# EXPERIMENTAL AND KINETIC SIMULATION STUDY OF ELECTRON POWER ABSORPTION MODE TRANSITIONS IN CAPACITIVE RF DISCHARGES IN NEON

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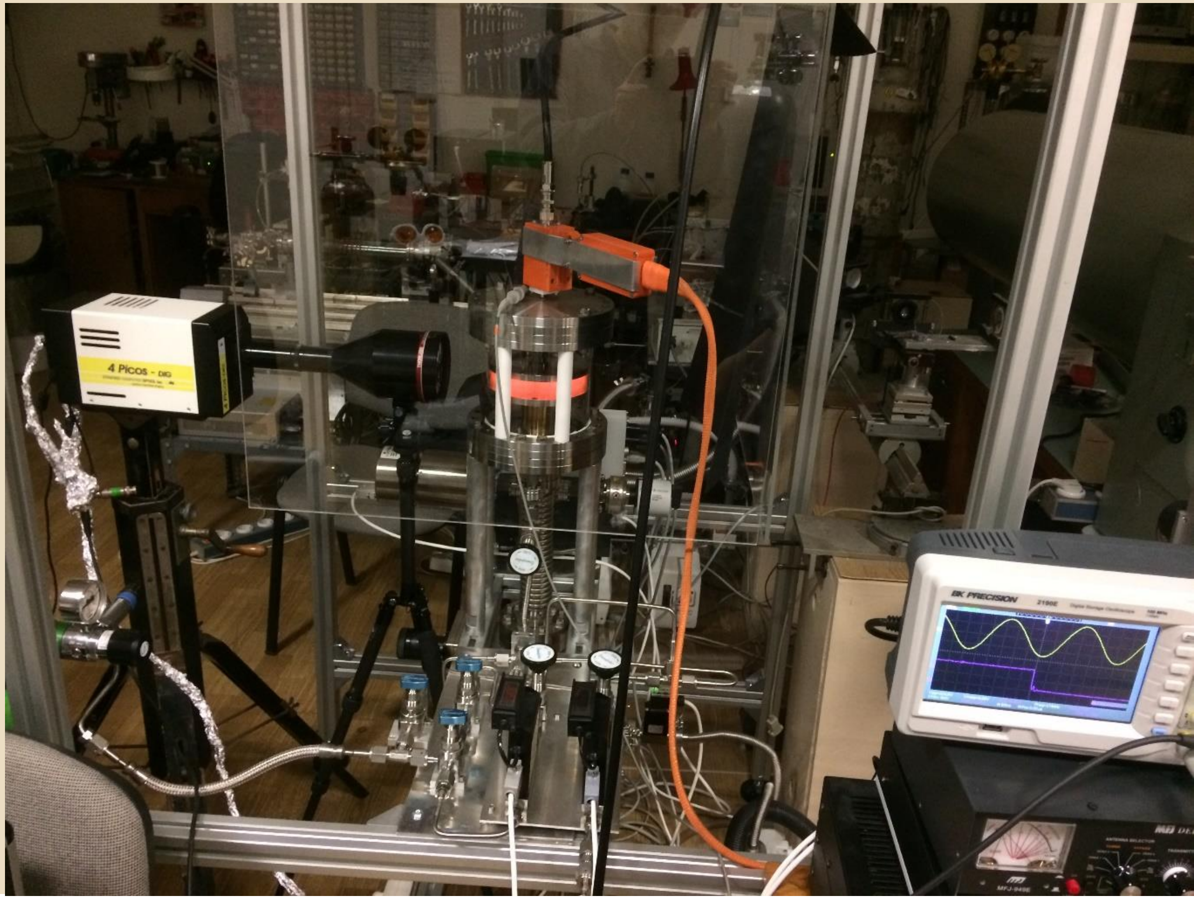


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International Online Plasma Seminar

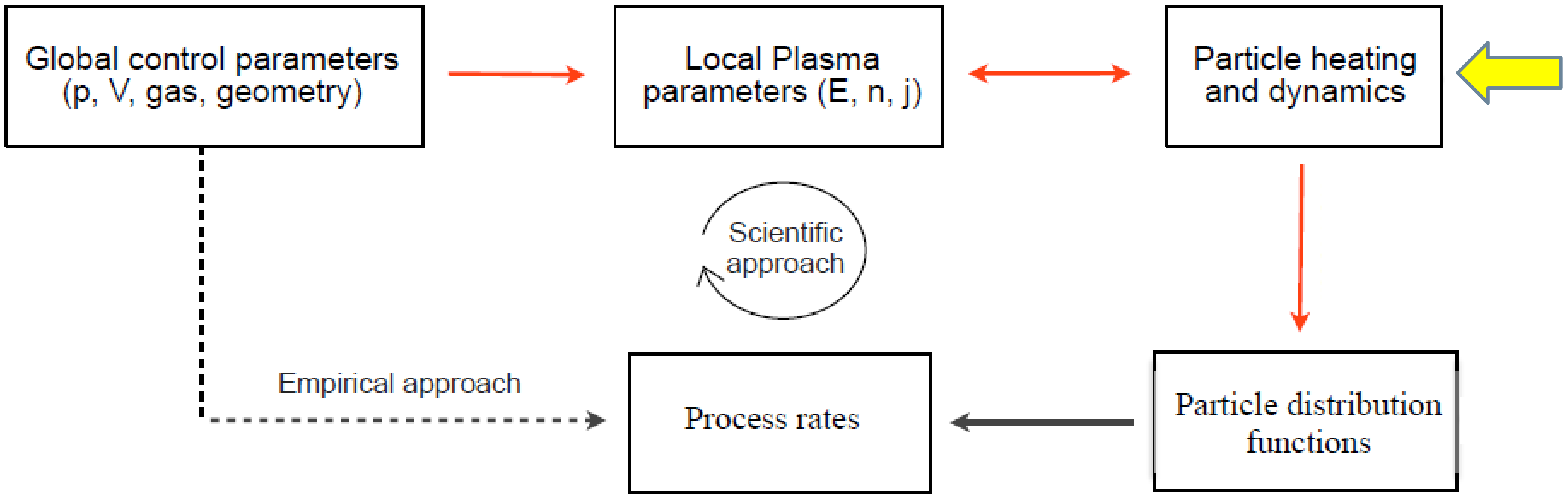
# Outline



- Motivation
- Experimental setup
- Simulation method
- Results
- Conclusions

# Motivation



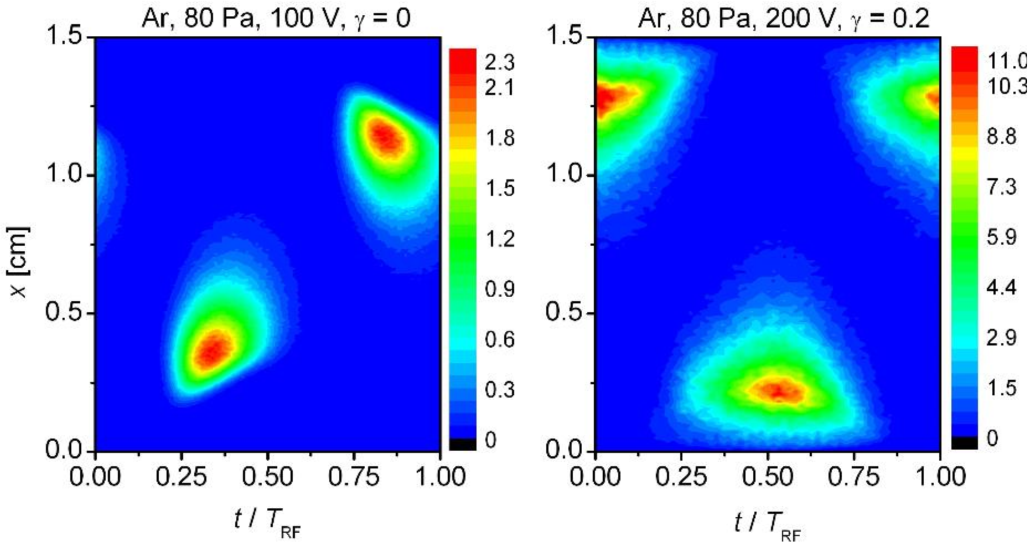



- Fundamental understanding of the charged particle dynamics helps the optimization of process rates for surface manufacturing.

# Motivation



Ionization rate




$\alpha$-mode

$\gamma$-mode

Discharge operation mode: defined by the spatio-temporal distribution of the ionization rate

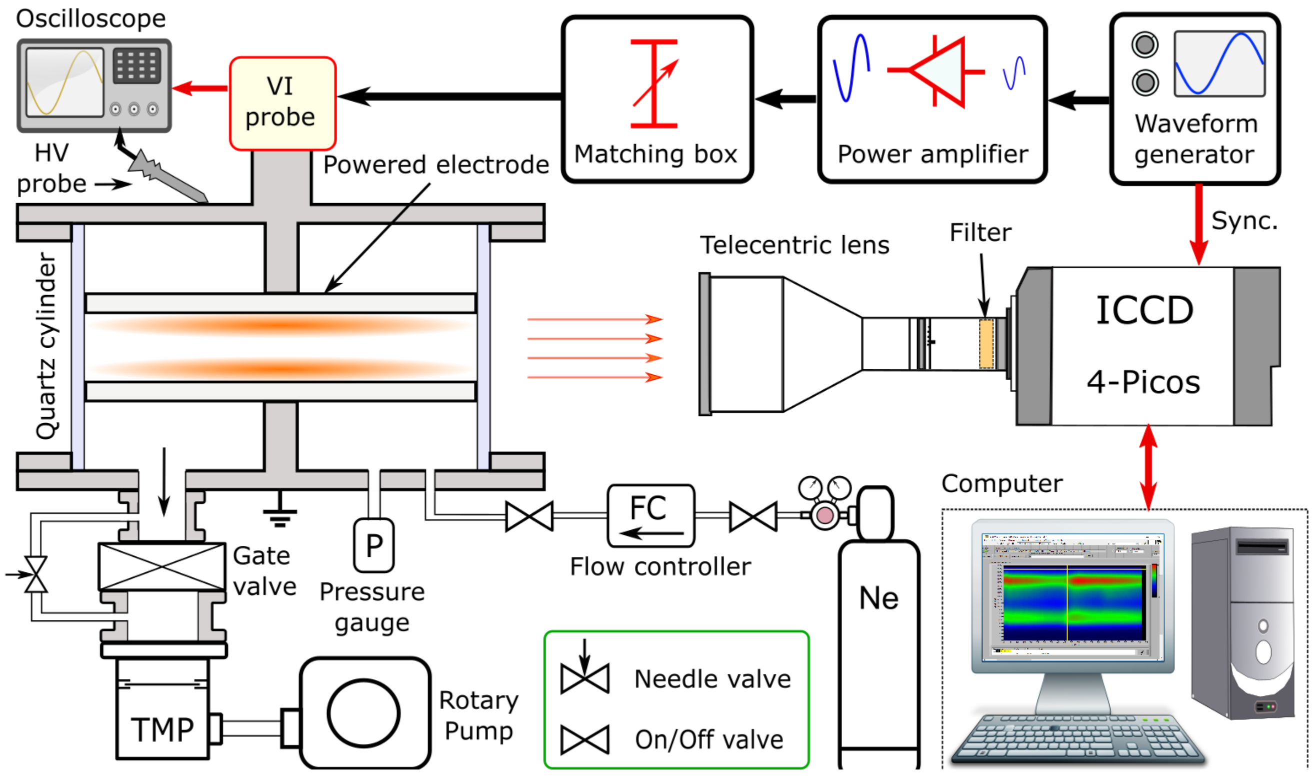
- Experimental method: PROES
- Computational method: PIC/MCC simulation

- Noone has ever seen $\alpha$- to $\gamma$-mode transition by PROES.
- A systematic comparison of computational and experimental results in a wide parameter regime has not been performed yet.

# Experimental setup



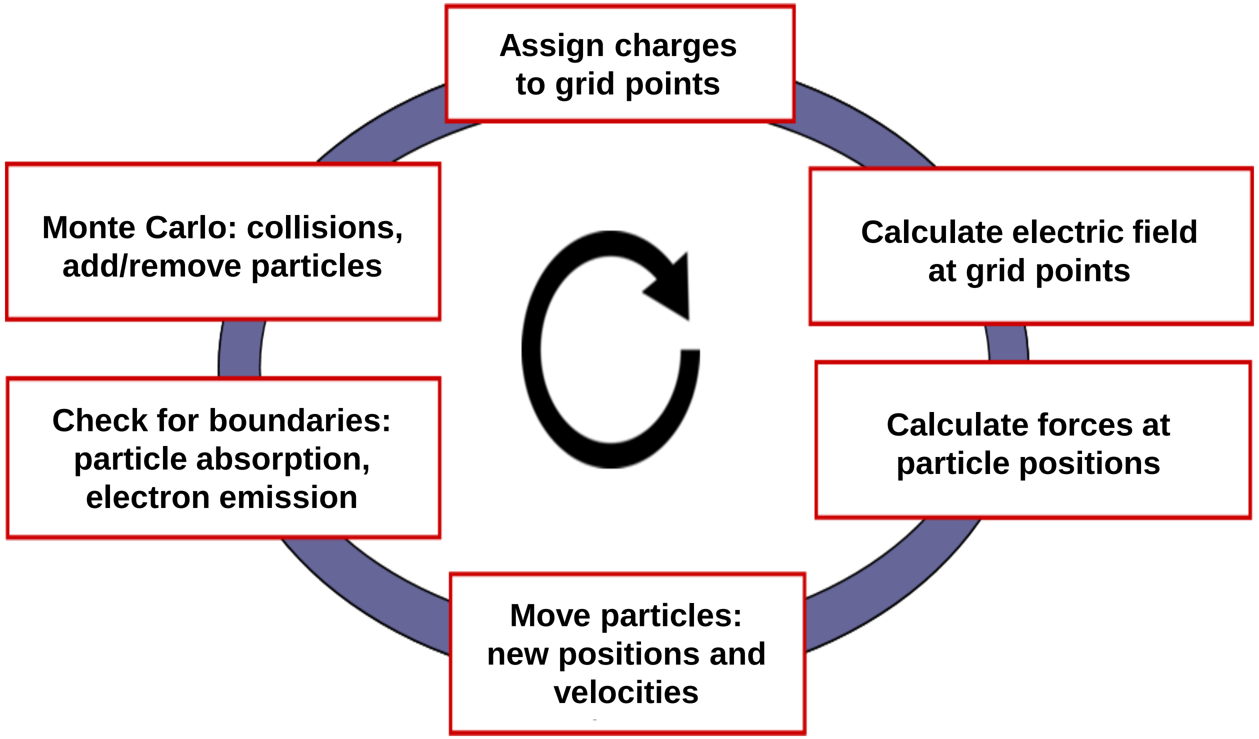
- Geometrically symmetric CCP reactor (cylindrical)
  - No grounded chamber
  - Stainless steel electrodes
  - High vacuum ($\approx 10^{-7}$ mbar)
  - Pure neon gas
- ICCD camera
  - Spatial resolution: 150 µm
  - Temporal resolution: 1 ns
- PROES measurements on the Ne I line (585.25 nm)
  - Spatio-temporal distribution of the excitation rate of the Ne $2p_1$ state from the ground state is obtained



# PIC/MCC simulations

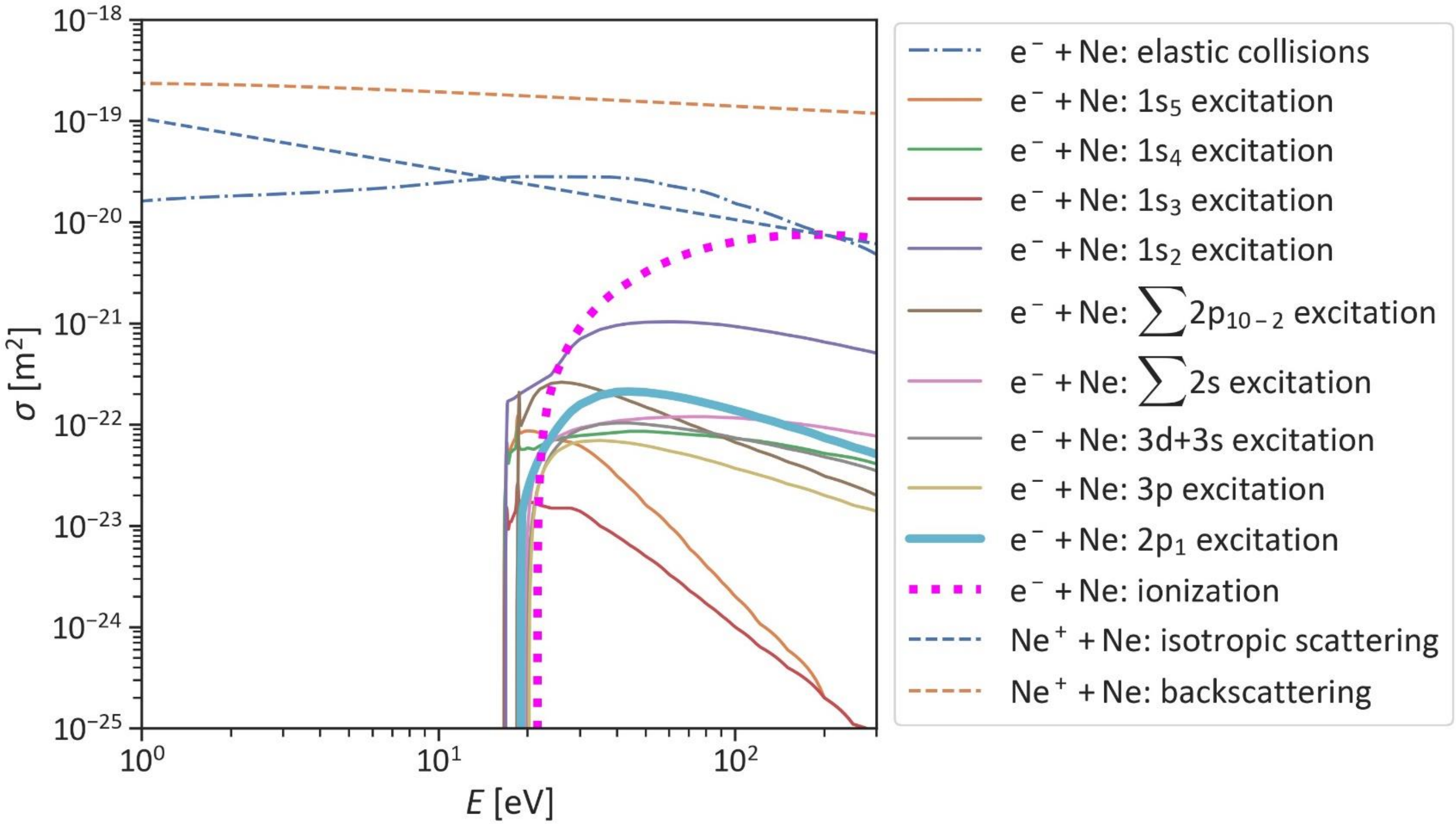


- Integration of the equations of motion for each particles
  - Particles traced: electrons and $Ne^{+}$ ions
- Electrostatic interaction
  - meanfield approximation
- Gas phase collisions
  - Monte Carlo method, probability based on energy dependent cross sections
- Surface processes
  - Elastic electron reflection: $\eta_e = 0.2$
  - Ion-induced secondary electron emission: $\gamma$



# Cross sections for PIC/MCC in neon






Electrons: Biagi-v7.1 database, www.lxcat.net, retrieved on April 8, 2019. Cross sections extracted from PROGRAM MAGBOLTZ, VERSION 7.1 JUNE 2004.
Ions: A. V. Phelps, unpublished, ftp://jila.colorado.edu/collision_data/, retrieved on August 22, 2005.

# Discharge conditions



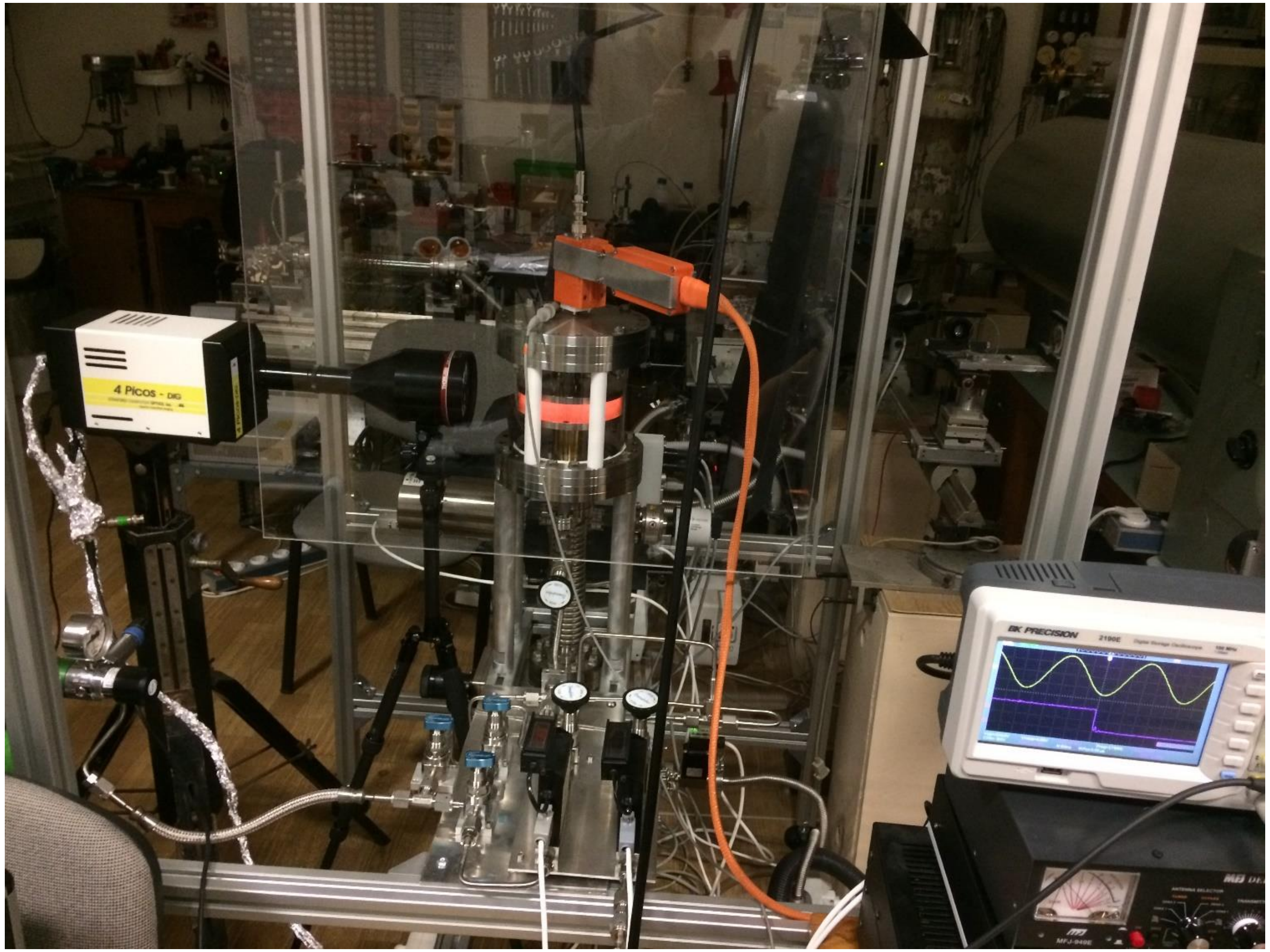
- Driving voltage waveform:

$$V = \frac{1}{2} V_{pp} \cos(2\pi f t)$$

  - Driving frequency from 3.39 MHz to 13.56 MHz
  - Peak-to-peak voltage: 330 V

- Electrode gap: 2.5 cm

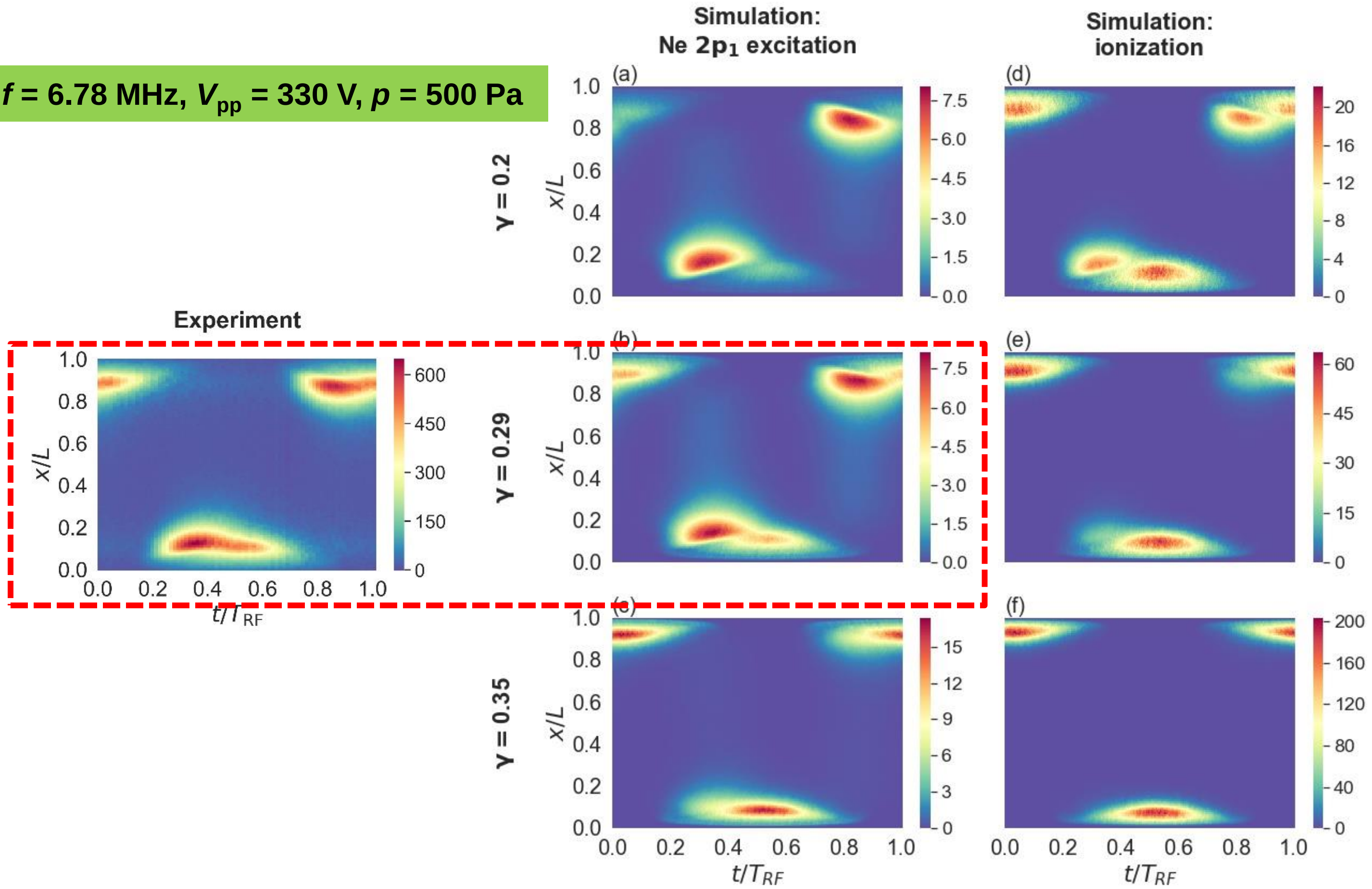
- Pressure: from 60 Pa to 500 Pa



# Critical role of $\gamma$



**$f$ = 6.78 MHz, $V_{pp}$ = 330 V, $p$ = 500 Pa**




- Completely different dynamics as $\gamma$ is changed from 0.2 to 0.35
- $\gamma$-CAST: comparing the Ne $2p_1$ excitation rates obtained from PROES and PIC/MCC
  - $I_\alpha$ and $I_\gamma$ average intensities are calculated within a ROI around the local maximum
  - $I_\gamma/I_\alpha$ ratios need to match

Result: $\gamma = 0.29$

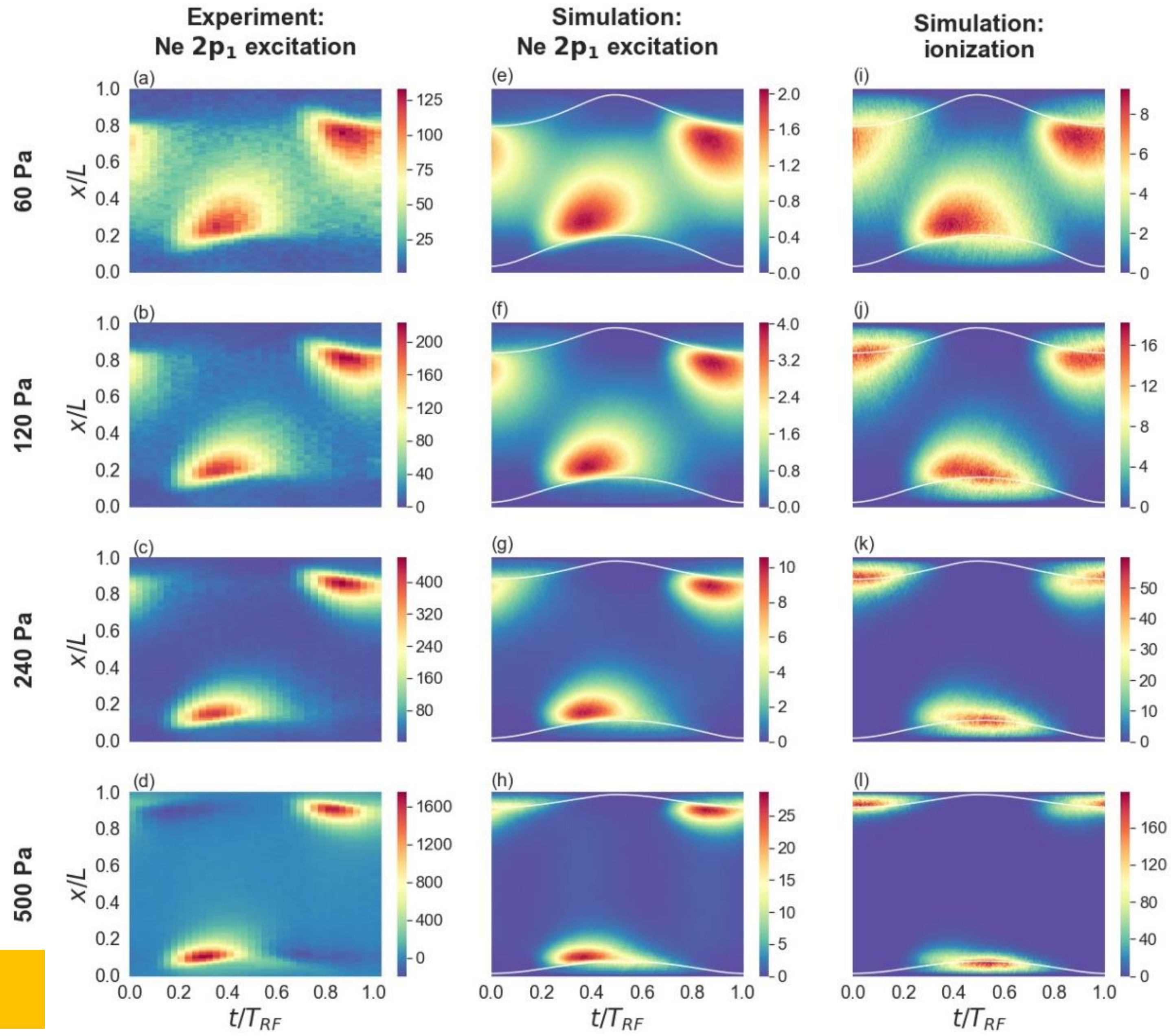
M. Daksha, B. Berger, E. Schüngel, I. Korolov, A. Derzsi, M. Koepke, Z. Donkó, and J. Schulze *J. Phys. D: Appl. Phys.* **49** 234001, 2016.

# Results



$f$ = 13.56 MHz, $V_{pp}$ = 330 V

- Simulation and experiment agrees well for the excitation rate
- Excitation peak only at sheath expansion.
- The ionization rate differs from the excitation.
- A transition from $\alpha$- to $\gamma$-mode occurs (see the ionization rate), which cannot be detected by PROES

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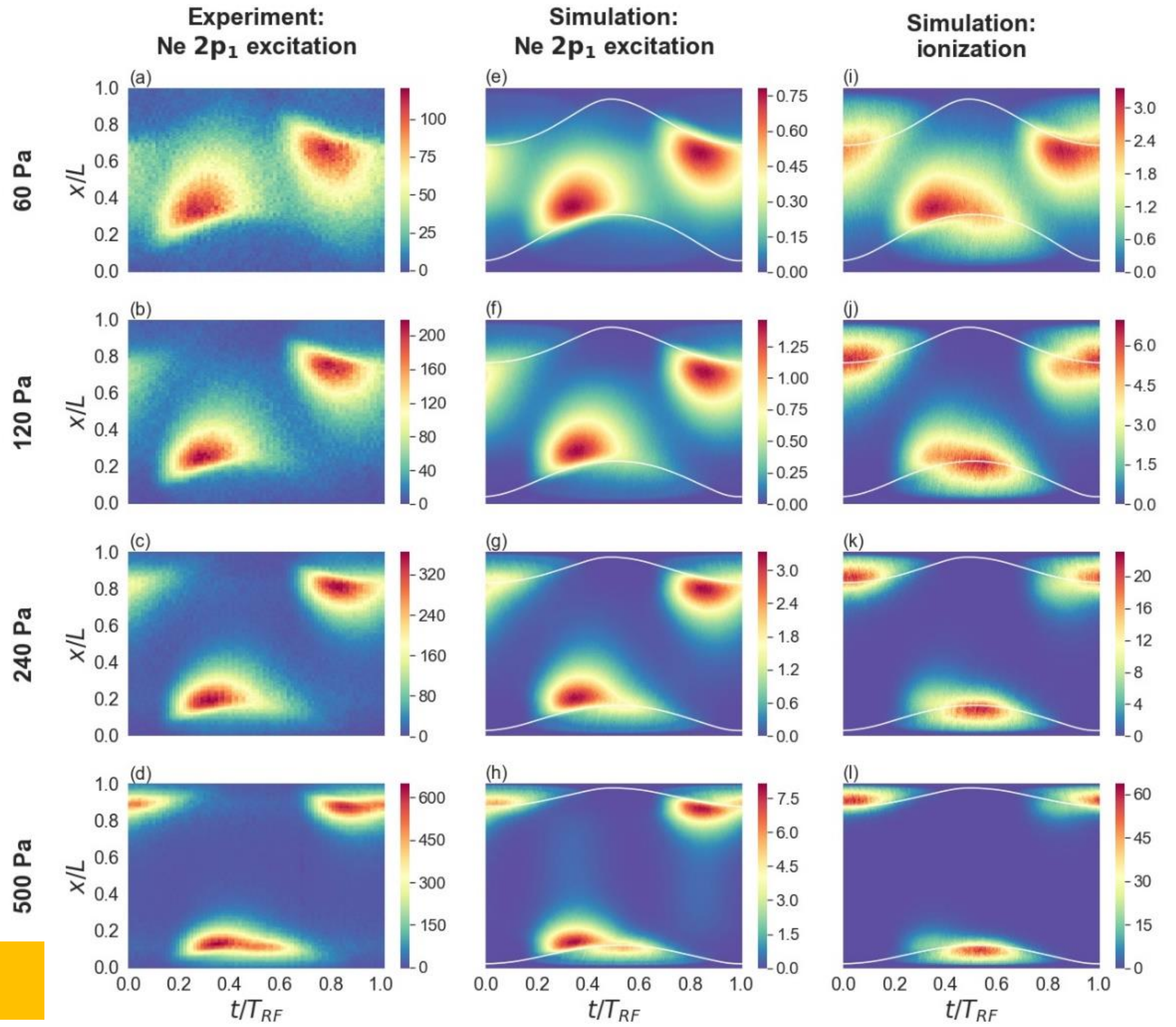
# Results



**$f$ = 6.78 MHz, $V_{pp}$ = 330 V**

- Simulation and experiment agrees well for the excitation rate
- Excitation:
  - Dominant at sheath expansion
  - A peak within the sheath appears for higher pressures
- Ionization:
  - Always present within the sheaths
  - A transition from $\alpha$- to $\gamma$-mode occurs

B. Horváth, A. Derzsi, J. Schulze, I. Korolov, P. Hartmann, and Z. Donkó *Plasma Sources Sci. Technol.* **29** 055002, 2020.



# Results



**$f$ = 3.39 MHz, $V_{pp}$ = 330 V**

- Simulation and experiment agrees well for the excitation rate
- Excitation:
  - Dominant at sheath expansion
  - A peak within the sheath intensifies with the increase of the pressure
- Ionization:
  - Dominant $\gamma$-mode for all pressures

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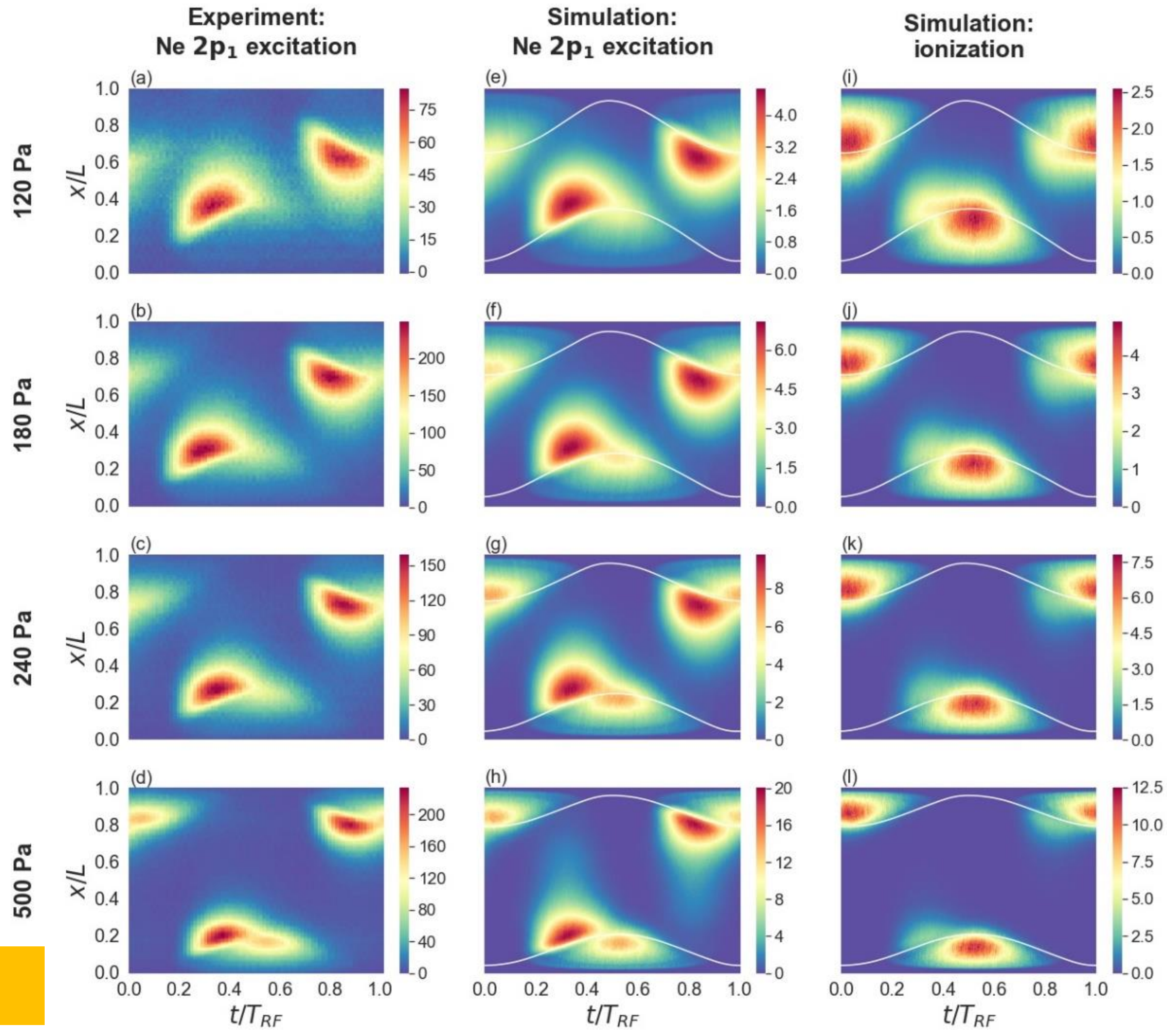
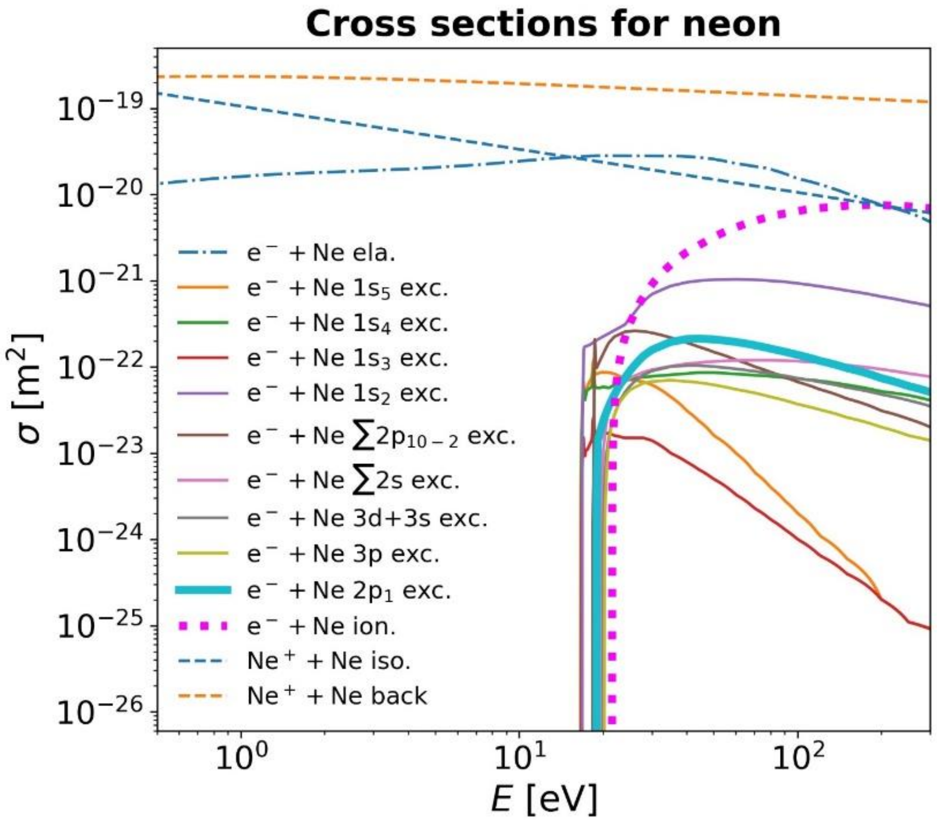
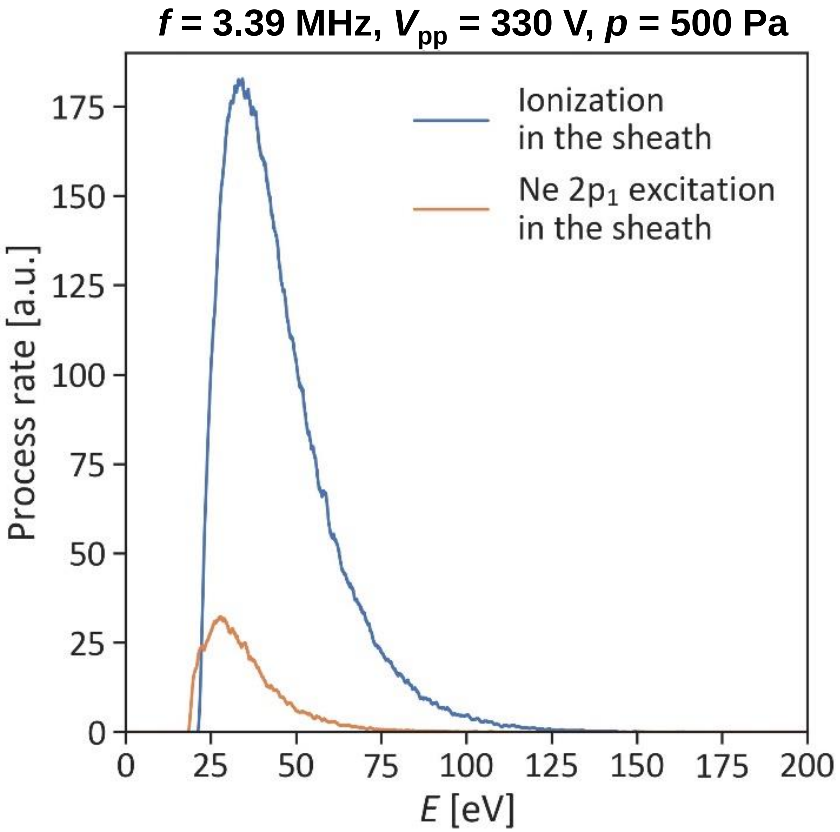


# Results






- The ionization dynamics is more sensitive to high-energy $\gamma$-electrons than the Ne $2p_1$ excitation dynamics.

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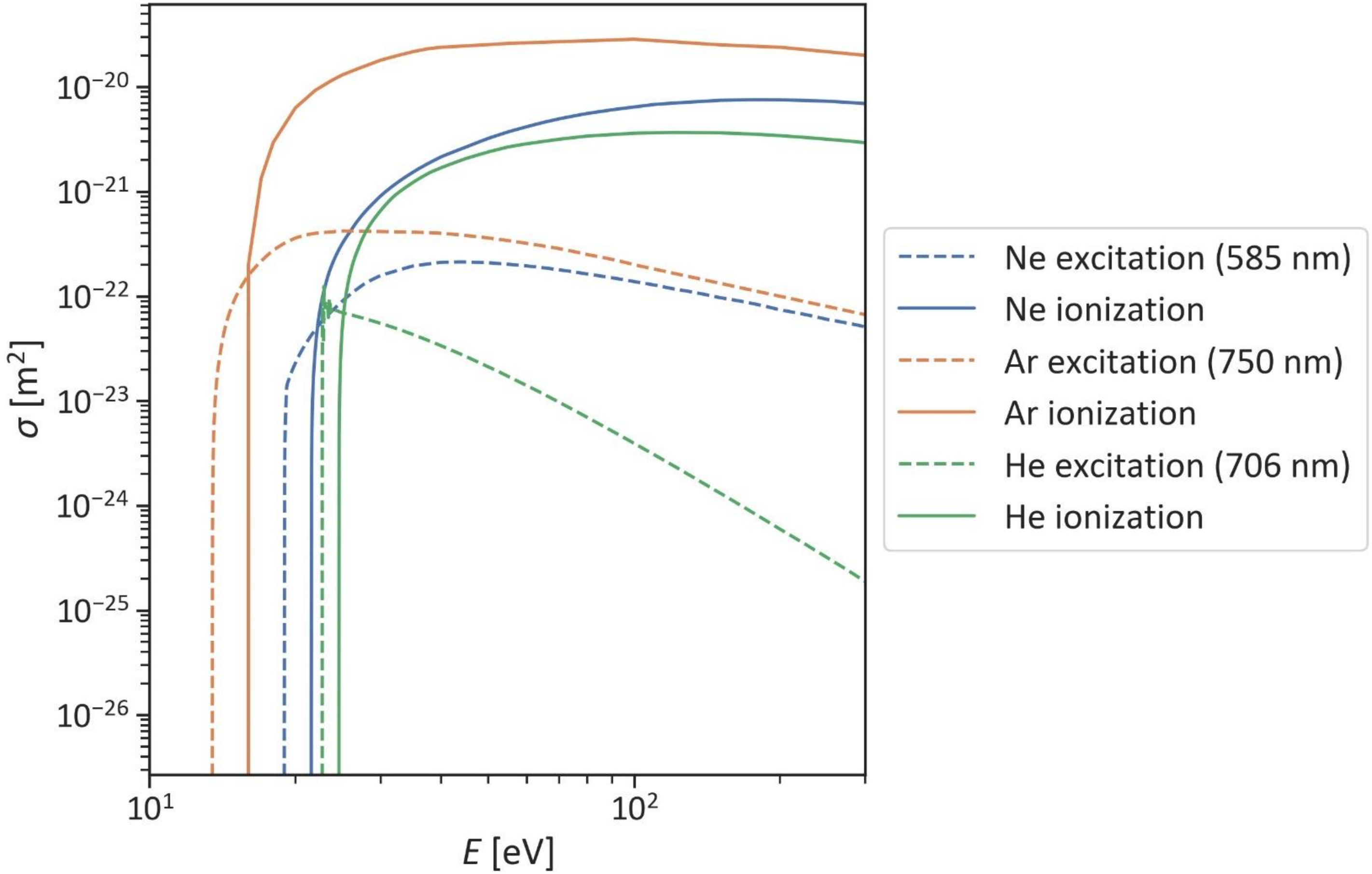
# Outlook: PROES in other gases



- A good agreement between the excitation rate and the ionization rate cannot be guaranteed.

- One should generally be careful with predicting the operation mode of the discharge based on PROES data.




Ar and He: Biagi database, www.lxcat.net, retrieved on February 18, 2020. Transcribed from S.F. Biagi's Fortran Magboltz, version 8.97 (Sept 2011).

# Conclusions



- PROES is limited to the observation of the dynamics of the electron-impact excitation from the ground state into the chosen excited state.
  - It can significantly differ from the ionization dynamics.
  - One should generally be careful with predicting the operation mode of the discharge based on PROES data.
- Energetic $\gamma$-electrons in neon cause ionization more likely than excitation because of the difference in the shape of the respective cross sections as a function of the electron energy.
- Both experiments and simulations confirm a transition of the discharge operation mode in neon from the $\alpha$-mode to the $\gamma$-mode by increasing the pressure at a fixed frequency and voltage amplitude.
- The value of the $\gamma$ secondary electron emission coefficient is crucial in PIC/MCC simulations to obtain realistic results.

*Thank you for your attention!*

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