Nonlocal and Nonlinear Electron Dynamics in Capacitively Coupled Radio Frequency Discharges

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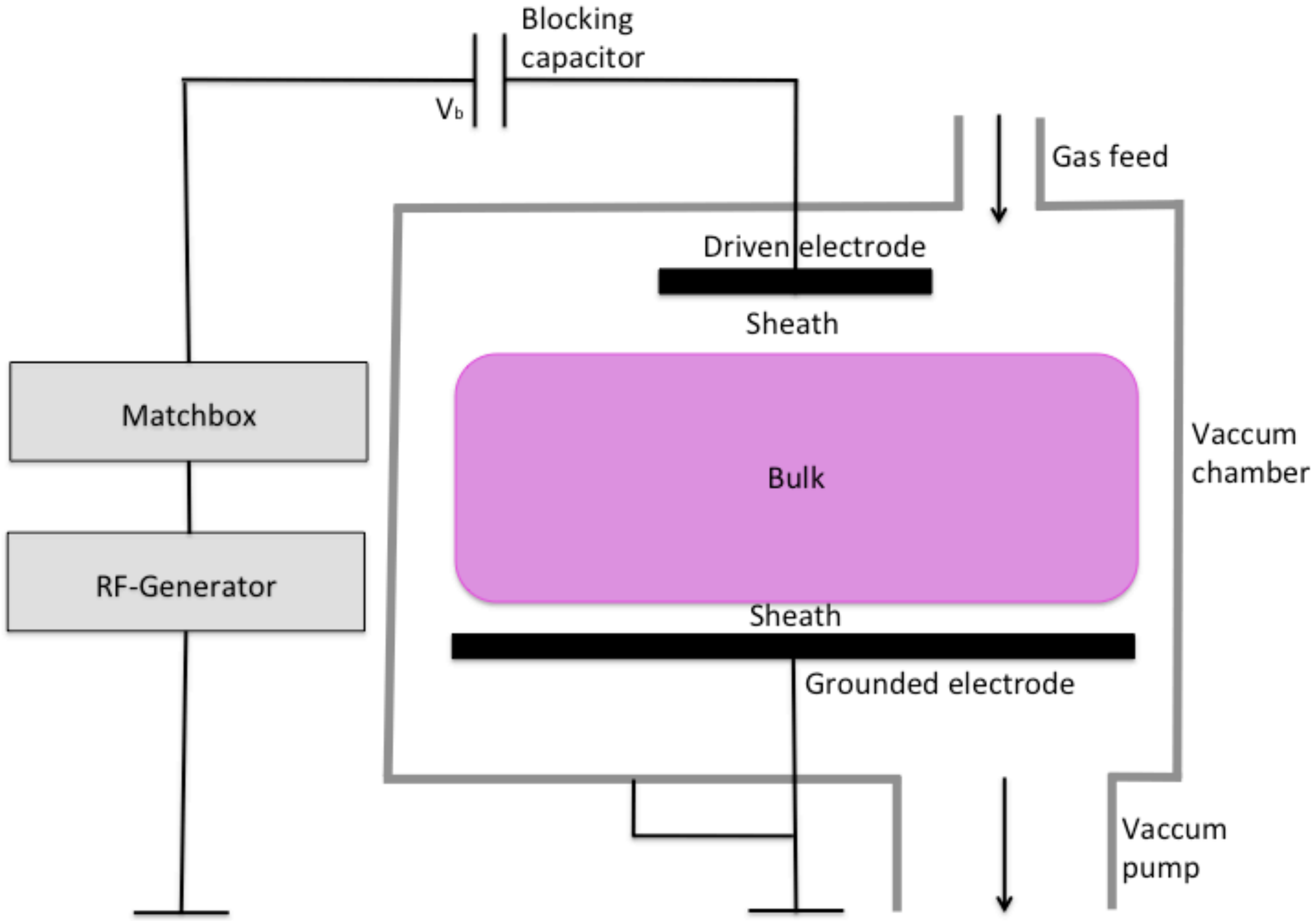
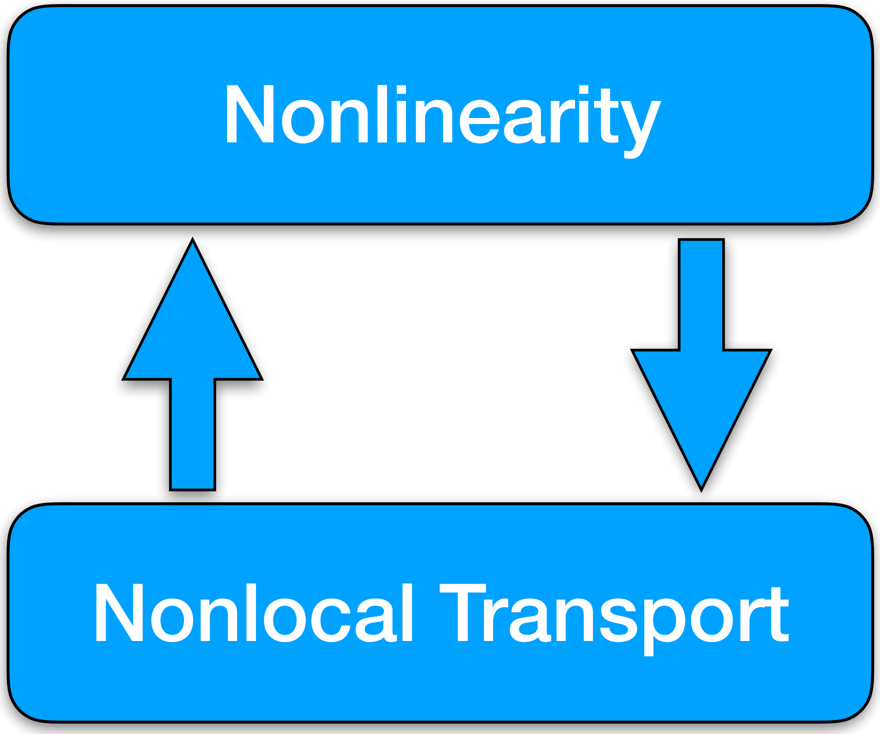
Motivation: Electron Dynamics

RUB

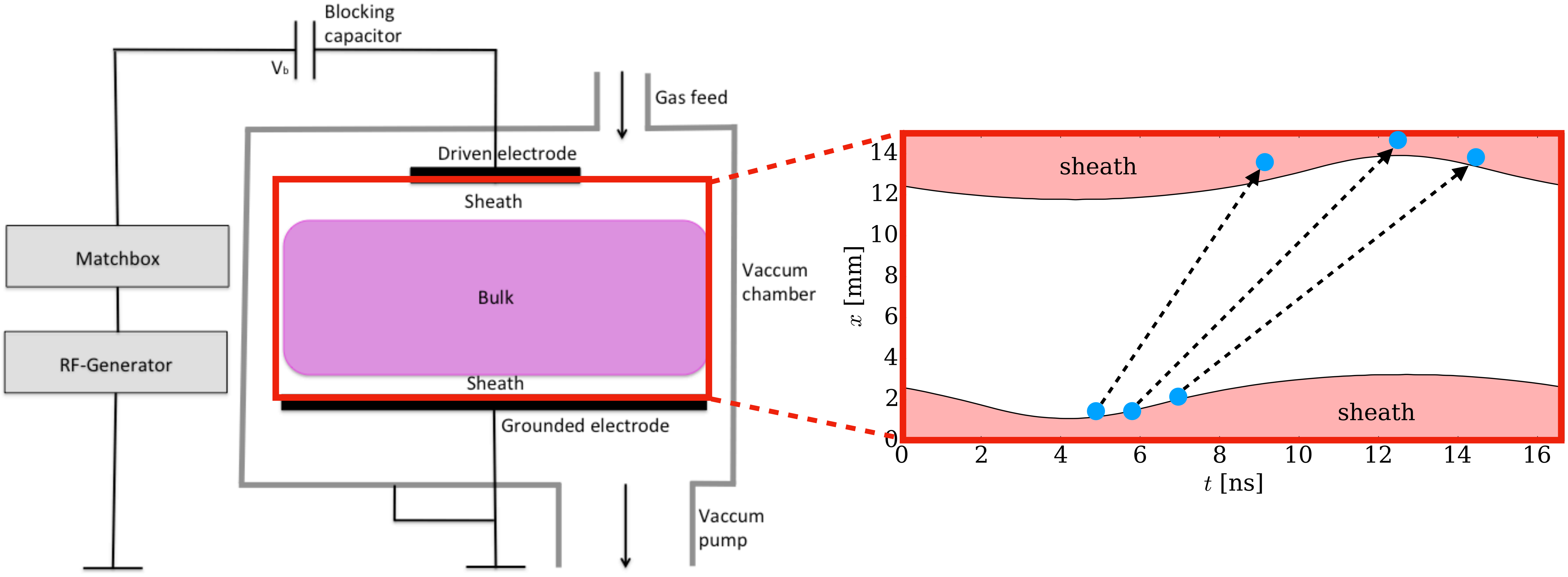




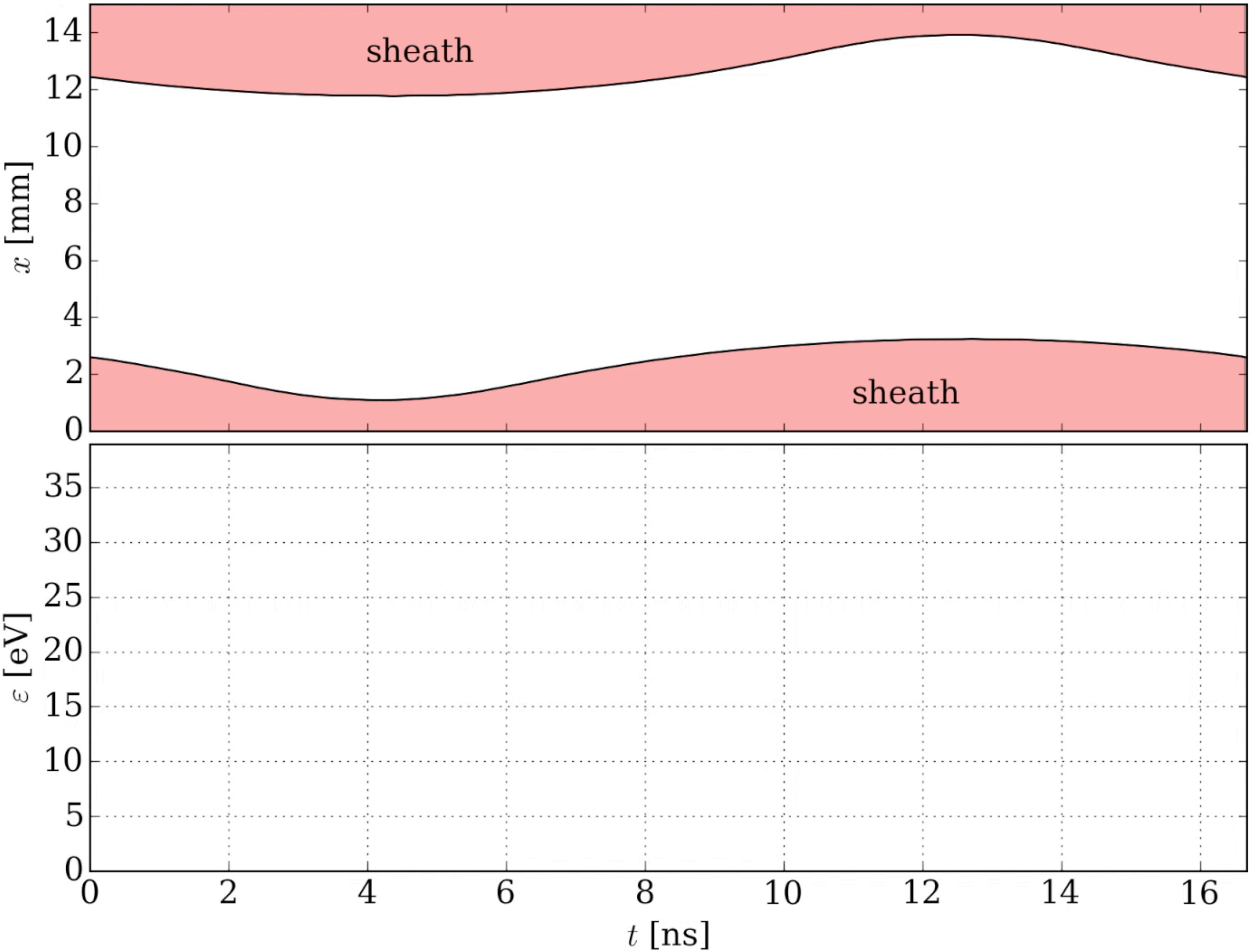
- classical CCRF discharge for etching and sputtering processes
- optimization and control of the plasma density and the ion flux to the wall
- fundamental phenomena are still not fully understood
- electron power gain and loss at low pressures on a kinetic level

Nonlocal Transport

Motivation: Nonlocal Transport



- low pressure (1 Pa), electron mean free path > electrode gap length
- electrons transport their energy almost collisionslessly through the discharge
- confinement and reflection of beam electrons become crucial


sheath
sheath
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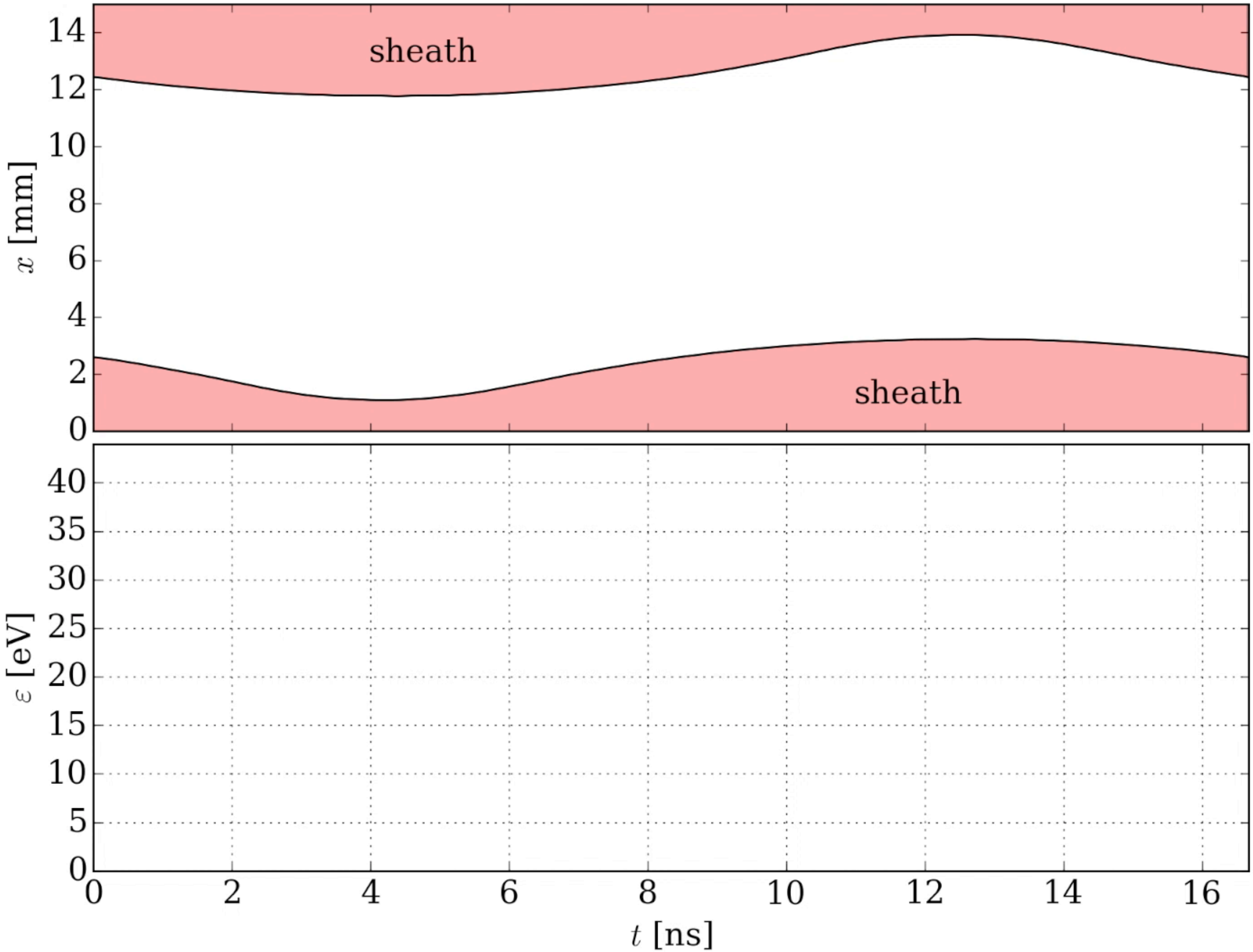

sheath
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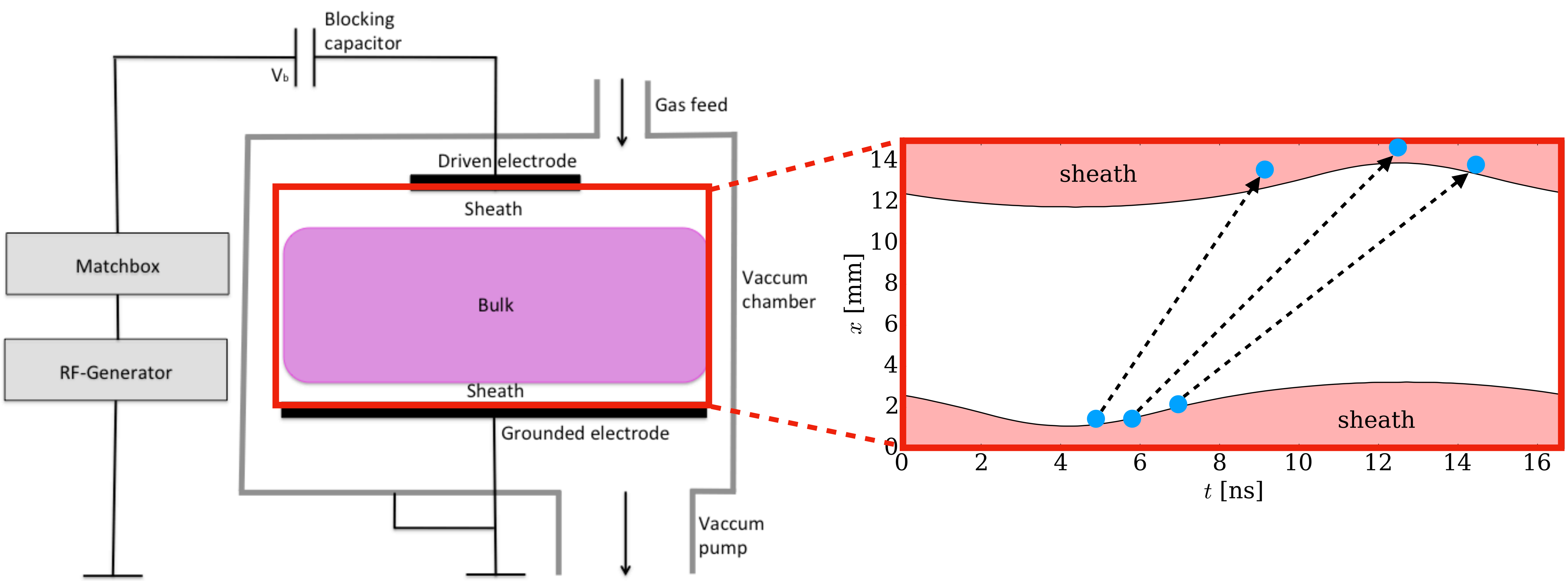
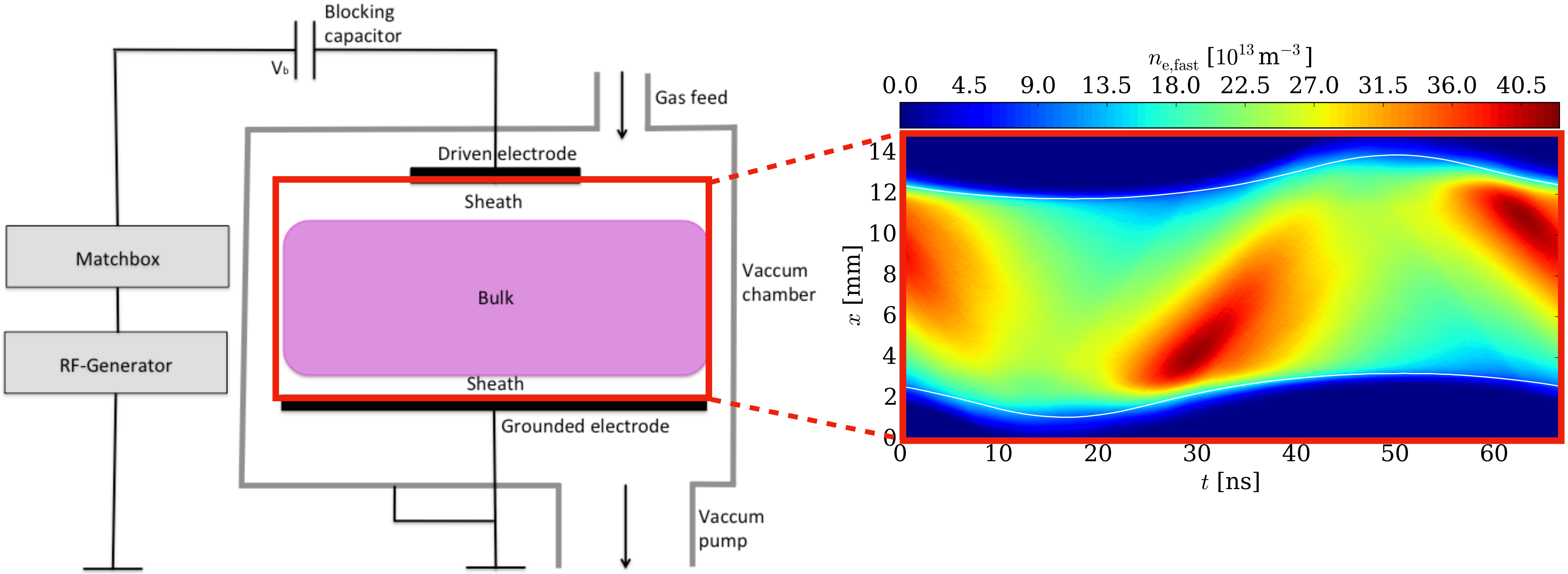
x [mm]
ε [eV]
t [ns]

Goal of this work: Nonlocal Transport



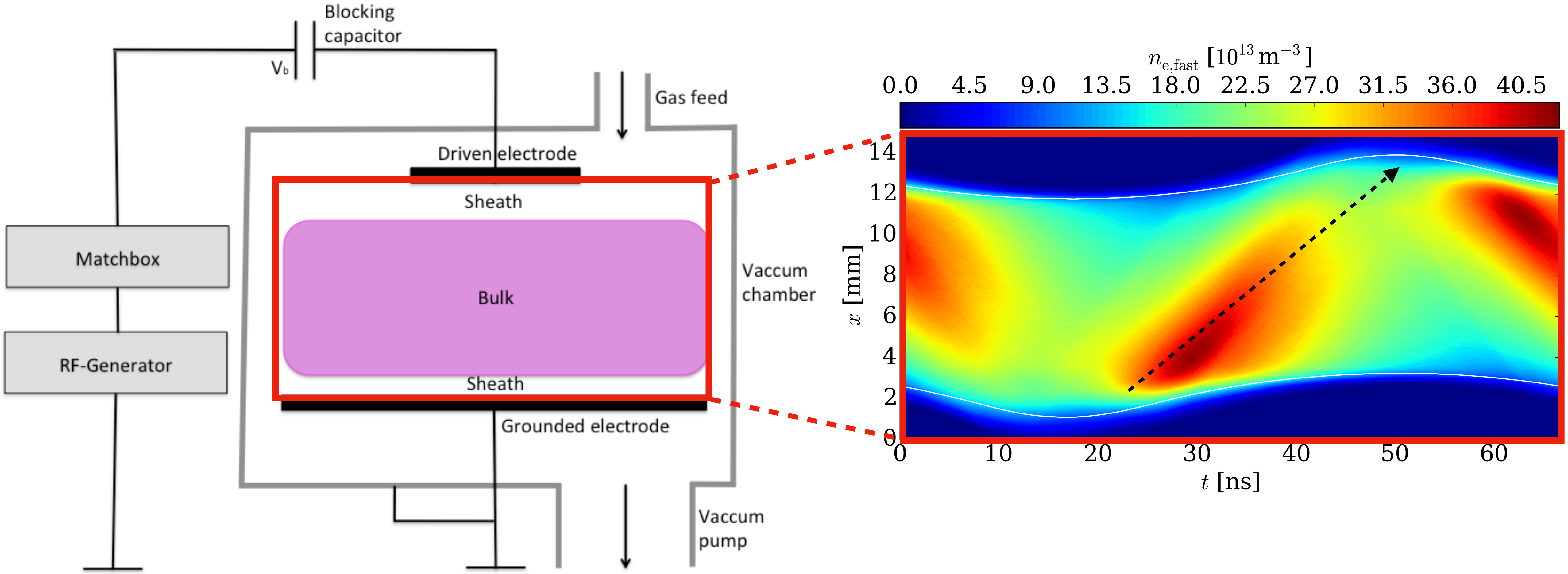
- can we control the trajectory and the impingement phase of energetic electrons?

Goal of this work: Nonlocal Transport



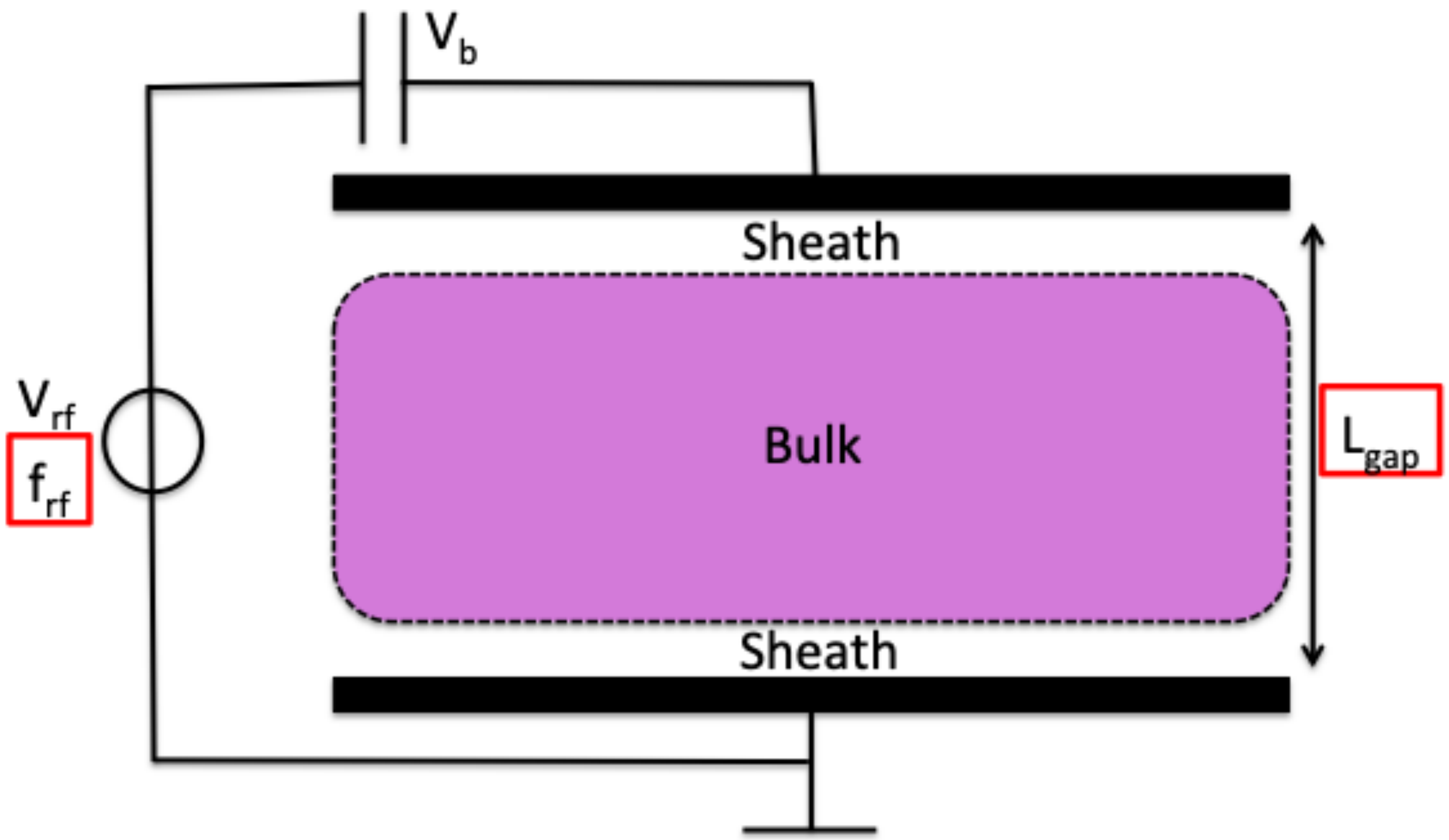
- can we control the trajectory and the impingement phase of energetic electrons?
- electron density of fast electrons above 15.7 eV (comparable to PROES)

Goal of this work: Nonlocal Transport



- can we control the trajectory and the impingement phase of energetic electrons?
- electron density of fast electrons above 15.7 eV (comparable to PROES)
- how does input parameter affect the impingement phase?
  - gap size variation
  - driving frequency variation

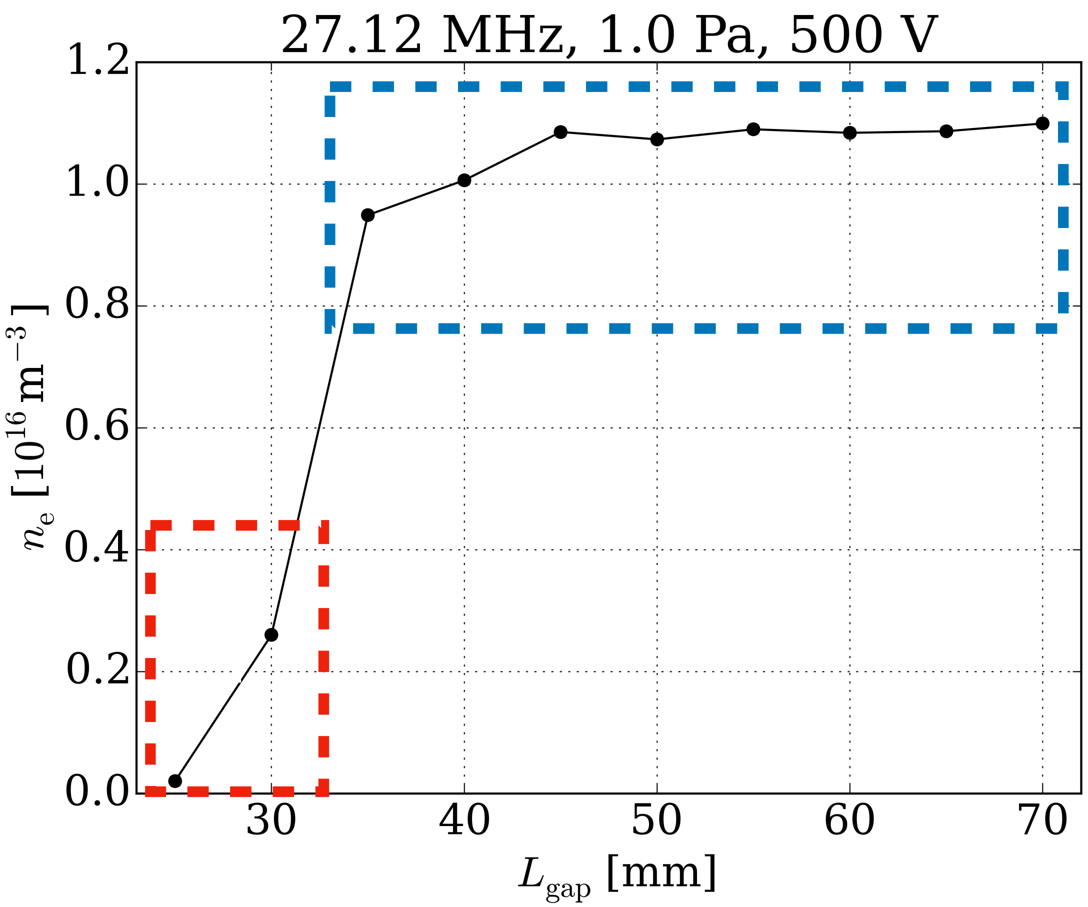
Gap variation

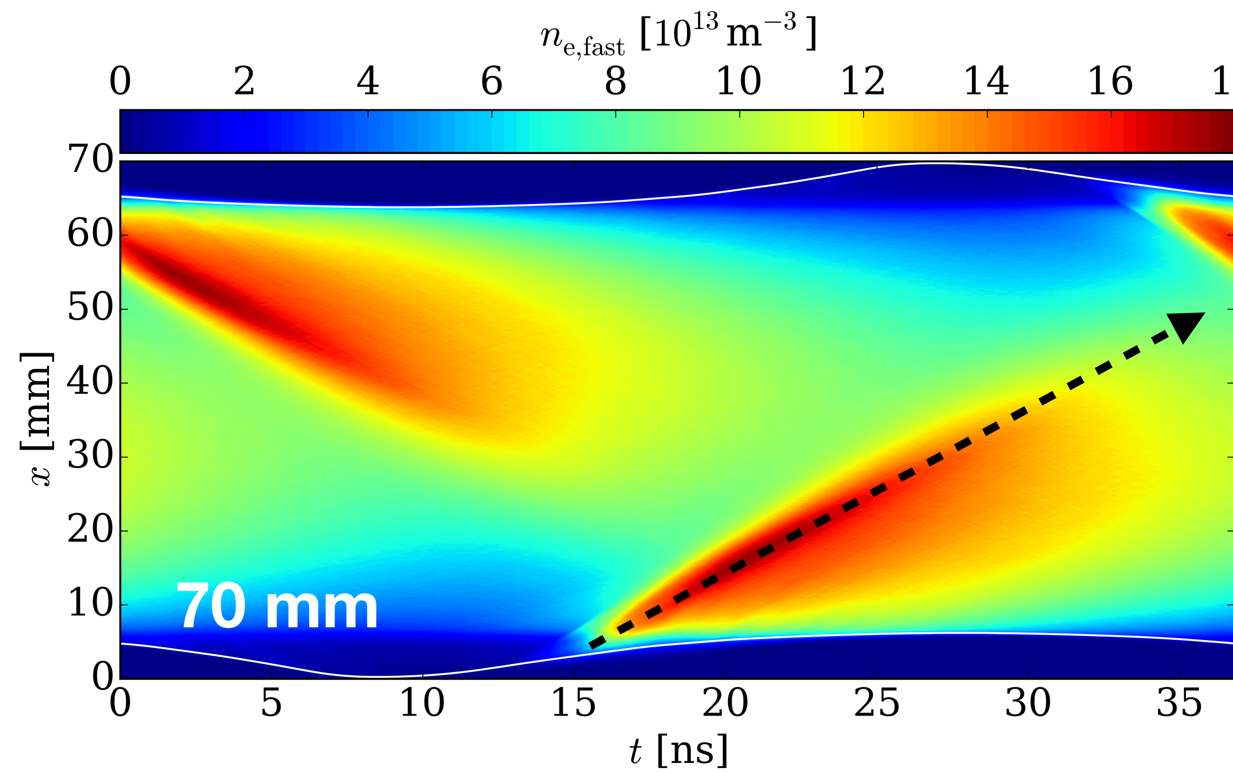


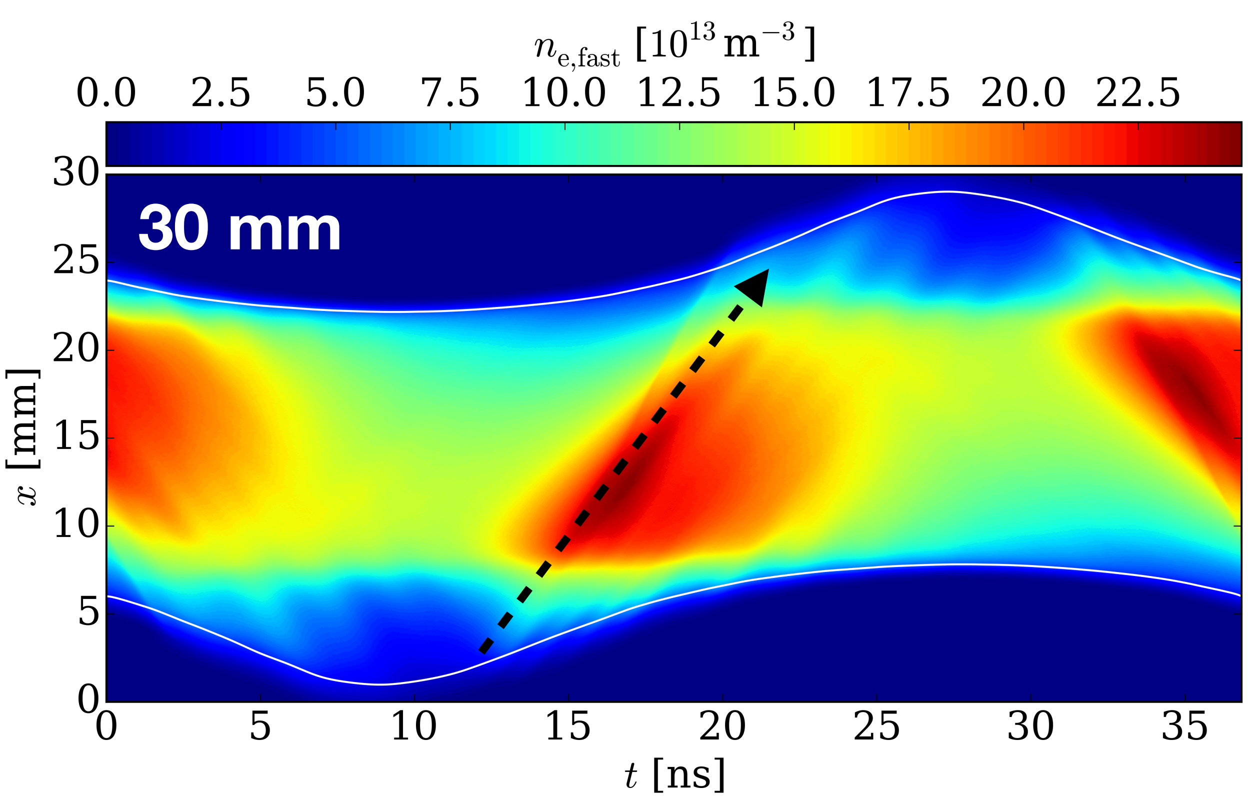
- 1d3v Particle-In-Cell simulation, Cartesian grid (perfectly symmetric), argon
- no secondary electron emission and no reflection at the boundary
- frequency: 27.12 MHz
- gas pressure: 1 Pa
- driving voltage: 500 V
- **gap size: 25 - 70 mm**

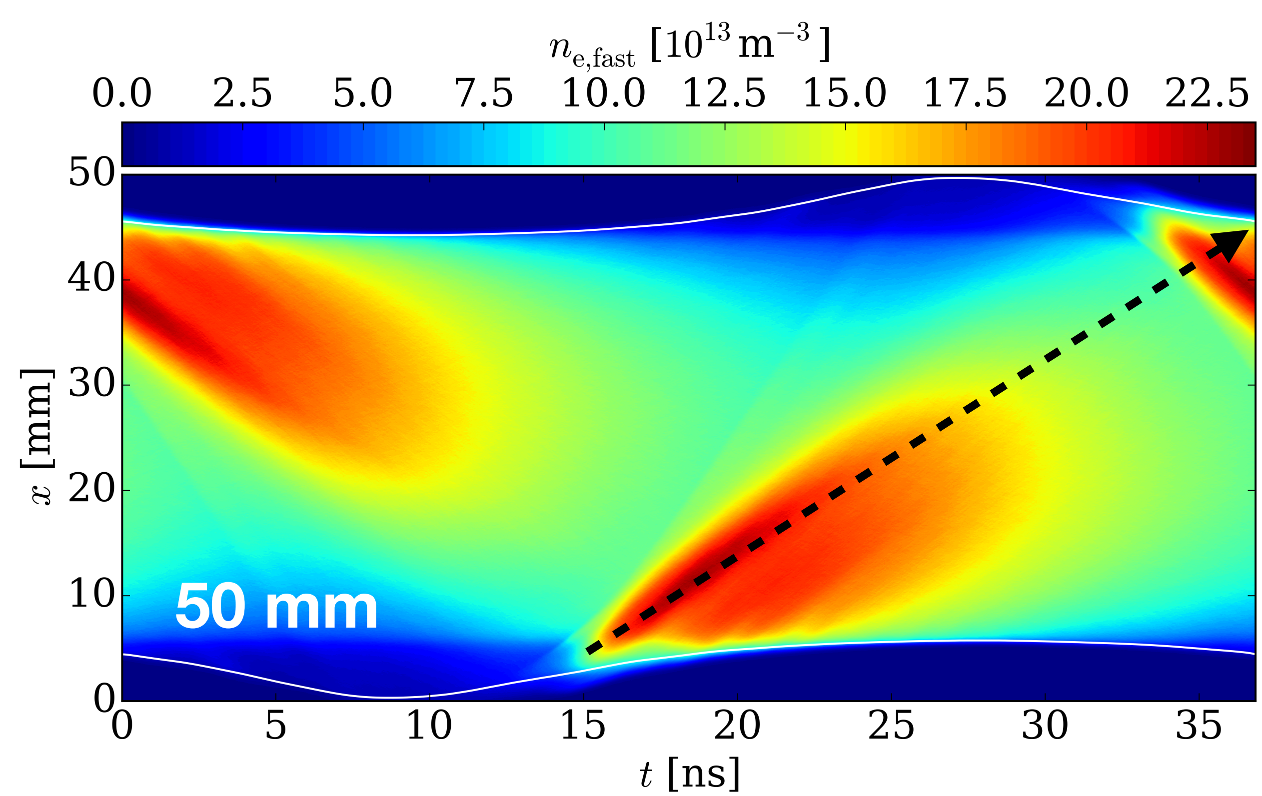
Gap variation: Fast electrons (E > 15.7 eV)

RUB

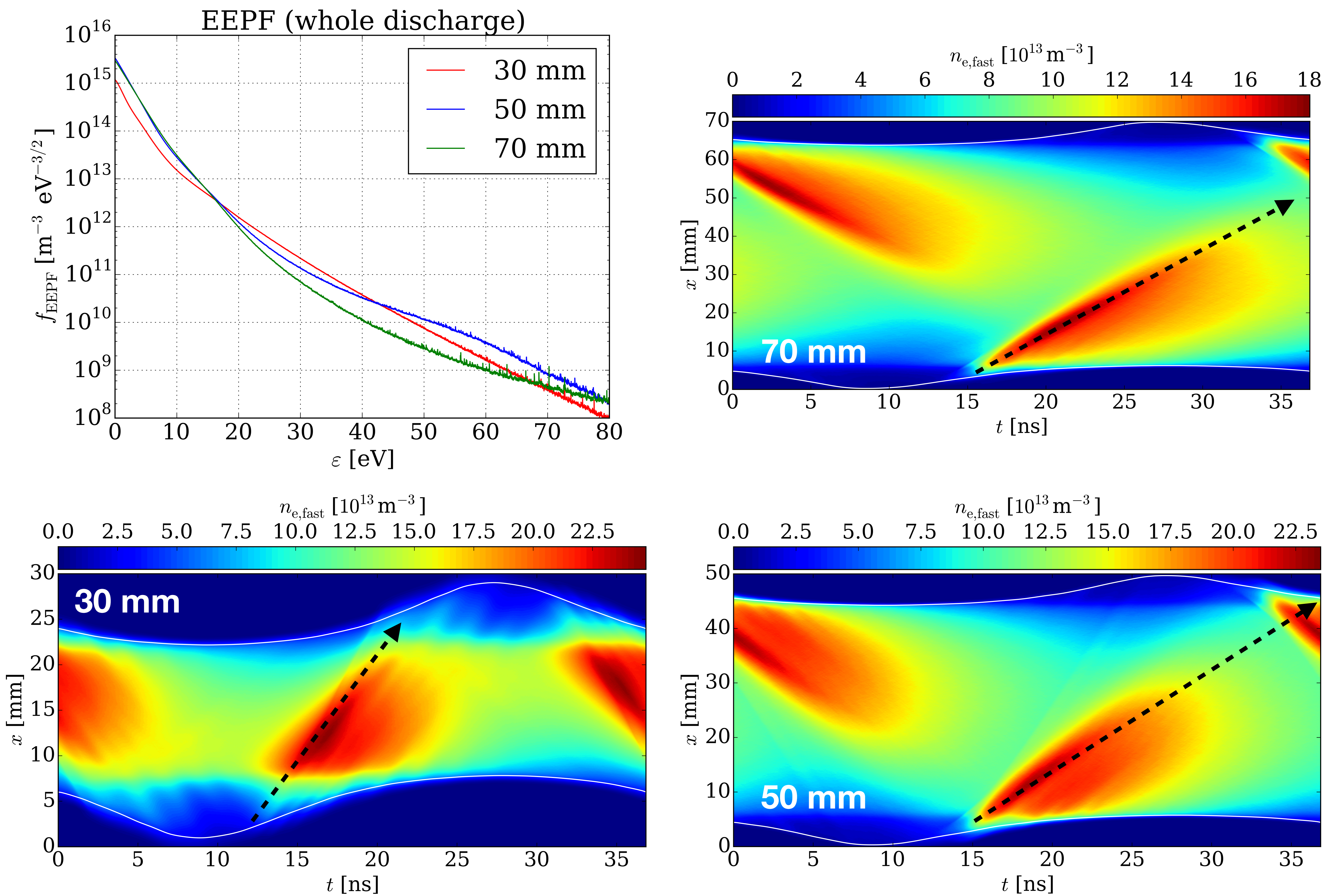








Gap variation: Distribution function



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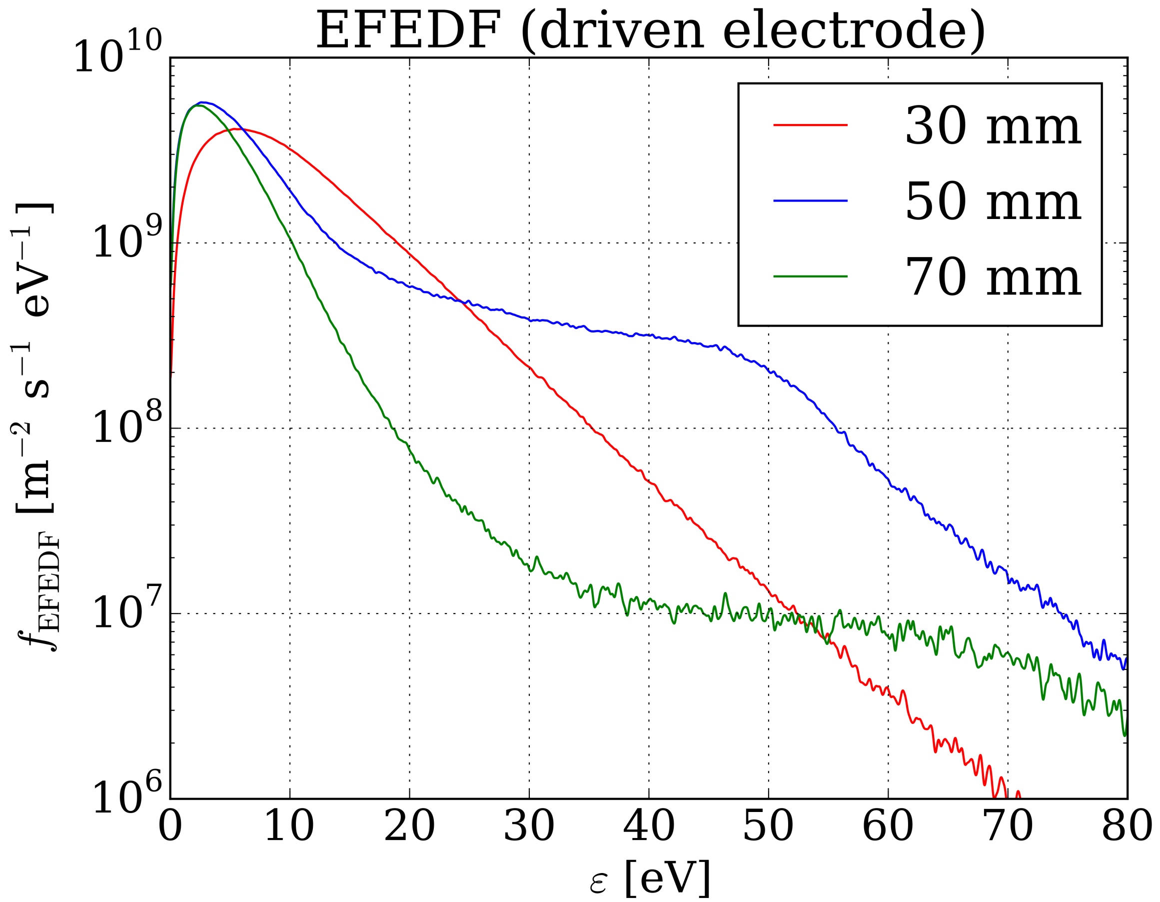
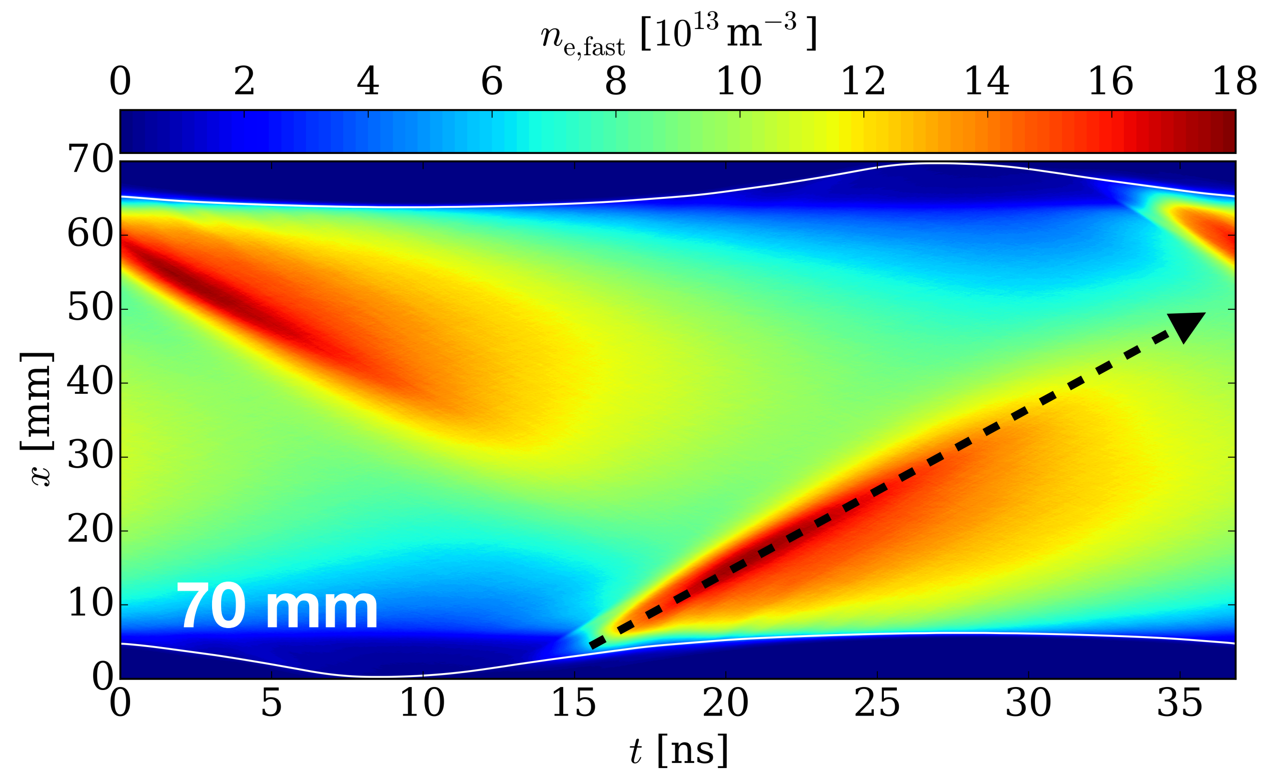
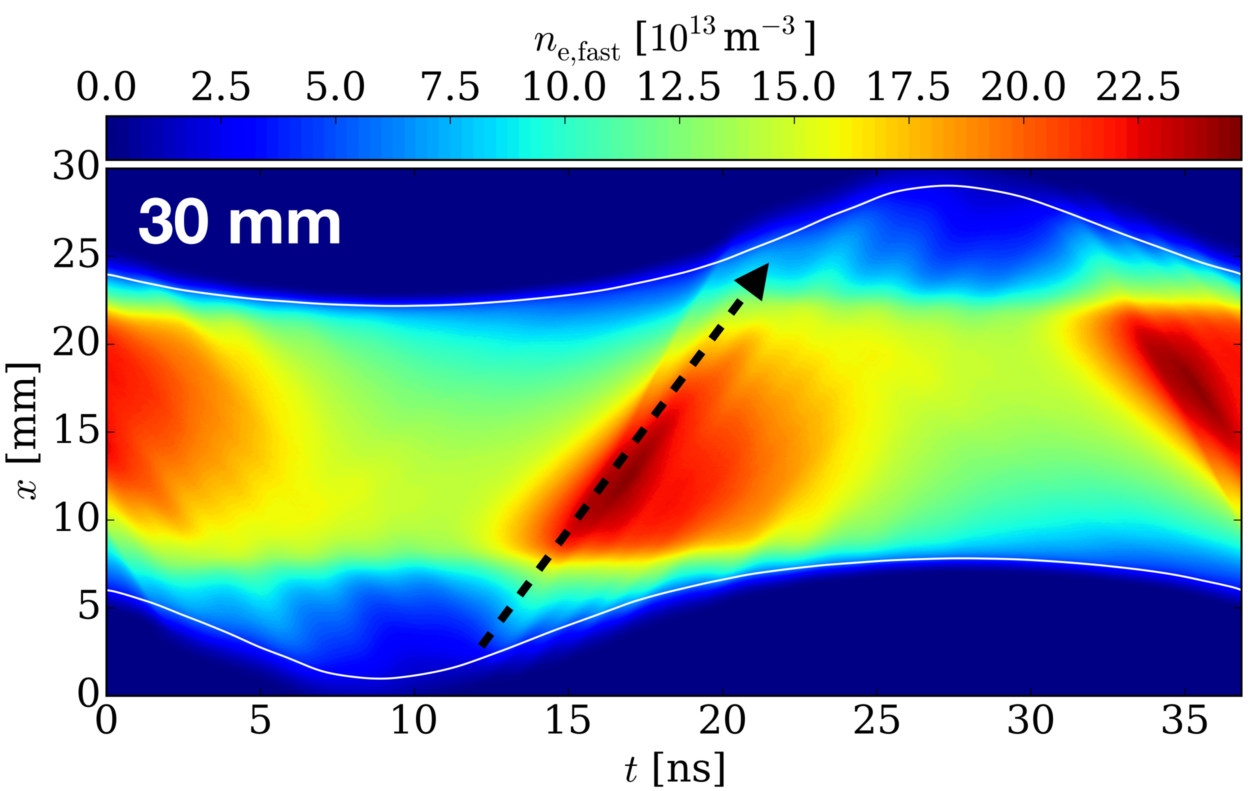
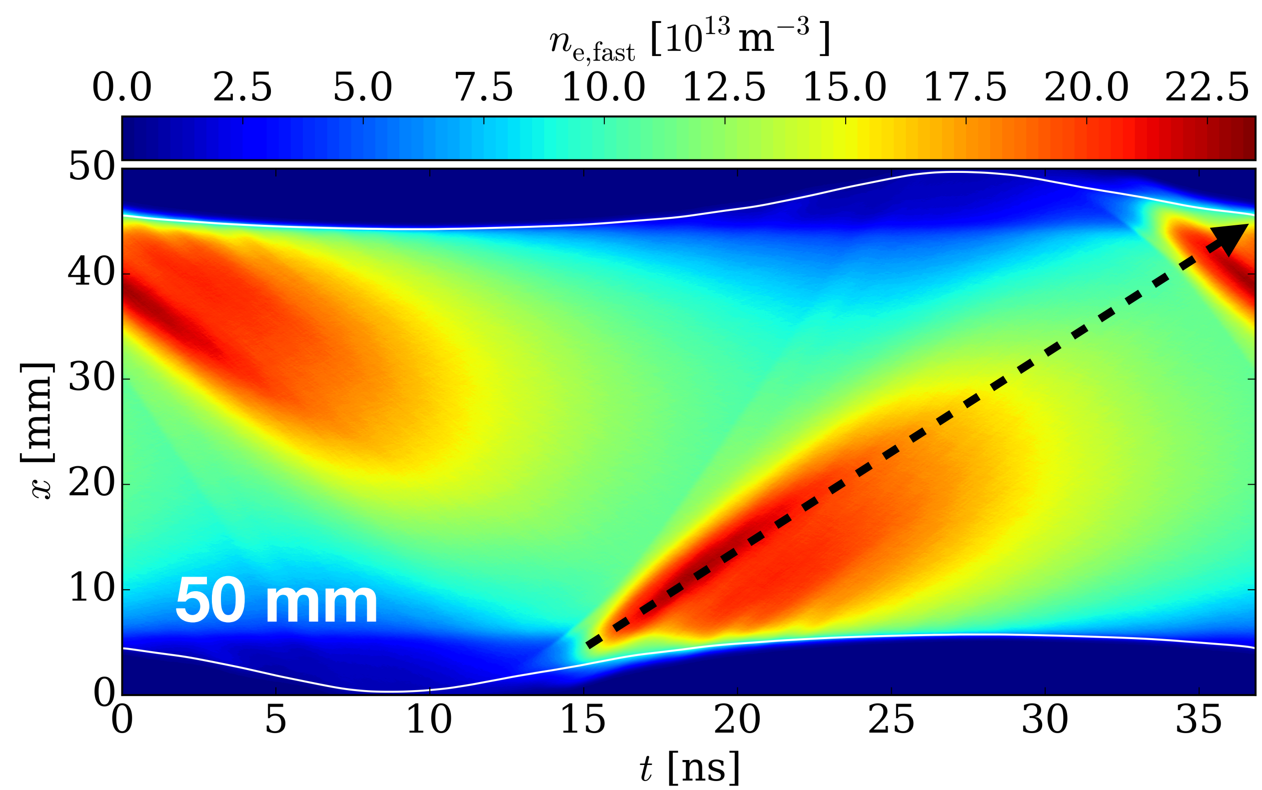
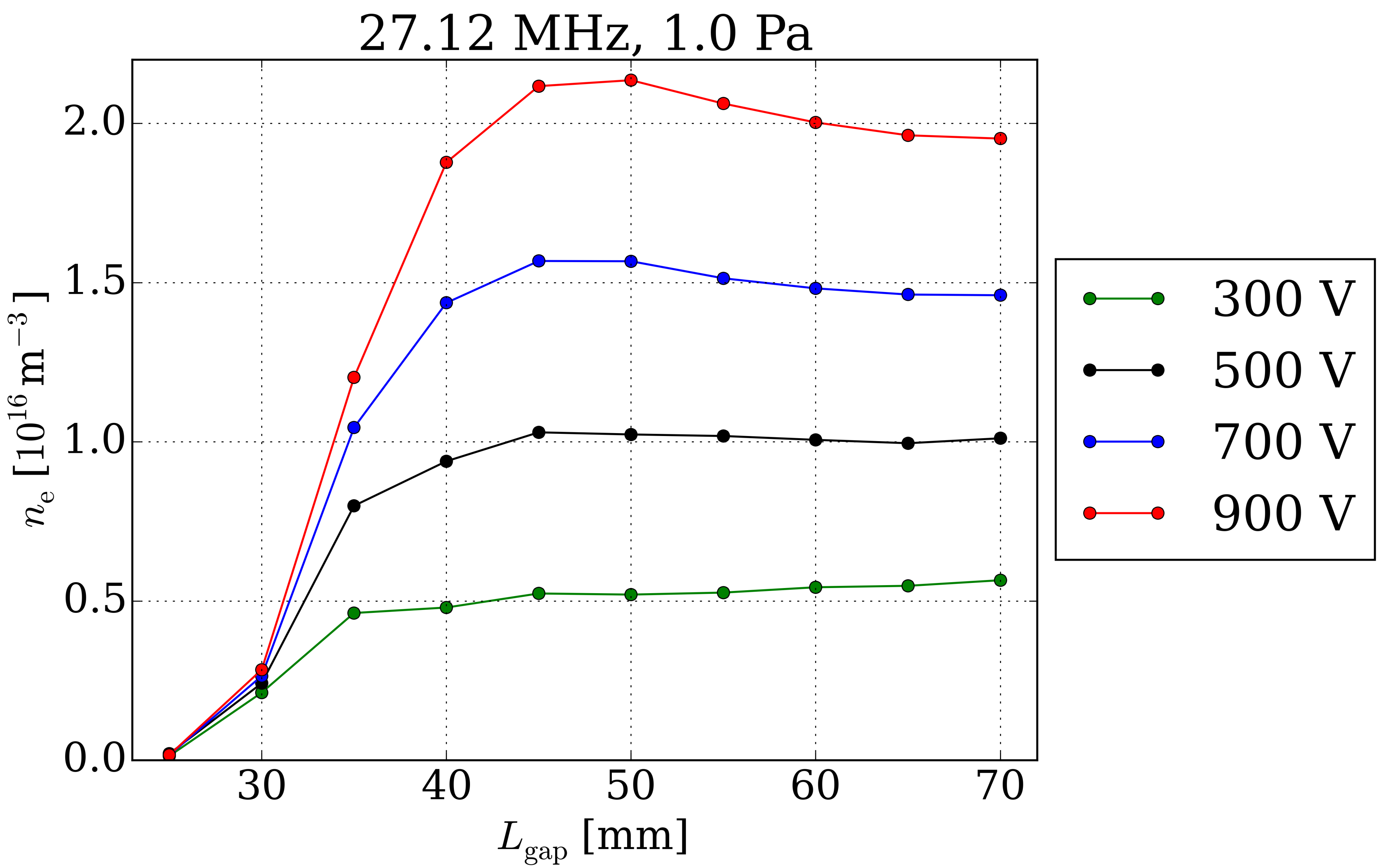






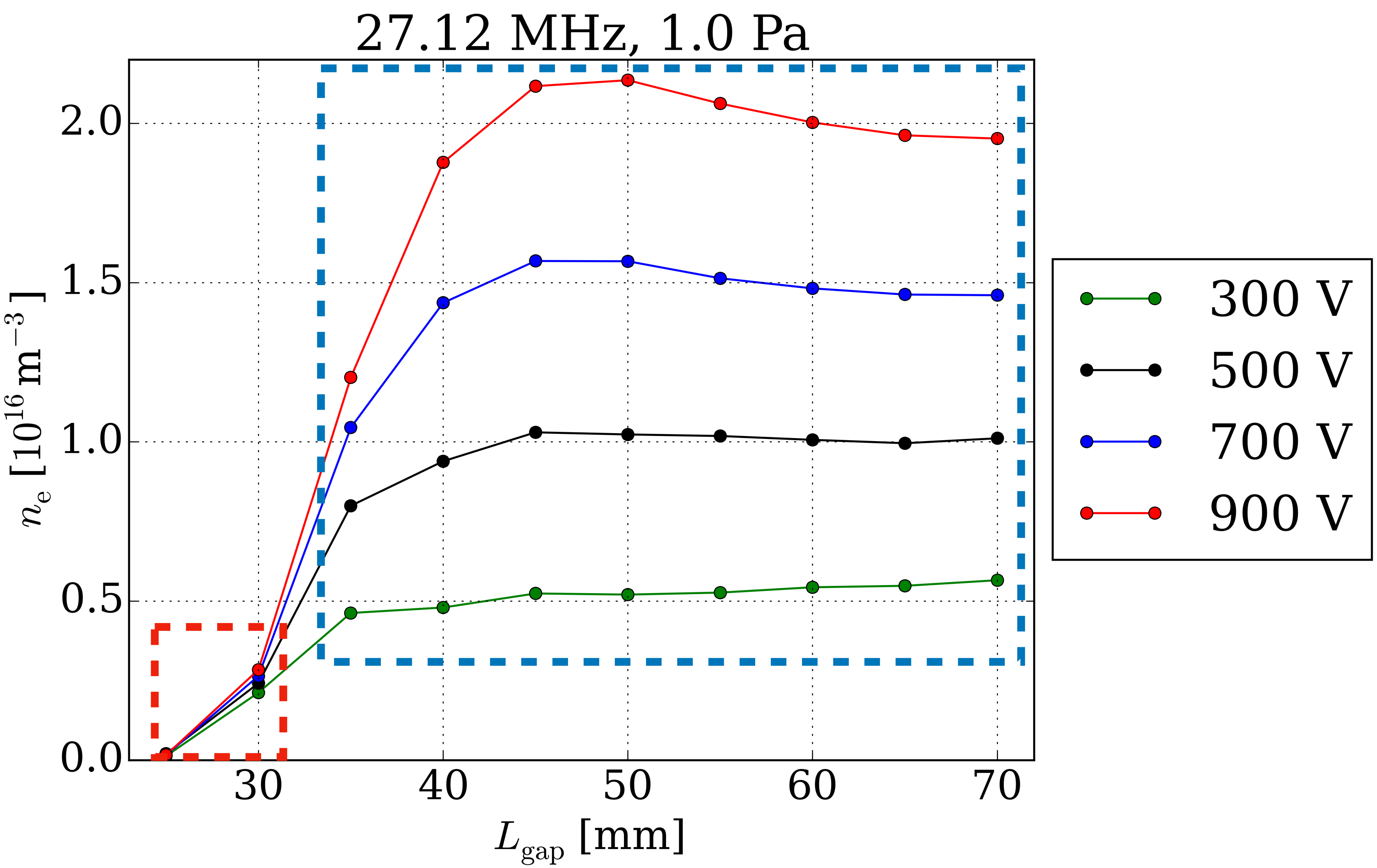


Gap variation: Operation regime



- gap size variation for different rf-voltages
- increasing the rf-voltage leads to higher densities (only at larger gap sizes)

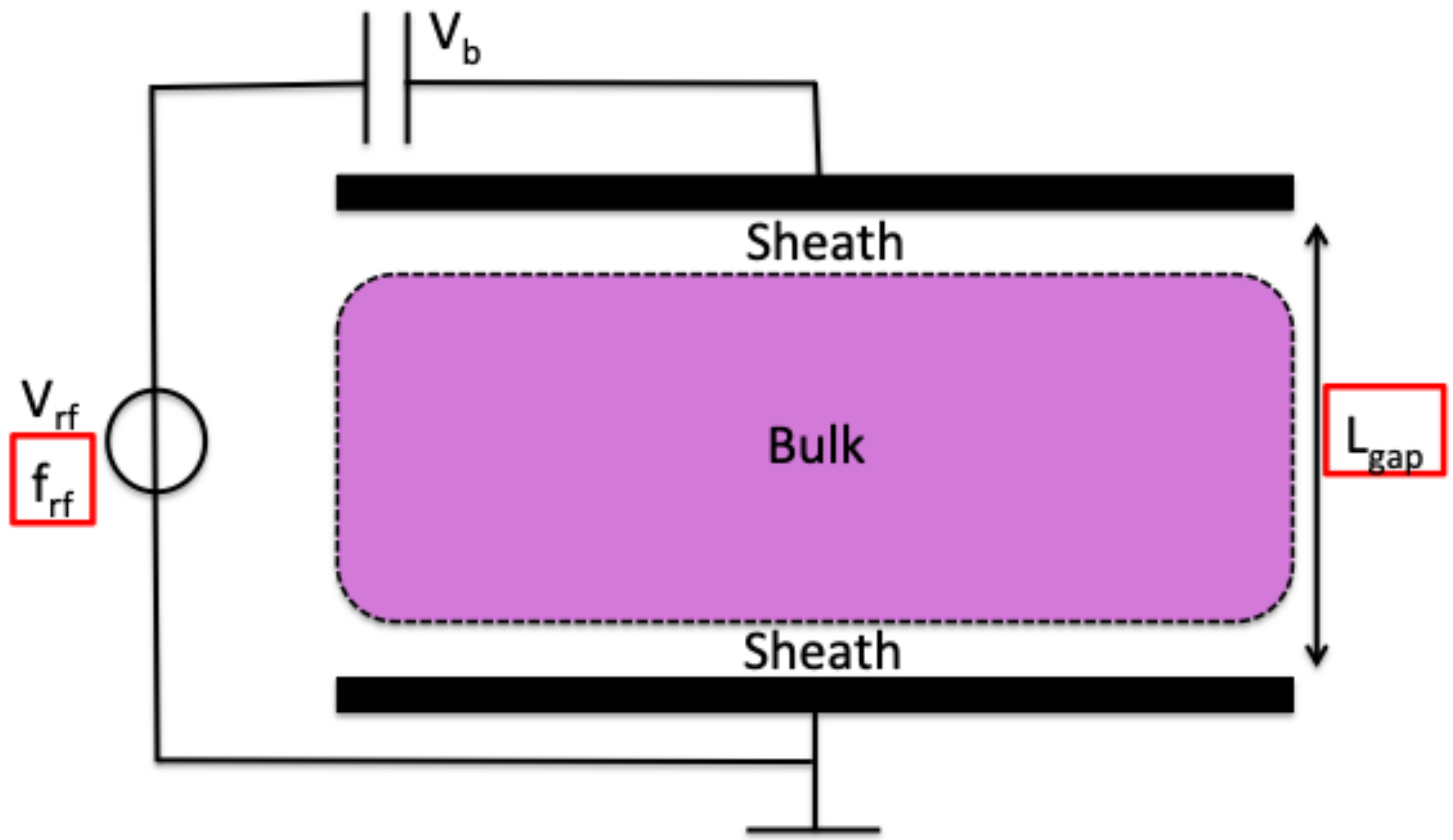
Gap variation: Operation regime



- gap size variation for different rf-voltages
- increasing the rf-voltage leads to higher densities (only at larger gap sizes)
- smaller gap sizes: no chance to obtain a significant increase
- limitation of process control

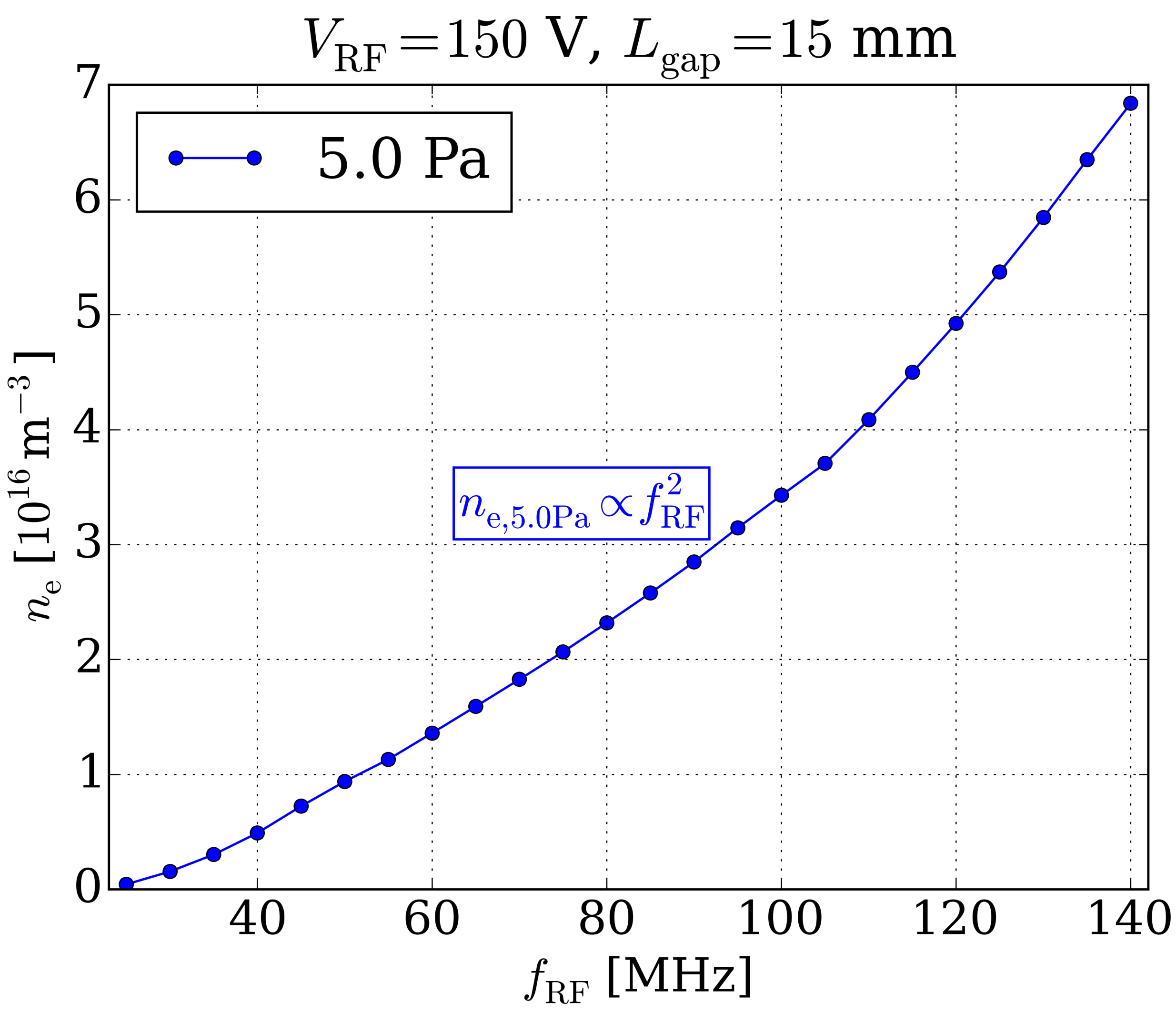
Driving frequency variation

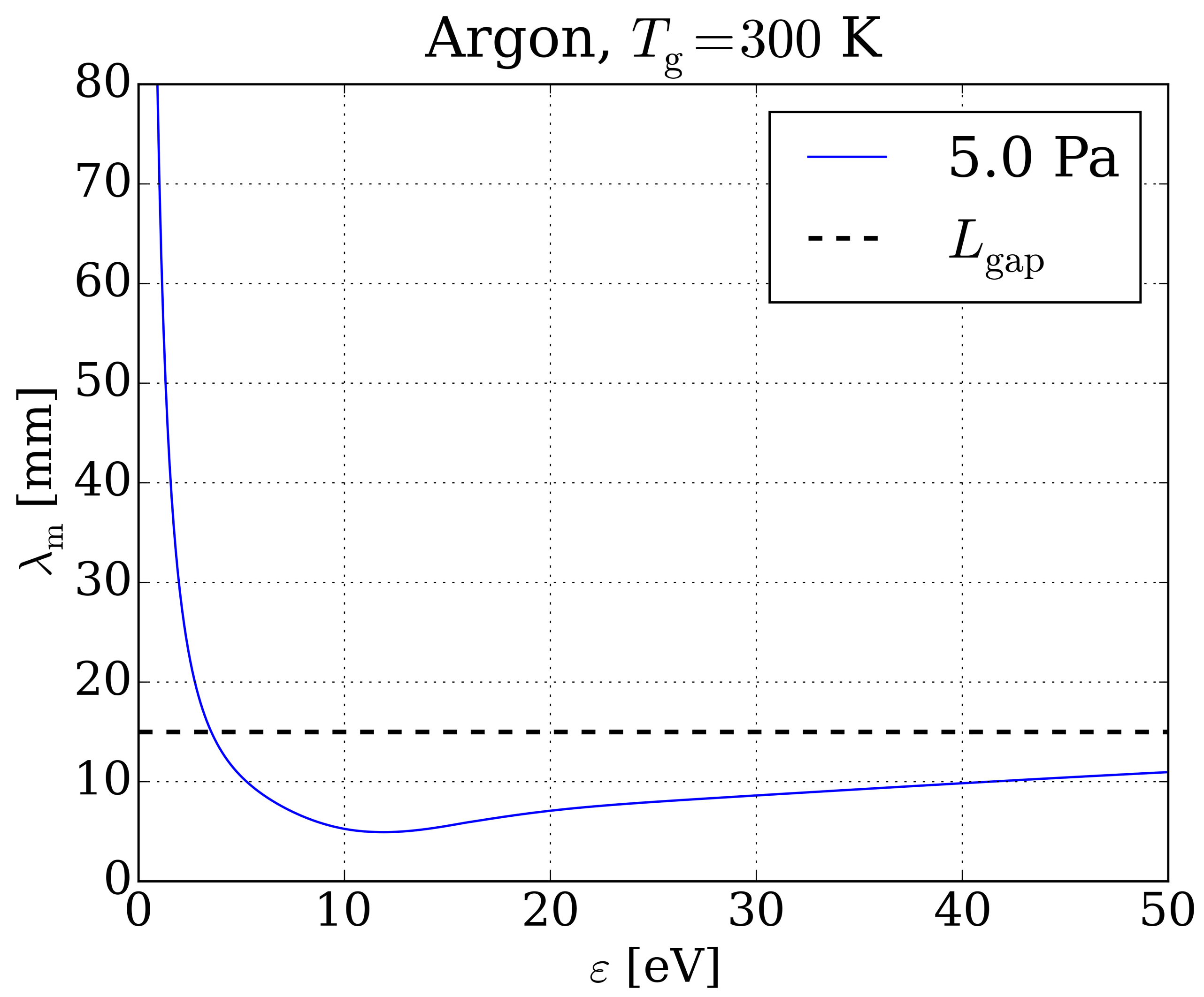
RUB



- 1d3v Particle-In-Cell simulation, Cartesian grid (perfectly symmetric), argon
- no secondary electron emission and no reflection at the boundary
- gap size: 15 mm
- gas pressure: 1 - 5 Pa
- driving voltage: 150 V
- **driving frequency: 25 - 100 MHz**

Driving frequency variation

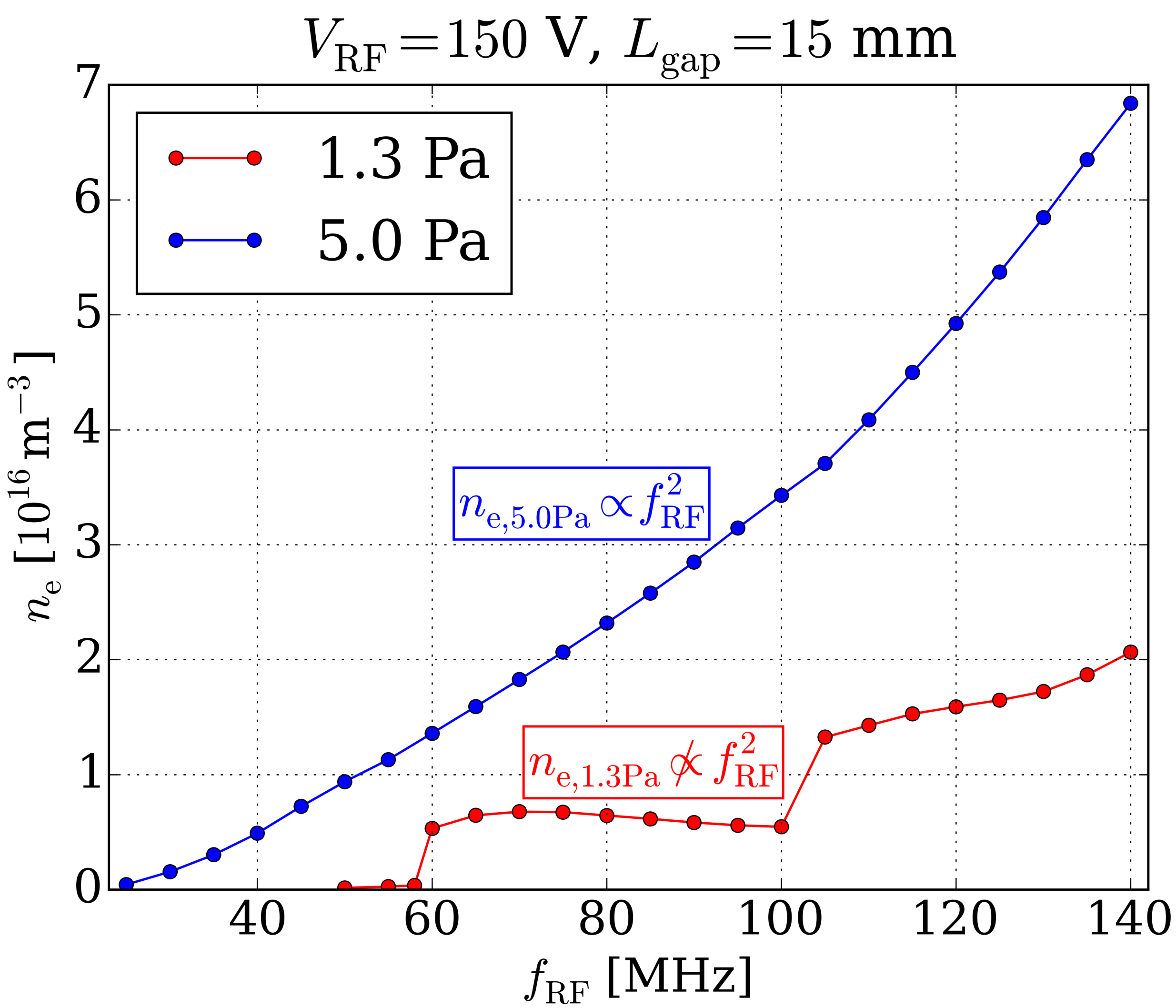


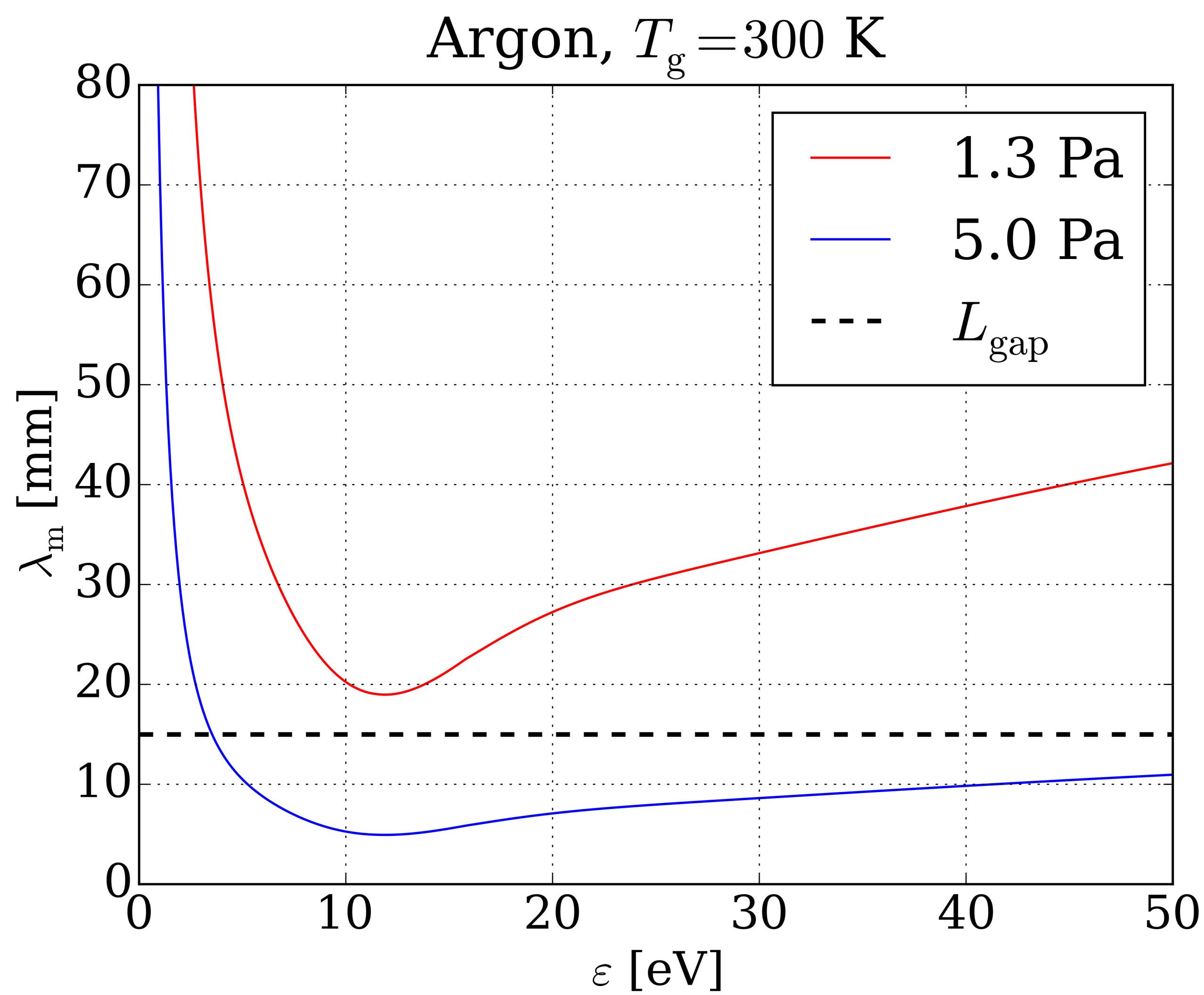


- expected quadratic dependence of the driving frequency[1]
- 5 Pa —> collisional regime for energetic electrons

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

Driving frequency variation



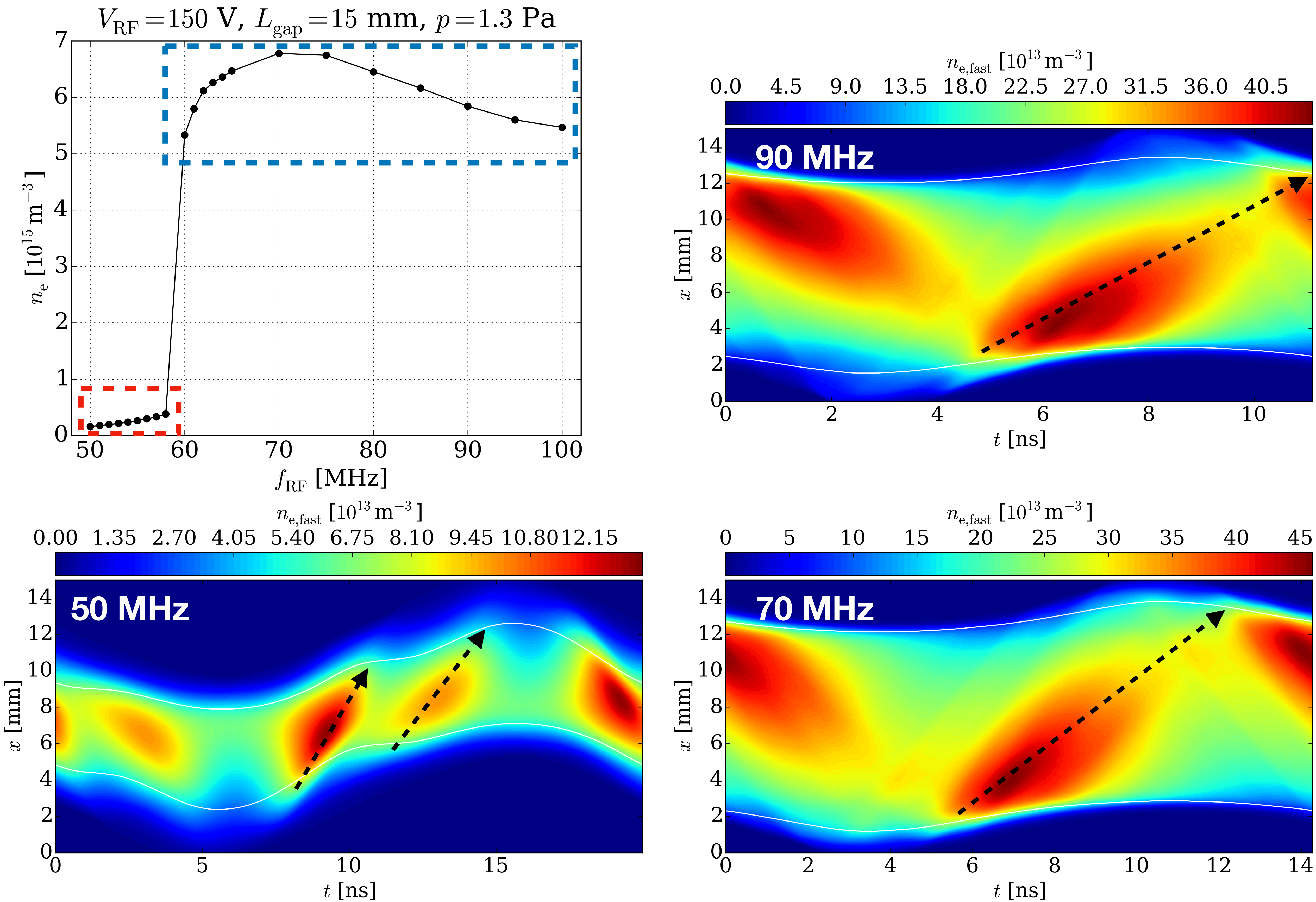


- expected quadratic dependence of the driving frequency[1]
- 5 Pa —> collisional regime for energetic electrons
- decreasing the pressure, no quadratic dependence of the driving frequency[2]
- 1.3 Pa —> energetic electrons traverse collisionlessly through the discharge

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

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

RF variation: Fast electrons (E > 15.7 eV)



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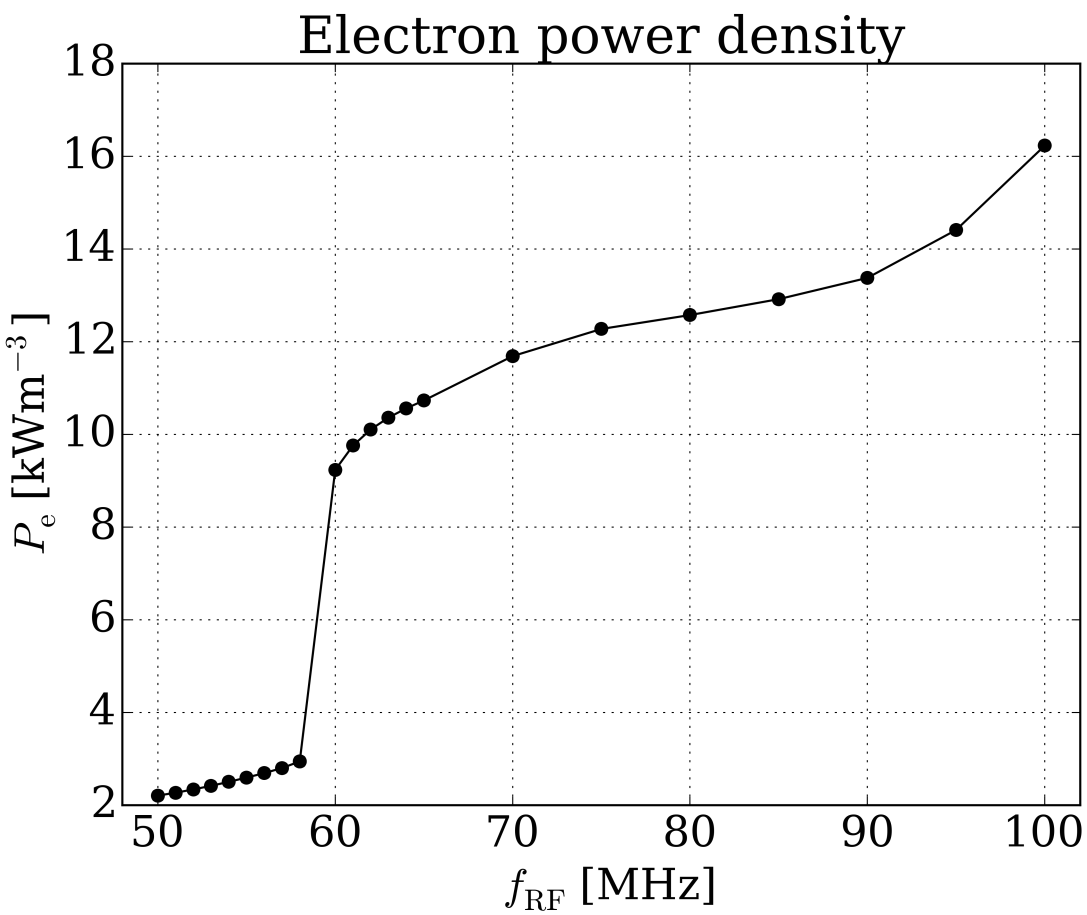

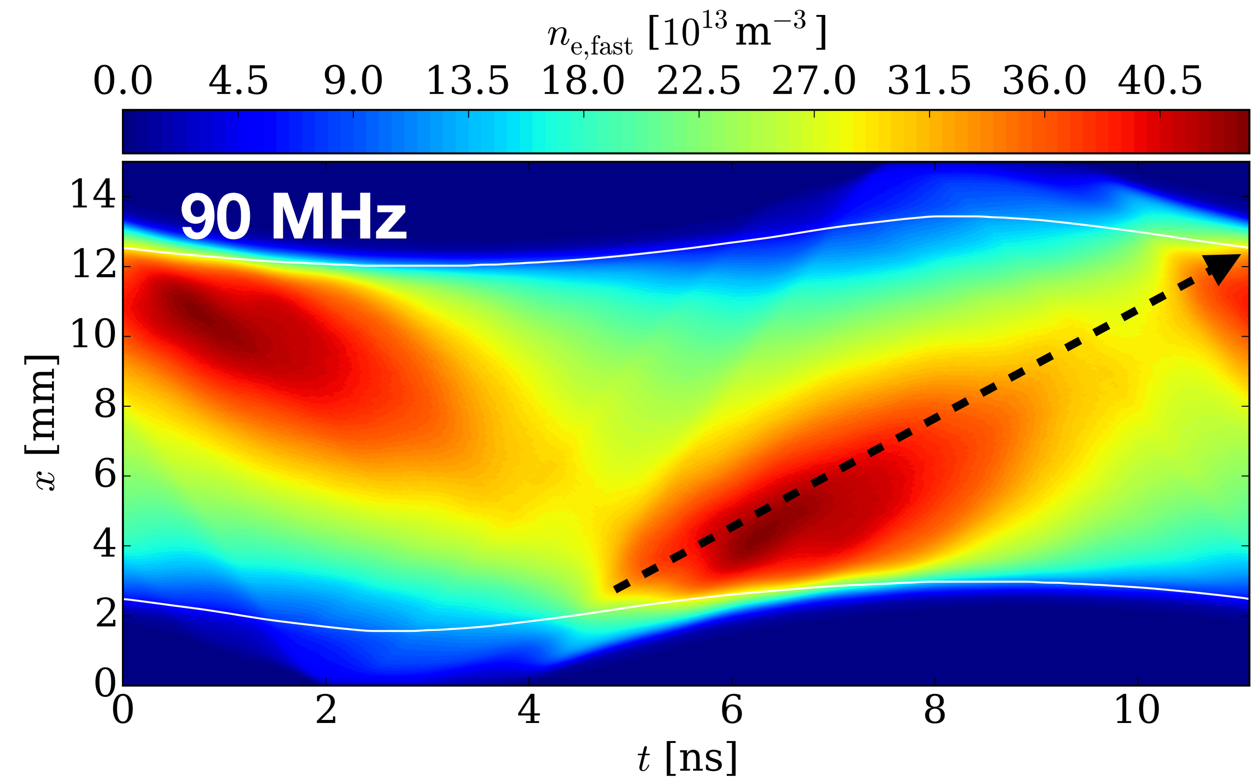

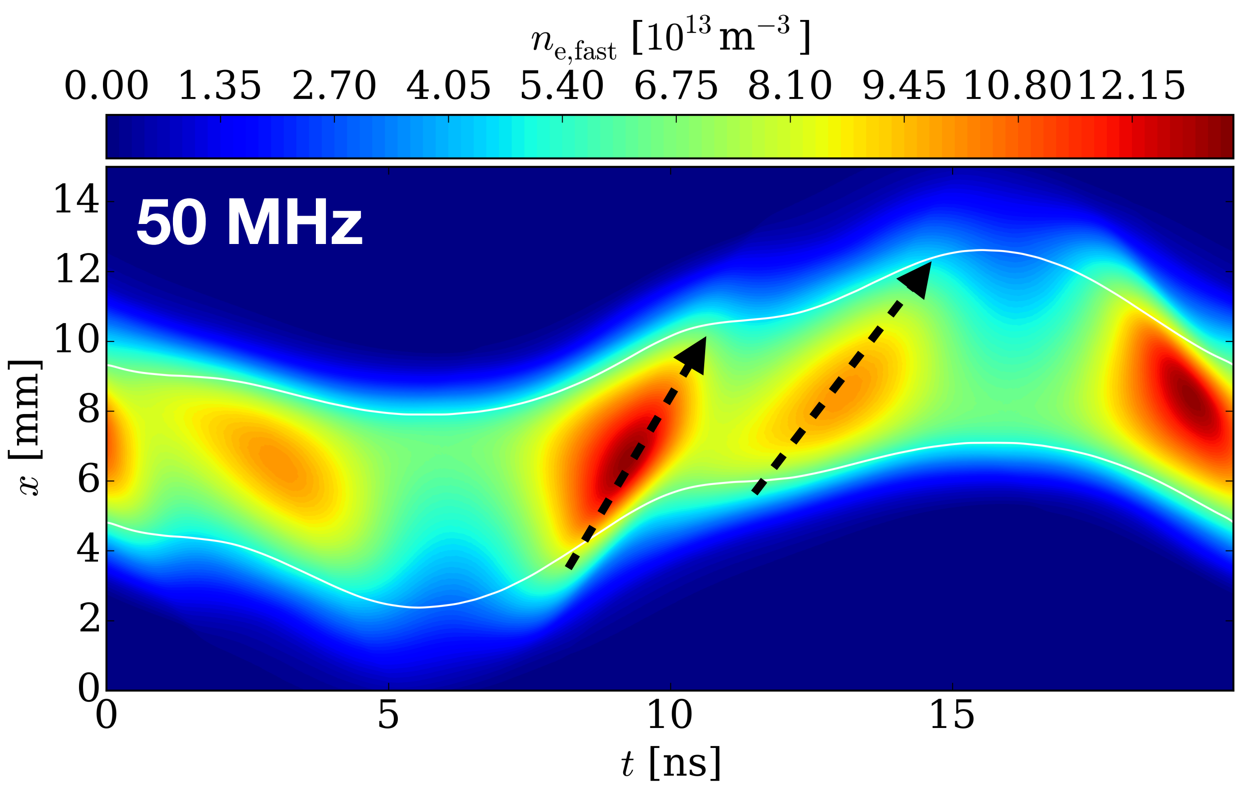

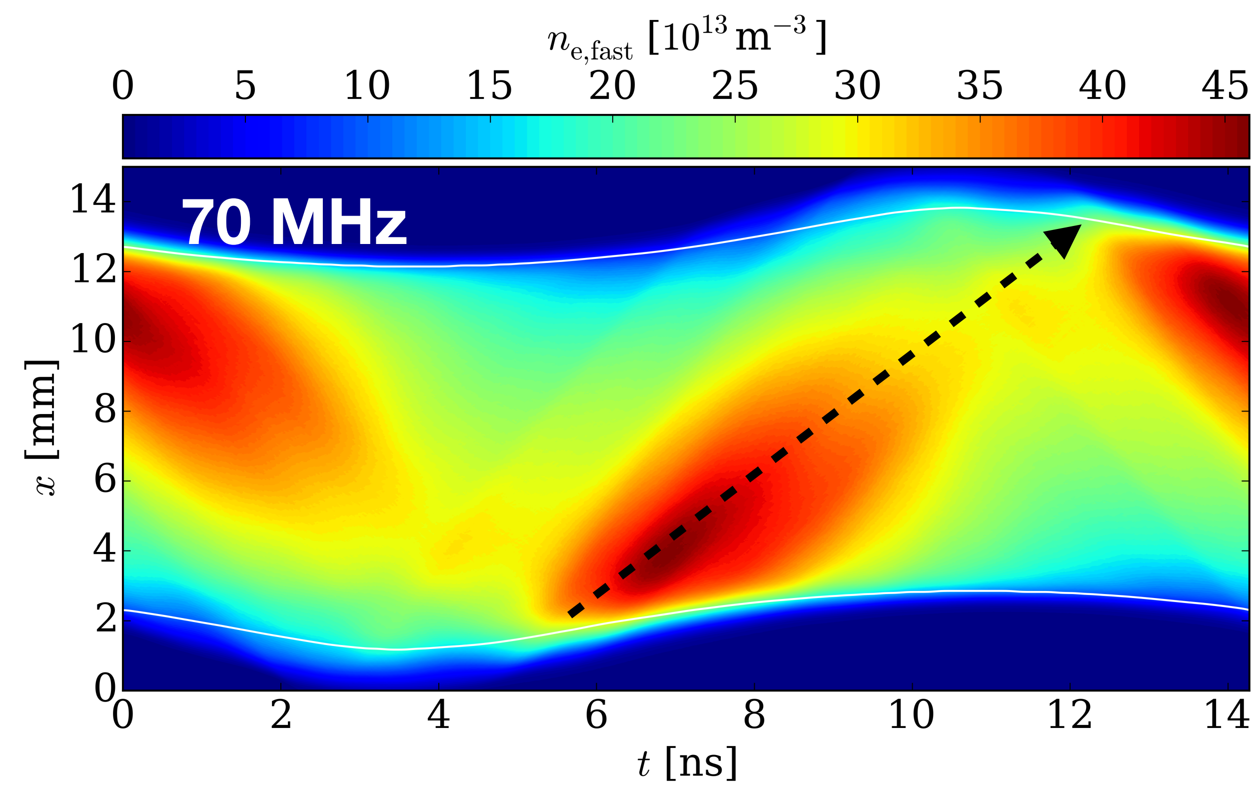

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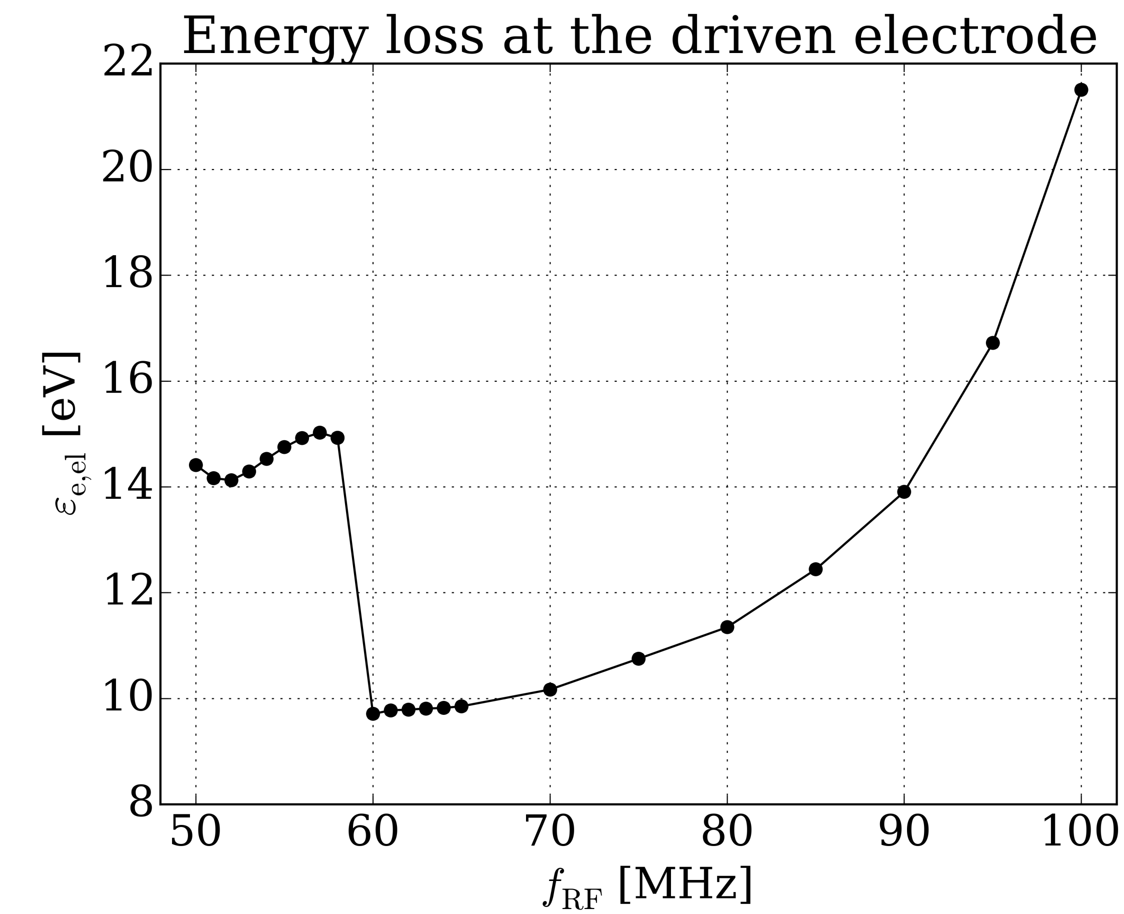

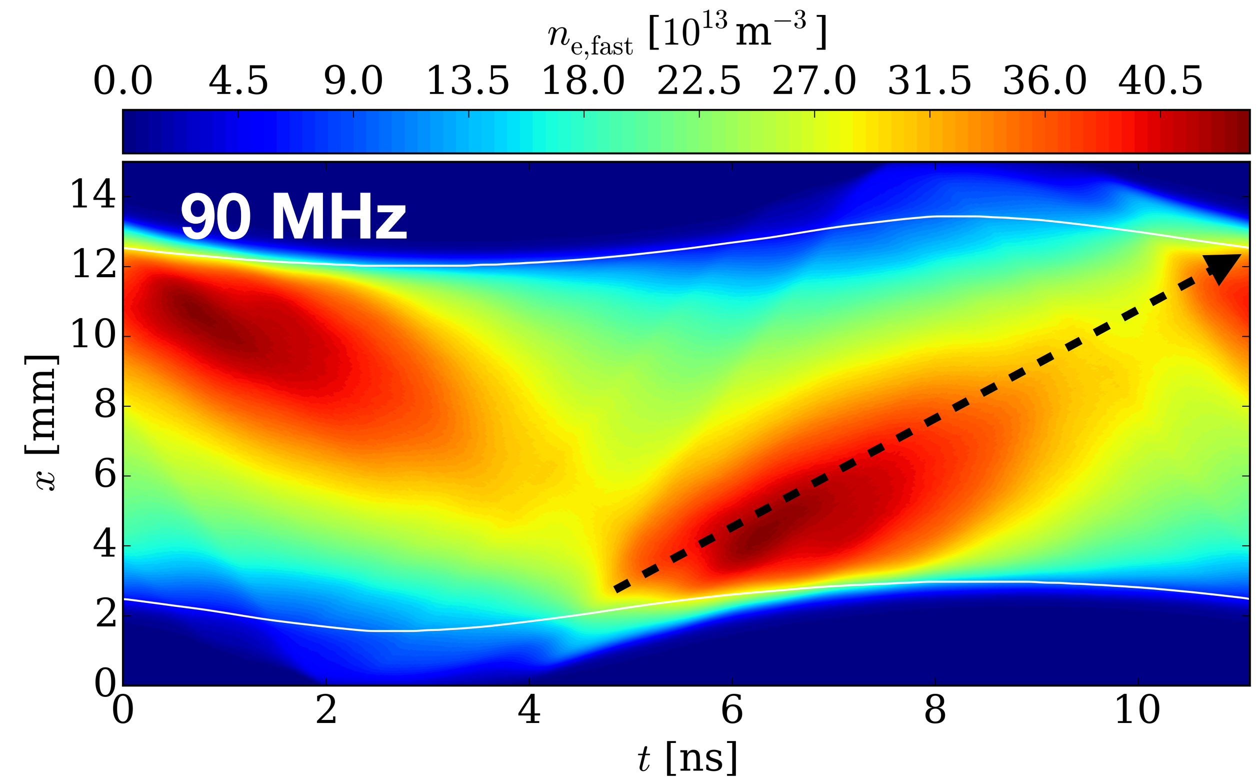

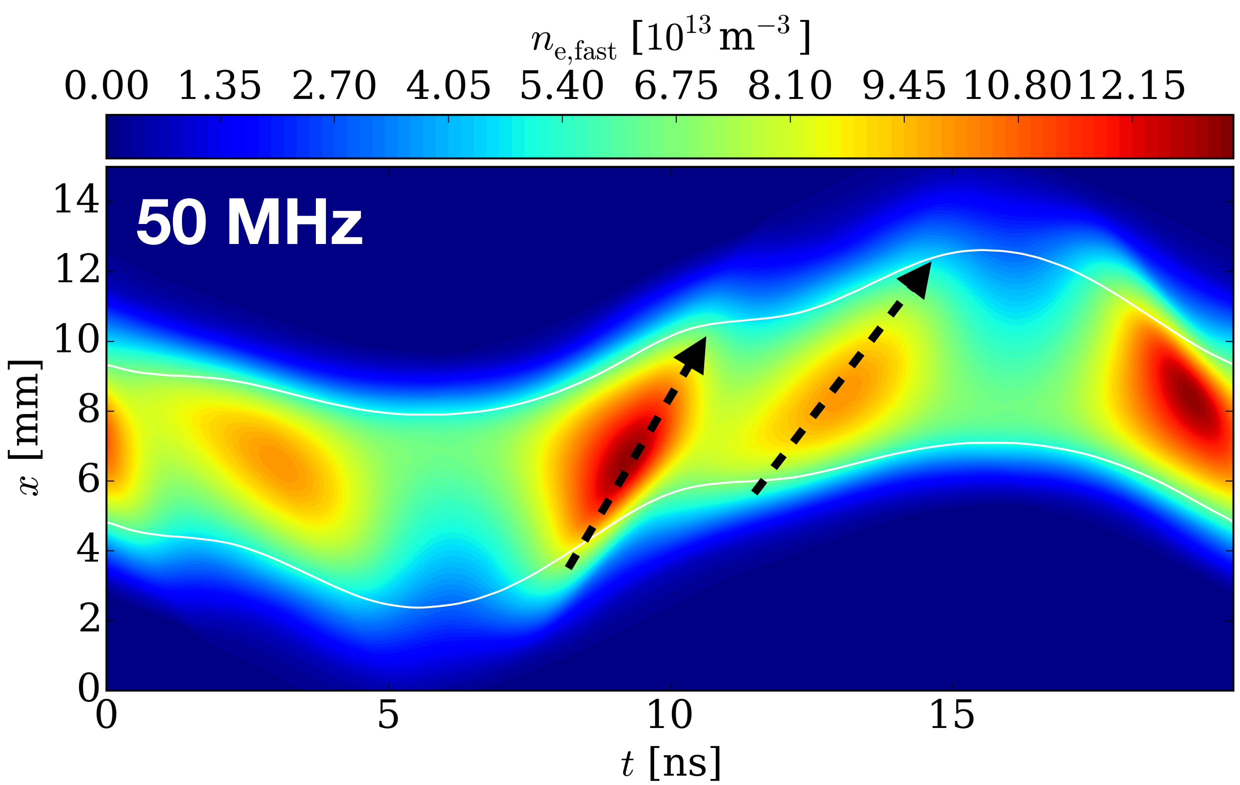

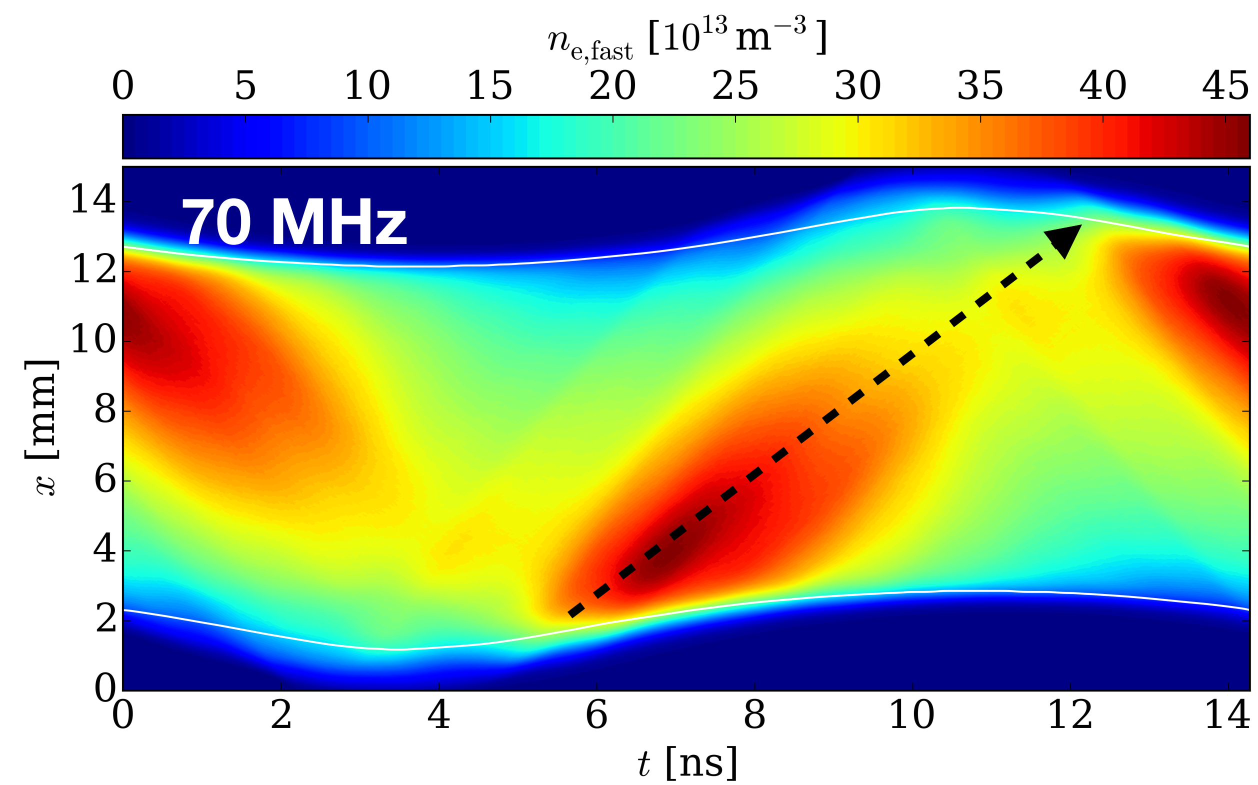

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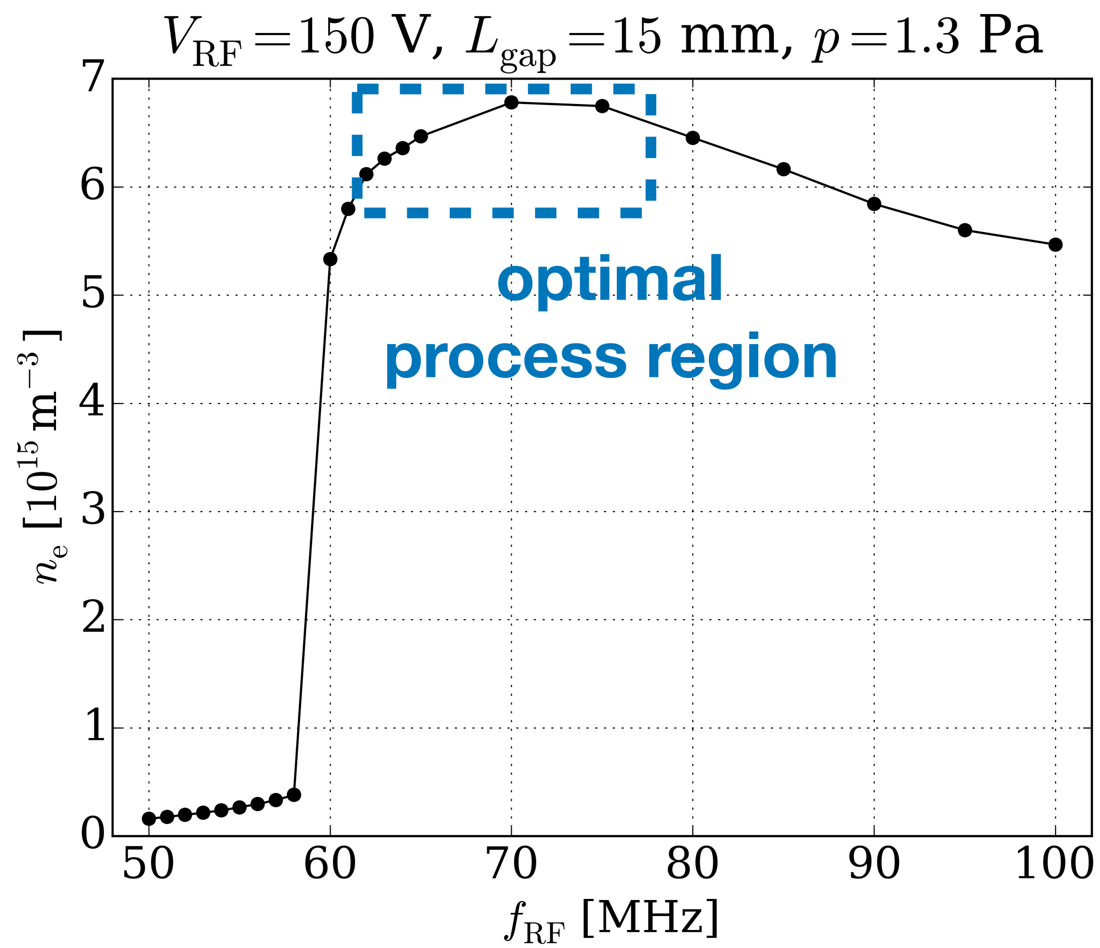
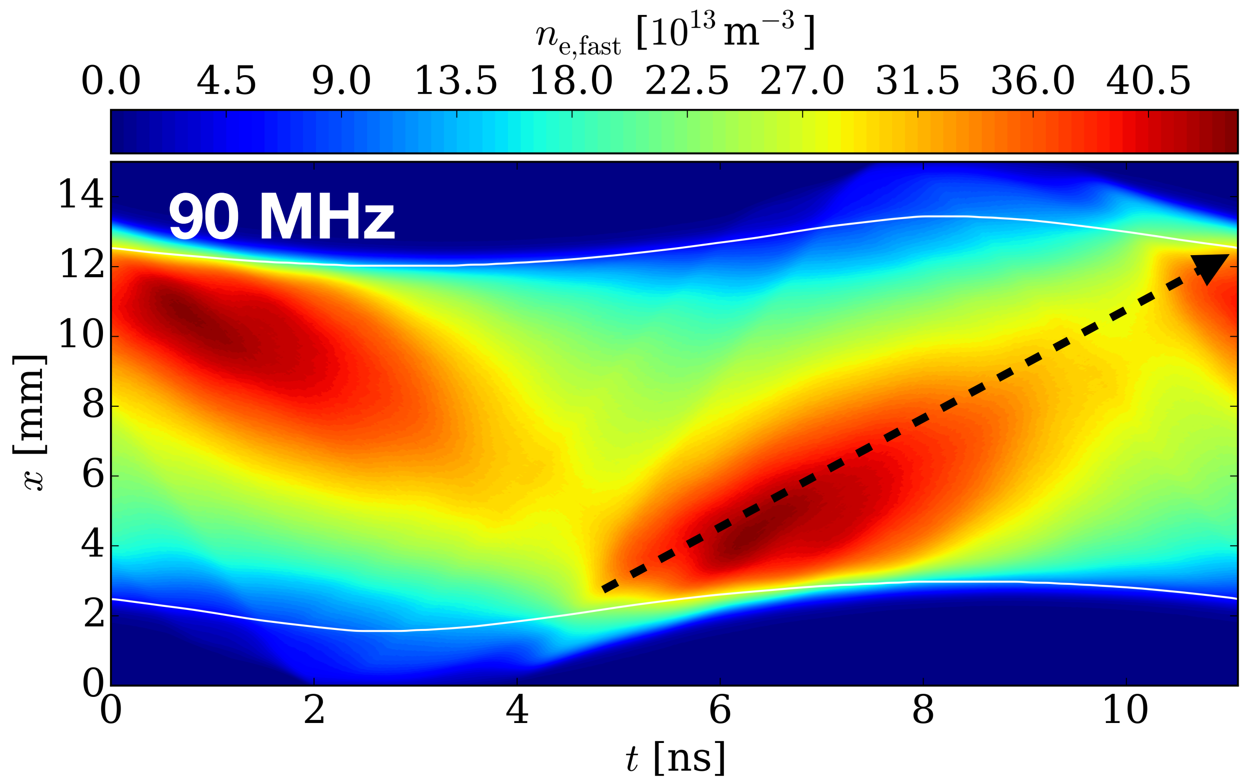
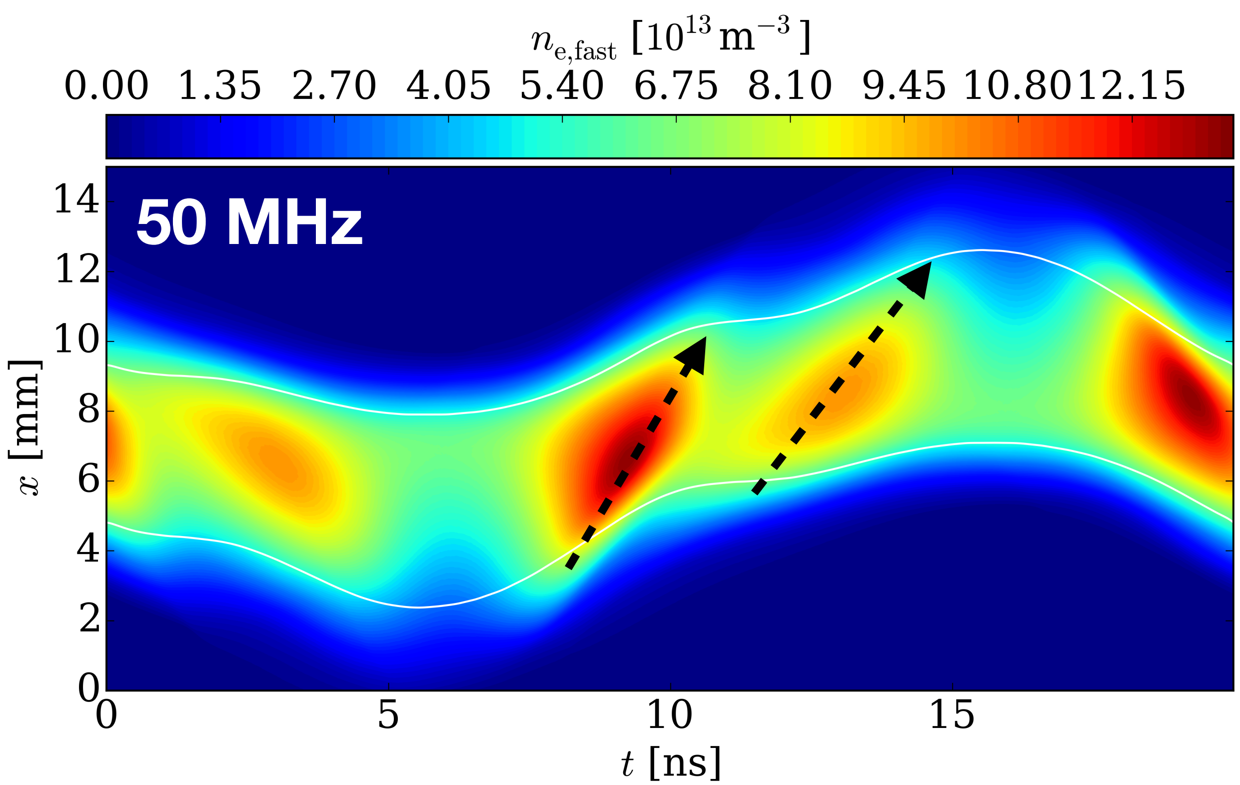
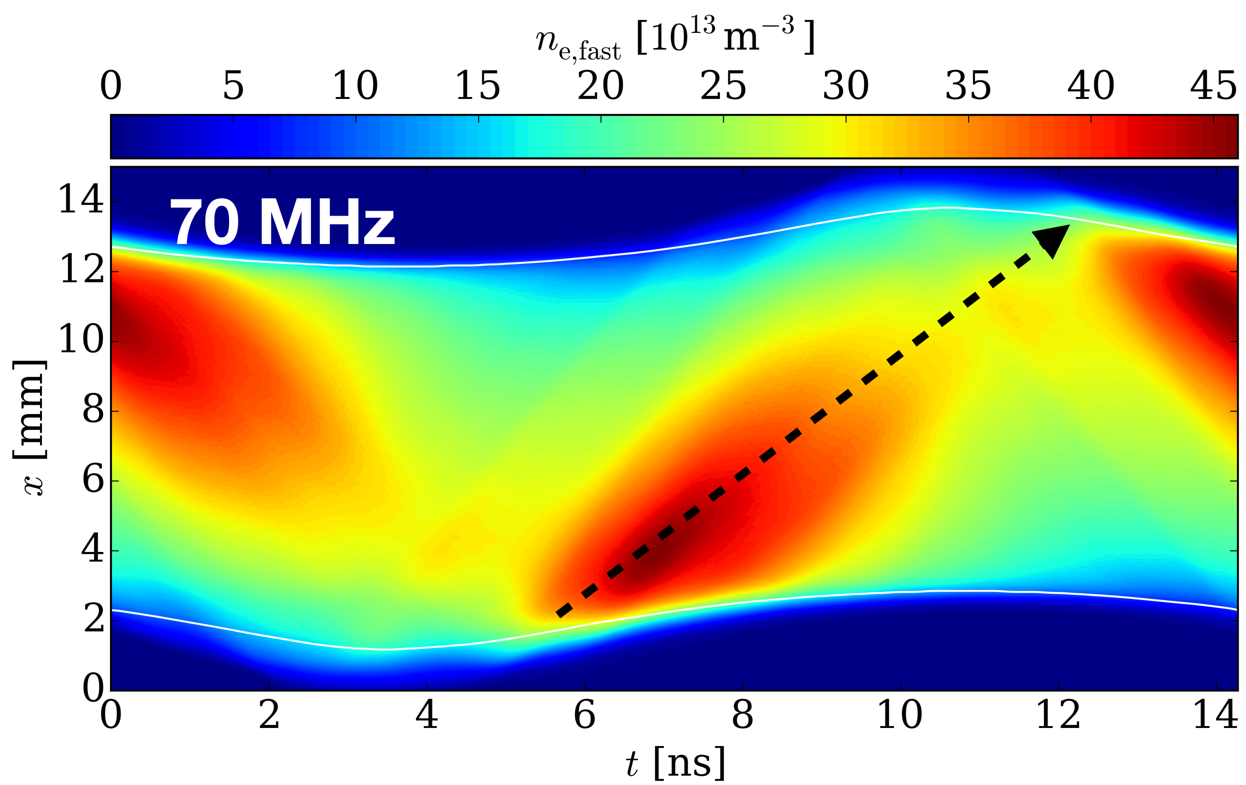






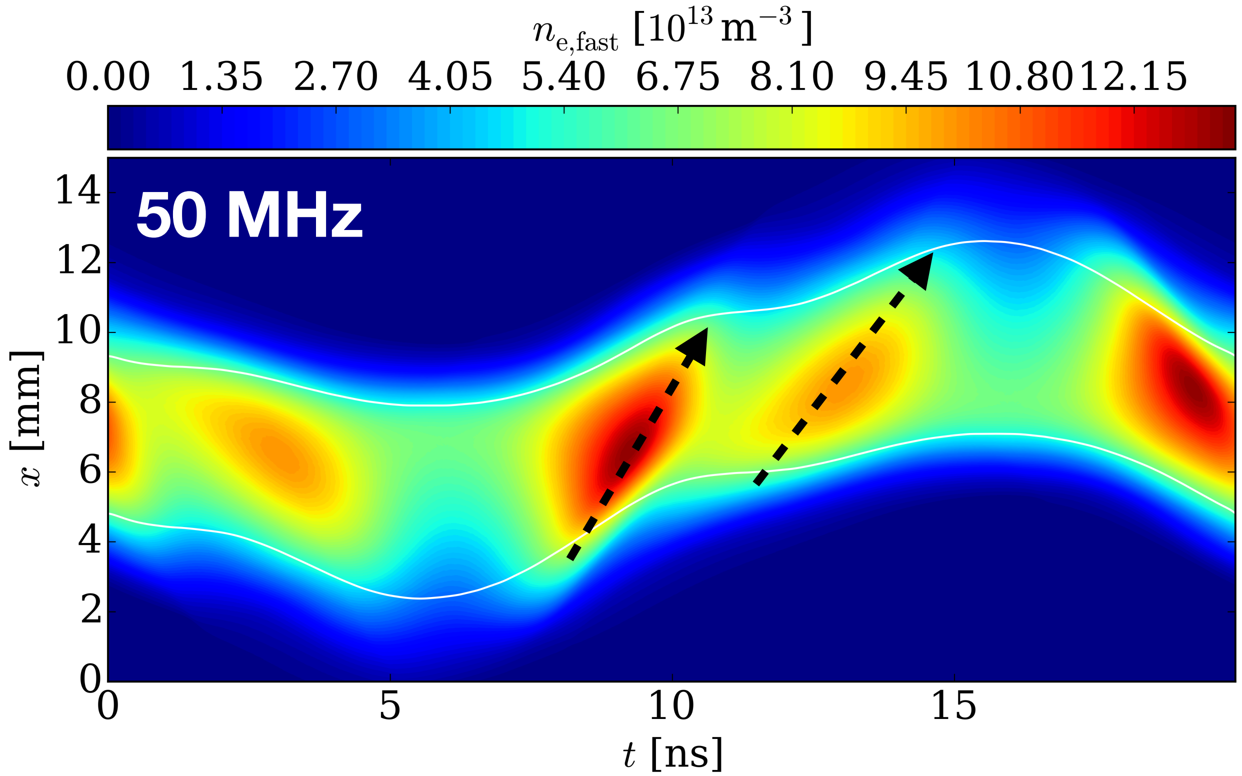


Next Step:

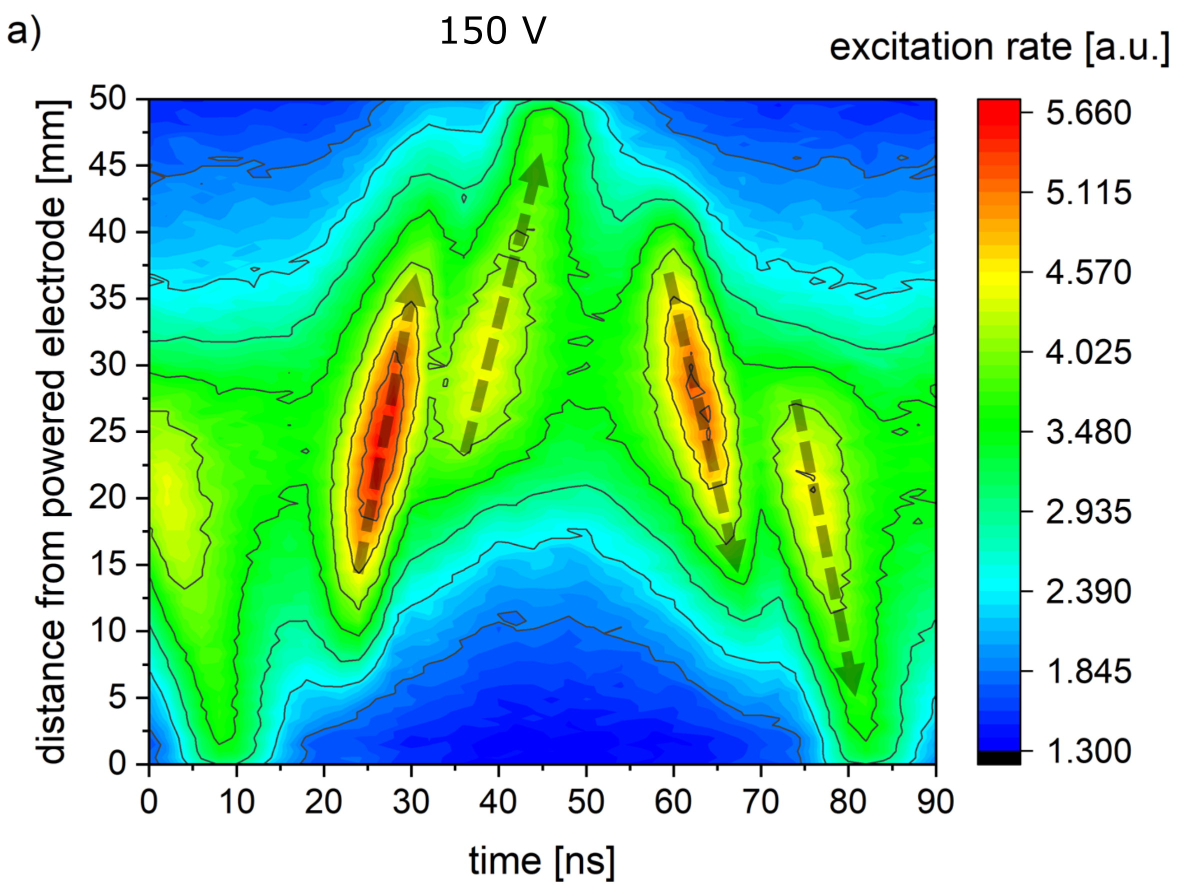
RUB

Why do we see sometimes multiple electron beams?

PIC[3]



Experiment, PROES[4]

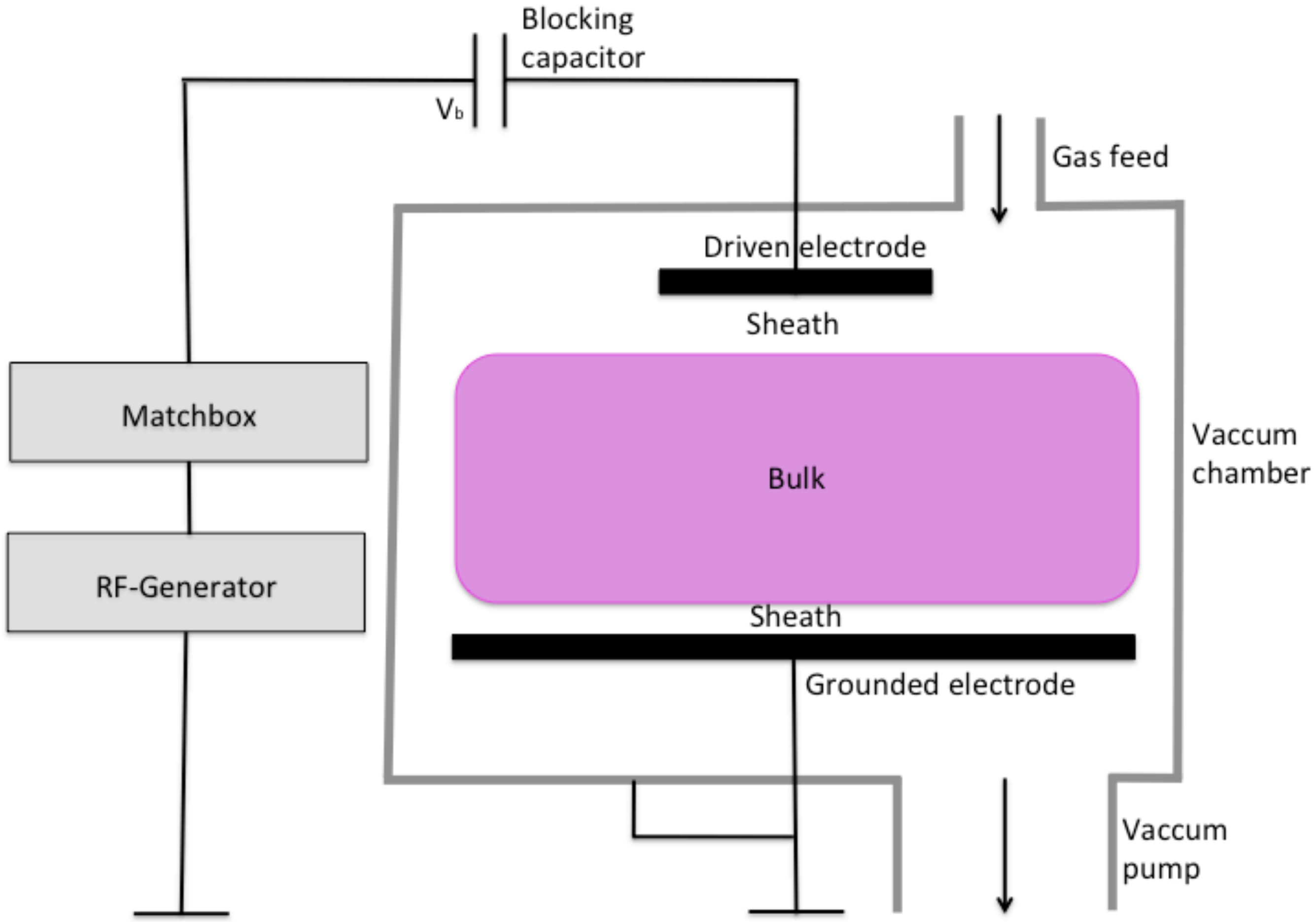


[3] S. Wilczek et al., Phys. Plasma 23, 063514 (2016)

[4] B. Berger et al., Plasma Sources Sci. Technol. 27, 12LT02 (2018)

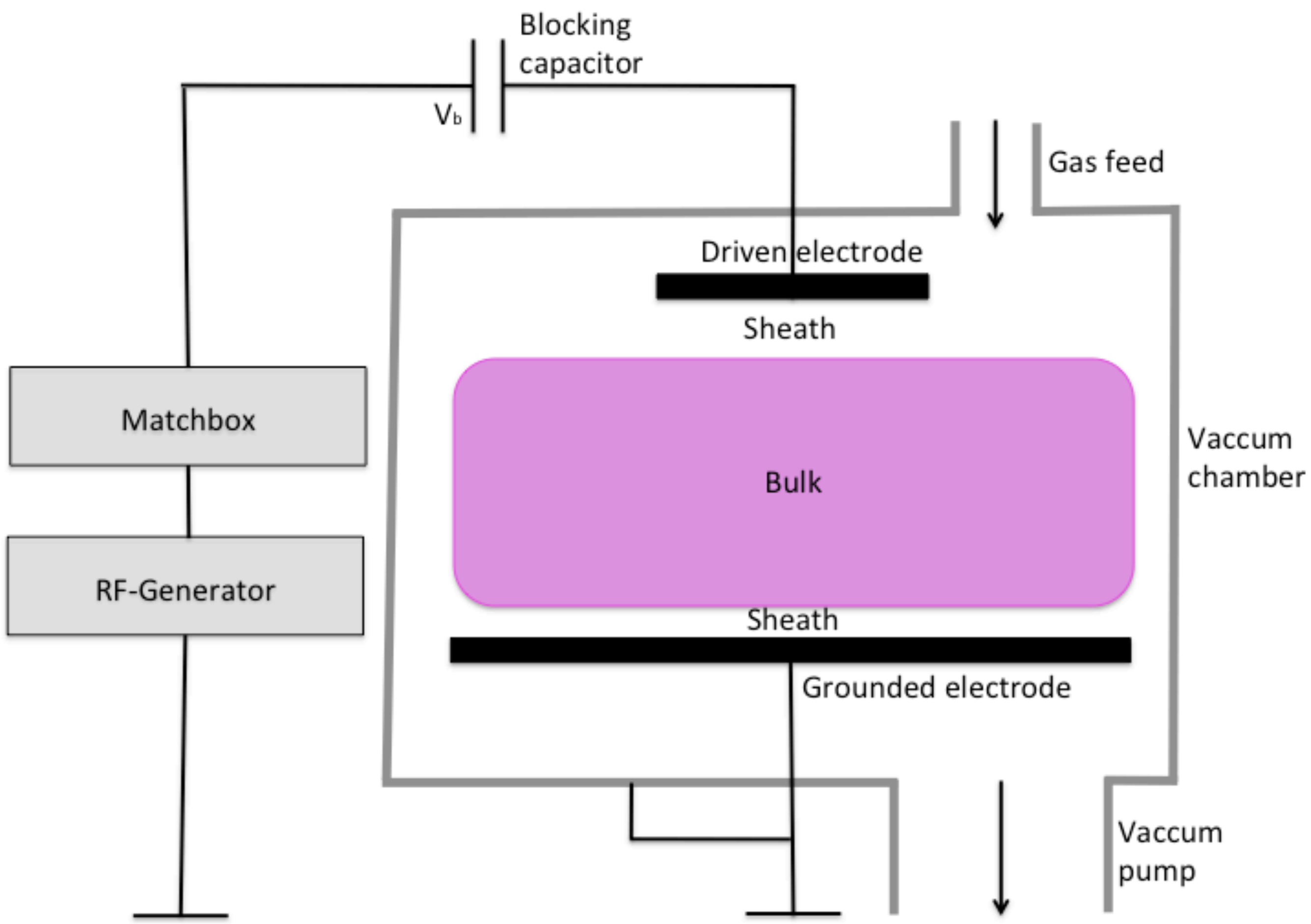
Nonlinearity

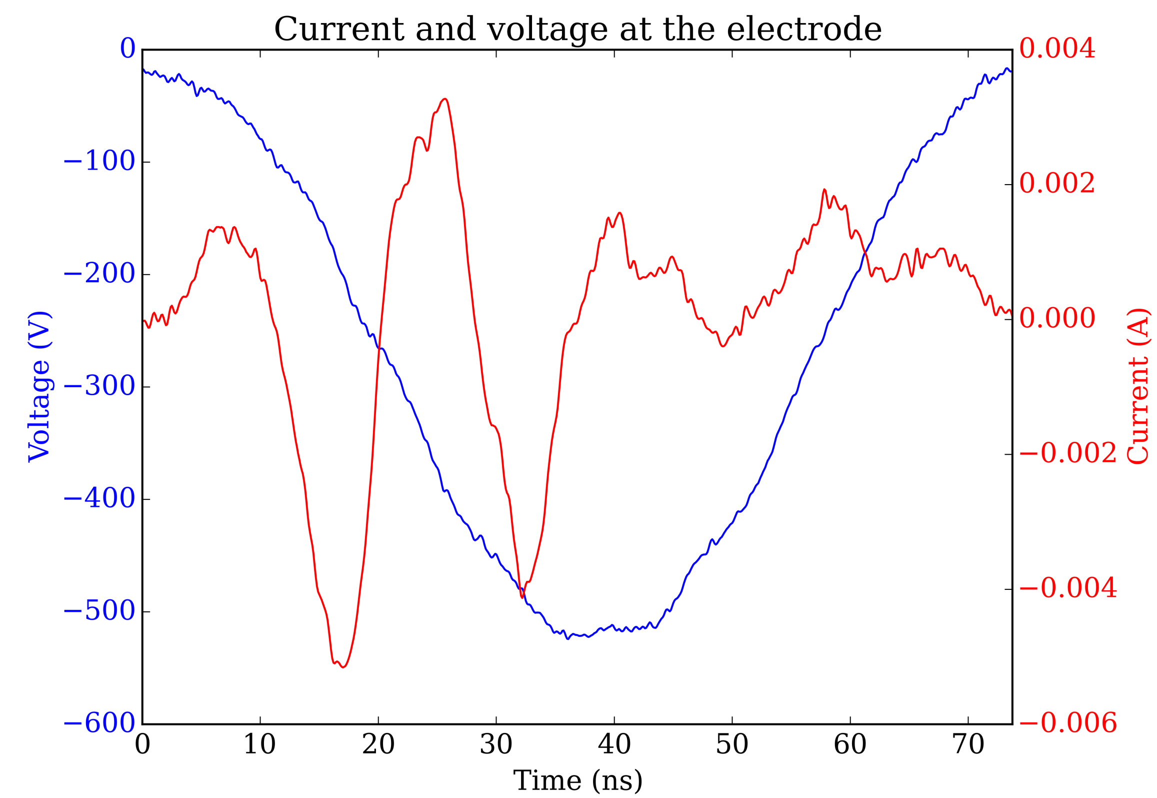
Motivation: Non-linearity



- CCRF discharges are mostly asymmetric, surfaces are naturally grounded
- measuring global parameters, like the voltage and the current at the electrode

Motivation: Non-linearity

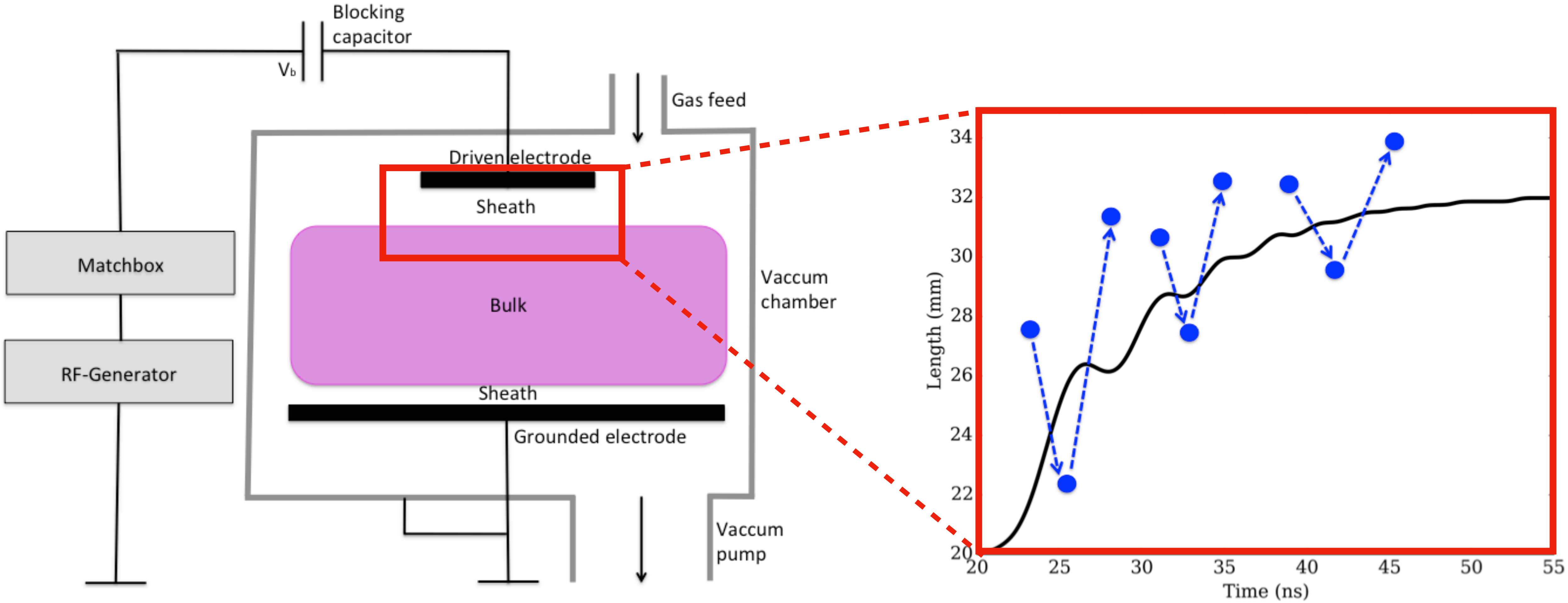




- CCRF discharges are mostly asymmetric, surfaces are naturally grounded
- measuring global parameters, like the voltage and the current at the electrode
- voltage is almost sinusoidal but current indicates harmonic oscillations[5]
- response of the nonlinear dynamics of the system

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

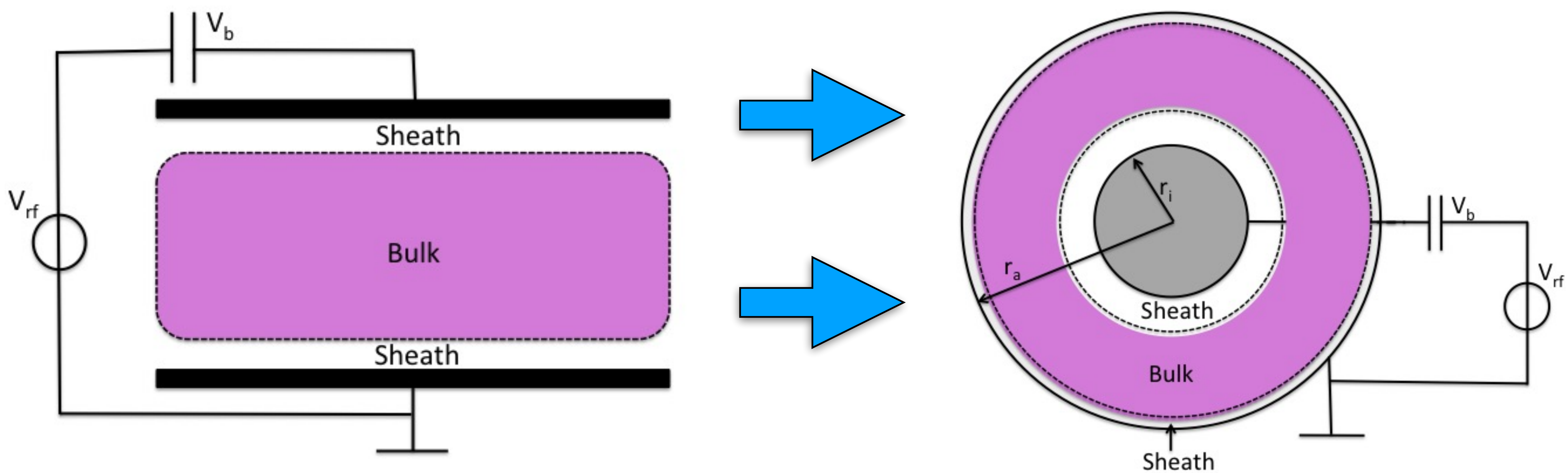
Goal of this work: Non-linearity



- focus on the nonlinear interaction between sheath and bulk on a ns timescale
- what is the physical origin of the generation of harmonics?
- how does the nonlinearity influence the electron power dynamics?

Nonlinear Electron Dynamics

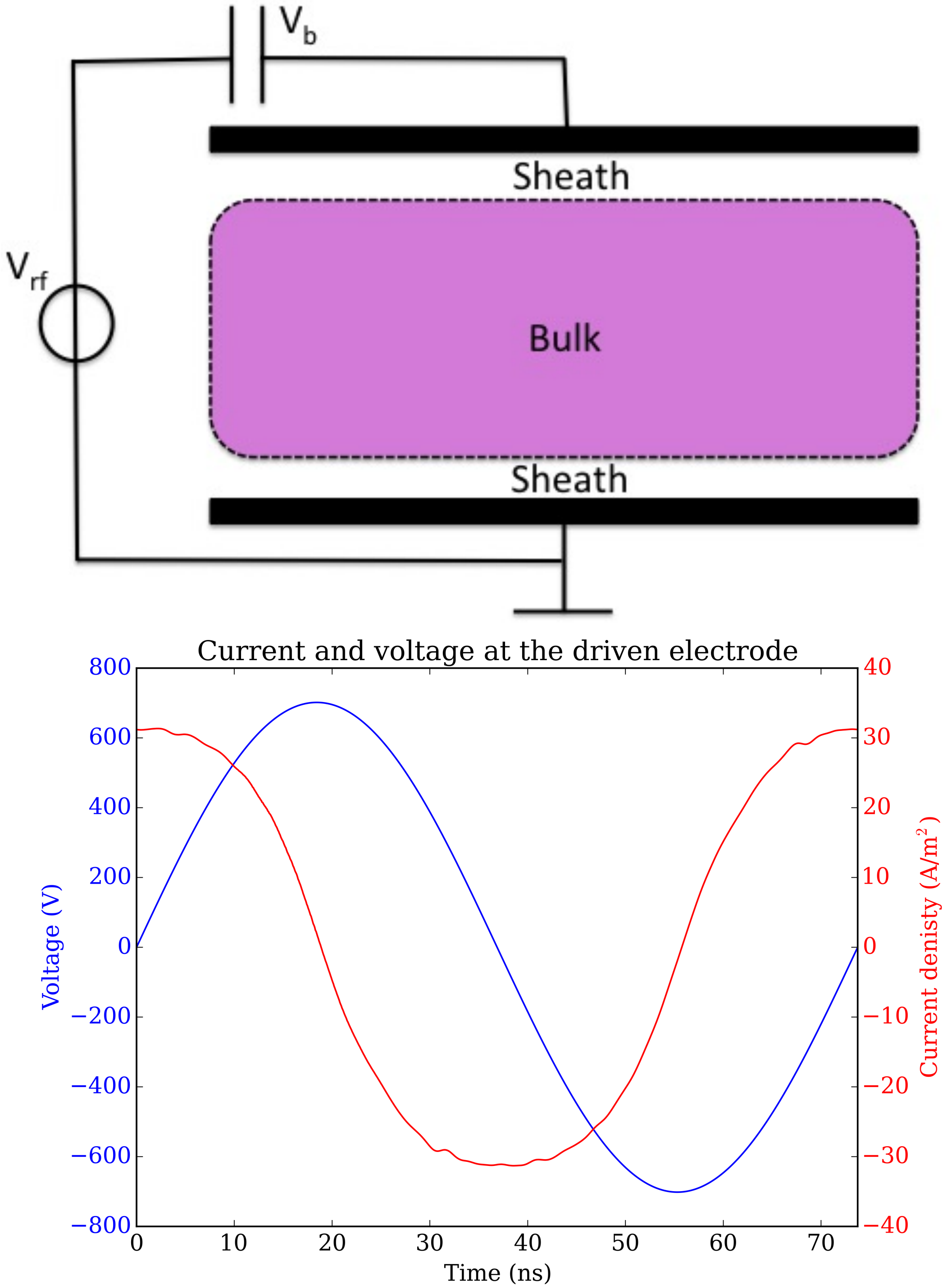
symmetric (Cartesian) **asymmetric (cylindrical)**



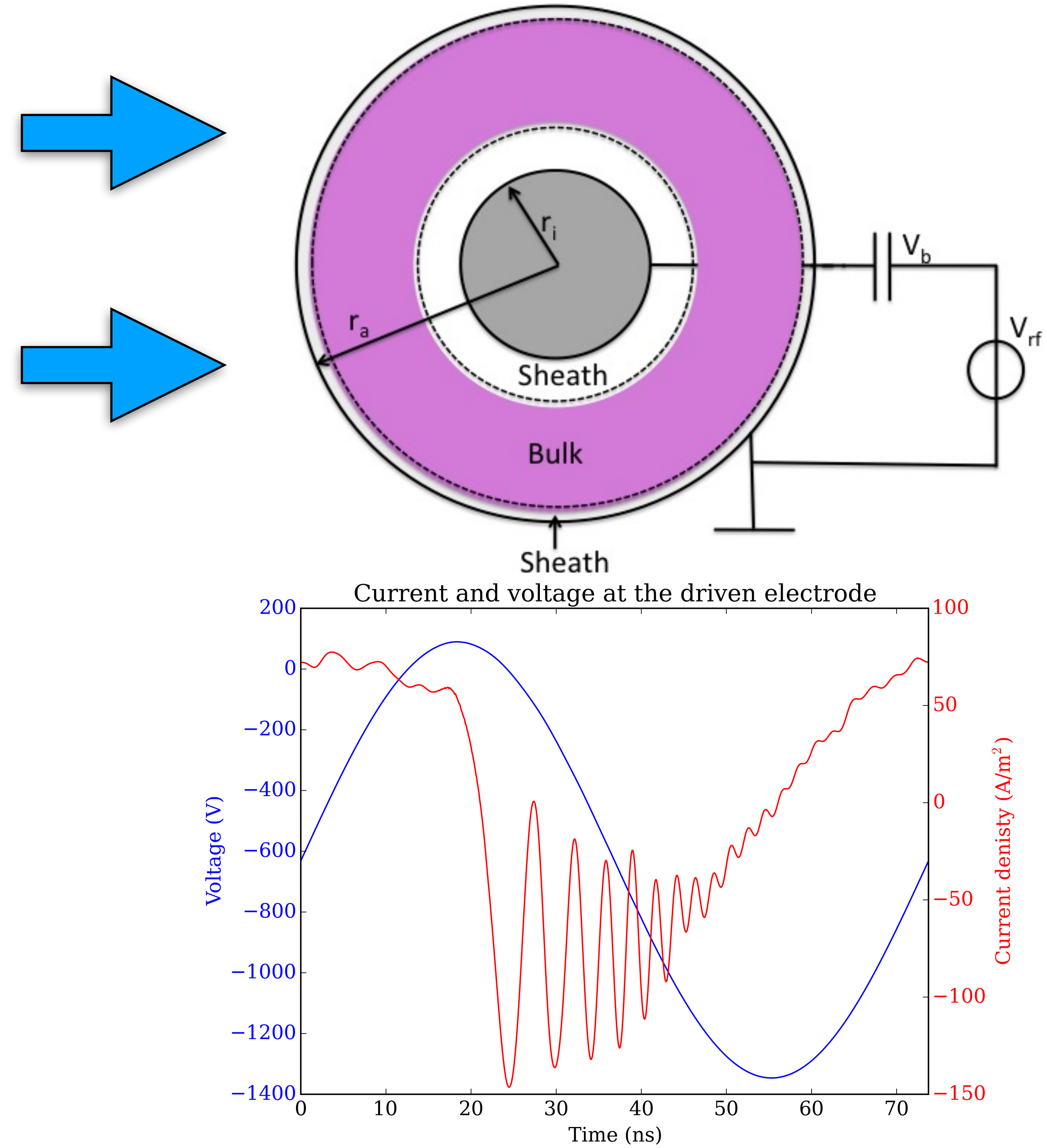
- cylindrical shells, purely 1d along the radial coordinate
- obtain a geometrical asymmetry and a self-consistent self-bias

Particle-In-Cell Simulation

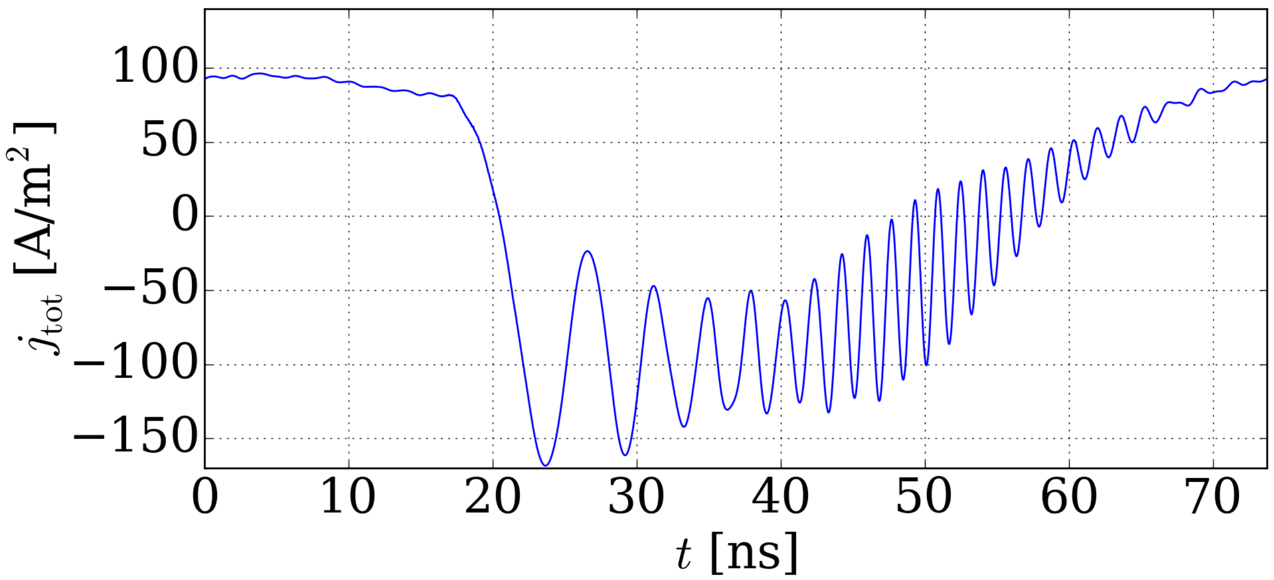
symmetric (Cartesian)

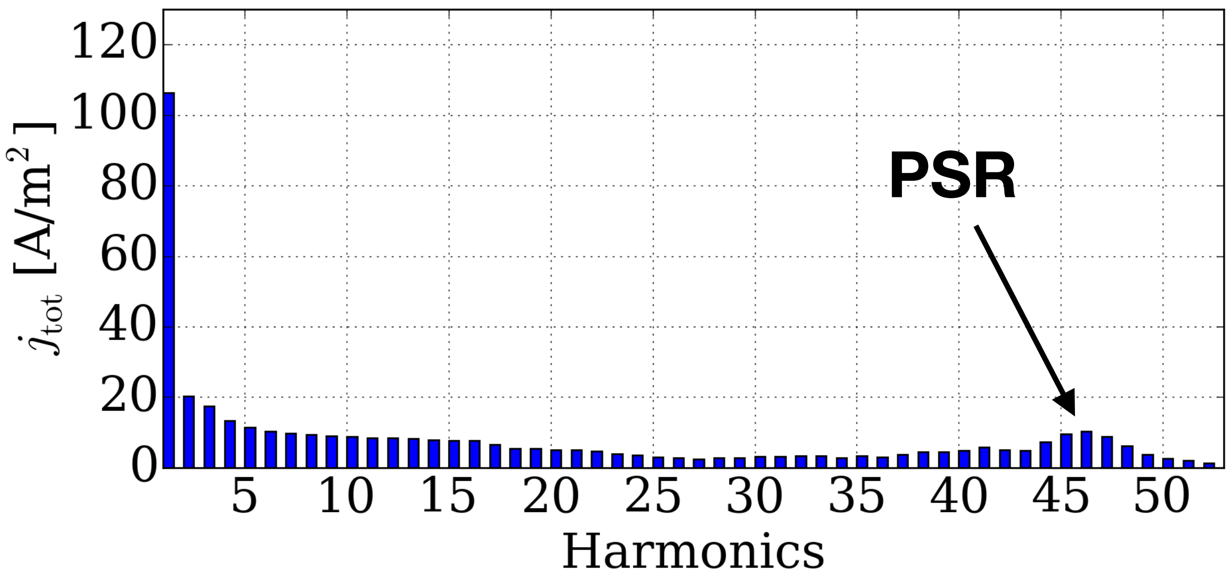


asymmetric (cylindrical)



RF-current at the electrode

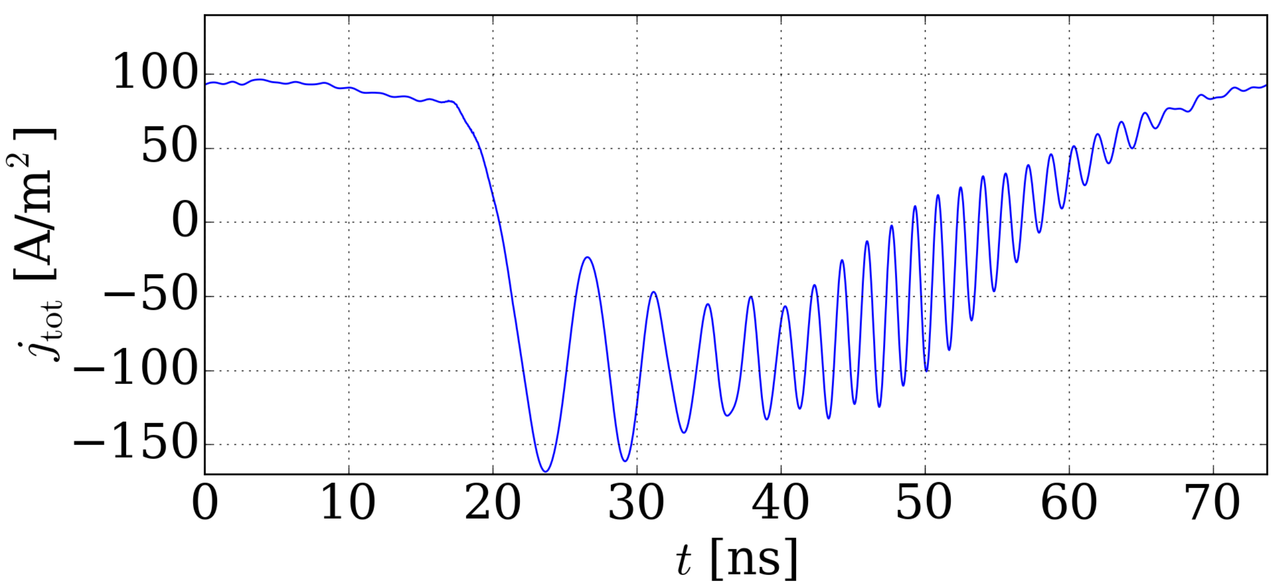


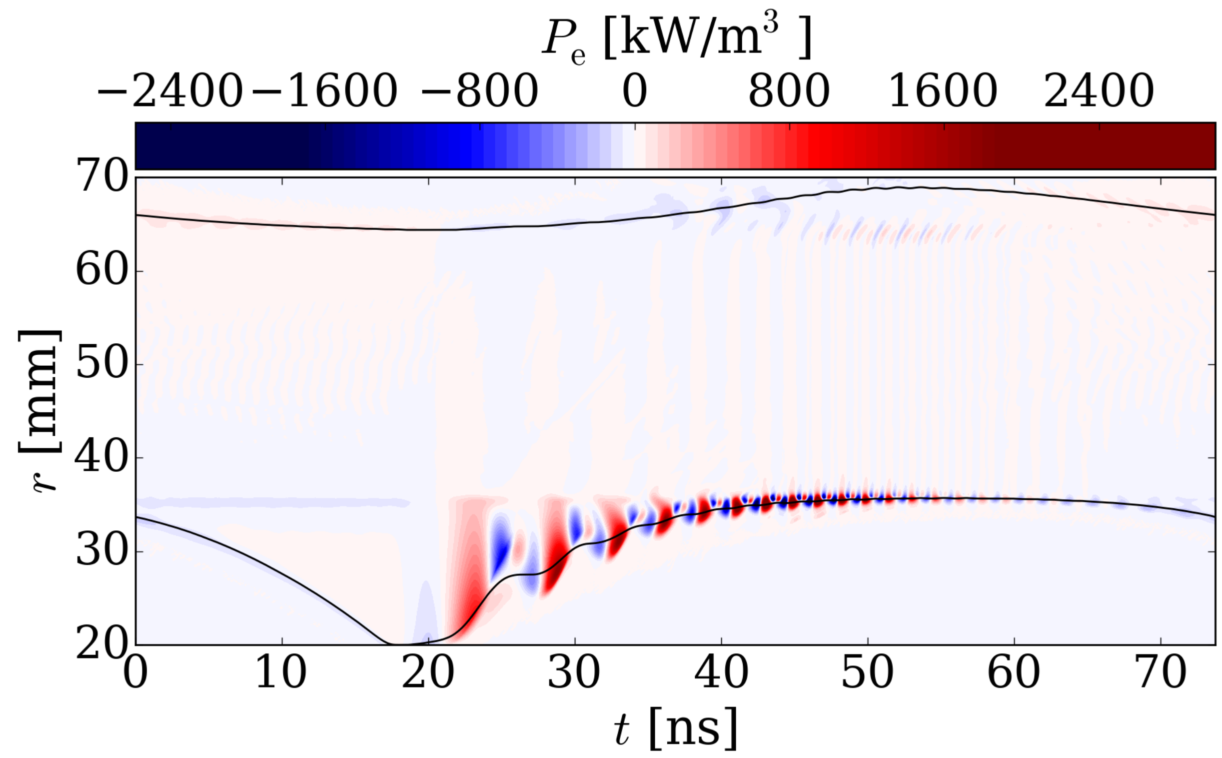


- asymmetric discharge: f_{RF} = 13.56 MHz, p = 1 Pa argon, L_{gap} = 50 mm, V_{RF} = 1400 V
- strong nonlinear dynamics in the rf-current
- Fourier spectrum indicates higher harmonics which match the PSR frequency
- final goal: understand the origin of these oscillations

[6] S. Wilczek et al., Plasma Sources Sci. Technol., 27, 125010 (2018)

Electron power gain and loss



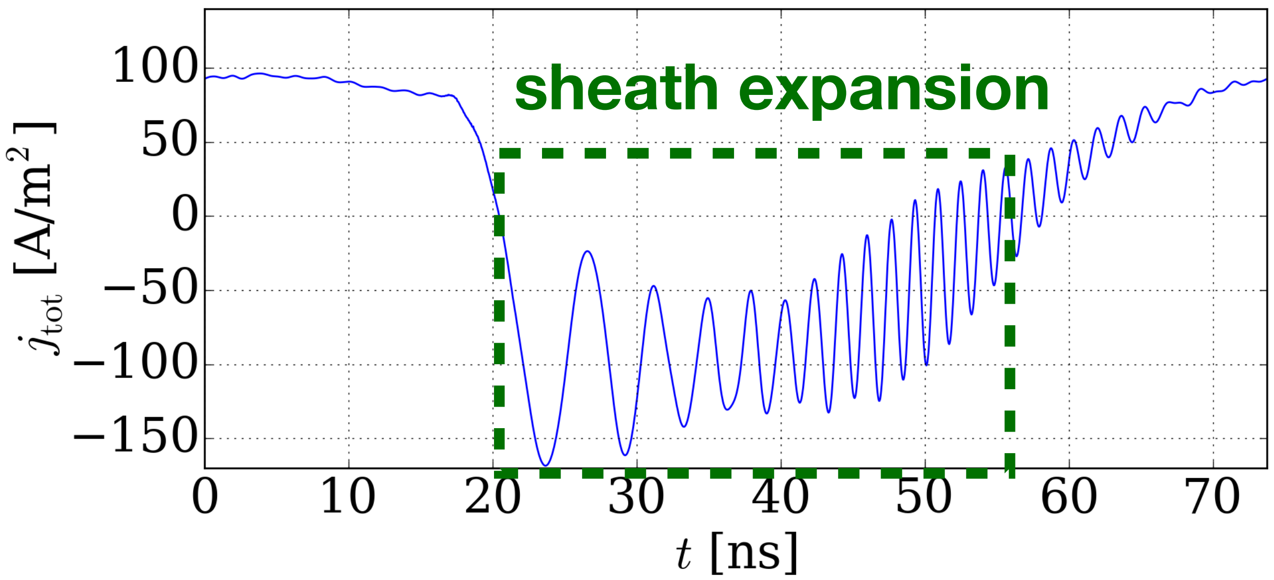


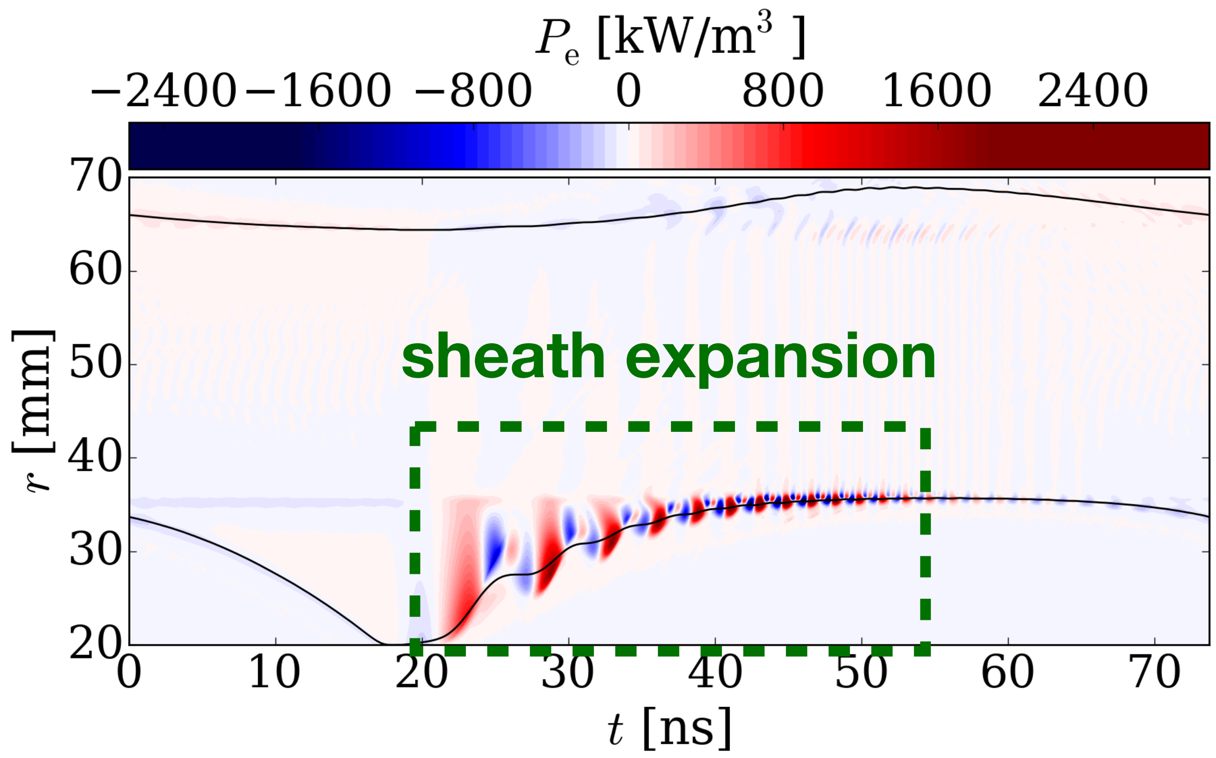
- nonlinear dynamics leads to a complex electron power gain and loss mechanism

[6] S. Wilczek et al., Plasma Sources Sci. Technol., 27, 125010 (2018)

Electron power gain and loss

RUB





- nonlinear dynamics leads to a complex electron power gain and loss mechanism
- focus on phase of sheath expansion in order to explain the generation of harmonics

[6] S. Wilczek et al., Plasma Sources Sci. Technol., 27, 125010 (2018)

Electron power gain and loss

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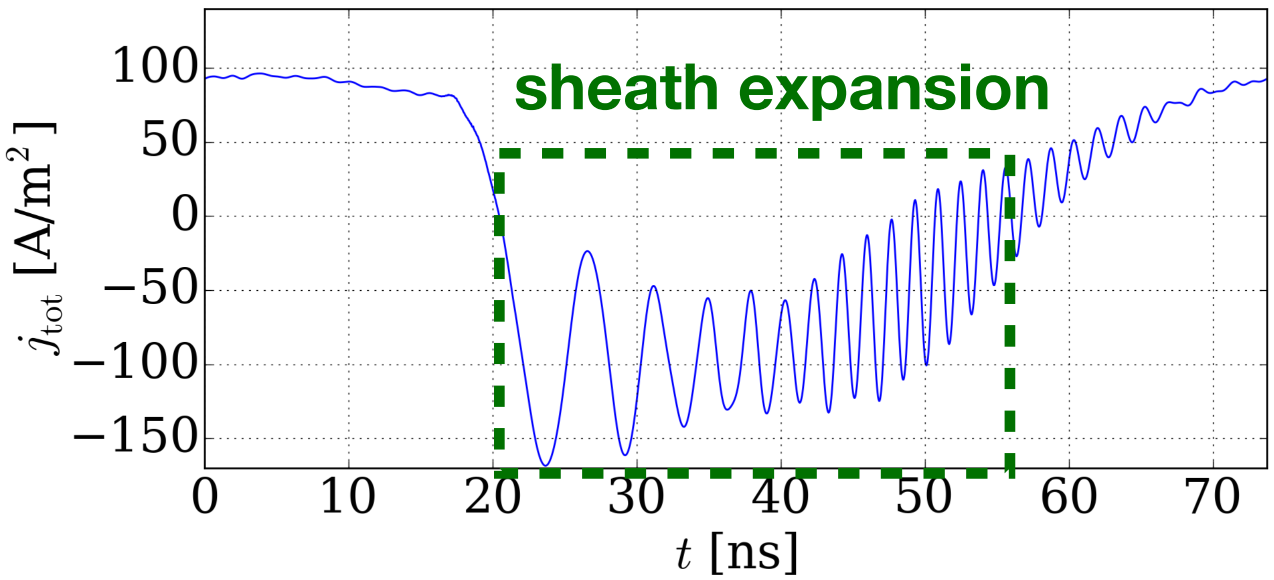
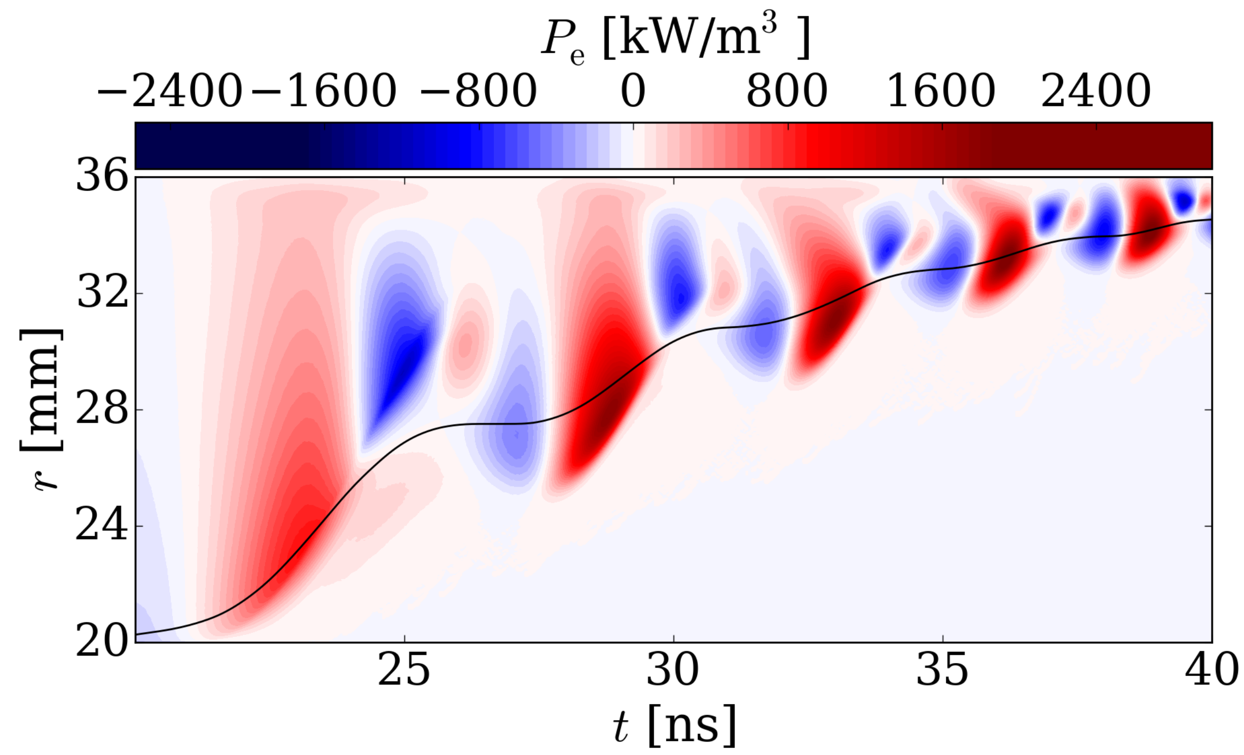
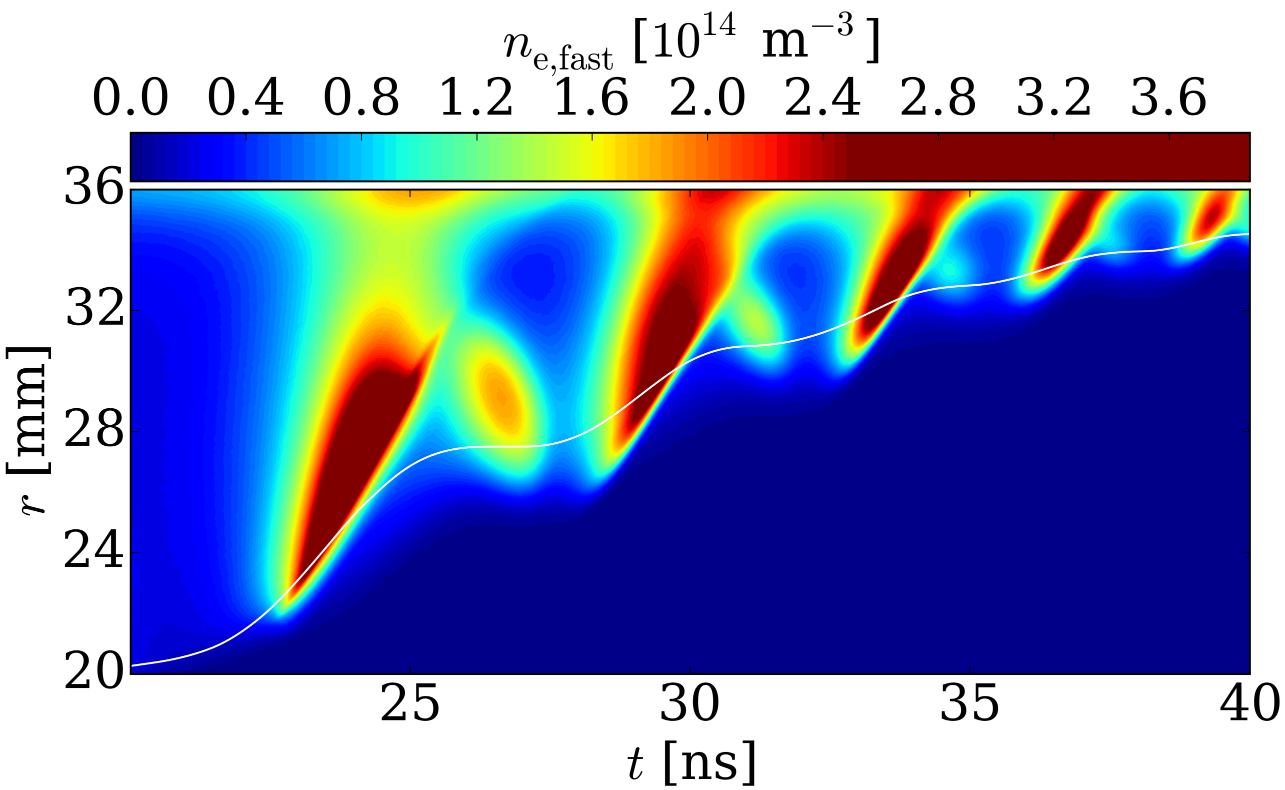


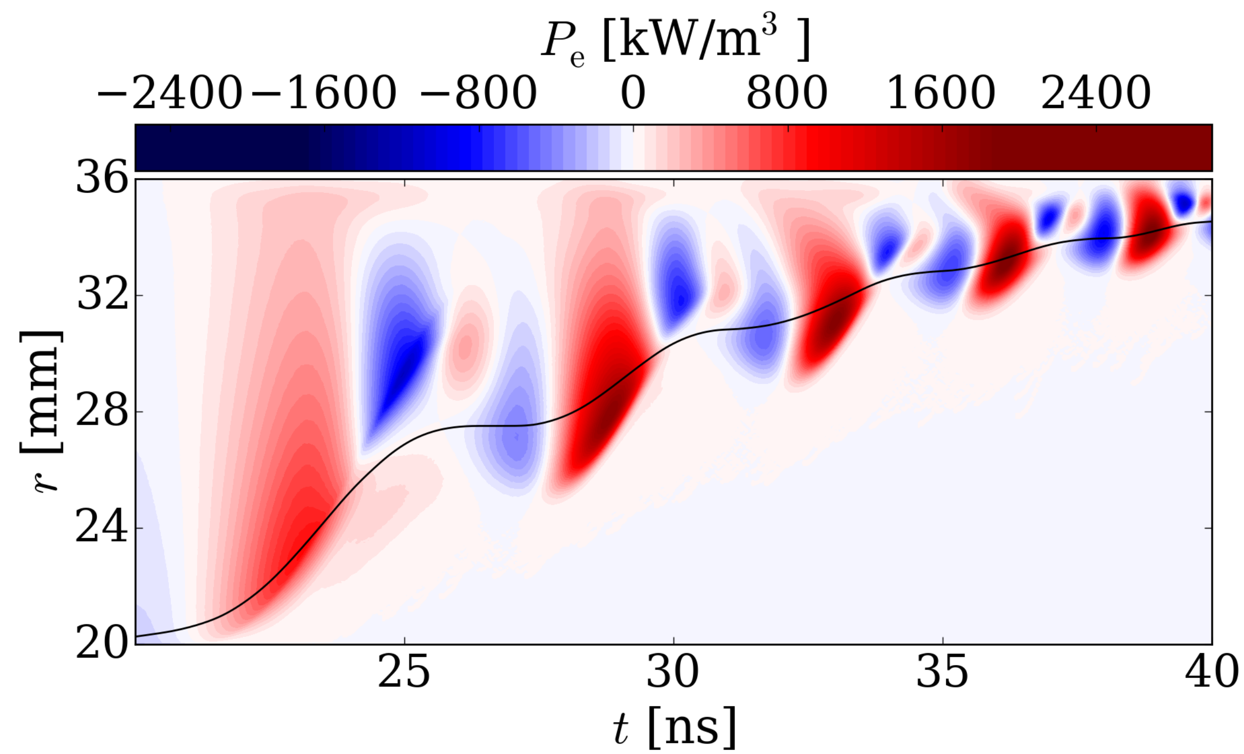


- nonlinear dynamics leads to a complex electron power gain and loss mechanism
- focus on phase of sheath expansion in order to explain the generation of harmonics
- change between electron power gain and loss during expansion
- what does kinetically happen during these power gain and loss phases?

[6] S. Wilczek et al., Plasma Sources Sci. Technol., 27, 125010 (2018)

Generation of electron beams

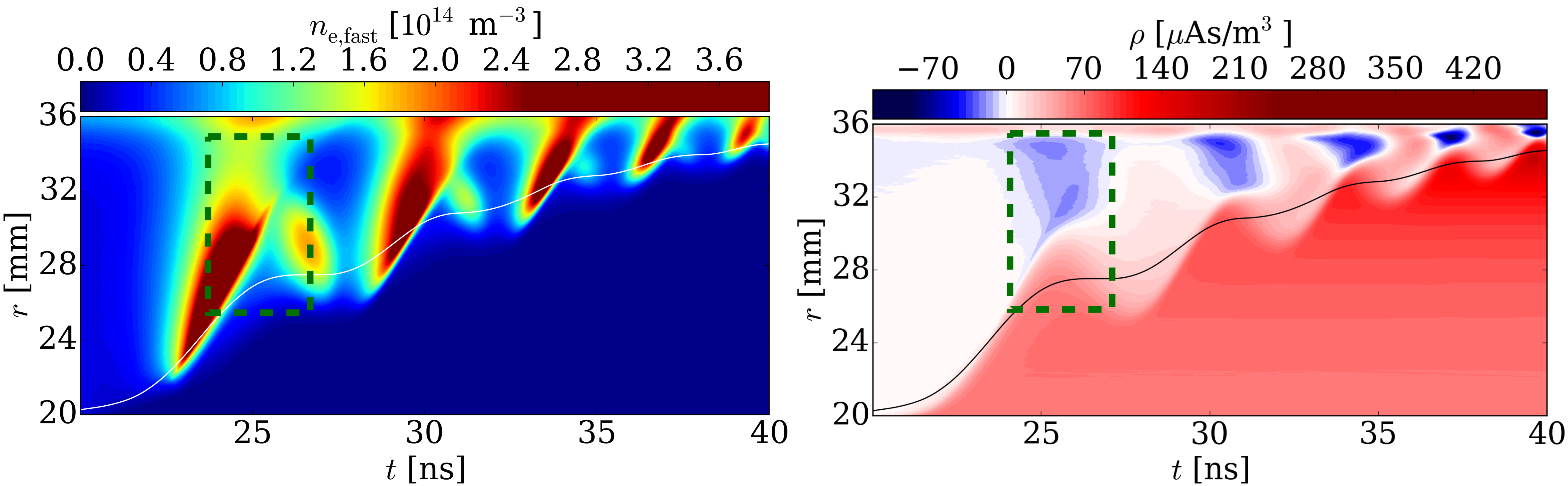




- during electron power gain, energetic beam electrons are generated
- due to the low pressure (1 Pa), they penetrate into the bulk almost collisionlessly
- additionally electrons are flowing back from the bulk into the sheath
- why are electrons attracted back to the sheath?

[6] S. Wilczek et al., Plasma Sources Sci. Technol., 27, 125010 (2018)

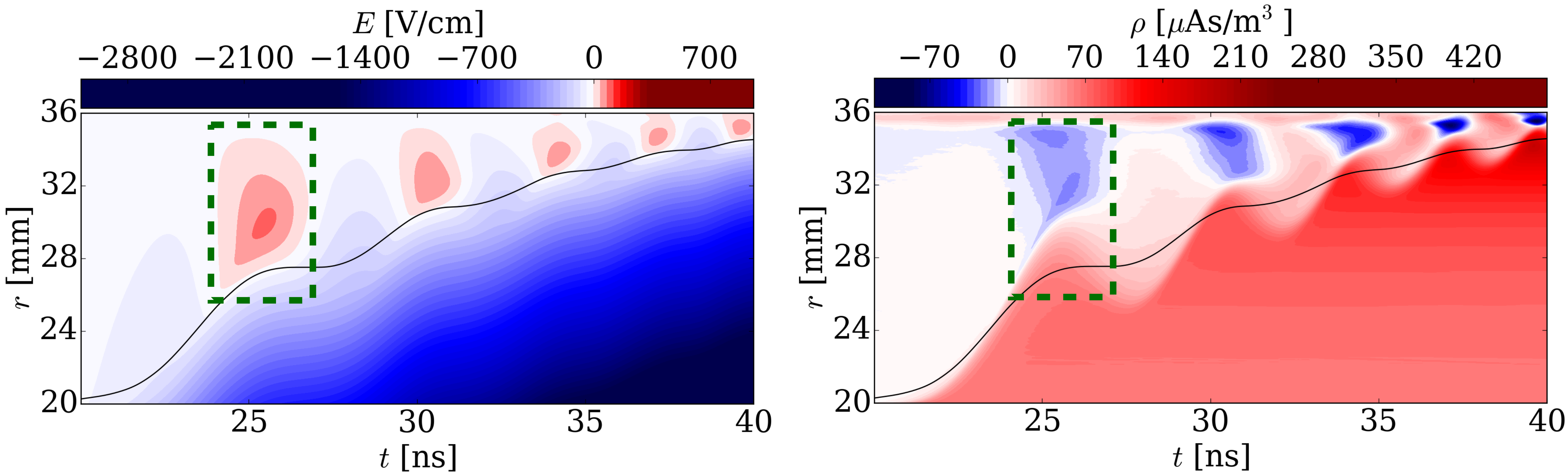
Formation of local charge densities



- very non-local regime, beam dynamics generates significant charge densities
- positive charge density is formed close to the sheath edge
- negative charge density is formed in front of the sheath edge
- what is the result of such a charge difference?

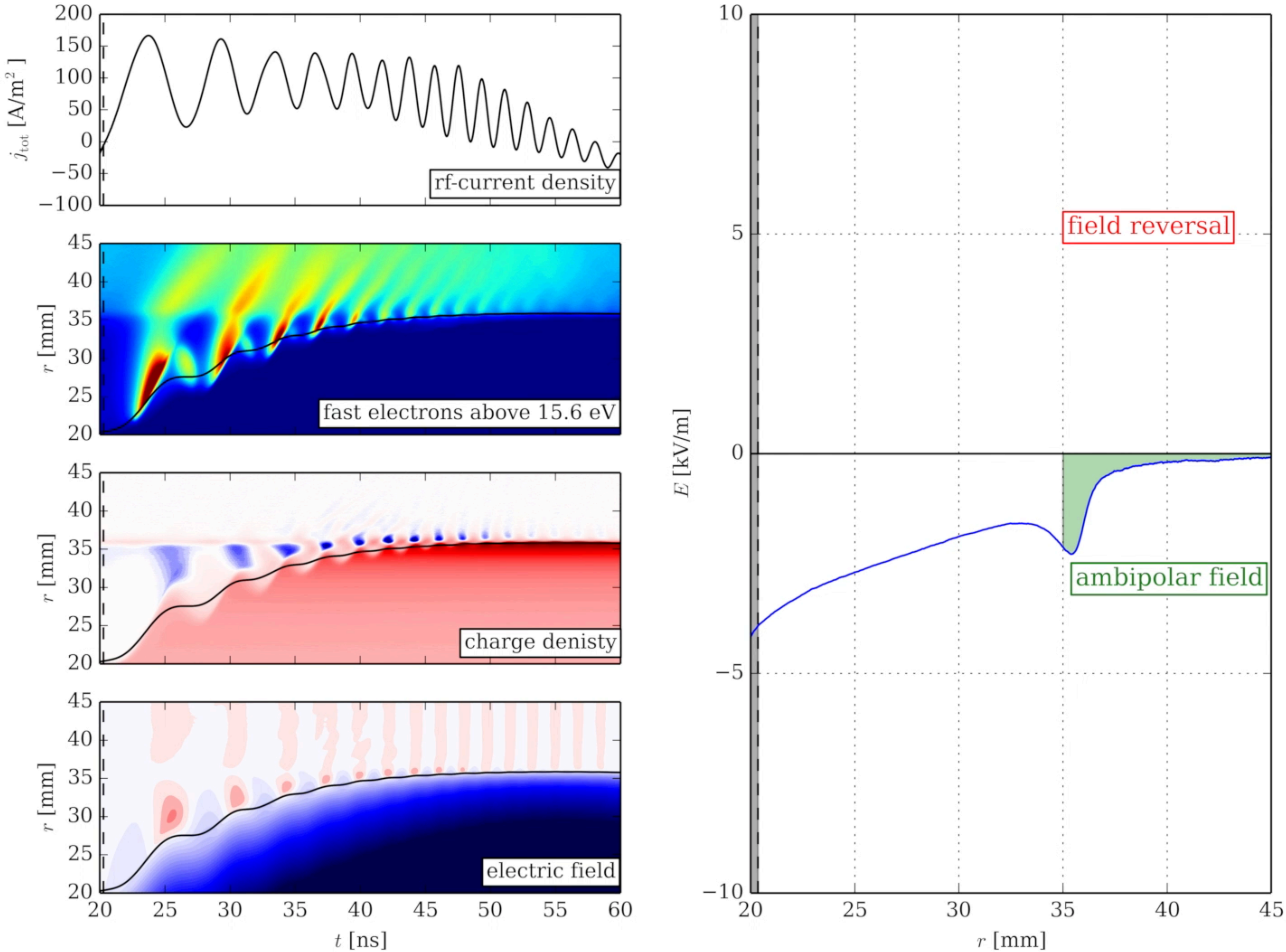
[6] S. Wilczek et al., Plasma Sources Sci. Technol., 27, 125010 (2018)

Electric field reversal

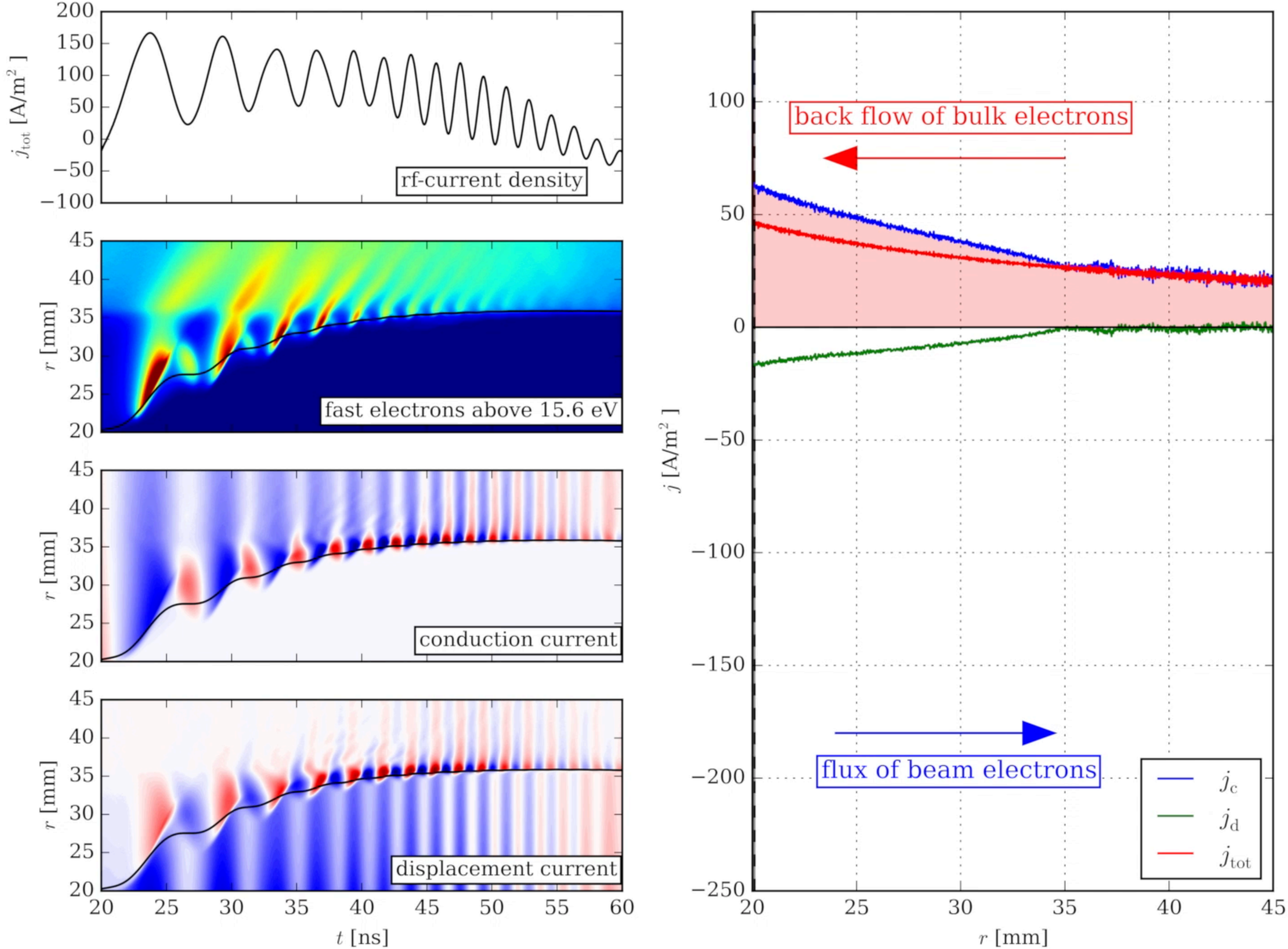


- formation of charge densities generates an electric field reversal in front of the sheath
- this positive electric field accelerates bulk electrons back to the sheath
- these bulk electrons interact with the nonlinear sheath
- this interaction strongly affects the global rf-current and generates harmonics

[6] S. Wilczek et al., Plasma Sources Sci. Technol., 27, 125010 (2018)

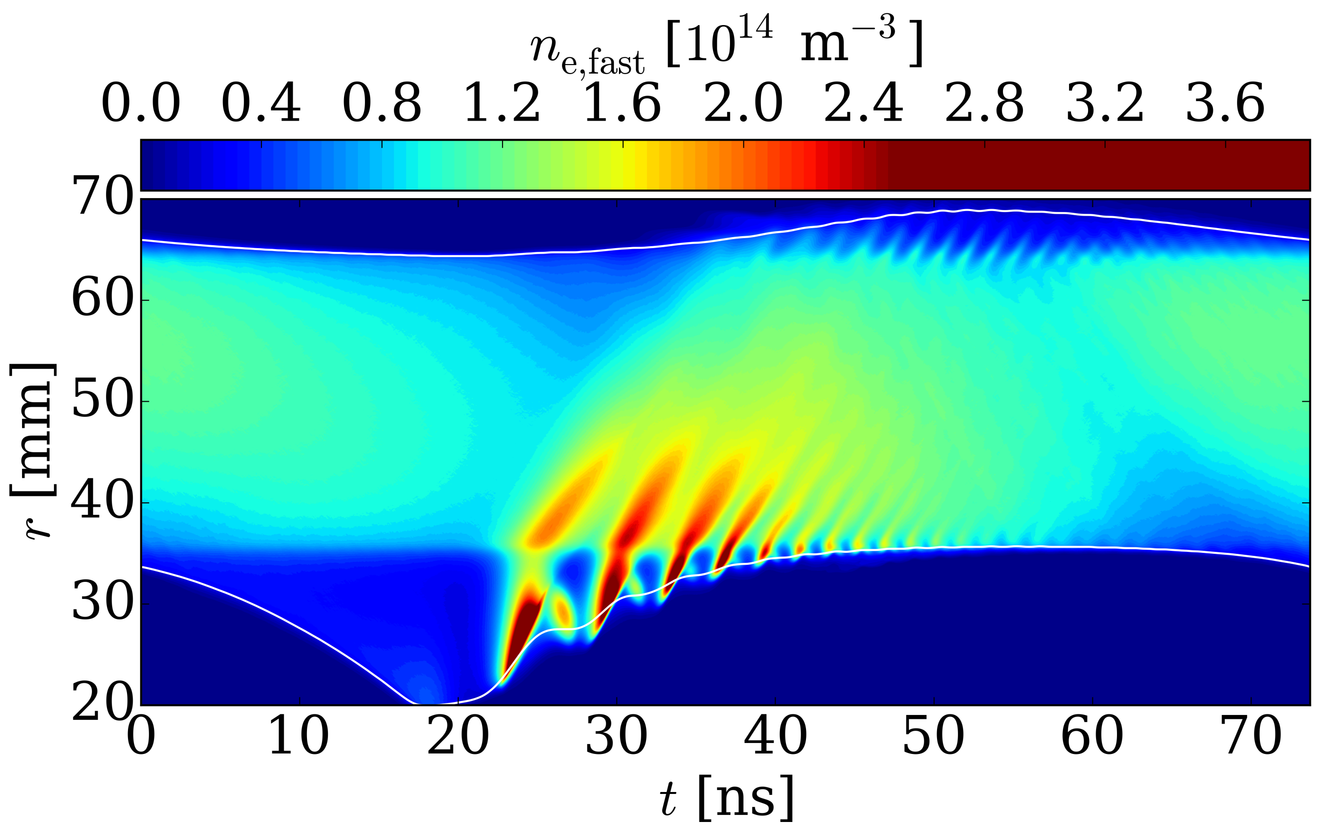


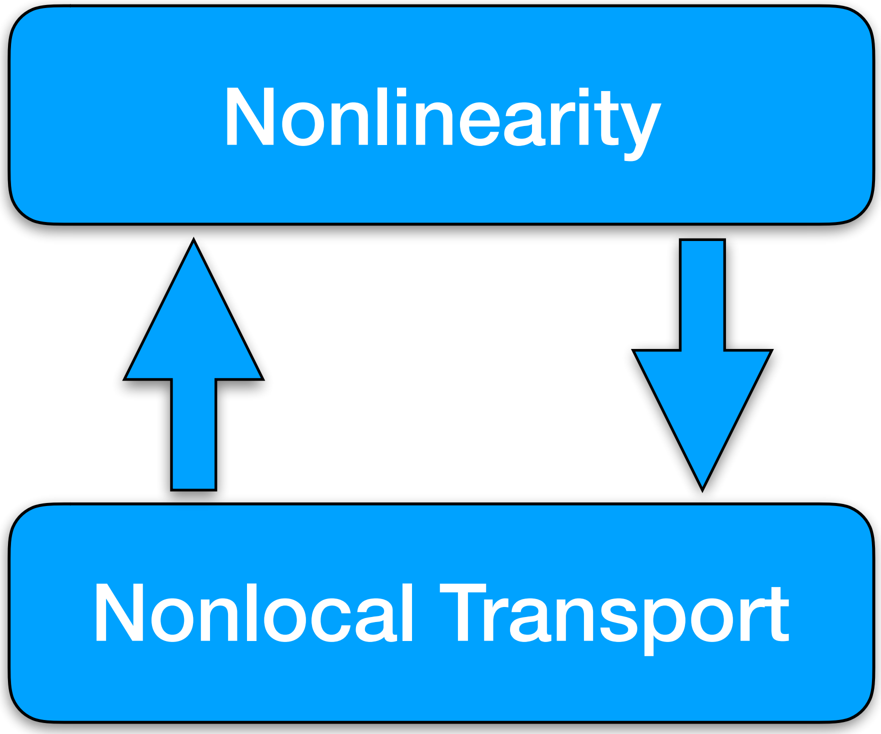
rf-current density
j_{tot} [A/m^2]
fast electrons above 15.6 eV
charge denisty
electric field
r [mm]
t [ns]
field reversal
ambipolar field
E [kV/m]
r [mm]


rf-current density
fast electrons above 15.6 eV
conduction current
displacement current
back flow of bulk electrons
flux of beam electrons
$j_{\rm tot}$ [A/m^2]
r [mm]
t [ns]
j [A/m^2]
j_c
j_d
$j_{\rm tot}$

Summary: Nonlocal and nonlinear dynamics

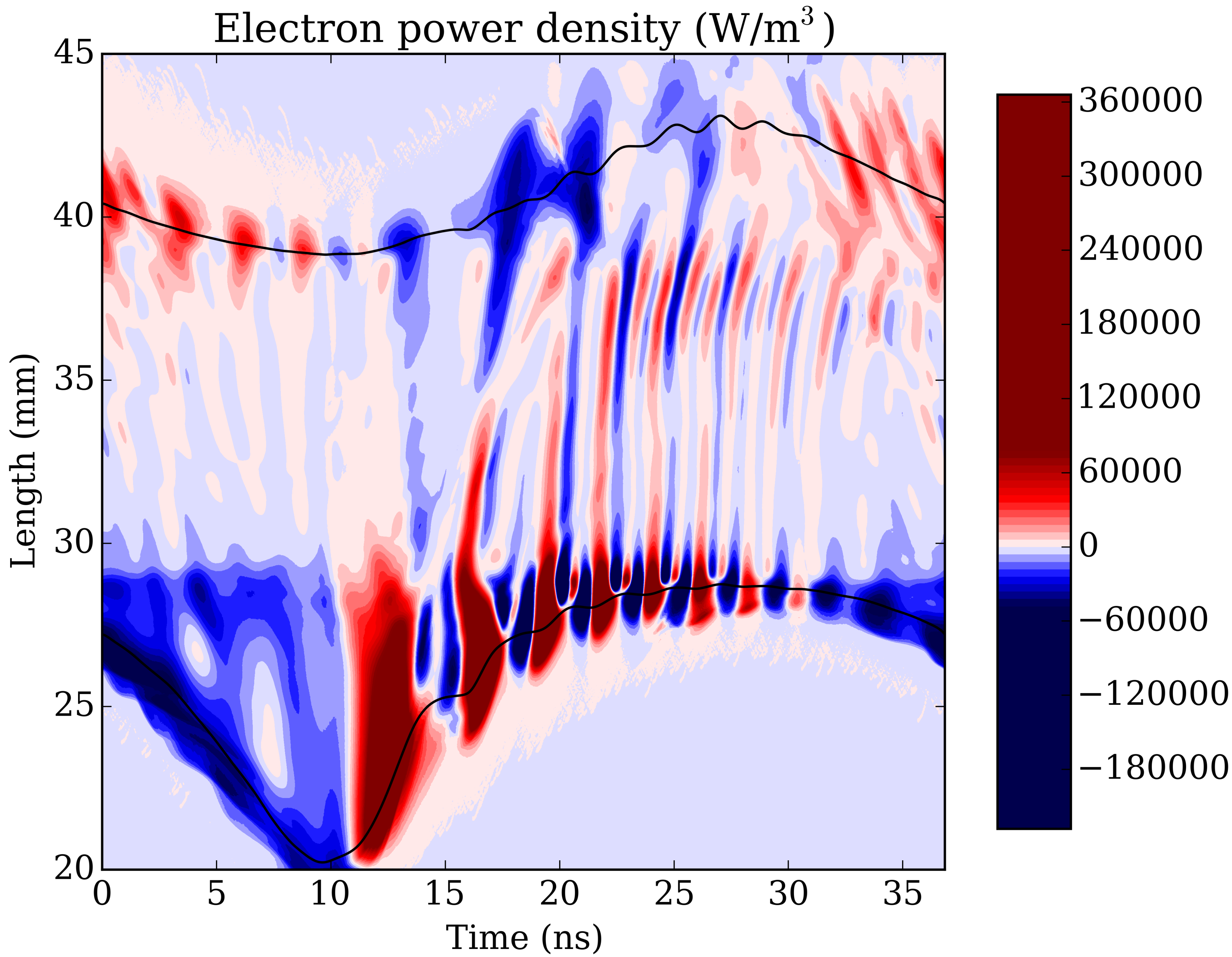
RUB





- nonlocal transport of beam electrons plays an important role at low pressures
- process optimization by controlling the impingement phase of beam electrons
- penetration of beam electrons leads to local field reversals in front of the sheath
- backflow of bulk electrons generates harmonics in the RF-current
- generation of multiple beam electrons as well as the excitation of electrostatic waves represent the nonlinearity of CCRF discharges

Conclusion



- electron heating in CCRF discharges at low pressures is still not fully understood
- nonlinear and nonlocal dynamics contribute significantly to the electron dynamics