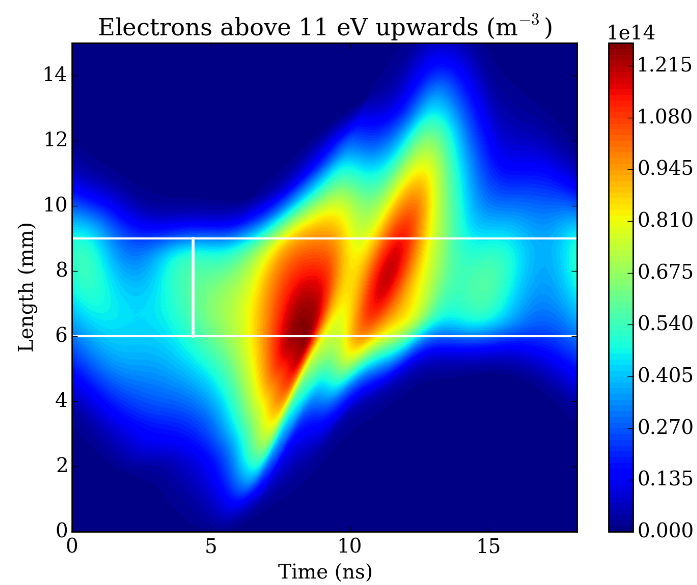
- plasma oscillation of bulk electrons leads to electric fields in the center
- higher harmonics (5th harmonic)

Bulk electrons vs. energetic electrons ($t = t_1$)

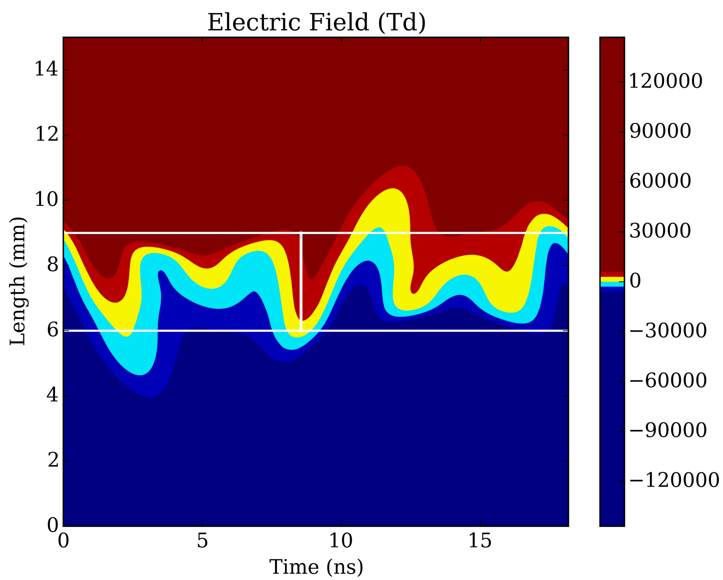


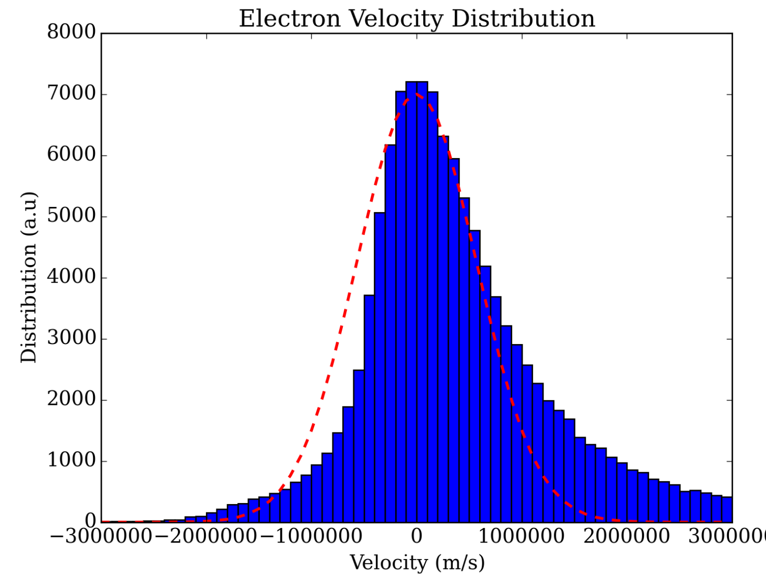


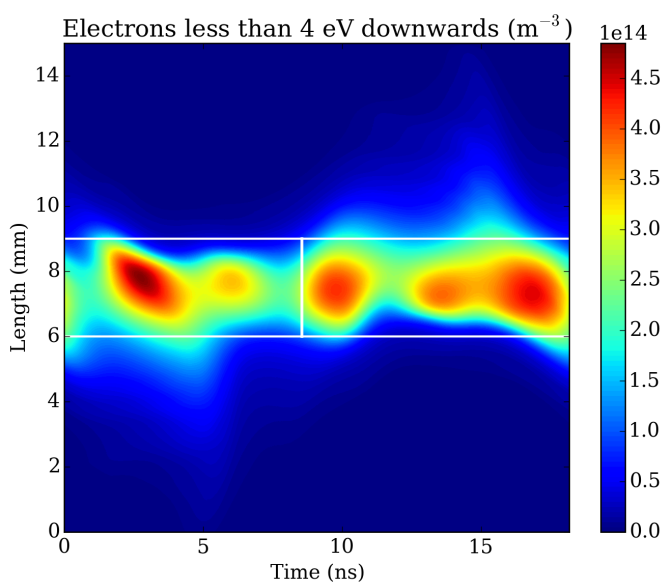


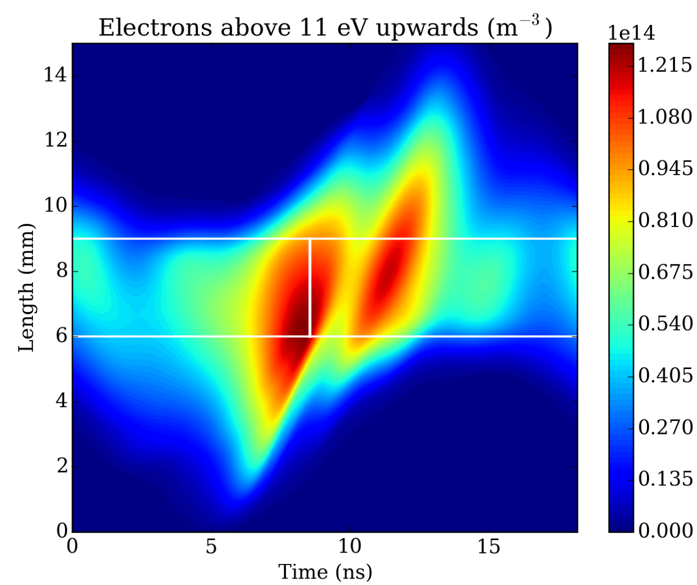


Bulk electrons vs. energetic electrons ($t = t_2$)

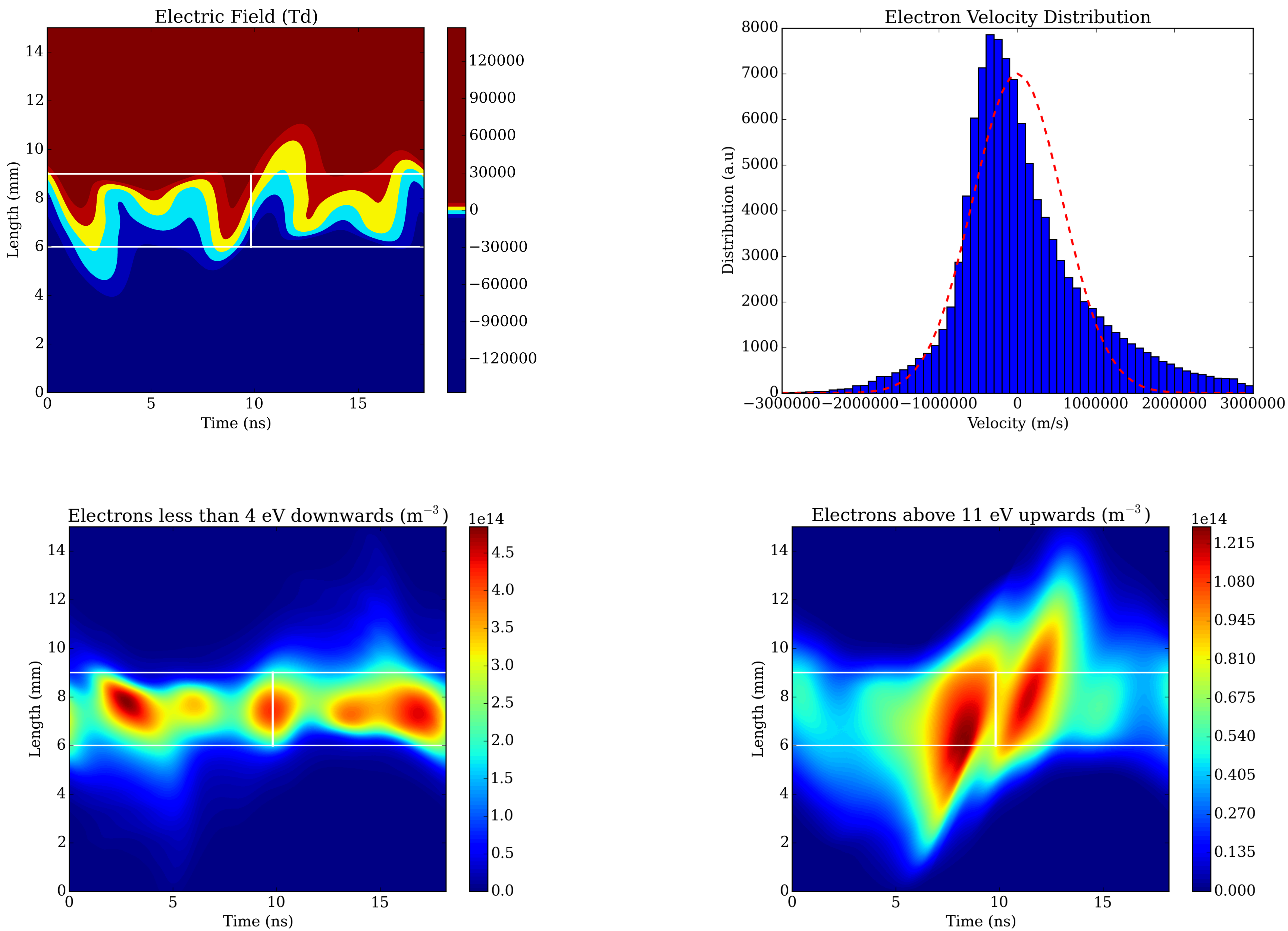




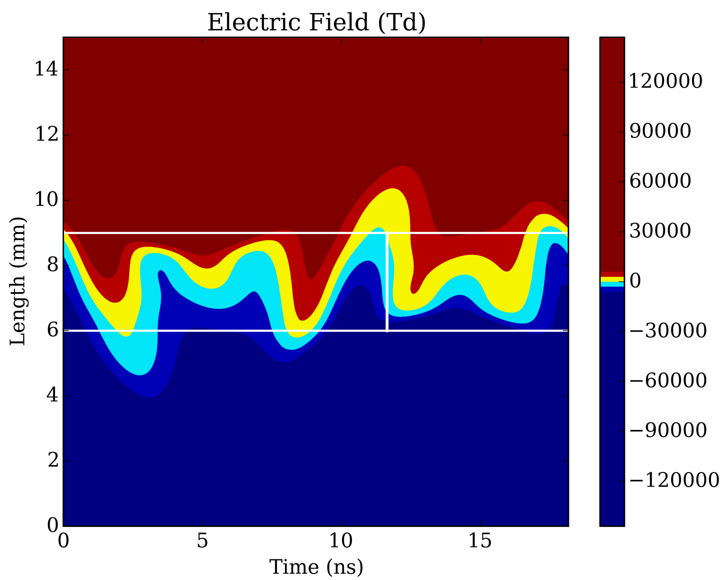


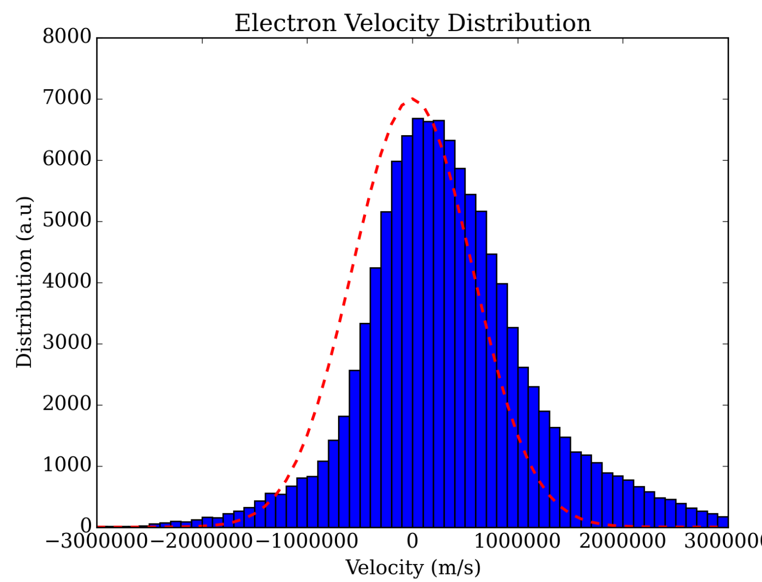


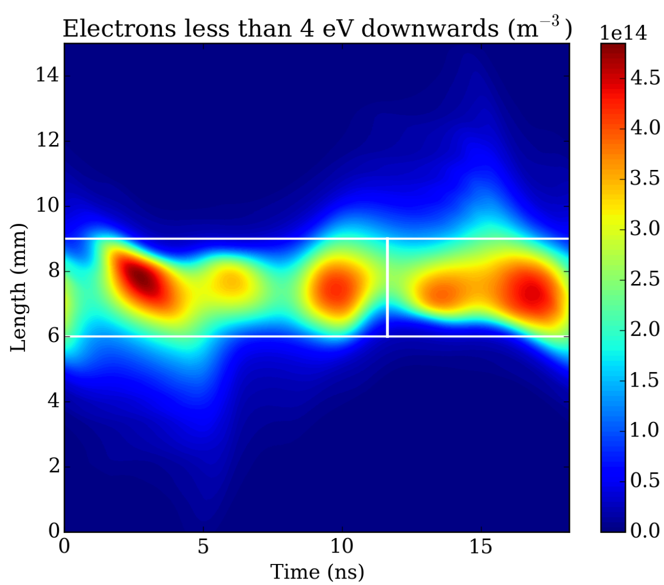
Bulk electrons vs. energetic electrons ($t = t_3$)

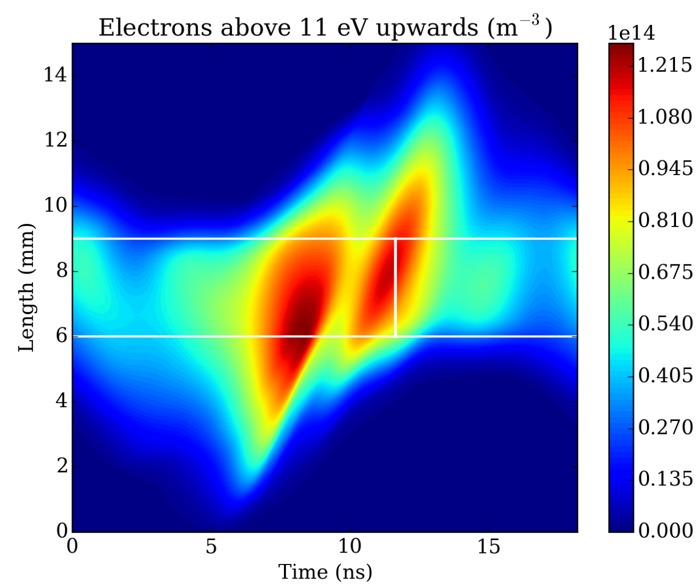


Bulk electrons vs. energetic electrons ($t = t_4$)









Conclusion

- non-local and collisionless effects are significantly important for the particle dynamics
- bulk electrons are modulated by the plasma oscillation which leads to electric fields in the center
- complex dynamics of low energetic bulk electrons and highly energetic beam electrons (second beam formation)
- influence the excitation and ionization rate
- cause higher harmonics in the current
- effect is also shown with different discharge setups
- kinetic description of the plasma series resonance (future work)