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Nonlocal and nonlinear dynamics in low pressure capacitively coupled radio frequency discharges

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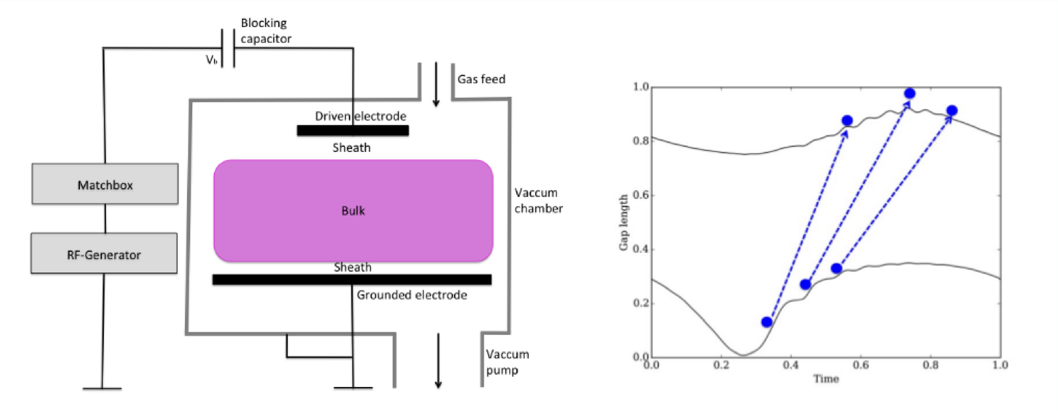
Abstract: In capacitively coupled radio frequency (CCRF) discharges at low pressures, the electron power gain is dominated by electron interaction with the plasma sheath. During sheath expansion a bunch of energetic electrons is accelerated into the bulk region and carries energy to sustain the discharge via ionization. Additionally, the penetration of these beam-like electrons into the plasma bulk can lead to a local electric field reversal which leads to a nonlinear interplay between bulk electrons and the expanding sheath. The consequences are higher order oscillations in the rf current as well as the excitation of electrostatic waves. Particularly at low pressures, the electron mean free path is frequently larger than the gap size. In this nonlocal regime, the nonlinear sheath dynamics at one electrode influence the behavior in front of the opposite electrode, i.e., energetic electrons traverse through the discharge almost collisionlessly and interact with the opposing sheath at different phases. Furthermore, the generation of secondary electrons vastly contributes to this mechanism, due to their beam-like behavior at low pressures. In this work, nonlinear and nonlocal dynamics, in particular the electron power gain, are investigated by means of 1d3v PIC simulations of symmetric and asymmetric CCRF discharges.

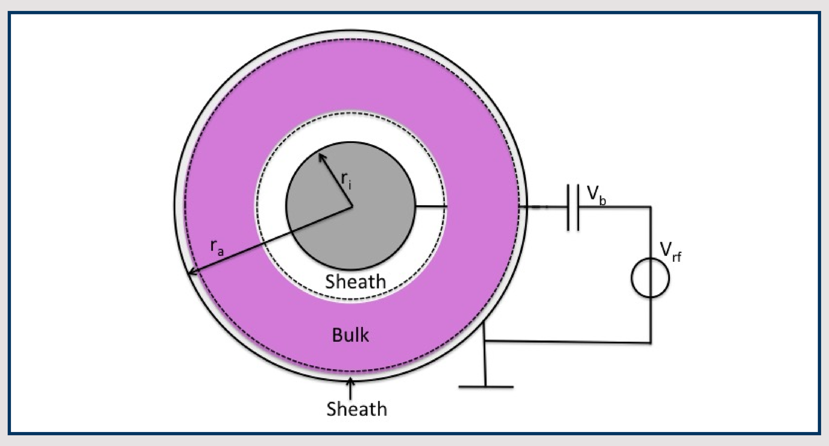
Nonlinear and Nonlocal Electron Dynamics

- nonlinear sheath motion strongly affects the electron dynamics
- generally present in geometrical asymmetric CCPs at low pressures
- leads to significant oscillations in the rf-current, excitation of the PSR [1]
- low pressures, electron mean free path increases, e.g. $\lambda_m(1\text{Pa}) \approx 45$ mm
- interaction at the opposing sheath becomes crucial, $L_{gap} < \lambda_m$ [2]

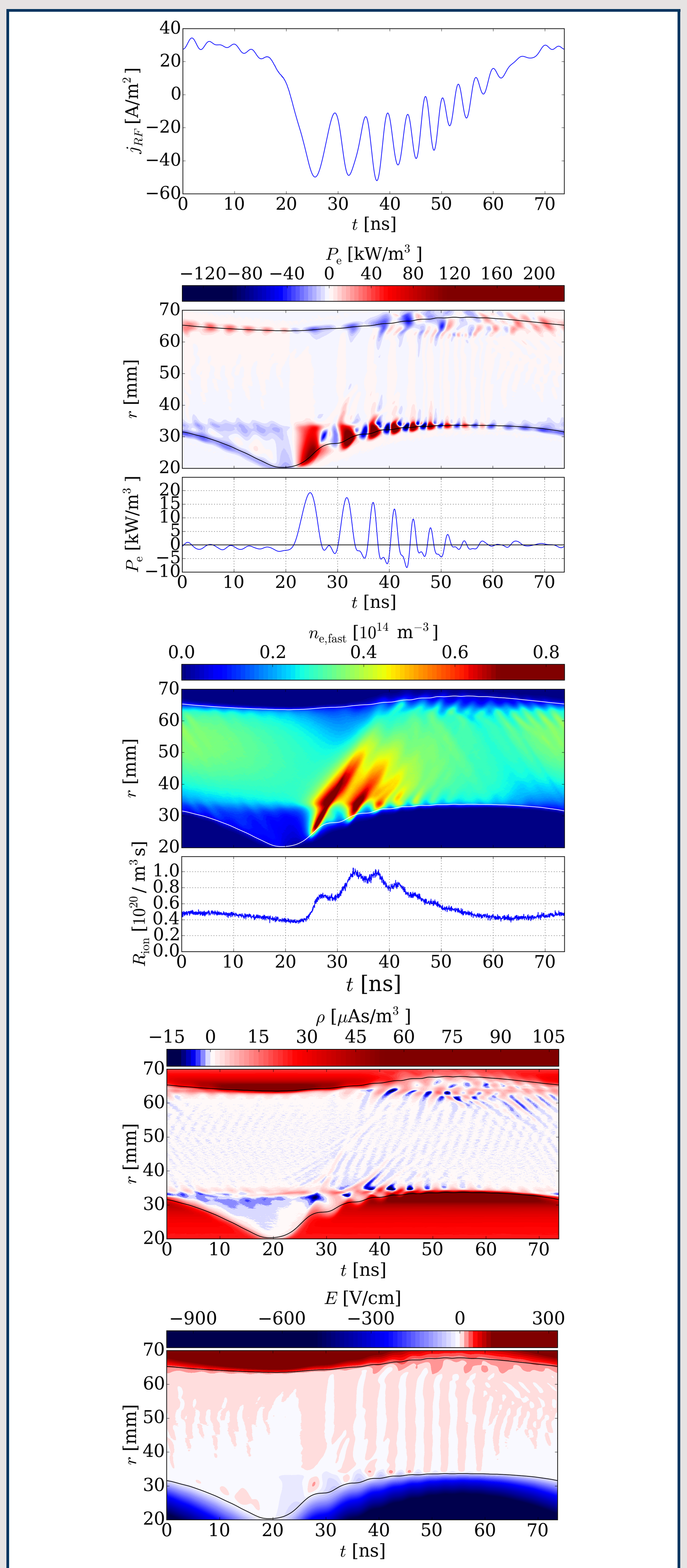


Nonlinear Electron Dynamics

- 1d3v PIC, cylindrical grid (asymmetric ccrf discharge) in order to obtain a DC self-bias
- the voltage and current driven simulations result in significantly different electron dynamics; as the experimental systems are usually voltage driven, the use of a voltage source in the numerical studies is recommended [3]
- $f_{rf} = 13.56$ MHz, $V_{rf} = 400$ V, $L_{gap} = 50$ mm
- electrodes: $A_g/A_d = 12.25$, argon background
- low pressure case: $p = 1$ Pa, $\longrightarrow V_{Bias} \approx -300$ V
- high pressure case: $p = 10$ Pa, $\longrightarrow V_{Bias} \approx -300$ V

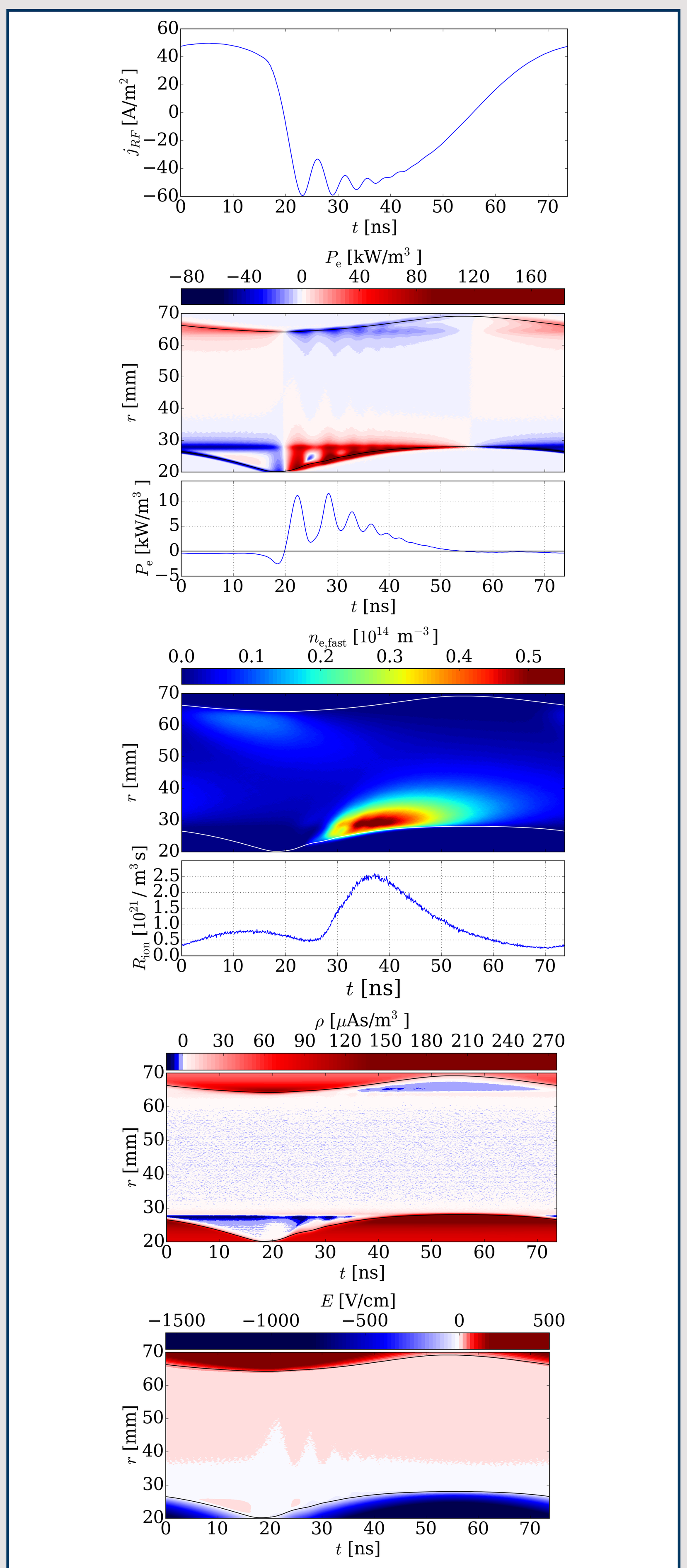


Low pressure: $p = 1$ Pa



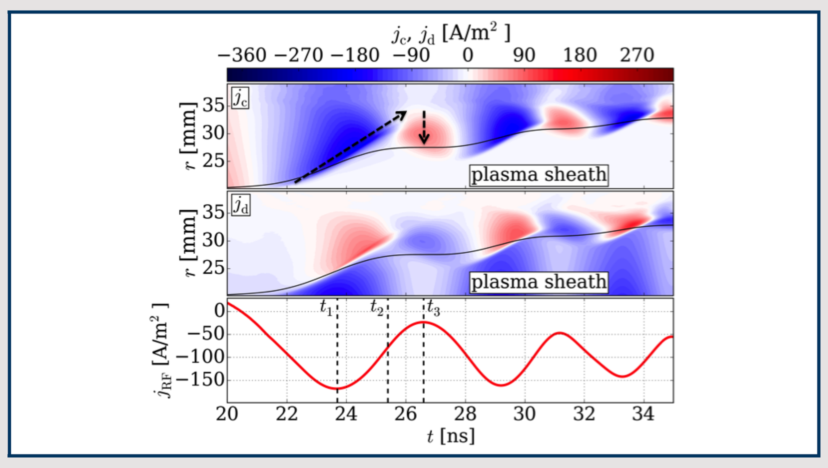
- acceleration of multiple electron beams [3]
- significant charge densities in the plasma bulk

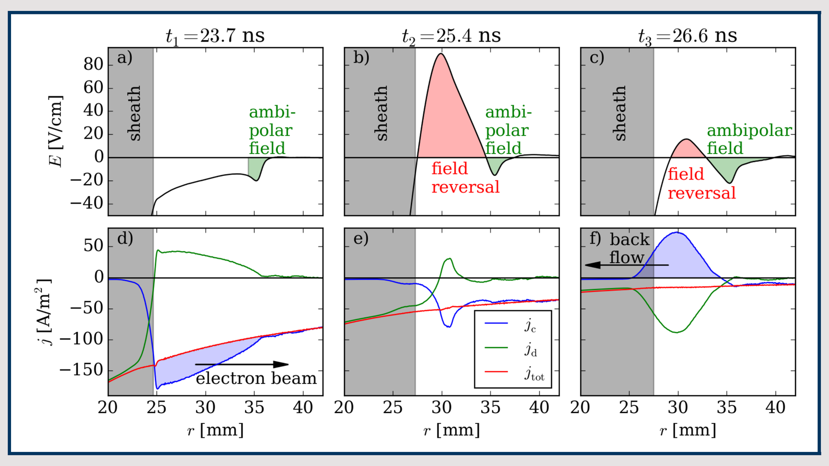
High pressure: $p = 10$ Pa



- nonlinear dynamics are suppressed but still present
- local field reversal close to the sheath edge

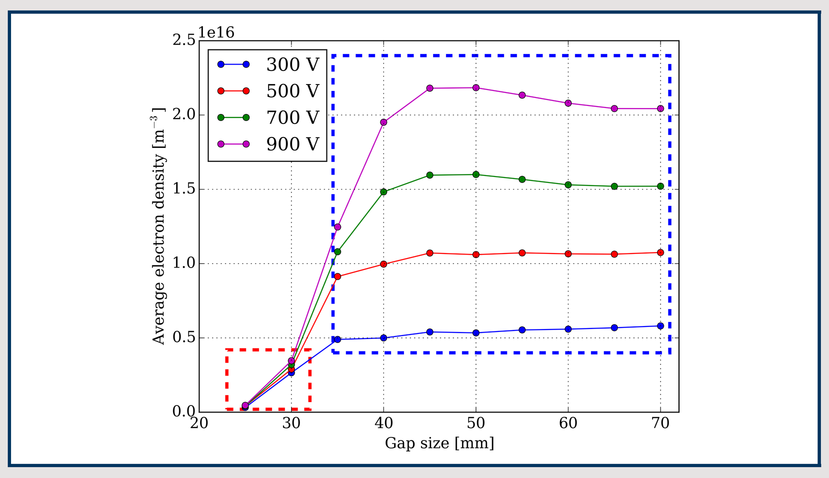
Electric Field Reversal

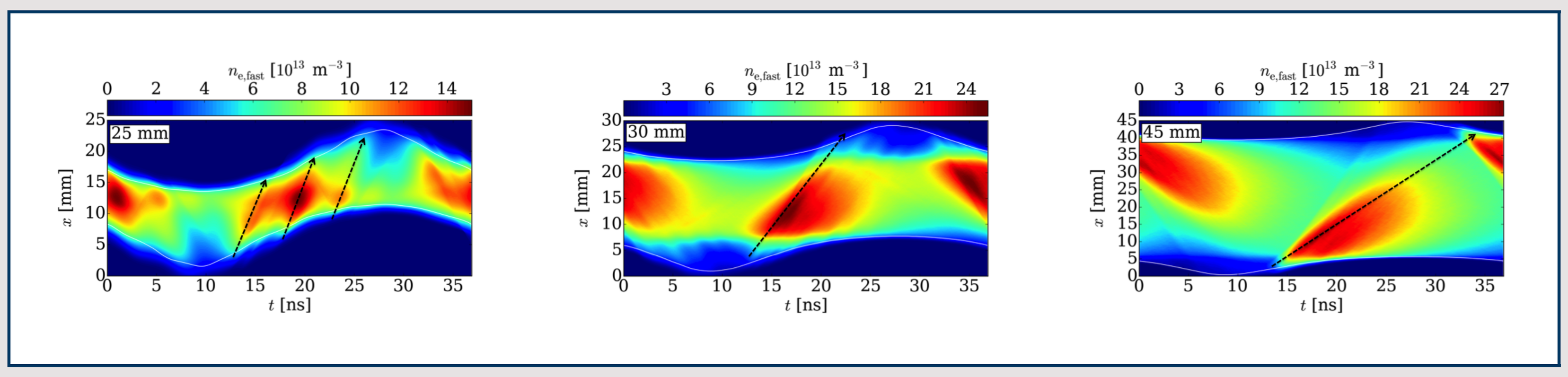




Gap Size Variation

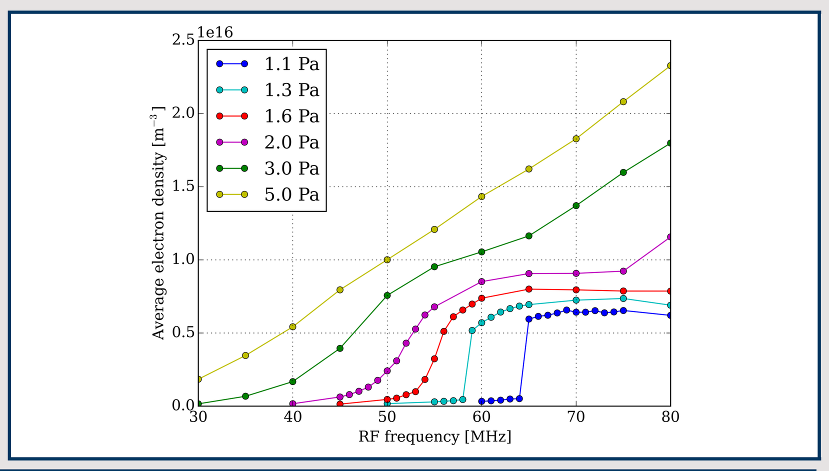
- 1d3v PIC, Cartesian grid (symmetric ccrf discharge)
- $f_{rf} = 27.12$ MHz, $p = 1$ Pa, argon
- rf voltage: 300 V $< V_{rf} <$ 900 V
- gap size: 25 mm $< L_{gap} <$ 70 mm
- significant increase of the plasma density at 40 mm
- impingement phase of energetic beam electrons at the opposing sheath becomes important:
  - red rectangle: beam reaches the collapsing phase, electrons lose energy during reflection
  - blue rectangle: beam reaches the expanding phase, electrons gain energy during reflection

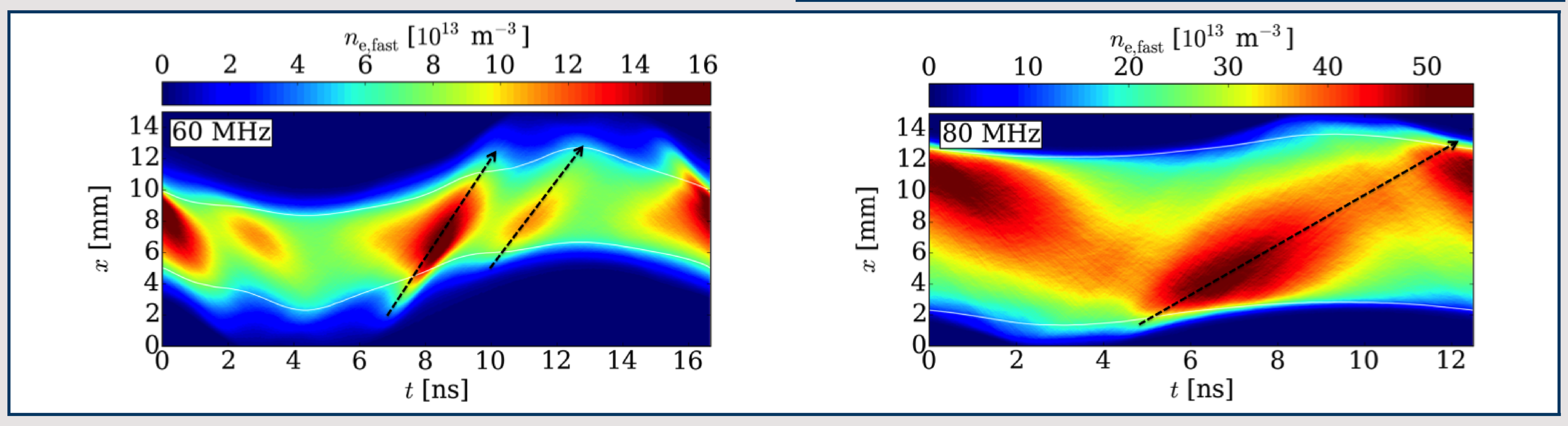




Frequency Variation

- 1d3v PIC, Cartesian grid (symmetric ccrf discharge) [2]
- $V_{rf} = 150$ V
- pressure: 1.1 Pa $< p <$ 5.0 Pa
- rf frequency: 30 MHz $< f_{rf} <$ 80 MHz
- significant density jump at a certain frequency
- impingement phase of energetic beam electrons at the opposing sheath becomes important (e.g. 1.1 Pa case):
  - low density region: beam reaches the collapsing phase
  - high density region: beam reaches the expanding phase





Conclusion

- nonlinear electron dynamics strongly influences the electron power gain and loss
- local electric field reversal accelerates bulk electrons back to the sheath
- at low pressures and small gap sizes, the impingement phase at the opposing sheath becomes crucial and can be controlled by changing the gap size, the rf frequency and the pressure

REFERENCES [1] Wilczek S et al. 2016 *Phys. Plasmas* **23** 063514; [2] Wilczek S et al. 2015 *Plasma Sources Sci. Technol.* **24** 024002; [3] Wilczek S et al. 2018 *Plasma Sources Sci. Technol.* accepted;
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