Dynamics of the Electron Temperature and Power Absorption in Capacitively Coupled Radio Frequency Discharges

S. Wilczek[1], J. Schulze[1,2], R. P. Brinkmann[1], Z. Donkó[3], J. Trieschmann[4], and T. Mussenbrock[4]

[1]Ruhr-University Bochum, Germany
[2]Dalian University of Technology, Dalian, China
[3]Wigner Research Centre for Physics, Budapest, Hungary
[4]Brandenburg University of Technology, Cottbus-Senftenberg, Germany

Journal of Applied Physics

RUB

Electron dynamics in low pressure capacitively coupled radio frequency discharges

Cite as: J. Appl. Phys. **127**, 181101 (2020); https://doi.org/10.1063/5.0003114
Submitted: 30 January 2020 . Accepted: 17 April 2020 . Published Online: 08 May 2020

S. Wilczek, J. Schulze, R. P. Brinkmann, Z. Donkó, J. Trieschmann, and T. Mussenbrock

COLLECTIONS

F This paper was selected as Featured

View Online Export Citation CrossMark

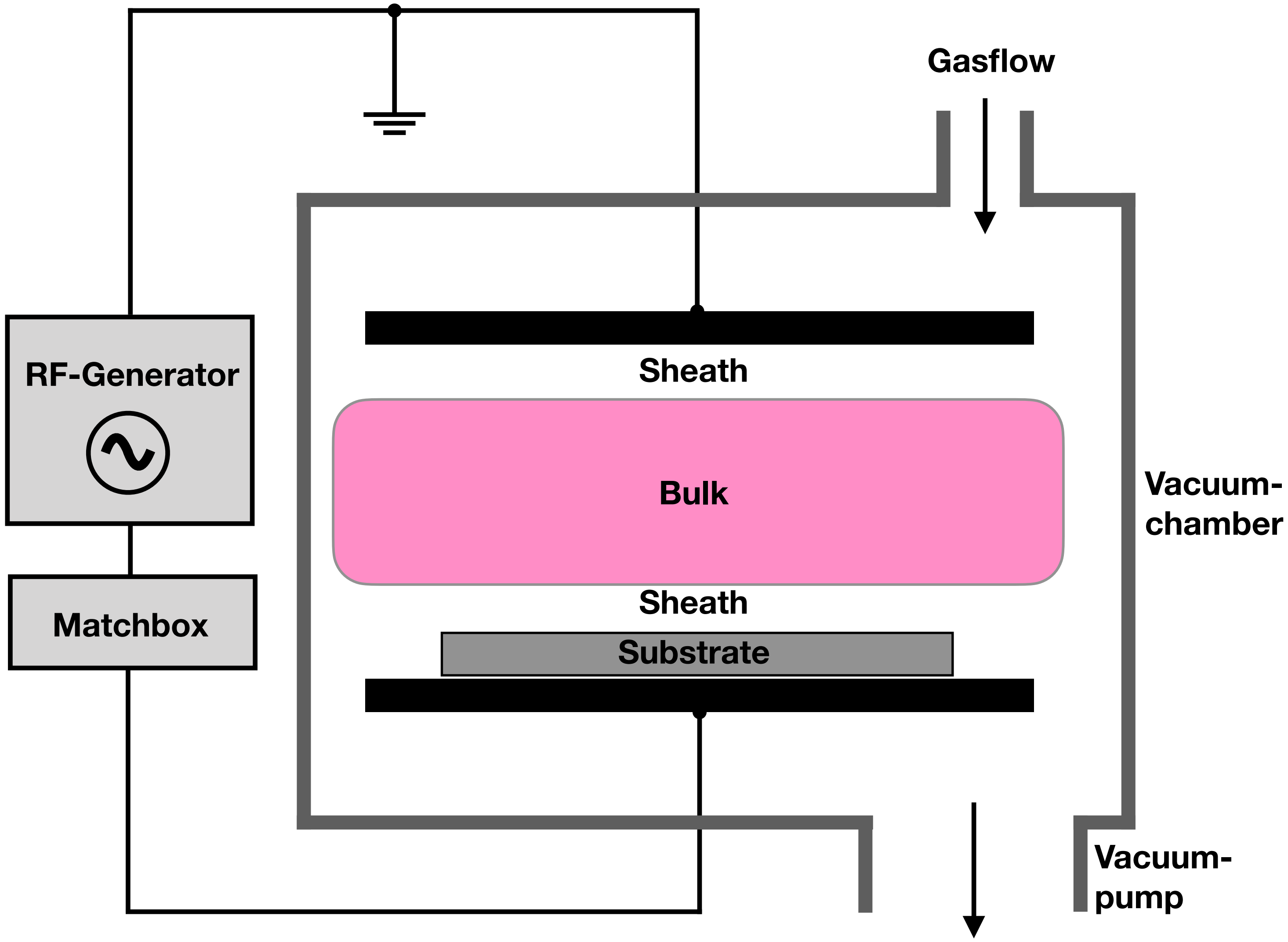
This presentation is based on the tutorial „Electron dynamics in low pressure capacitively coupled radio frequency discharges", which has already been published as a featured article in Journal of Applied Physics

https://doi.org/10.1063/5.0003114

S. Wilczek et al., J. Appl. Phys., 127, 181101 (2020)

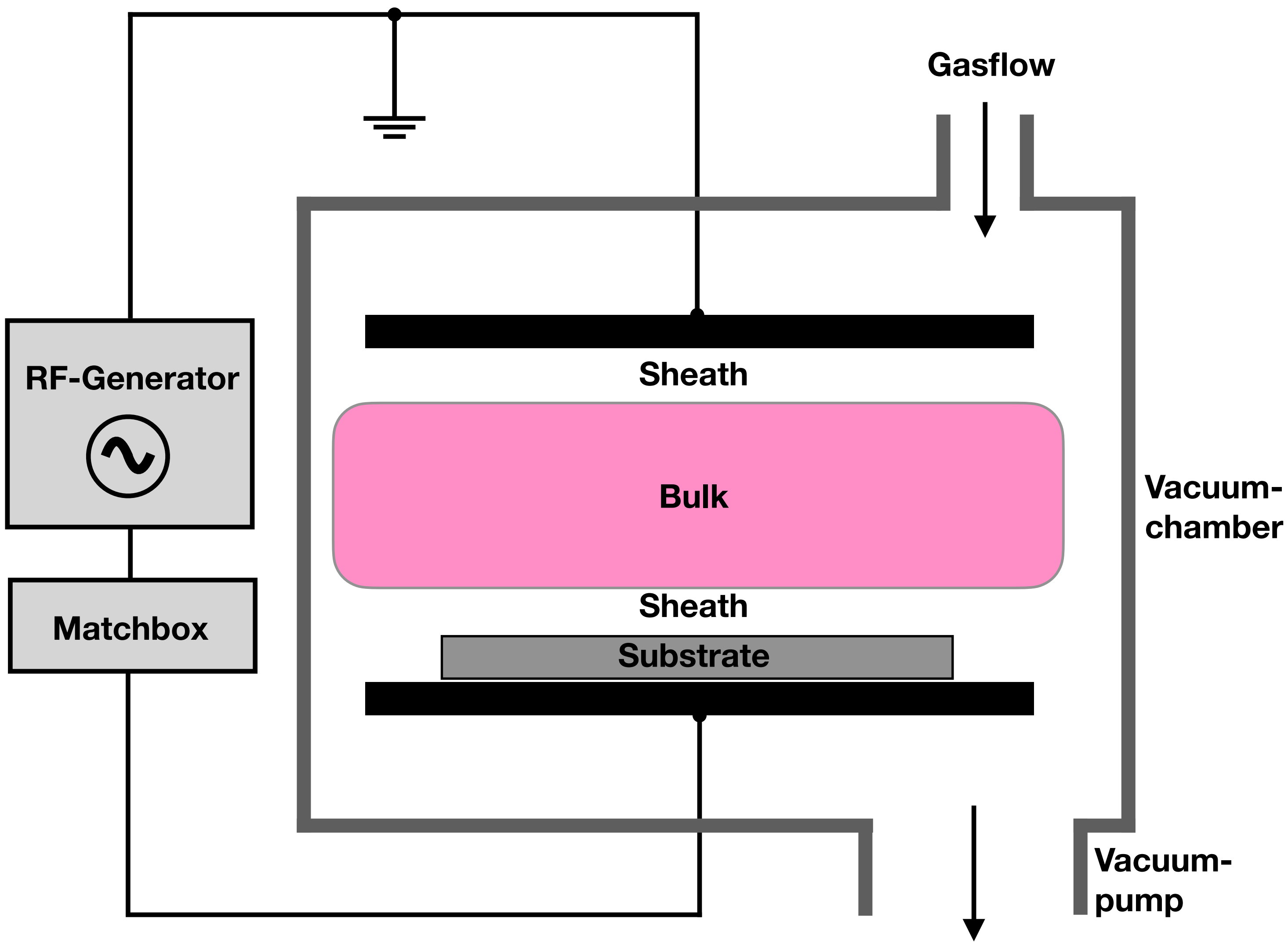
Motivation: Electron Dynamics

RUB



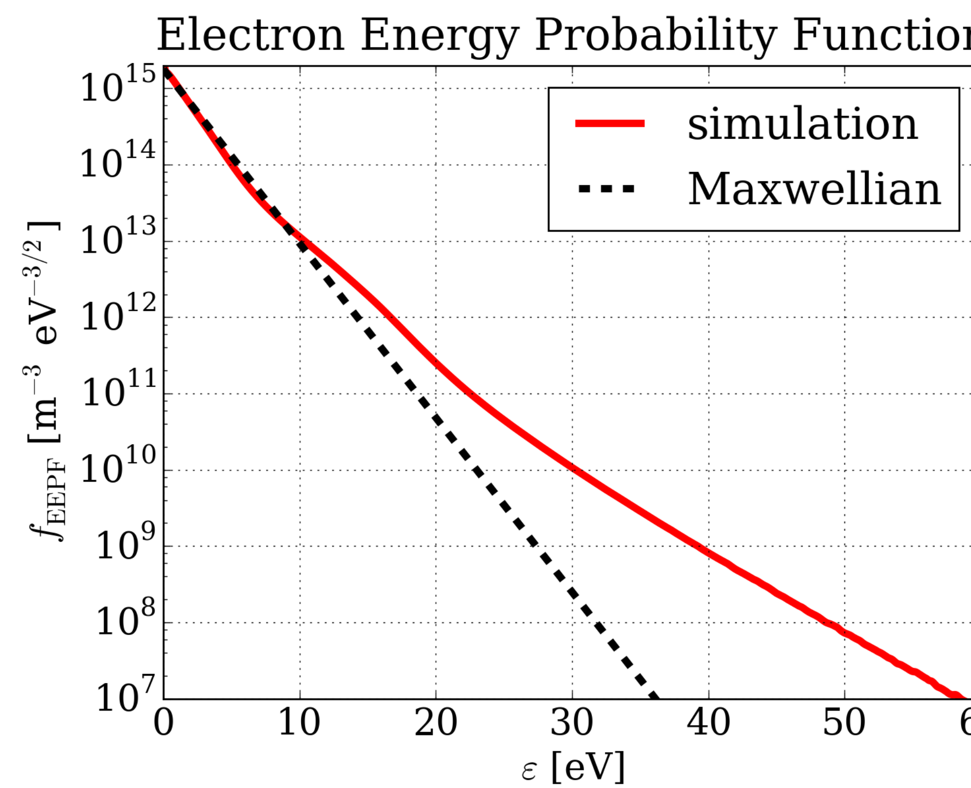
- control of the electrons in order to optimize the industrial relevant discharges
- however, electrons at low pressures (< 10 Pa) indicate a strong anisotropy

Motivation: Electron Dynamics



$p = 3\,\mathrm{Pa}\,(\mathrm{argon})$ $V_0 = 500\,\mathrm{V}$

$f = 13.56\,\mathrm{MHz}$ $L_{\mathrm{gap}} = 50\,\mathrm{mm}$



- control of the electrons in order to optimize the industrial relevant discharges
- however, electrons at low pressures (< 10 Pa) indicate a strong anisotropy
- electron distribution function strongly differs from a Maxwellian distribution
- challenging to understand and control the electron dynamics

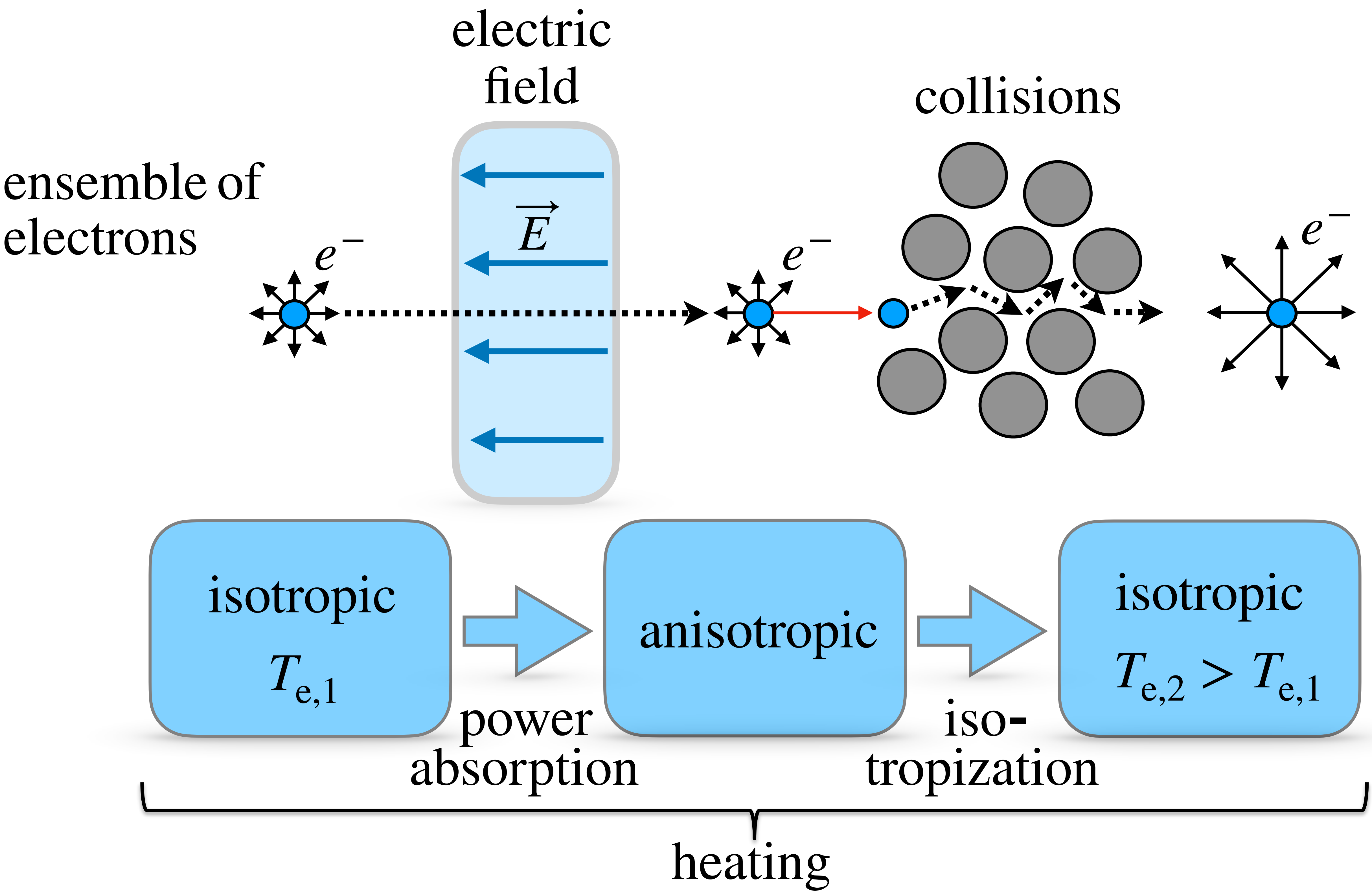
Goal of this Work

RUB

1. **How do the electrons gain and lose their energy in an electric field? Traditionally, how does the electron heating really work?**

2. **How to deal with the thermodynamic concept of the electron temperature in such a very nonlocal and anisotropic regime?**

What is actually Electron Heating?



Electron Heating Terminologies

(classical) ohmic heating

stochastic heating
(anomalous, sheath, transit time)

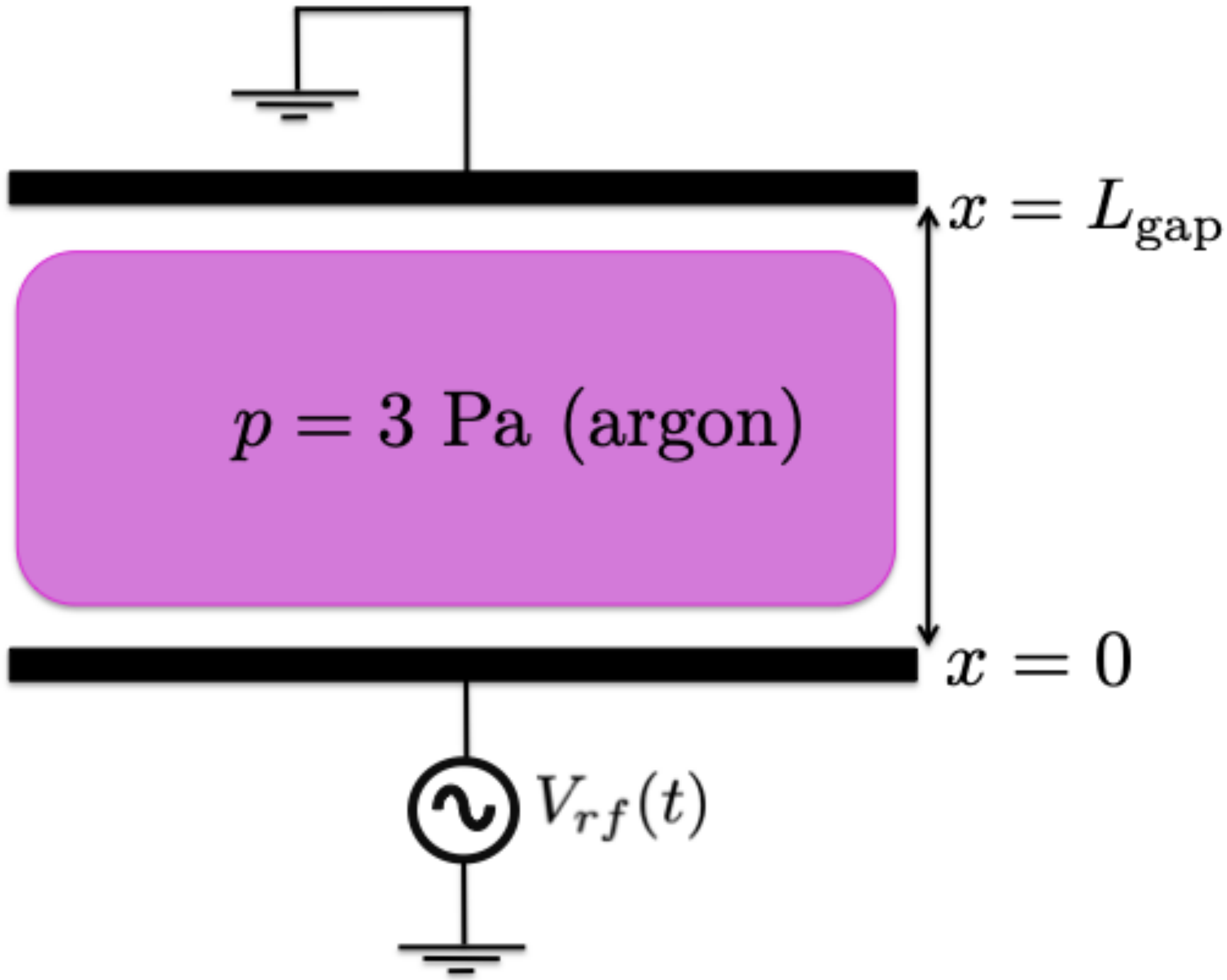
Further terminologies:

- nonlinear electron resonance heating
- pressure heating
- ambipolar heating
- bounce-resonance-heating
- secondary electron heating
- nonlinear wave-particle heating

Finally, most of the terms describe the same mechanism:
The particle interaction with a time-varying electric field!
However, no coherent terminologies!

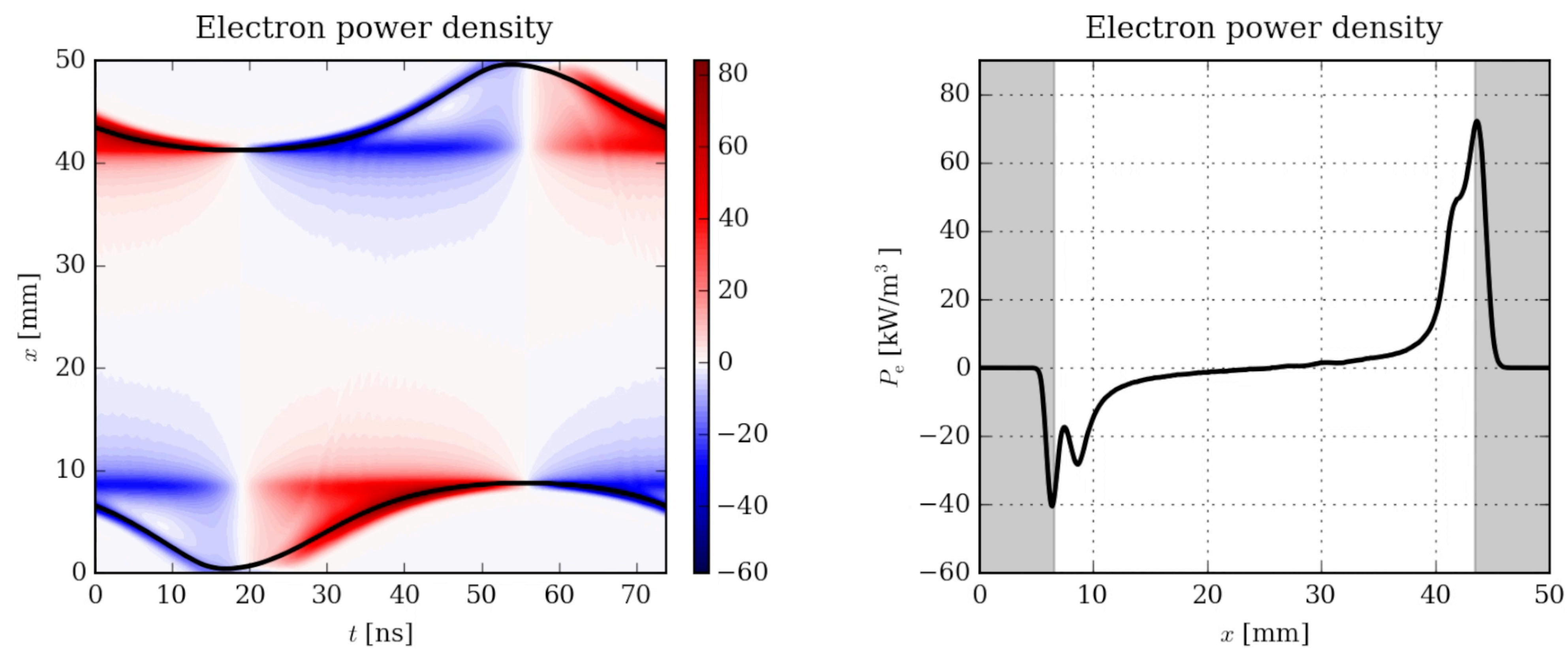
Simulation Setup

- 1d3v PIC/MCC simulation
- planar, parallel and infinite electrodes
- axial symmetric, translational invariant in y and z
- only parallel and perpendicular directions
- argon gas pressure: 3 Pa
- gap size: 50 mm
- driving frequency: 13.56 MHz
- voltage amplitude: 500 V
- no surface models



Electron Power Absorption

- electron power density: $P_e = j_e \cdot E$
- dominant power absorption near sheath edge (black solid line)
- dominant power absorption in the ambipolar region in front of the sheath edge
- how to study the electron power absorption mechanism in detail?



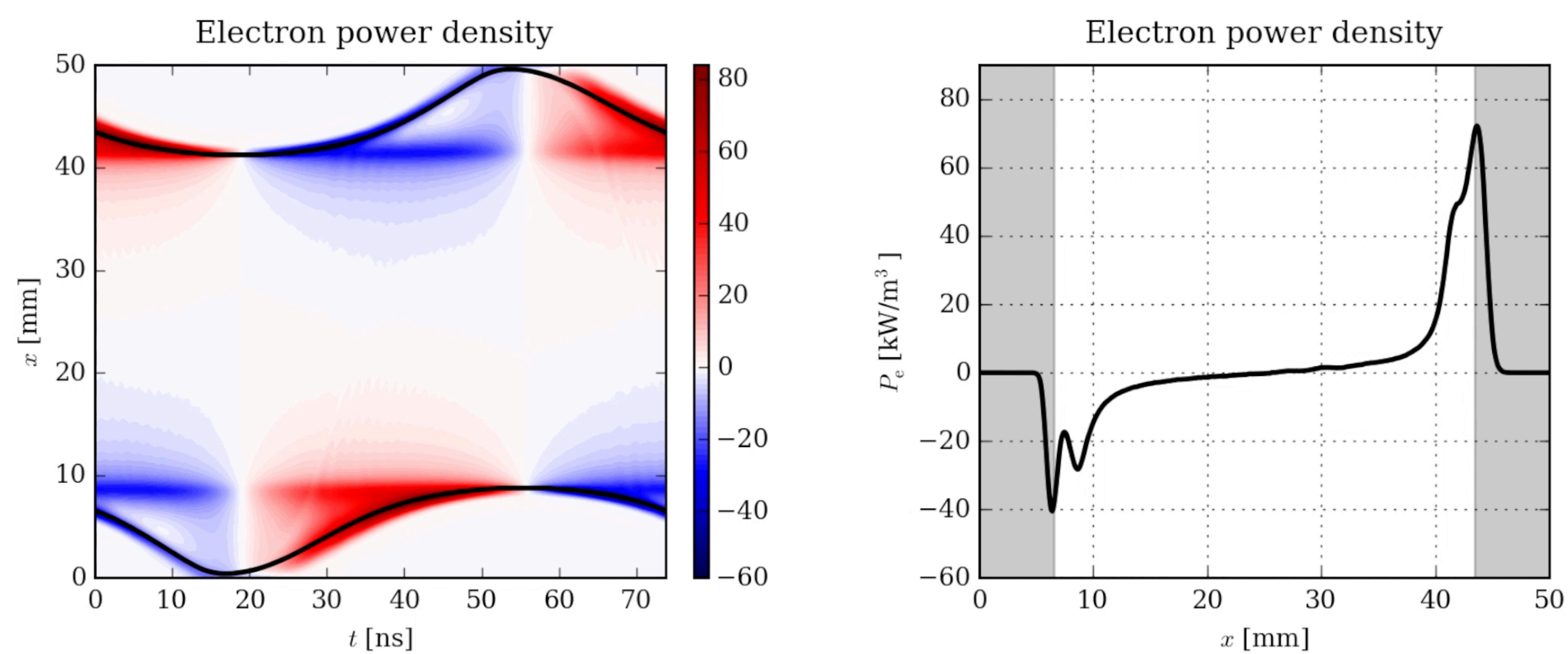
Please use the link to Movie 1

Electron Power Absorption

RUB

momentum balance in x-direction (parallel):

$$m_\mathrm{e}\frac{\partial(n_\mathrm{e}u_\parallel)}{\partial t} + m_\mathrm{e}\frac{\partial(n_\mathrm{e}u_\parallel^2)}{\partial x} + \frac{\partial p_\parallel}{\partial x} = -\,e n_\mathrm{e}E_\parallel - \Pi_{\mathrm{c}\parallel}$$

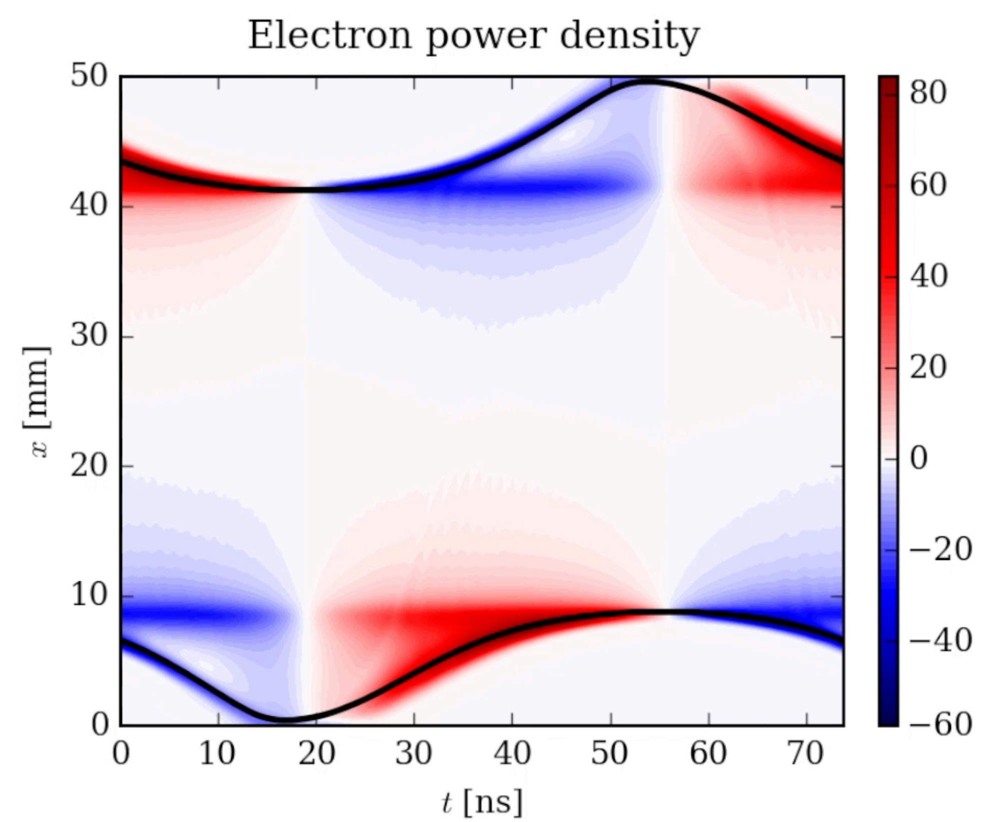


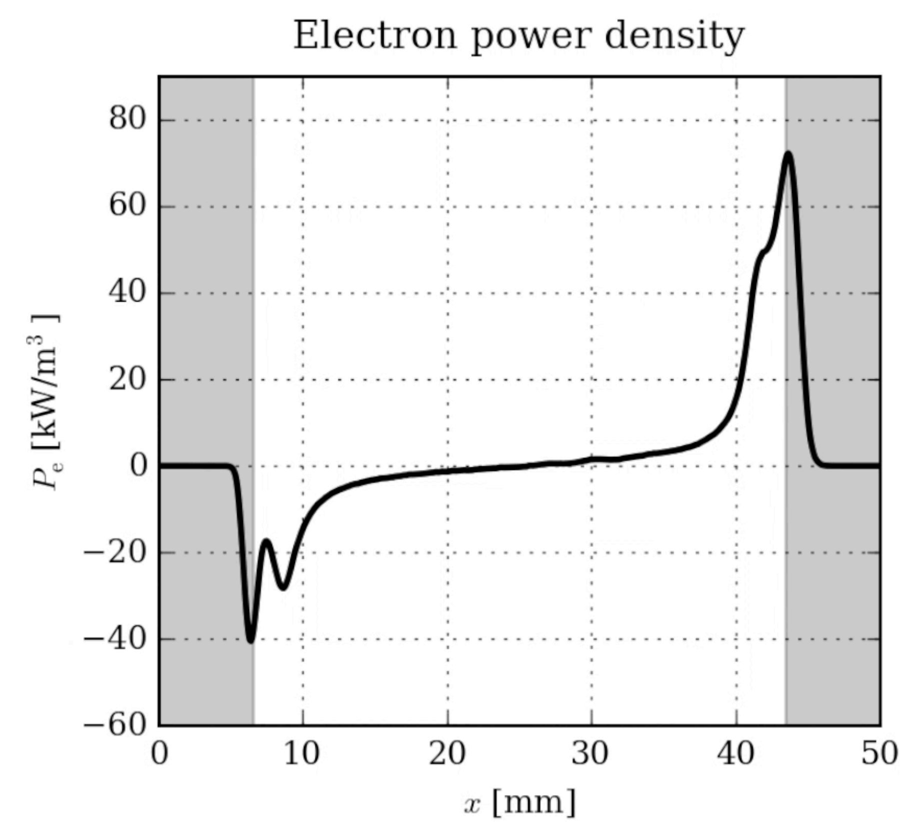
Please use the link to Movie 1

Electron Power Absorption

solving for the electric field:

$$E_{\parallel} = \underbrace{-\frac{m_\mathrm{e}}{n_\mathrm{e}}\left(\frac{\partial(u_{\parallel} n_\mathrm{e})}{\partial t} + \frac{\partial(n_\mathrm{e} u_{\parallel}^2)}{\partial x}\right)}_{E_\mathrm{in}} \underbrace{-\frac{1}{e n_\mathrm{e}}\frac{\partial p_{\parallel}}{\partial x}}_{E_\mathrm{pr}} \underbrace{-\frac{1}{n_\mathrm{e} e}\Pi_{\mathrm{c}\parallel}}_{E_\mathrm{Ohm}}$$



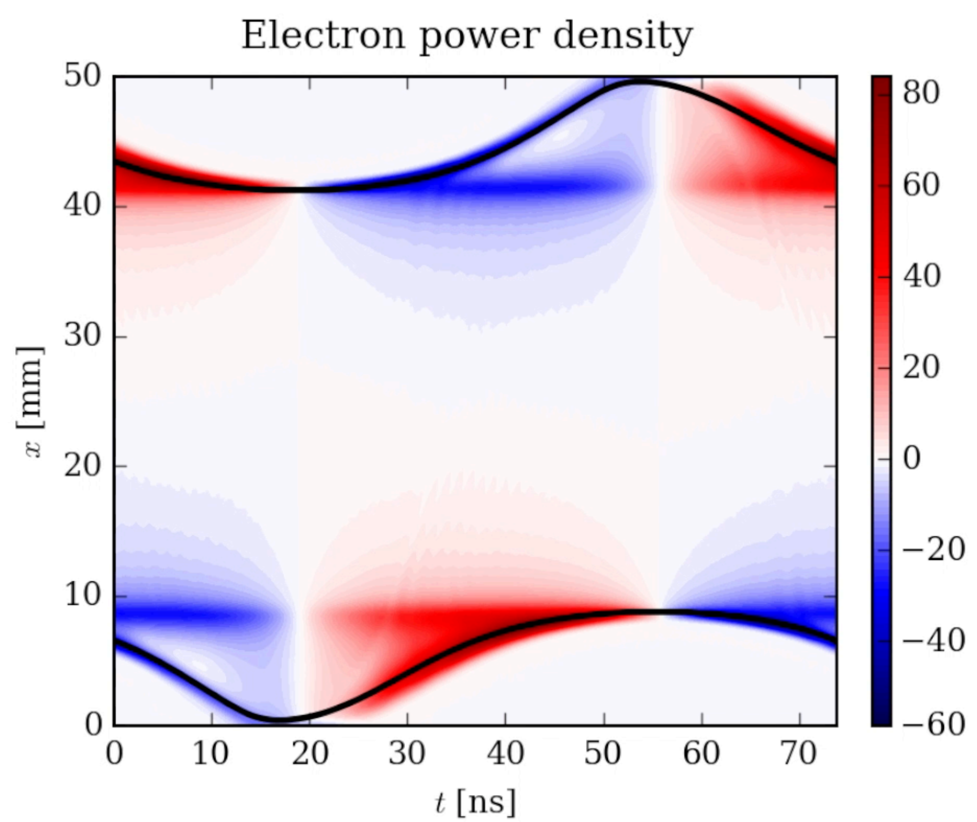


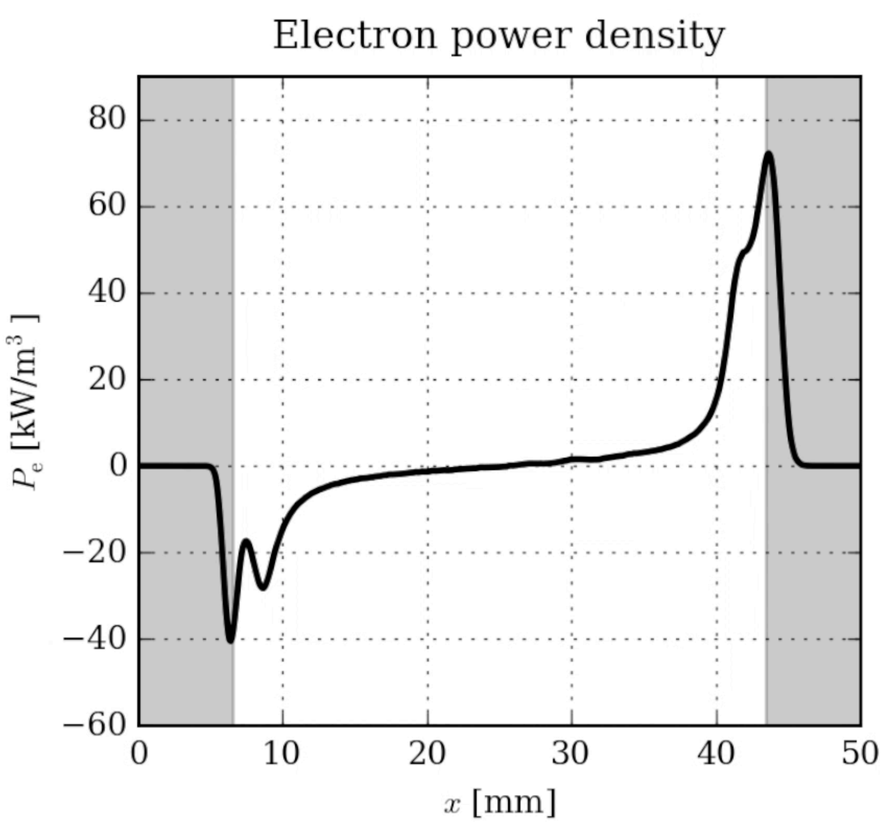
Please use the link to Movie 1

Electron Power Absorption

multiply by the electron current:

$$\underbrace{j_e E}_{P_e} = \underbrace{\underbrace{j_e E_{\text{in}}}_{P_{\text{in}}} + \underbrace{j_e E_{\text{pr}}}_{P_{\text{pr}}}}_{P_{\text{collsionless}}} + \underbrace{\underbrace{j_e E_{\text{Ohm}}}_{P_{\text{Ohm}}}}_{P_{\text{collisional}}}$$



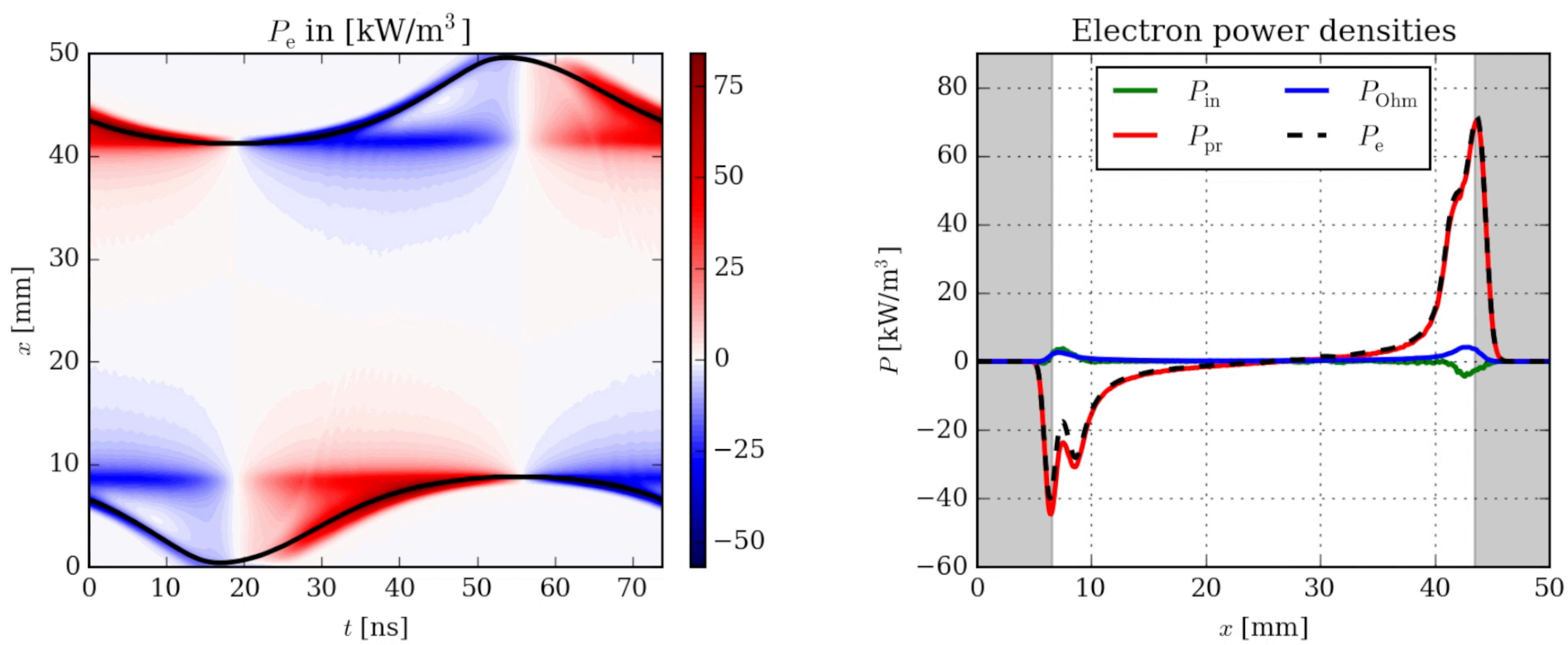


Please use the link to Movie 1

Boltzmann Term Analysis

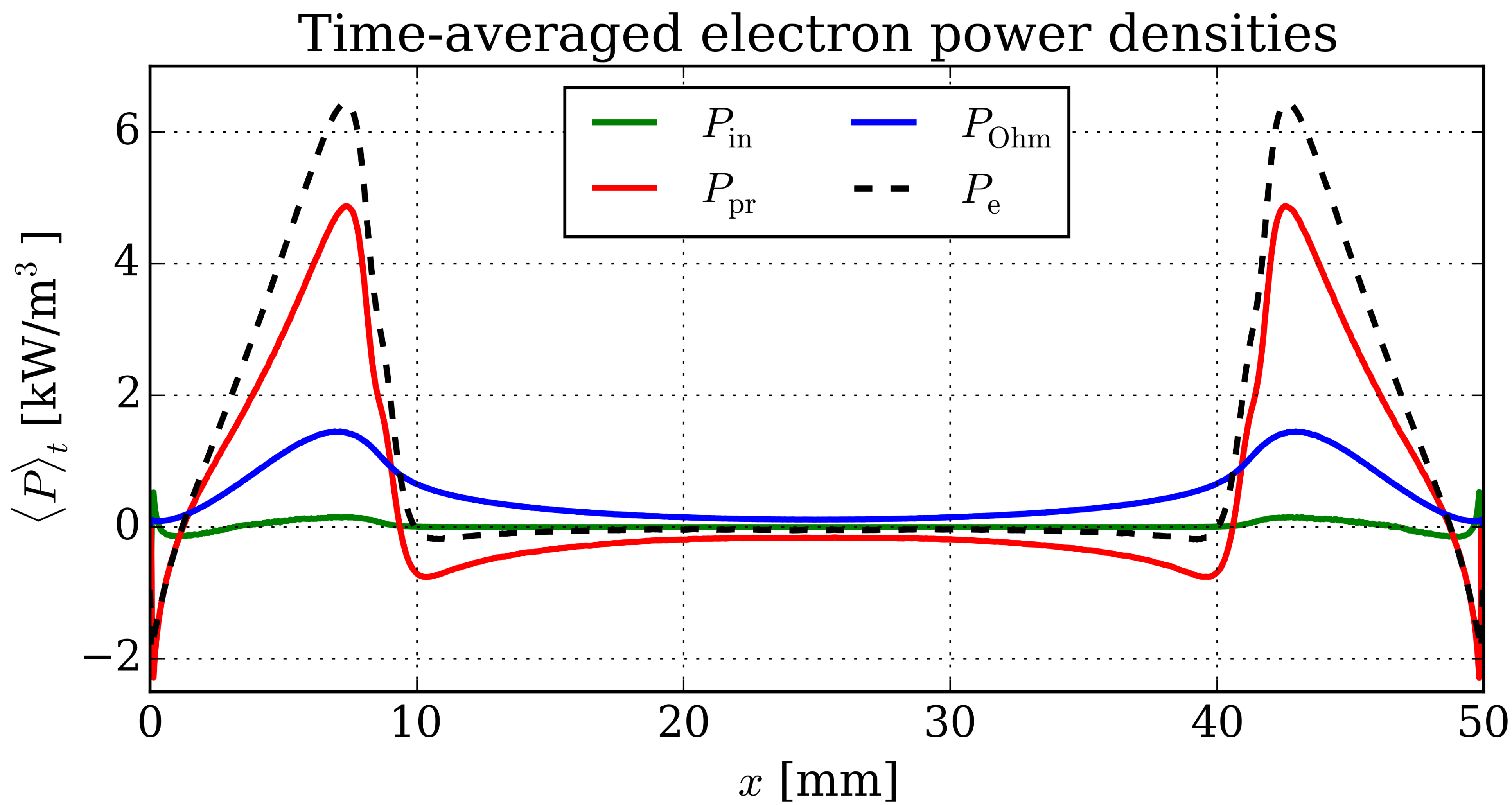
multiply by the electron current:

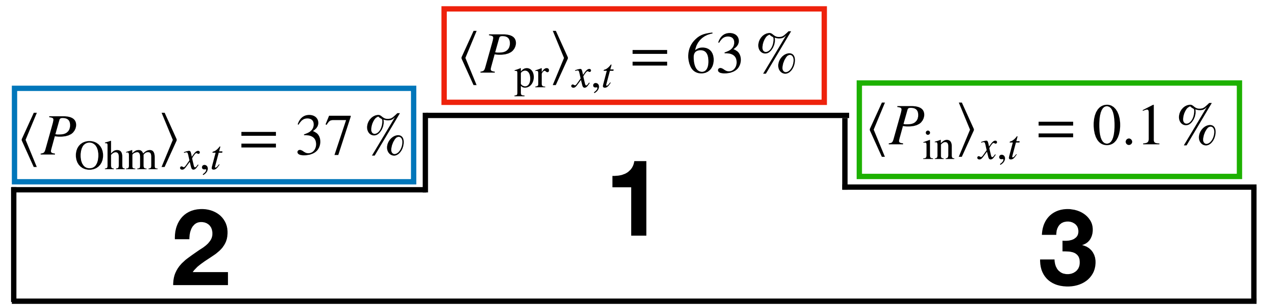
$$\underbrace{j_e E}_{P_e} = \underbrace{\underbrace{j_e E_{in}}_{P_{in}} + \underbrace{j_e E_{pr}}_{P_{pr}}}_{P_{collsionless}} + \underbrace{\underbrace{j_e E_{Ohm}}_{P_{Ohm}}}_{P_{collisional}}$$



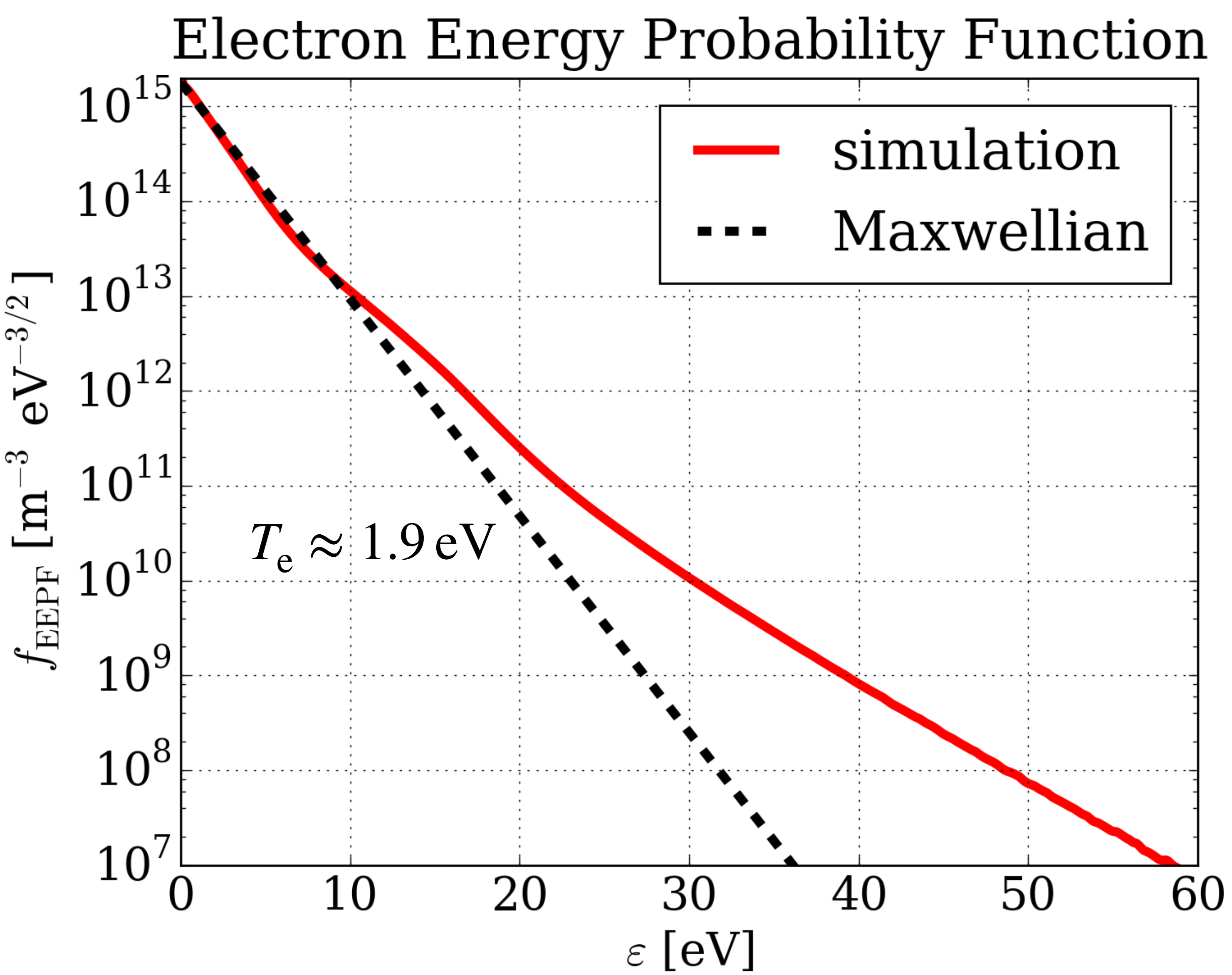
Please use the link to Movie 2

Boltzmann Term Analysis





Electron Temperature



- electron temperature (thermodynamic relation): $T_e = \frac{2}{3}\langle\epsilon\rangle \approx 1.9\,\mathrm{eV}$
- good approximation to represent the low energetic electrons (99% population)
- strong anisotropy for the high energetic electrons (1% population)
- provide a kinetic concept of the temperature to discuss the anisotropy

Electron Temperature

momentum balance in x-direction (parallel):

$$m_e \frac{\partial (n_e u_\parallel)}{\partial t} + m_e \frac{\partial (n_e u_\parallel^2)}{\partial x} + \frac{\partial (n_e T_\parallel)}{\partial x} = -e n_e E_\parallel - \Pi_{c\parallel}$$

$$\overline{\overline{p}} = \begin{pmatrix} p_{xx} & p_{xy} & p_{xz} \\ p_{yx} & p_{yy} & p_{yz} \\ p_{zx} & p_{zy} & p_{zz} \end{pmatrix} \Longrightarrow \begin{pmatrix} p_{xx} & 0 & 0 \\ 0 & p_{yy} & 0 \\ 0 & 0 & p_{zz} \end{pmatrix} \Longrightarrow \begin{pmatrix} p_\parallel & 0 & 0 \\ 0 & p_\perp & 0 \\ 0 & 0 & p_\perp \end{pmatrix}$$

Electron Temperature

RUB

momentum balance in x-direction (parallel):

$$m_e \frac{\partial(n_e u_\parallel)}{\partial t} + m_e \frac{\partial(n_e u_\parallel^2)}{\partial x} + \frac{\partial(n_e T_\parallel)}{\partial x} = -e n_e E_\parallel - \Pi_{c\parallel}$$

momentum balance in perpendicular-direction:

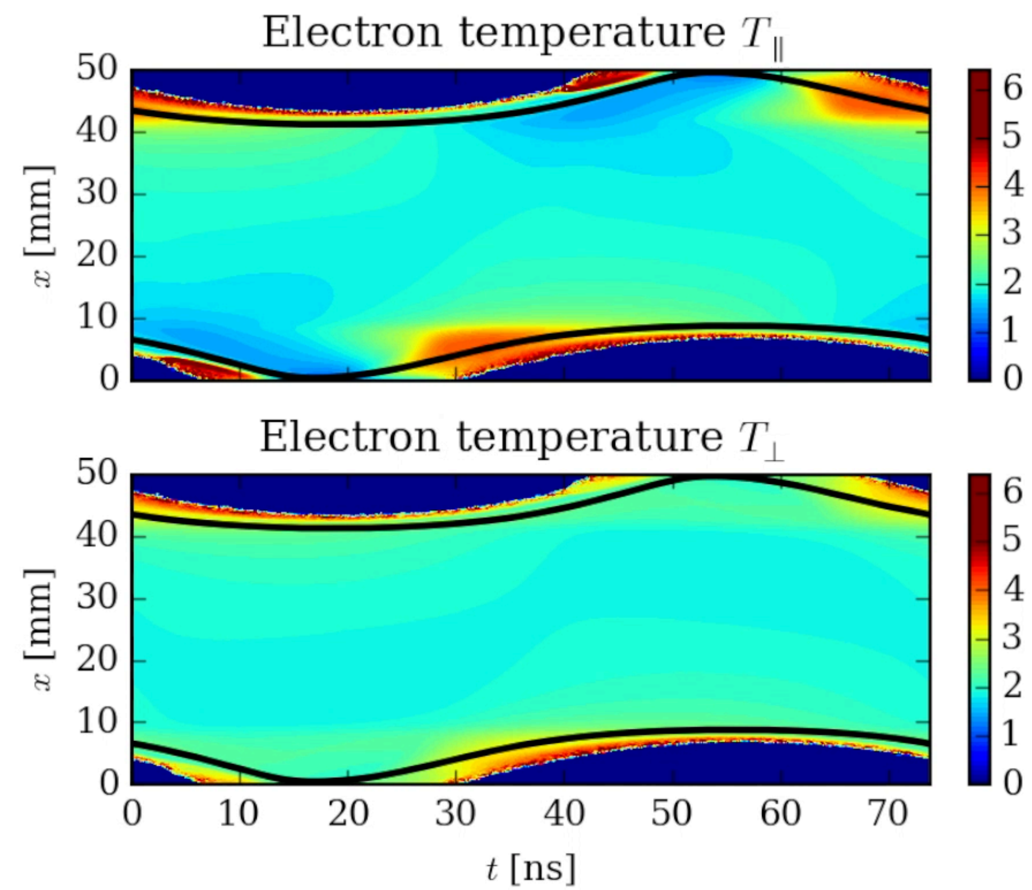
$$\cancel{m_e \frac{\partial(n_e u_\perp)}{\partial t}} + \cancel{m_e \frac{\partial(n_e u_\perp^2)}{\partial x}} + \frac{\partial(n_e T_\perp)}{\partial x} = \cancel{-e n_e E_\perp} - \Pi_{c\perp}$$

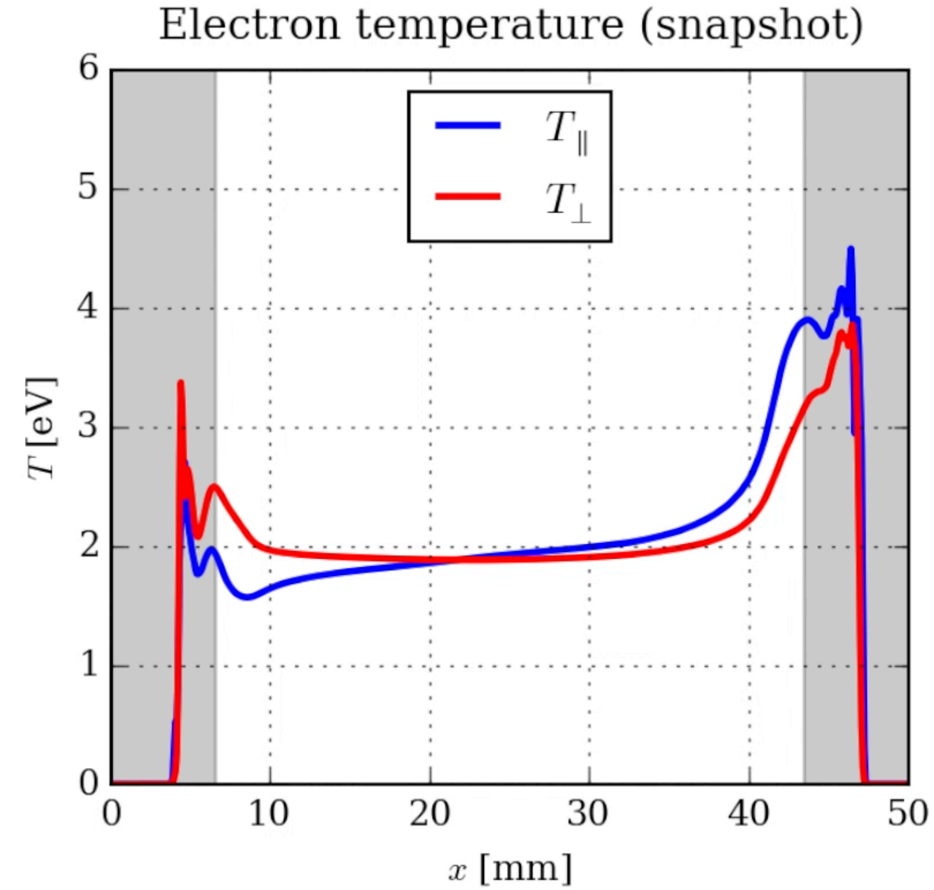
the parallel and perpendicular temperature communicate via collisions

Electron Temperature

$$T_{\parallel} = \frac{p_{\parallel}}{n_{\mathrm{e}}} = m_{\mathrm{e}} \left(< v_{\parallel}^2(x,t) > - u_{\parallel}^2(x,t) \right)$$

$$T_{\perp} = \frac{p_{\perp}}{n_{\mathrm{e}}} = m_{\mathrm{e}} \left(< v_{\perp}^2(x,t) > - \cancel{u_{\perp}^2(x,t)} \right)$$

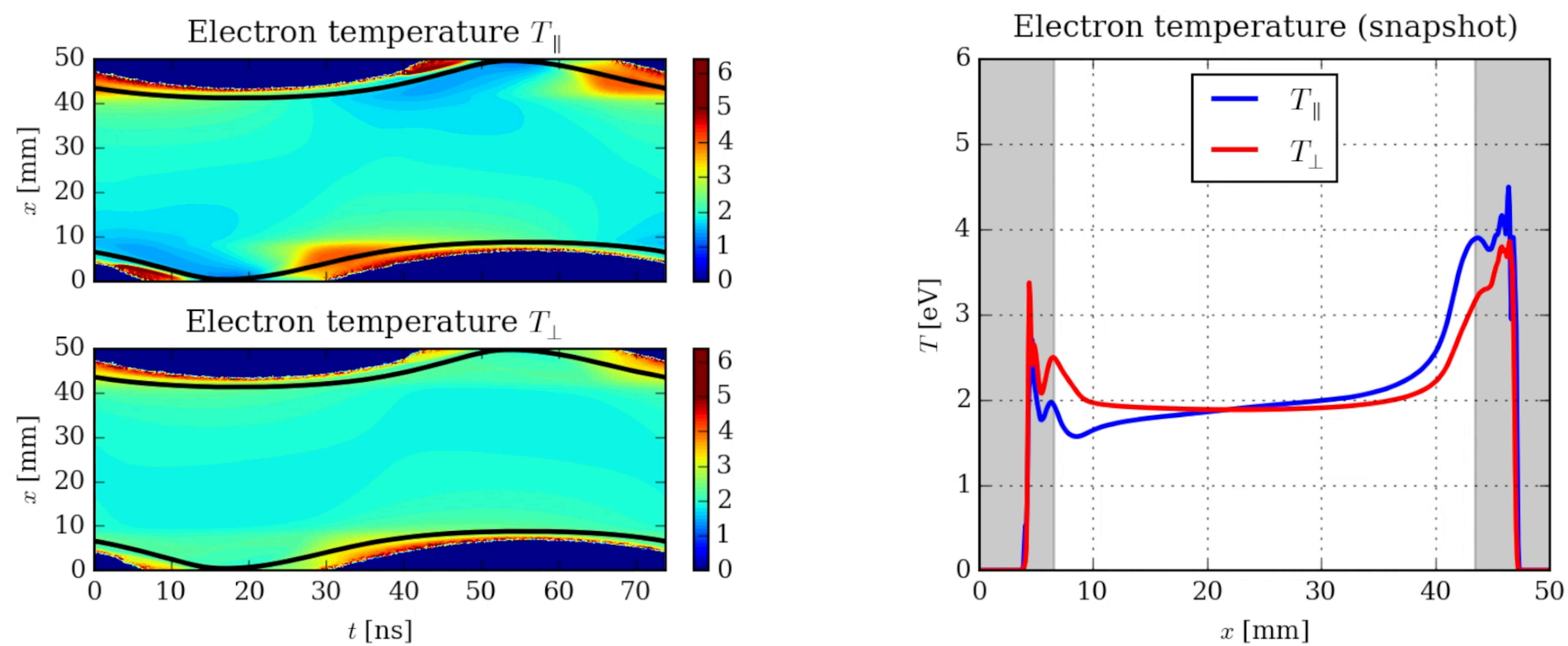




Please use the link to Movie 3

Electron Temperature

- almost isotropic in the center of the discharge (T = 1.9 eV)
- parallel electron temperature increases during sheath expansion
- perpendicular electron temperature temporally lags behind
- it needs a certain time to redistribute the energy due to collisions

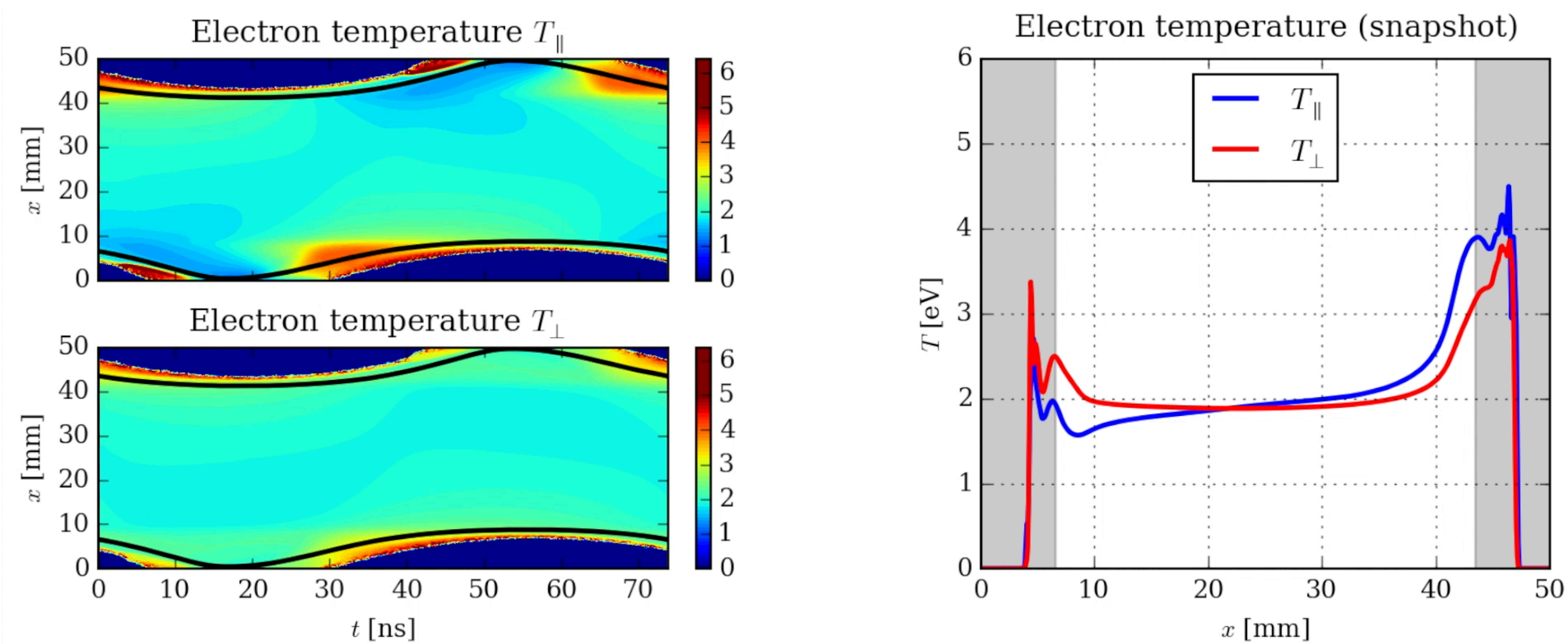


Please use the link to Movie 3

Electron Temperature

- this concept of the electron temperature clearly shows the degree of anisotropy
- both temperatures act like an energy reservoir and contribute to the energy density

$$w = \frac{1}{2} n_e (m_e u_\parallel^2 + T_\parallel + 2T_\perp)$$

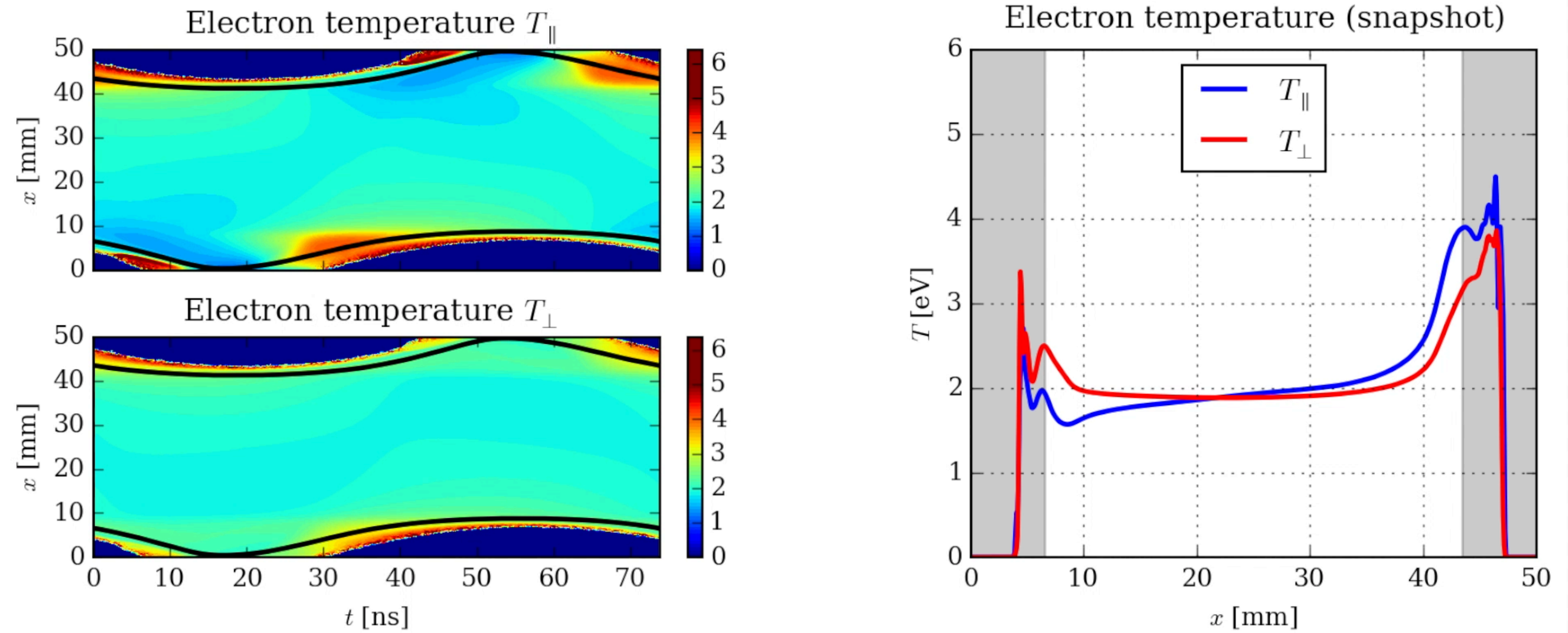


Please use the link to Movie 3

Electron Temperature

- this concept of the electron temperature clearly shows the degree of anisotropy
- both temperatures act like an energy reservoir and contribute to the energy density

energy conservation: $$\frac{\partial}{\partial t}w + \nabla \cdot \overrightarrow{Q} = P_{\text{tot}} - \varepsilon_c$$



Please use the link to Movie 3

Conclusion

RUB

- CCRF discharges at low pressures ($p < 10$ Pa), work in a very nonlocal regime
- the Boltzmann term analysis shows an coherent terminology of how to study the electron power gain and loss mechanism
- mostly the pressure heating term dominates at low pressures
- the concept of the kinetic electron temperature (parallel and perpendicular) indicates that electron power absorption and electron heating are physically two different mechanisms
- the difference of both temperatures demonstrates the degree of anisotropy