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# The Difference Between Electron Heating and Power Absorption In Capacitively Coupled Plasmas


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Journal of Applied Physics

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# 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

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**COLLECTIONS**

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**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

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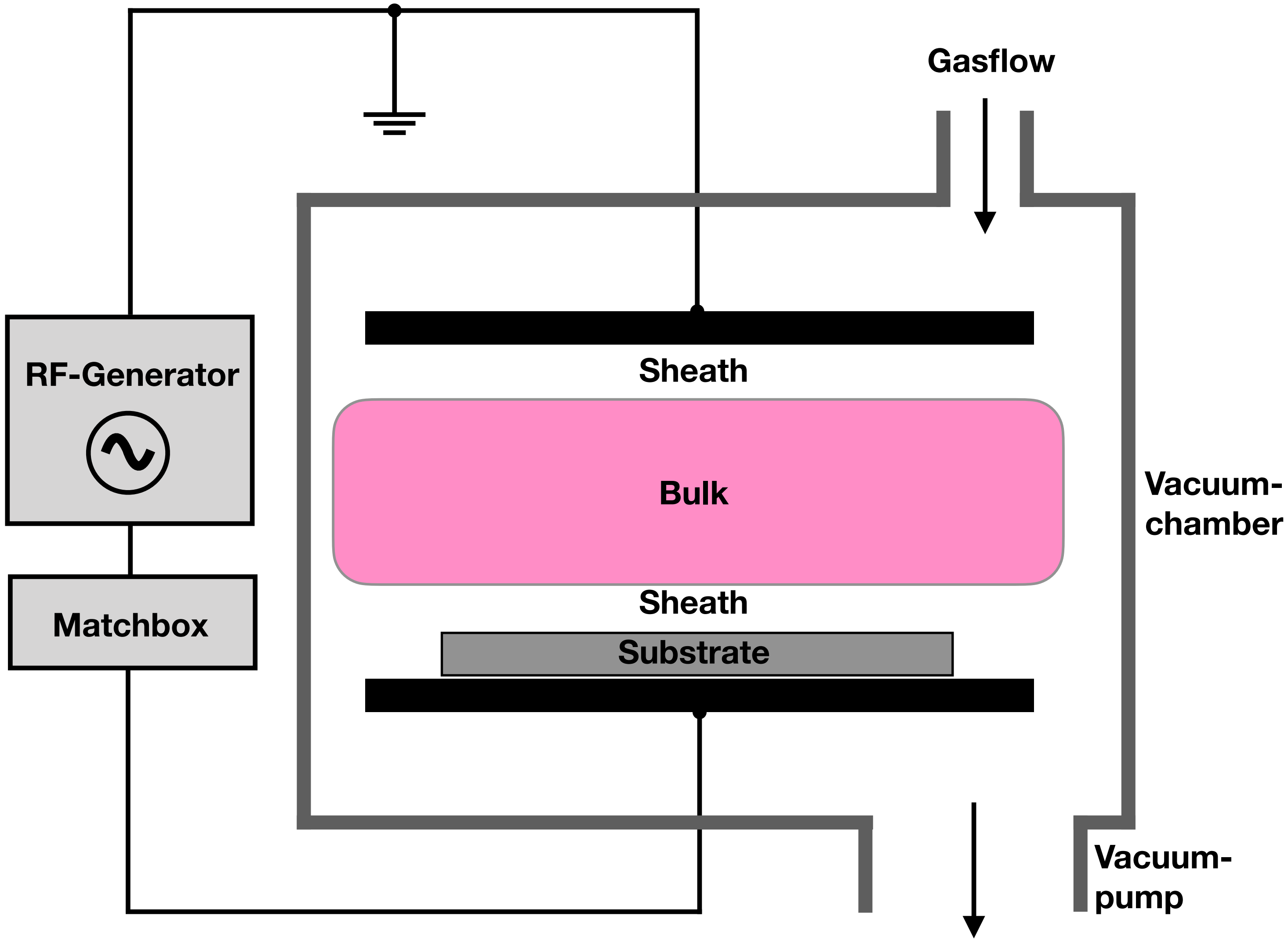
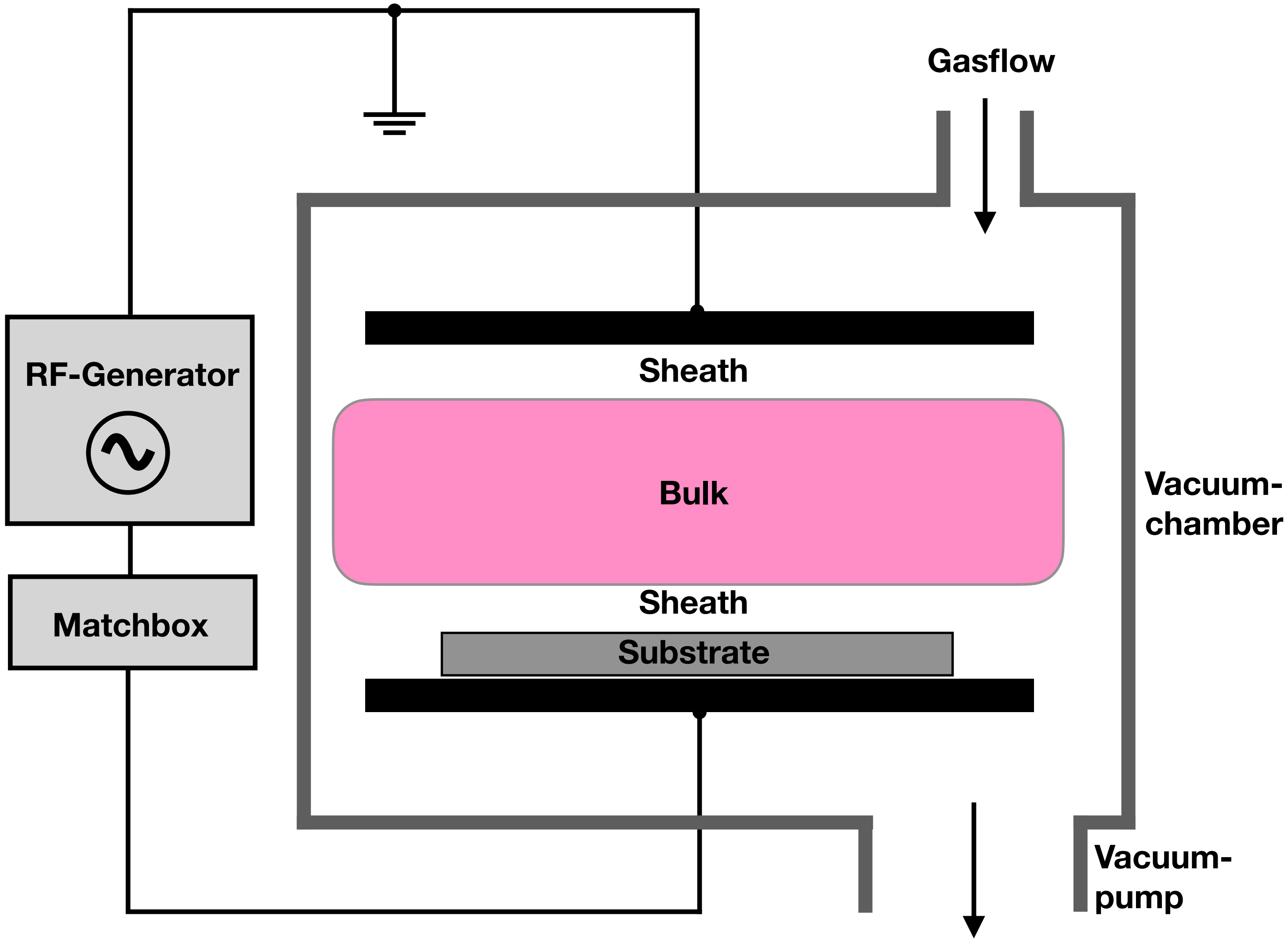


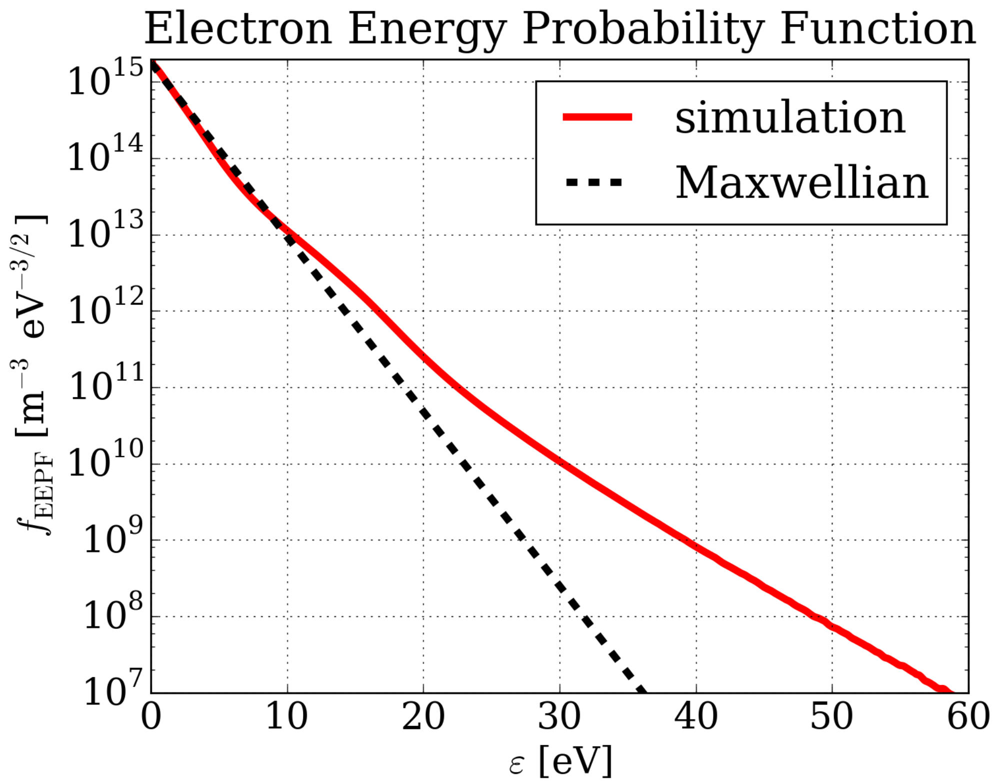

- control of the electrons in order to optimize the industrial relevant discharges
- however, electrons at low pressures (< 10 Pa) indicate a strong anisotropy

# Motivation: Electron Dynamics




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

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



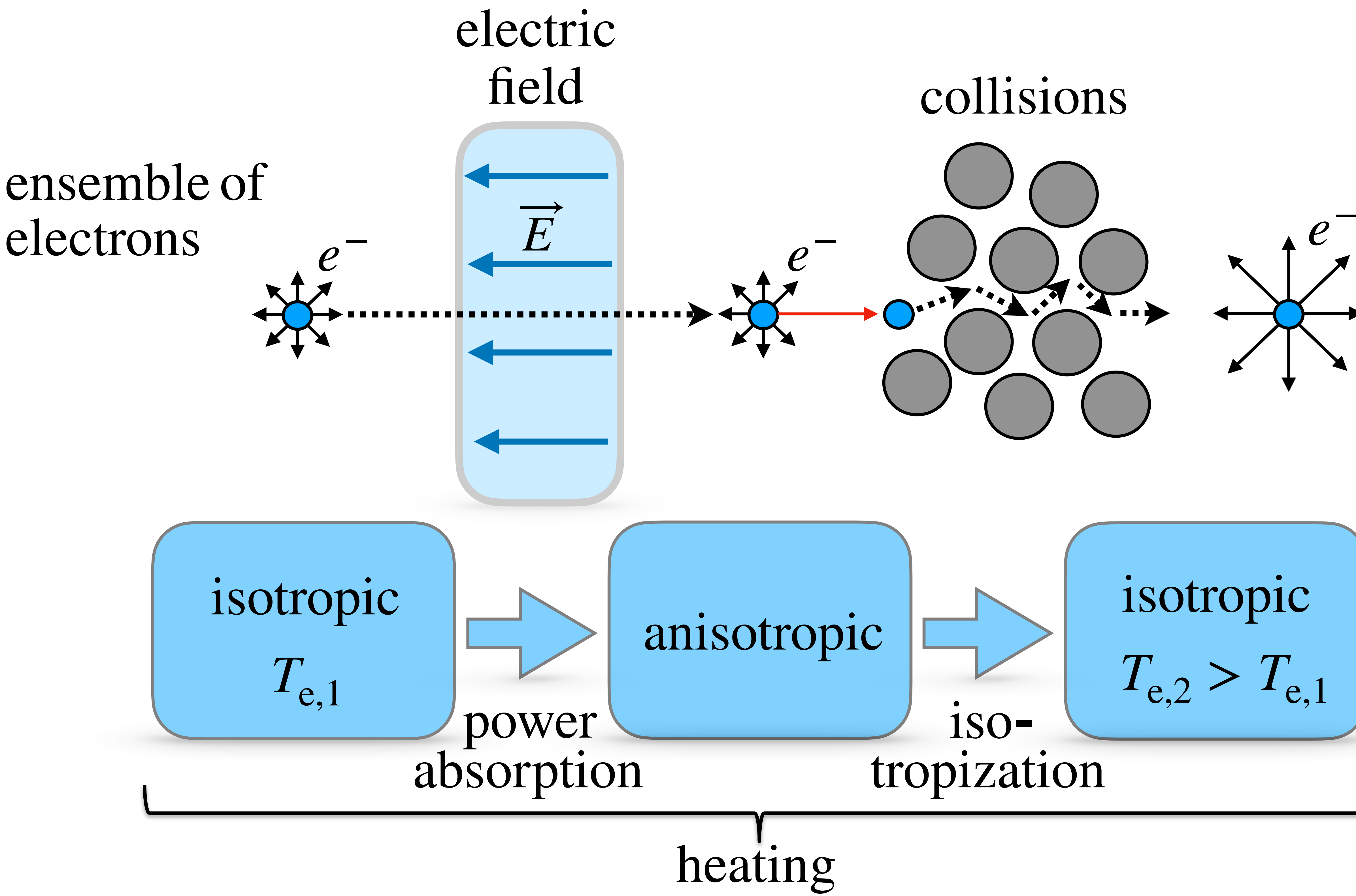

- control of the electrons in order to optimize the industrial relevant discharges
- however, electrons at low pressures (< 10 Pa) indicate a strong anisotropy
- electron distribution function strongly differs from a Maxwellian distribution
- challenging to understand and control the electron dynamics

# Goal of this Work

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

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**(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

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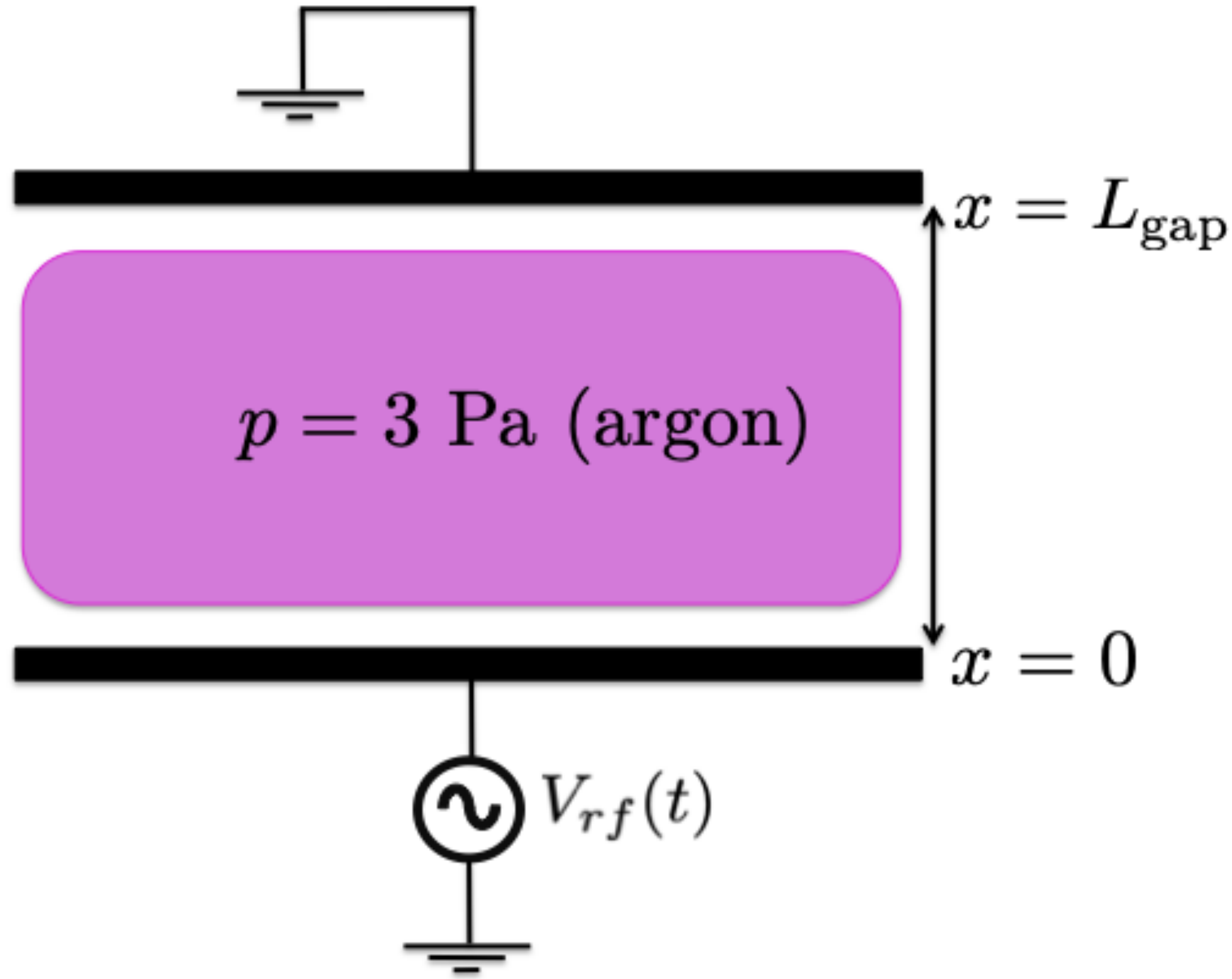
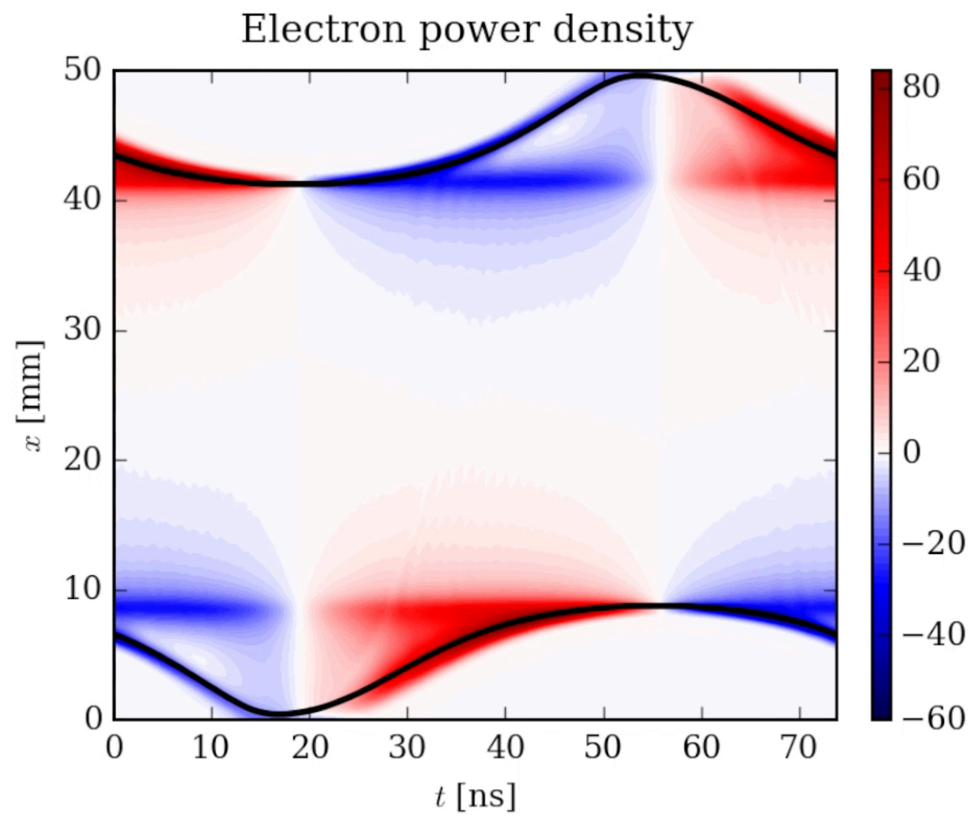
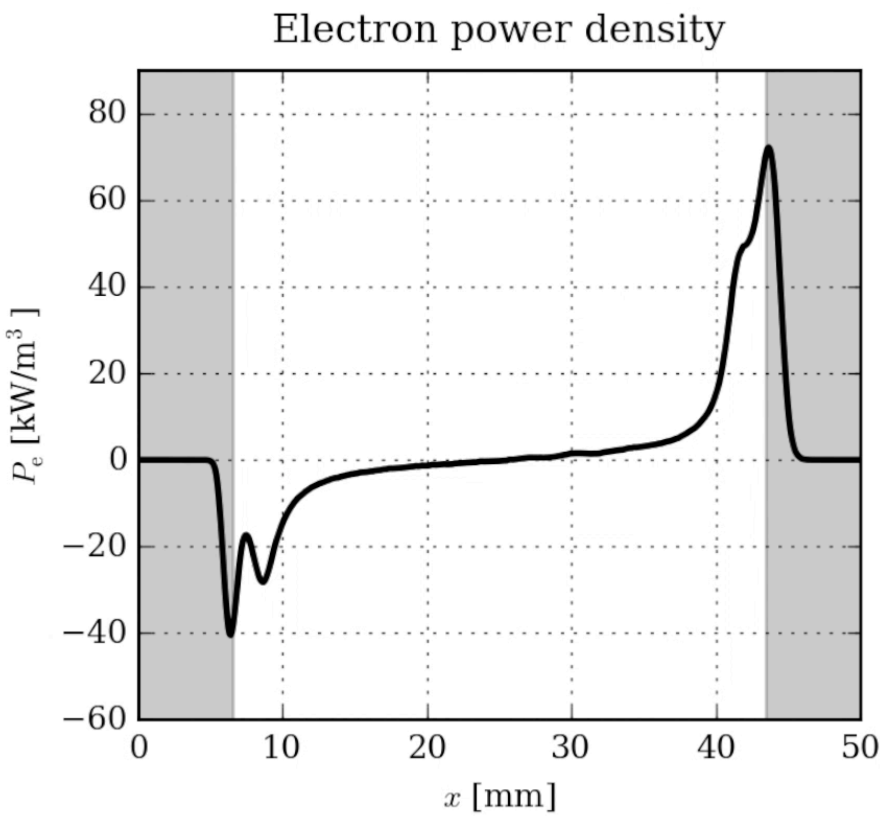
- 1d3v PIC/MCC simulation
- planar, parallel and infinite electrodes
- axial symmetric, translational invariant in y and z
- only parallel and perpendicular directions
- argon gas pressure: 3 Pa
- gap size: 50 mm
- driving frequency: 13.56 MHz
- voltage amplitude: 500 V
- no surface models



# Electron Power Absorption

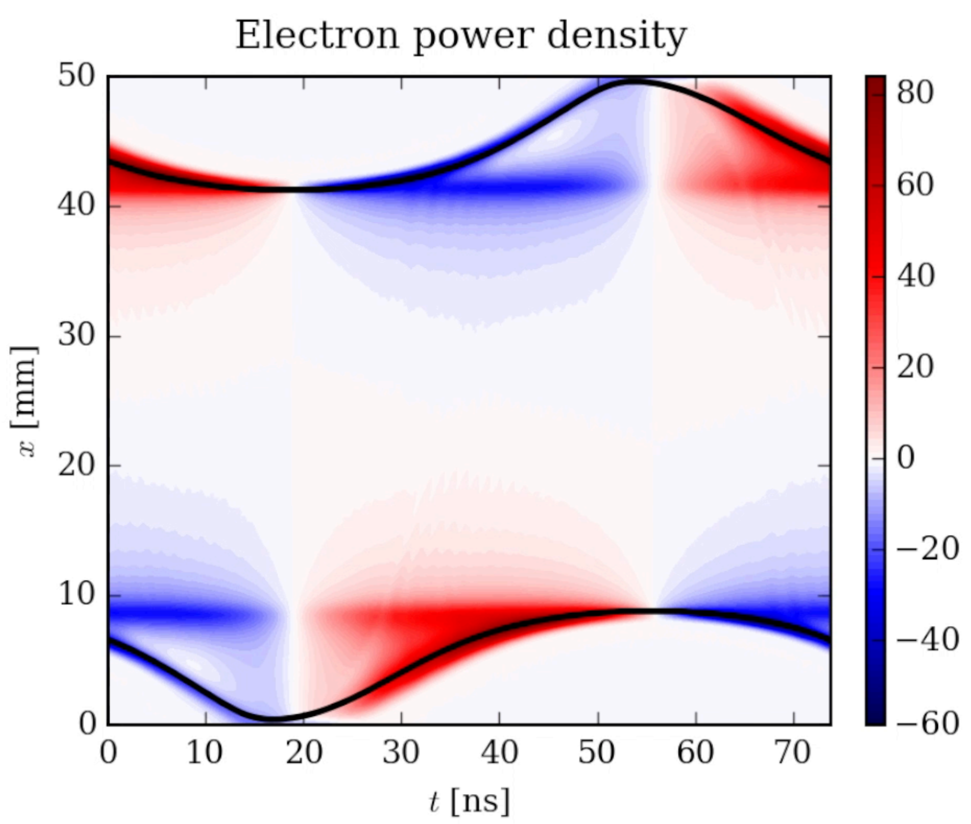
- electron power density: $P_e = j_e \cdot E$

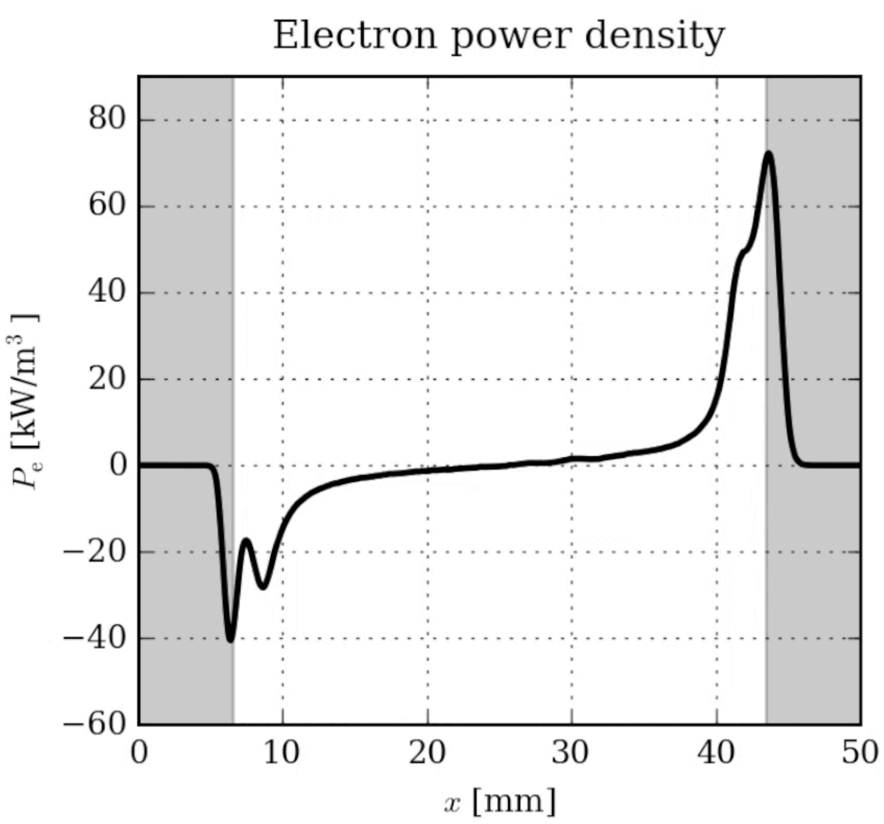


# Electron Power Absorption

- 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?

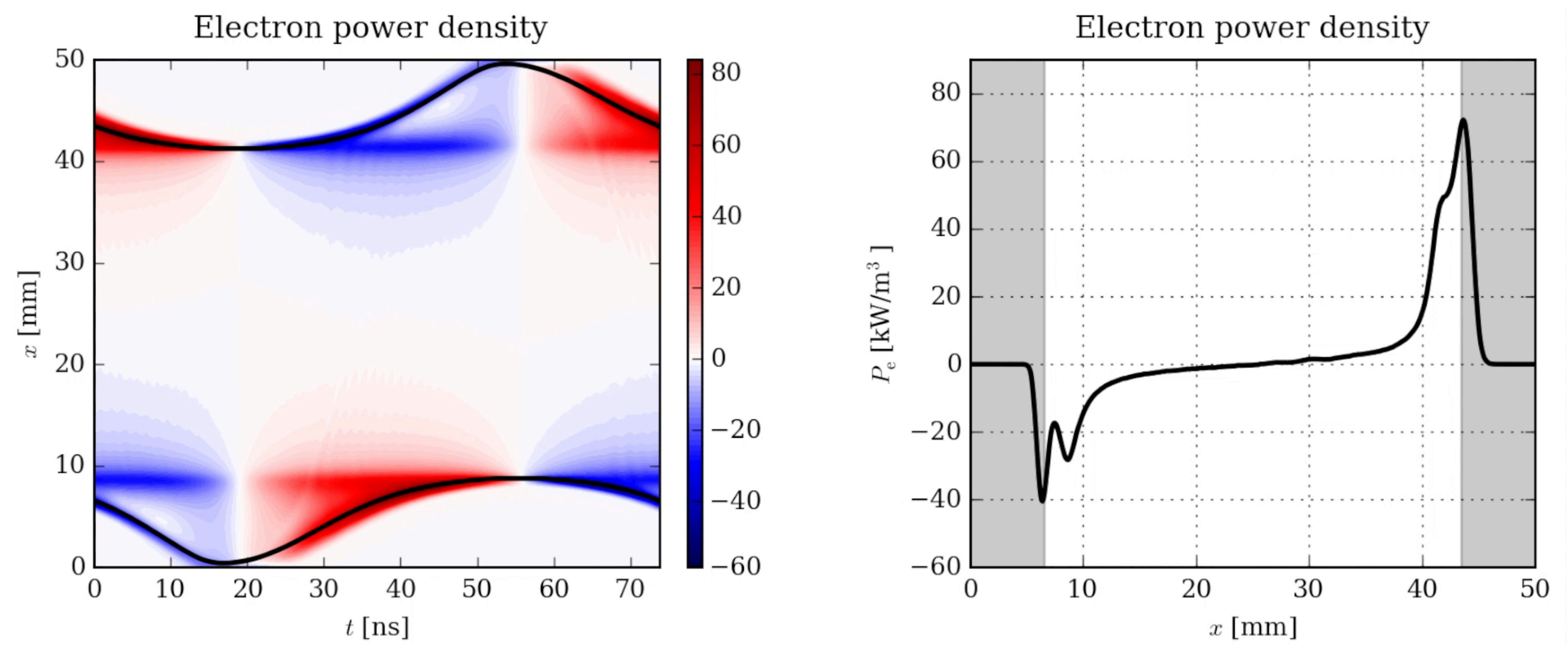


# Electron Power Absorption

**momentum balance in x-direction (parallel):**

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



# Electron Power Absorption

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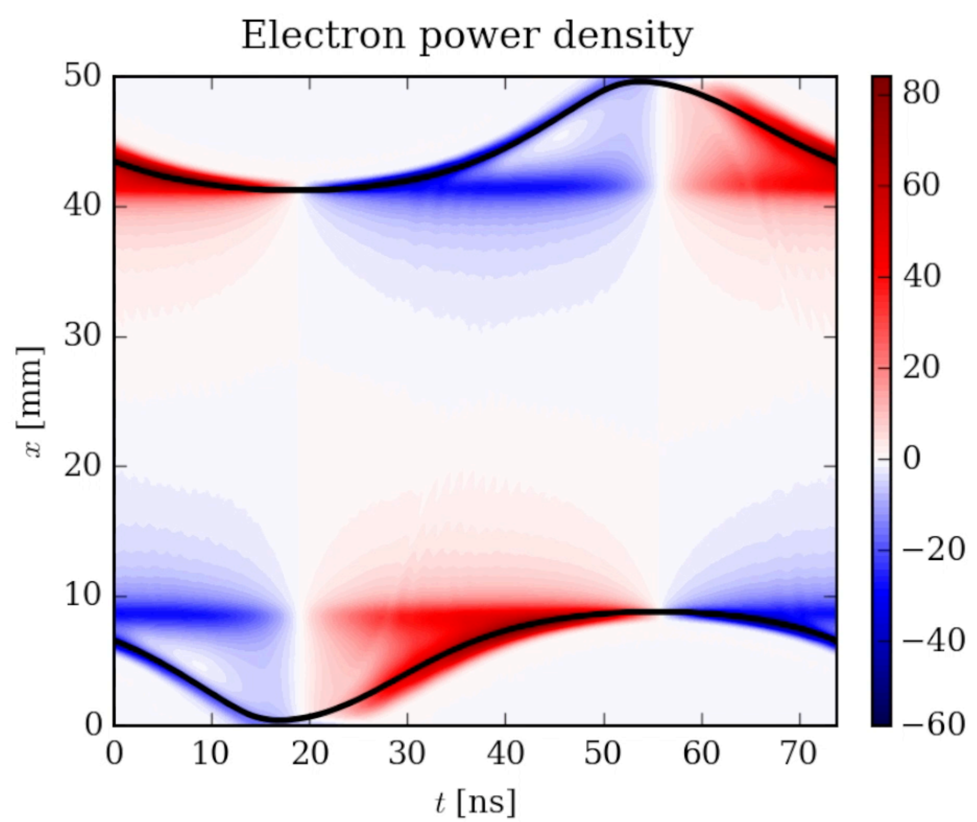
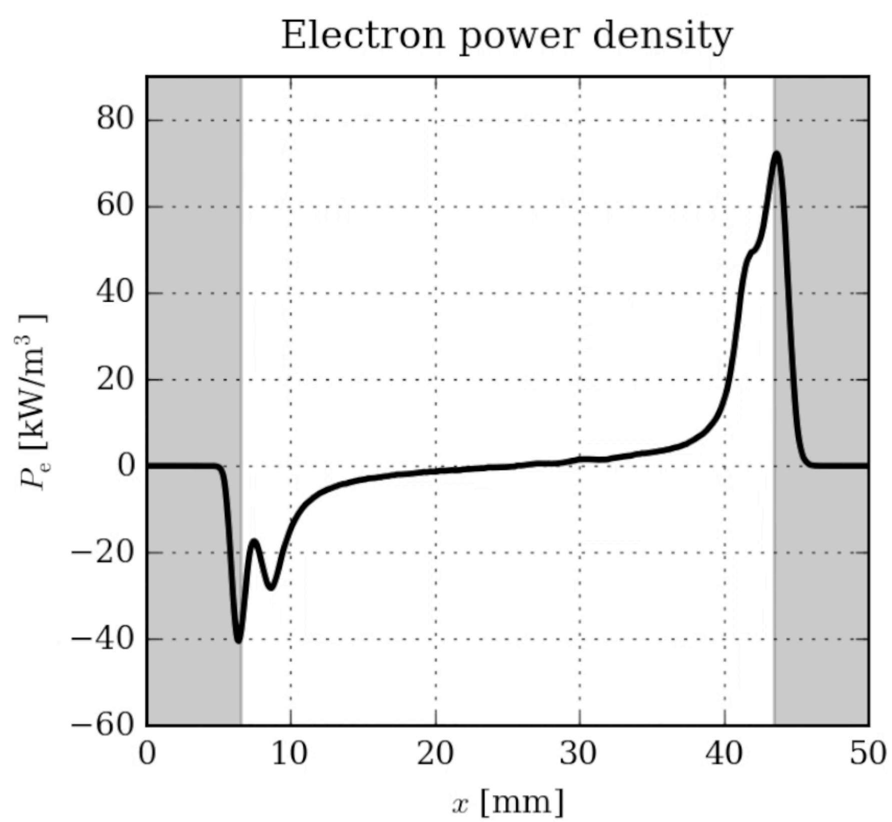
**solving for the electric field:**

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

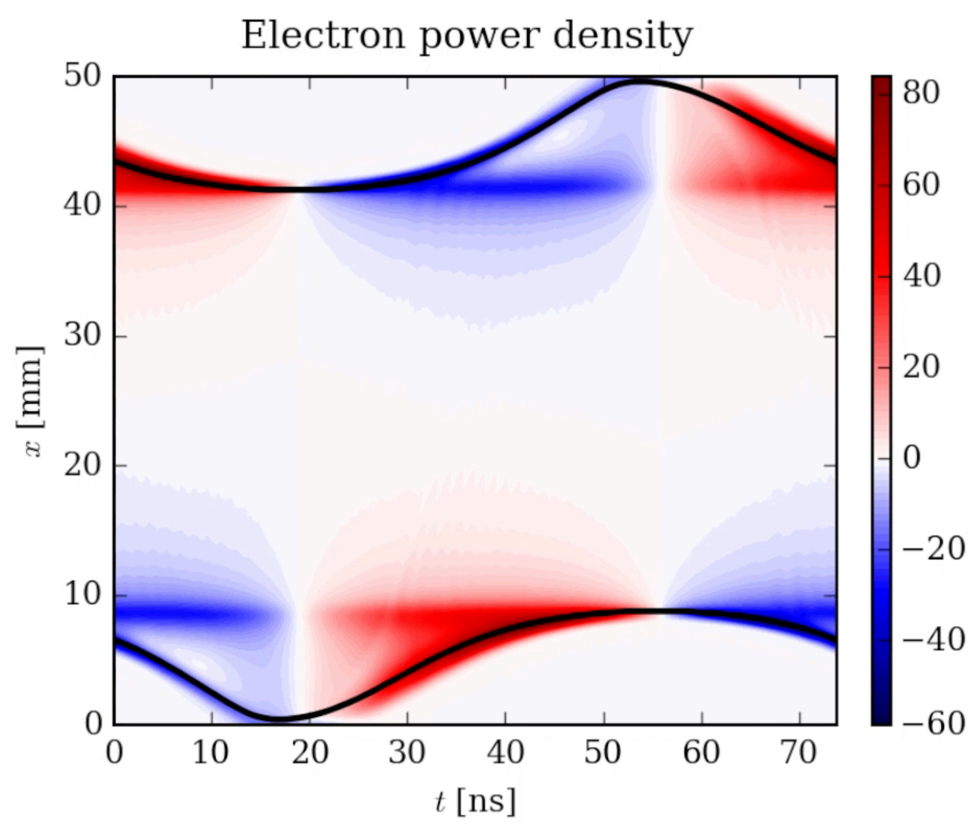


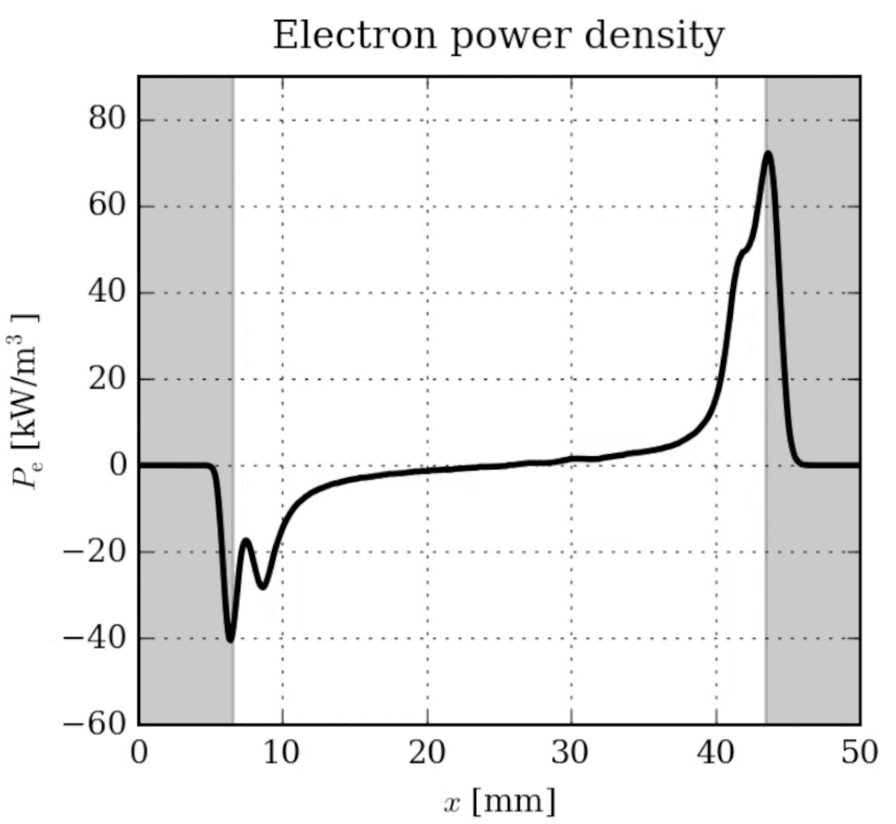



# Electron Power Absorption

**multiply by the electron current:**

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

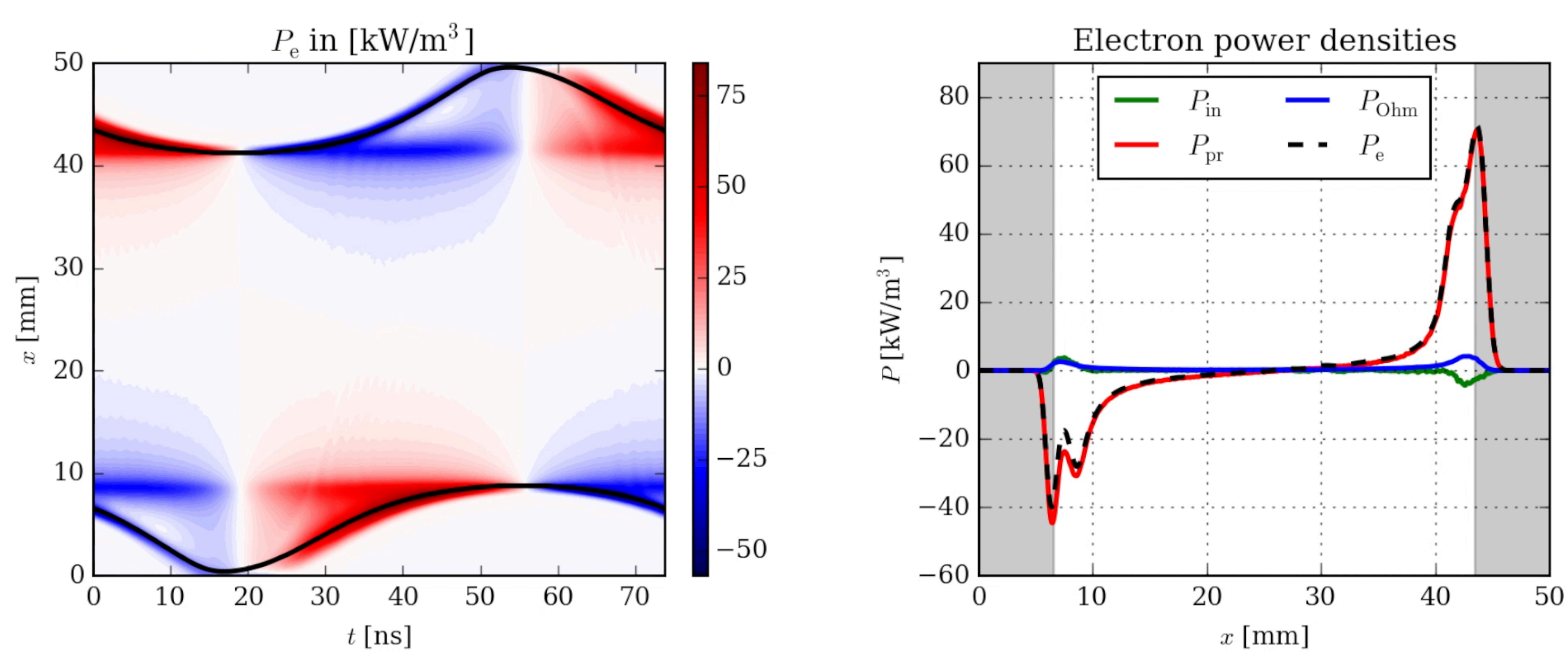


# Boltzmann Term Analysis

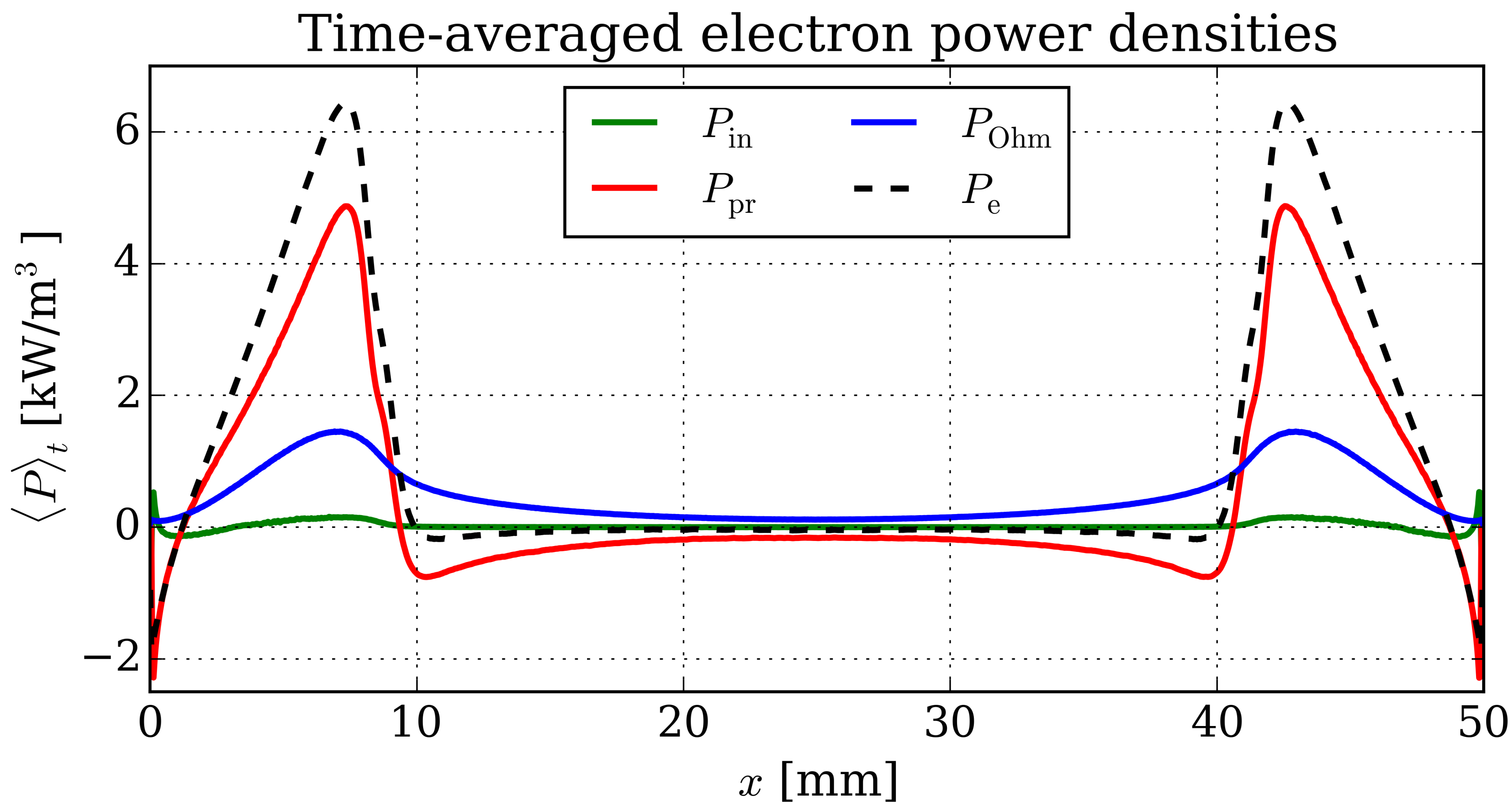
**multiply by the electron current:**

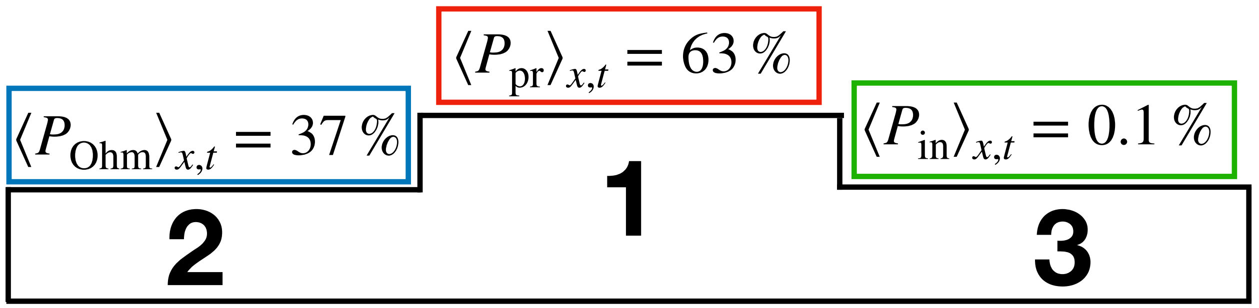
$$\underbrace{\underbrace{j_{\mathrm{e}}E}_{P_{\mathrm{e}}} = \underbrace{j_{\mathrm{e}}E_{\mathrm{in}}}_{P_{\mathrm{in}}} + \underbrace{j_{\mathrm{e}}E_{\mathrm{pr}}}_{P_{\mathrm{pr}}}}_{P_{\mathrm{collsionless}}} + \underbrace{\underbrace{j_{\mathrm{e}}E_{\mathrm{Ohm}}}_{P_{\mathrm{Ohm}}}}_{P_{\mathrm{collisional}}}$$



# Boltzmann Term Analysis





# Mechanism of Electron Power Absorption

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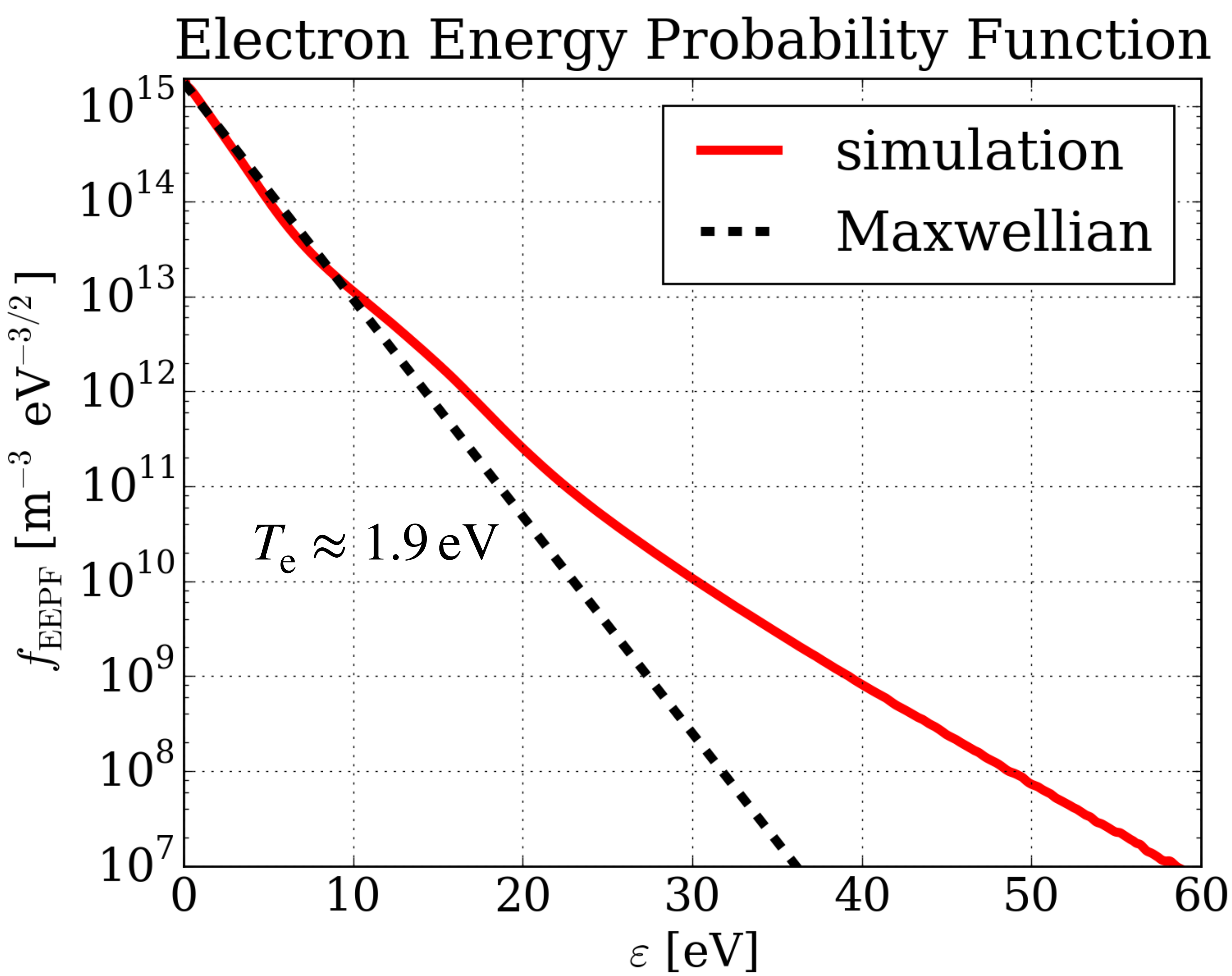
**more information about the electron power absorption by Máté Vass**

**Session PW2: Capacitively Coupled Plasmas II**
1:00 PM–2:30 PM, Wednesday, October 7, 2020

Chair: Xiaopu Li, Applied Materials

**Abstract: PW2.00001 : Electron power absorption in capacitive RF plasmas based on a moment analysis of the Boltzmann equation**
1:00 PM–1:30 PM Live

# Electron Temperature




- electron temperature (thermodynamic relation): $T_e = \frac{2}{3}\langle \epsilon \rangle \approx 1.9\,\text{eV}$
- 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

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**momentum balance in x-direction (parallel):**

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

**momentum balance in perpendicular-direction:**

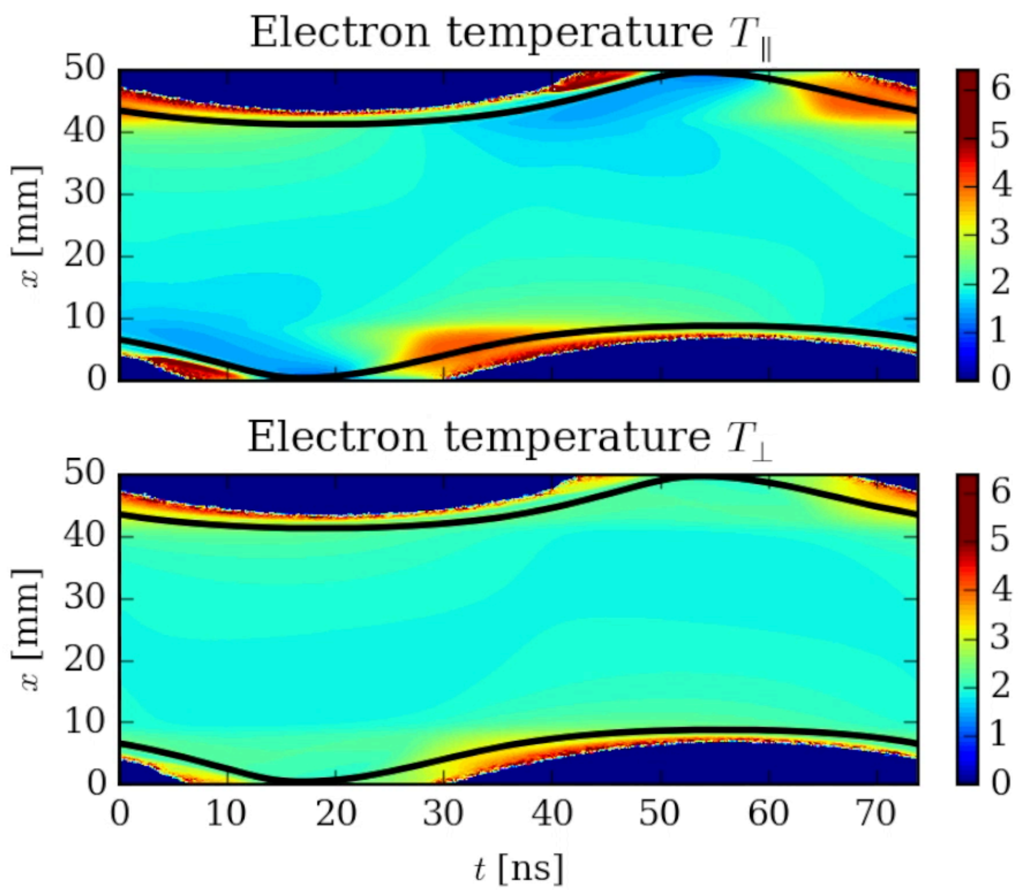
$$m_\mathrm{e}\frac{\partial(n_\mathrm{e}u_\perp)}{\partial t} + m_\mathrm{e}\frac{\partial(n_\mathrm{e}u_\perp^2)}{\partial x} + \frac{\partial(n_\mathrm{e}T_\perp)}{\partial x} = -en_\mathrm{e}E_\perp - \Pi_{\mathrm{c}\perp}$$

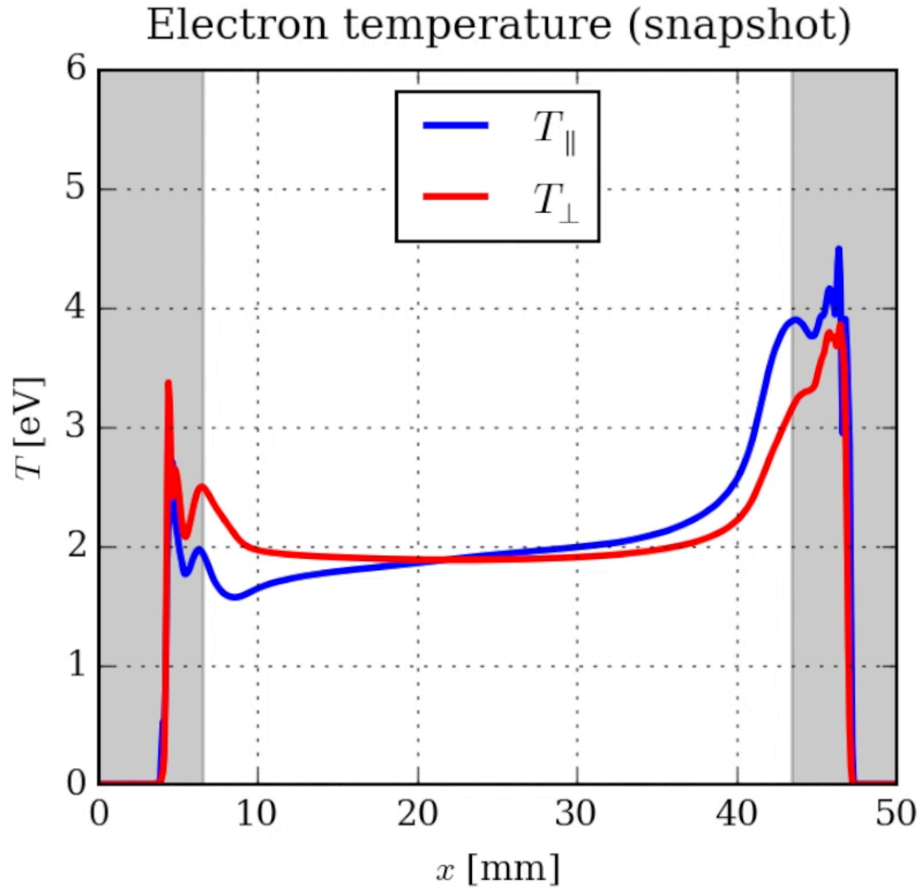
**the parallel and perpendicular temperature communicate via collisions**

# Electron Temperature

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

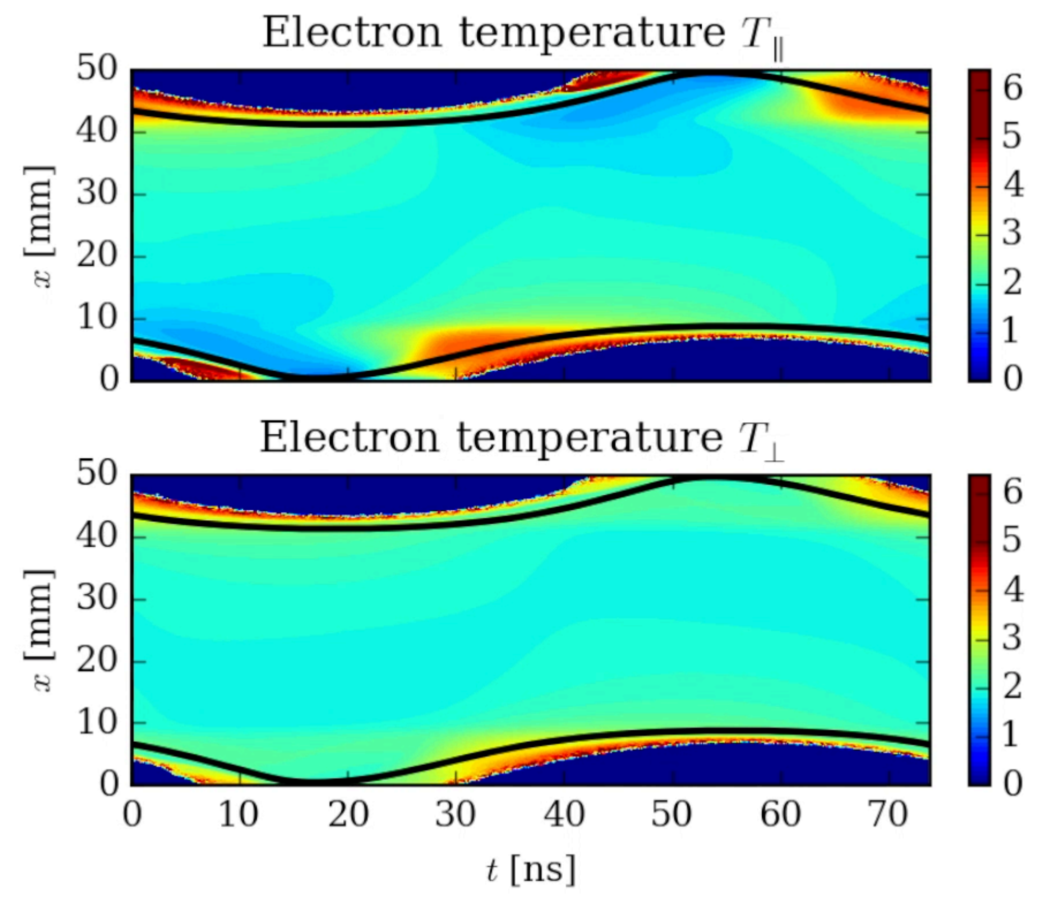
$$T_{\perp} = \frac{p_{\perp}}{n_{\mathrm{e}}} = m_{\mathrm{e}}\left( < v_{\perp}^2(x,t) > - u_{\perp}^2(x,t)\right)$$

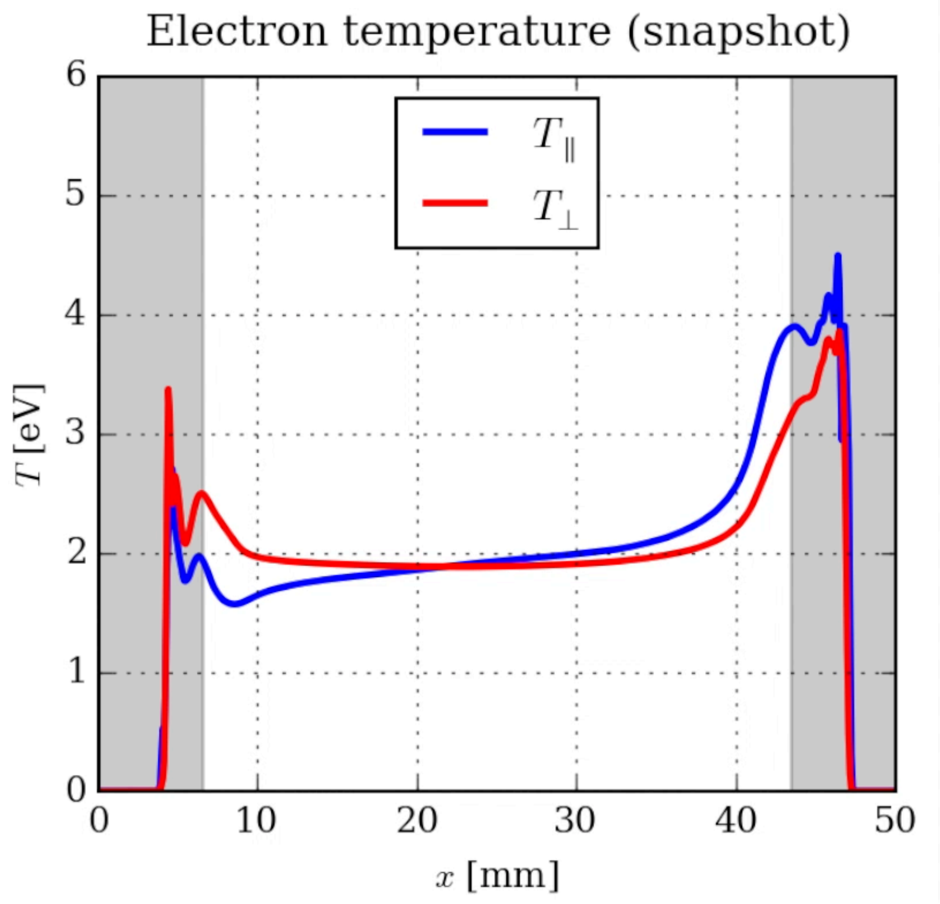


# Electron Temperature

- 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

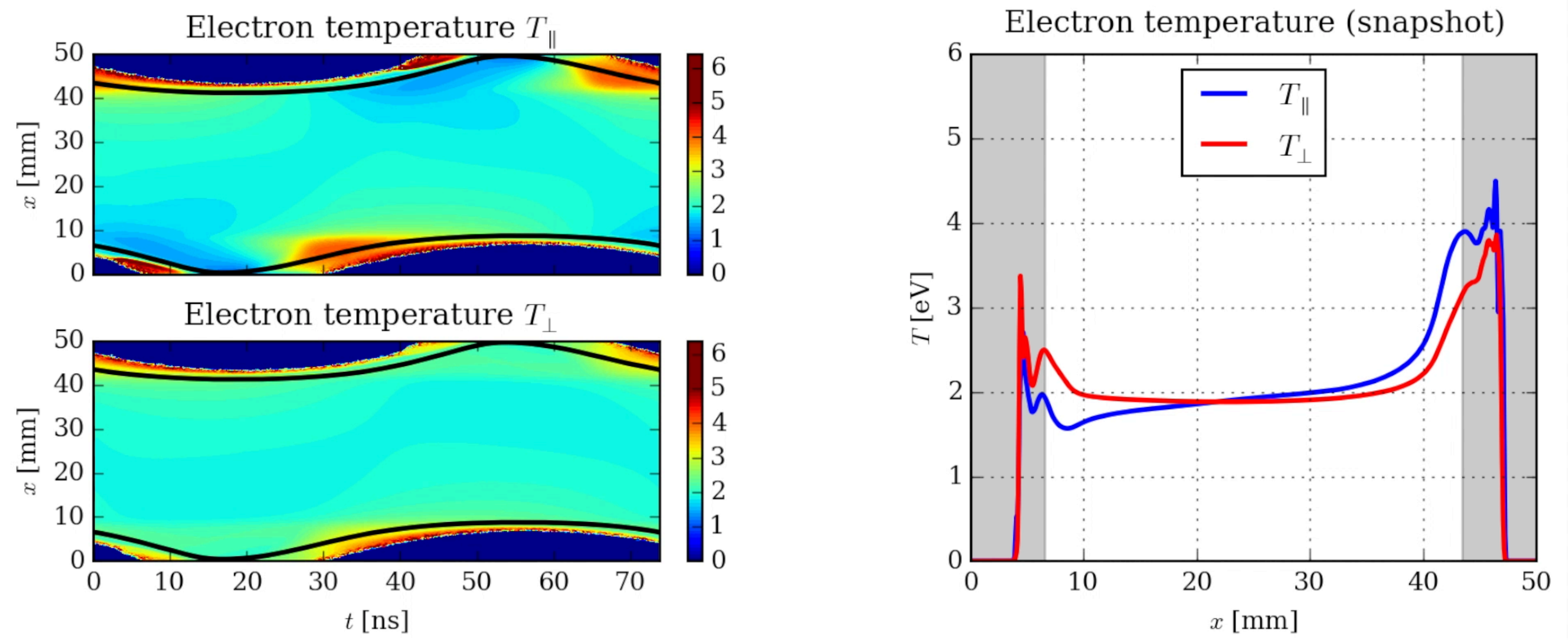


# Electron Temperature

- 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

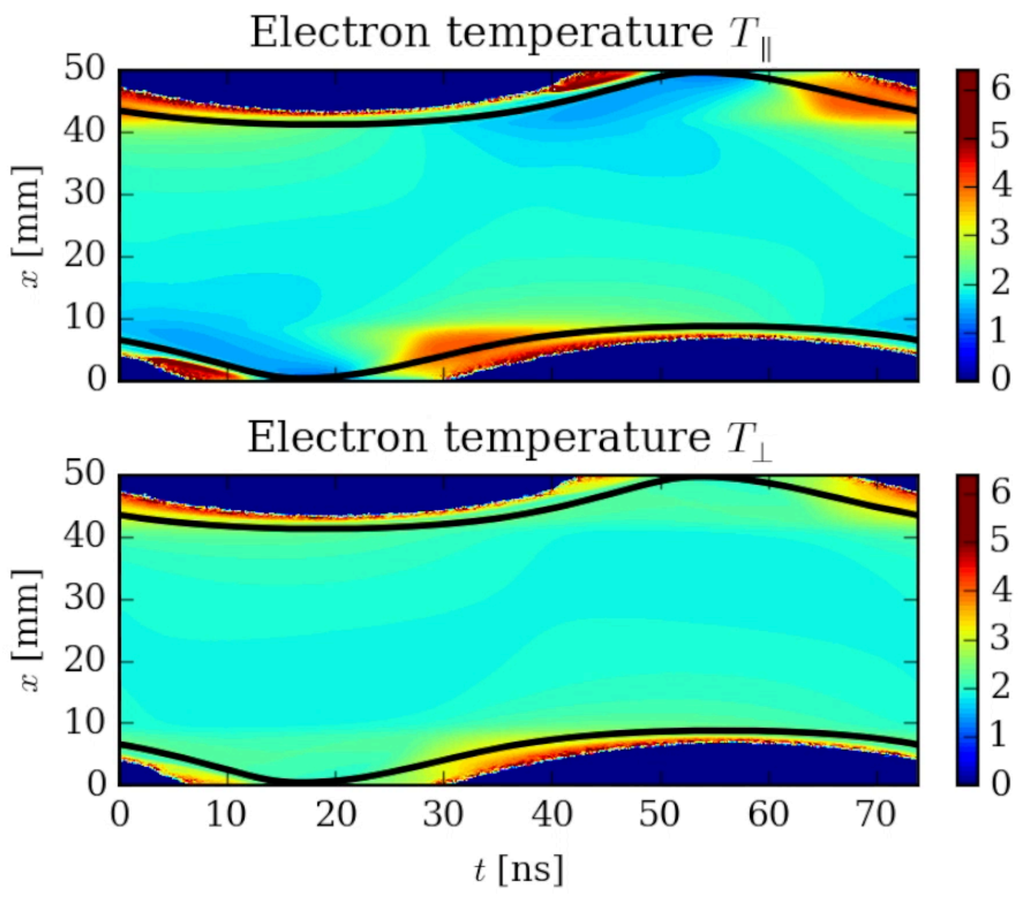
$$w = \frac{1}{2} n_e (m_e u_\parallel^2 + T_\parallel + 2T_\perp)$$

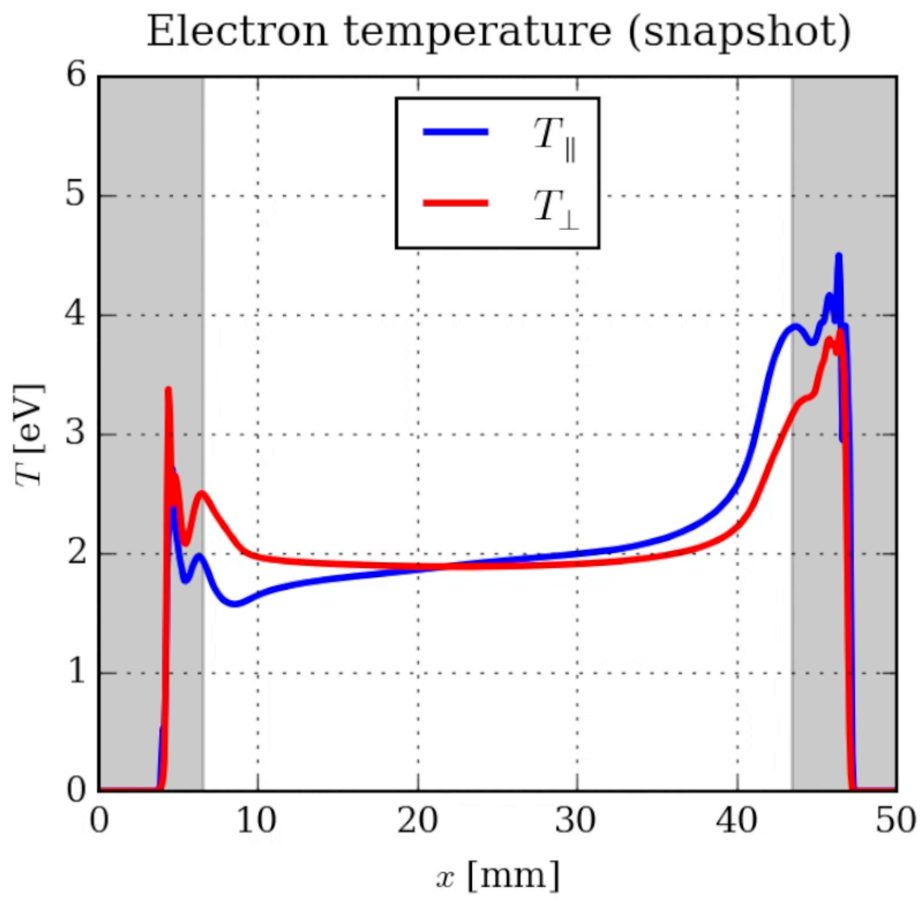


# Electron Temperature

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



# Conclusion

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- 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

**Poster Session Today:**

**Abstract: LT2.00023 : Basic research of electron dynamics in low pressure capacitively coupled plasmas**