The Influence of Electron Inertia in Low Pressure Capacitively Coupled Plasmas

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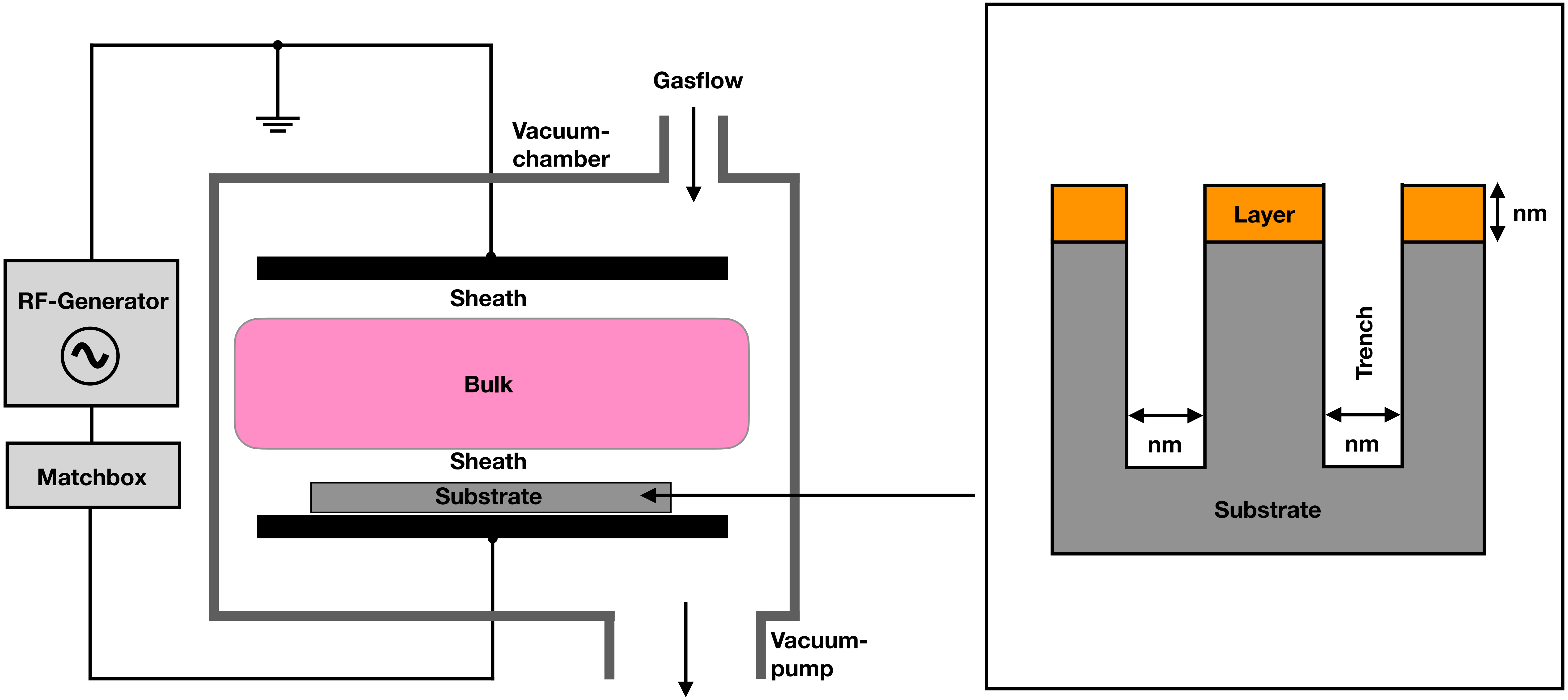
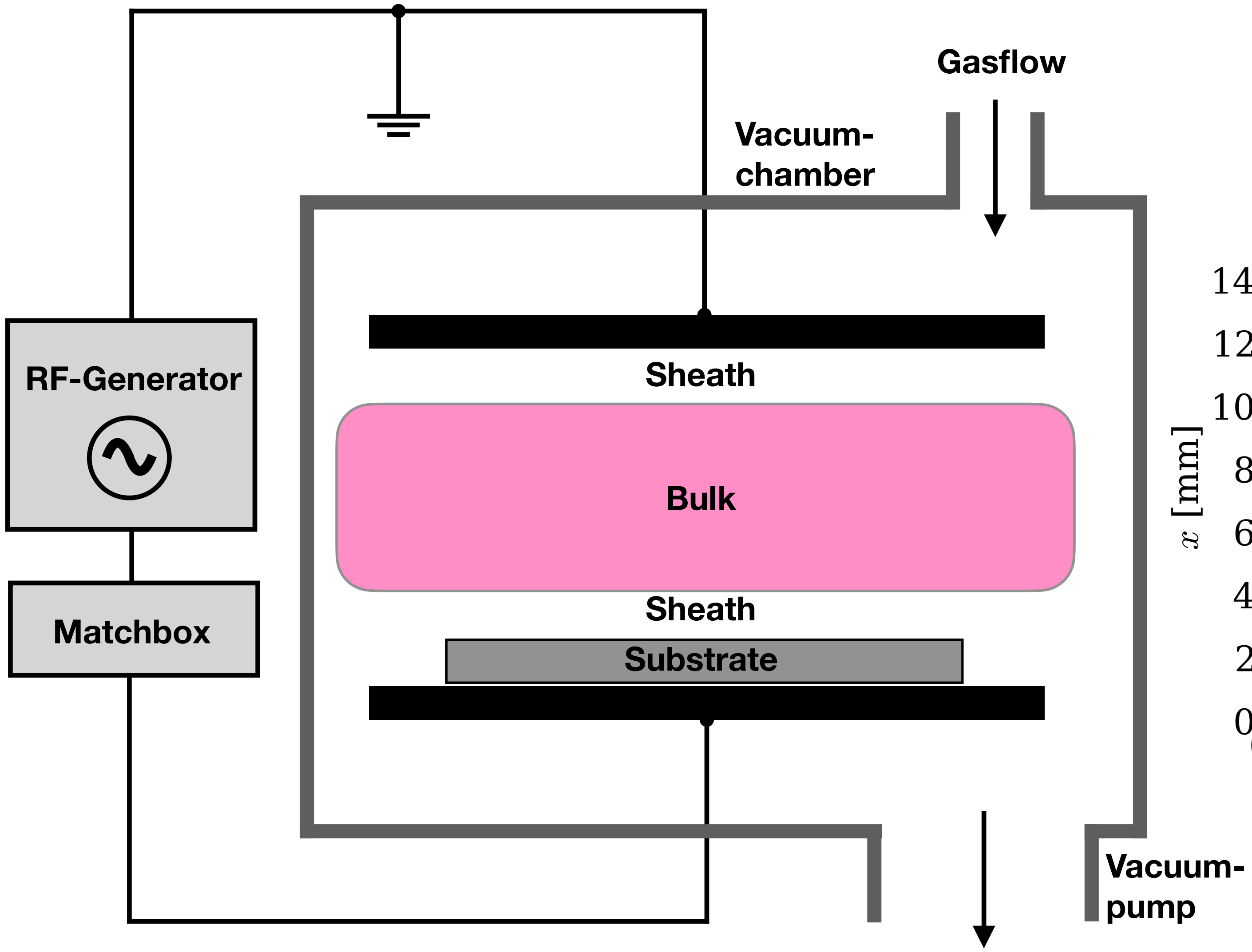
Motivation: CCRF Discharge

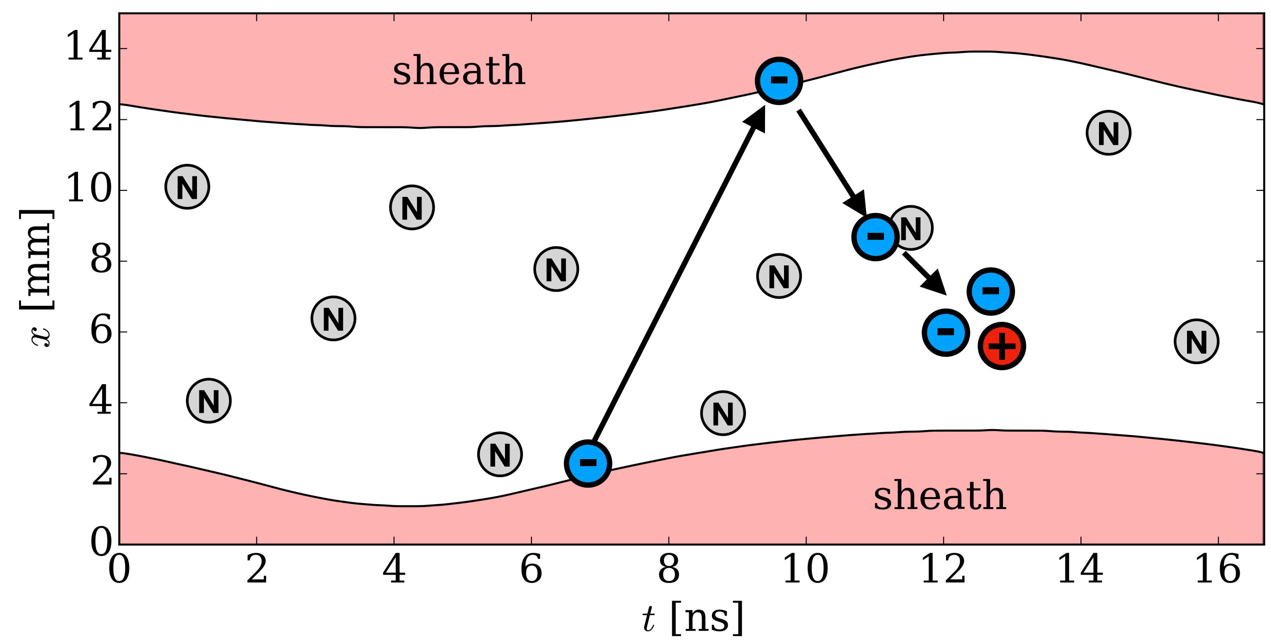


- classical CCRF discharges for etching and deposition processes
- both processes reach the precision of single atomic layers
- requires a fundamental understanding of the particle dynamics in order to obtain a much better process control

Motivation: Electron Dynamics

RUB

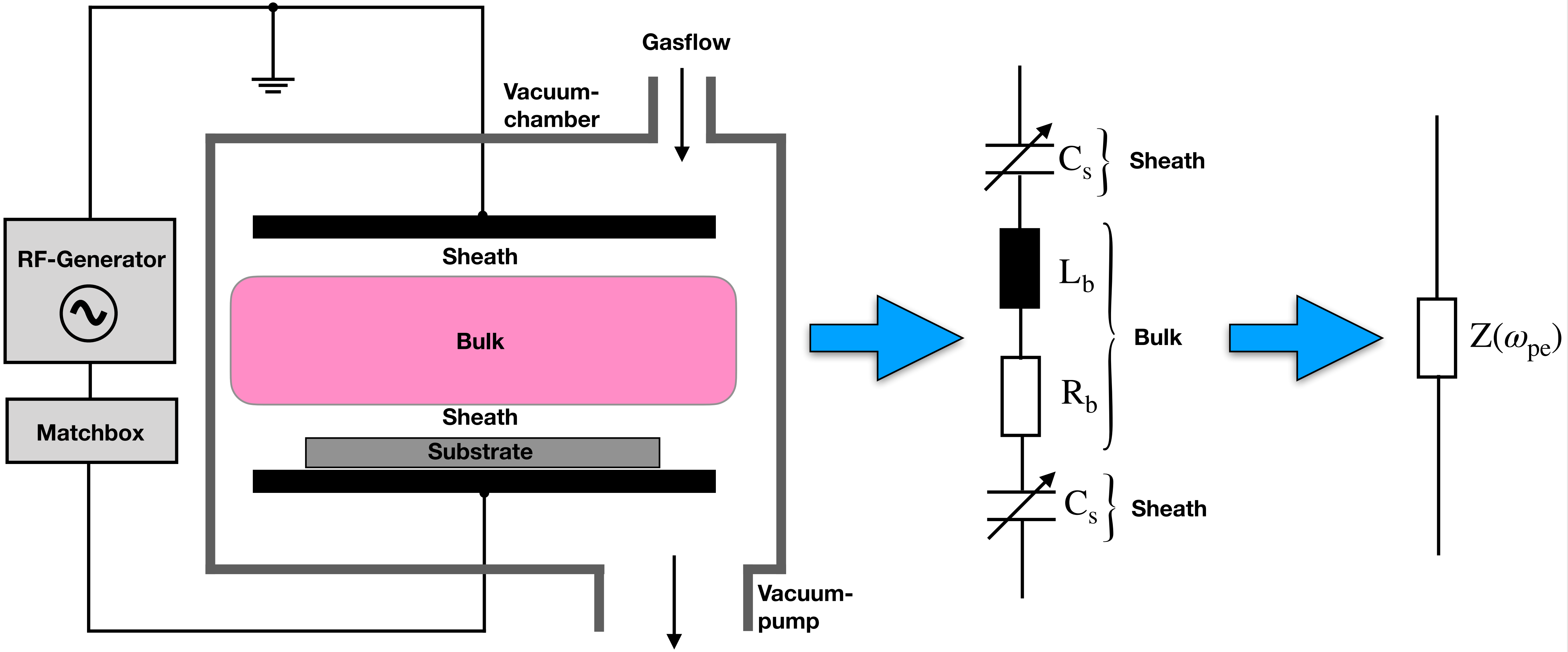




- control of the electrons in order to optimize ionization and generation of radicals
- operated at low pressure conditions ($p < 10$ Pa) in the so called nonlocal regime
- electrons move a certain distance collisionlessly through the plasma bulk
- at the same time, nonlinear dynamics can significantly influence the plasma

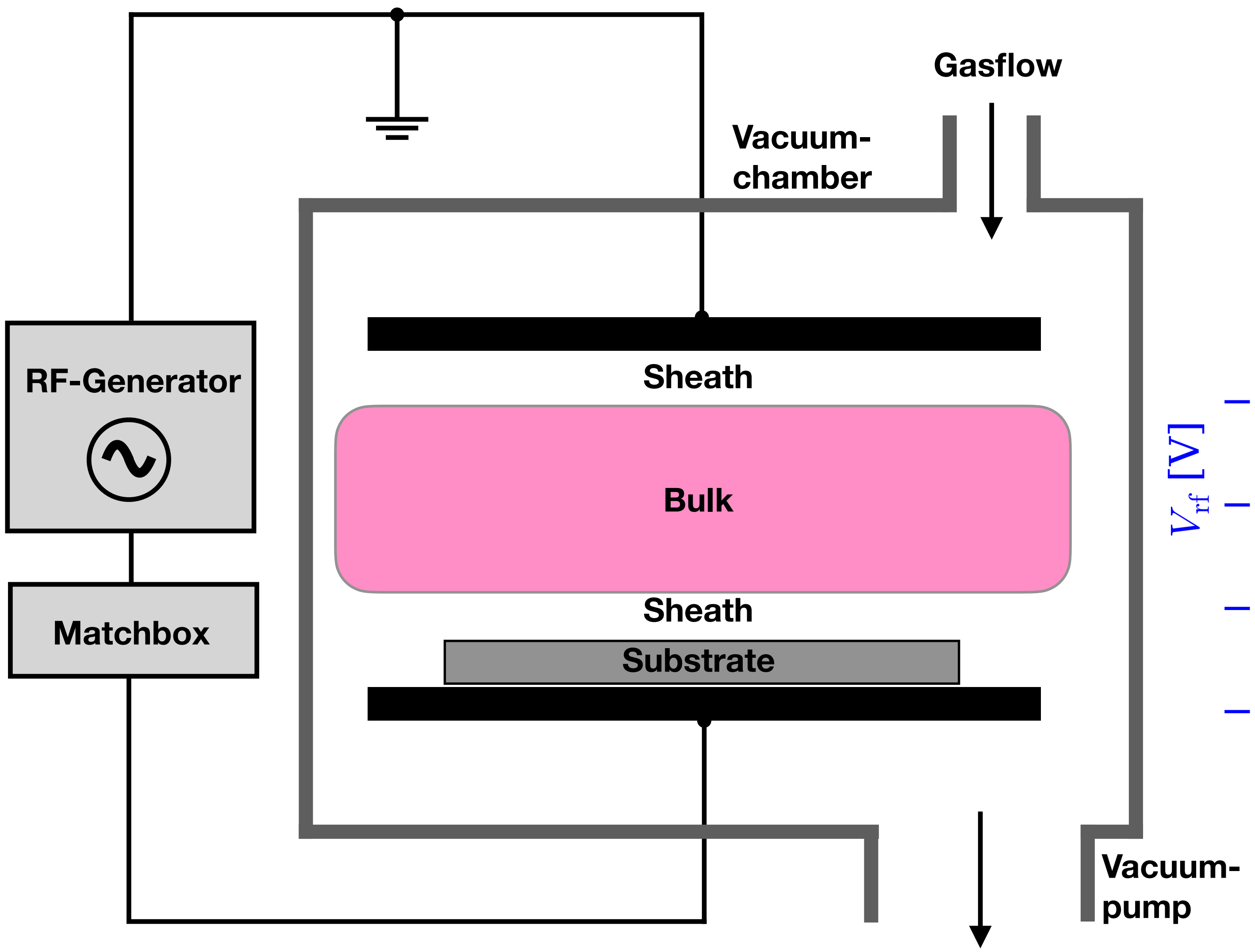
What does it mean?

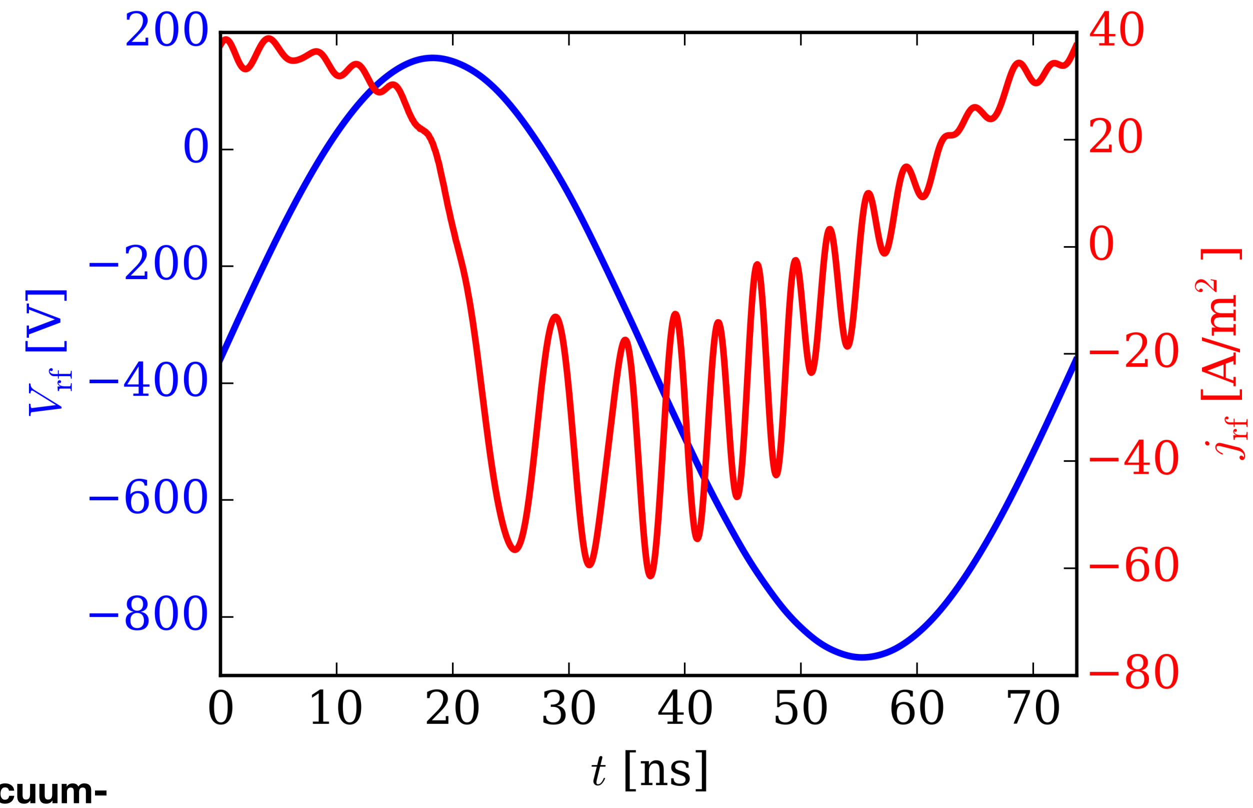
Motivation: Nonlinear Dynamics



- the plasma can be described by a series of lumped elements
- which consists of two nonlinear capacitors, an inductor and a resistor
- makes the plasma to a highly complex system, resonances can be excited
- the most well known resonance is the plasma series resonance (PSR)

Motivation: Nonlinear Dynamics





- rf voltage and current can be measured easily at the driven electrode
- pronounced nonlinear relation between both quantities
- related to the excitation of the PSR
- these dynamics play also an important role in the upcoming talks of this session

Goal of this Work

1. **How important are these rf current oscillations (PSR) in the low pressure regime of geometrically symmetric and asymmetric capacitively coupled radio frequency discharges?**

2. **What is the role of electron inertia and how does it influence the electron power absorption (electron heating)?**

What do we need?

RUB

full momentum balance (no approximations):

$$m_\mathrm{e}\left(\frac{\partial(n_\mathrm{e}u)}{\partial t} + \nabla\cdot(n_\mathrm{e}u^2)\right) = -en_\mathrm{e}E - \nabla p_e - \Pi_\mathrm{c}$$

- obtained by the first velocity moment of the Boltzmann equation
- fundamental equation for theoretical models (Boltzmann-equilibrium) and fluid simulations (drift-diffusion approach)
- however, in these models critical approximations are done
- especially, the inertia terms are usually neglected
- using 1d3v PIC/MCC simulations, these terms can be calculated self-consistently

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solving for the electric field:

$$E = \underbrace{-\frac{m_\mathrm{e}}{n_\mathrm{e}}\left(\frac{\partial(un_\mathrm{e})}{\partial t} + \nabla\cdot(n_\mathrm{e}u^2)\right)}_{E_\mathrm{in}} \underbrace{-\frac{1}{en_\mathrm{e}}\nabla p_e}_{E_\mathrm{pr}} \underbrace{-\frac{1}{n_\mathrm{e}e}\Pi_\mathrm{c}}_{E_\mathrm{Ohm}}$$

multiply by the electron current:

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

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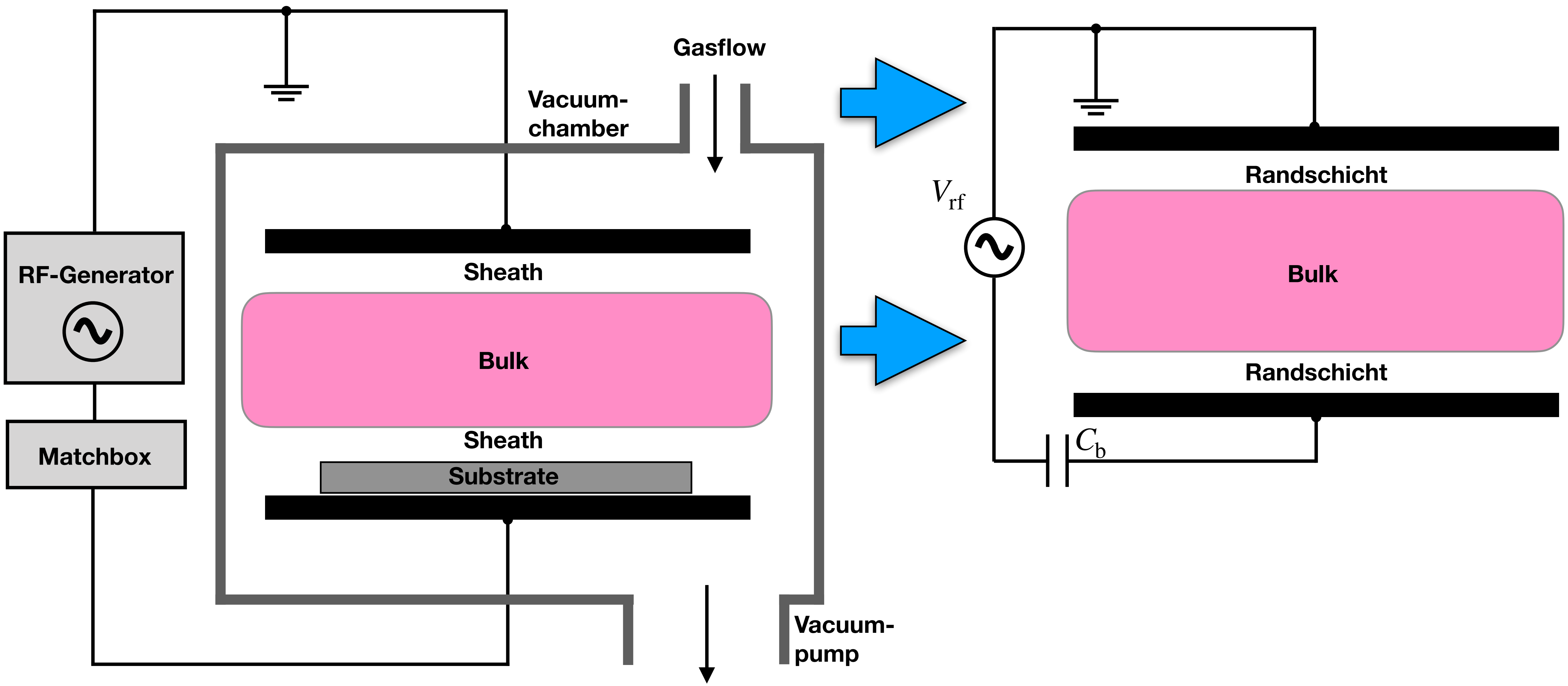
Analysis in symmetric CCRF discharges



- 1d3v PIC/MCC simulation
- planar, parallel and infinite electrodes
- argon gas pressure: 0.5 - 10 Pa
- no surface models

- gap size: 70 mm
- driving frequency: 13.56 MHz
- voltage amplitude: 700 V

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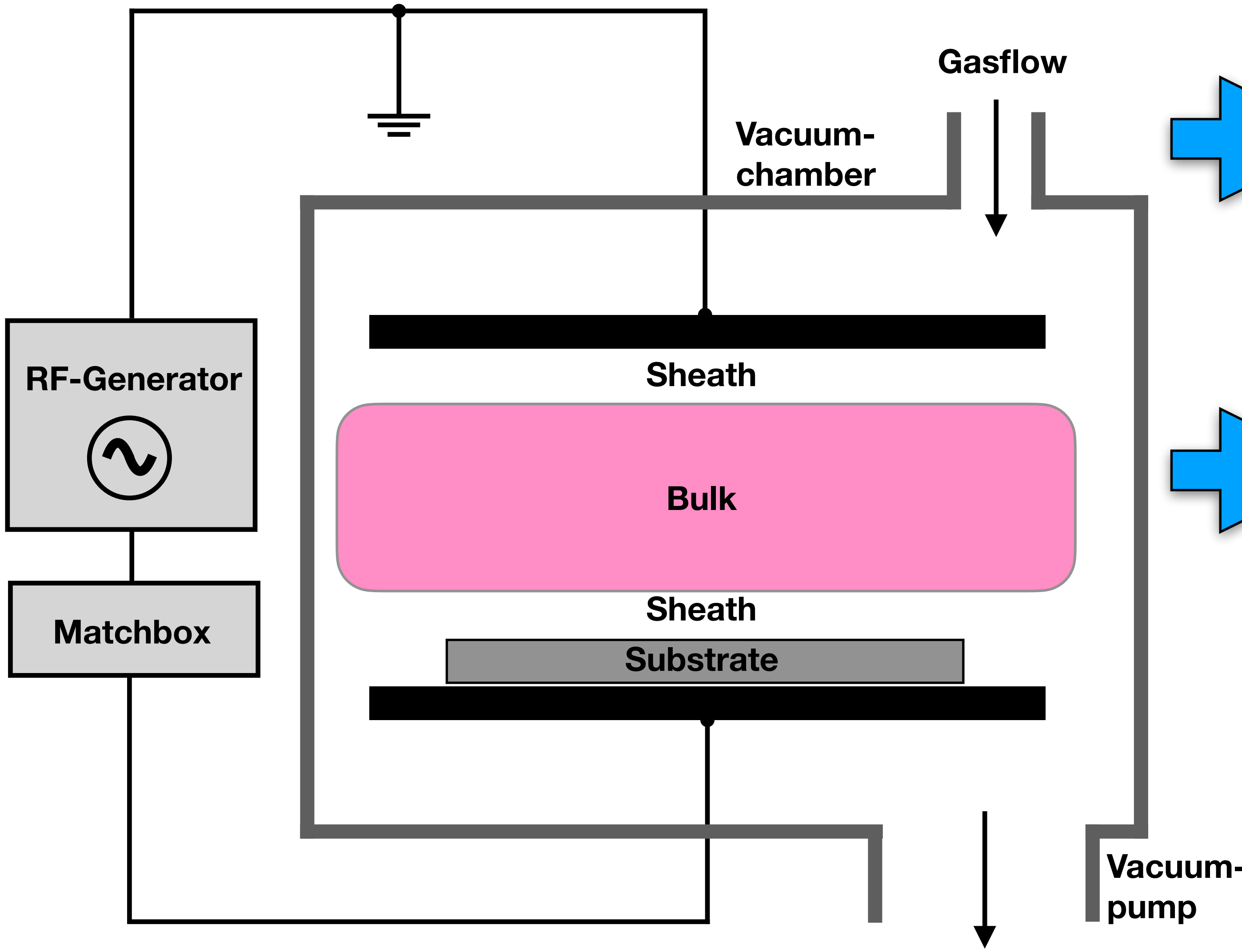
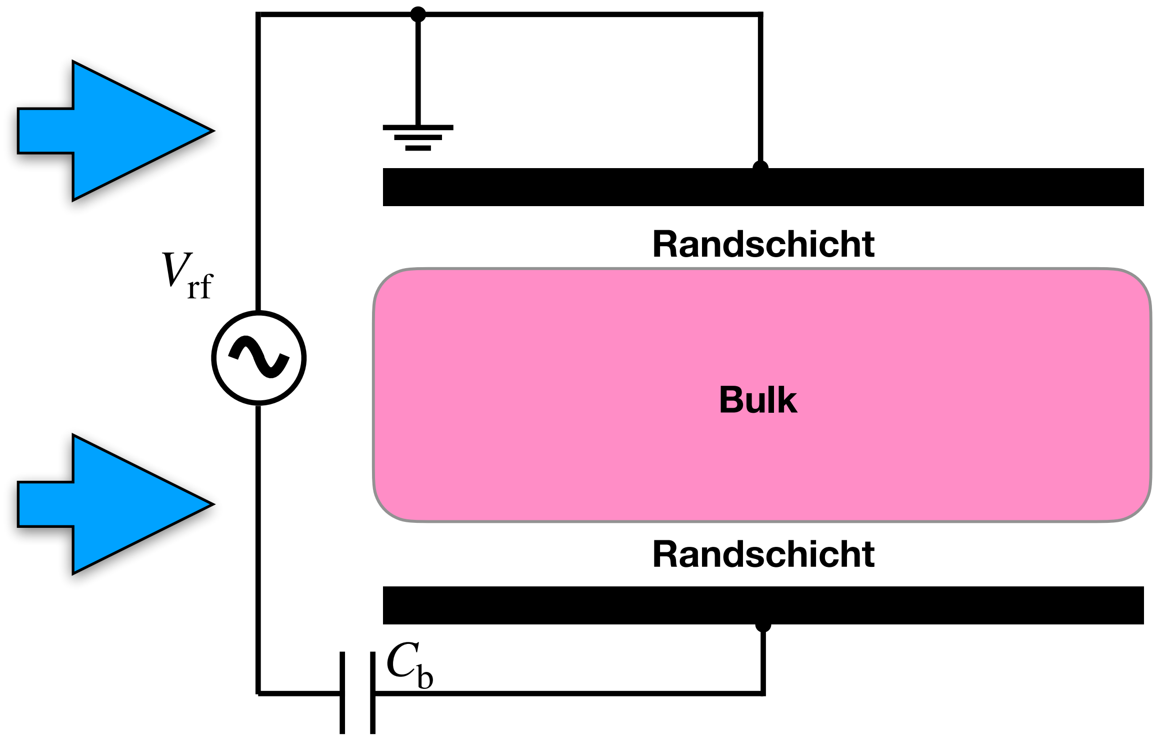
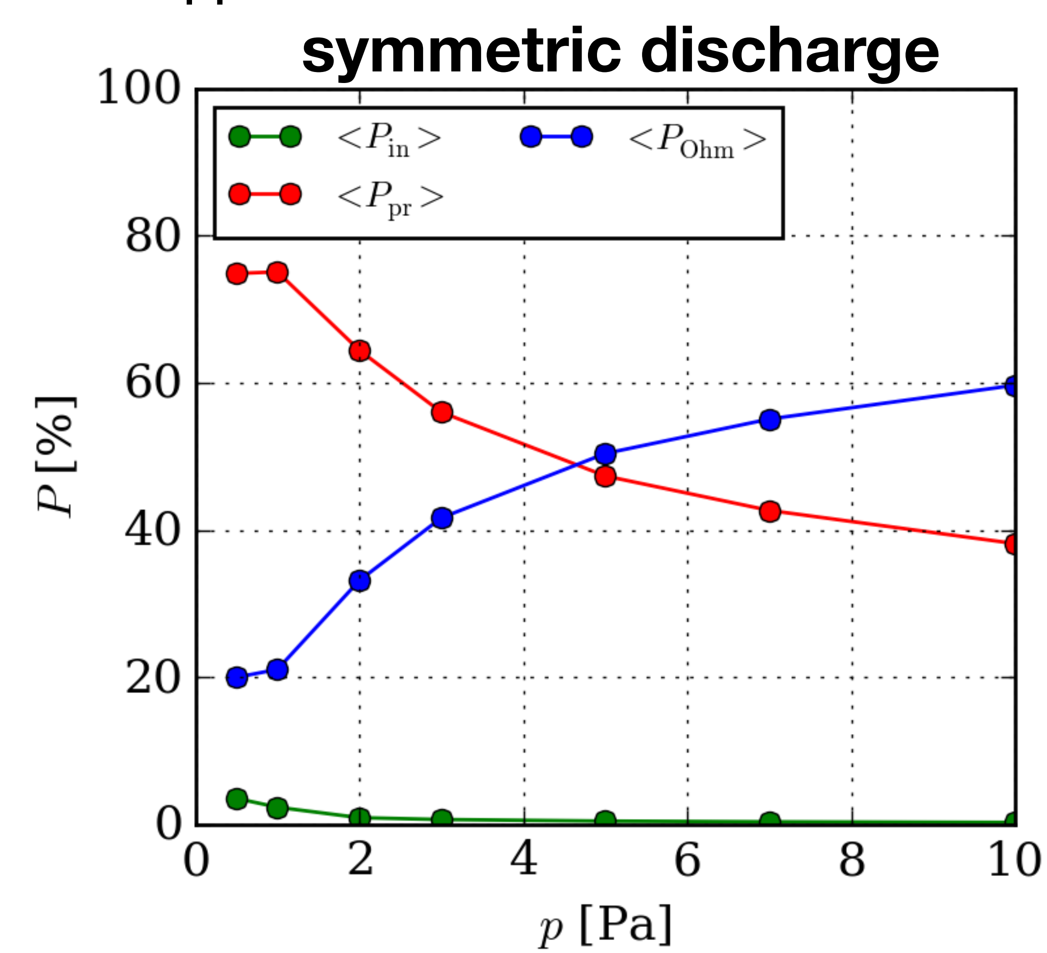
Analysis in symmetric CCRF discharges







J. Schulze et al., Plasma Sources Sci. Technol., 27, 055010 (2018)
M. Vass et al., Plasma Sources Sci. Technol., 29, 085014 (2020)
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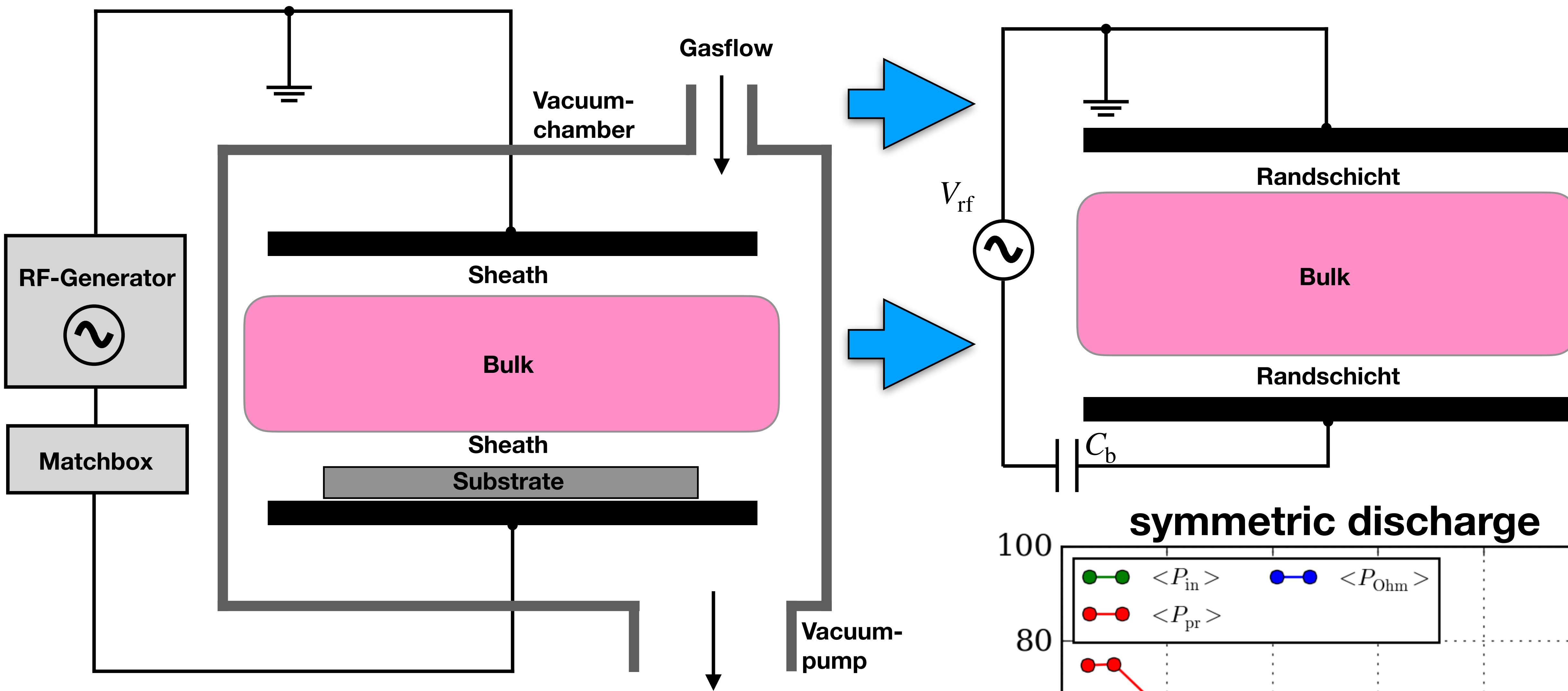

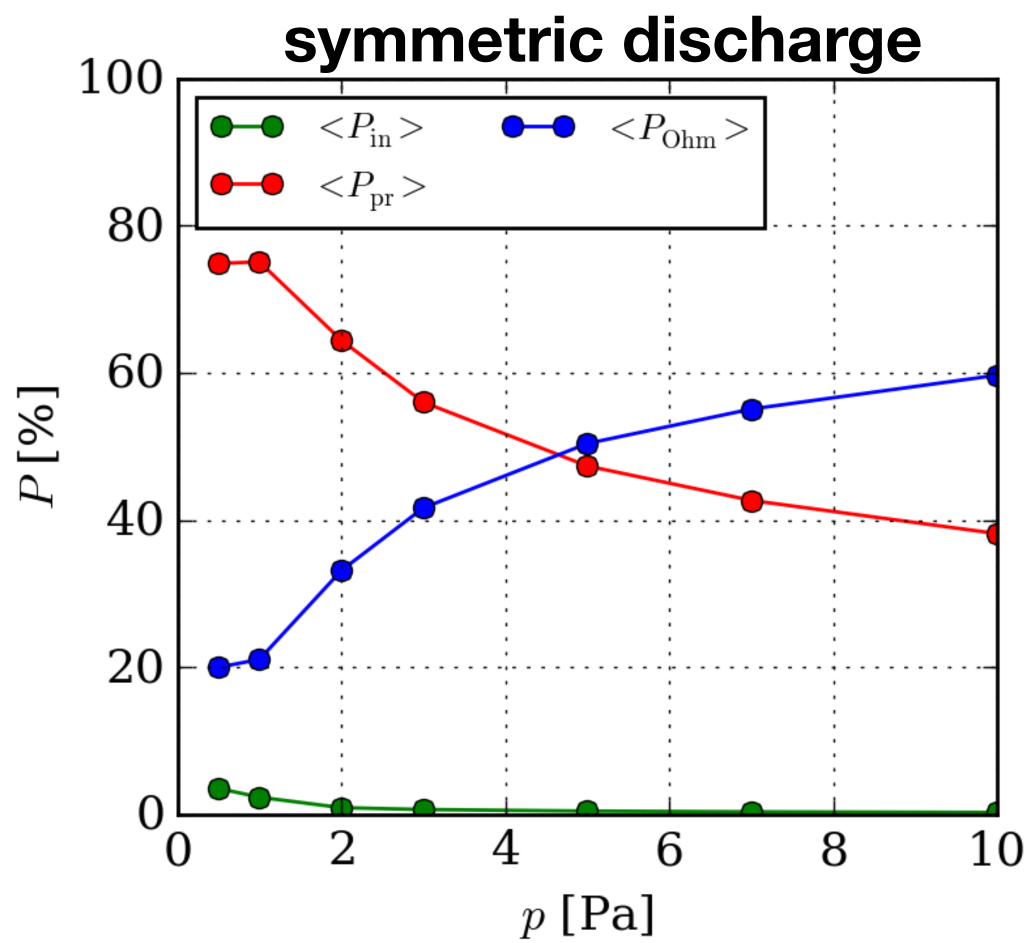

However, technological CCRF discharges are frequently geometrically asymmetric!

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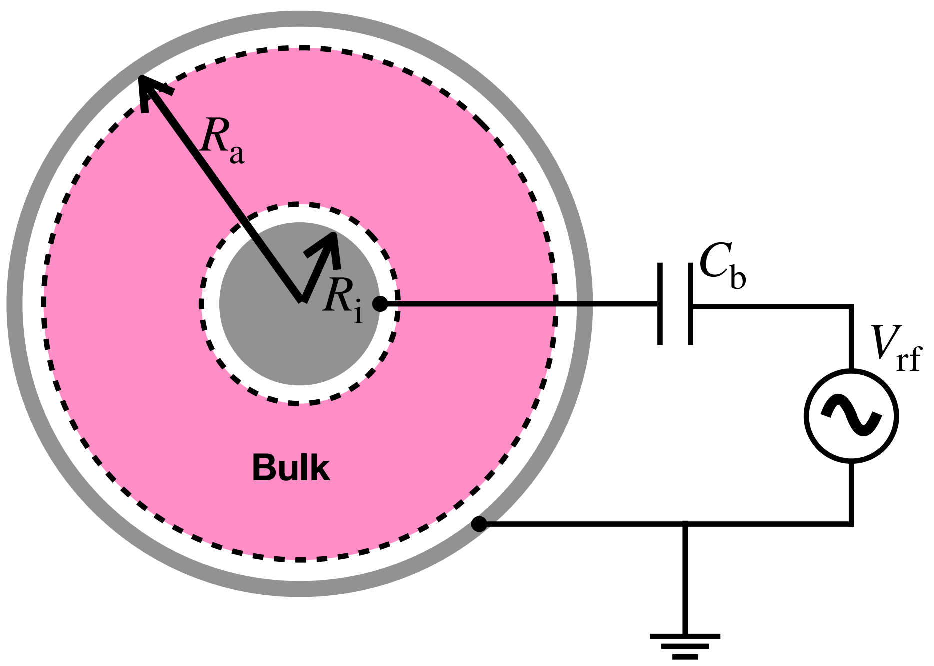
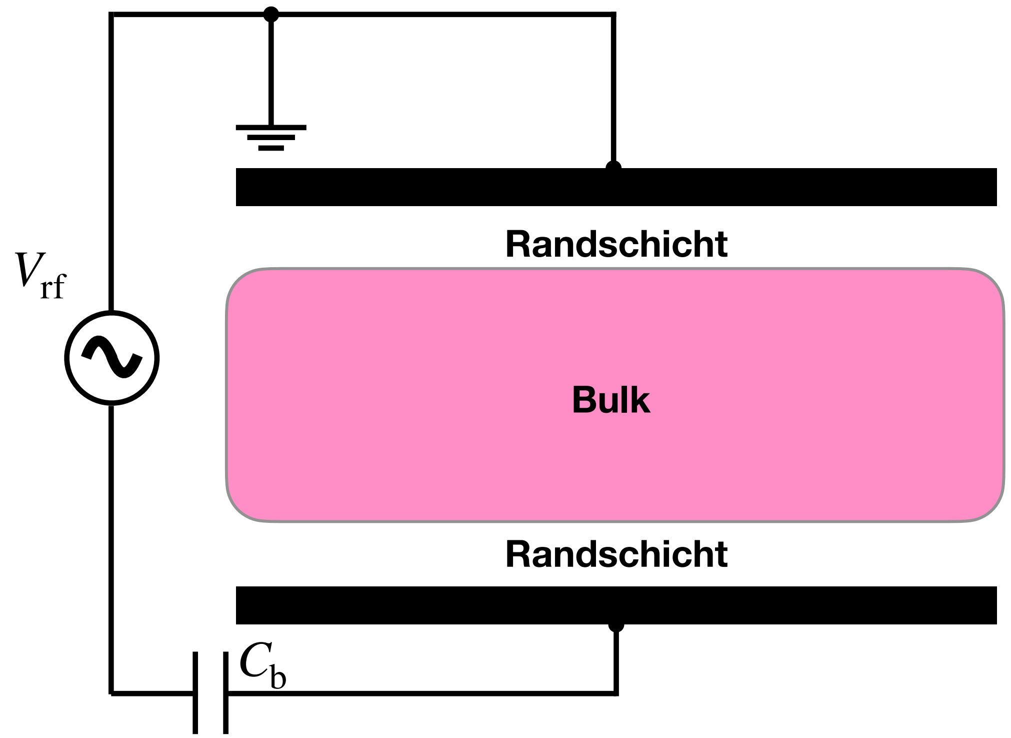
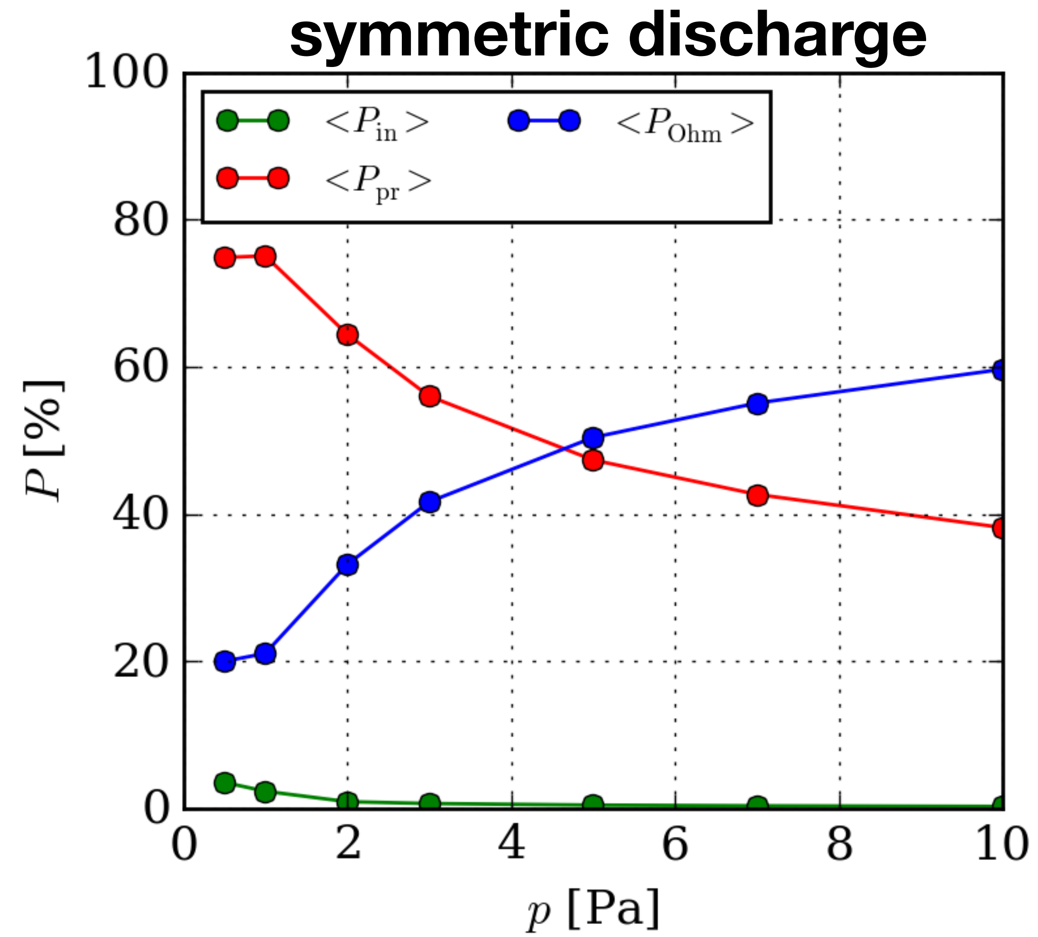
Asymmetric vs. symmetric discharge



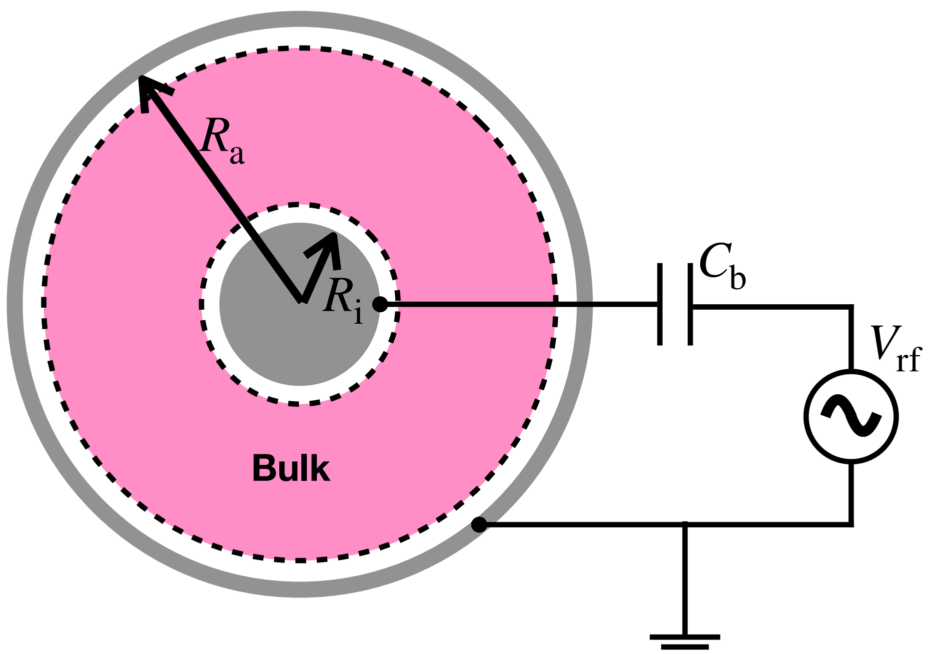


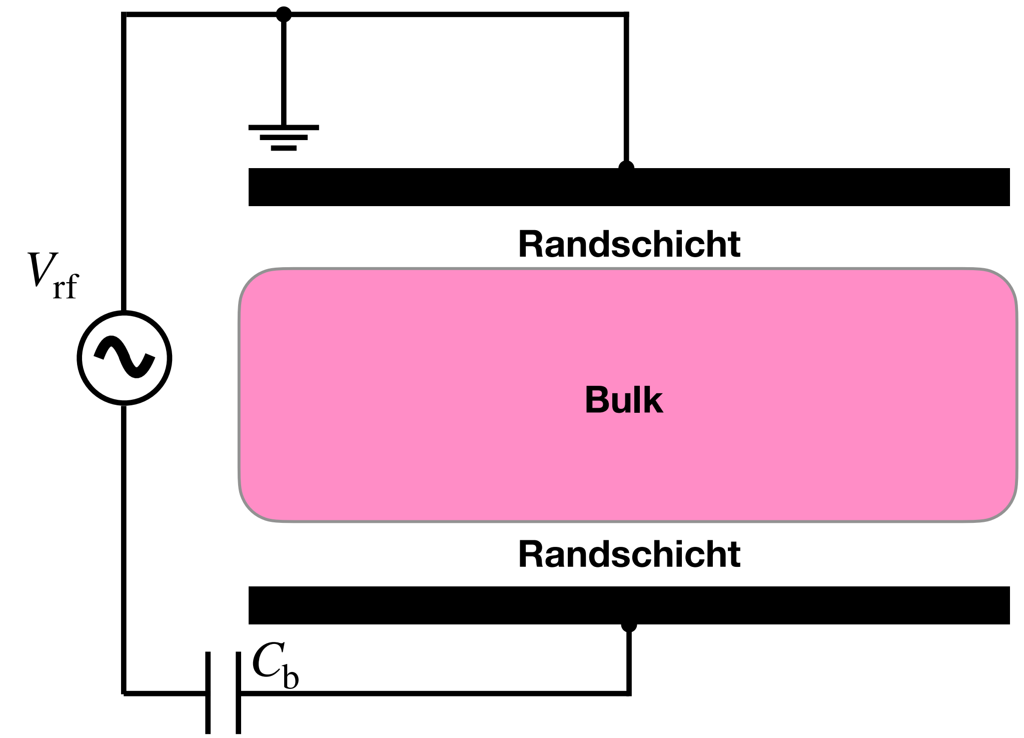
- infinitely extended cylinder
- inner (powered) and outer (grounded) electrode, Ag/Ap = 7/2
- same discharge conditions (70 mm, 700 V, 13.56 MHz)



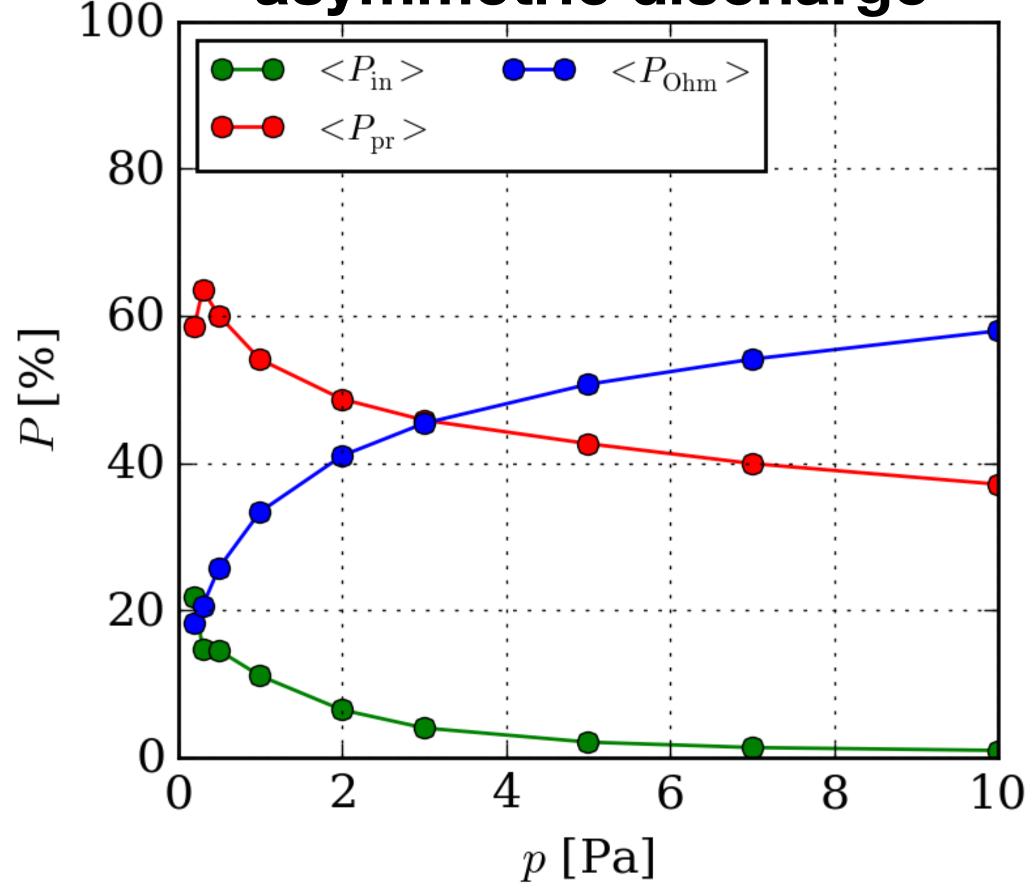
Asymmetric vs. symmetric discharge

RUB

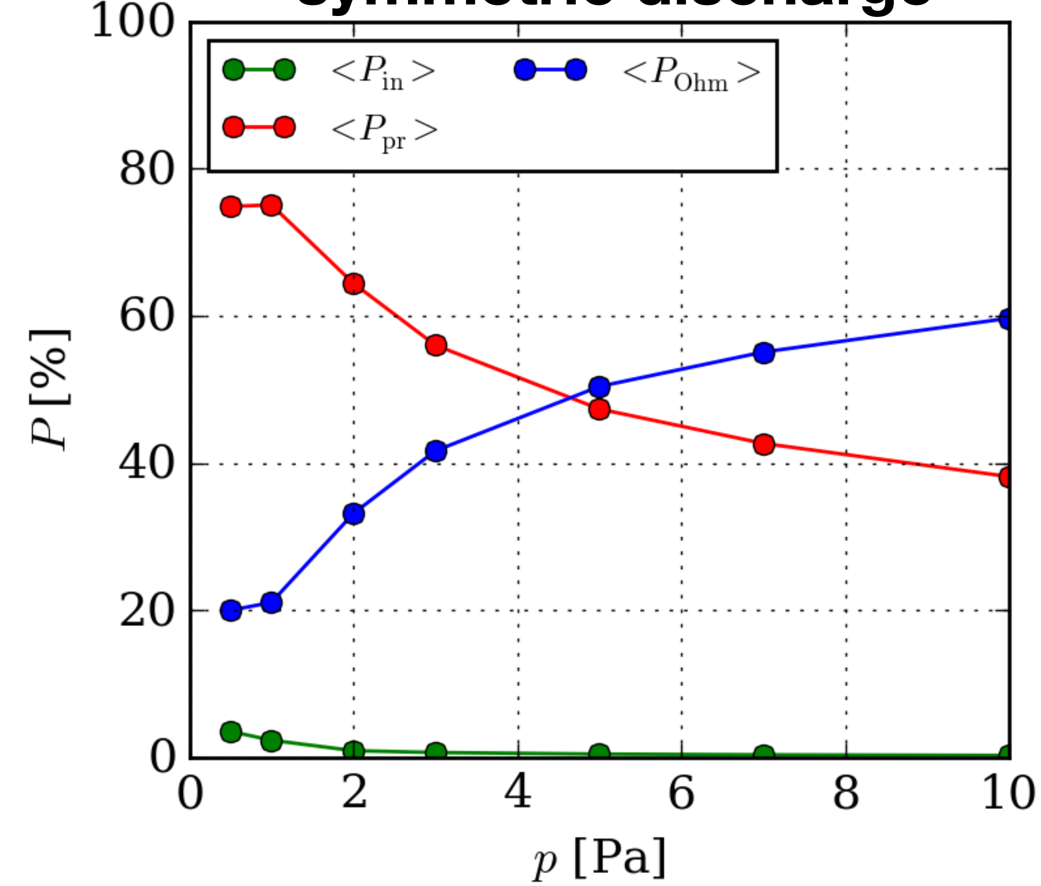




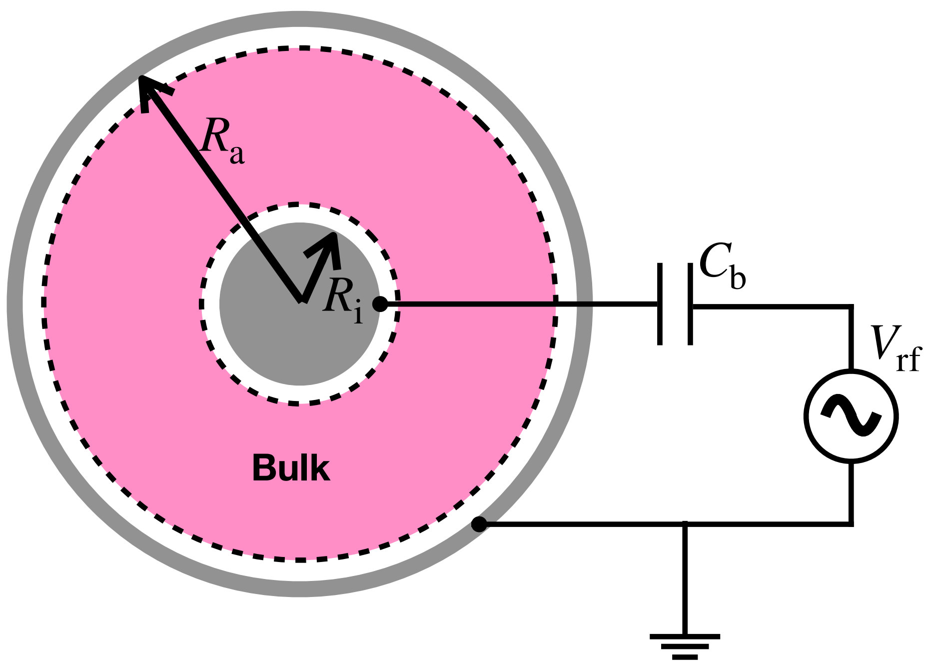
asymmetric discharge

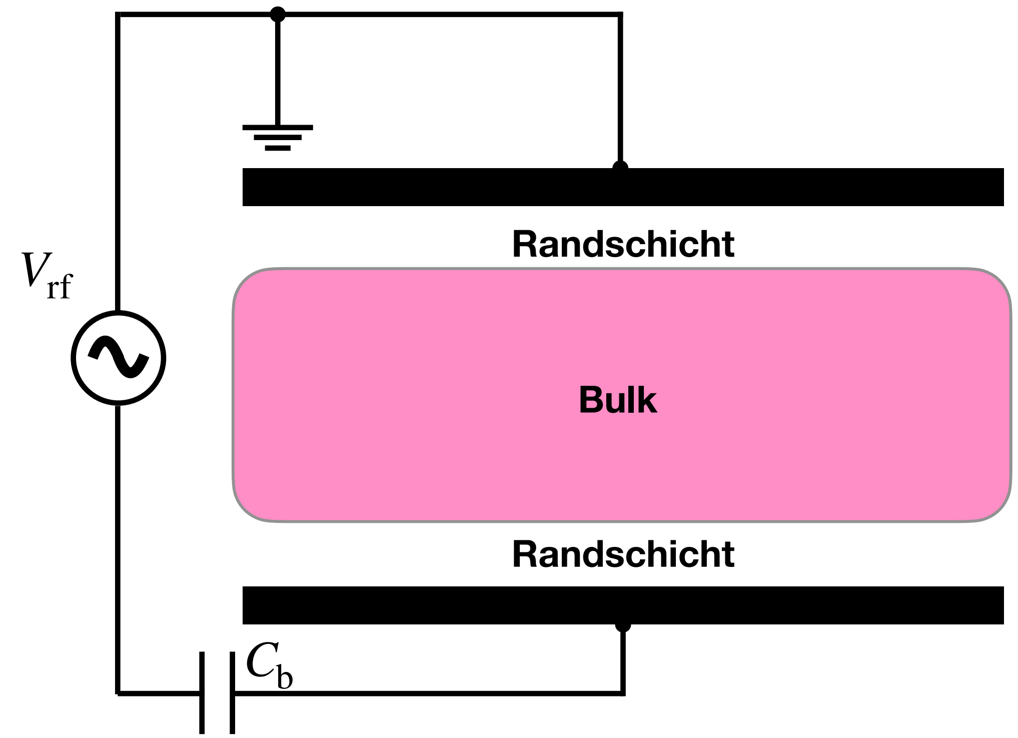


symmetric discharge

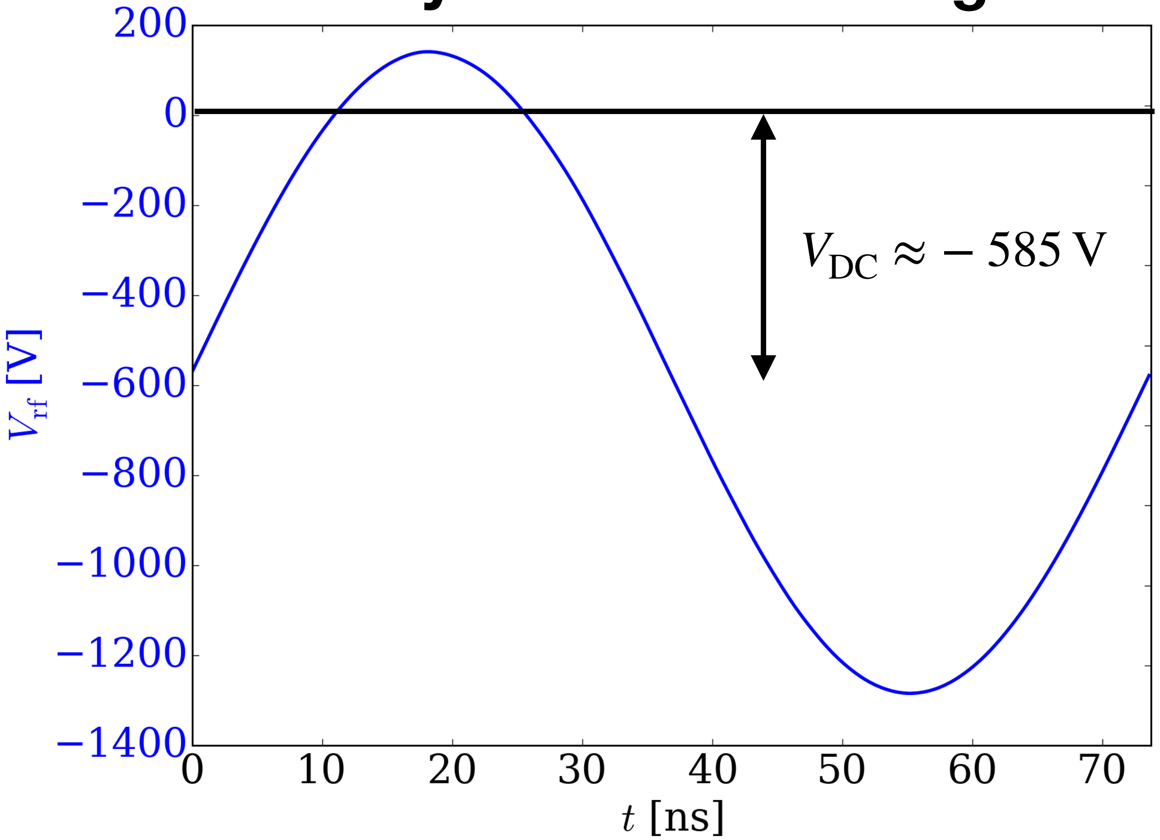


Asymmetric vs. symmetric discharge

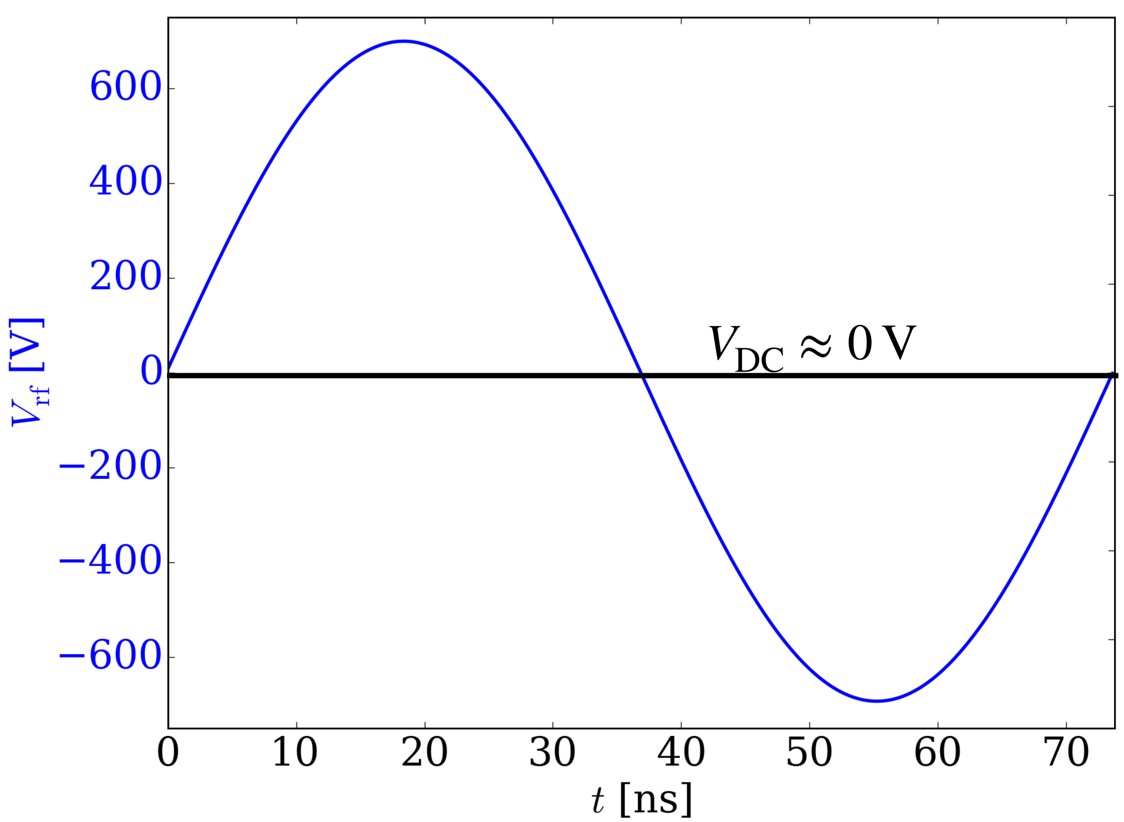




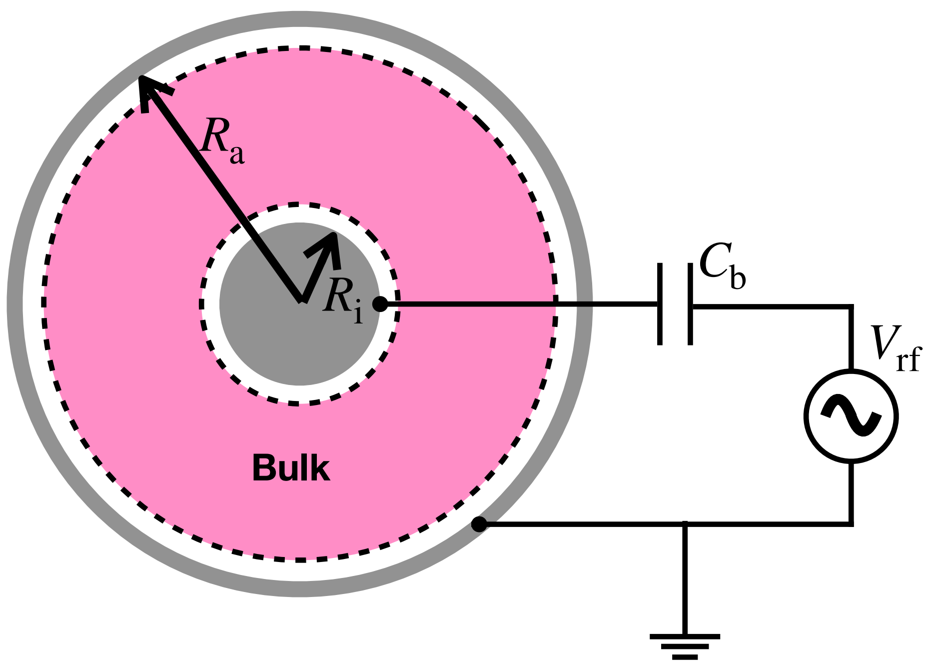
asymmetric discharge

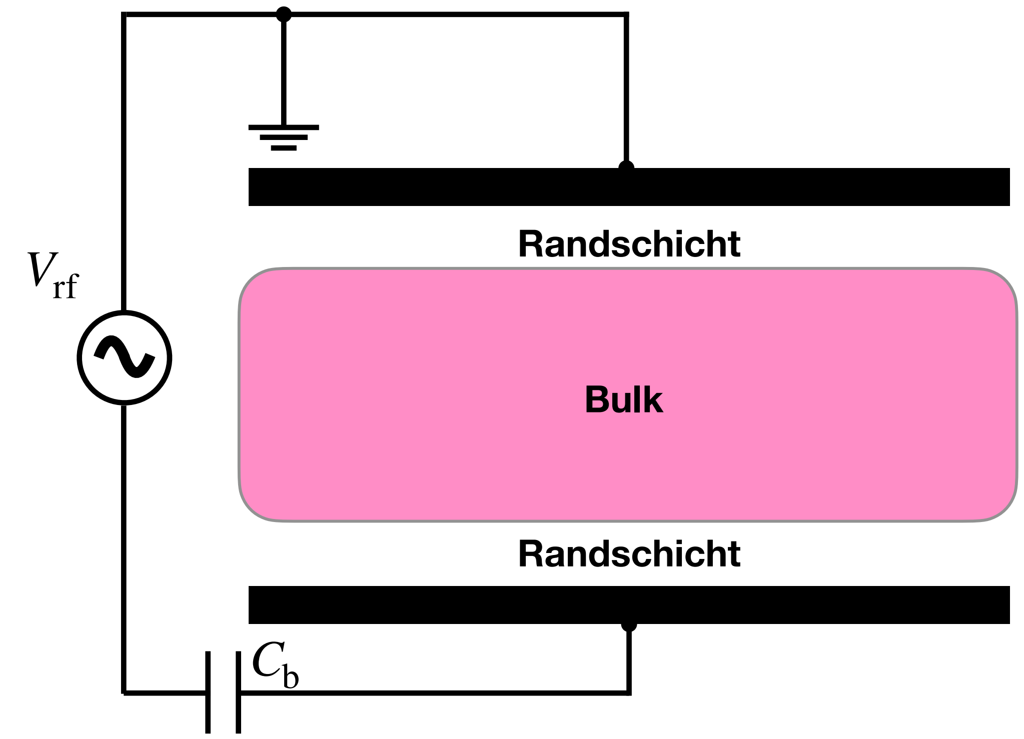


symmetric discharge

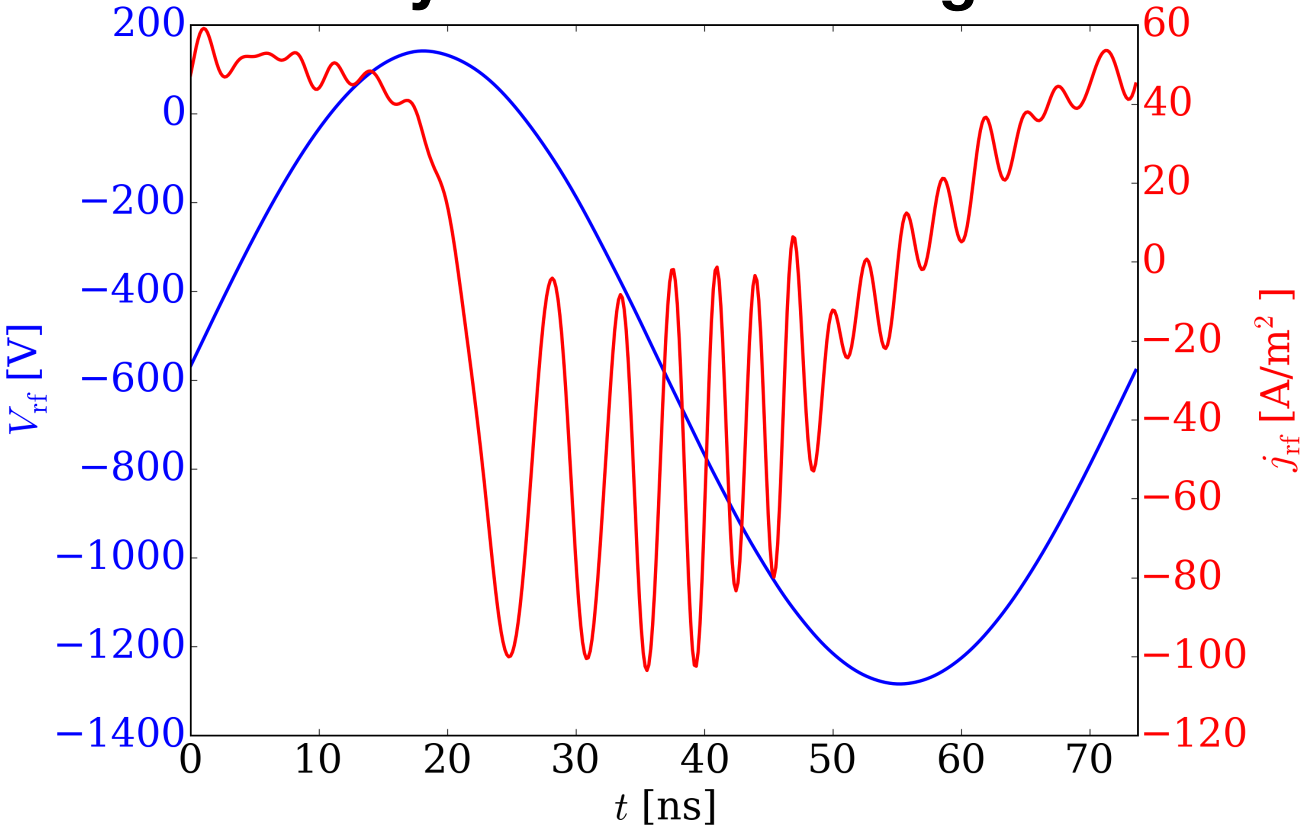


Asymmetric vs. symmetric discharge

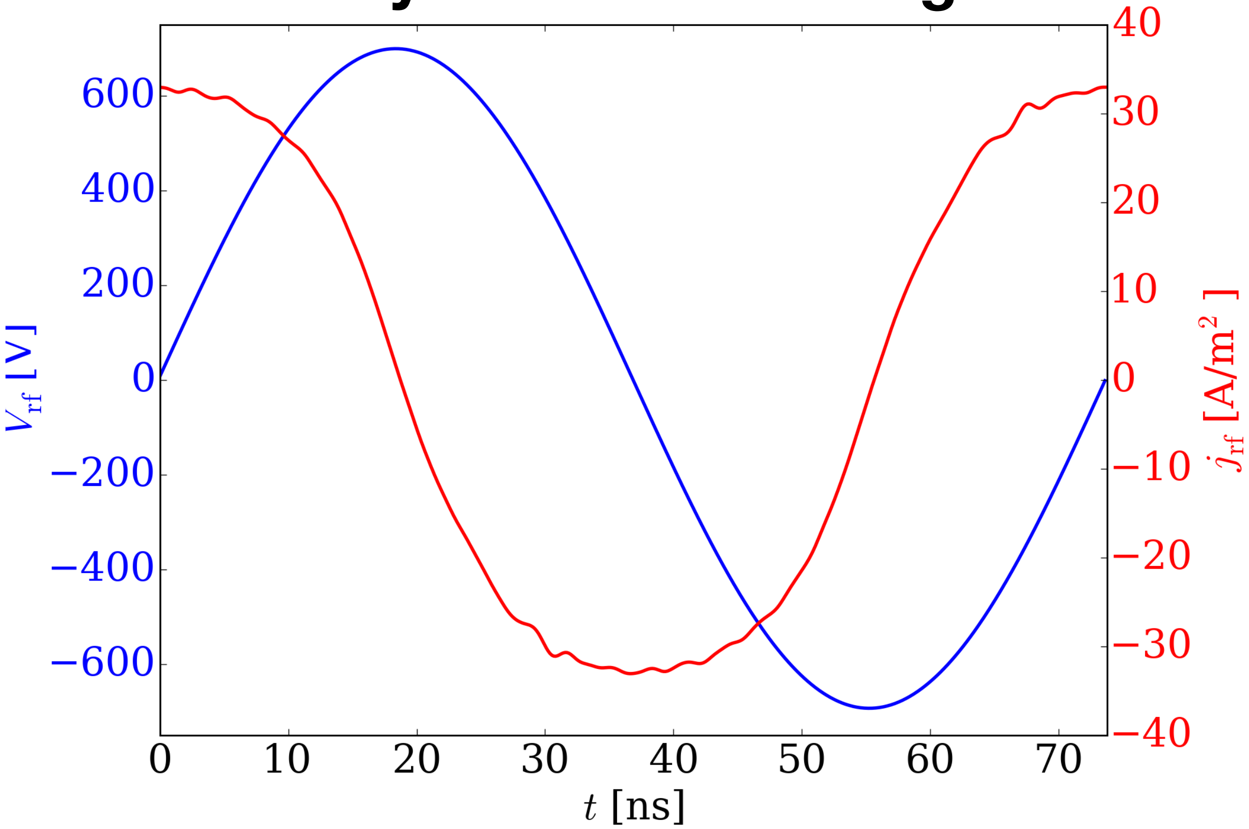




asymmetric discharge



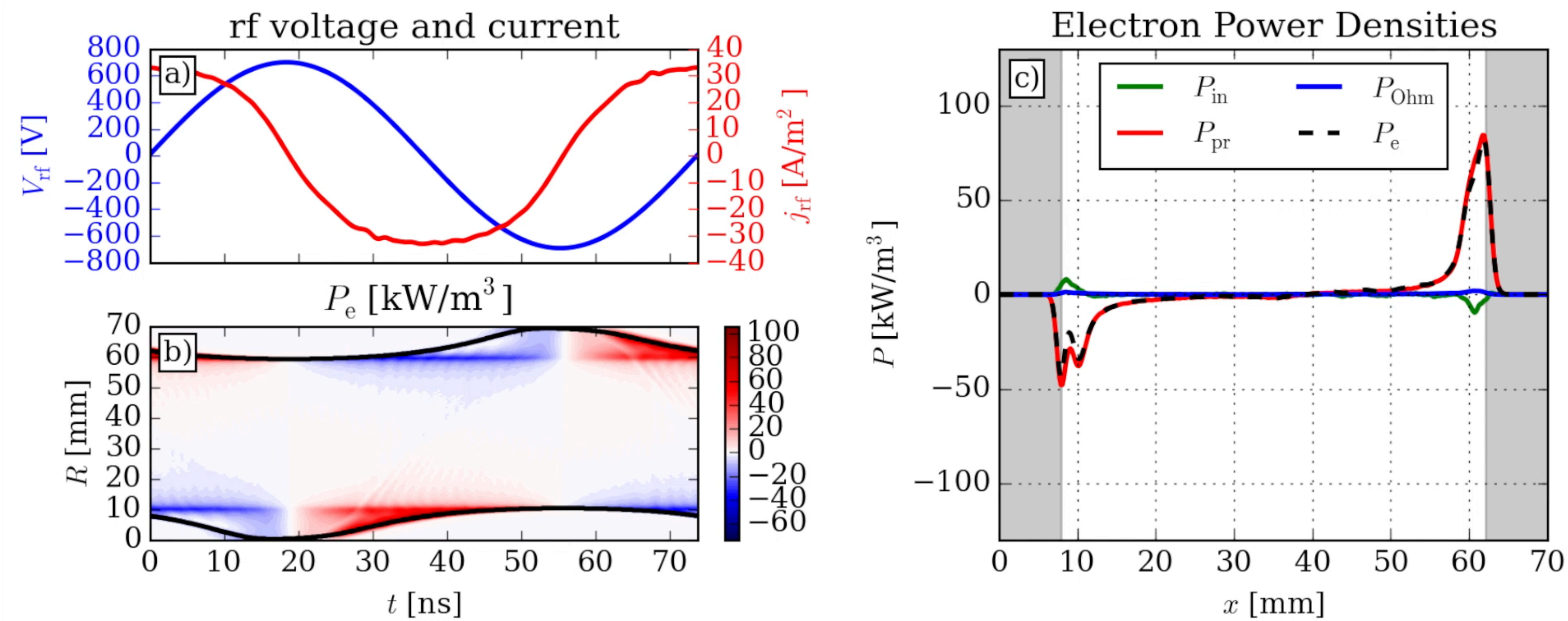
symmetric discharge



Symmetric discharge: Power absorption

- spatio und temporal dynamics of the electron power absorption
- here, the pressure power absorption term dominates the discharge
- related to density gradients that result in an ambipolar electric field

$p = 1\,\mathrm{Pa}$ (argon), $\mathrm{L_{gap}} = 70\,\mathrm{mm}$, $\mathrm{V_0} = 700\,\mathrm{V}$, $\mathrm{f_{rf}} = 13.56\,\mathrm{MHz}$, $\mathrm{A_g/A_p} = 1$

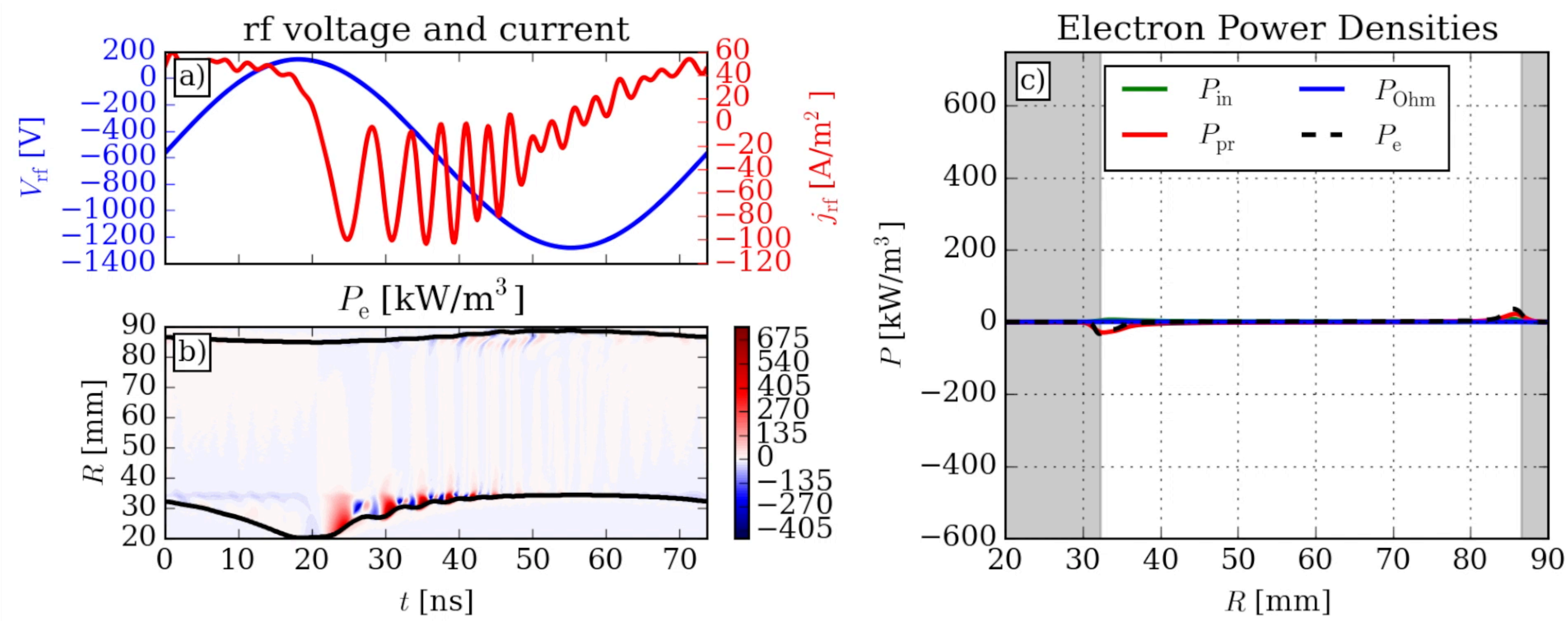


more information in the next session „Plasma Diagnostics and Process Monitoring Technology I“, talk given by Máté Vass

Asymmetric discharge: Power absorption

- change between electron power gain and loss during sheath expansion
- interplay between the pressure and inertia terms
- related to the excitation of resonance phenomena

$p = 1\,\mathrm{Pa}$ (argon), $\mathrm{L_{gap}} = 70\,\mathrm{mm}$, $\mathrm{V_0} = 700\,\mathrm{V}$, $\mathrm{f_{rf}} = 13.56\,\mathrm{MHz}$, $\mathrm{A_g/A_p} = 3.5$



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

Power absorption and ionization rate

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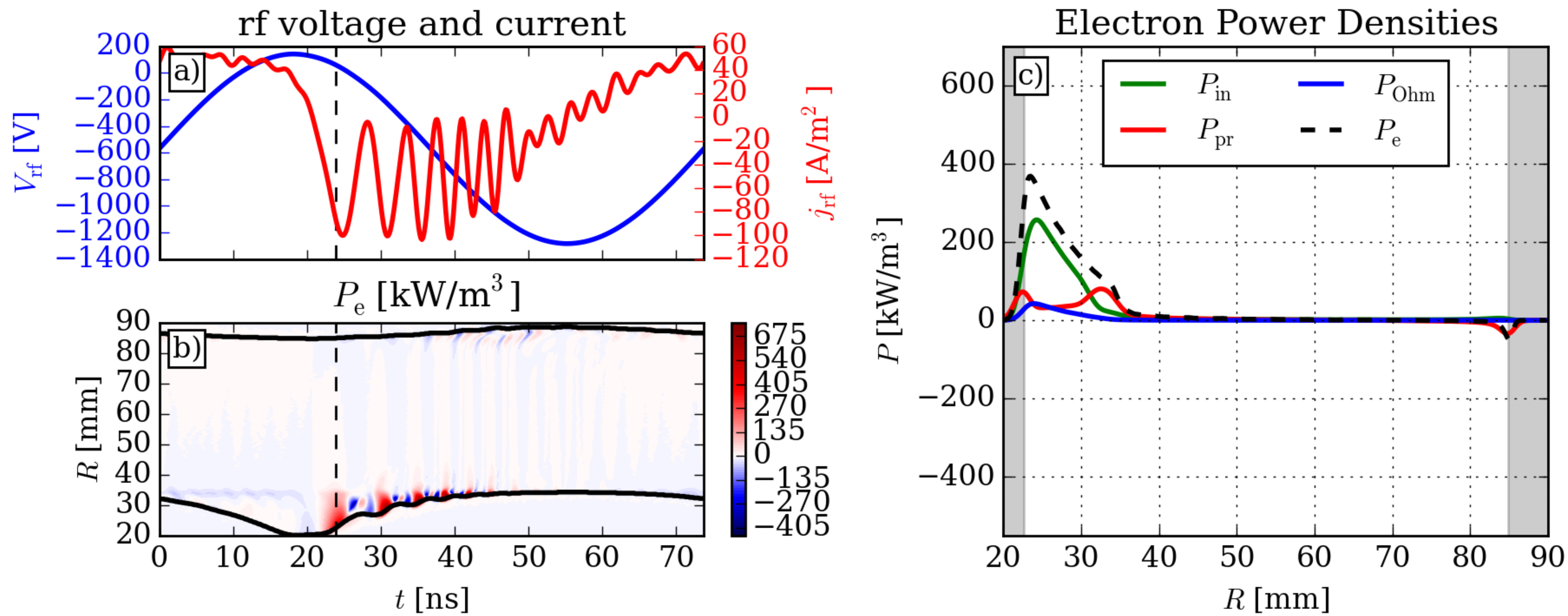

$$m_{\mathrm{e}}\left(\frac{\partial(n_{\mathrm{e}}u)}{\partial t} + \nabla\cdot(n_{\mathrm{e}}u^2)\right) = -en_{\mathrm{e}}E - \nabla p_e - \Pi_{\mathrm{c}}$$

Fluid models usually fail, since they neglect inertia terms

Power absorption and ionization rate

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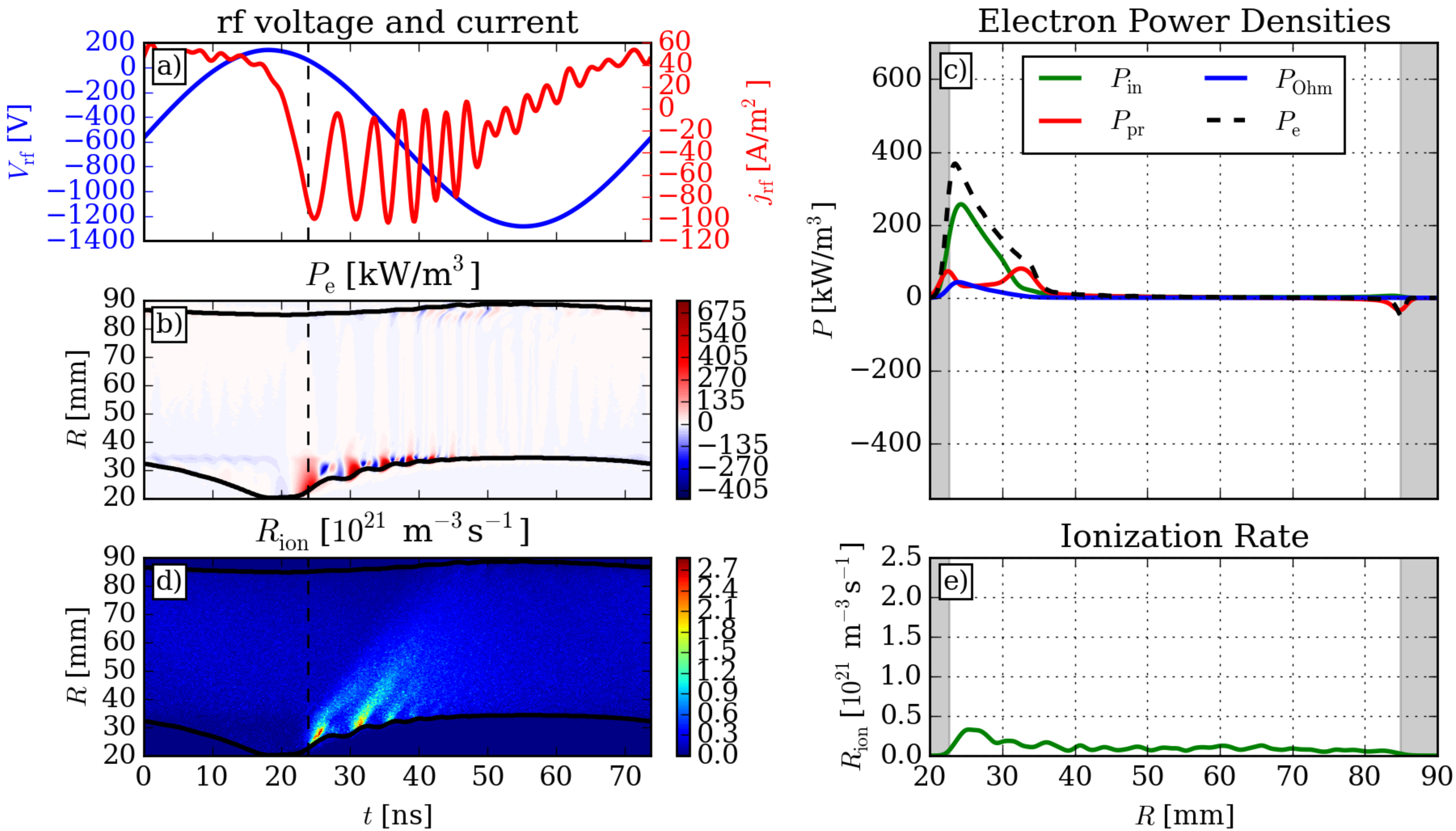

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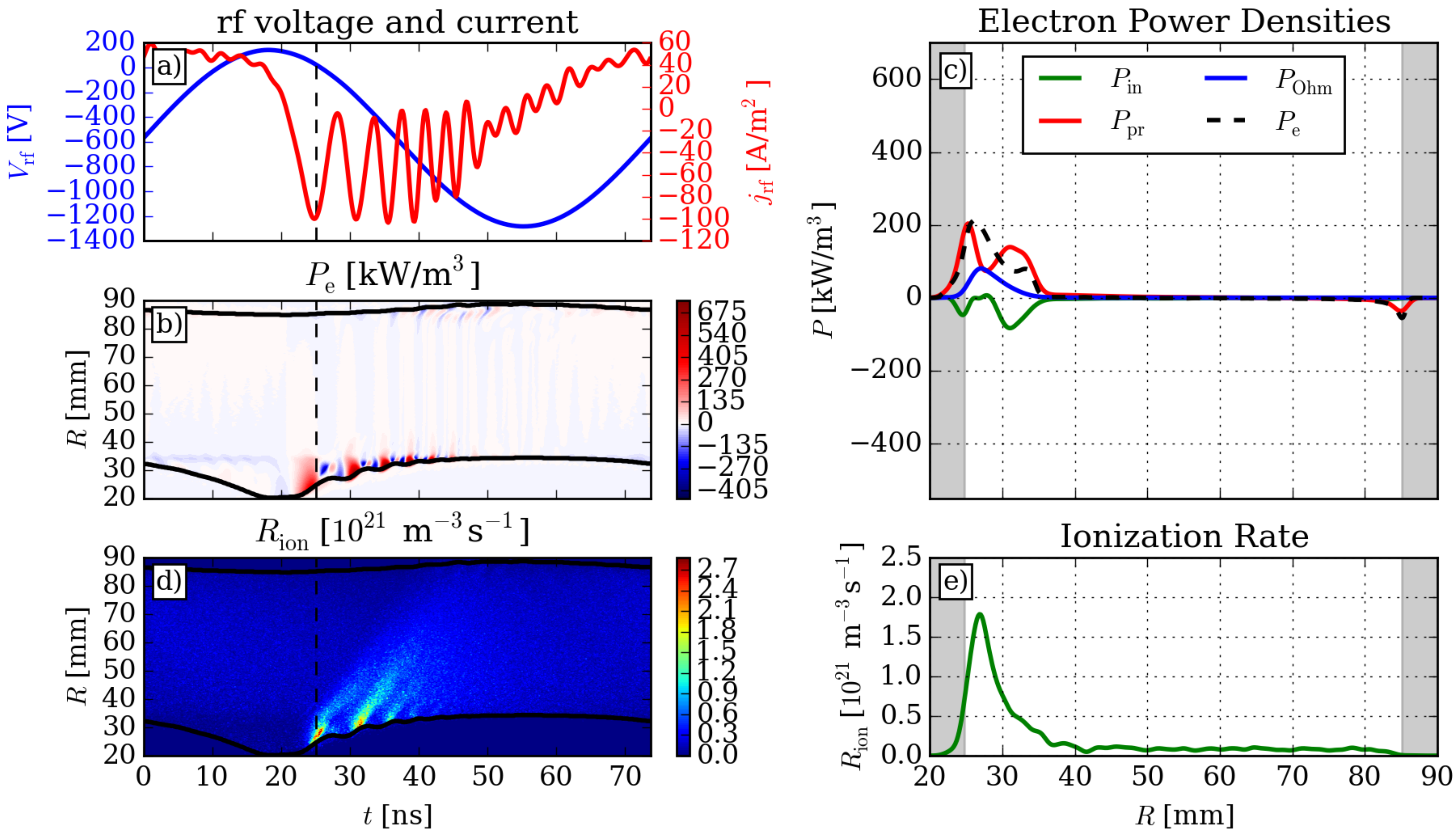

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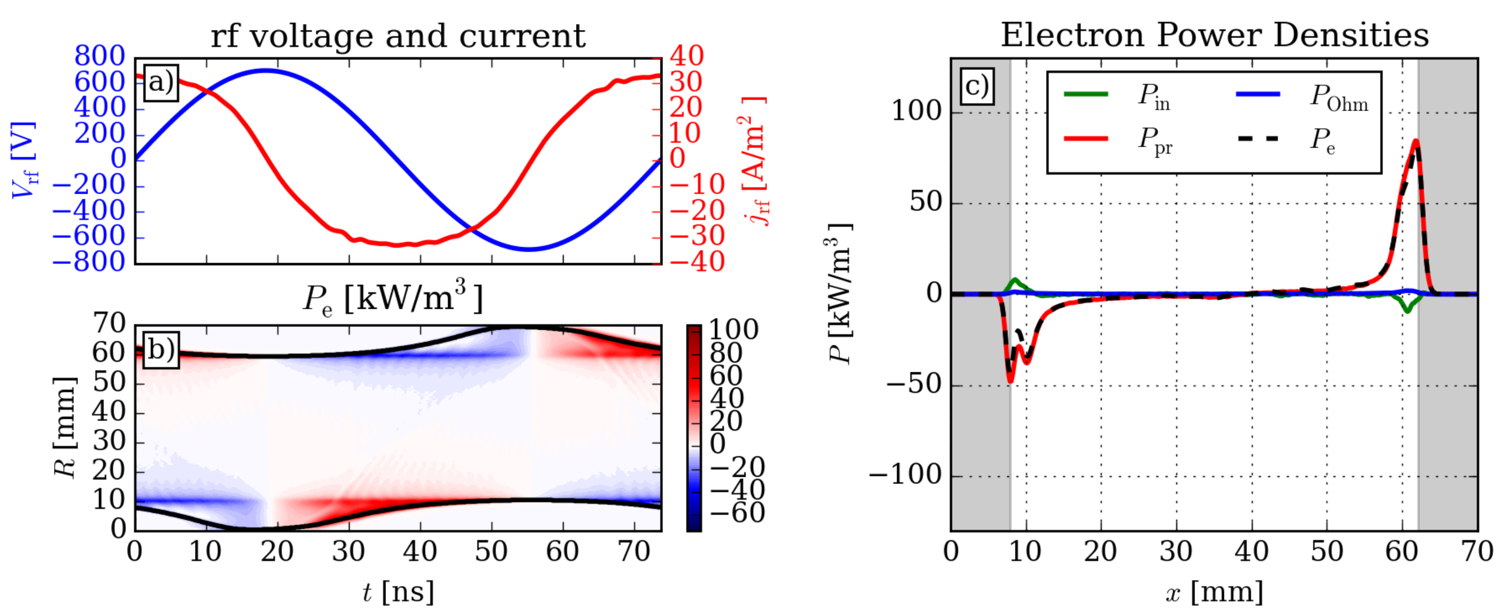
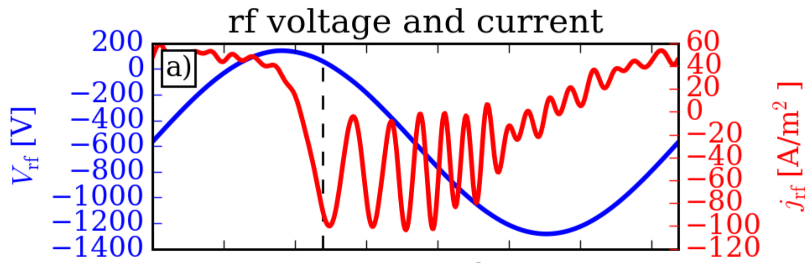
Conclusion

- in perfectly symmetric ccrf discharges, the excitation of higher harmonics in the rf current is strongly suppressed



Conclusion

- in perfectly symmetric ccrf discharges, the excitation of higher harmonics in the rf current is strongly suppressed and the pressure heating dominates at low pressure
- in geometrically (electrically or magnetically) asymmetric discharges, harmonic oscillations in the rf current occur (easy to measure)



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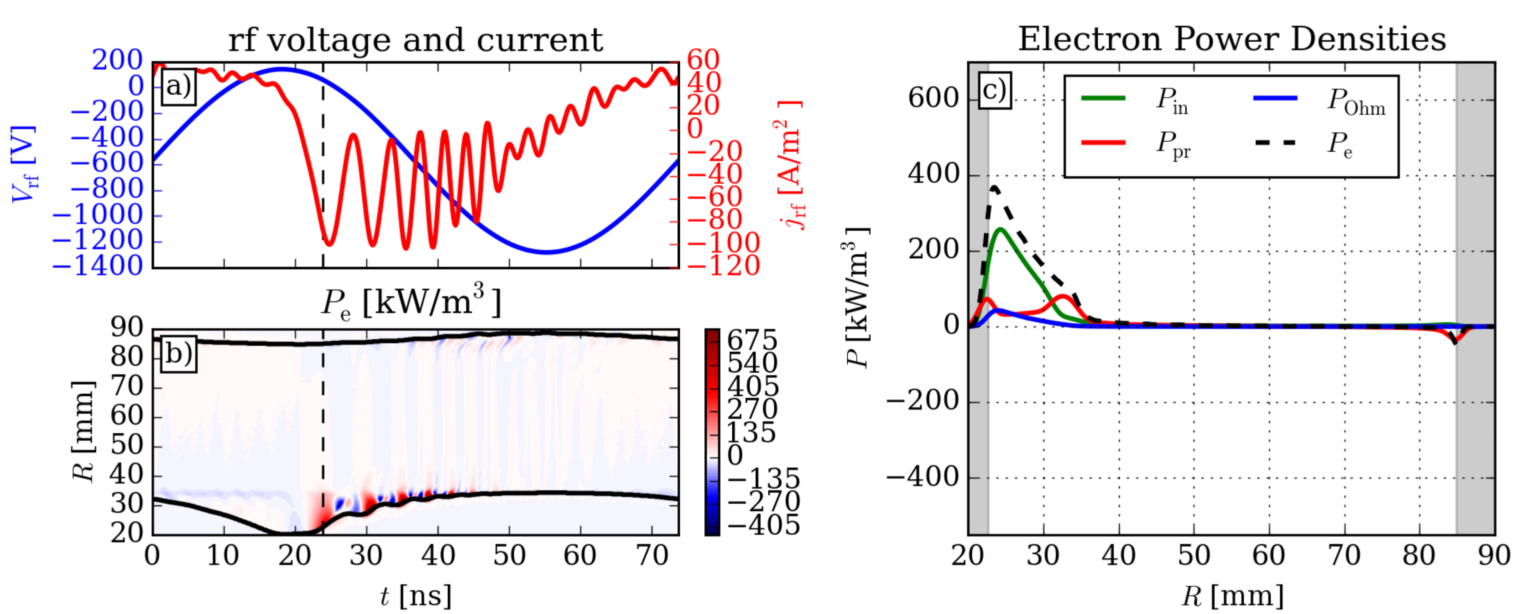

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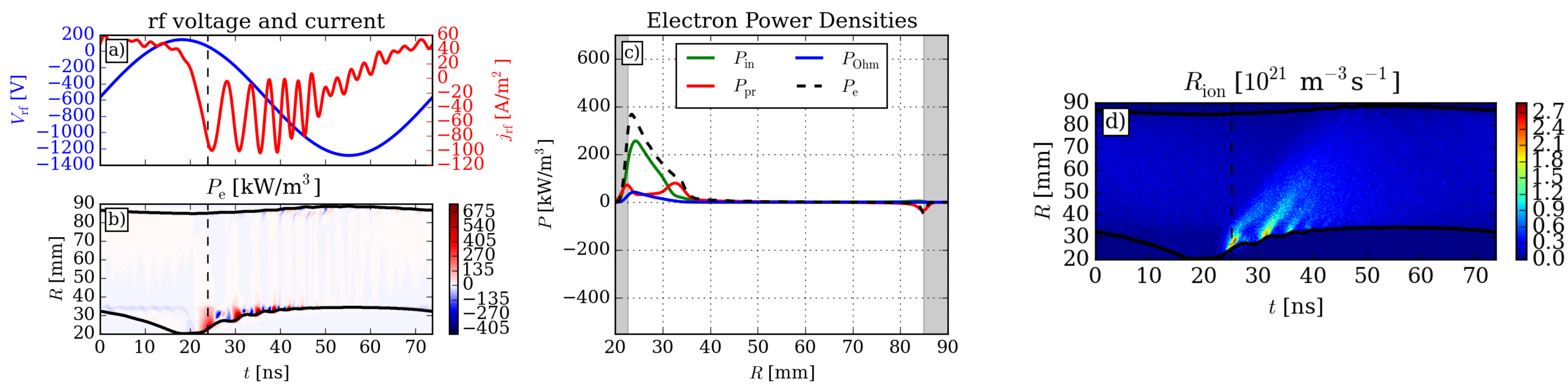
- in geometrically (electrically or magnetically) asymmetric discharges, harmonic oscillations in the rf current occur (easy to measure)
- due to the fast sheath expansion, electrons are accelerated to high energies
- this power absorption has a strong contribution to the ionization process



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Electron dynamics in low pressure capacitively coupled radio frequency discharges F

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More information about the fundamentals of electron dynamics can be found in this tutorial paper (free to download)

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