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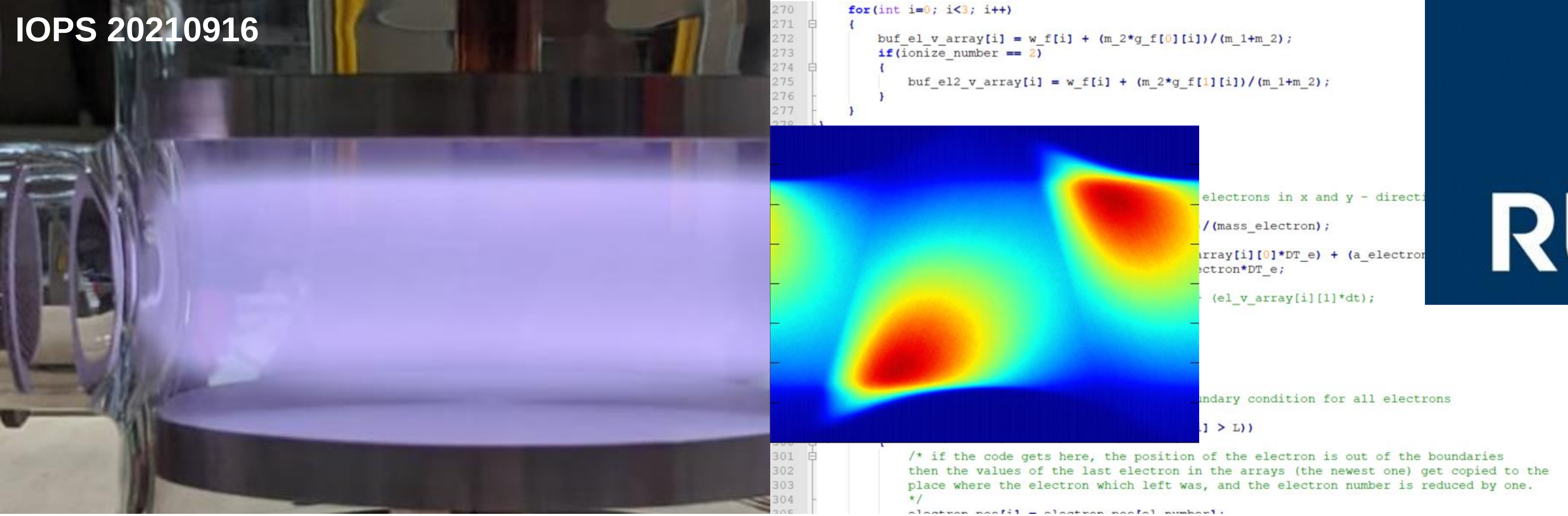

RUHR-UNIVERSITÄT BOCHUM

Multi-diagnostic experimental validation of 1d3v PIC/MCC simulations of low pressure RF CCPs in argon

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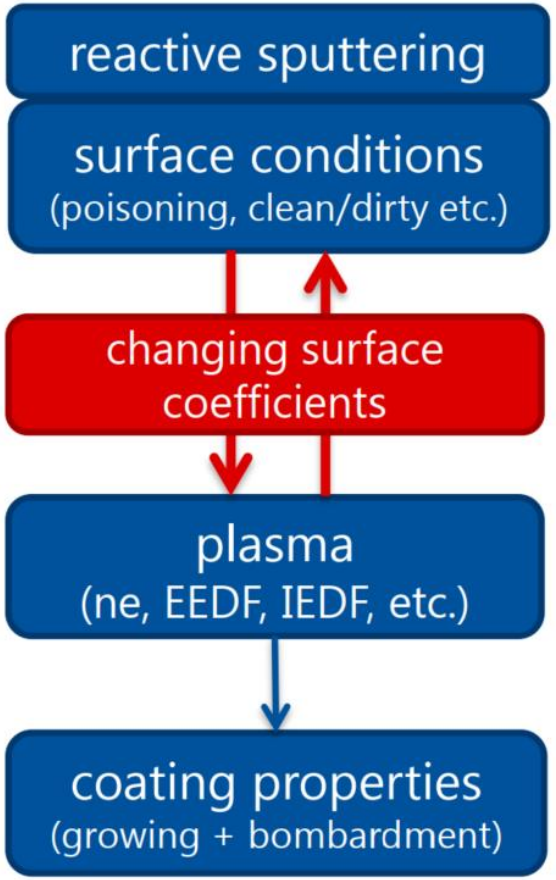
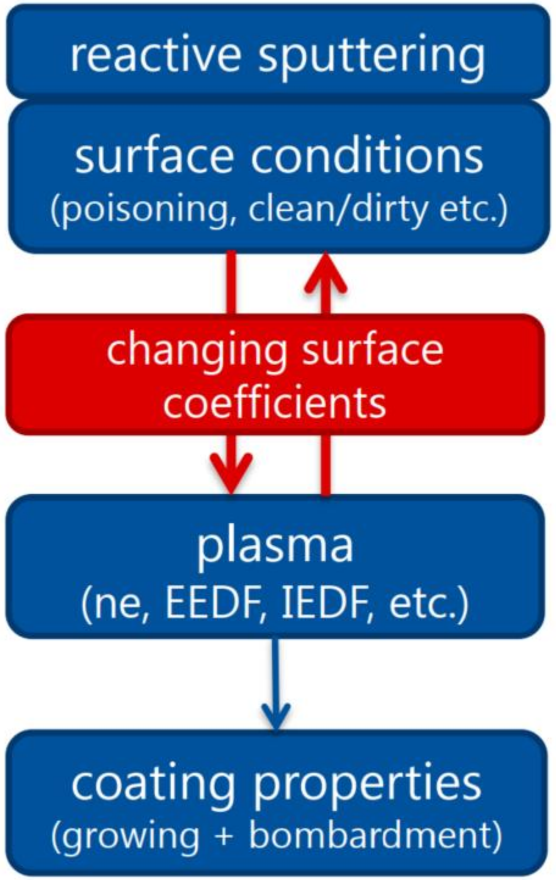
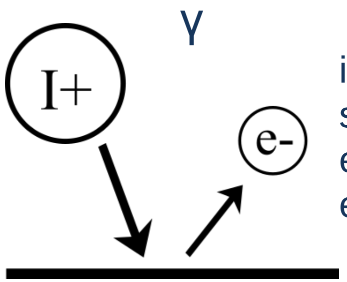
[3] Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, 1121 Budapest, Hungary
[4] Key Laboratory of Materials Modification by Laser, Ion and Electron Beams, School of Physics, Dalian University of Technology, China

Motivation

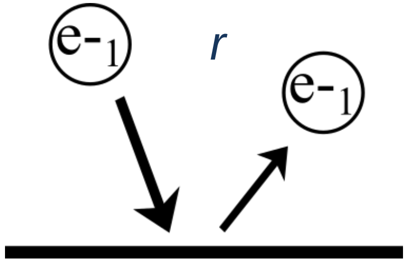

reactive sputtering
surface conditions
(poisoning, clean/dirty etc.)
changing surface coefficients
plasma
(ne, EEDF, IEDF, etc.)
coating properties
(growing + bombardment)

Motivation

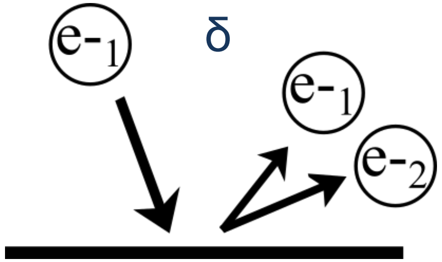




ion induced secondary electron emission

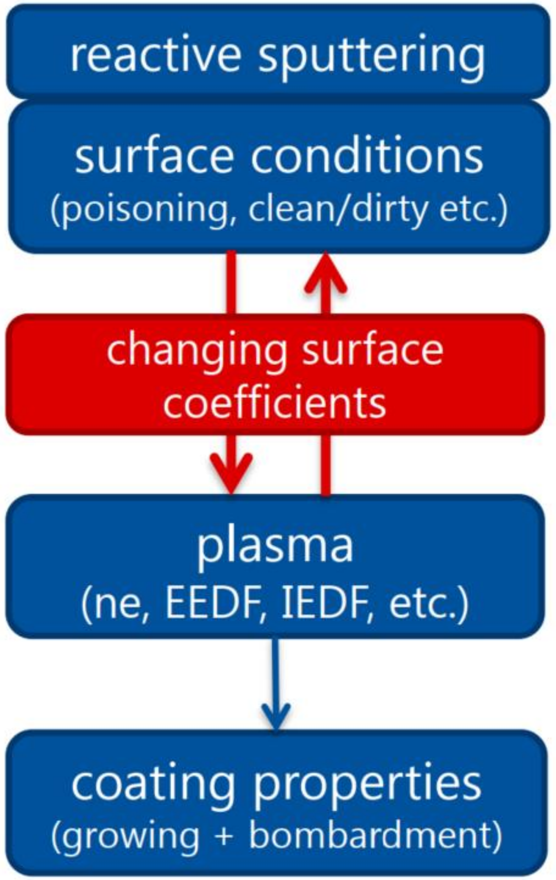


electron reflection

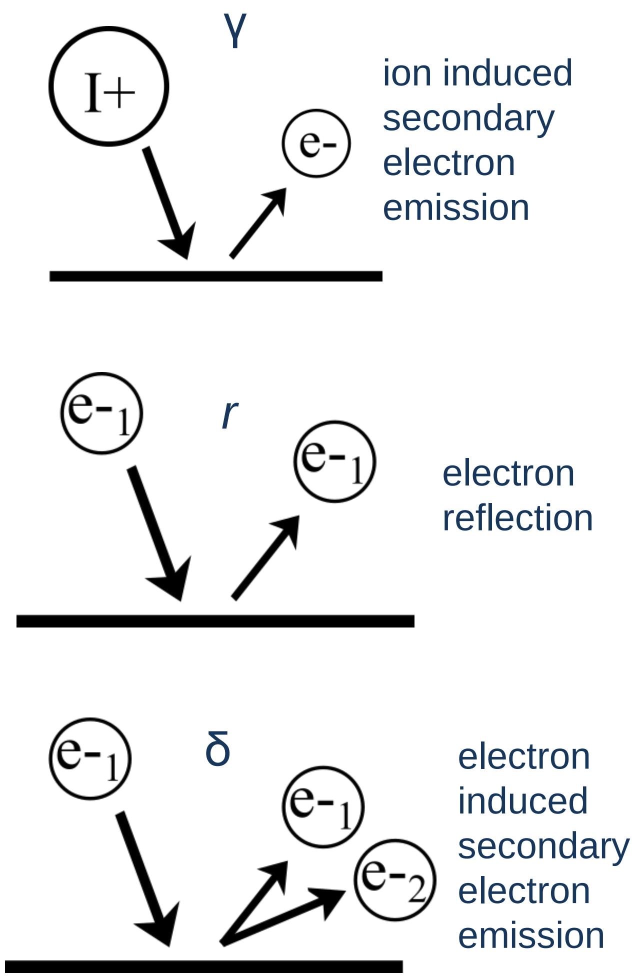


electron induced secondary electron emission

Motivation



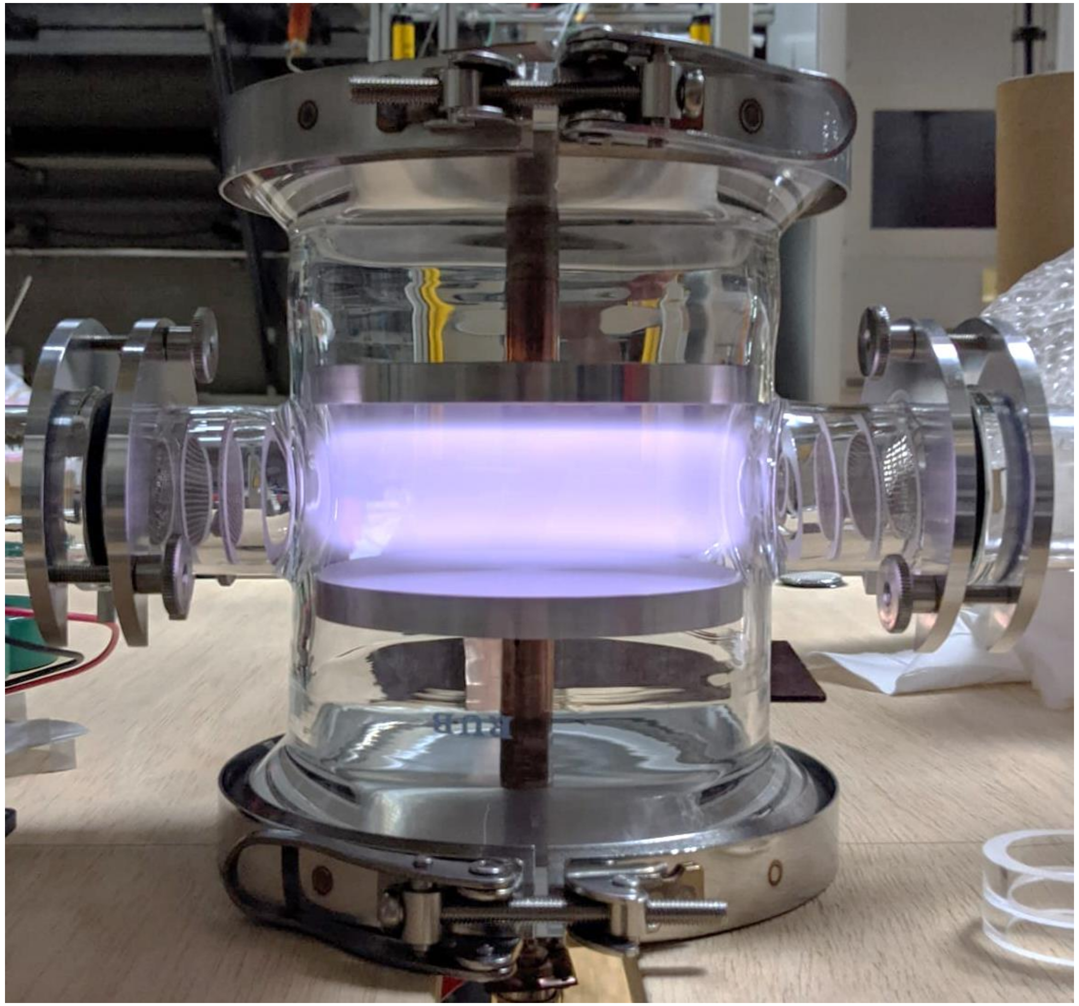
- **Increasing demand for simulations with well known input parameters, especially surface coefficients**
    - γ(E), r(*E*), δ(E) **not known under plasma conditions**
    - especially sputtering: dirty process
    - coefficients must be obtained under these conditions
- **→ CCP reference cell in combination with PIC simulation**
    - 1D simulation needs symmetric experiment for direct comparison
    - systematic, multi-diagnostic comparison PIC <> experiment
- PIC (in this case): $r_{\mathrm{eff}} = r + \delta = \frac{\text{\# of electrons leaving the surface}}{\text{\# of electrons reaching the surface}}$



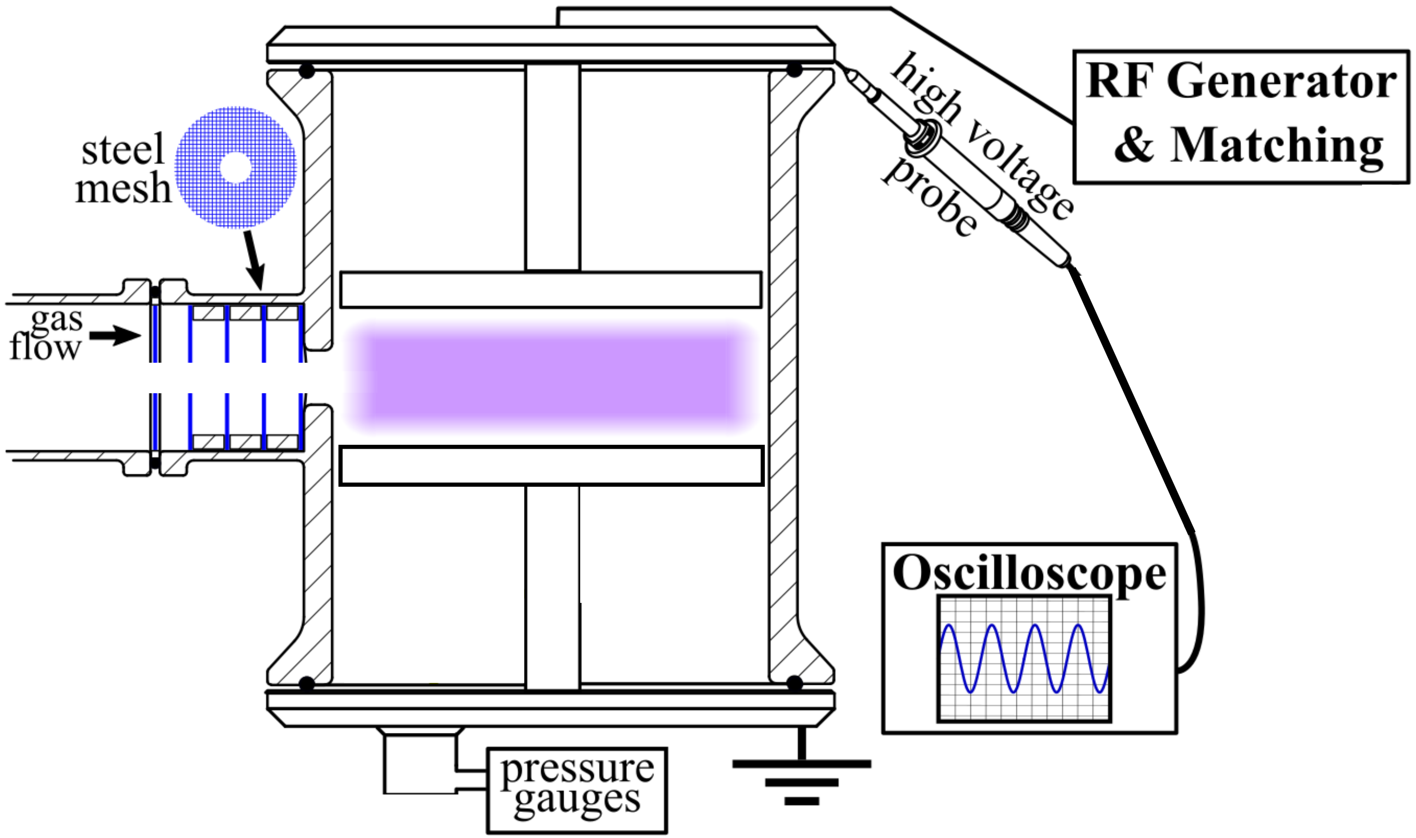
The experimental setup

The experimental setup – Photo and basic data

- electrode gap: 40 mm
- frequency: 13.56 MHz
- voltage waveform: sine
- voltage amplitudes: 150 V – 350 V
- pressure: 1 Pa - 100 Pa
- gas: Ar (5.0)
- base pressure: ~5E-5 Pa
- leakage rate: ~1E-4 sccm
- gas flow: ~1 to 10 sccm
- diagnostics:
  - Phase resolved optical emission spectroscopy (PROES)
  - Langmuir probe
  - Retrading field energy analyzer (RFEA)
  - Tunable diode laser absorption spectroscopy (TDLAS)



The experimental setup – Diagnostics 1



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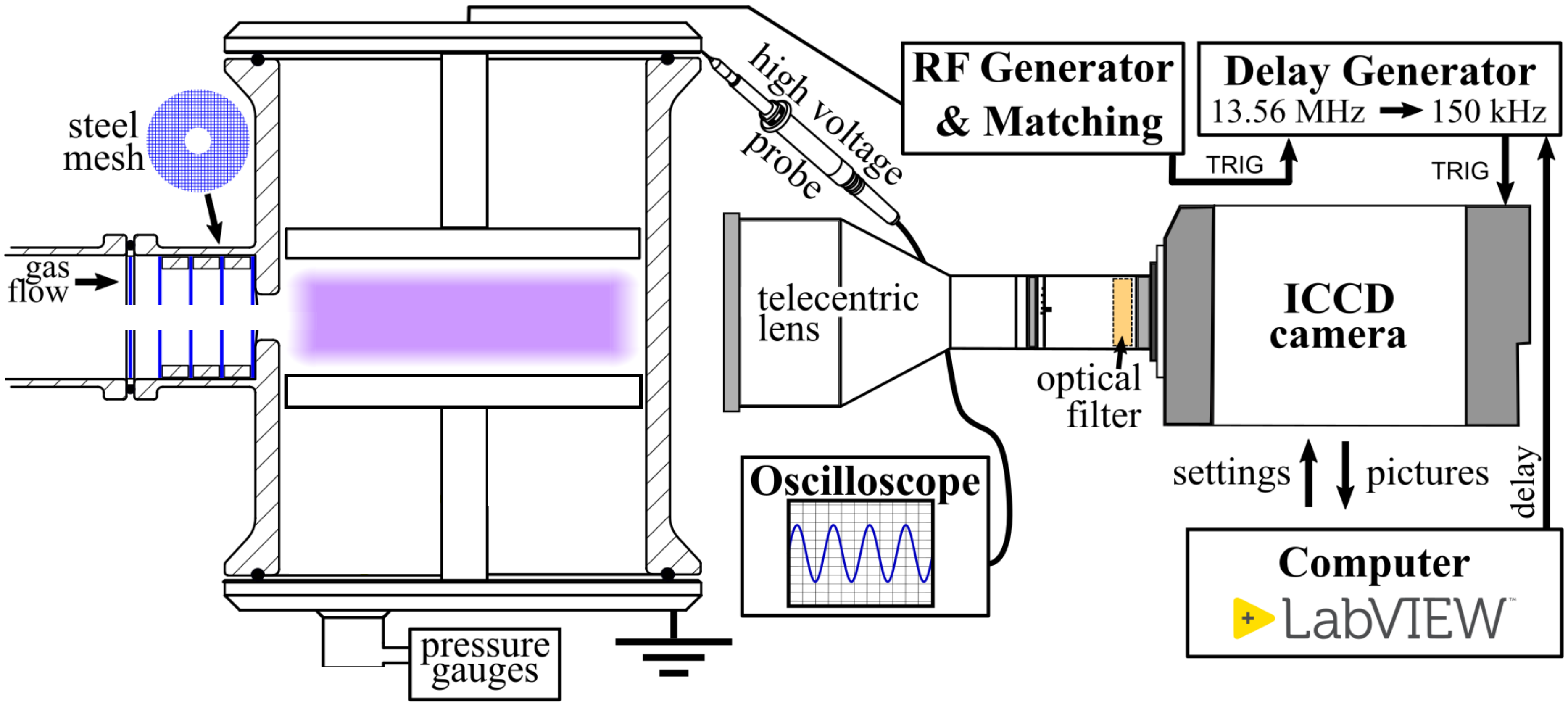

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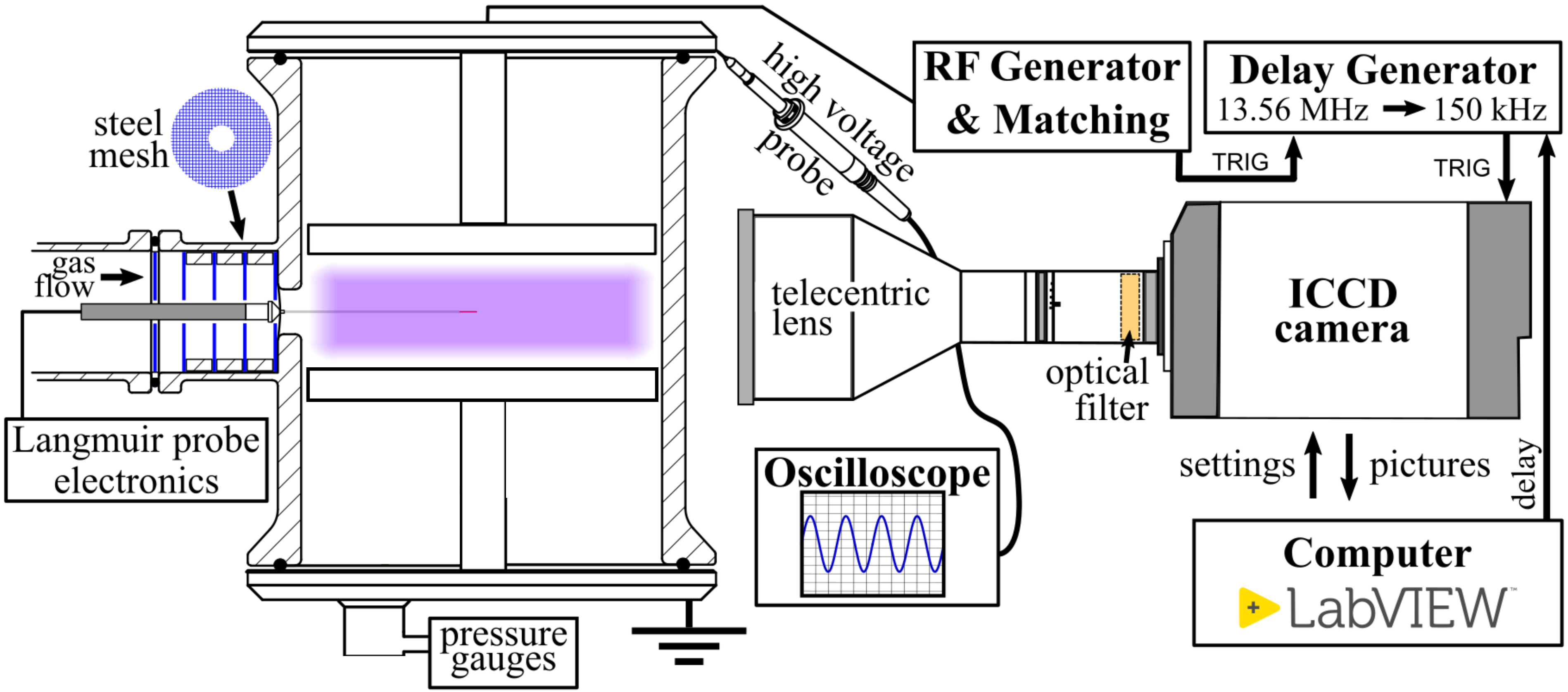

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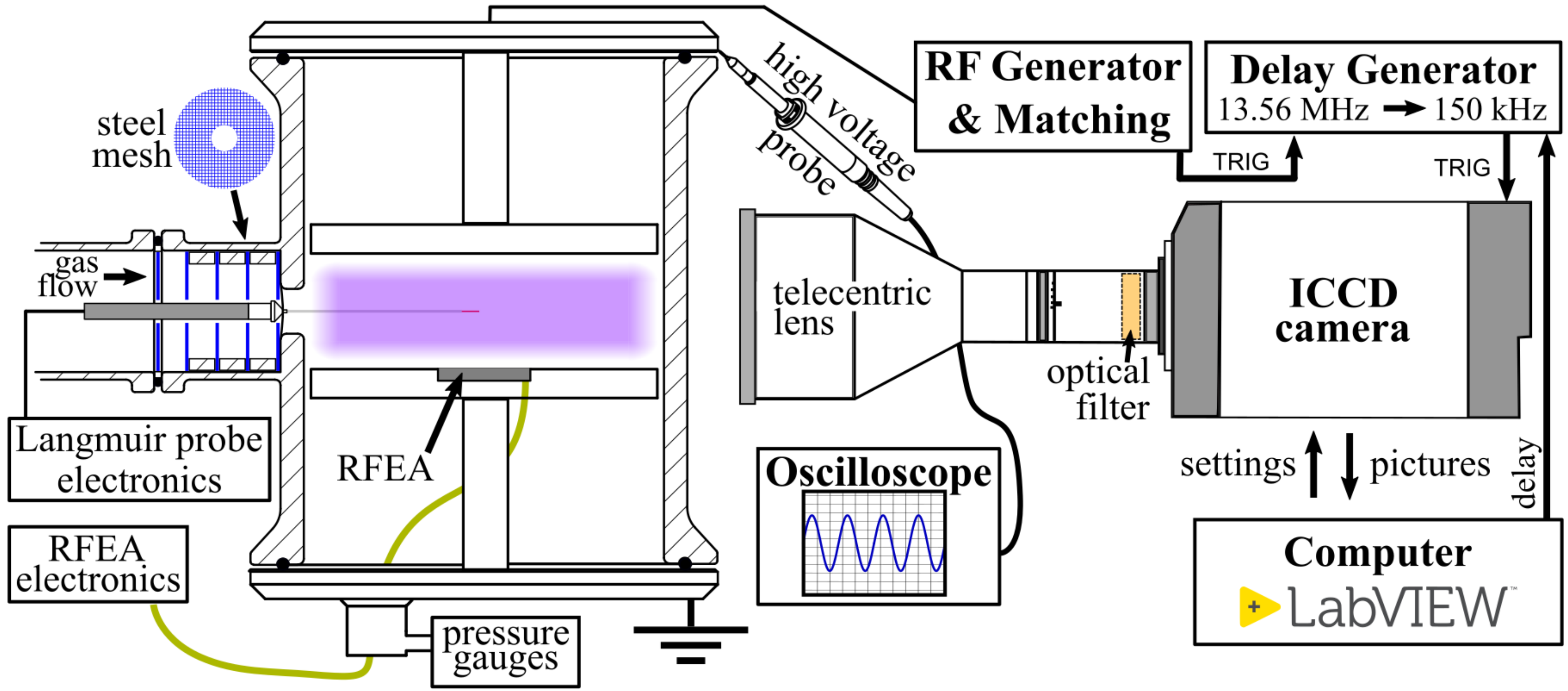
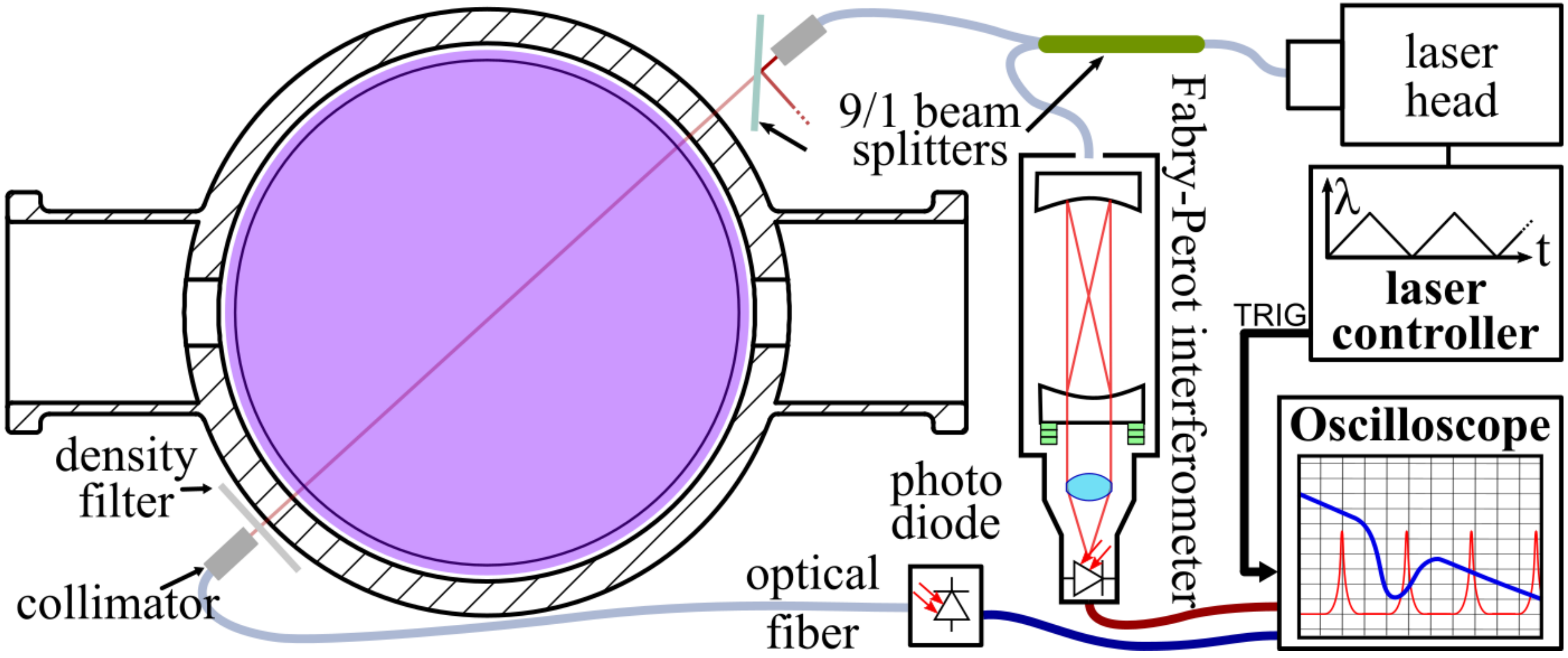


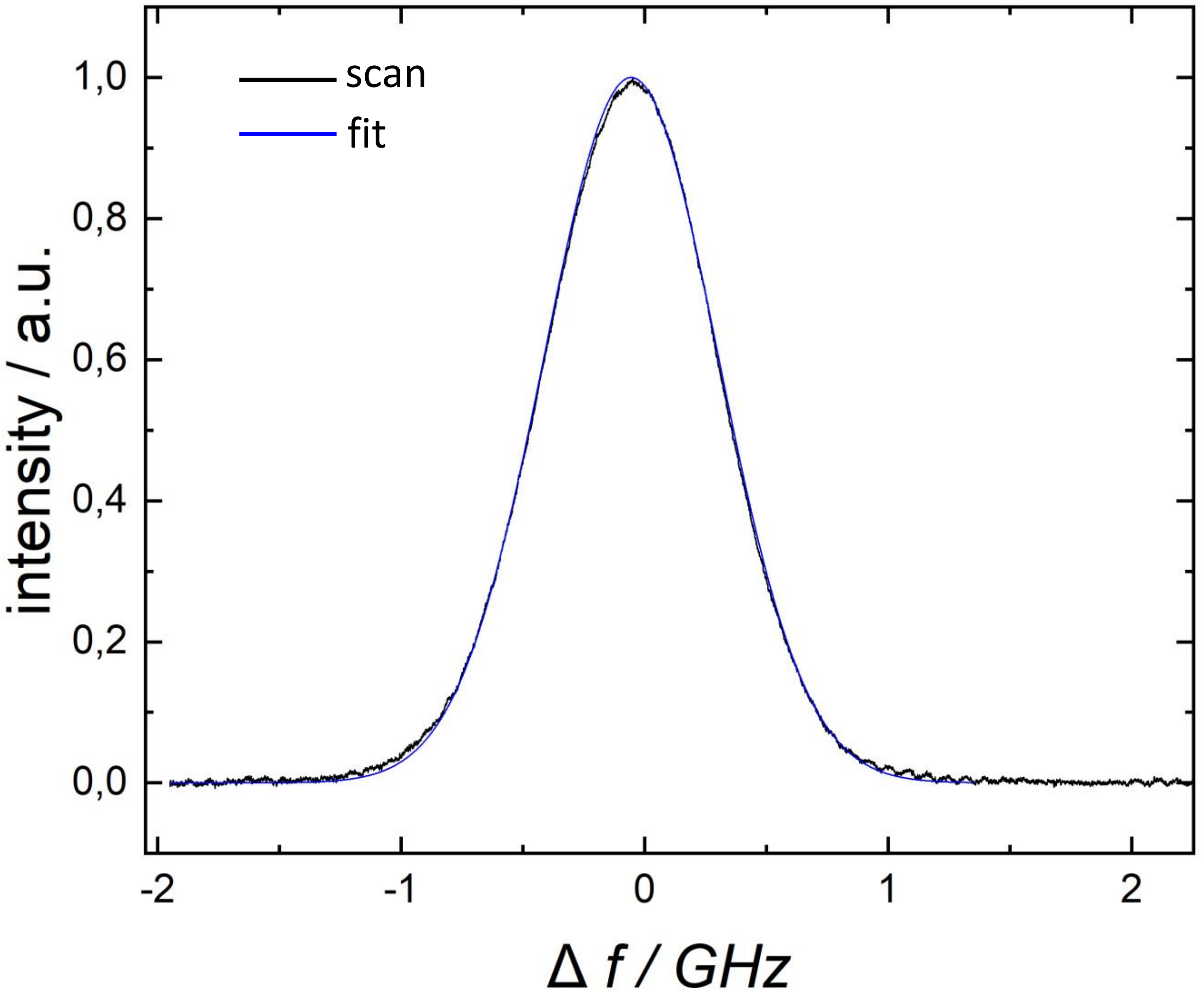
The experimental setup – Diagnostics 2



Results: neutral gas temperature

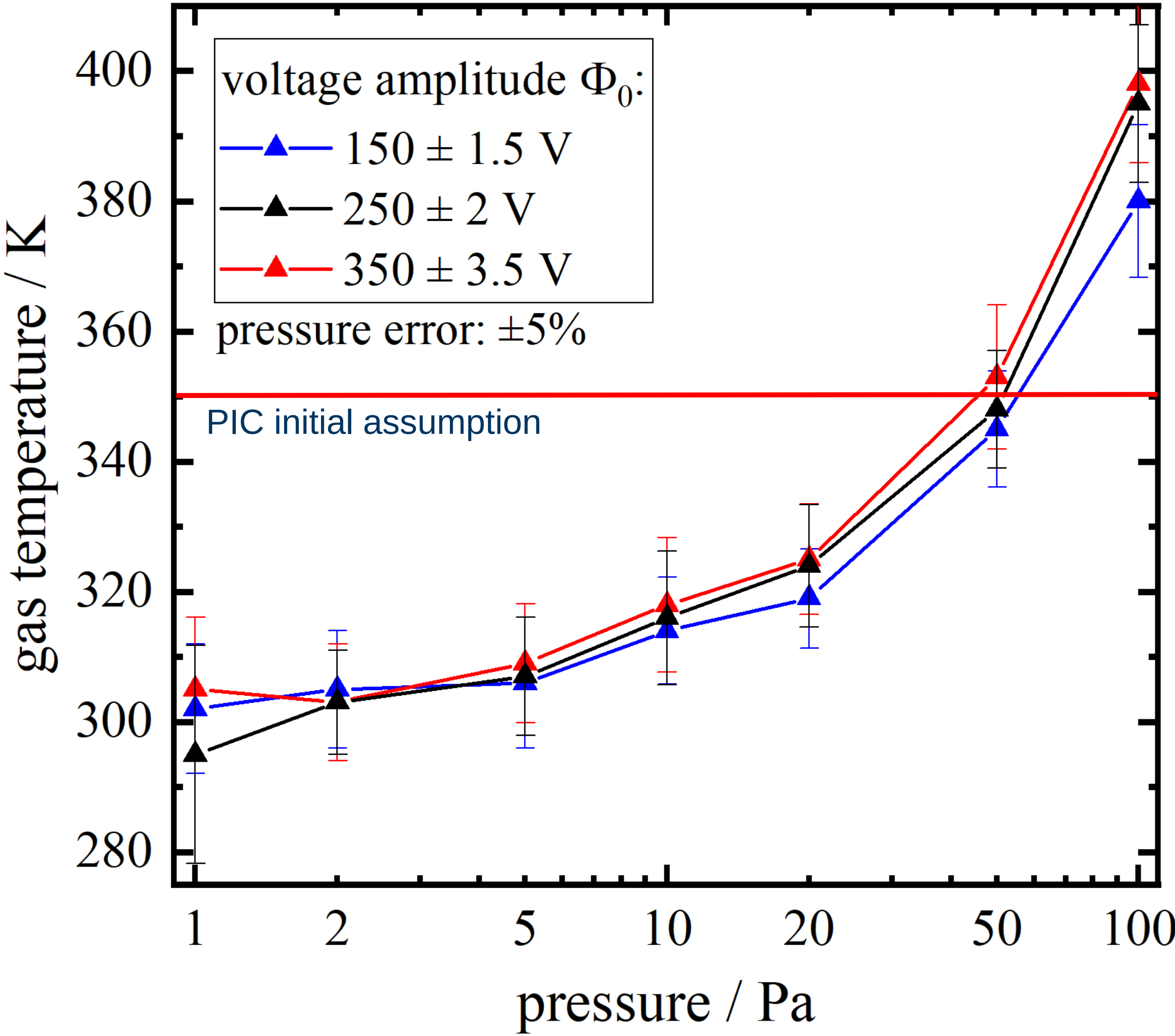
Tunable Diode Laser Absorption Spectroscopy

- scan of an argon metastable absorption line (772.37 nm) with a tunable diode laser
- Scanned line has a gaussian shape due to doppler broadening
  → determination of temperature via gaussian fit
- Ar* are not charged, therefor: metastable temperature = gas temperature



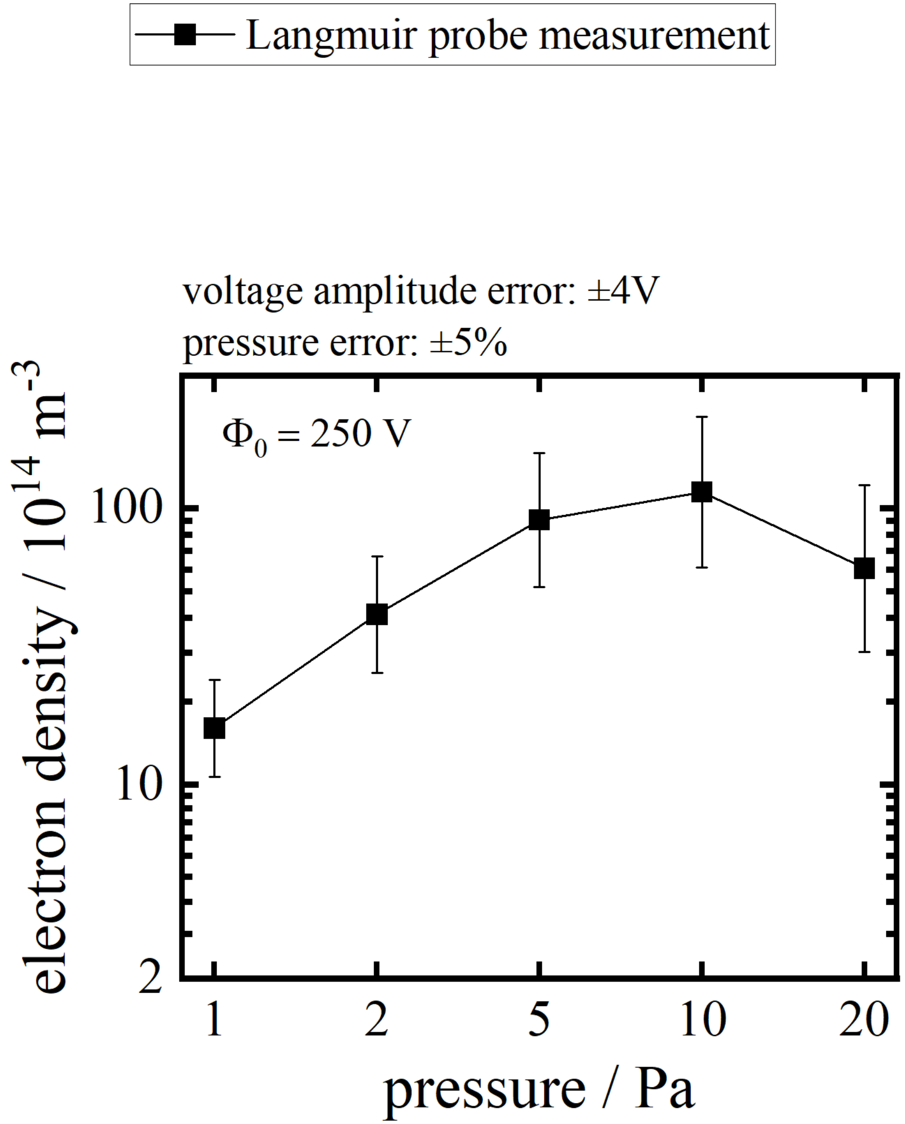
The neutral gas temperature in the symm. CCP

- **Gas temperature determined with TDLAS in the middle of the discharge**
- **Strongly pressure dependent**
- **Weakly driving voltage dependent for investigated conditions**
- **Initial assumption of constant 350 K is quite far off for most of the cases**



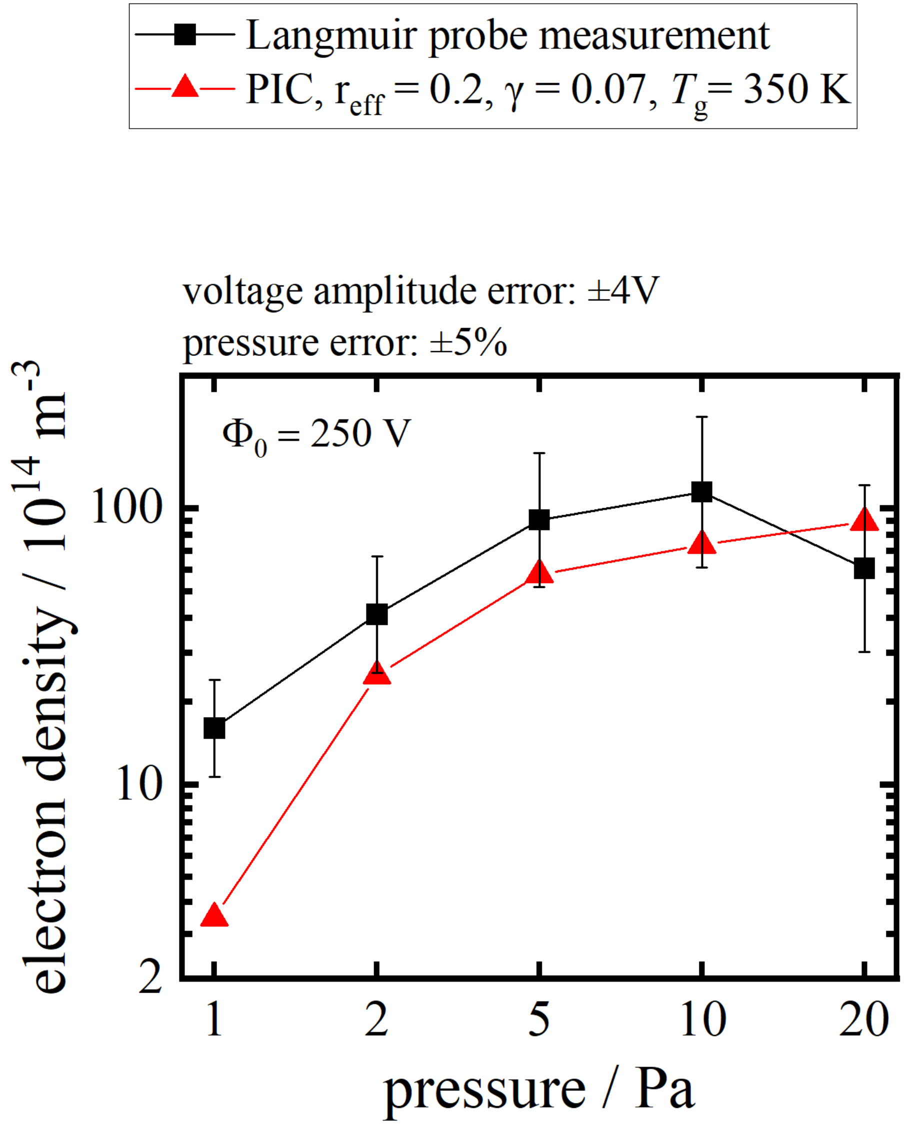
Results: electron density

Central plasma density: experiment vs simulation



Central plasma density: experiment vs simulation

- experiment and simulation “base case” results agree well in the high-pressure range
- clear deviation at the lowest pressures



γ-value:
A. V. Phelps and Z. Lj. Petrović, PSST 8 (1999)
M. Daksha et al., J. Phys. D 2016 49 234001

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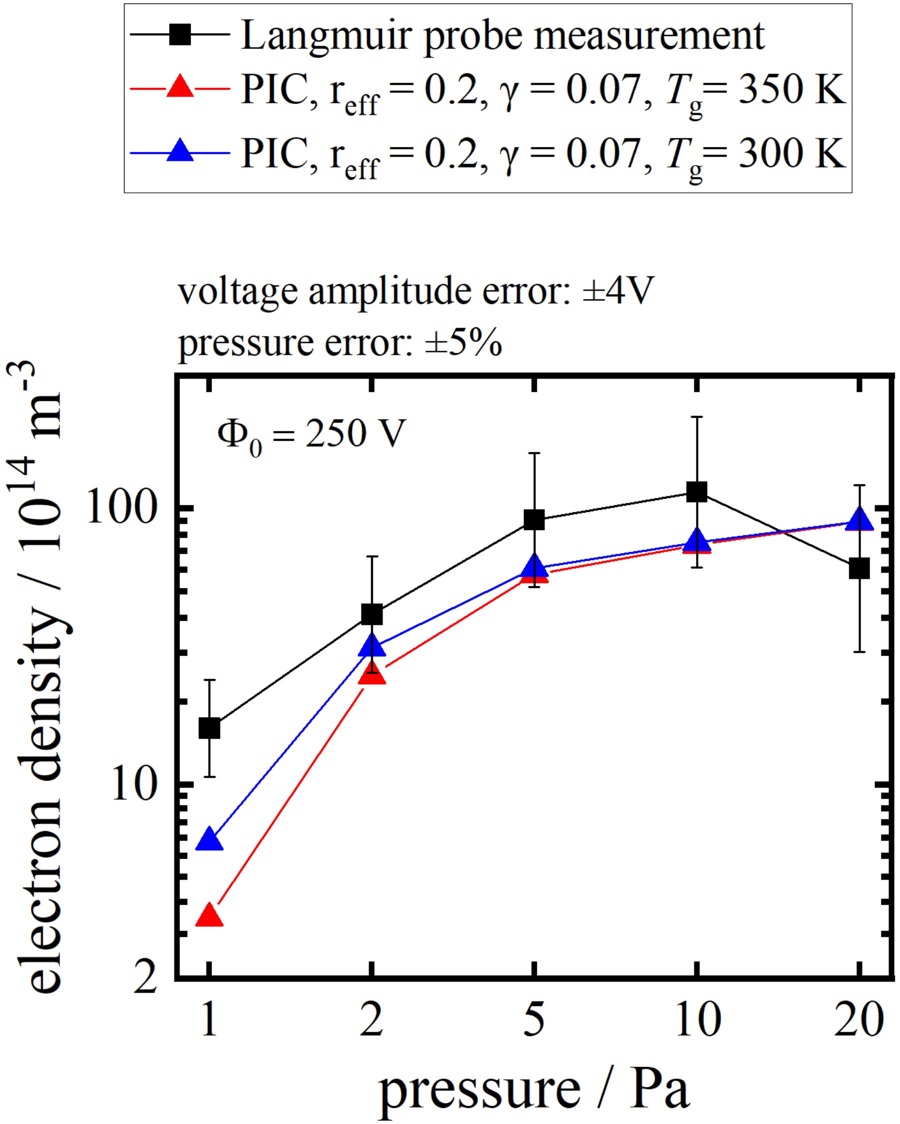

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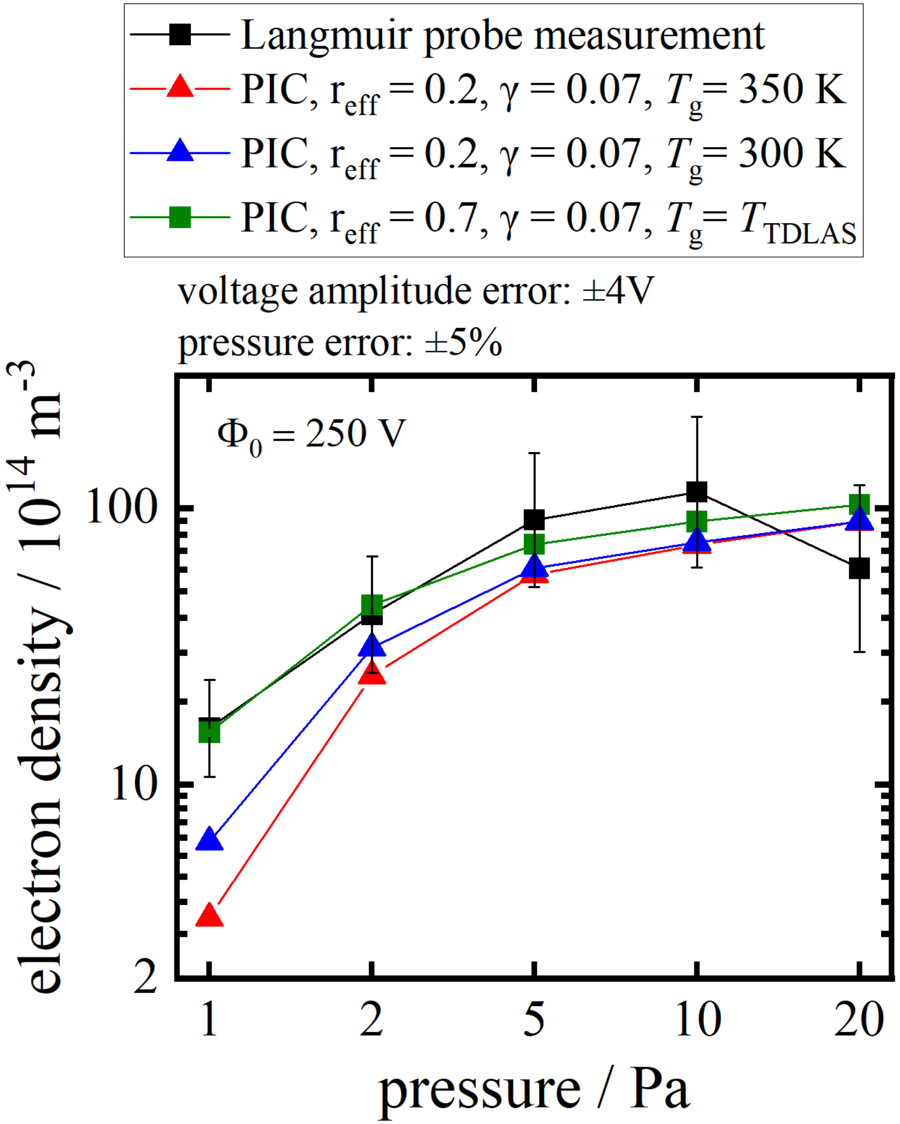
  $r_{\text{eff}} = 0.7$, $\gamma = 0.07$, $T_{gas} =$ measured



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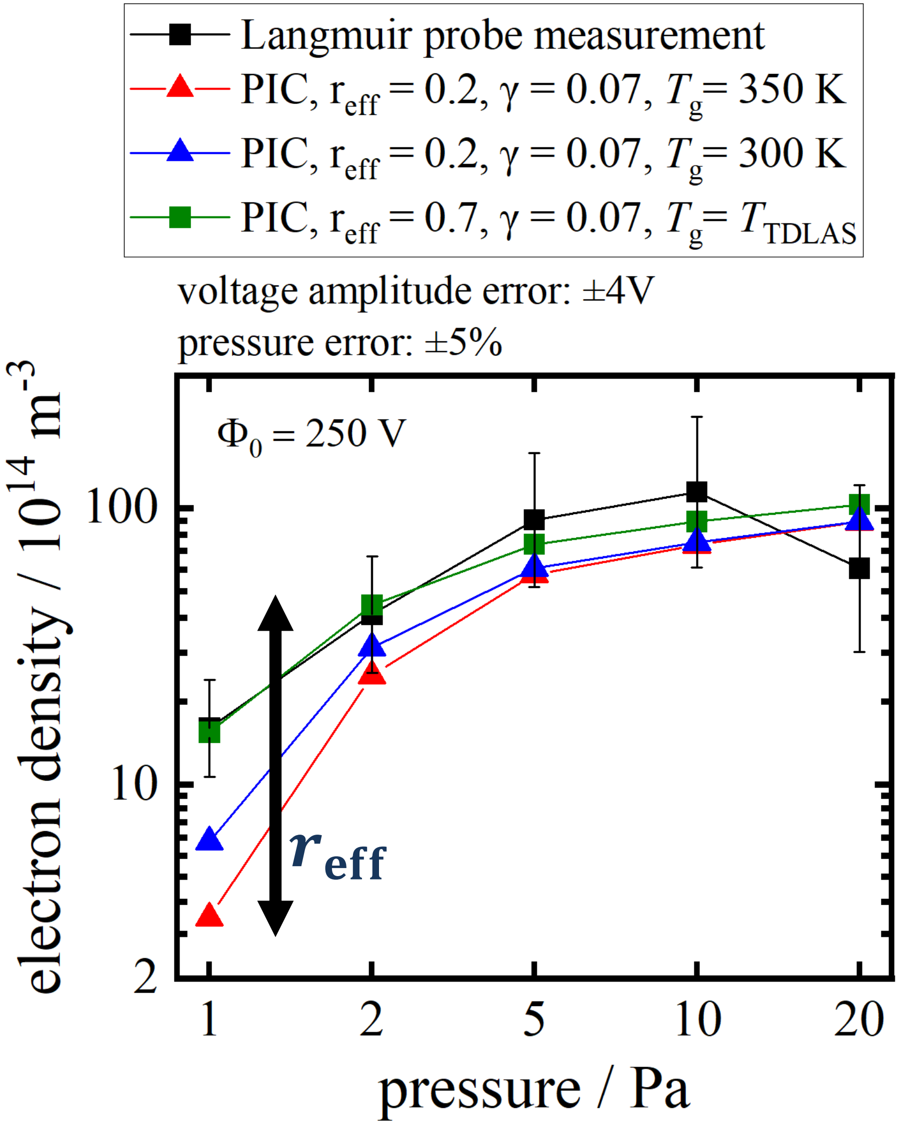

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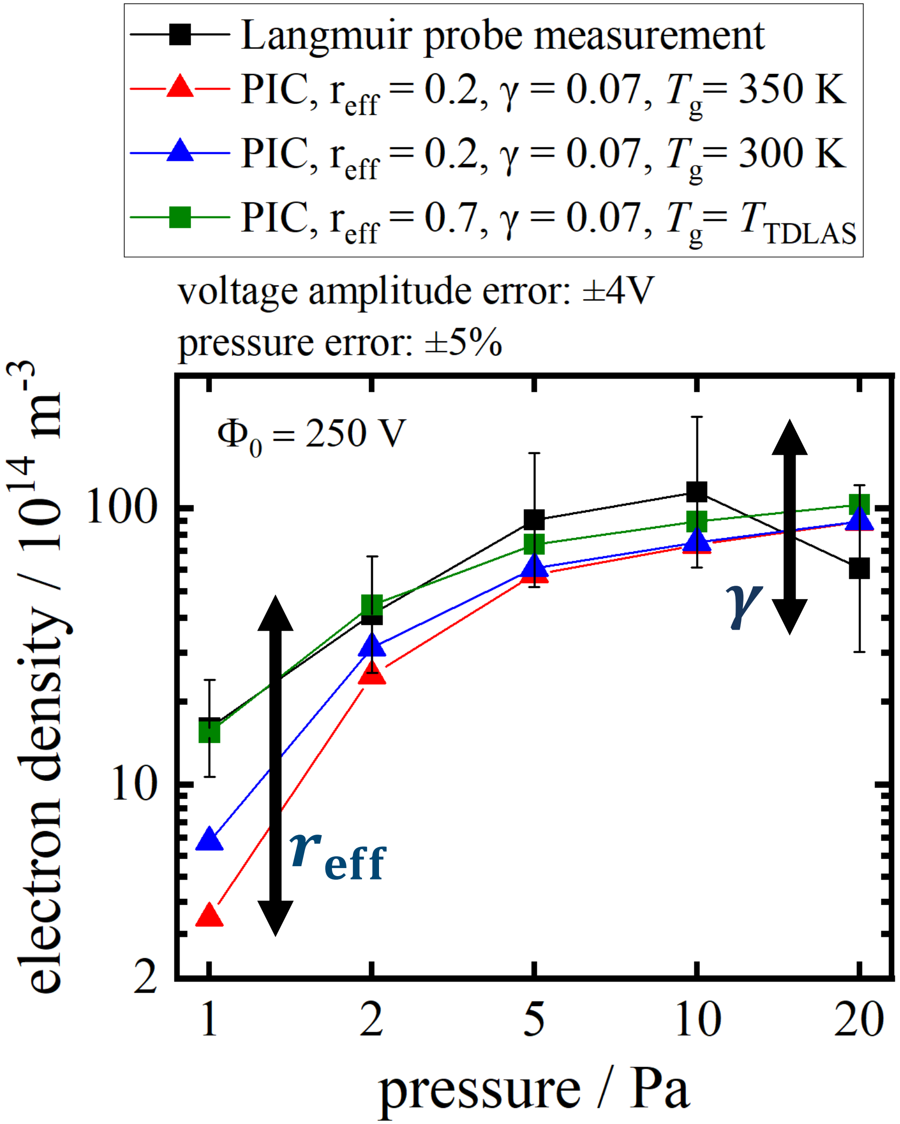

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wigner

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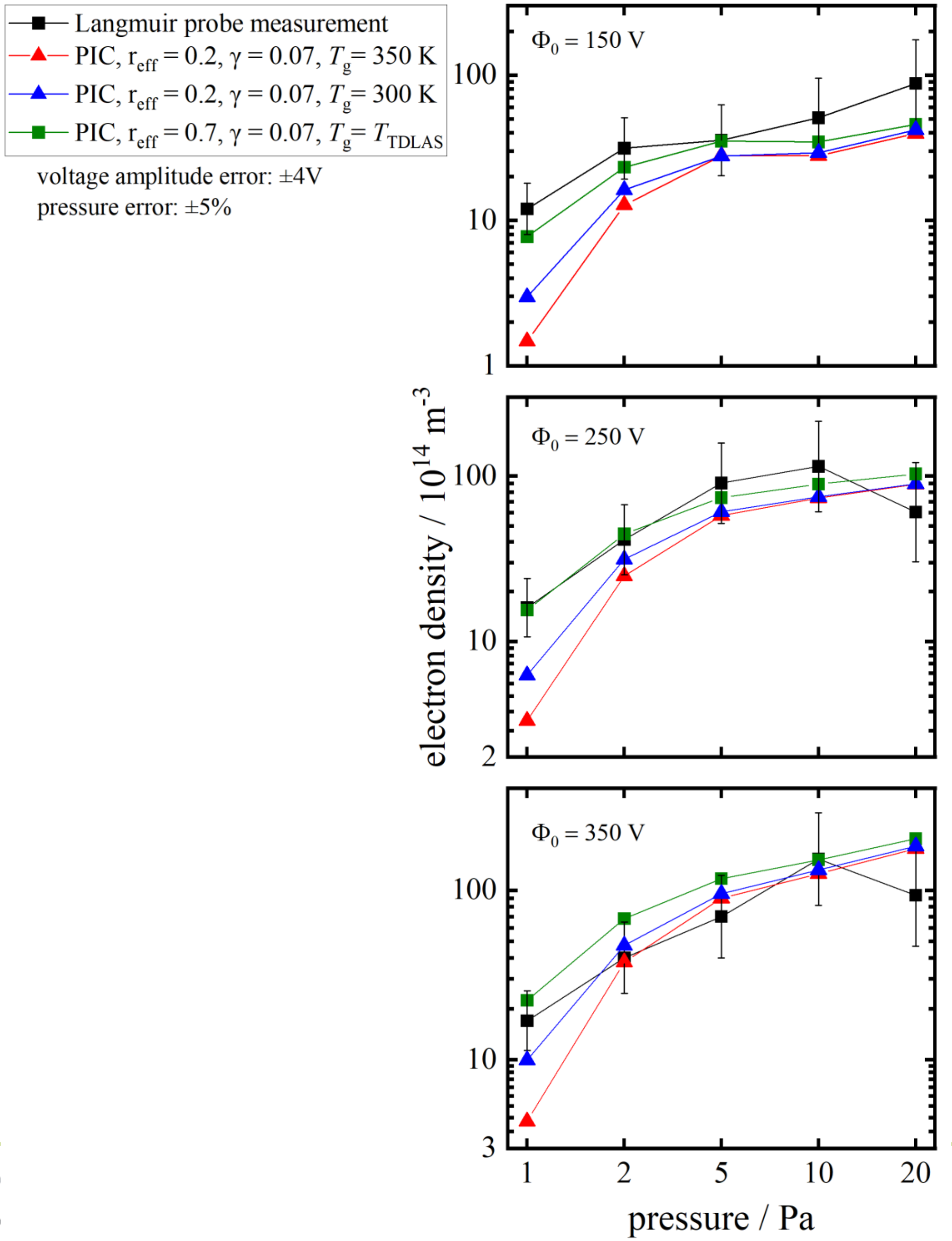
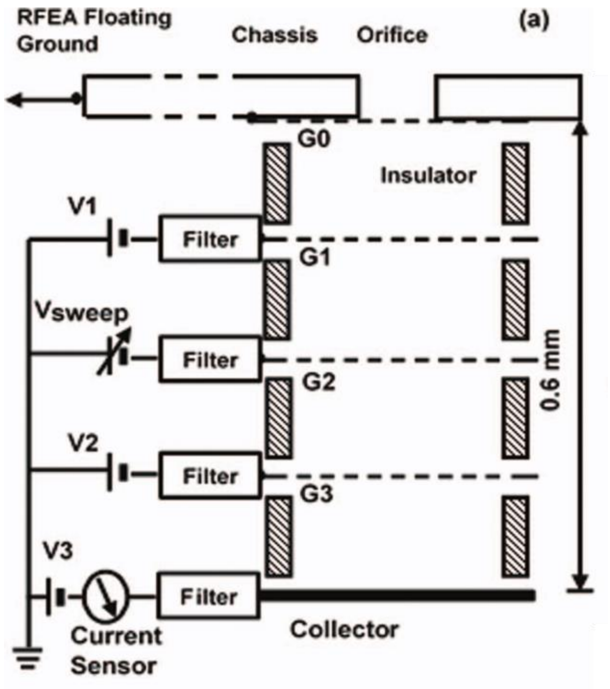


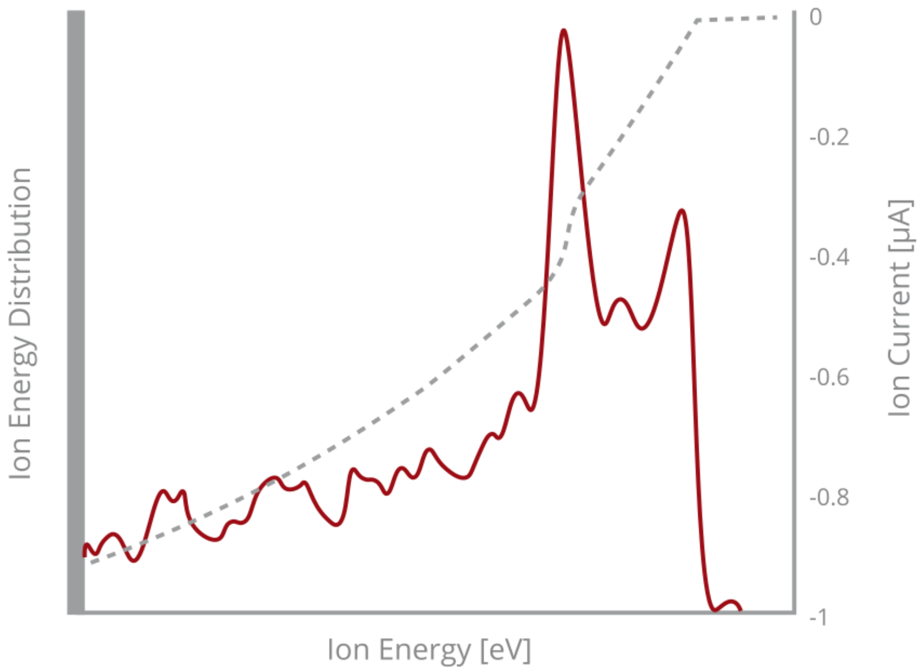
Results: ion energy distribution function

Retarding Field Energy Analyzer

- **stack of metal grids on selected potentials to let only ions reach the collector**
- **voltage sweep on G2 → limit energy of arriving ions**
- **derivative of ion current at the collector gives energy dependent ion flux**



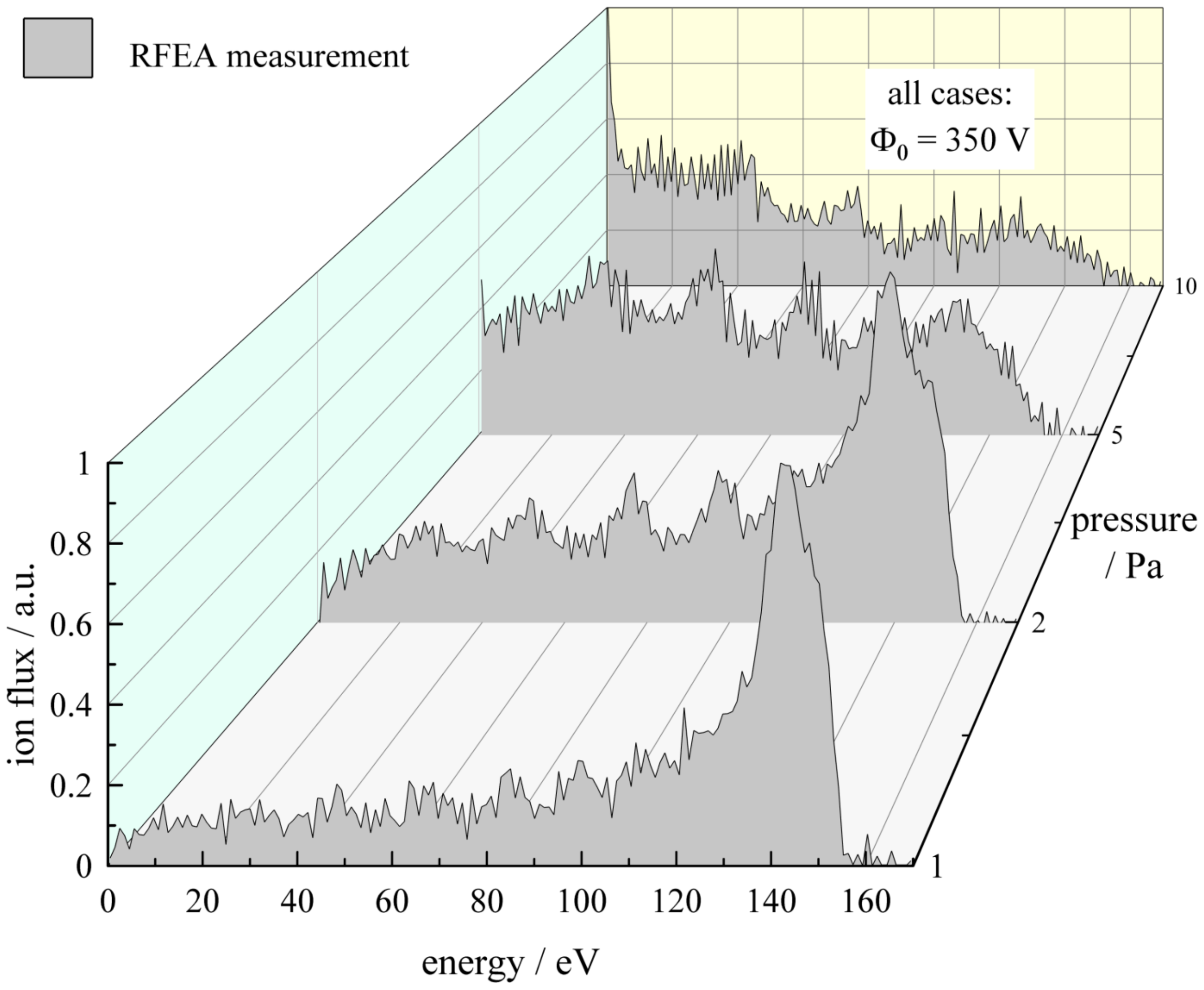
Schematic of the grid structure in the used RFEA. S. Sharma *et. al.*, Rev. Sci. Inst., vol. 85, no. 4, p. 043509, 2014



Example of typical RFEA measurement result: current-voltage-characteristic (grey dashed) and IEDF (red). Impedans Ltd., “THEORY OF OPERATION Semion System Retarding Potential Analyser”

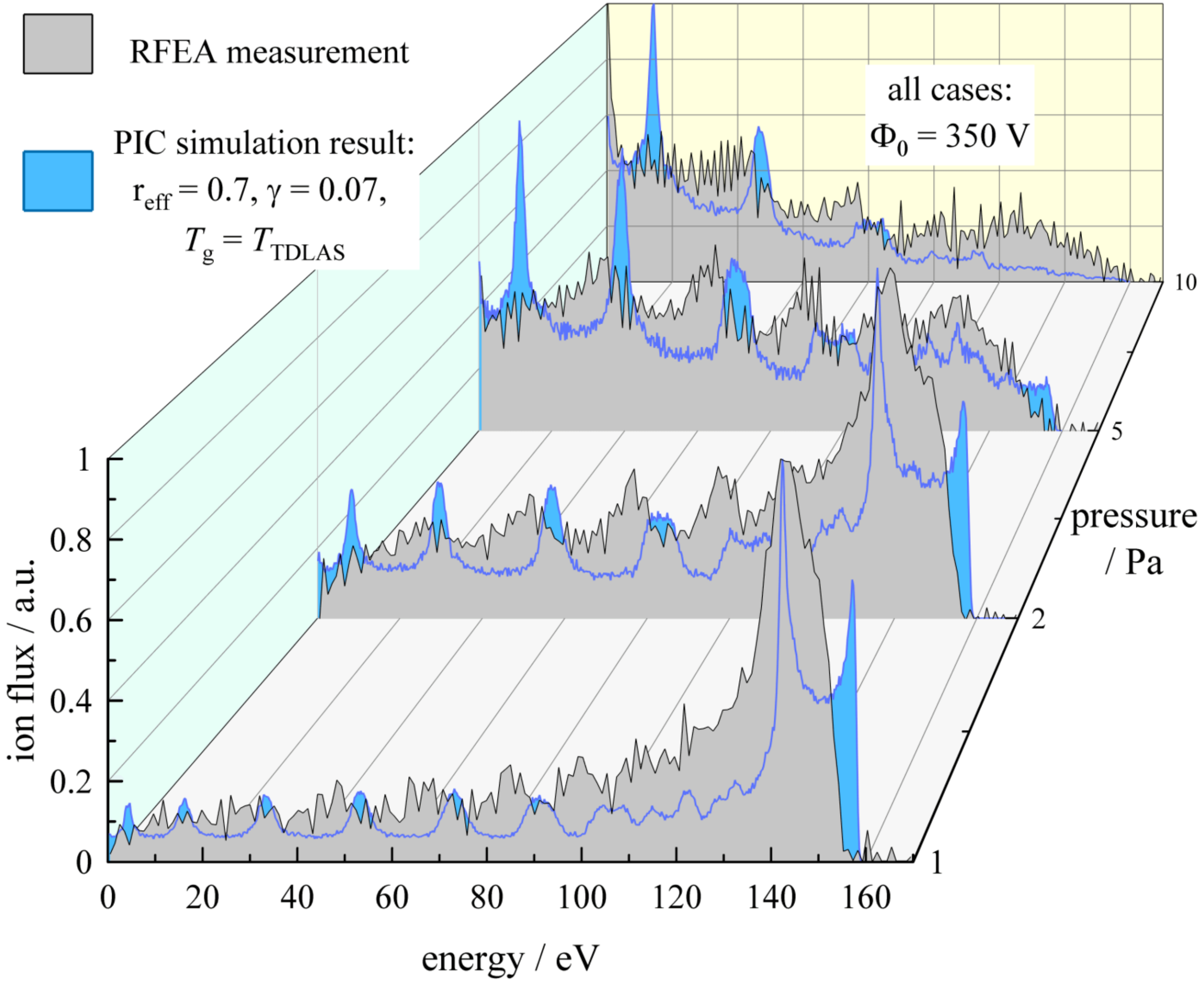
IEDFs: pressure variation

- high energy peak disappears with rising pressure due to more collisions



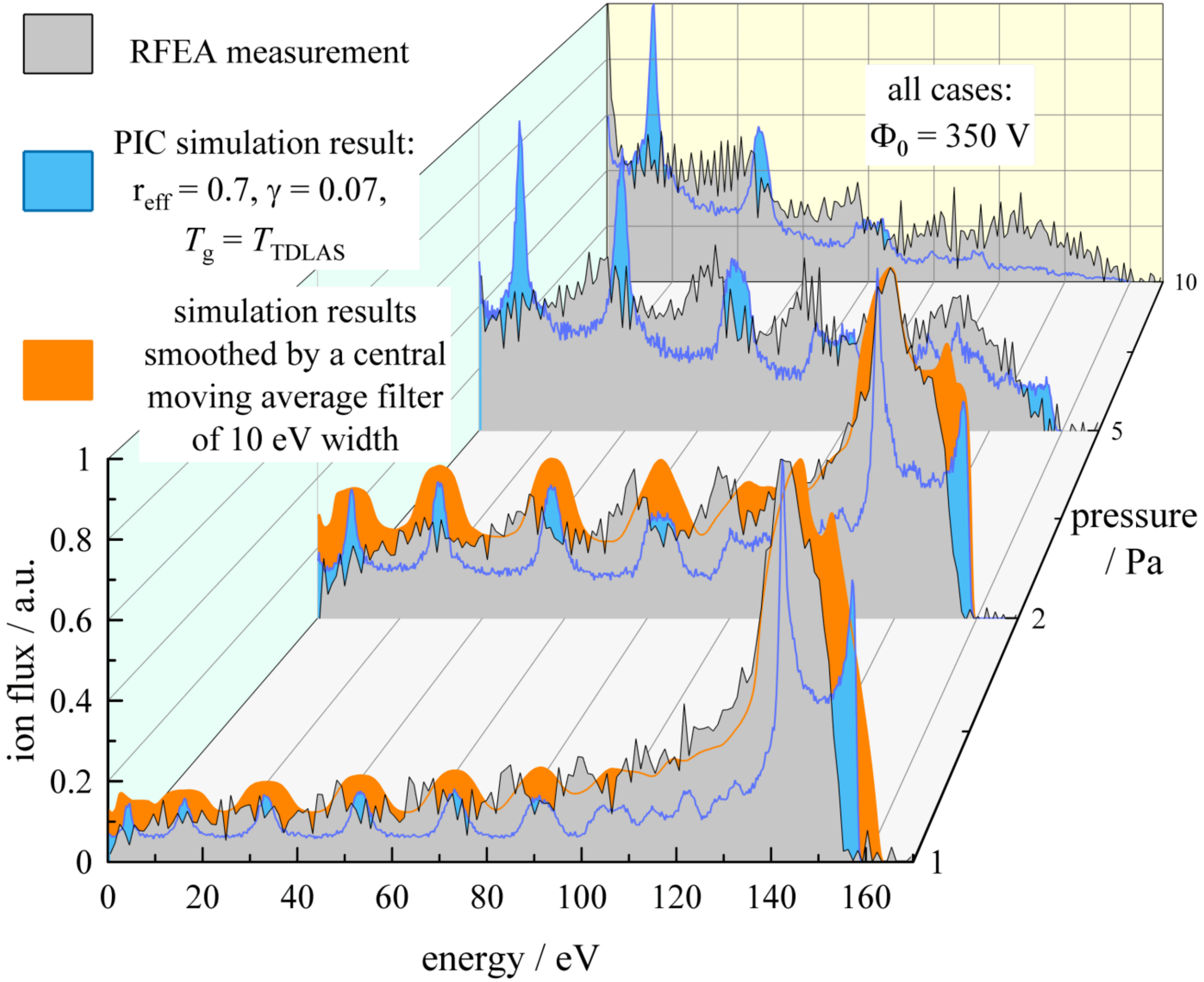
IEDFs: pressure variation

- high energy peak disappears with rising pressure due to more collisions
- shift between experiment and simulation
- good agreement between number of simulated & measured peaks positions
- lowest peak at higher pressures can not be measured



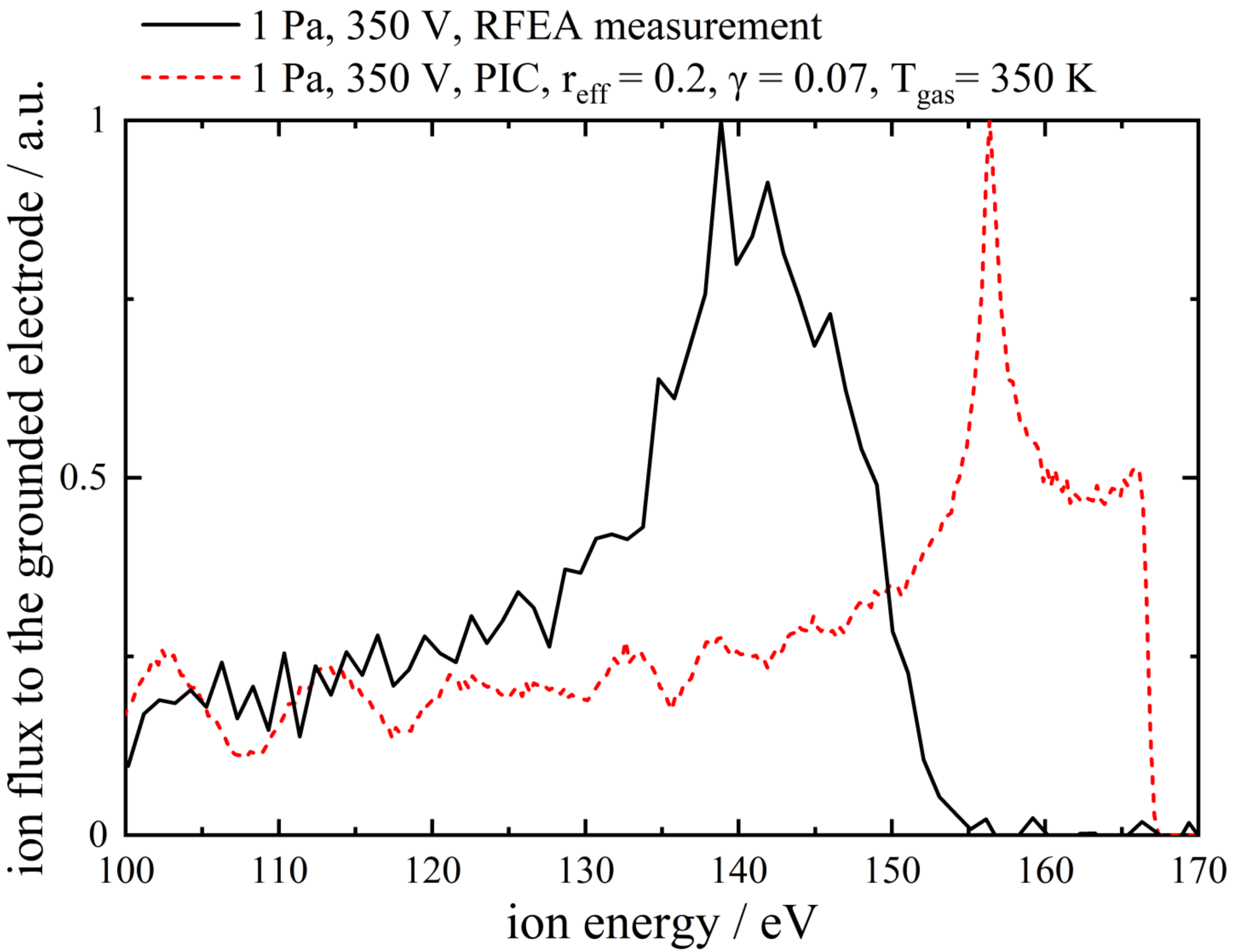
IEDFs: pressure variation

- **high energy peak disappears with rising pressure due to more collisions**
- **shift between experiment and simulation**
- **good agreement between number of simulated & measured peaks positions**
- **lowest peak at higher pressures can not be measured**
- **resolution of the RFEA is ≠ grid voltage step (1 V)**



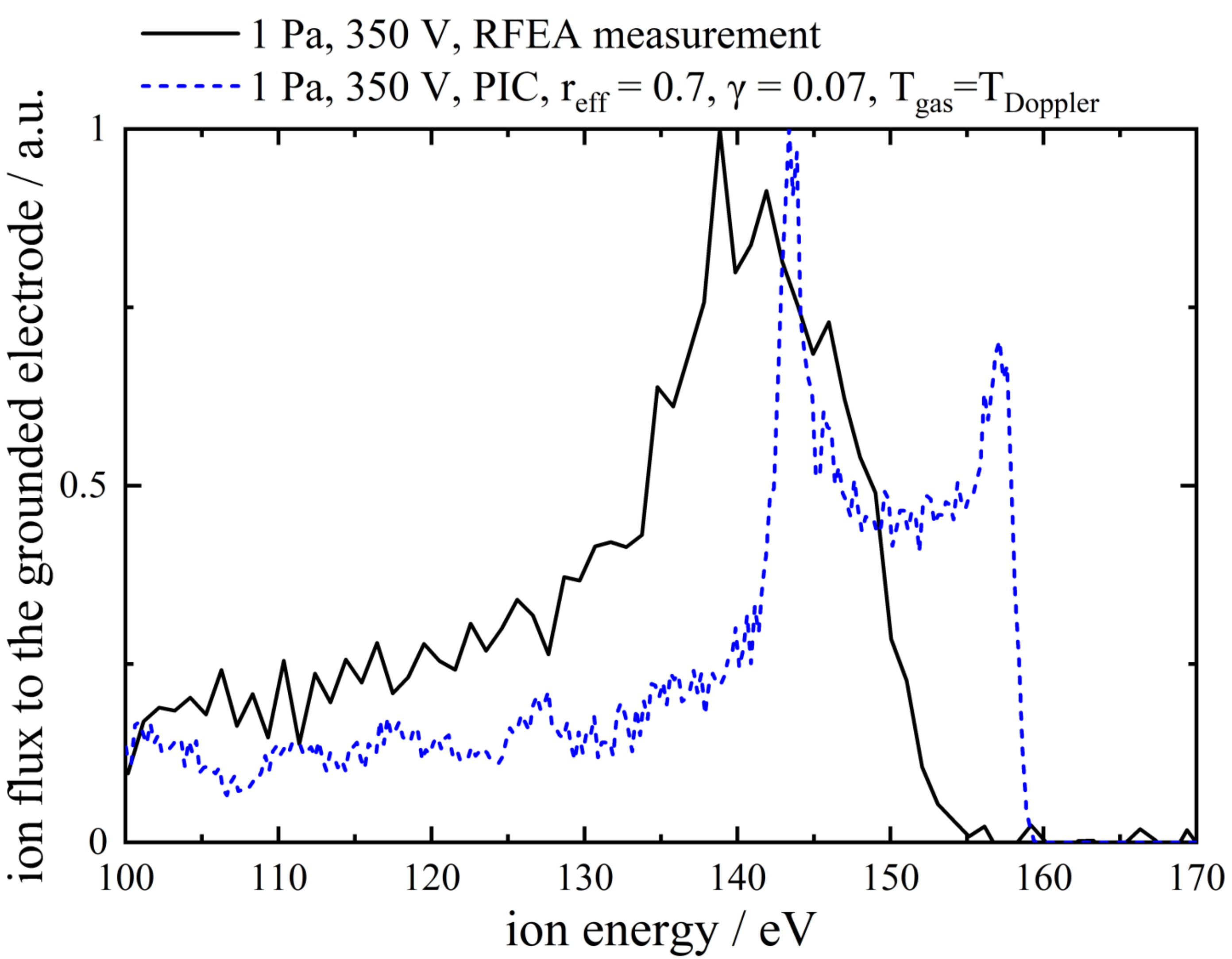
IEDFs at 1 Pa in detail

- **shift of ~20 eV between measurement and simulation base case**



IEDFs at 1 Pa in detail

- shift of ~20 eV between measurement and simulation base case
- shift of ~10 eV between measurement and simulation best case
- double peak structure not visible in the measurement



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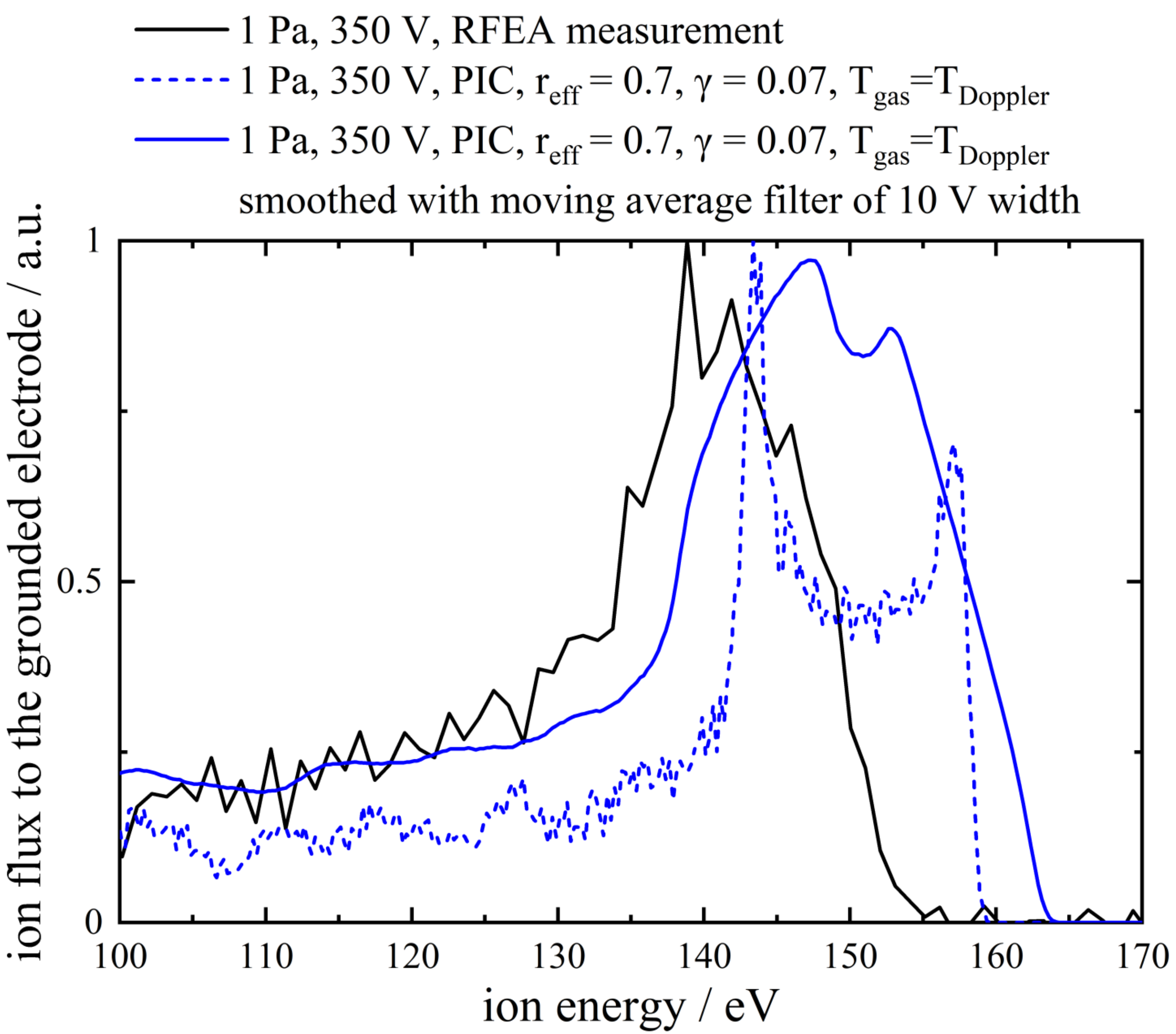
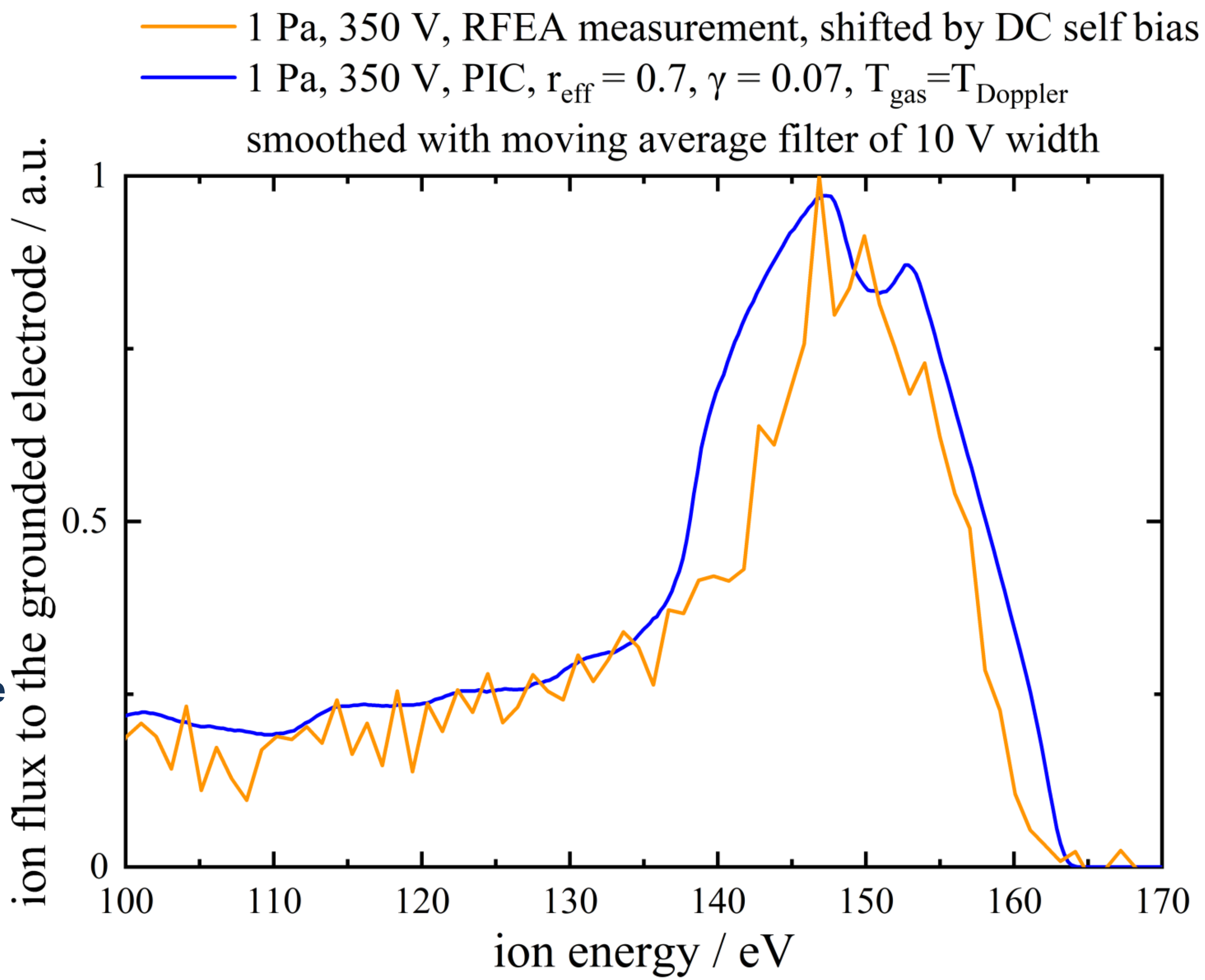


IEDFs at 1 Pa in detail

- shift of ~20 eV between measurement and simulation base case
- shift of ~10 eV between measurement and simulation best case
- double peak structure not visible in the measurement → RF noise pickup of RFEA cables
- remaining shift can be explained by small DC self bias in experiment → correction results in excellent agreement regarding the position on the energy axis



Results: spatio-temporal excitation

Phase Resolved Optical Emission Spectroscopy

- **measuring light at specific wavelength at specific points in time**
- **transitions are specifically chosen to be only produced by electron-impact excitation from the ground state**
- **de-excitation only via spontaneous emission**
    - Ne 585.2 nm, lifetime 16 ns
    - Ar 750.4 nm, lifetime 22 ns
- **calculation of relative excitation rate from measured emission**
- **excitation rate can also be calculated in PIC simulation**

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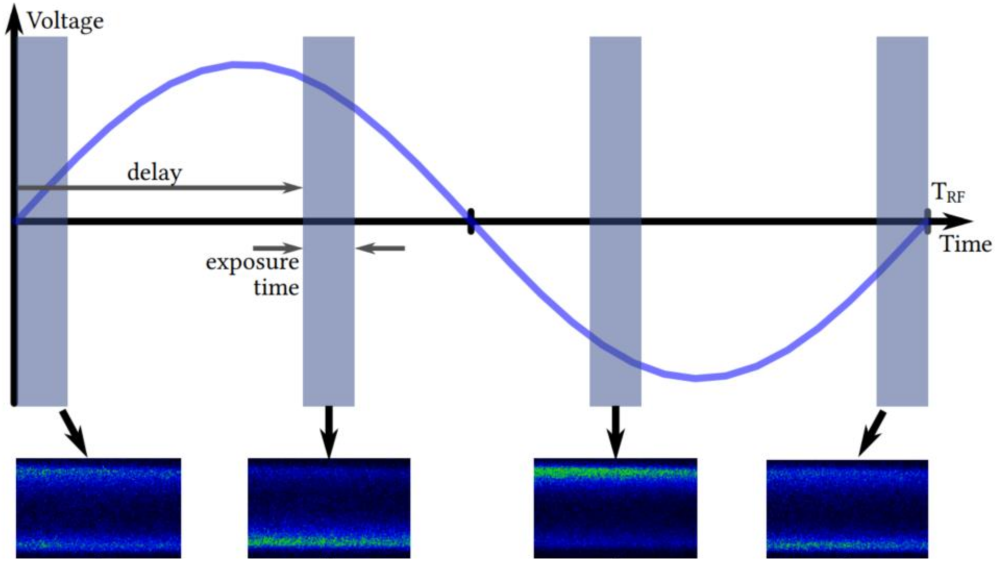

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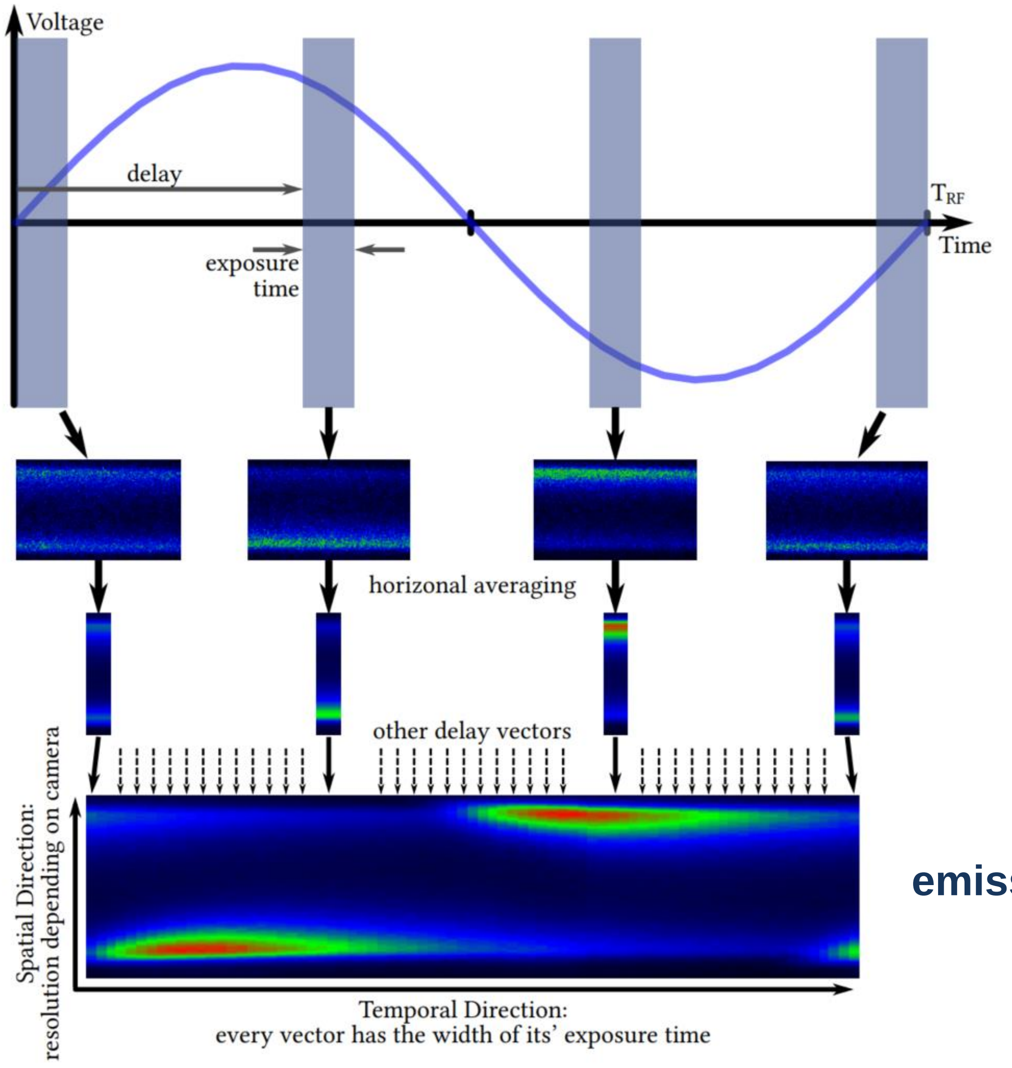

emission

RUB

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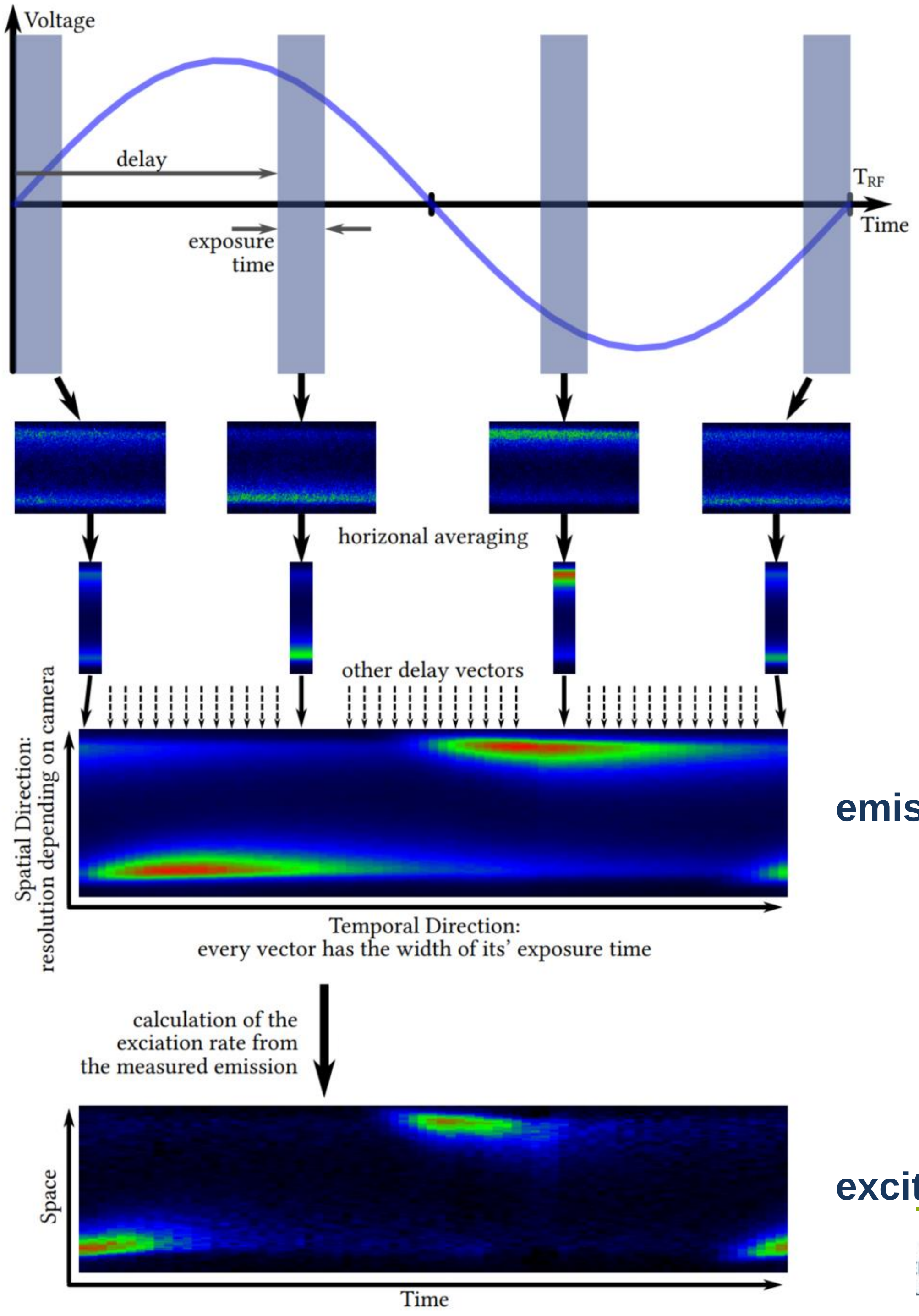
More info: J. Schulze et al., J. Phys. D. 43 (2010)

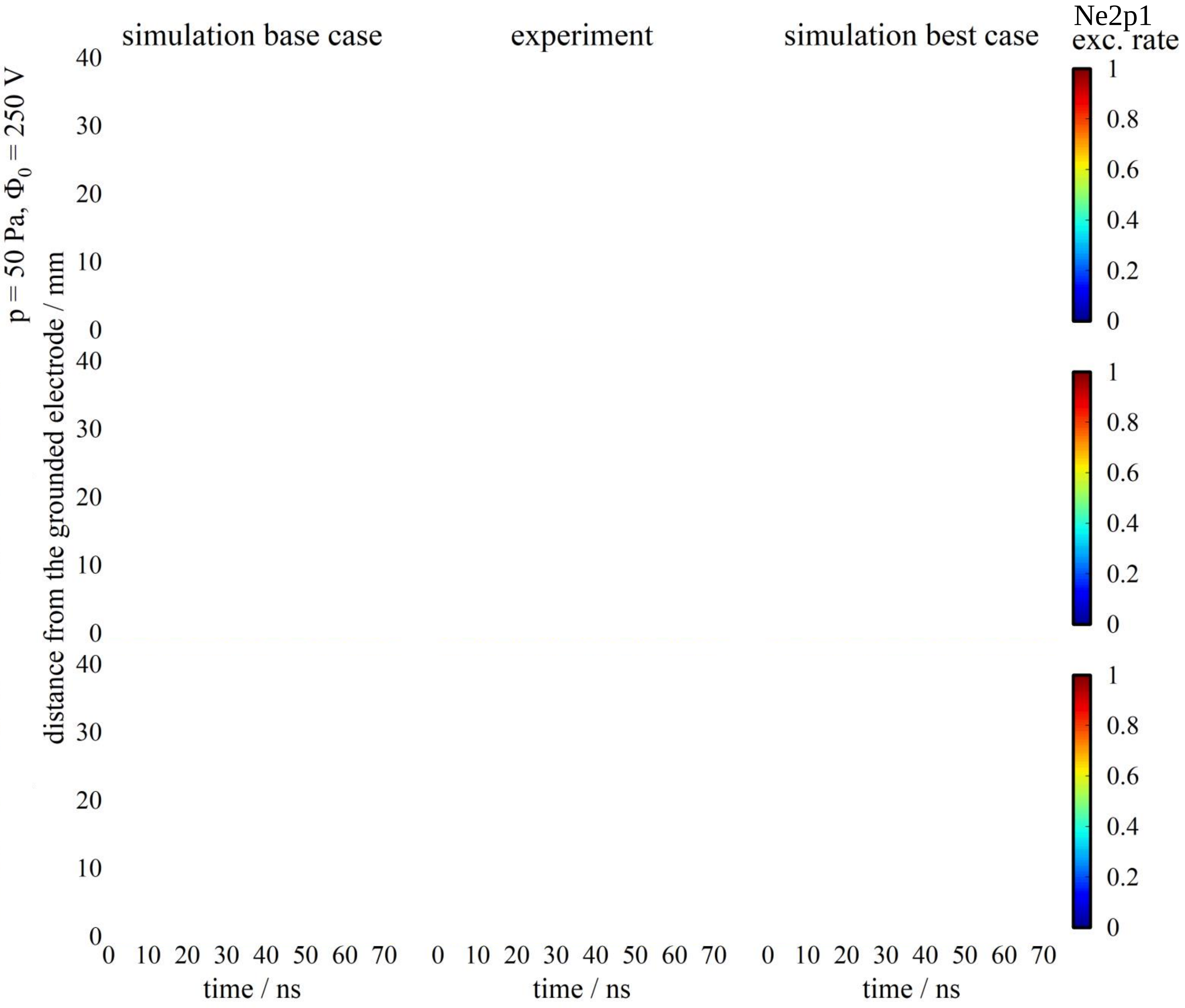


emission

excitation

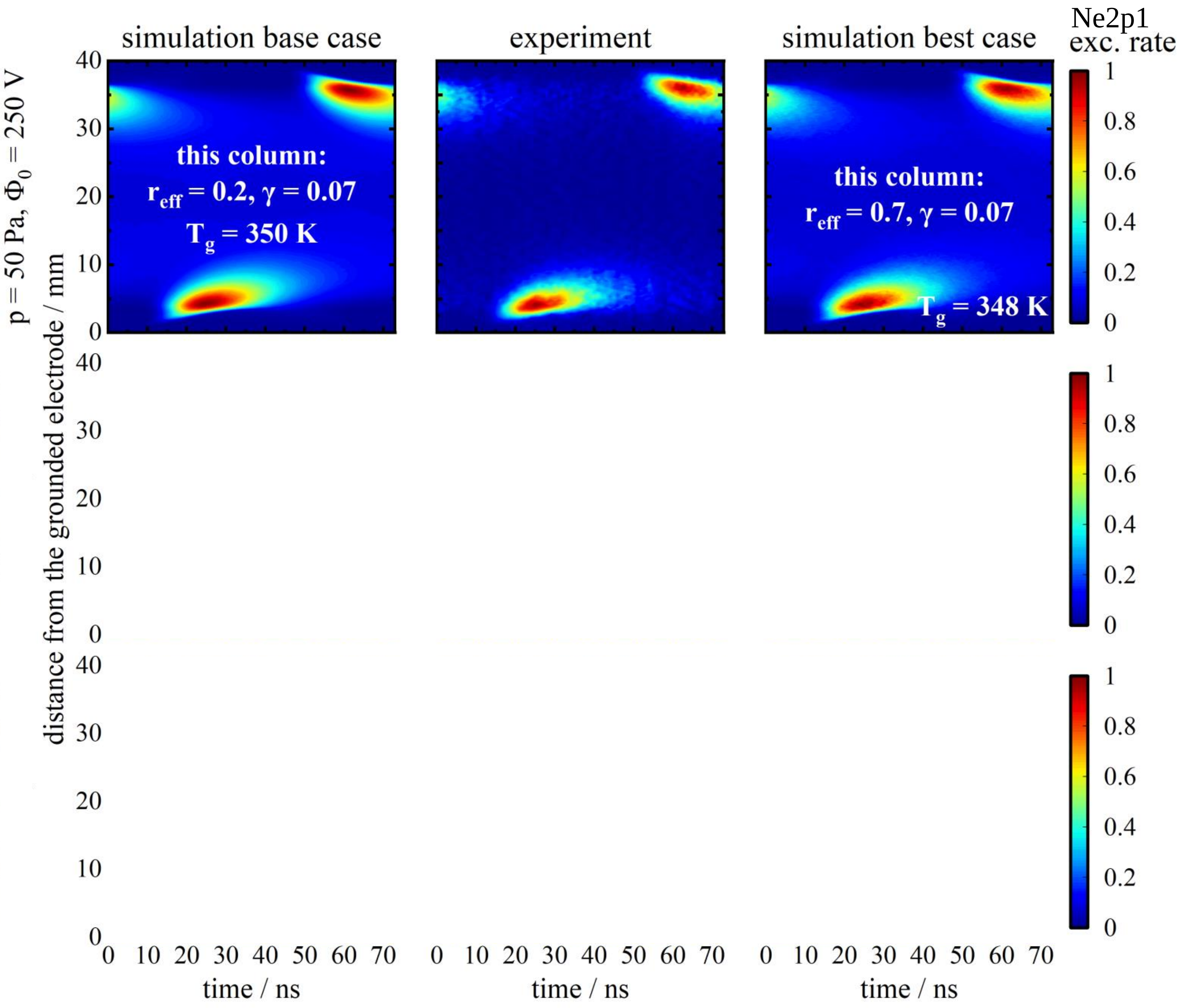
RSITÄT JM RUB

Spatio-temporal excitation rates for different conditions



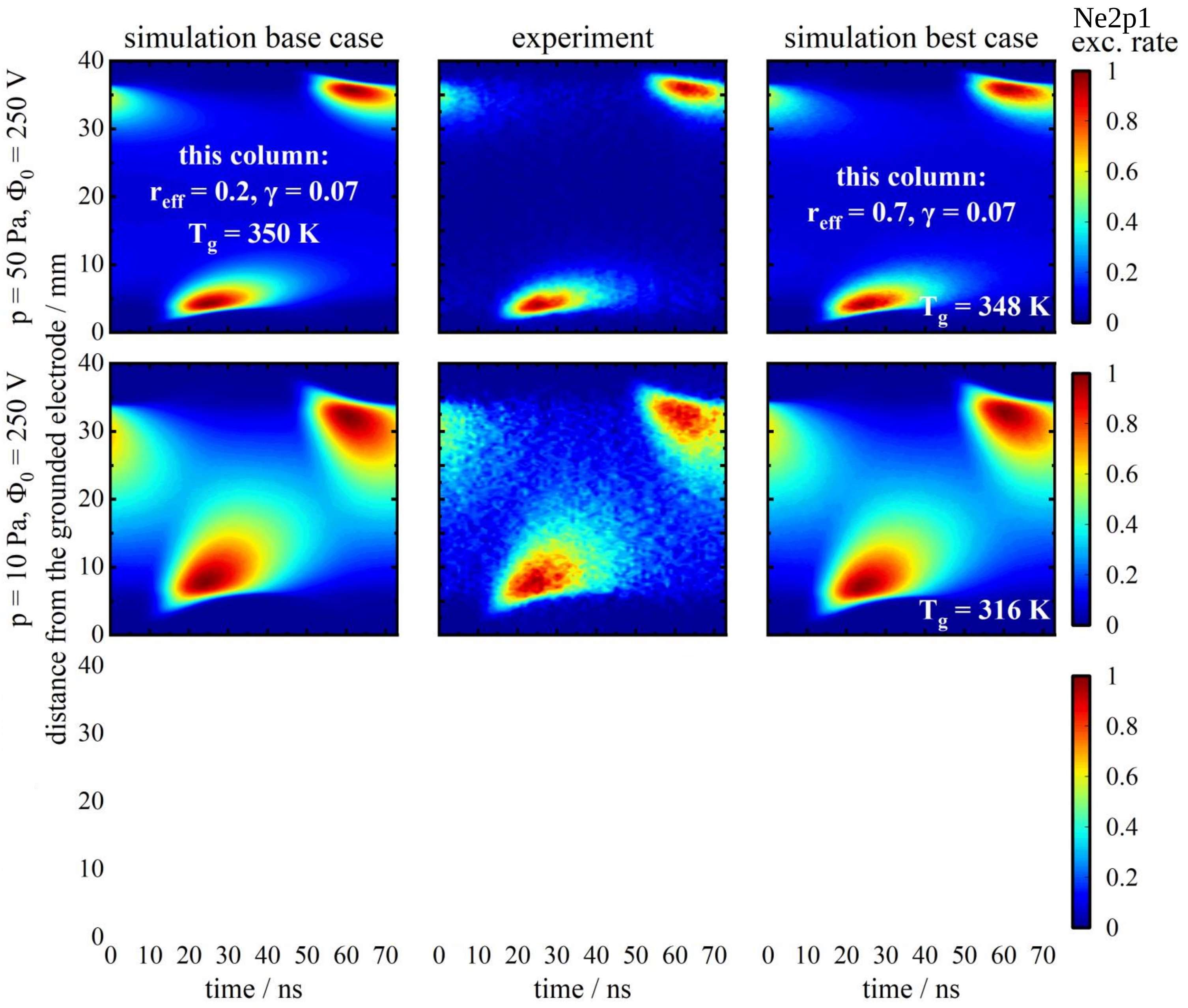
Spatio-temporal excitation rates for different conditions

- 50 Pa: no visible differences



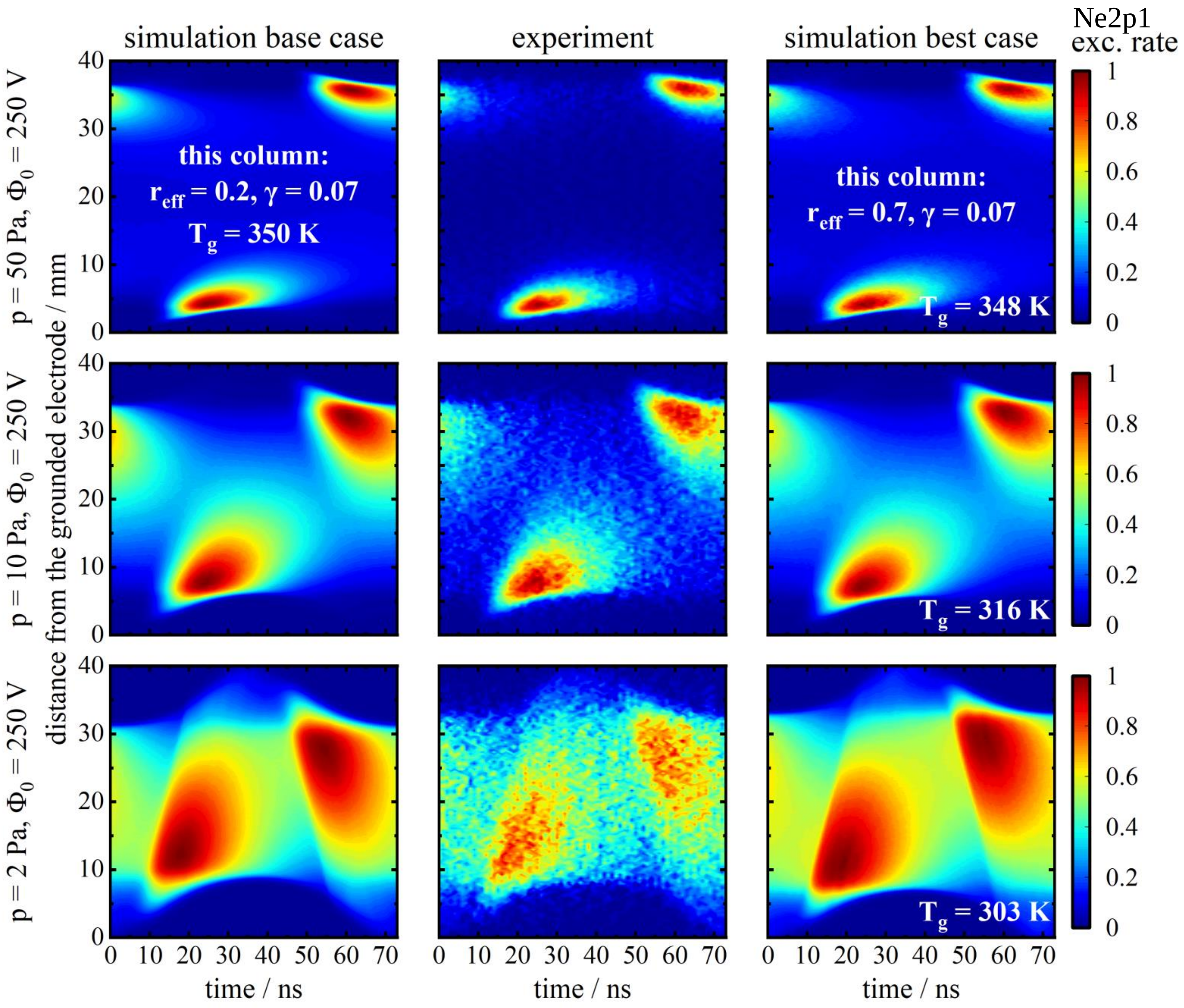
Spatio-temporal excitation rates for different conditions

- 50 Pa: no visible differences
- 10 Pa: still no big differences

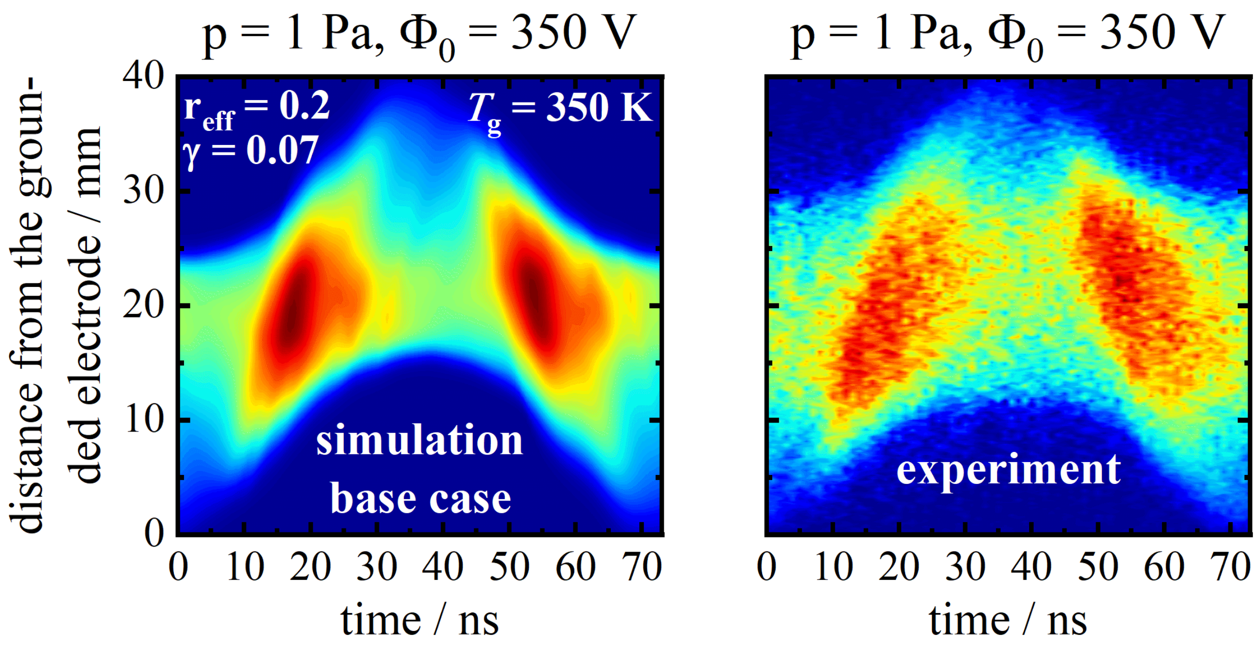


Spatio-temporal excitation rates for different conditions

- 50 Pa: no visible differences
- 10 Pa: still no big differences
- 2 Pa: small differences in sheath width



Excitation rate comparison at 1 Pa



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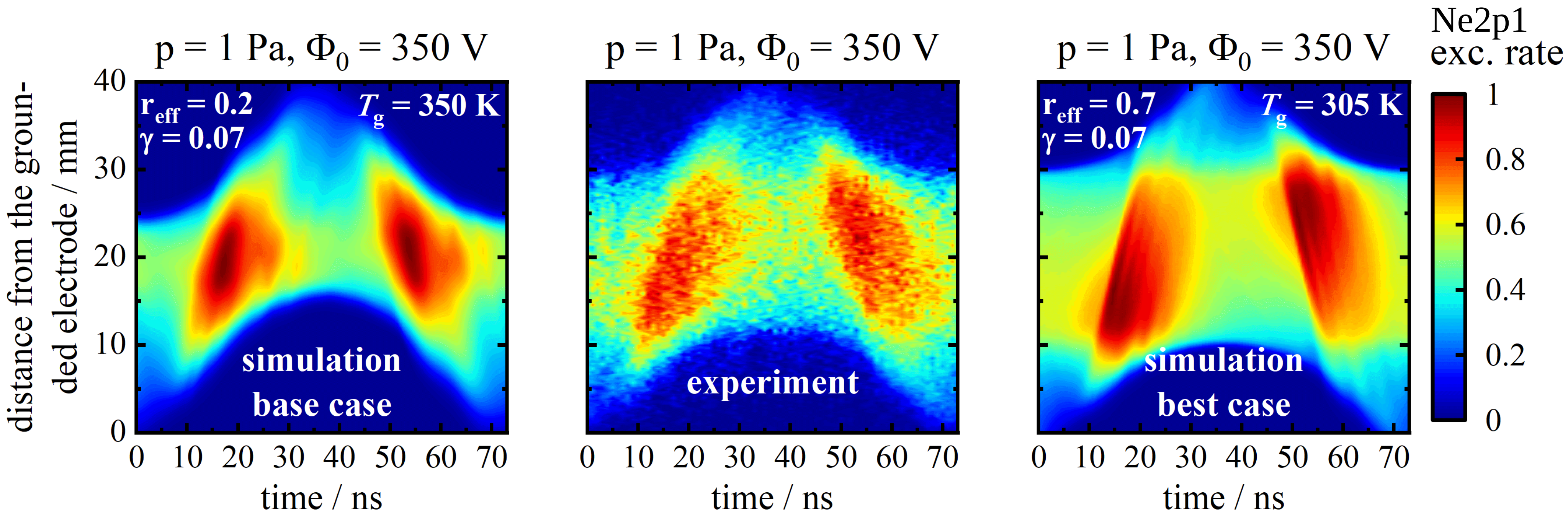

- difference in sheath thickness between experiment and simulation for base case
- Increase of r_{eff} and decrease of T_{gas} decreases sheath thickness
- 2 Pa: much smaller difference
  - 1 Pa: electron mean free path > electrode gap
  - 2 Pa: electron mean free path < electrode gap

Summary

- results from different diagnostics are consistent
- precise knowledge of the gas temperature is required for accurate simulation results
- r_{eff} for stainless steel is ~0.7
- Based on a systematic variation of pressure and voltage, surface coefficients can be determined!

- Acknowledgement: DFG: SFB-TR 87, Project C1

- Have a look:

  „Multi-diagnostic experimental validation of 1d3v PIC/MCC simulations of low pressure capacitive RF plasmas operated in argon“ (Accepted Manuscript), David Alexander Schulenberg, Ihor Korolov, Zoltán Donkó, Aranka Derzsi and Julian Schulze, PSST 2021, https://doi.org/10.1088/1361-6595/ac2222

Thank you for your attention!