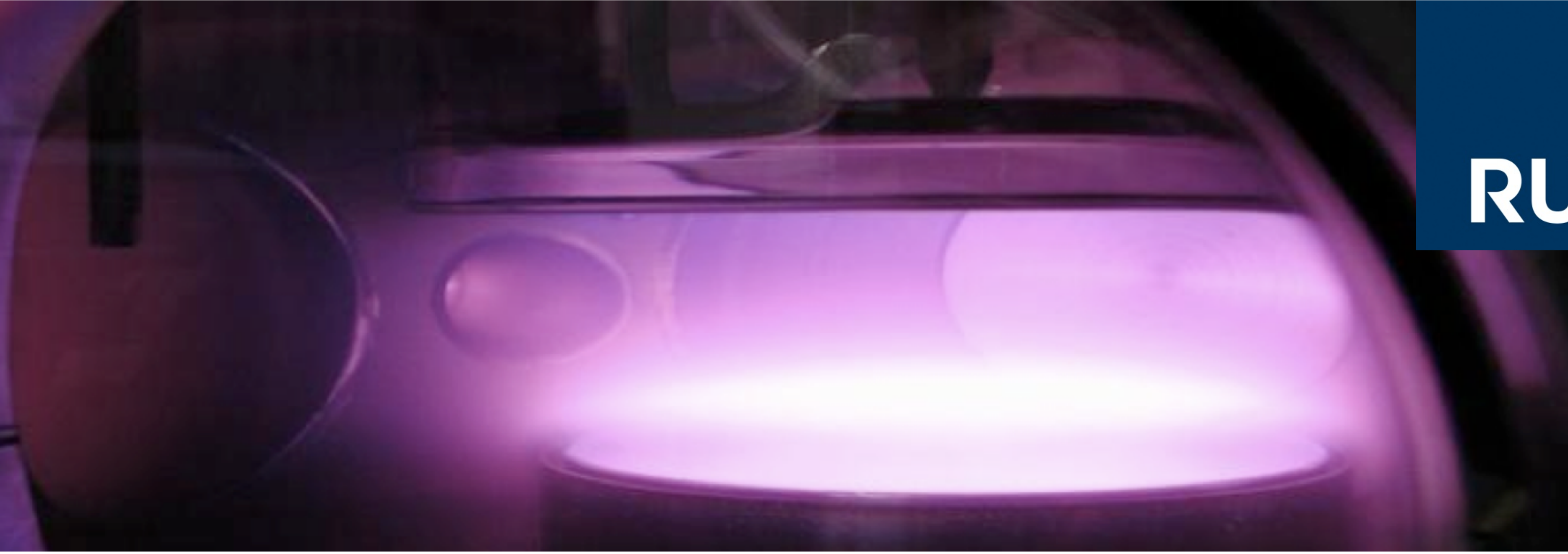
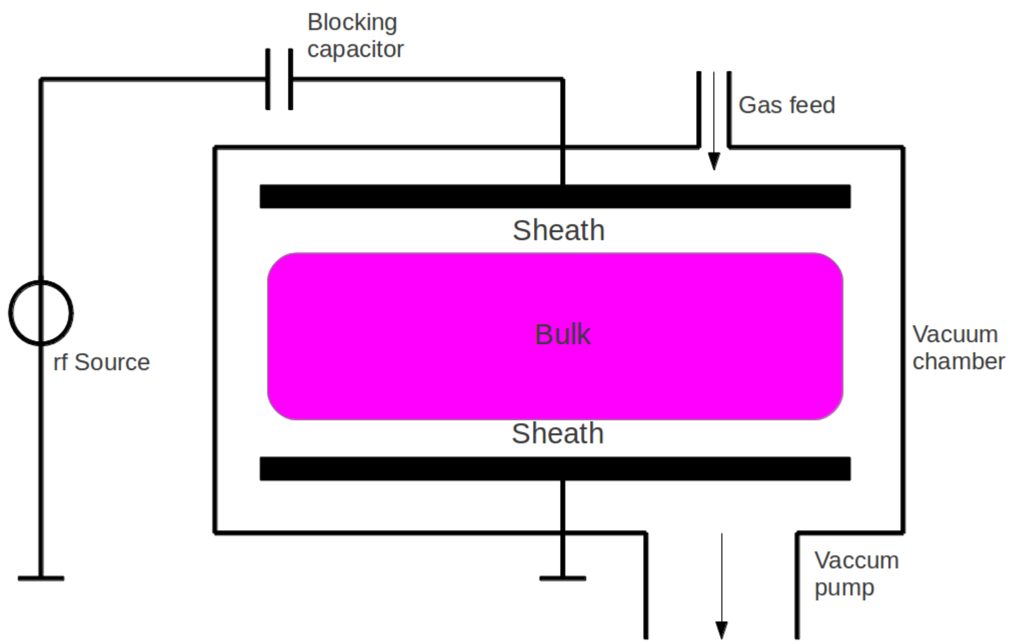


# Non-Linear Electron Resonance Heating in CCRF Discharges: A Kinetic Interpretation

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

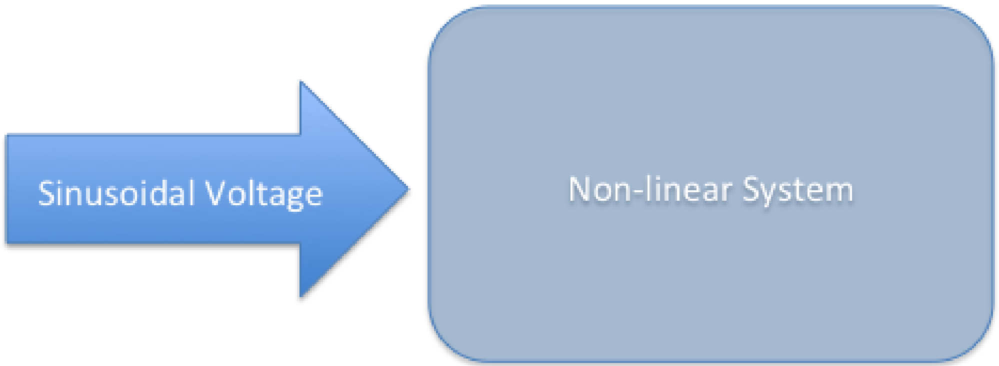
[1]Ruhr-University Bochum
[2]West Virginia University
[3]Wigner Research Centre for Physics

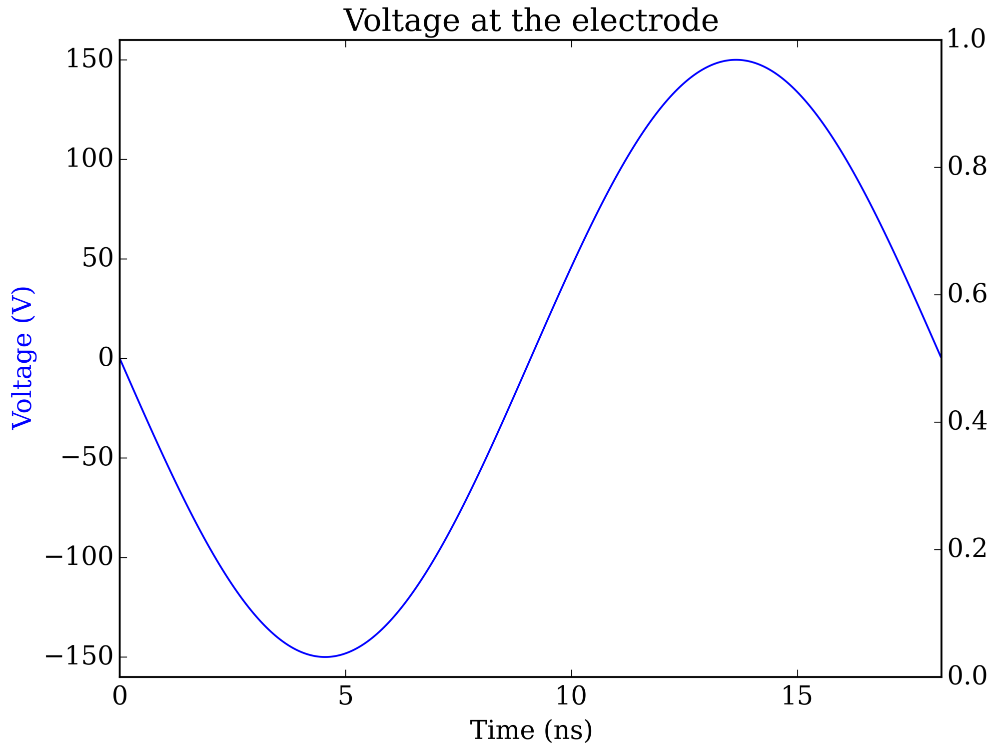
# Electron heating in ccrf discharges at low pressures



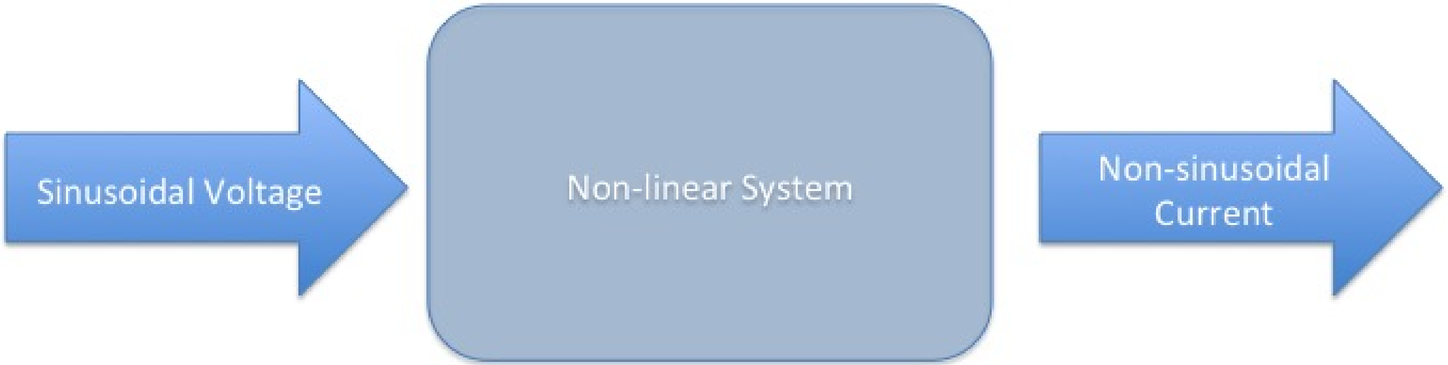

- dominated by stochastic heating
- expanding sheaths accelerate beam-like electrons
- non-local and nearly collisionless regime
- non-linear system

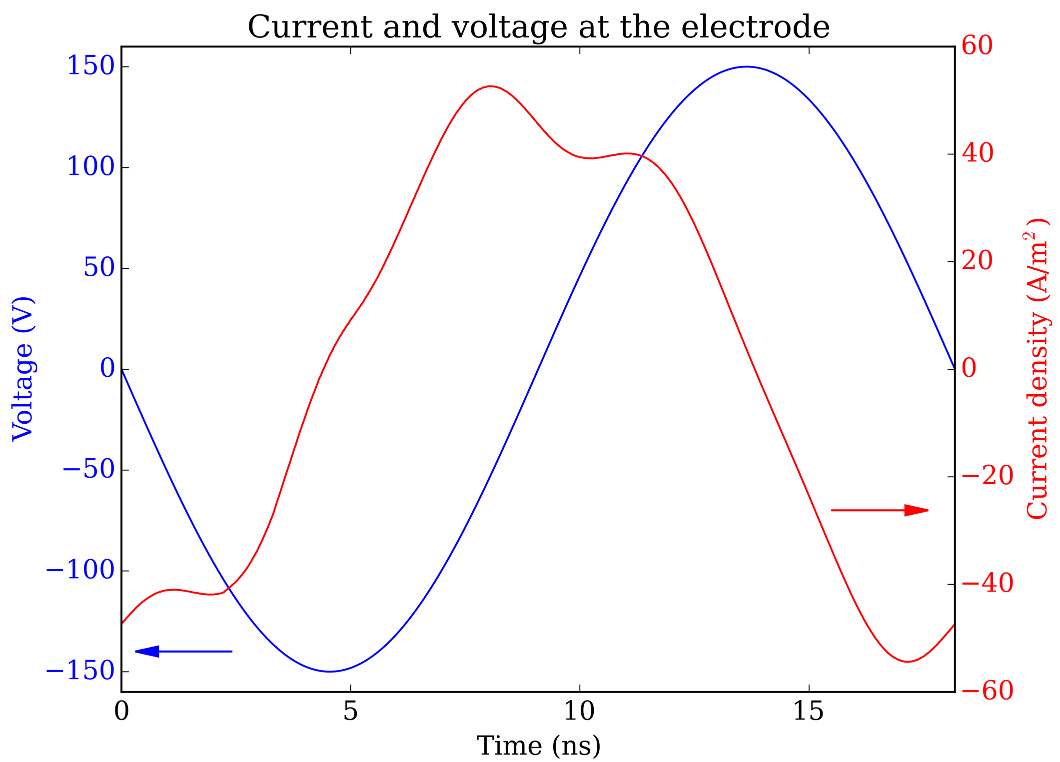
# Non-linearity of the system



# Non-linearity of the system



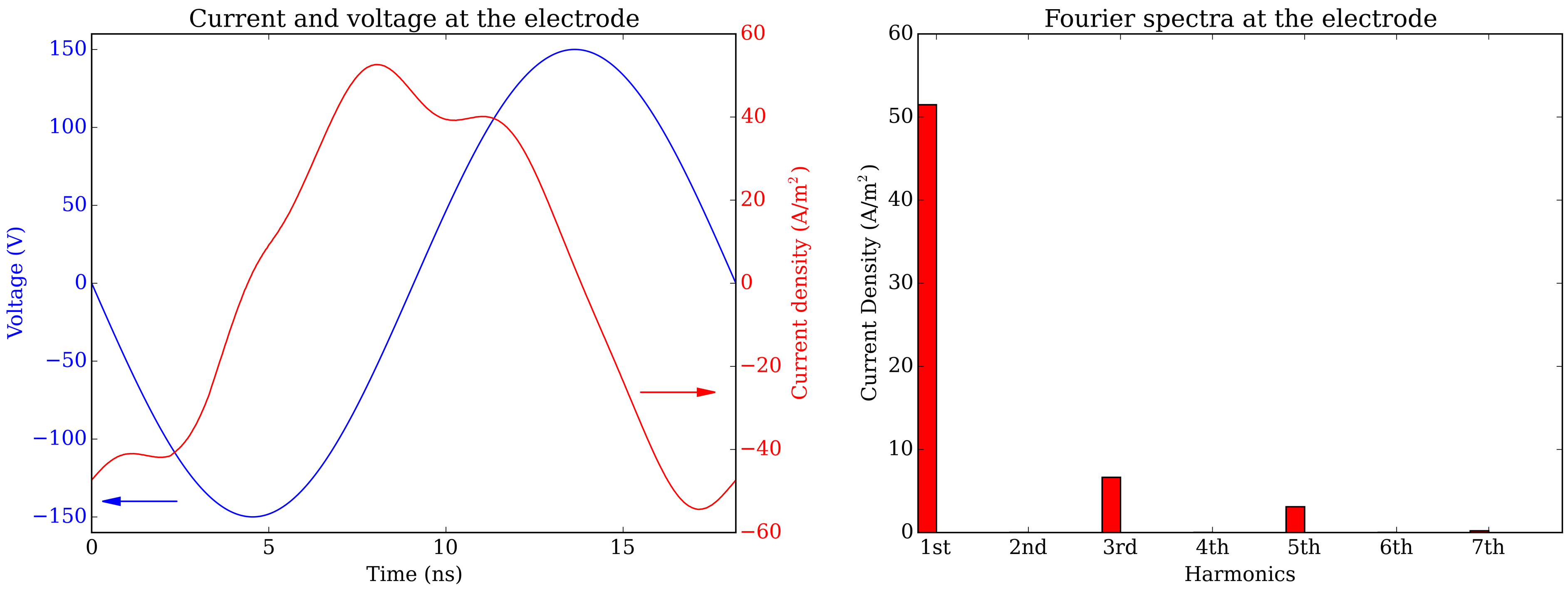
# Outline and goal of this work

- harmonic oscillations in the rf current investigated by PIC simulations[1]
- local behavior of conduction and displacement current regarding the nonlinearity of the rf current
- interplay between electron beams and bulk electrons
- **Questions**

  1. What is the kinetic origin of high frequency oscillations in the rf current?
  2. In what way is current continuity ensured all the times?

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

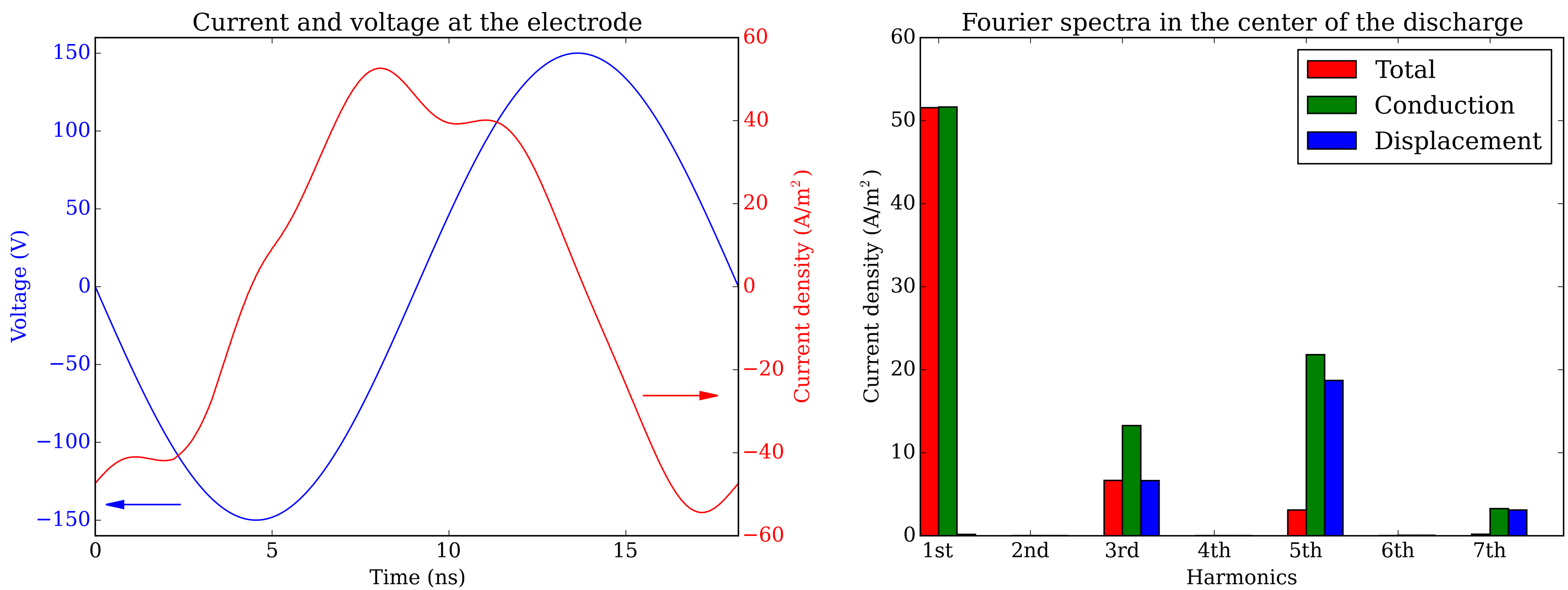
# Excitation of harmonics (global parameters)




- 150 V, 55 MHz, 1.3 Pa argon, 15 mm gap size[2] $\Rightarrow \bar{n}_e \approx 6 \cdot 10^{14} \mathrm{m}^{-3}$
- excitation of harmonics in the total current
- Nonlinear Electron Resonance Heating (NERH)

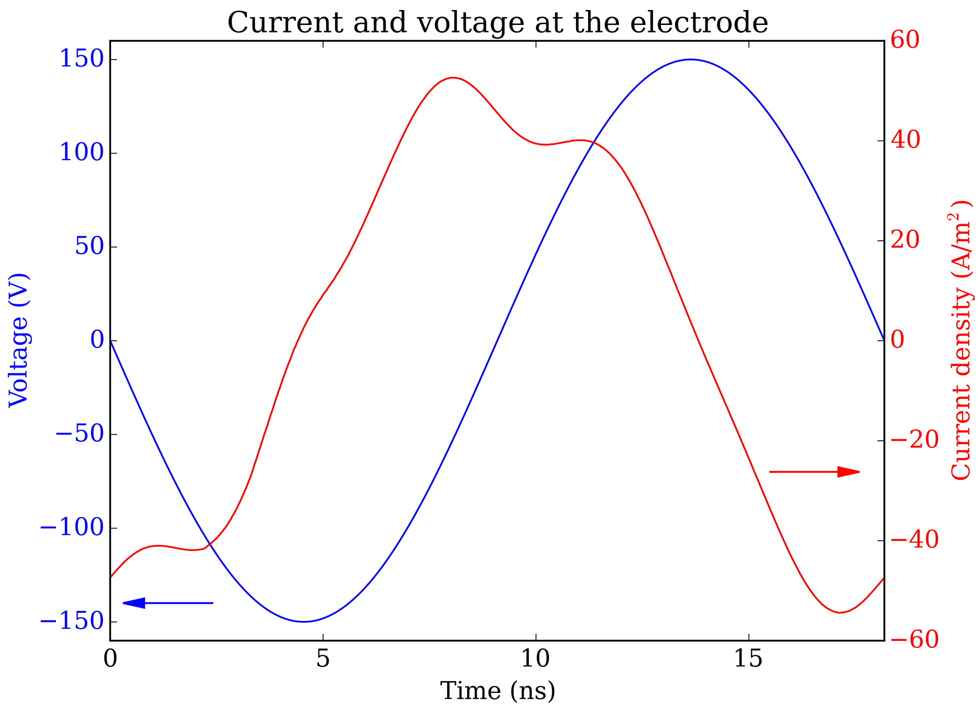
[2] S. Wilczek et. al, Plasma Sourc. Sci. Technol. 24 024002 (2015)

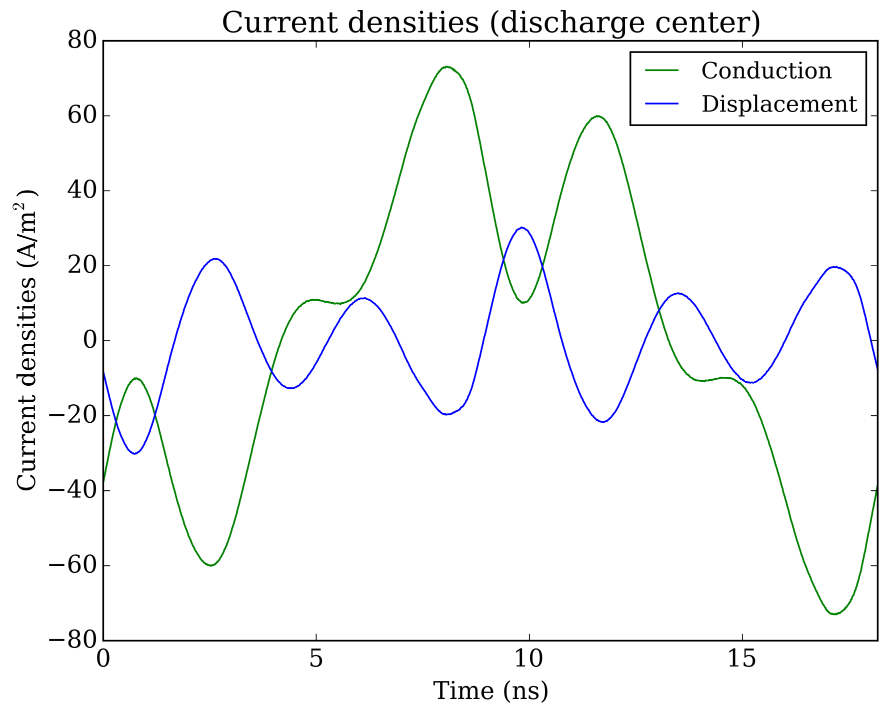
# Excitation of harmonics (local parameters )




- current continuity must be ensured all the times ($\nabla \cdot j_{tot} = 0$)
- the 180° phase shifted displacement current tries to compensate the harmonics of the conduction current
- $j_{tot}(x,t) = j_c(x,t) + j_d(x,t) = (\Gamma_i(x,t) - \Gamma_e(x,t))e + \varepsilon_0 \frac{\partial E(x,t)}{\partial t}$

# Conduction vs. displacement current density

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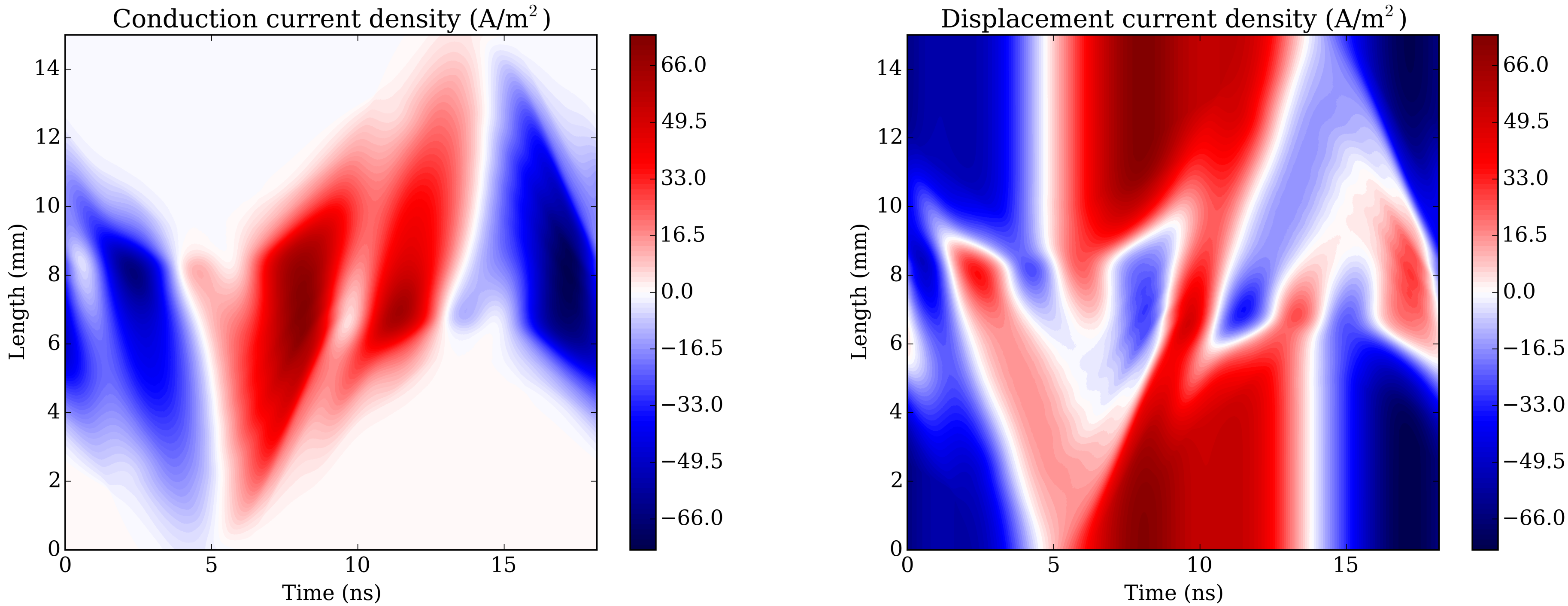
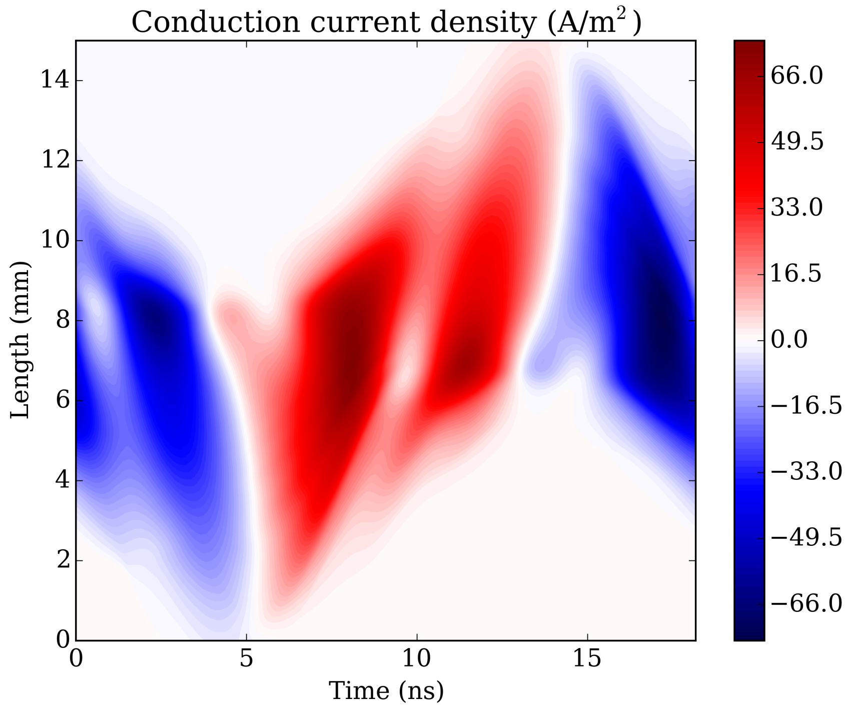
- kinetic interpretation on a nanosecond timescale is necessary

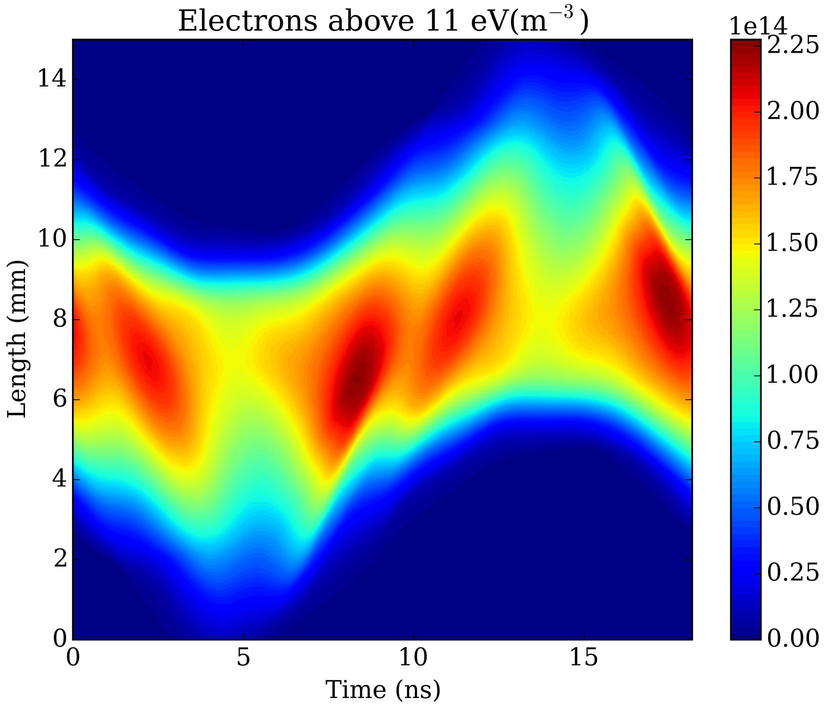
# Spatio-temporal distribution of the current densities




- current continuity ensured locally and temporal ($\nabla \cdot j_{tot} = 0$)
- pronounced double beam structure in the conduction current
- current compensation influences the whole electron dynamic, especially the plasma bulk

# Conduction current and beam-like electrons

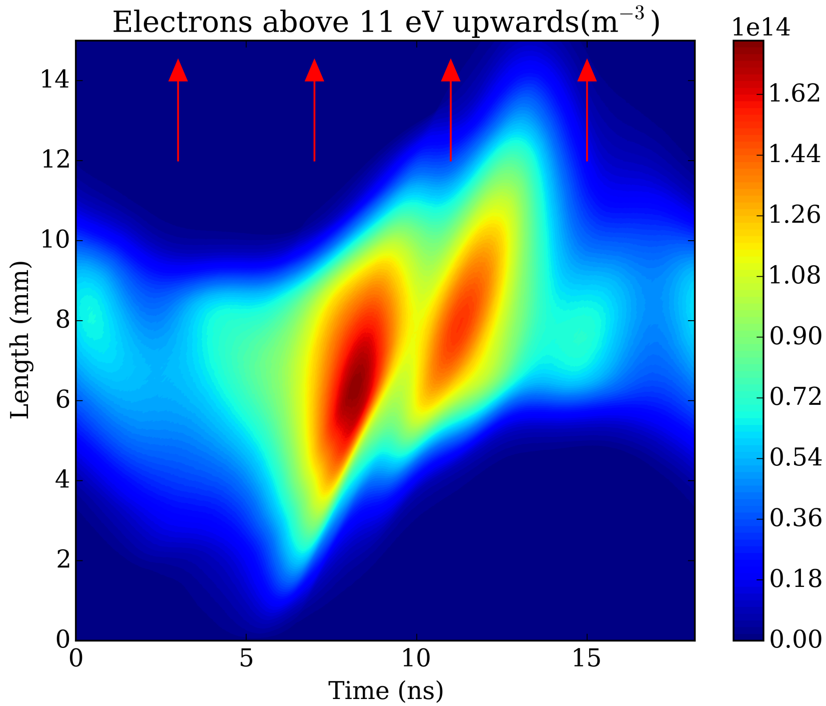


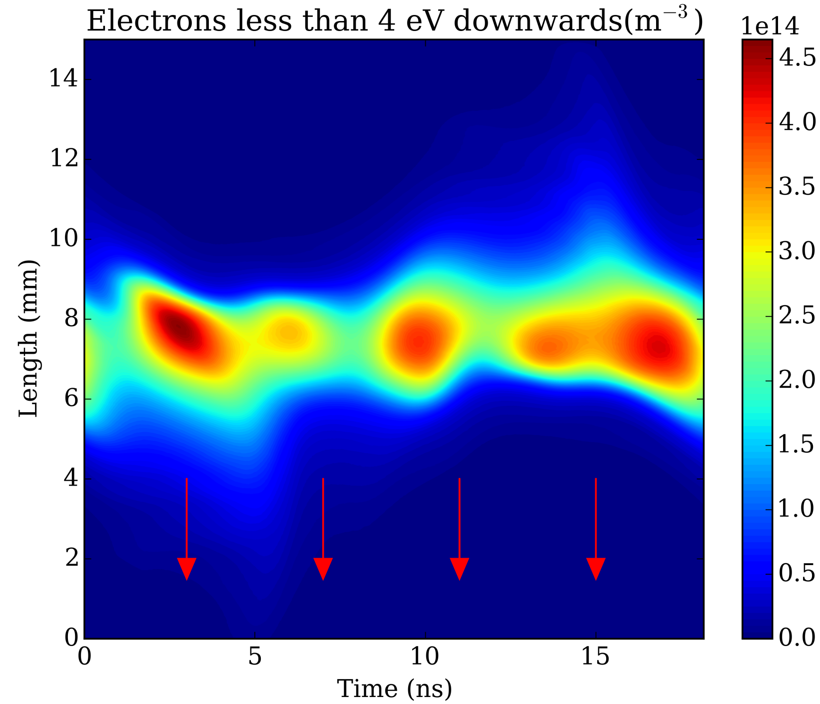




- the major part of the conduction current is represented by the spatio-temporal distribution of fast electrons above 11 eV
- these beam-like electrons are accelerated by the modulated plasma sheath and are responsible for the ionization and excitation[3]
- important to sustain the plasma

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

# Bulk electrons vs. energetic electrons



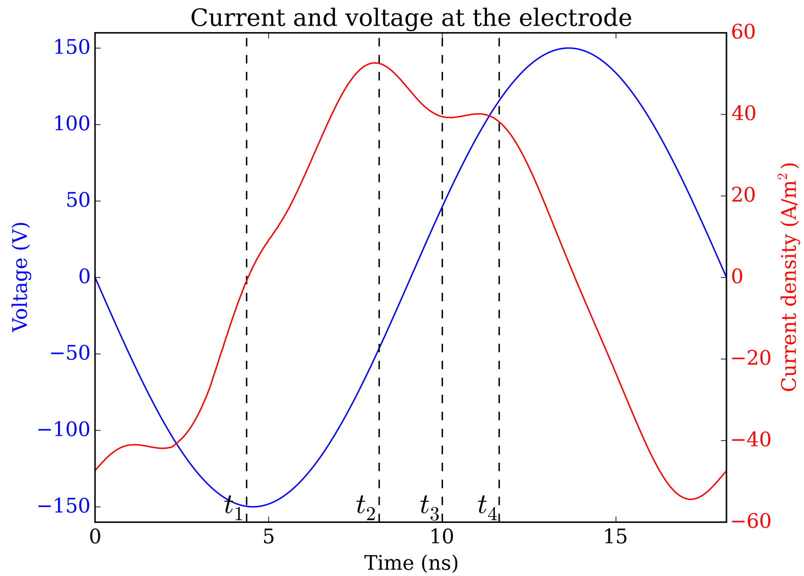

hot electrons: $\varepsilon_h > 11$ eV
moving upwards: $v_x > 0$

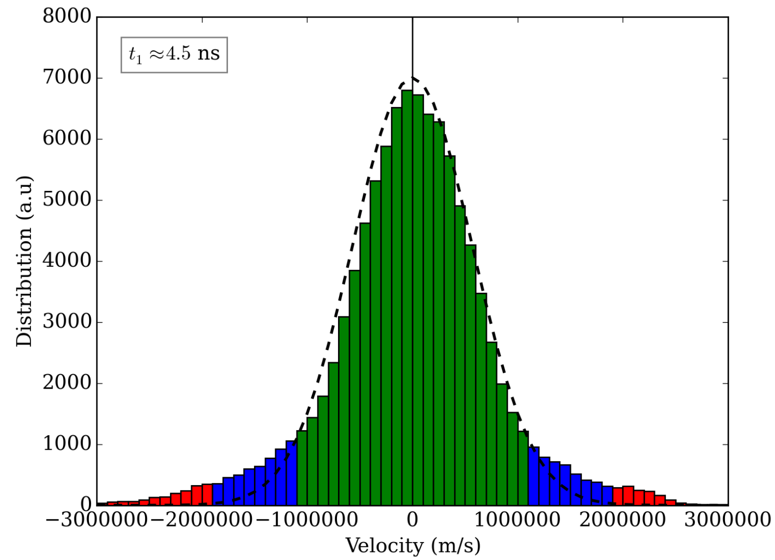
cold electrons: $\varepsilon_c < 4$ eV
moving downwards: $v_x < 0$

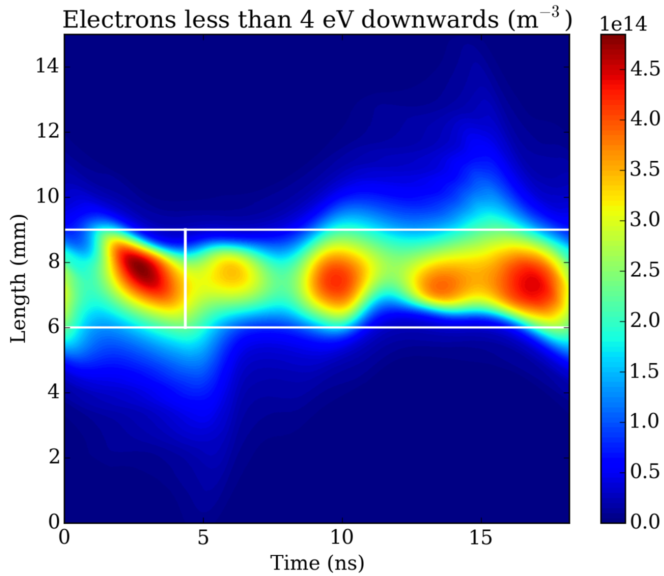
- electron-sheath interaction[4]
- electron beam interacting with bulk electrons

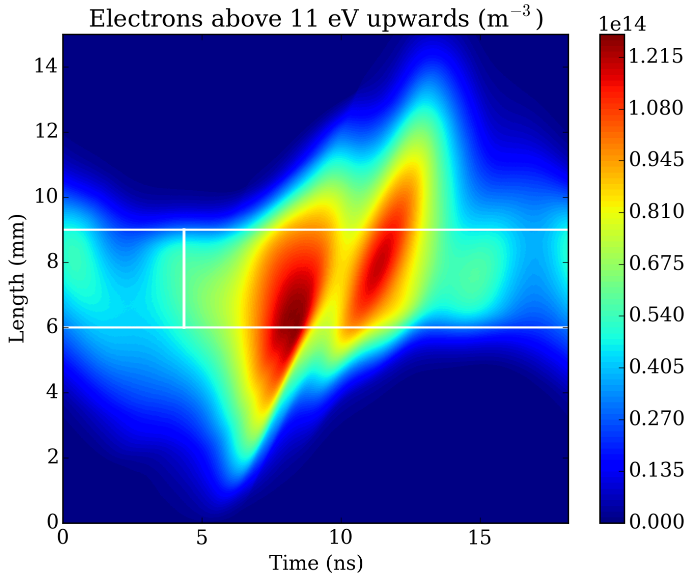
[4] D. Vender et. al., J. Vac. Sci. Technol. A 10, 1331 (1992)

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

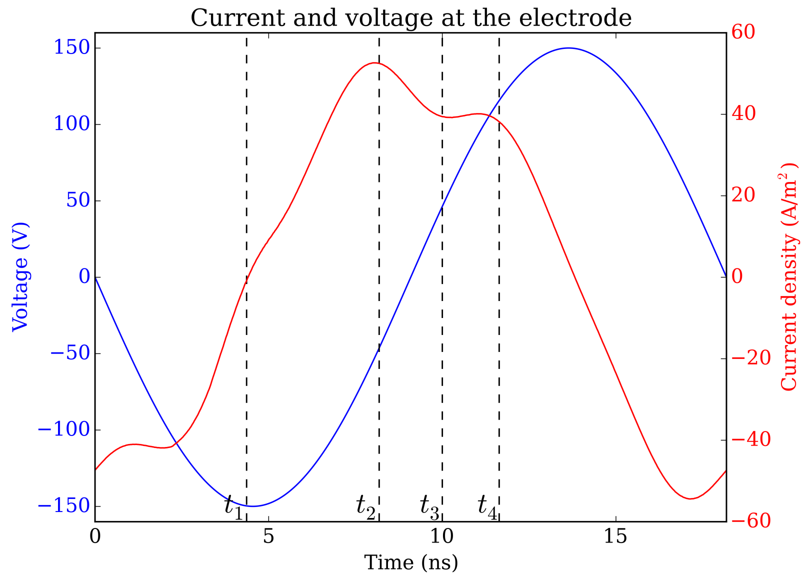


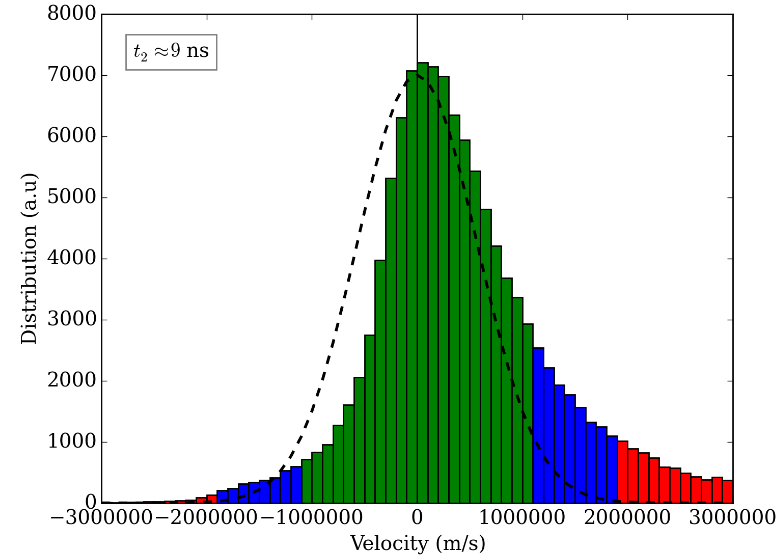



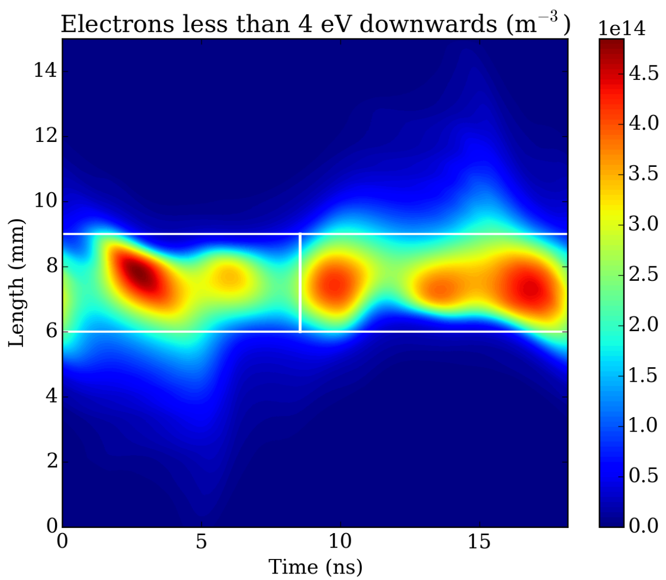



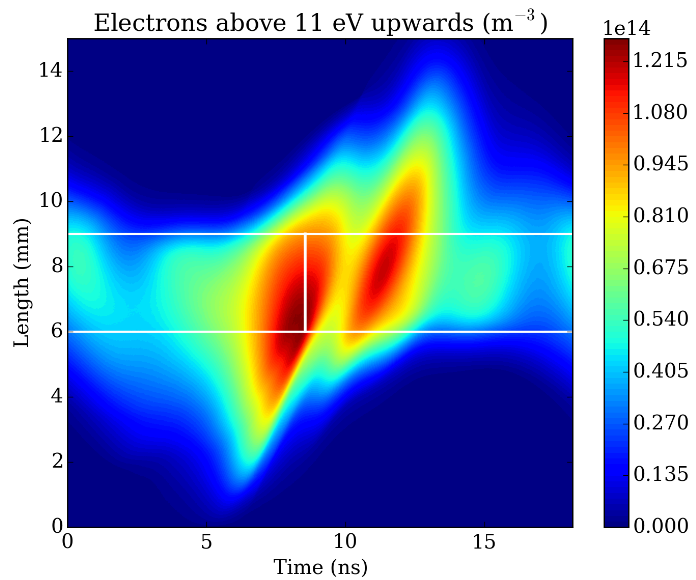



# Bulk electrons vs. energetic electrons ($t = t_2$)

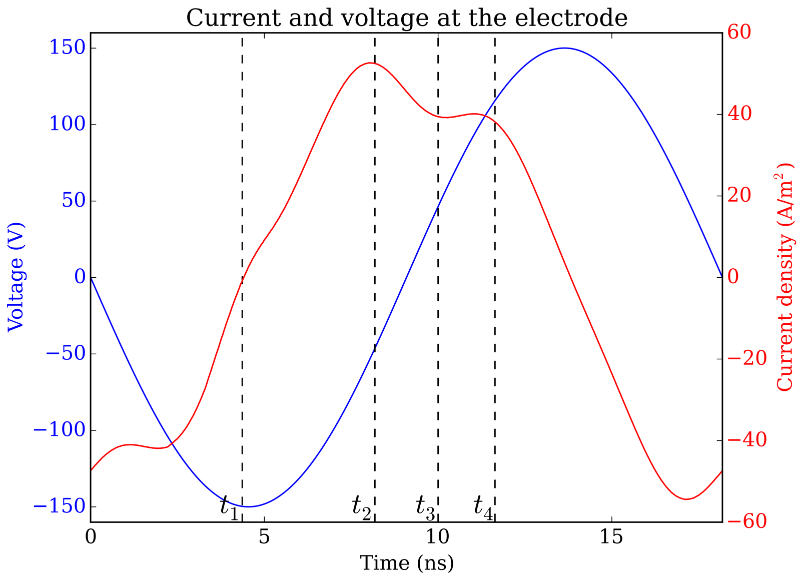


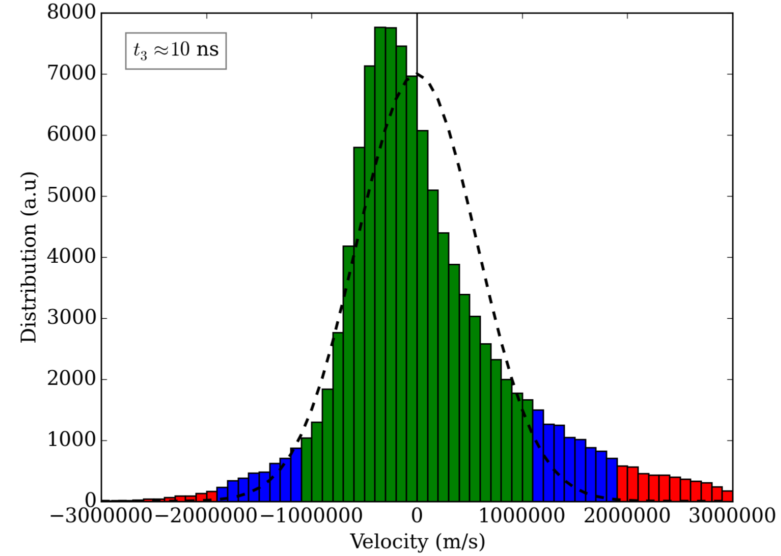



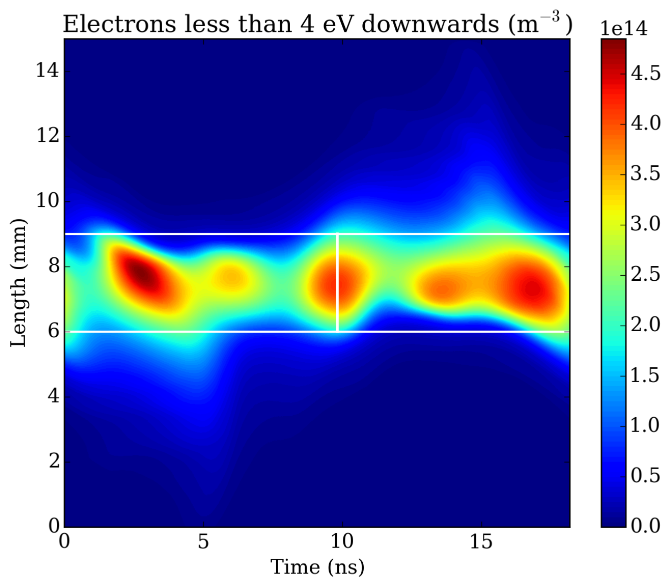



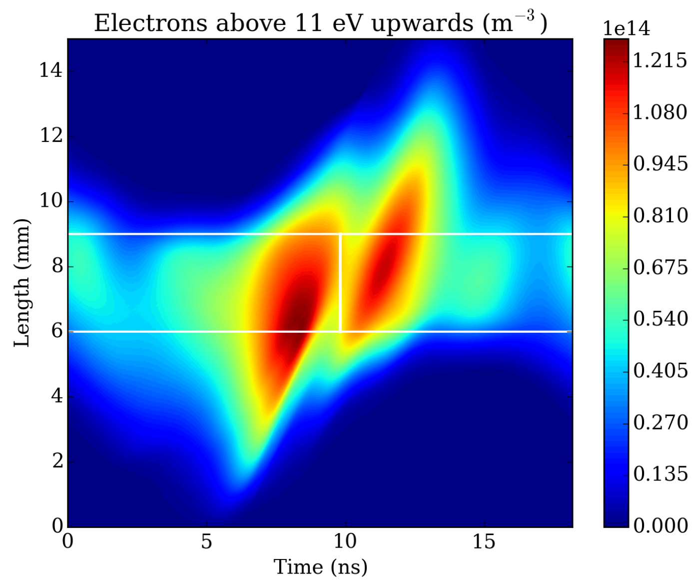



# Bulk electrons vs. energetic electrons ($t = t_3$)

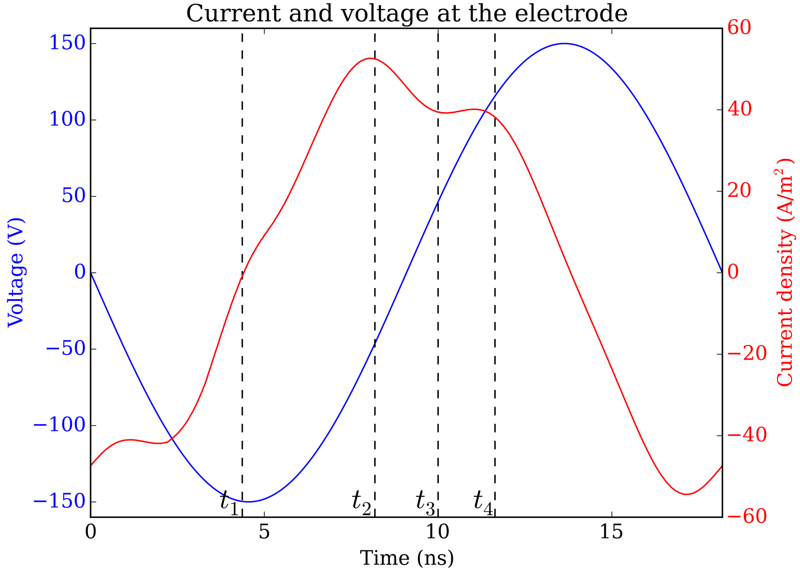


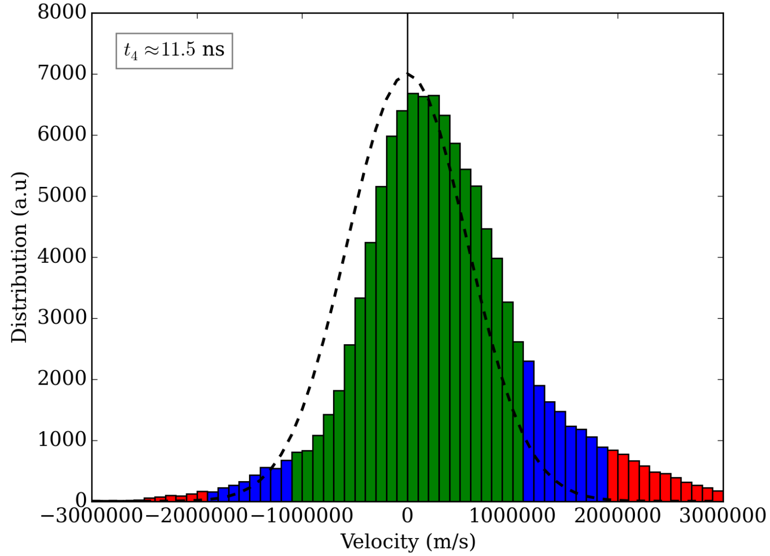



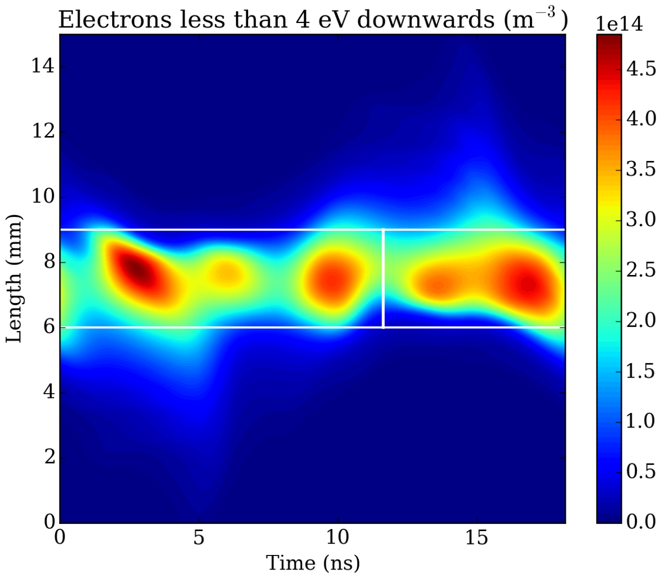



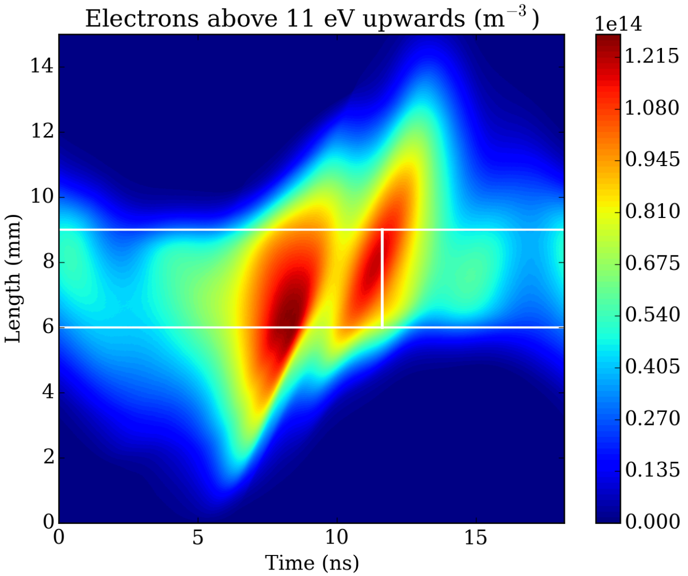



# Bulk electrons vs. energetic electrons ($t = t_4$)

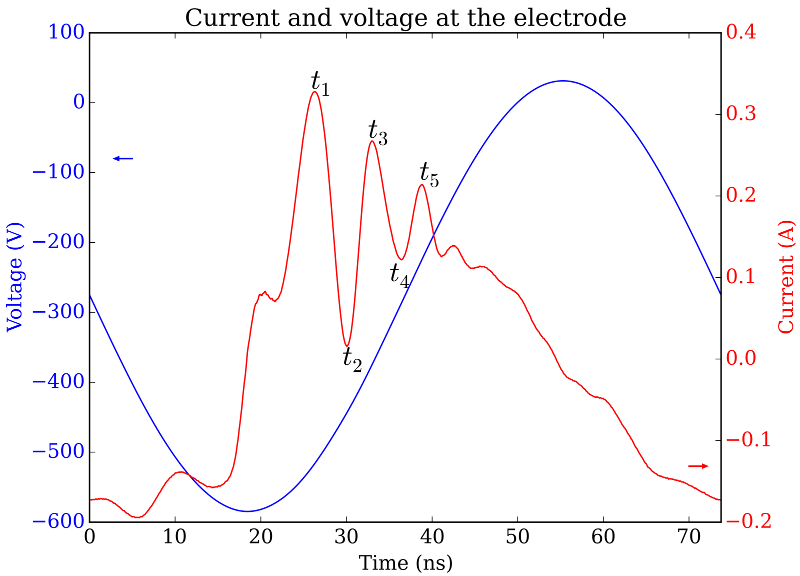


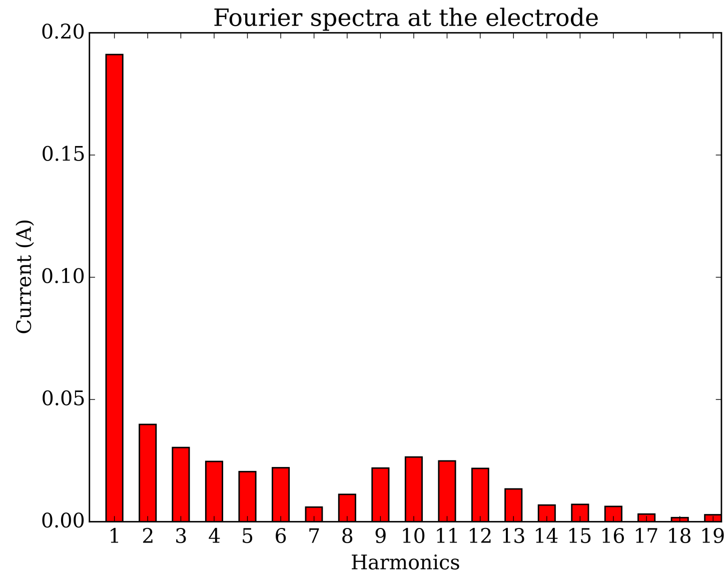



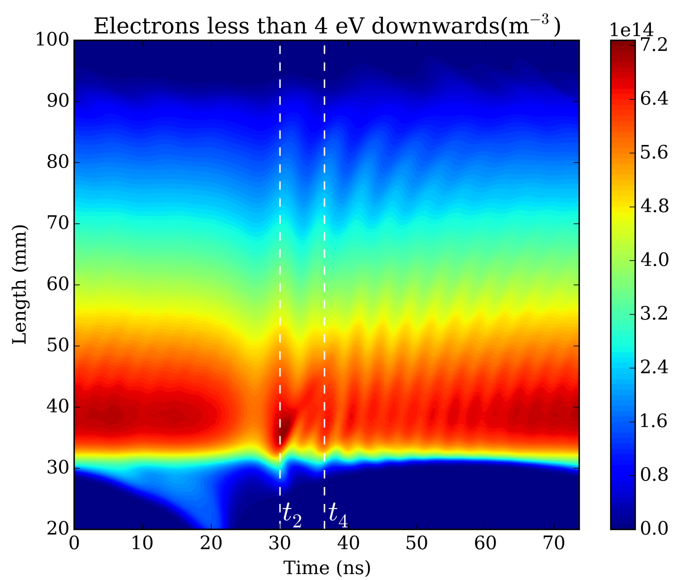



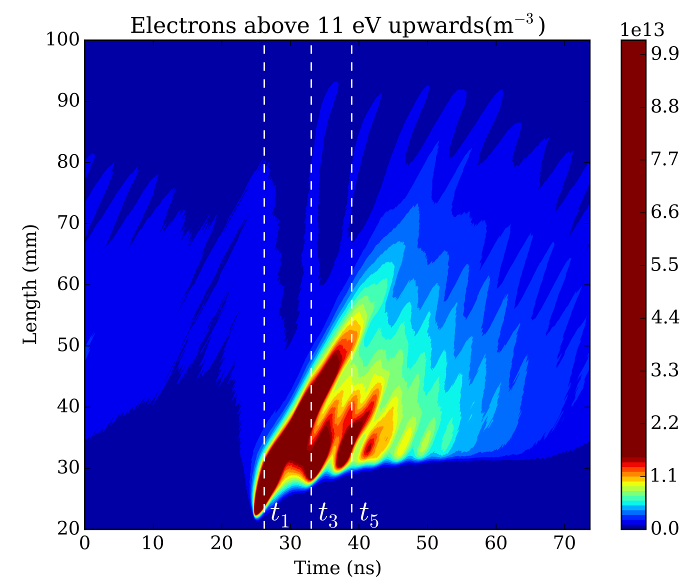



# Asymmetric discharge (300 V, 13.56 MHz, 1 Pa, 80 mm)



# Conclusion

- non-linearity of the system leads to harmonic excitation
- kinetic interpretation presents the mechanism of energetic electron beams interacting with bulk electrons
- bulk electrons are attracted to the modulated plasma sheath
- interaction leads to further beam acceleration
- conduction and displacement current must ensure current conservation during the presence of electron beams
- asymmetric discharge pronounced excitation of PSR

# Outlook: Poster Session II on Wednesday

LW1.00018 : Resonance Phenomena of Voltage and Current Driven Capacitively Coupled Plasmas