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Contactless optical hygrometry in turbulent Leipzig Aerosol Cloud Interaction Simulator (LACIS-T)

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Seminarium fizyki atmosfery

LACIS-T - A moist air wind tunnel for investigating the interactions between turbulence and cloud microphysics

dr Dennis Niedermeier

Leibniz Institute for Tropospheric Research, Leipzig, Germany

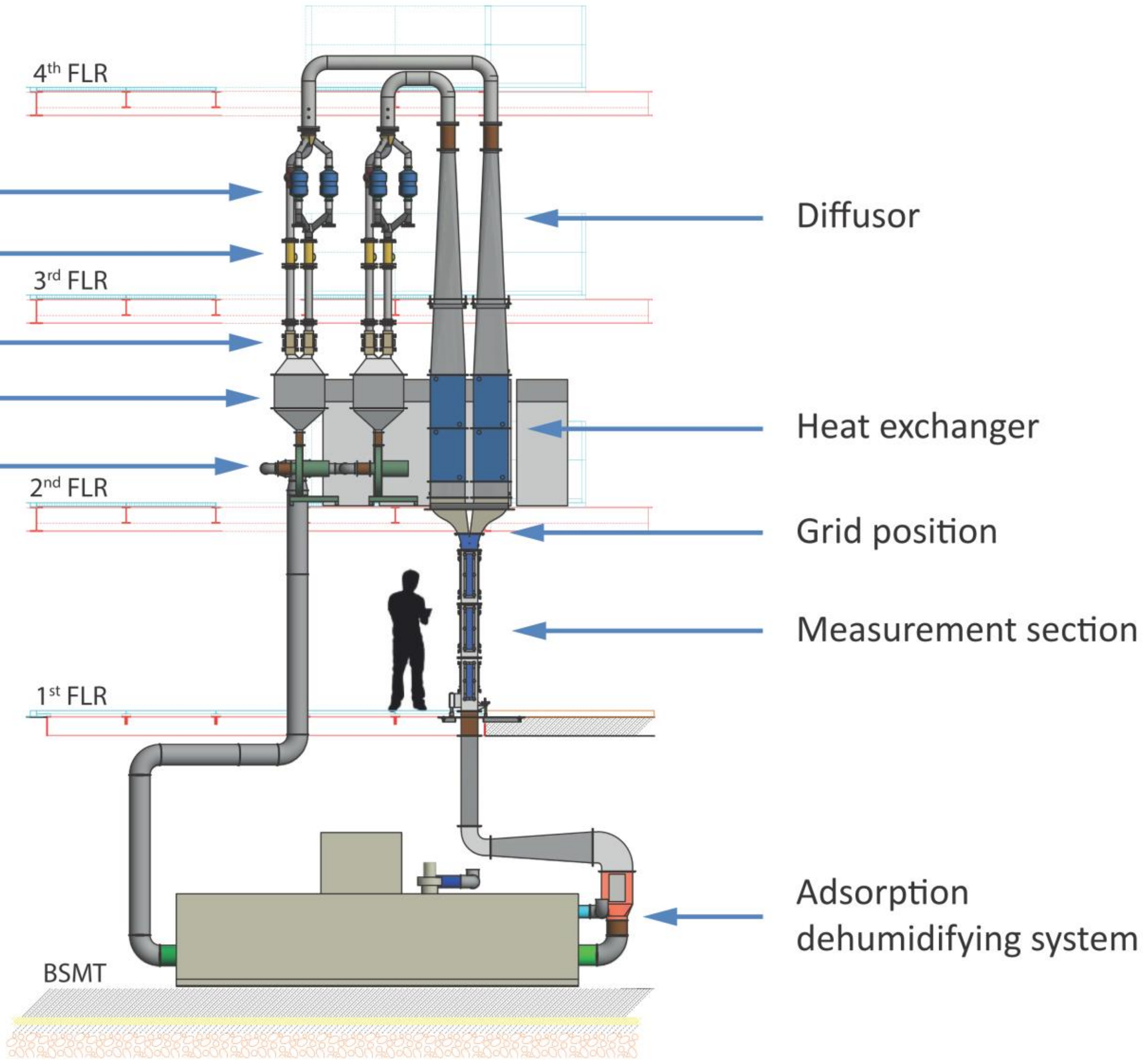
11 października 2019 13:15, ul. Pasteura 5, B0.14

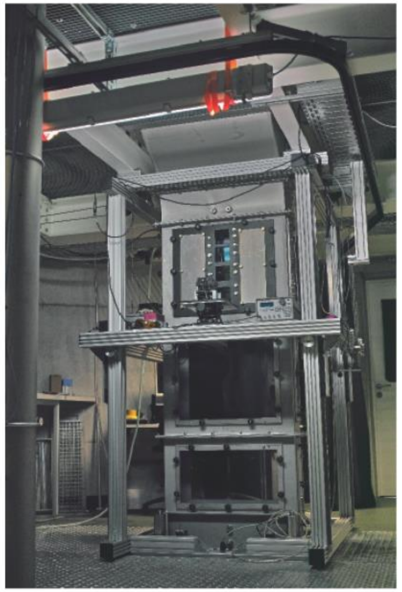
The interactions between turbulence and cloud microphysical processes have been investigated primarily through numerical simulation and field measurements over the last ten years. However, only in the laboratory we can be confident in our knowledge of initial and boundary conditions, and are able to measure under statistically stationary and repeatable conditions. In this talk, a unique turbulent moist-air wind tunnel will be presented, called the Turbulent Leipzig Aerosol Cloud Interaction Simulator (LACIS-T) which has been developed in order to study cloud physical processes in general and interactions between turbulence and cloud microphysical processes in particular. Investigations take place under well-defined and reproducible turbulent and thermodynamic conditions covering the temperature range of warm, mixed-phase and cold clouds (25°C > T > -40°C). The continuous-flow design of the facility allows for the investigation of processes occurring on small time (up to a few seconds) and spatial scales (micrometer to meter scale) and with a Lagrangian perspective. The experimental studies using LACIS-T are accompanied and complemented by Computational Fluid Dynamics (CFD) simulations which are helpful to design experiments as well as to interpret experimental results.
In this talk, I will present the fundamental operating principle of LACIS-T, the numerical model as well as results concerning the thermodynamic and flow conditions prevailing inside the wind tunnel combining both characterization measurements and numerical simulations. Finally, results are depicted from deliquescence/hygroscopic growth as well as droplet activation and growth experiments.

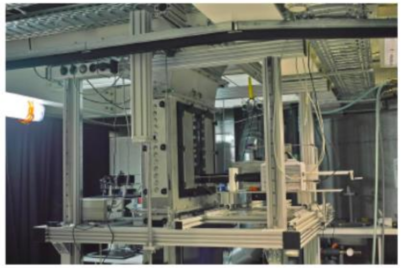
Niedermeier, D., Voigtländer, J., Schmalfuß, S., Busch, D., Schumacher, J., Shaw, R. A., and Stratmann, F
Atmospheric Measurement Techniques, **13**, 2015–2033, 2020

LACIS-T (turbulent Leipzig Aerosol Cloud Interaction Simulator)

Humidification system







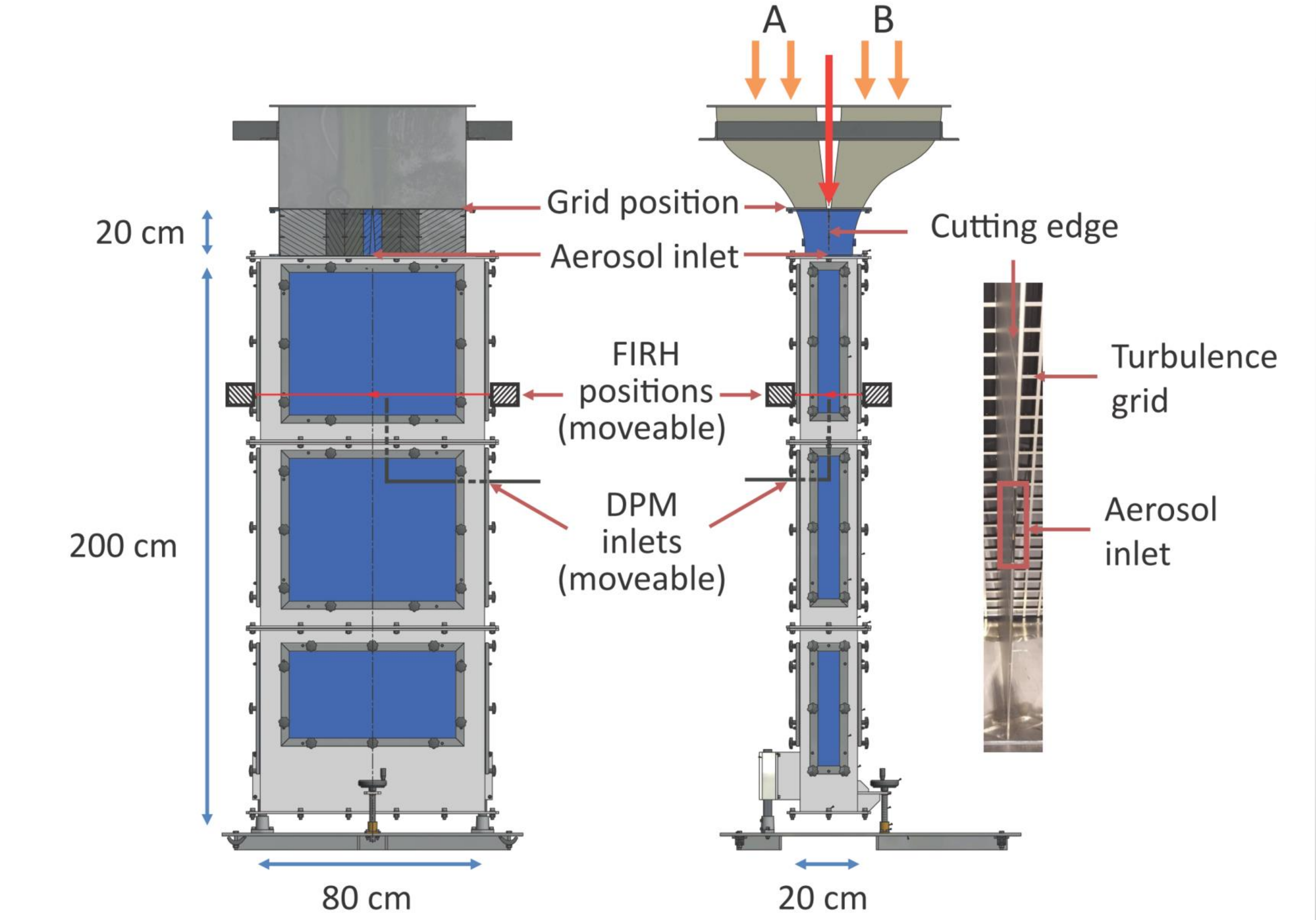
Measurement section

- study cloud physical processes;

- the interactions between cloud microphysics and turbulence under a wide range of well-defined, reproducible conditions resembling warm, mixed-phase and cold clouds.

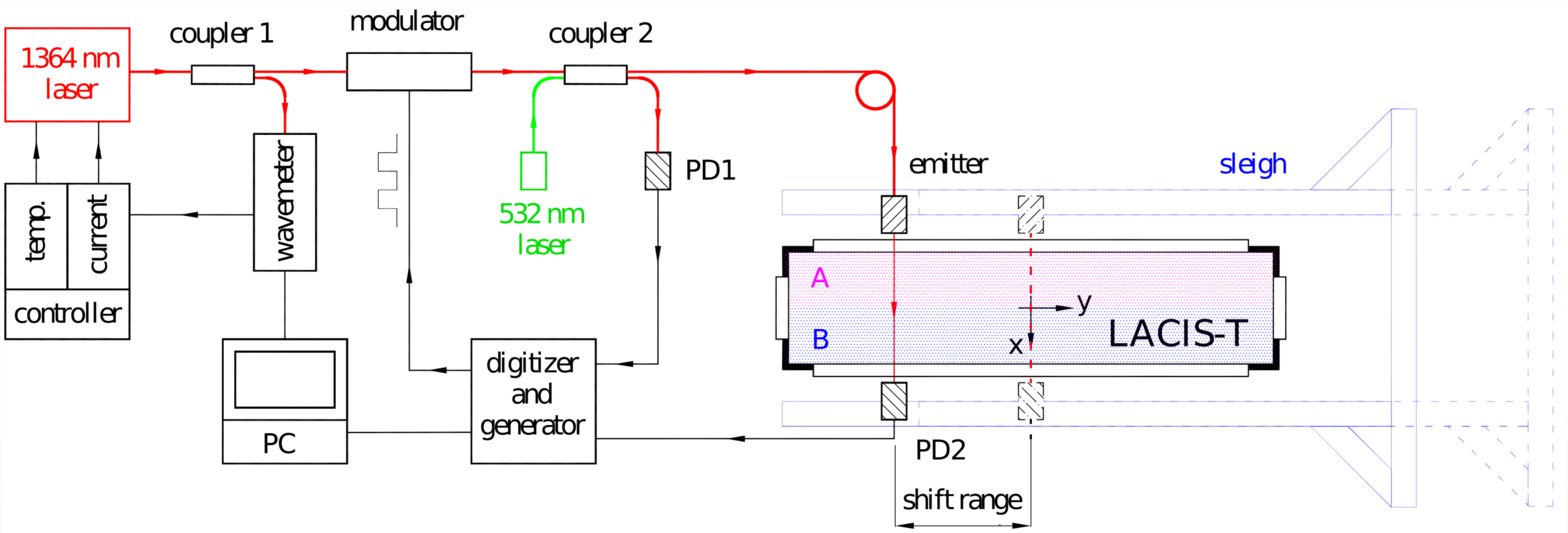
Niedermeier et al. (2020)

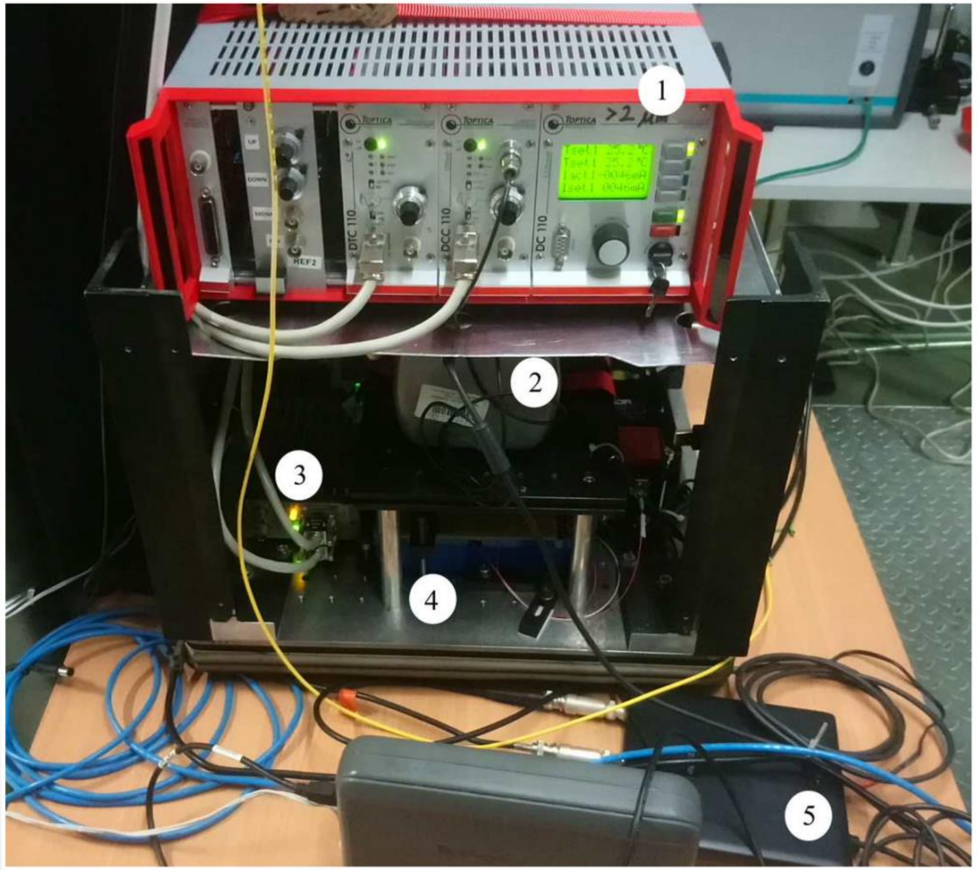
LACIS-T (turbulent Leipzig Aerosol Cloud Interaction Simulator)



Adapted from Niedermeier et al. (2020)

Fast InfraRed Hygrometer (FIRH) is an optical system, measuring absorption of laser light tuned to a specific rovibronic absorption line of H_2O molecules. It was developed for quick measurements of small-scale humidity fluctuations in turbulent atmospheric flows.

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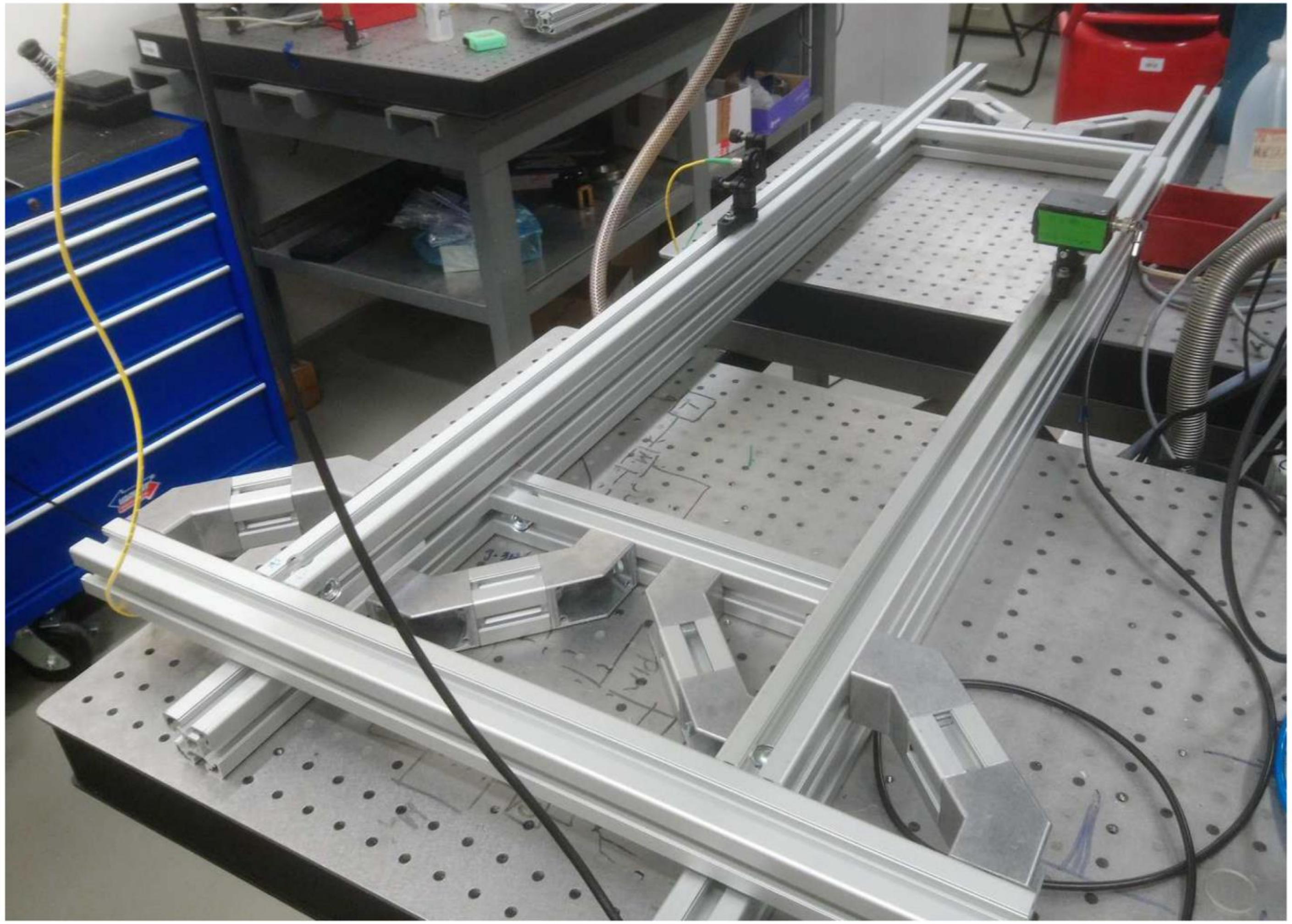


Operating principle of the hygrometer bases on Lambert-Beer Law:

$$I = I_0 e^{-\sigma n z}$$

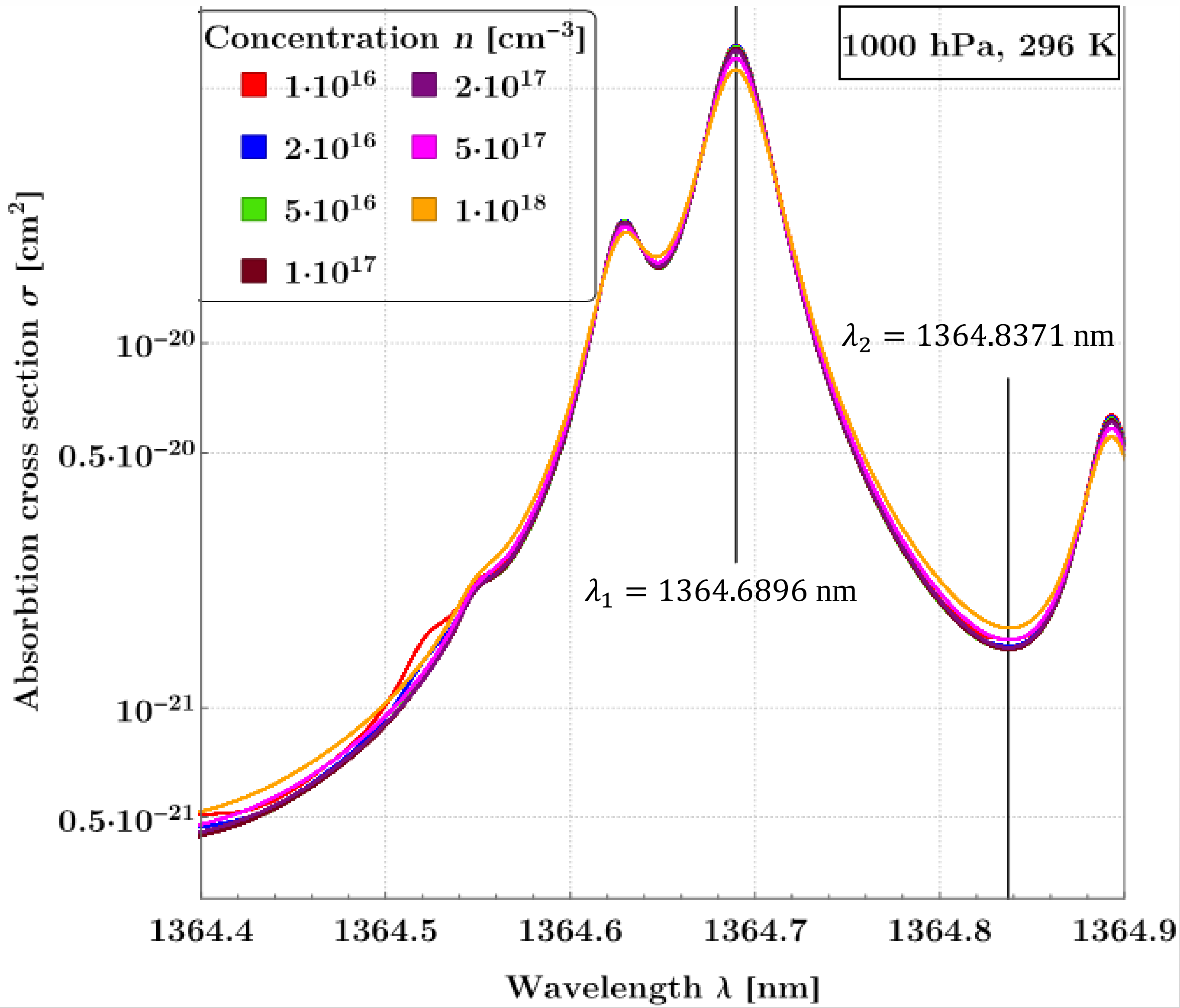
Absorbtion cross section (σ) depends on H_2O molecules concentration.

The goal of the series of experiments was two-fold:

(1) to evaluate the properties of FIRH under a wide range of well-defined reproducible conditions resembling those in the real atmosphere,

(2) to characterize the humidity field and turbulent fluctuations of humidity inside LACIS-T for different settings of the tunnel.

Absorption spectrum of H_2O



To reduce the influence of factors like optical noises, different photodetectors' sensitivities, signal losses on optical paths one needs to use two wavelenghts (λ_1 and λ_2). It implicates also the usage of two Lambert-Beer equations as well.

$$n = \frac{1}{z\left(\sigma_{\lambda_1}(n) - \sigma_{\lambda_2}(n)\right)} \log\left(\frac{I_{0_{\lambda_1}}}{I_{\lambda_1}} \cdot \frac{I_{\lambda_2}}{I_{0_{\lambda_2}}}\right).$$

I_0 - intensity recorded with PD1, I - intensity recorded with PD2

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Even despite drying the ambient air in the laboratory, parasitic absorption at z_l path in lab could not be entirely avoided:

$$n = \frac{1}{z\left(\sigma_{\lambda_1}(n) - \sigma_{\lambda_2}(n)\right)} \left[\log\left(\frac{I_{0_{\lambda_1}}}{I_{\lambda_1}} \cdot \frac{I_{\lambda_2}}{I_{0_{\lambda_2}}}\right) - n_l \cdot z_l \cdot \left(\sigma_{\lambda_1}(n_l) - \sigma_{\lambda_2}(n_l)\right)\right],$$

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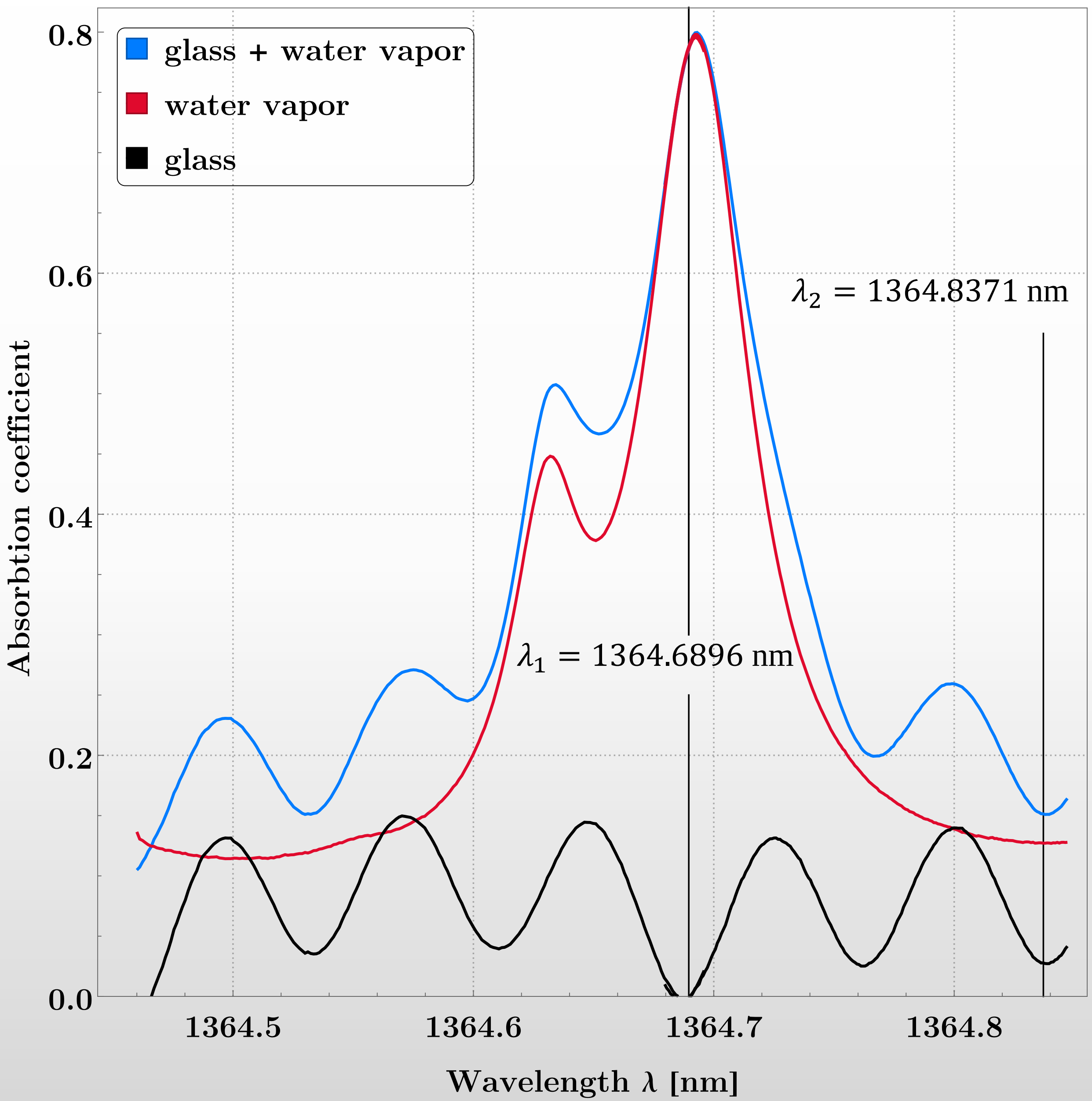
The absorption spectrum of the glass is negligible for this study. However, multiple reflections of the light beam between the surfaces and the interference between the reflected beams lead to periodic oscillations in the transmission spectrum (T_{λ_1} and T_{λ_2})

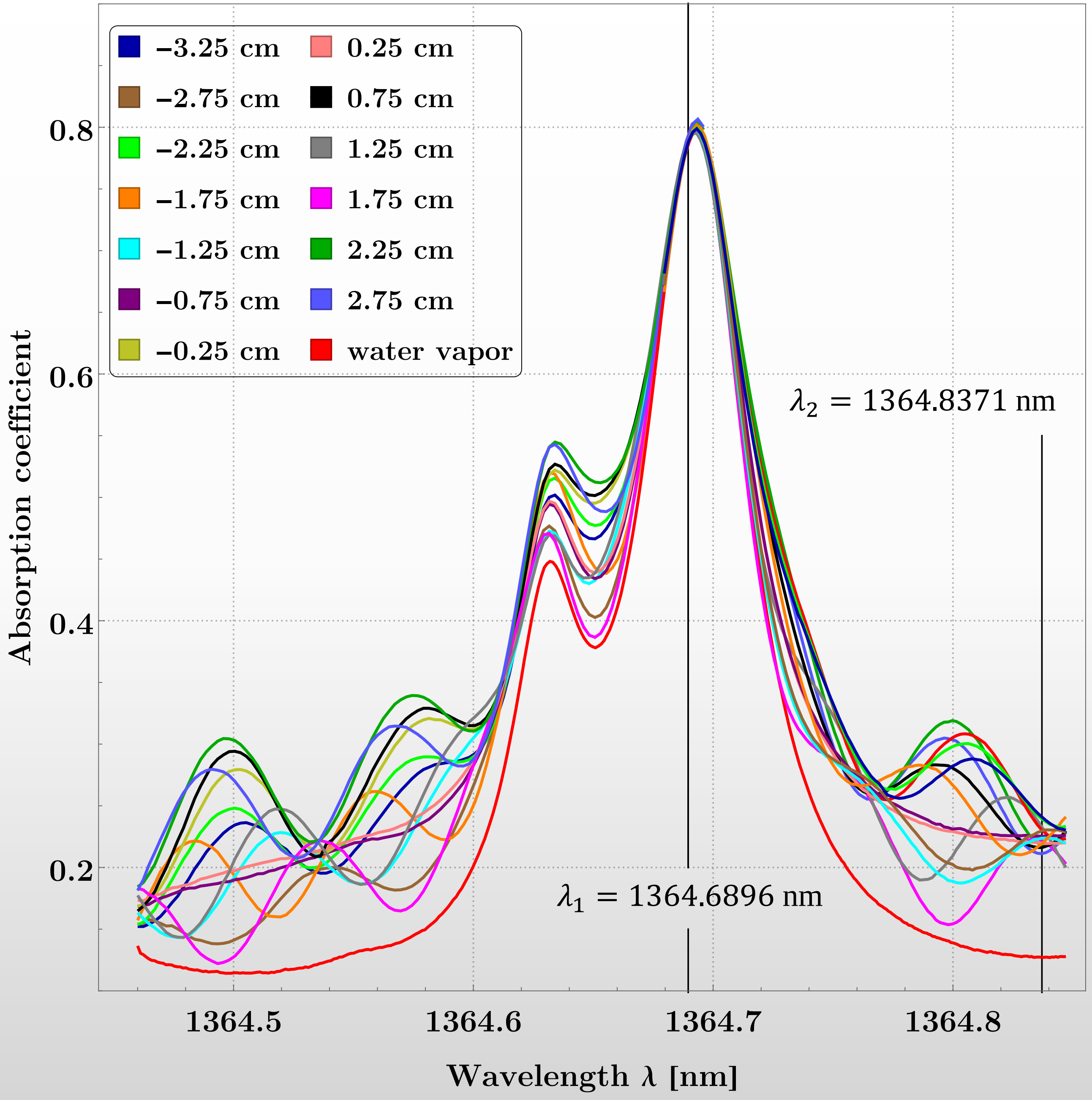
$$n = \frac{1}{z\left(\sigma_{\lambda_1}(n) - \sigma_{\lambda_2}(n)\right)} \left[\log\left(\frac{T_{\lambda_1} \cdot I_{0_{\lambda_1}}}{I_{\lambda_1}} \cdot \frac{I_{\lambda_2}}{T_{\lambda_2} \cdot I_{0_{\lambda_2}}}\right) - n_l \cdot z_l \cdot \left(\sigma_{\lambda_1}(n_l) - \sigma_{\lambda_2}(n_l)\right)\right].$$

I_0 - intensity recorded with PD1, I - intensity recorded with PD2, n_l - H_2O molecules concentration in laboratory

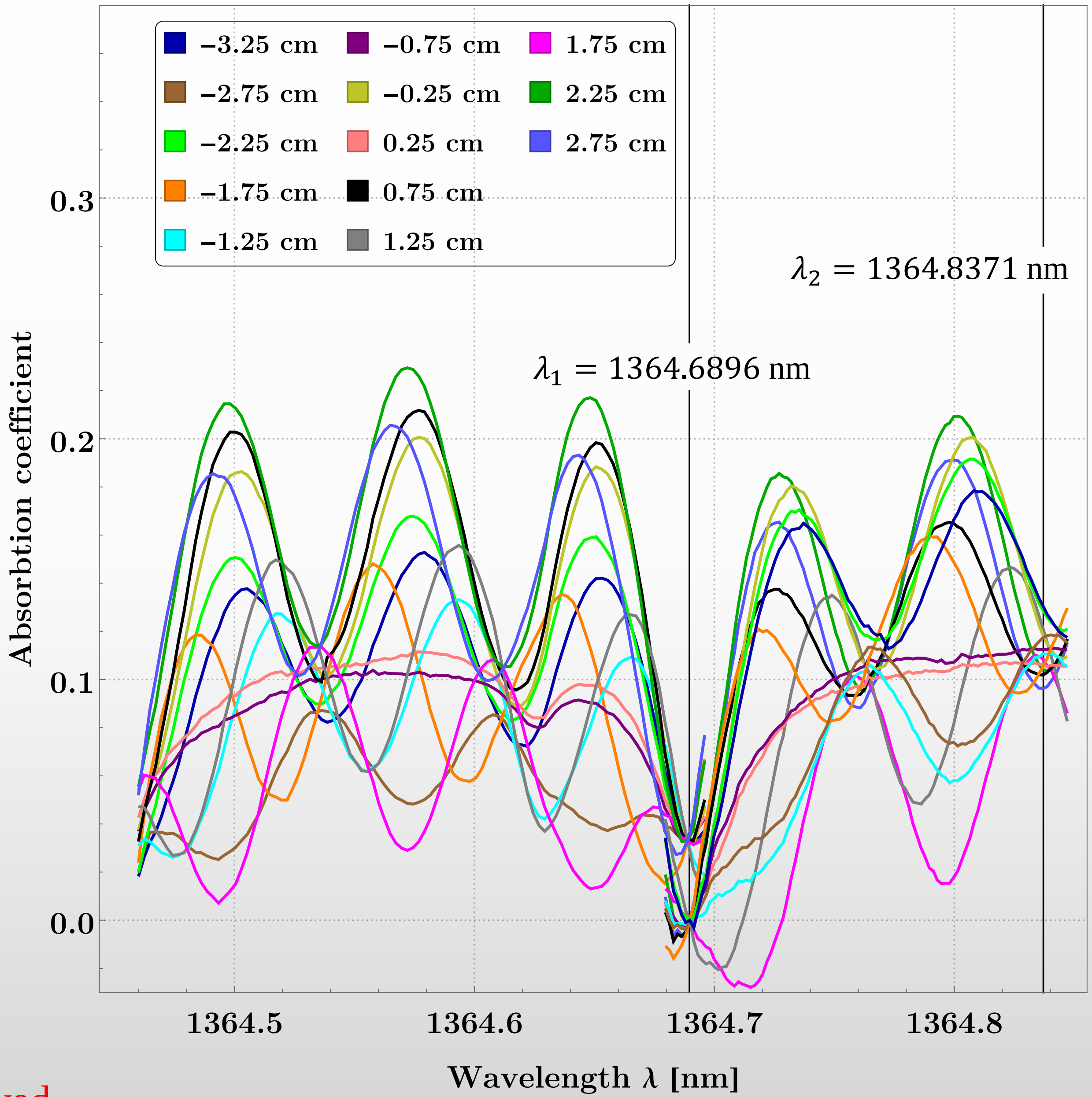
Glass modulation



Glass modulation

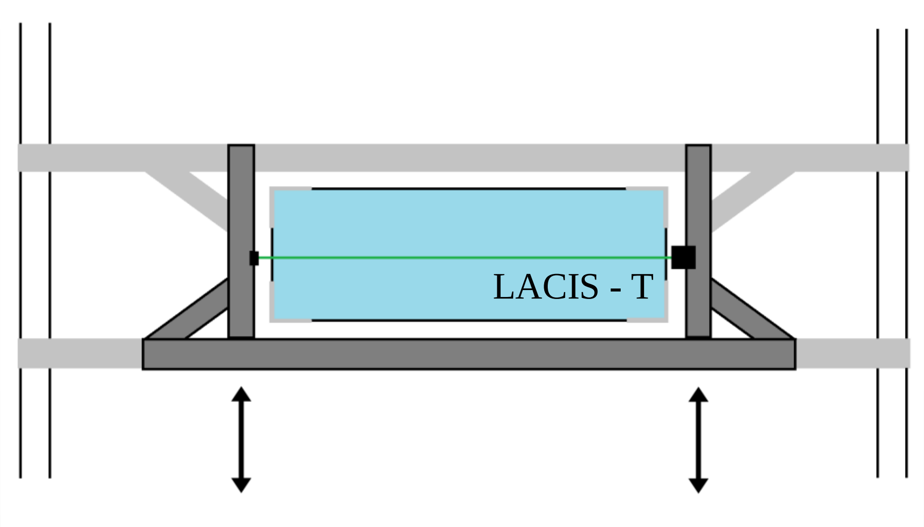


Glass modulation

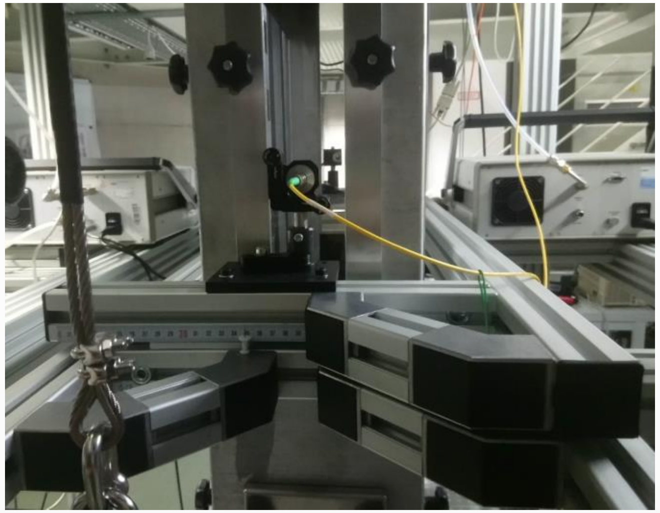


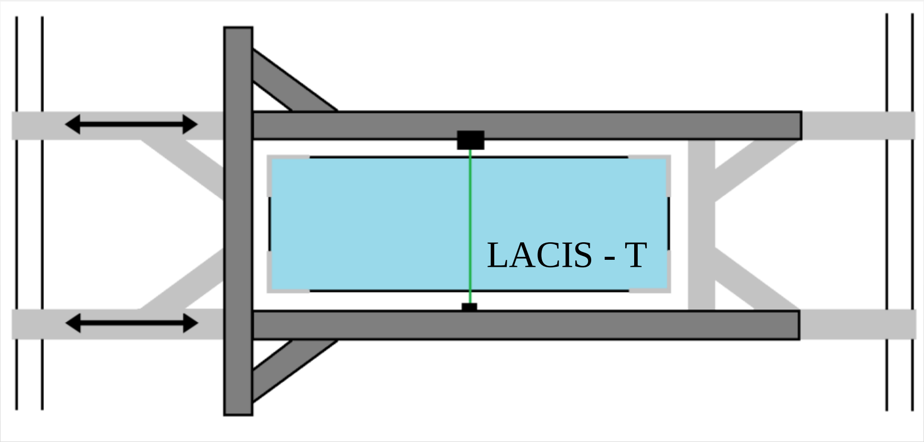
Node-like features were observed.

Scanning platforms

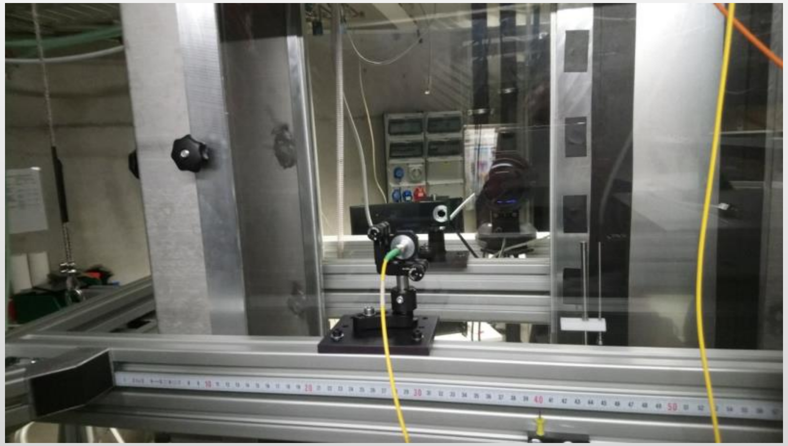


Longitudinal

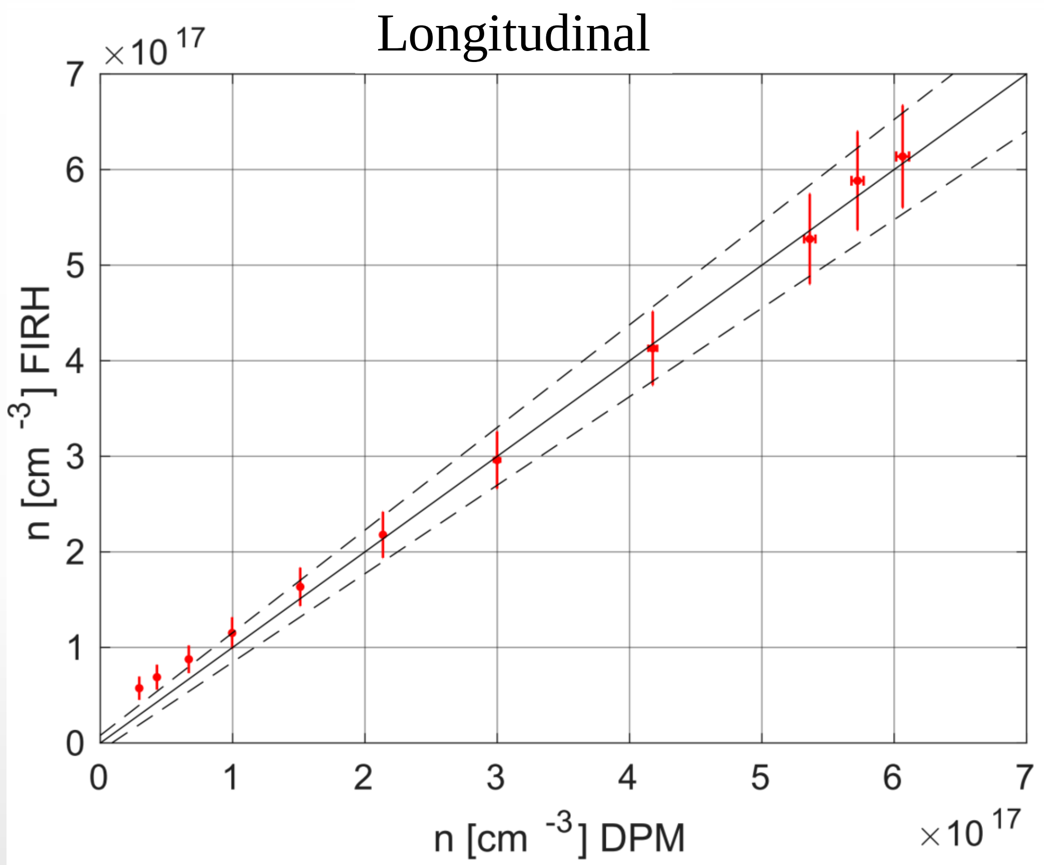


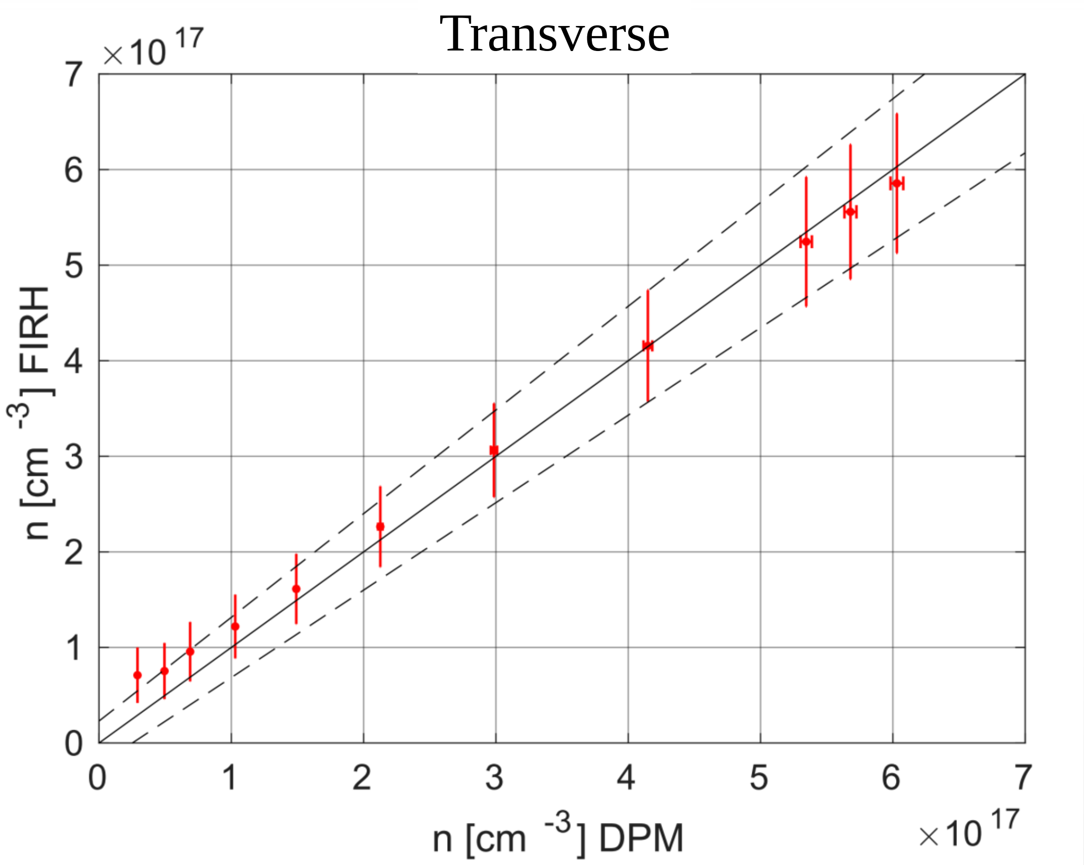


Transverse



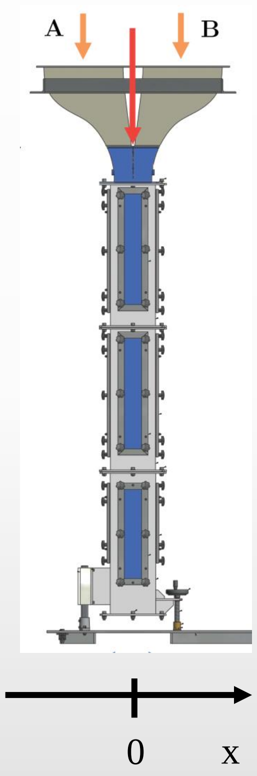
Comparison of FIRH with DPM

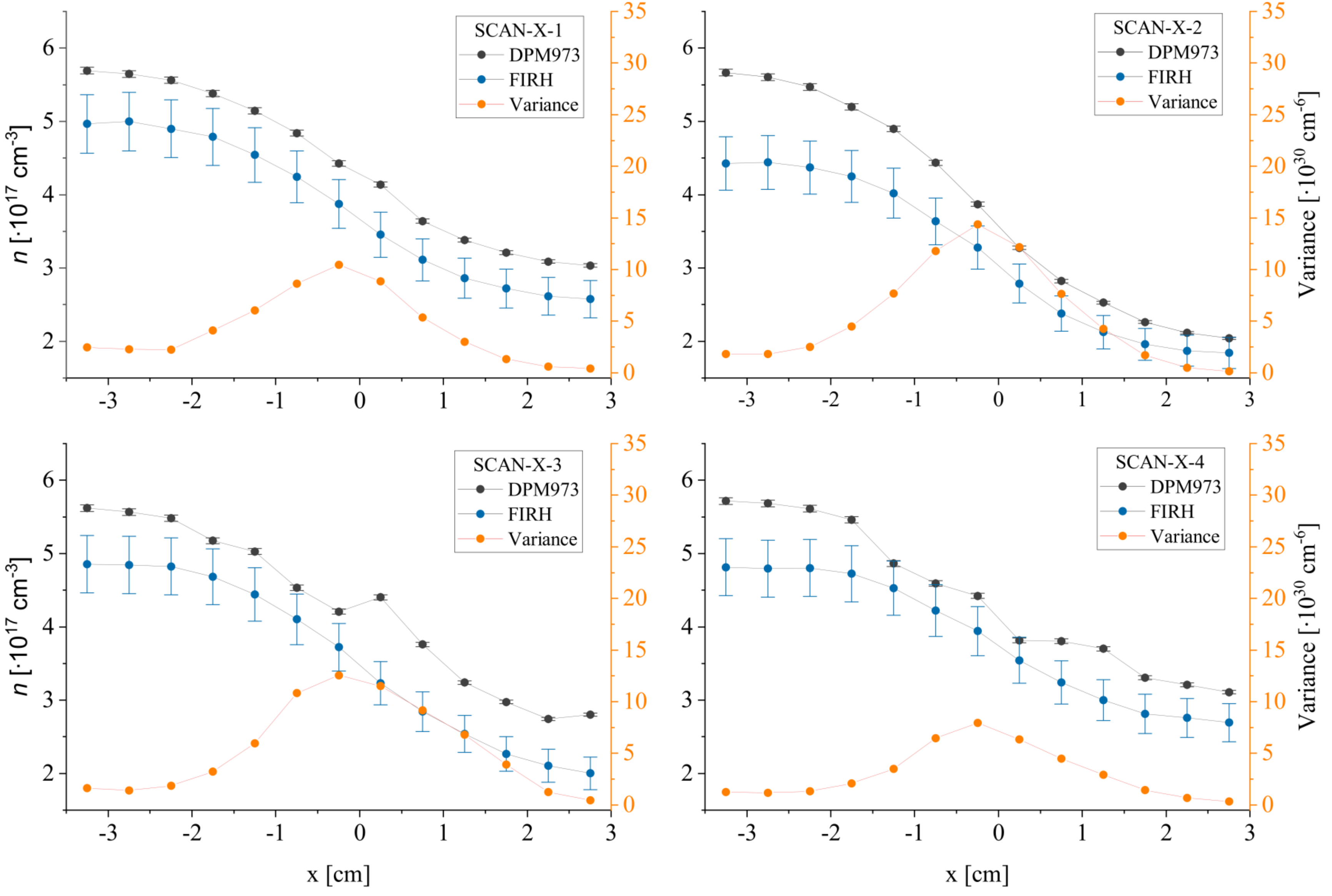




At low humidity ($n < 10^{17}\ cm^{-3}$) the values of n are overestimated by FIRH in comparison to DPM. For the case of very low humidity inside the tunnel, the three terms representing tunnel absorption, window transmission and ambient air absorption are of comparable magnitudes. Hence, the biases in the estimations of window transmission and ambient air absorption become particularly important for the outcome.

Longitudinal scanning





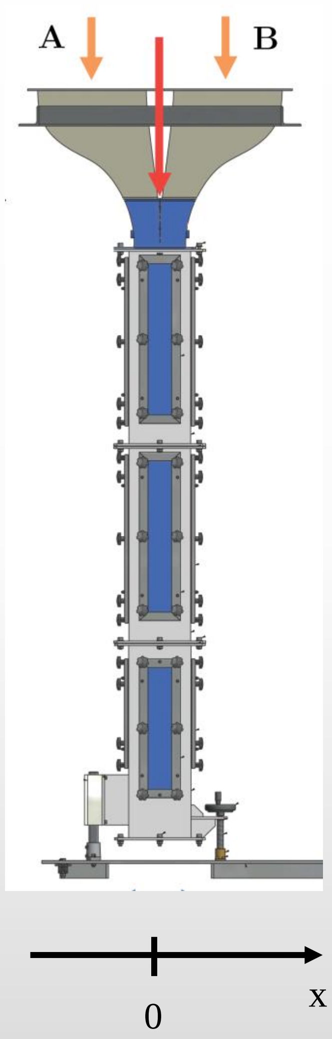
The offset can be attributed to three factors:

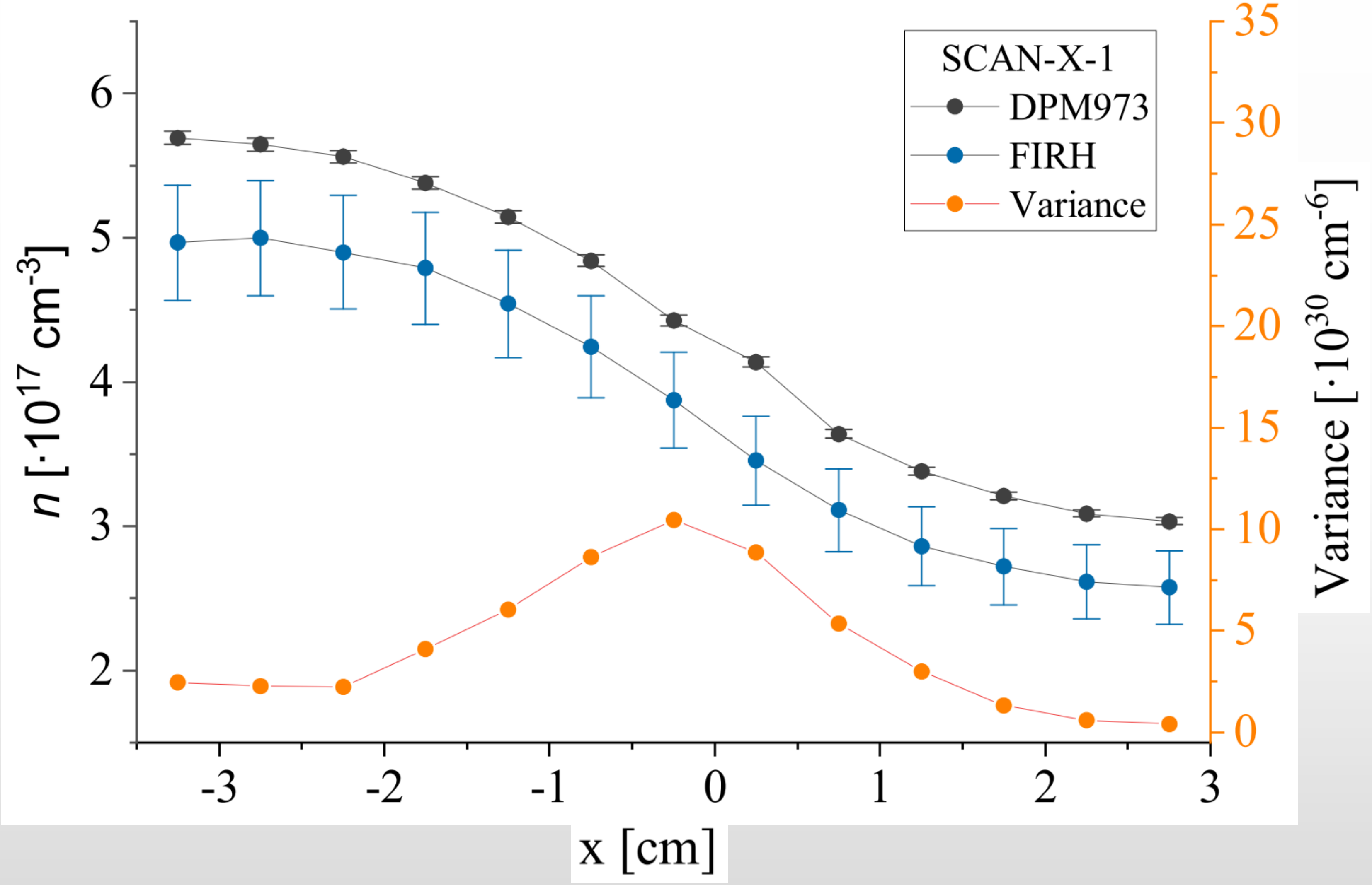
(1) the limited accuracy of FIRH

(2) the displacement between the FIRH optical path and the DPM inlet

(3) inherent difference in sampling regime between the instruments

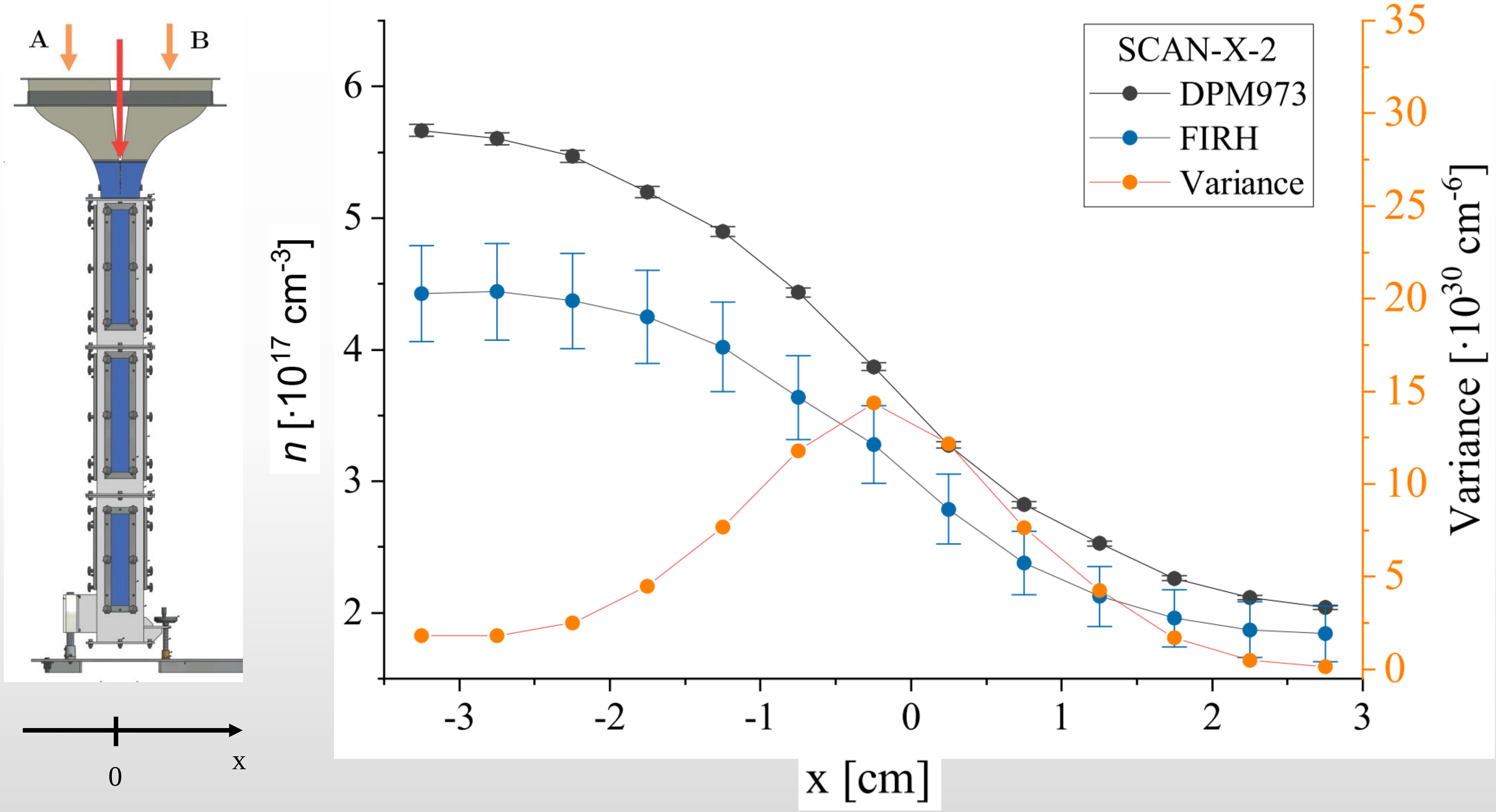
Longitudinal scanning





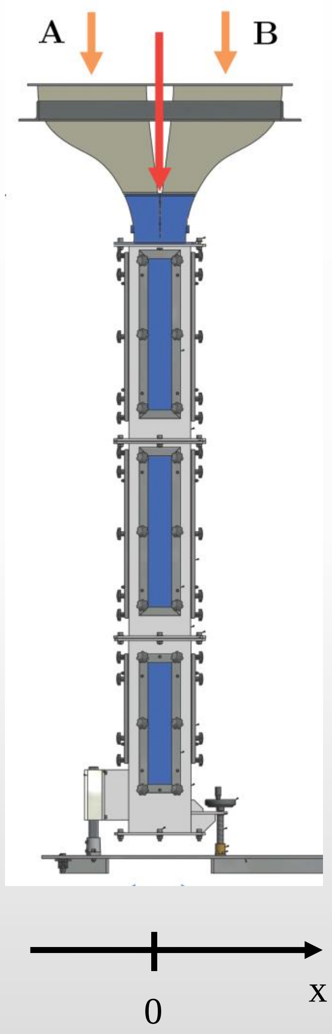
$T_A = T_B = 23℃ \quad T_{p_A} = 20℃, T_{p_B} = 10℃$

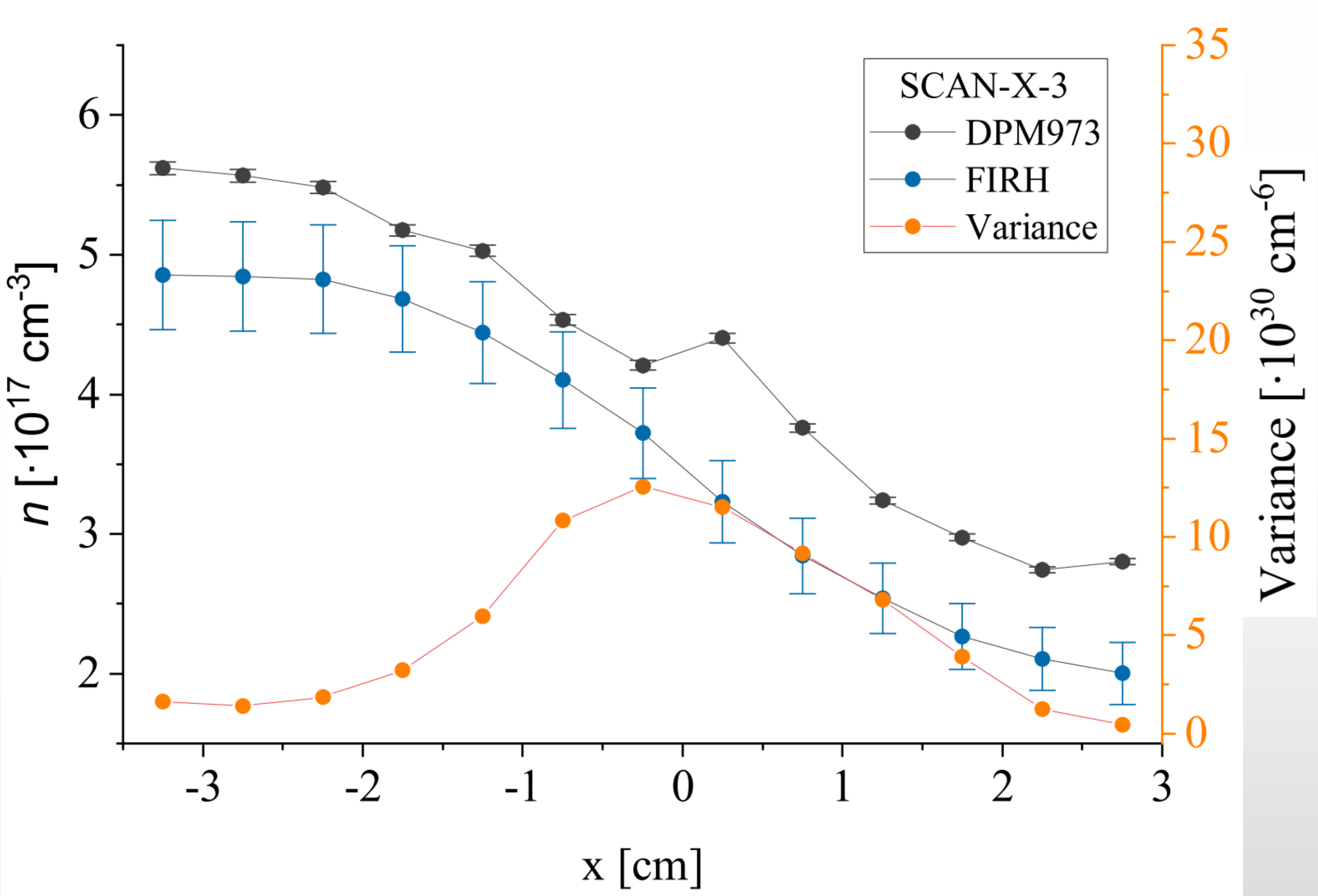
Longitudinal scanning



$T_A = T_B = 23℃ \quad T_{p_A} = 20℃, T_{p_B} = 4℃$

Longitudinal scanning



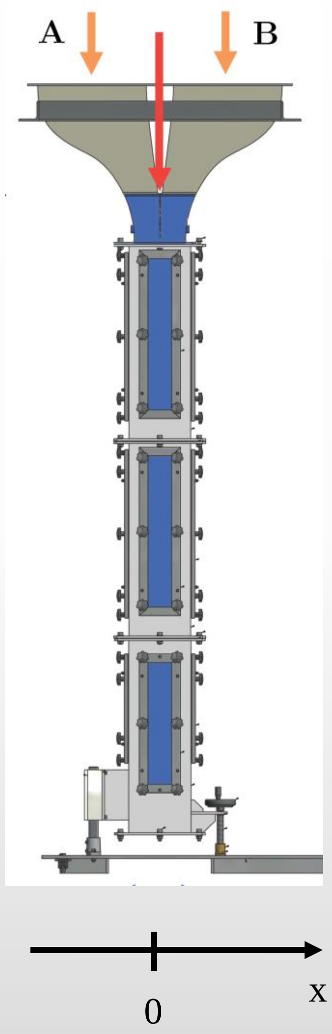


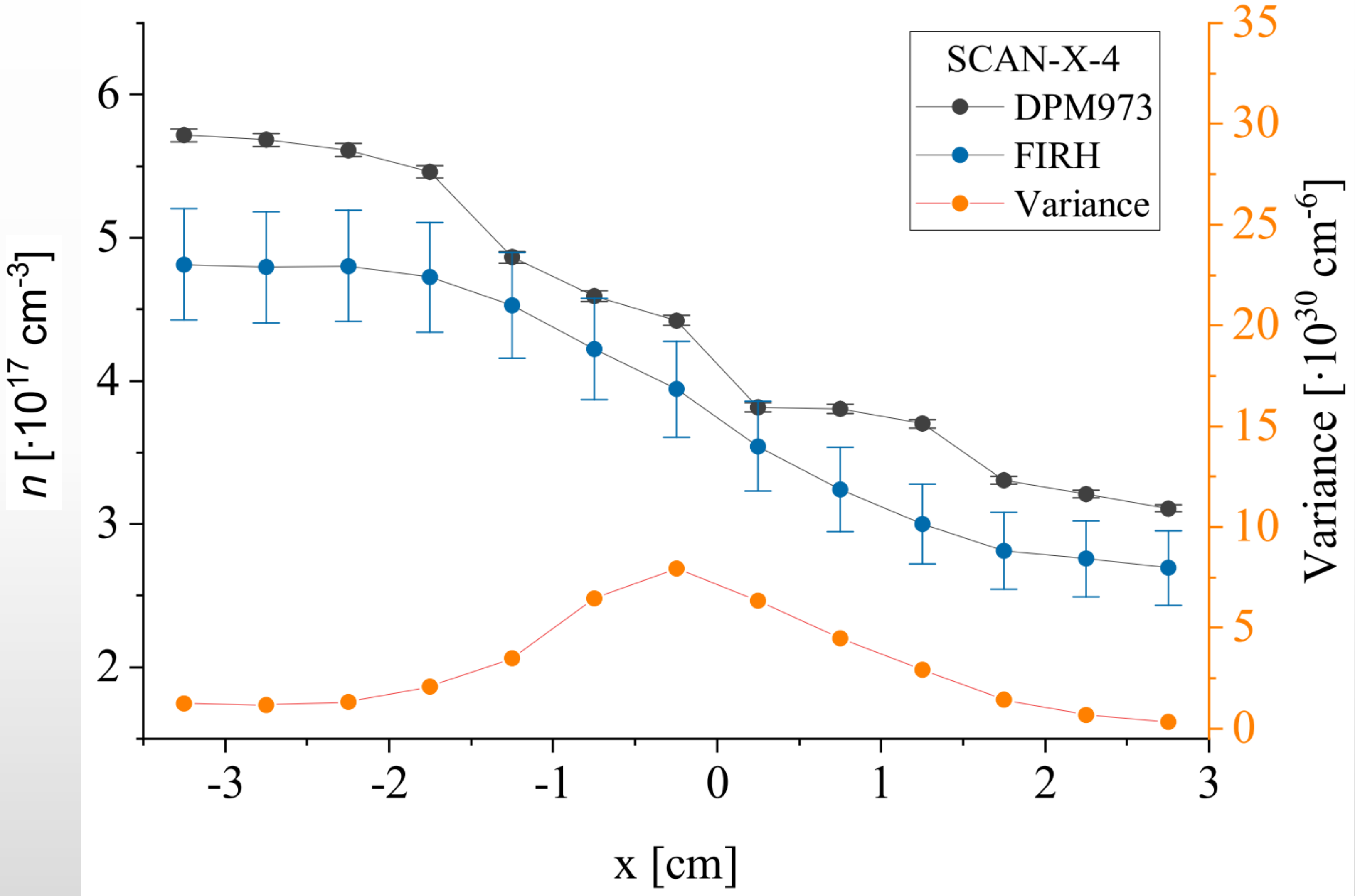
- contamination of sensor head of DPM. FIRH contactless measurents not affected by inside processes.

- the influence of outside conditions. ~ 20 °C in the laboratory

$T_A = 20°C, T_B = 4°C \quad T_{p_A} = 20°C, T_{p_B} = 4°C$

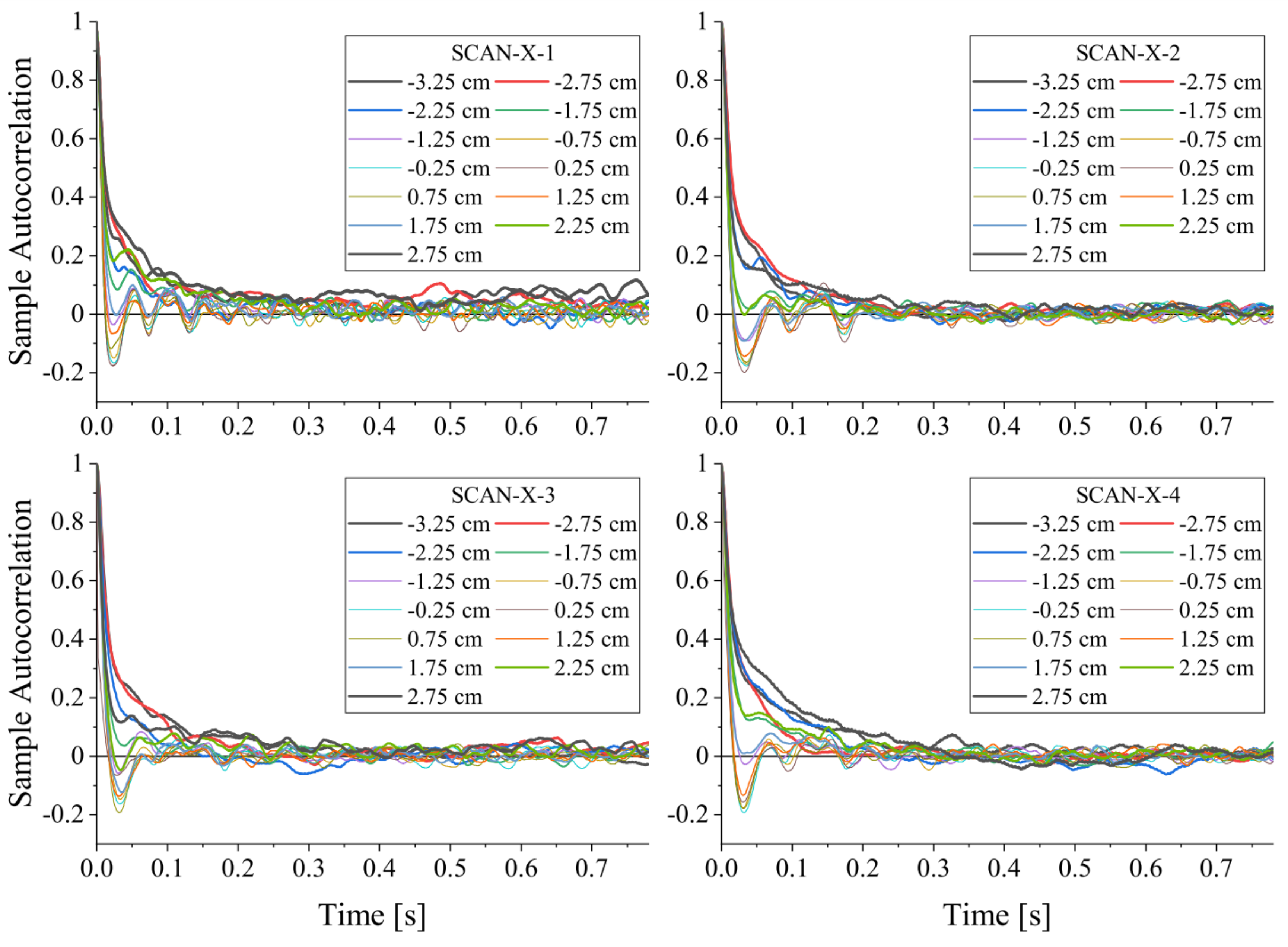
Longitudinal scanning



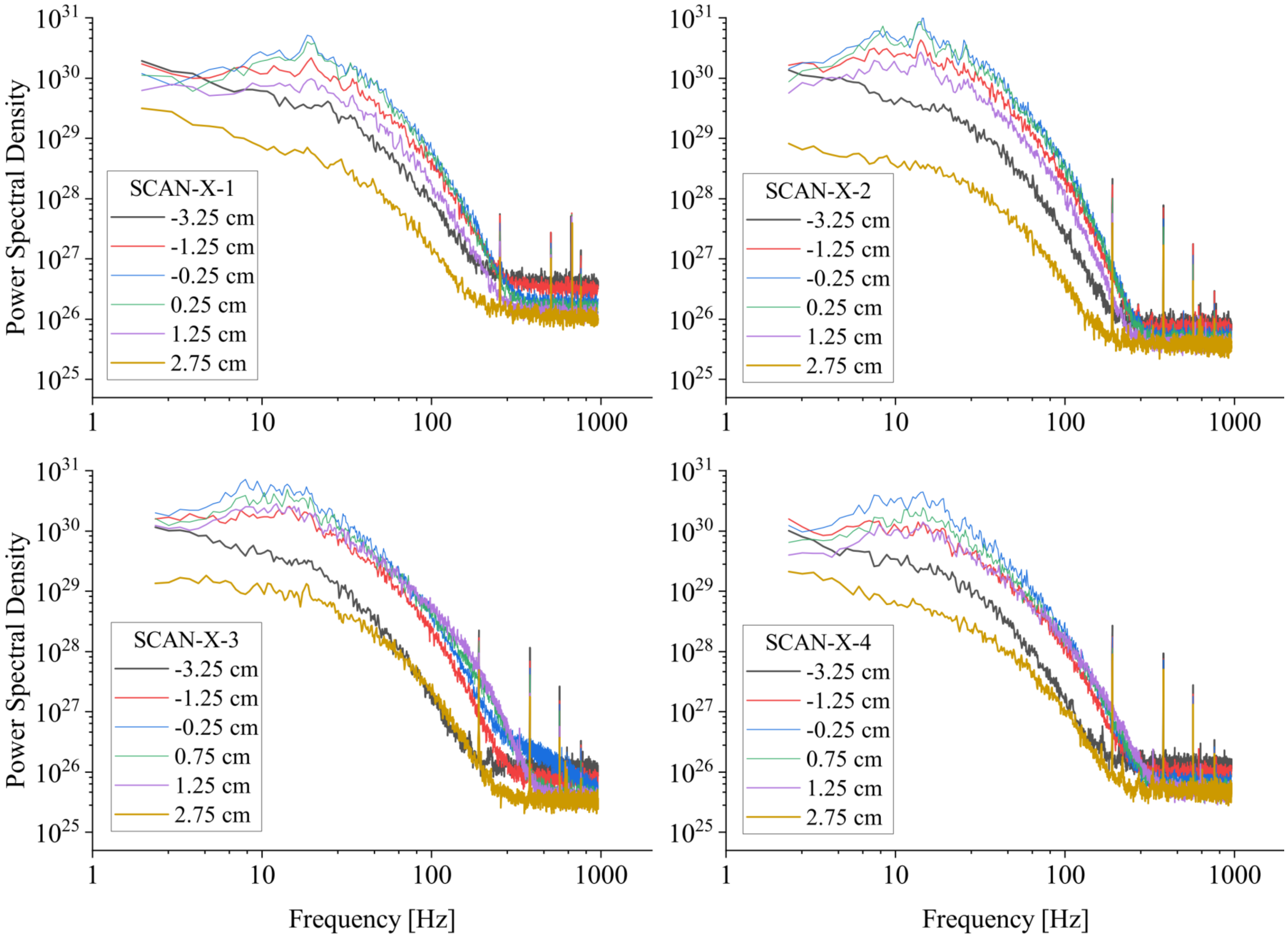


$T_A = 22°C, T_B = 12°C \quad T_{p_A} = 20°C, T_{p_B} = 10°C$

Autocorrelation



Power Spectral Density



- maximum at ~14 Hz – frequency might be related to flow velocity variations but a separate experiment needs to be designed;
- frequency corresponds to the wavelength of ~11 cm;
- floor level slightly increases with increasing mean humidity;
- at the extreme positions, the noise floor is reached at lower frequencies - only minor humidity gradient outside the mixing zone

Conclusions

- FIRH adaptation to a contactelss optical sampling from outside the tunel - eliminates the influence of the sensor on the investigated processes;
- three major physical factors which strongly influence the measurement were identified: self-broadening of the absorption line, interference in the glass windows and parasitic absorption in the ambient air outside the tunel;
- the profiles of mean *n* across the mixing zone measured with the two instruments exhibit similar behavior with a systematic offset between them - limited accuracy of FIRH, the displacement of the DPM inlet with respect to the FIRH optical path and the inherent difference in sampling regimes relevant for those instruments;
- due to the high temporal resolution of FIRH (∼2 kHz), the turbulent fluctuations in the mixing zone were analyzed. The variance maximizes in the central part which coincides with the strongest gradient. The width of the mixing zone is estimated to be ∼5 cm;
- it would be desirable to reduce parasitic absorption and window transmission effects, e.g. with anti-reflective coatings or the integration of emitter and detector into the windows;
- biggest limitations: two wavelengths need to be collected consecutively, no reliable knowledge how FIRH operates in the presence of cloud droplets in the optical path.

17 Mar 2022

Review status: this preprint is currently under review for the journal AMT.

Contactless optical hygrometry in LACIS-T

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