DEVELOPMENT AND EXPERIMENTAL RESULTS OF A SYNTHETIC DISPERSION INTERFEROMETER FOR AIR DISPERSION MEASUREMENT

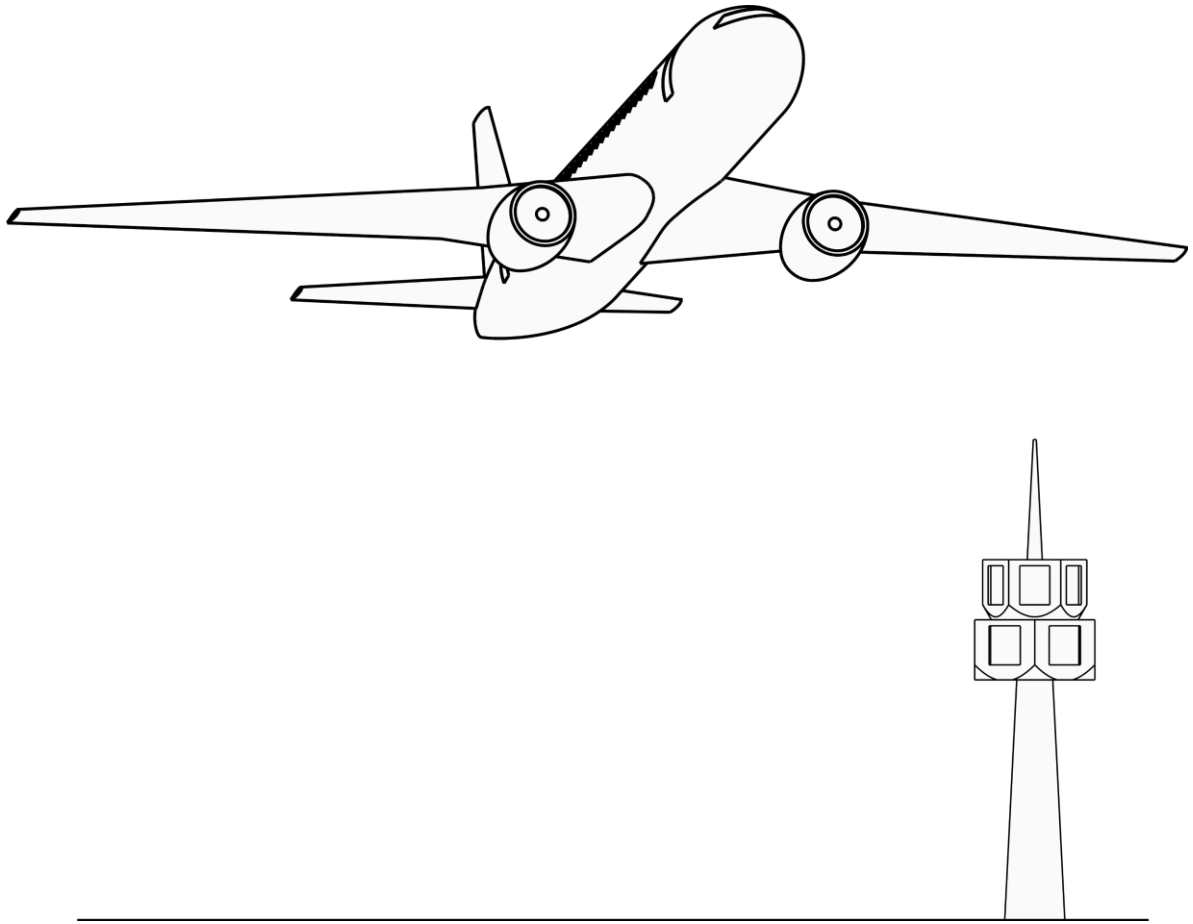
Hugo Uittenbosch, Raoul-Amadeus Lorbeer, Oliver Kliebisch, Peter Mahnke, Tobias Janke and Thomas Dekorsy

Institute of Technical Physics - German Aerospace Center (DLR), Stuttgart, Germany

Motivation

Altitude measurement in aviation

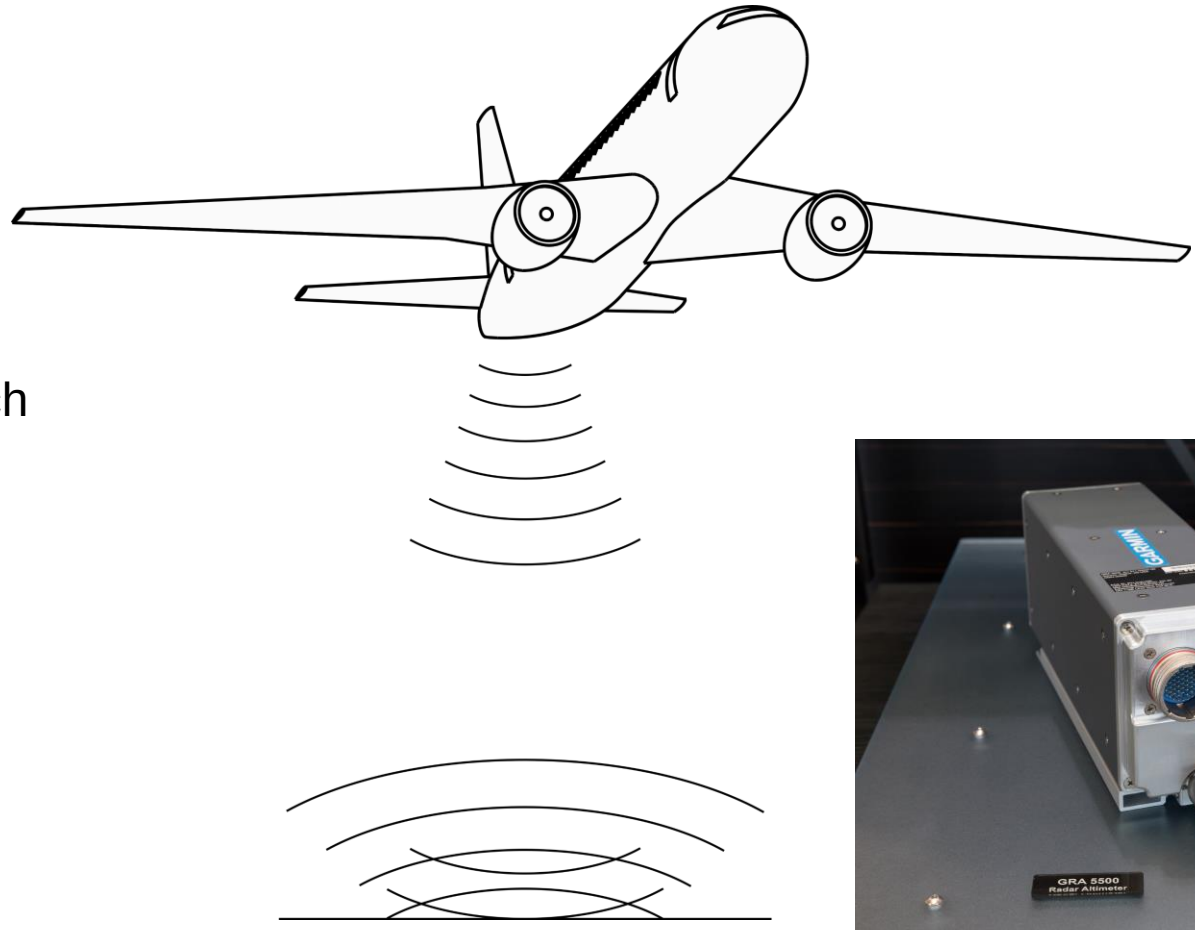
- Air traffic control



Motivation

Altitude measurement in aviation

- Air traffic control
- Radar altimeter
  - Take-off and landing approach
  - Height above ground

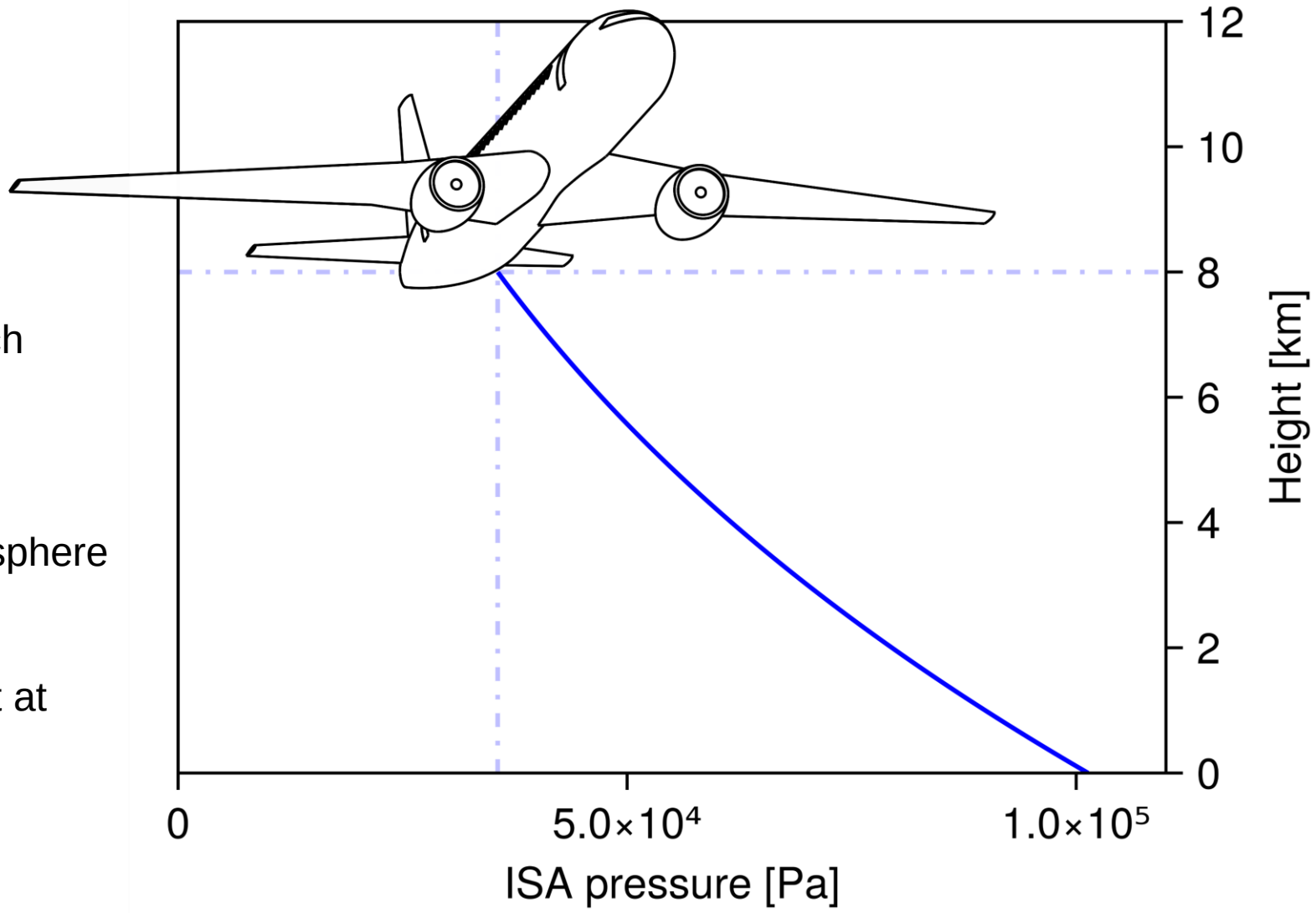


Matti Blume, Garmin radar altimeter at AERO Friedrichshafen 2018, CC BY-SA 4.0

Motivation

Altitude measurement in aviation

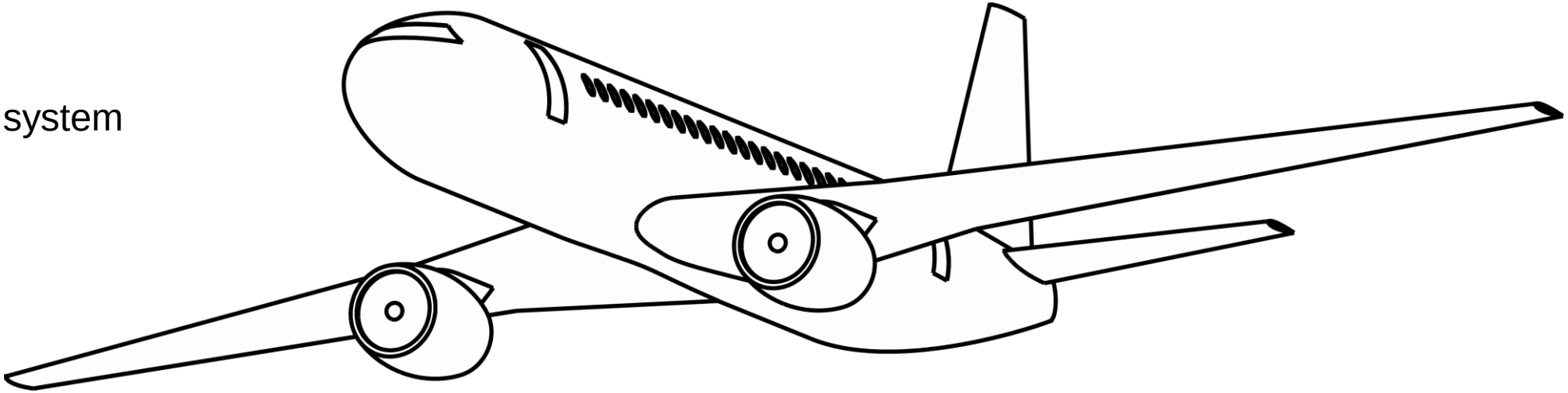
- Air traffic control
- Radar altimeter
  - Take-off and landing approach
  - Height above ground
- Barometer / Variometer
  - **I**nternational **S**tandard **A**tmosphere
  - Height above see level
  - Consistency in measurement at higher altitudes



Motivation

Static pressure measurement

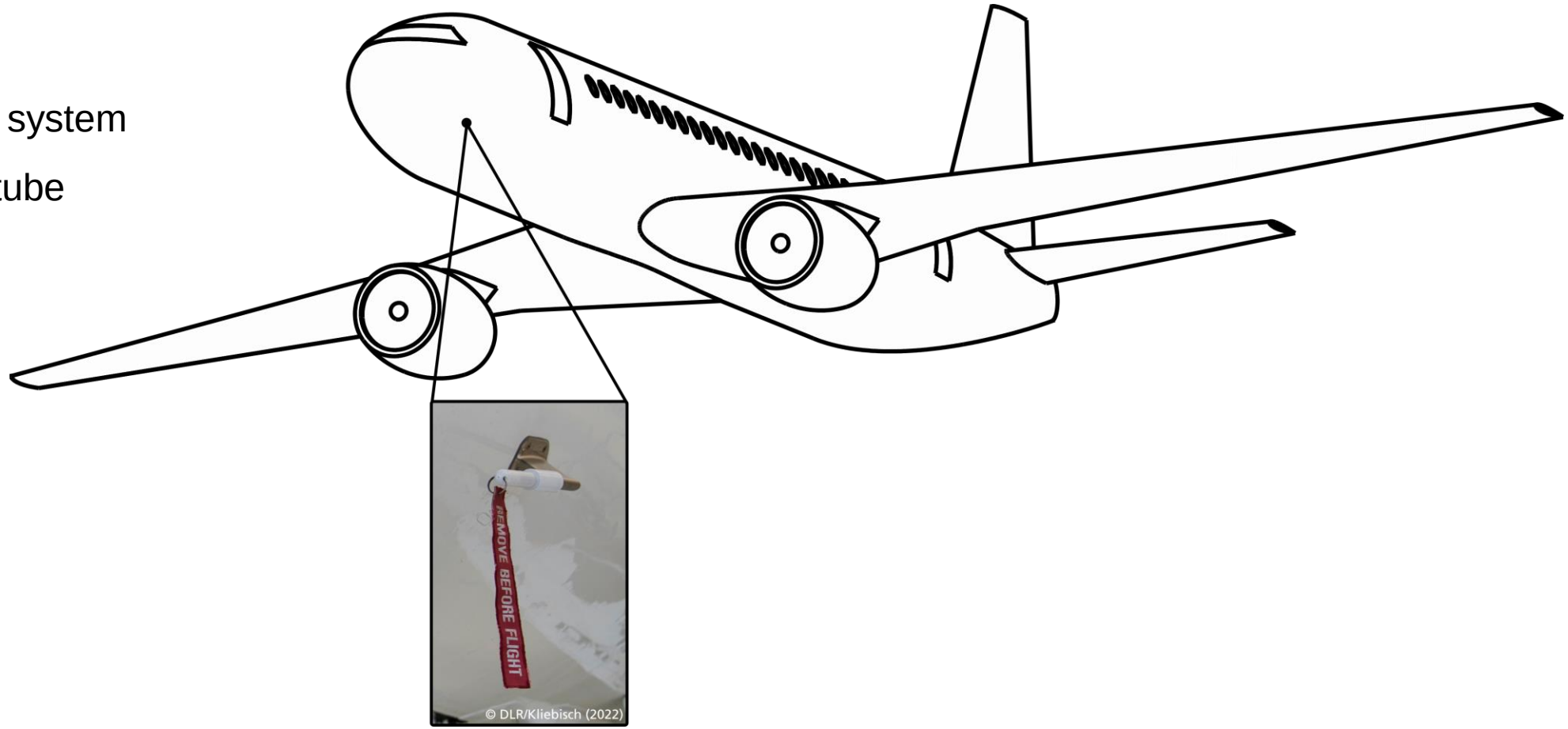
- State of the Art
  - Pitot-static system



Motivation

Static pressure measurement

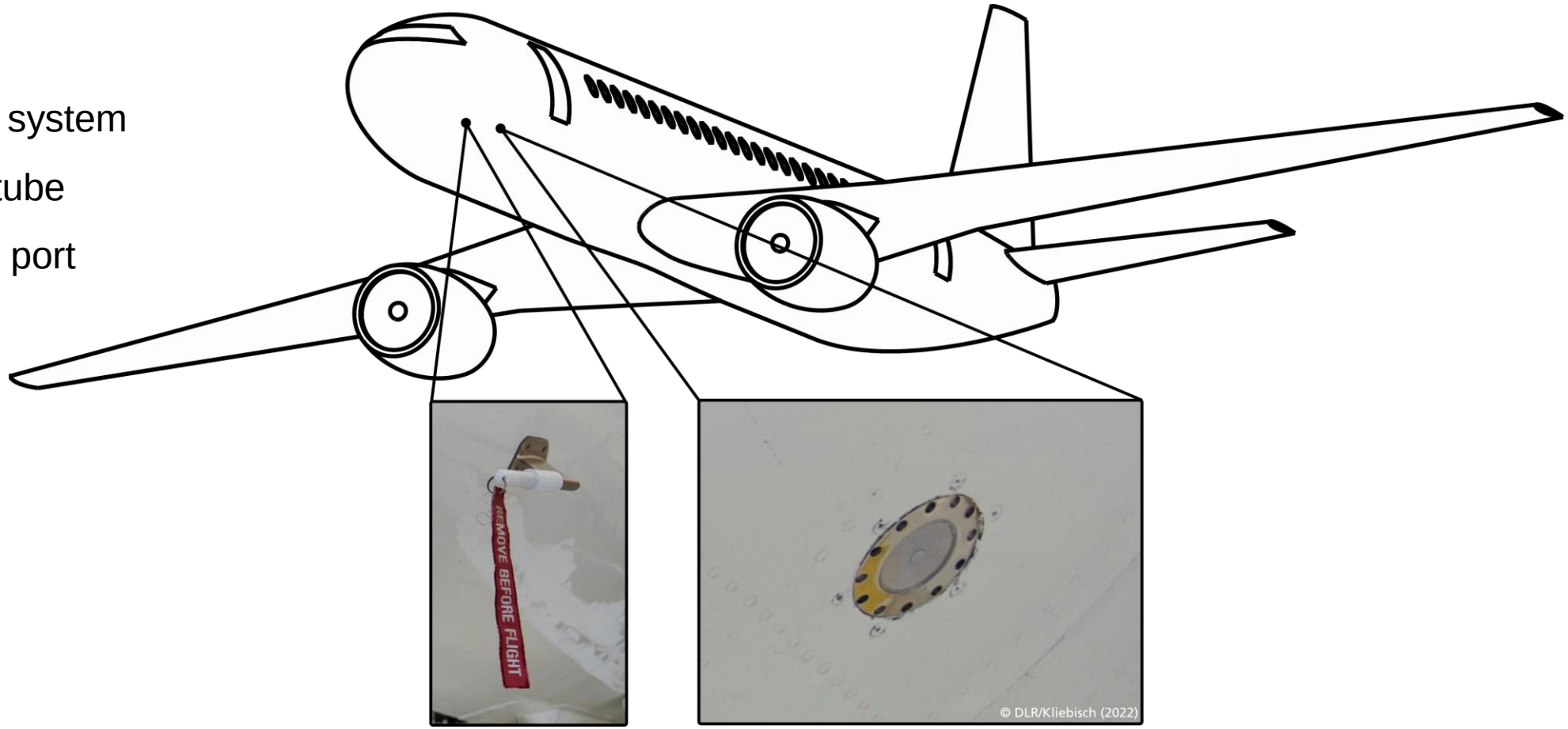
- State of the Art
  - Pitot-static system
    1. Pitot tube



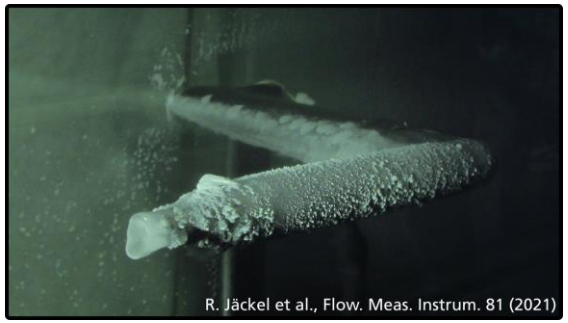
Motivation

Static pressure measurement

- State of the Art
  - Pitot-static system
    1. Pitot tube
    2. Static port

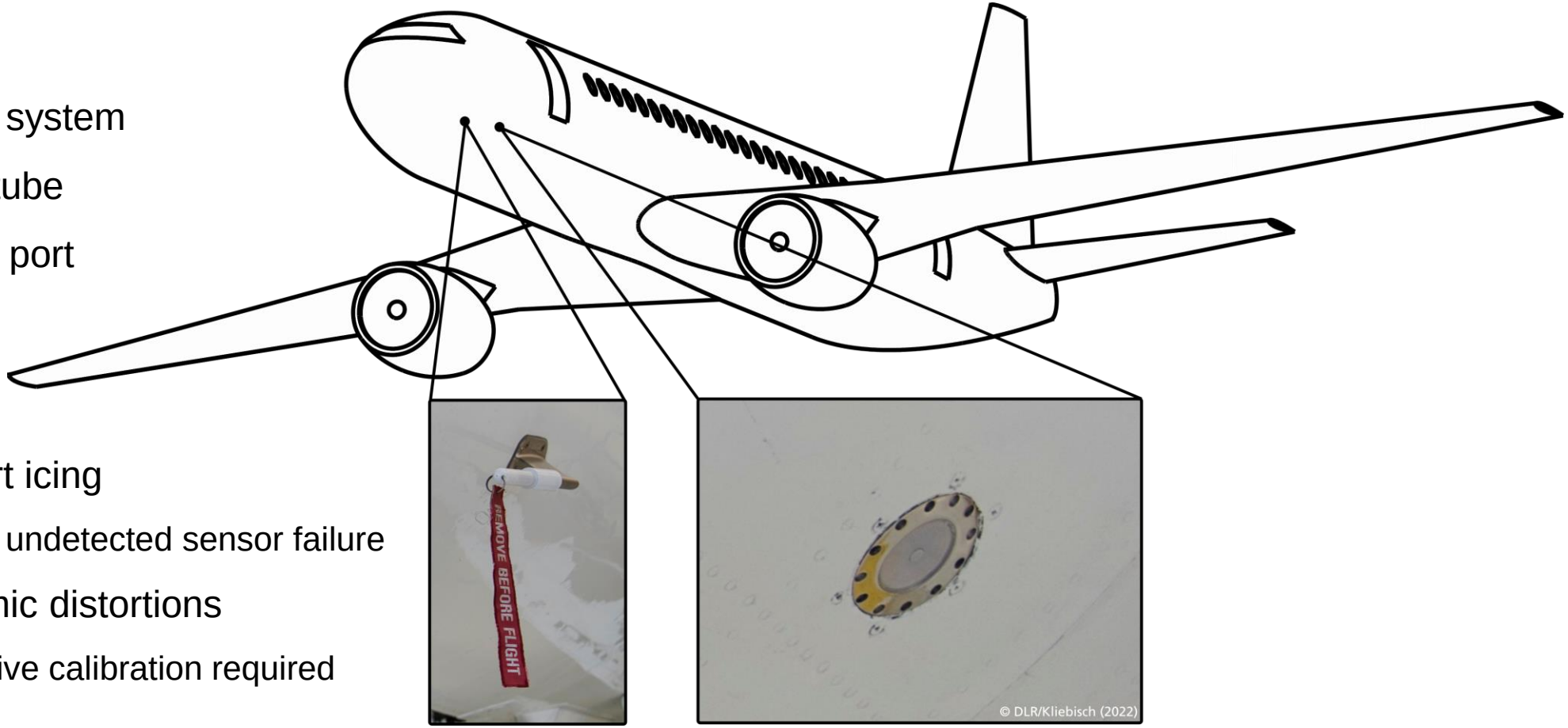


Motivation



Static pressure measurement

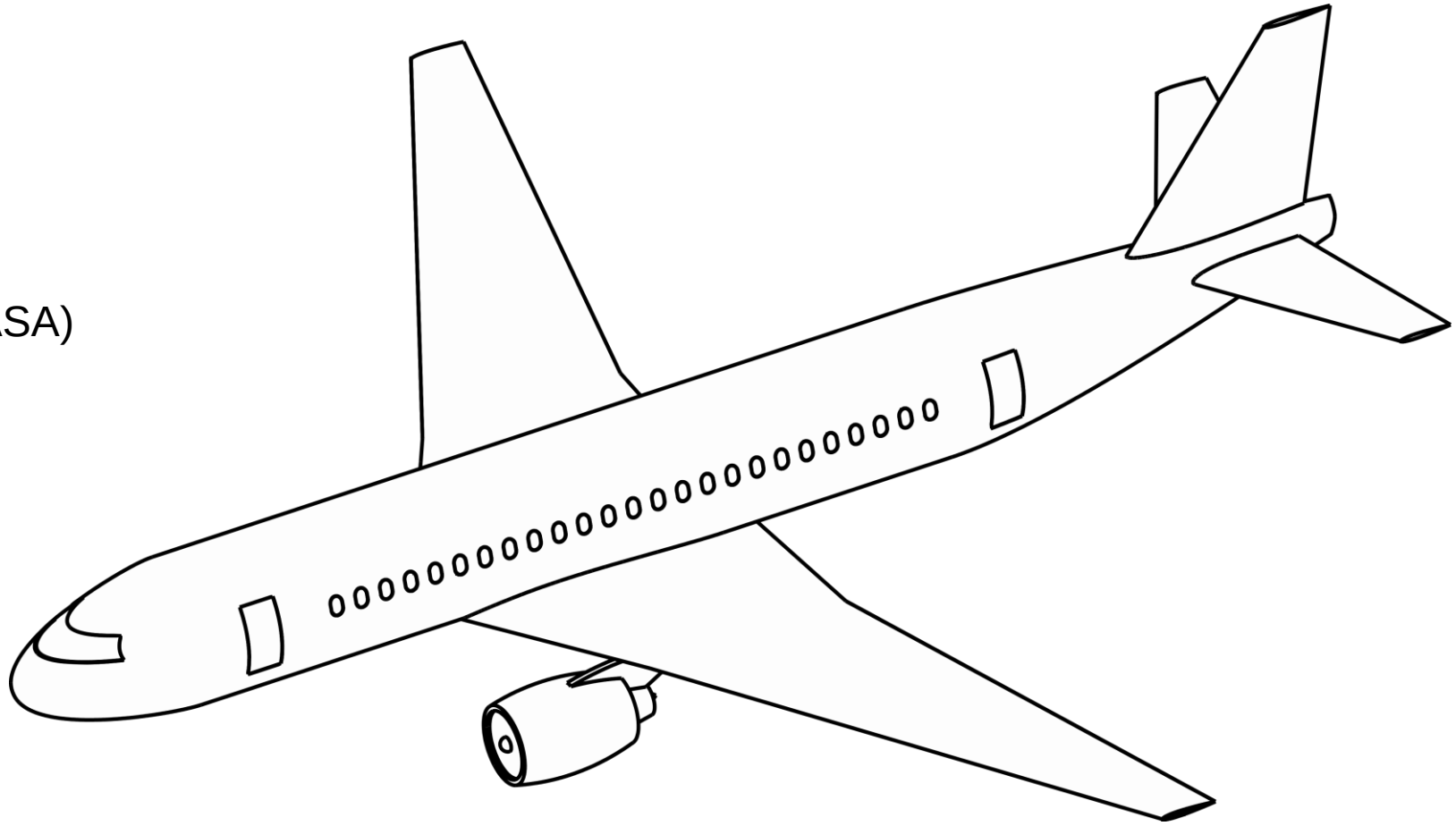
- State of the Art
  - Pitot-static system
    1. Pitot tube
    2. Static port
- Safety issues
  - Tube & port icing
    - Risk of undetected sensor failure
  - Aerodynamic distortions
    - Extensive calibration required



Concept

Optical pressure measurement

- Sensor requirements
  - Civil aviation reqs. (FAA/EASA)

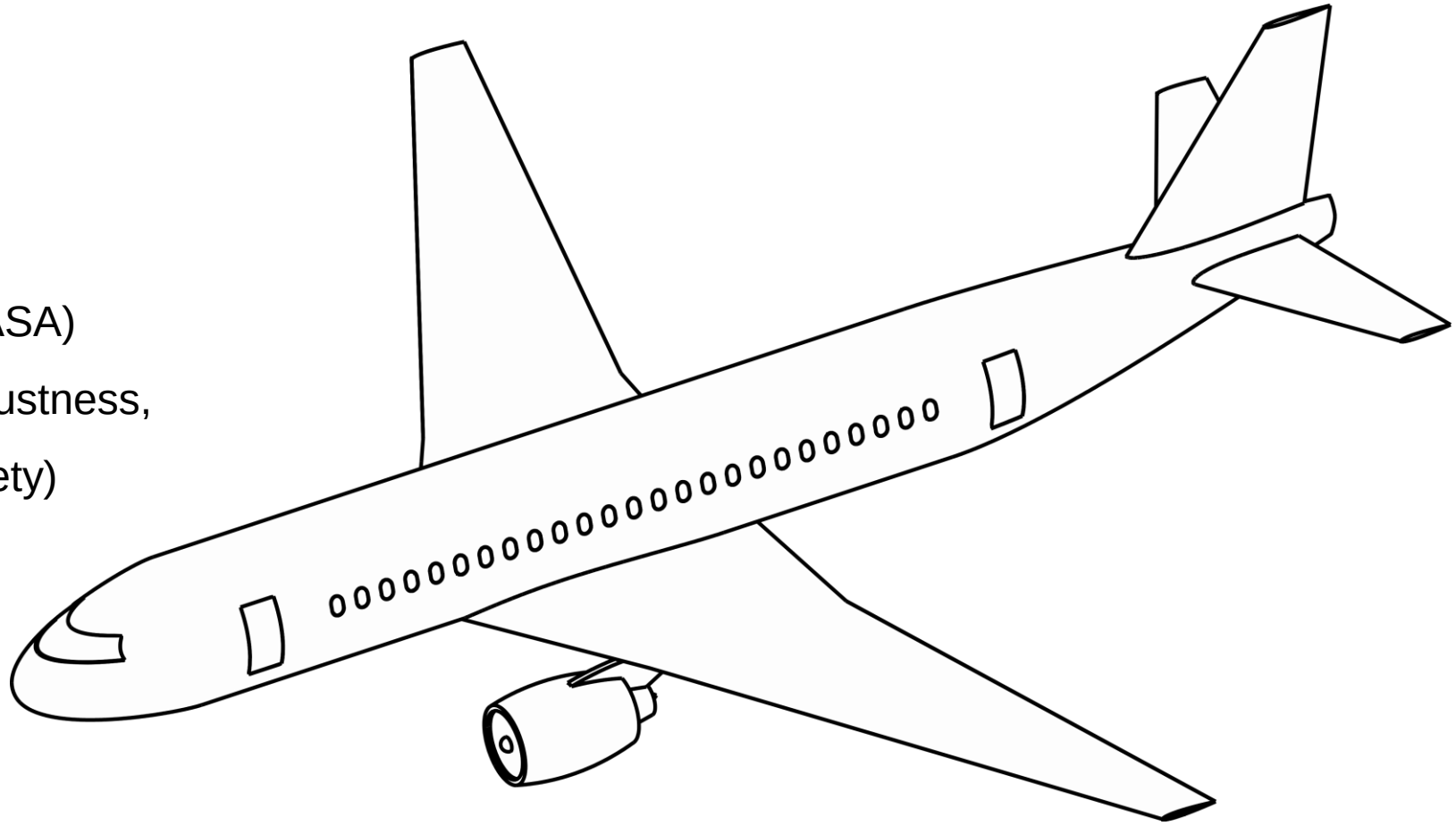


- Deviation ≈ ± 30 Pa
- Bandwidth ≈ 33 Hz

Concept

Optical pressure measurement

- Sensor requirements
  - Civil aviation reqs. (FAA/EASA)
  - In addition: mechanical robustness, long term stability, (eye safety)

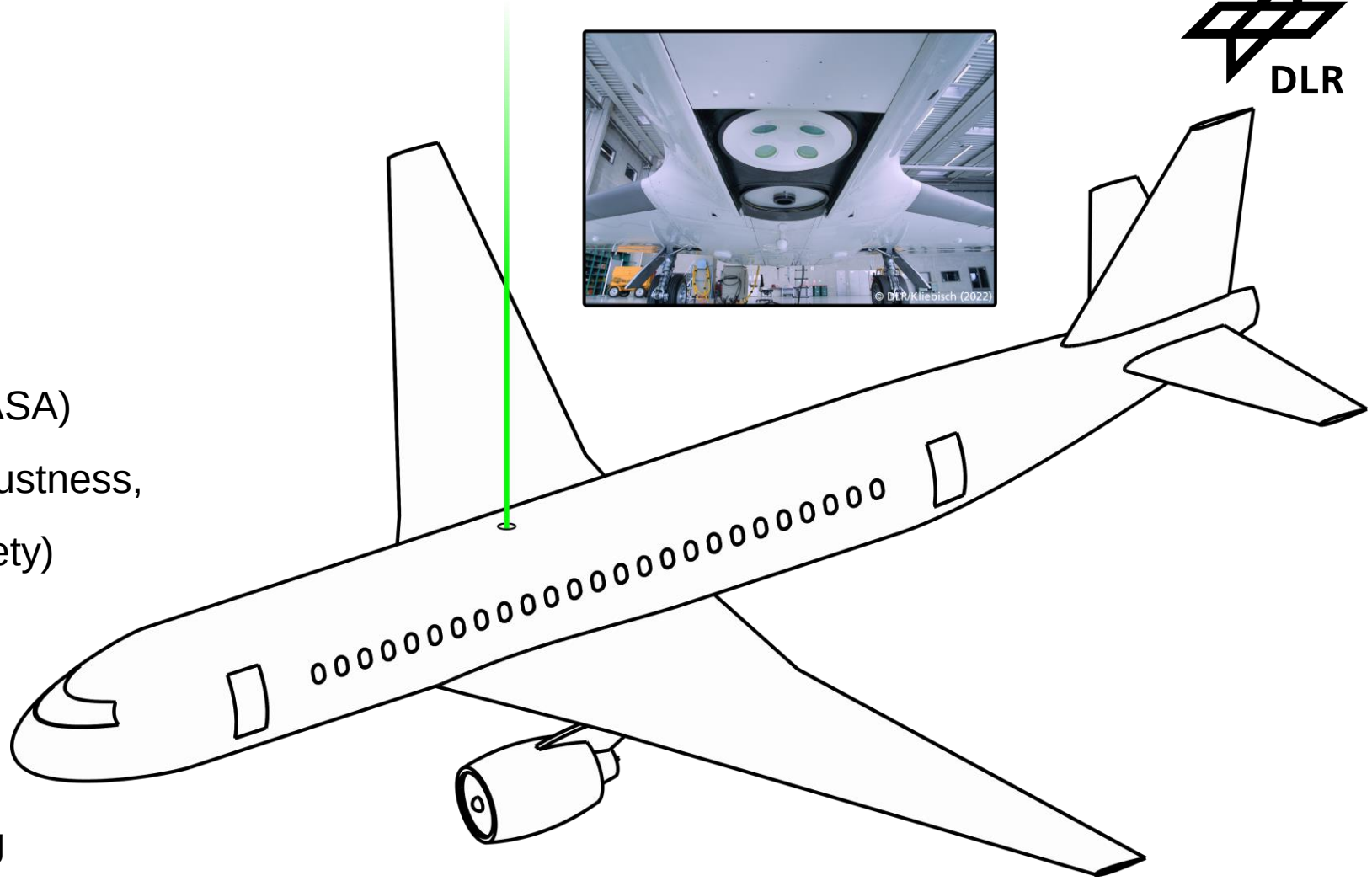


- Deviation ≈ ± 30 Pa
- Bandwidth ≈ 33 Hz

Concept

Optical pressure measurement

- Sensor requirements
  - Civil aviation reqs. (FAA/EASA)
  - In addition: mechanical robustness, long term stability, (eye safety)
- Optical methods
  - Filtered Rayleigh Scattering



Concept

Optical pressure measurement

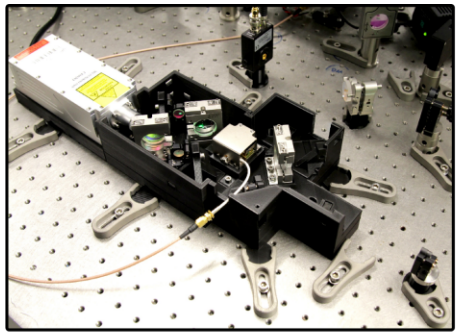
- Sensor requirements
  - Civil aviation reqs. (FAA/EASA)
  - In addition: mechanical robustness, long term stability, (eye safety)

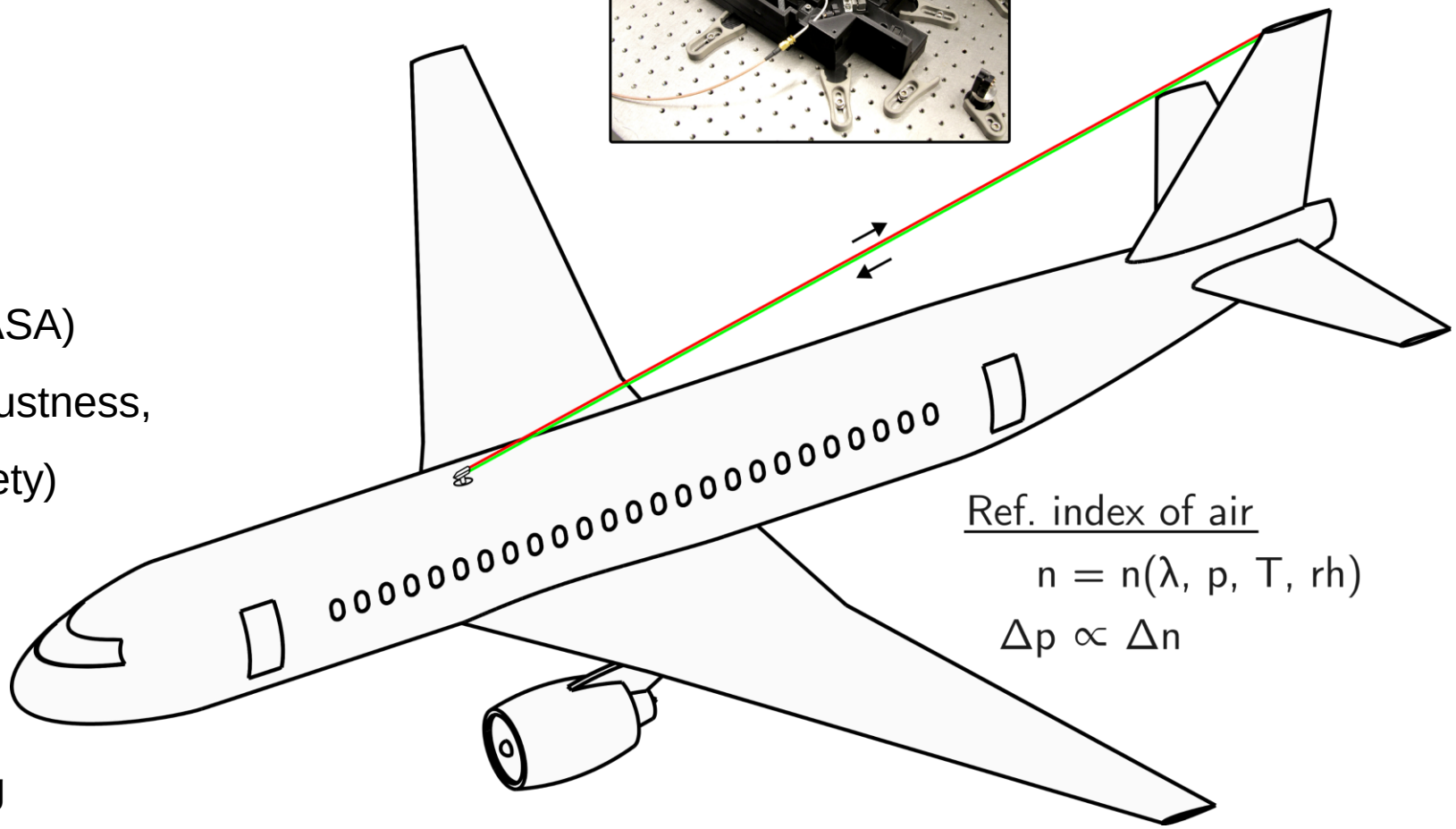
- Optical methods
  - Filtered Rayleigh Scattering
  - Tunable Diode Laser Absorption Spectroscopy

Concept

Optical pressure measurement

- Sensor requirements
  - Civil aviation reqs. (FAA/EASA)
  - In addition: mechanical robustness, long term stability, (eye safety)



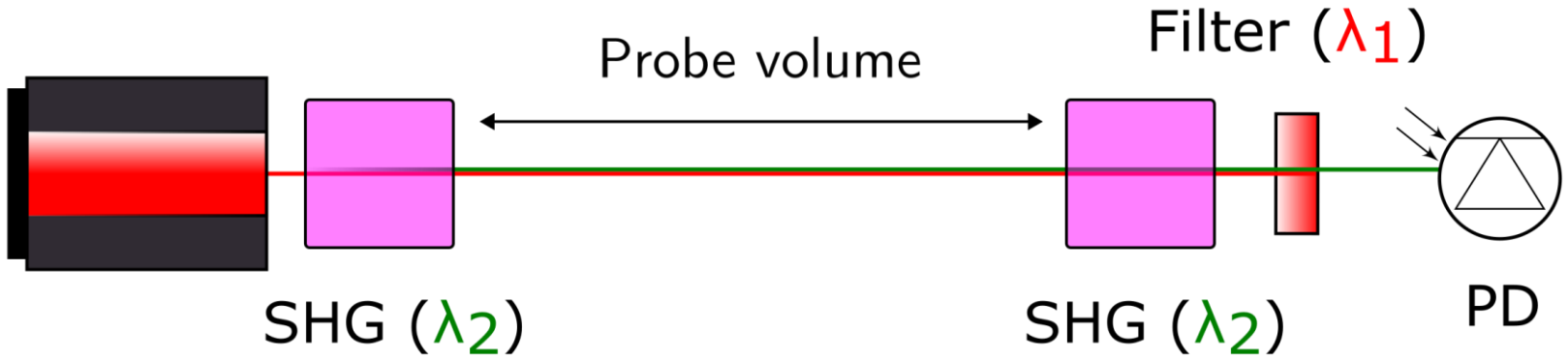


- Optical methods
  - Filtered Rayleigh Scattering
  - Tunable Diode Laser Absorption Spectroscopy
  - **Dispersion / Two-Color Interferometry (DI)**

Experimental Setup I

Dispersion Interferometry

- Density measurement
- Robust against mechanical vibrations
- Sensitive to changes of dispersion of probe medium



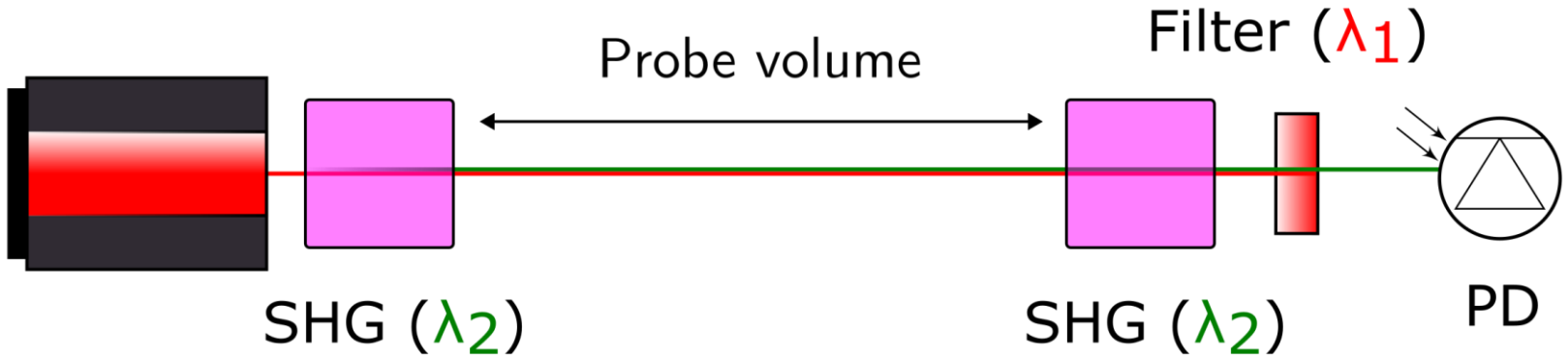
Experimental Setup I

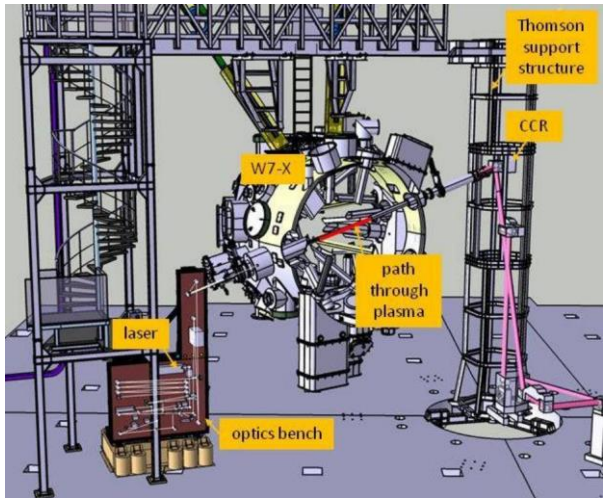
Dispersion Interferometry

- Density measurement
- Robust against mechanical vibrations
- Sensitive to changes of dispersion of probe medium

Related publications:
- V.P. Drachev, Meas Tech **33**, 1125–1127 (1990)
- K.J. Brunner et al., J. Instrum. **13** P09002 (2018)
- T. Akiyama et al., J. Instrum. **15** C01004 (2020)

Used on **ITER, W7-X and many more** for line-integrated electron density measurement…





P. Kornejew et al, 40th EPS Conference on Plasma Physics. European Physical Society, 2013.

Experimental Setup I

Dispersion Interferometry

- Density measurement
- Robust against mechanical vibrations
- Sensitive to changes of dispersion of probe medium

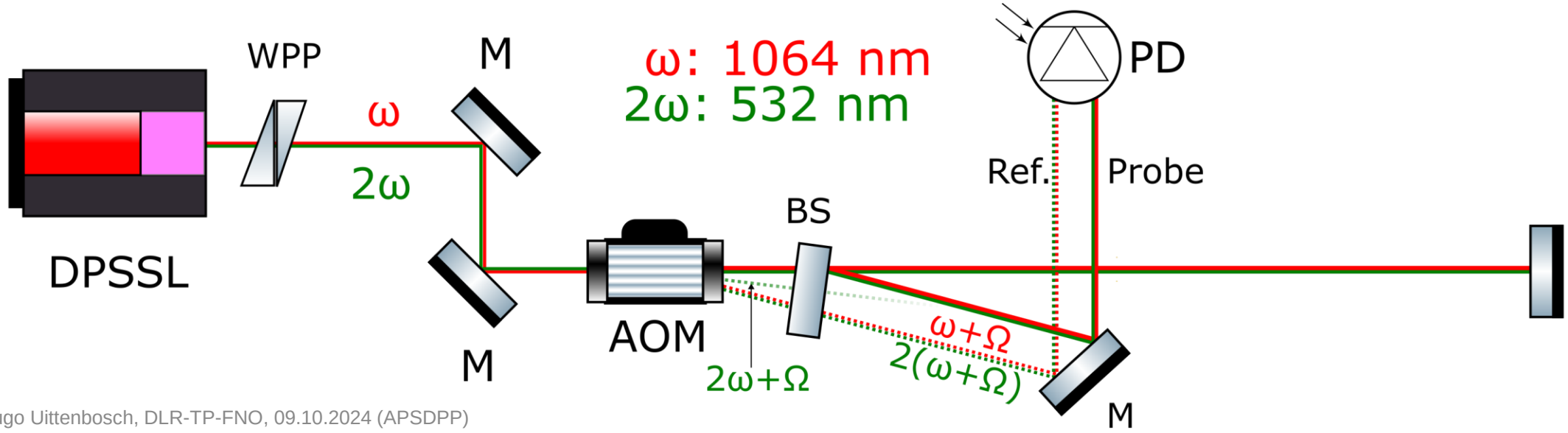
Two-arm synthetic DI (SDI)

- Heterodyne, two-arm DI
- Digital second SHG step
- 2.3 mW VIS and 11.5 mW IR optical power in probe beam
- Single detector unit

Related publications:

- J. Irby et. al., Rev. Sci. Instrum. **70**, 699 (1999)
- D.-G. Lee et al., Rev. Sci. Instrum. **92**, 033536 (2021)
- H. Uittenbosch et al., Opt. Express **31**, 6356-6369 (2023)

Similar devices used on **Alcator C-MOD**, **KSTAR**



Experimental Setup I

Dispersion Interferometry

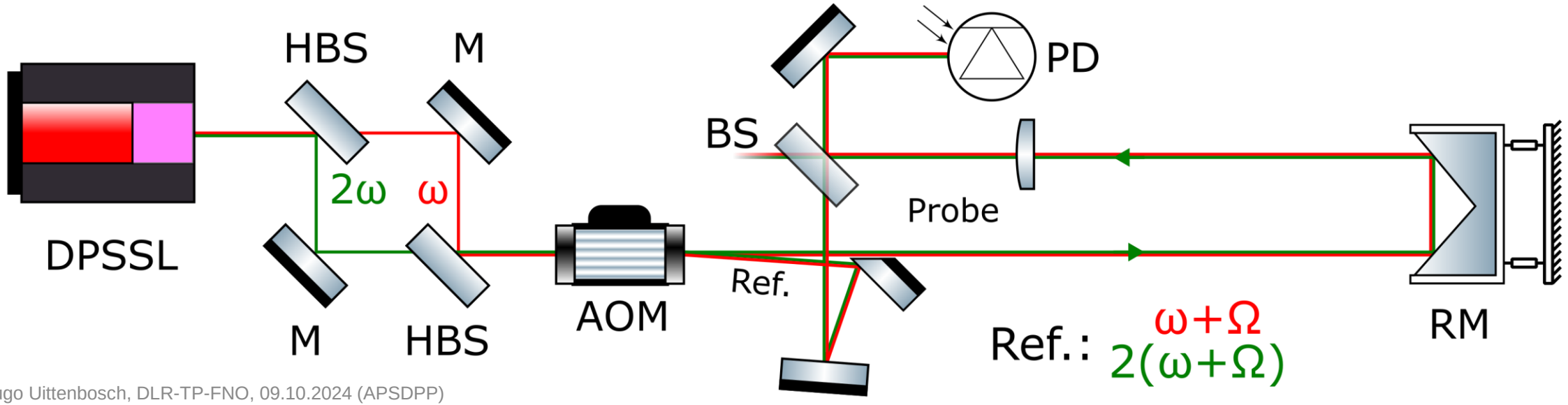
- Density measurement
- Robust against mechanical vibrations
- Sensitive to changes of dispersion of probe medium

Two-arm synthetic DI (SDI)

- Heterodyne, two-arm DI
- Digital second SHG step
- 2.3 mW VIS and 11.5 mW IR optical power in probe beam
- Single detector unit

“Stable” SDI

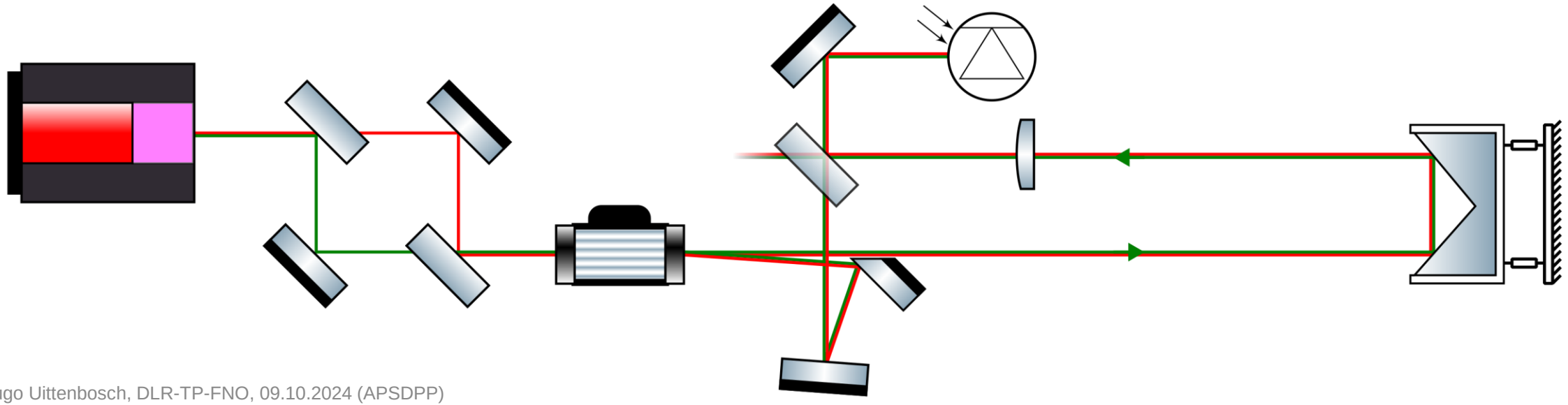
- Focus on
  - Vibrational robustness
  - Long-term stability
- Minimization of drift and noise
- Real-time measurement



Experimental Setup II

Air Pressure Measurement

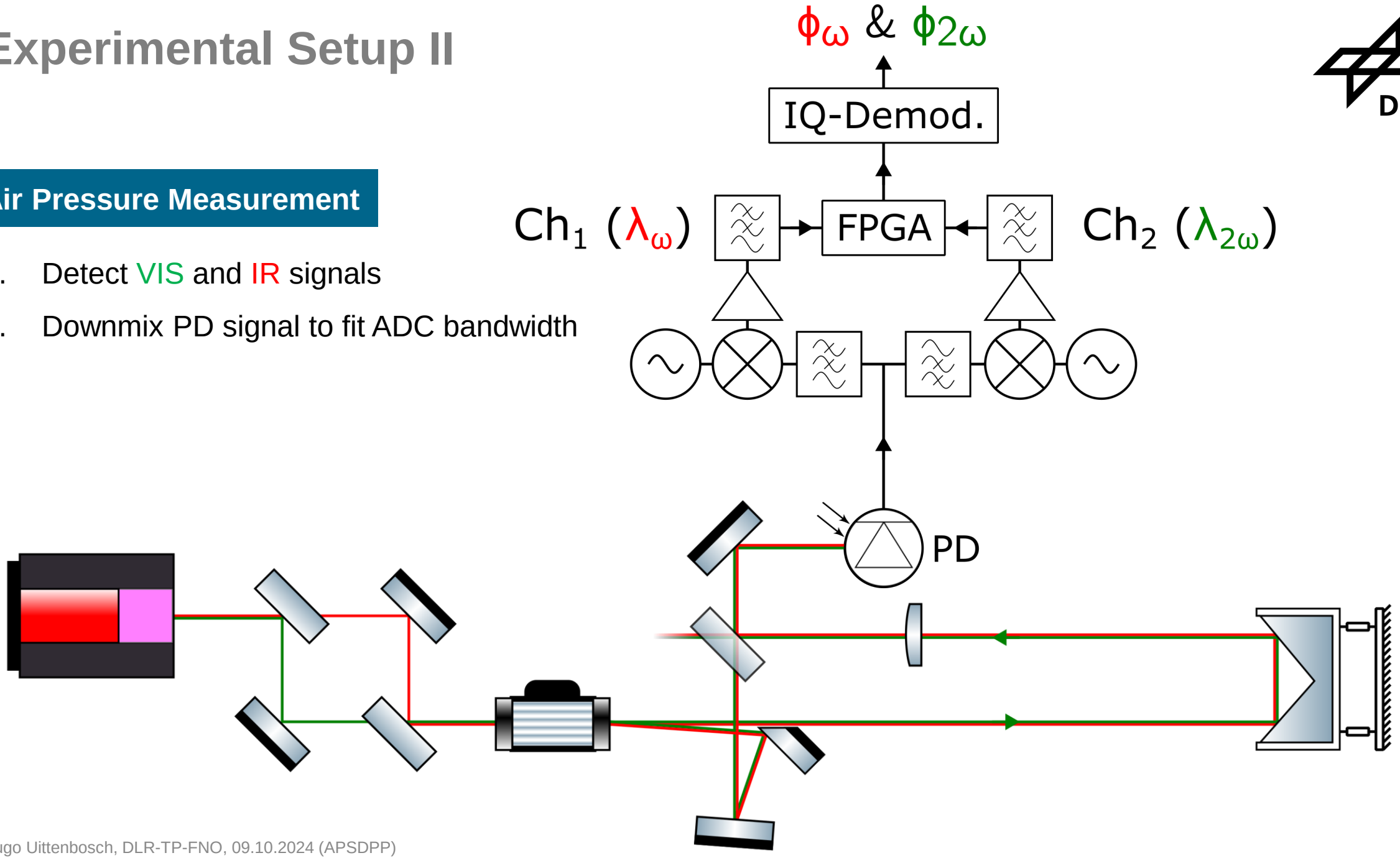
1. Detect VIS and IR signals



Experimental Setup II

Air Pressure Measurement

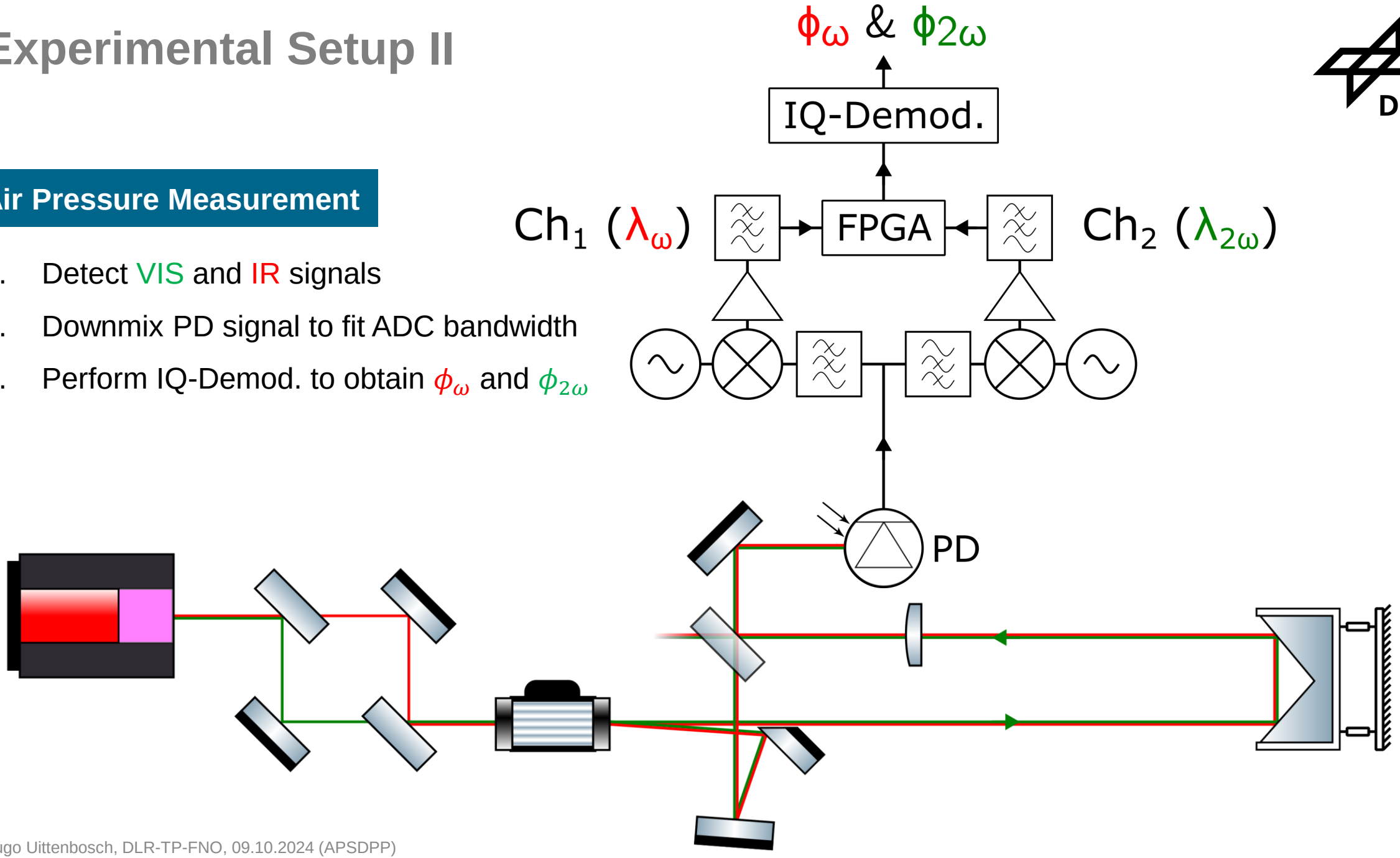
1. Detect VIS and IR signals
2. Downmix PD signal to fit ADC bandwidth



Experimental Setup II

Air Pressure Measurement

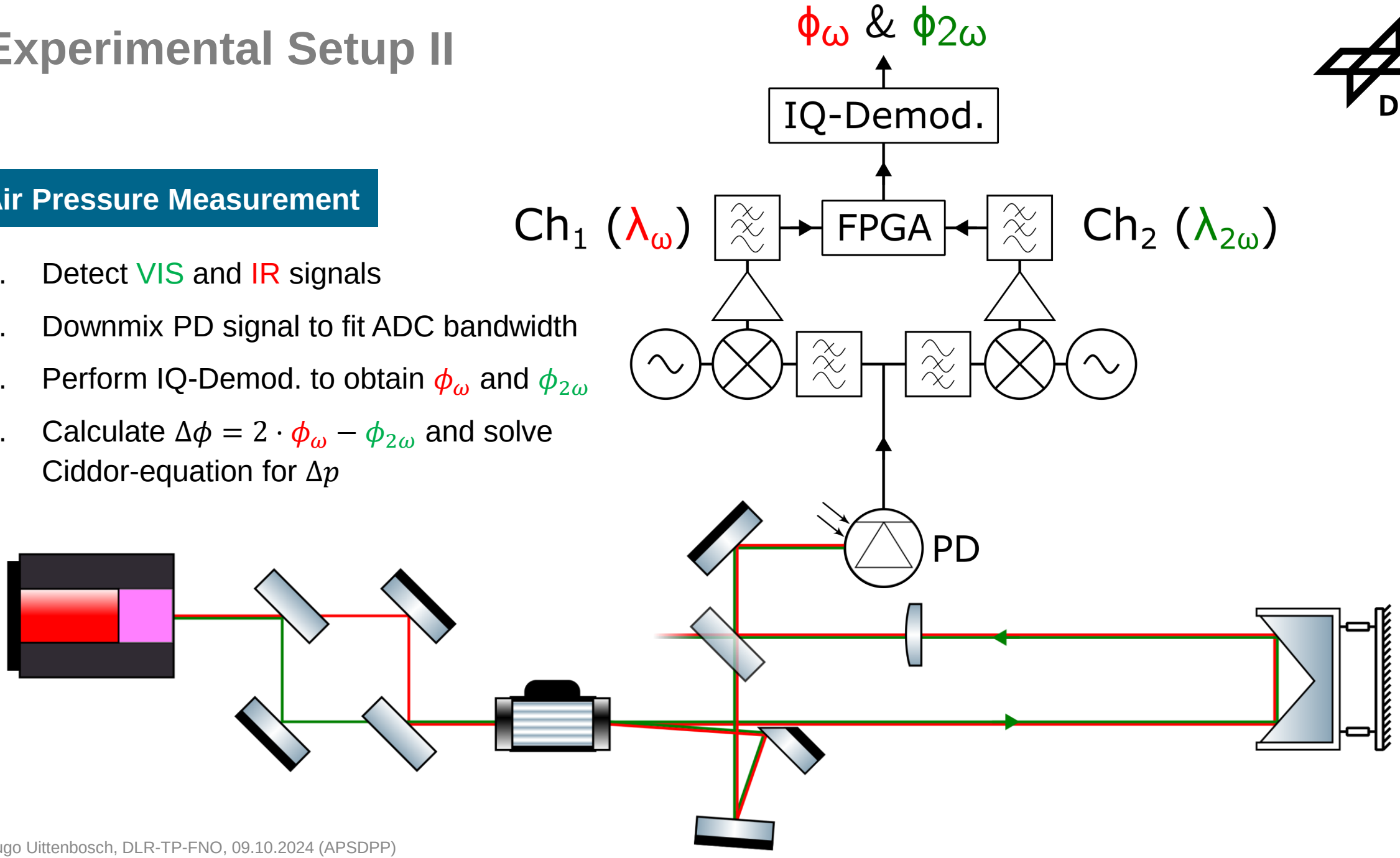
1. Detect VIS and IR signals
2. Downmix PD signal to fit ADC bandwidth
3. Perform IQ-Demod. to obtain ϕ_ω and $\phi_{2\omega}$



Experimental Setup II

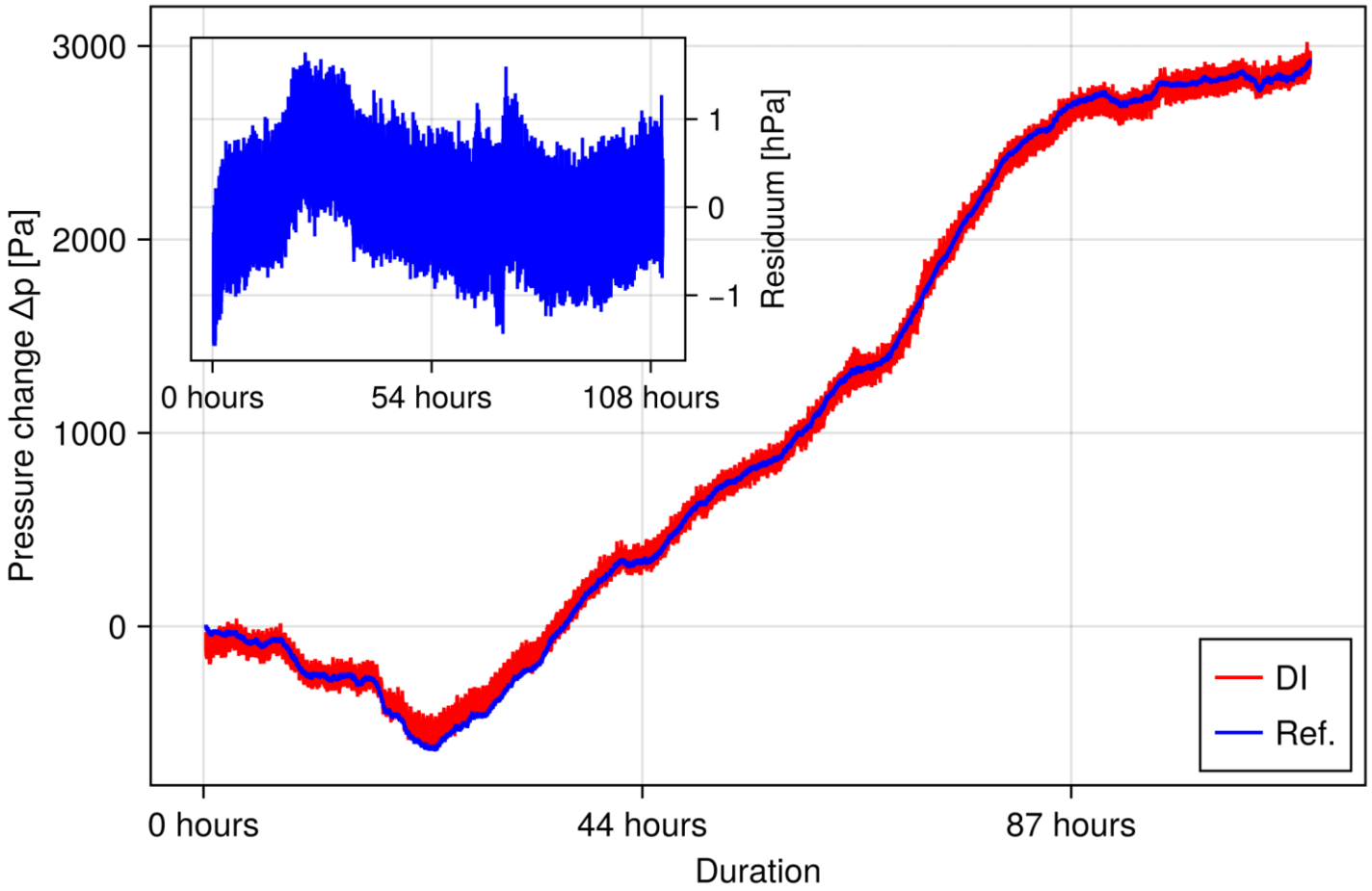
Air Pressure Measurement

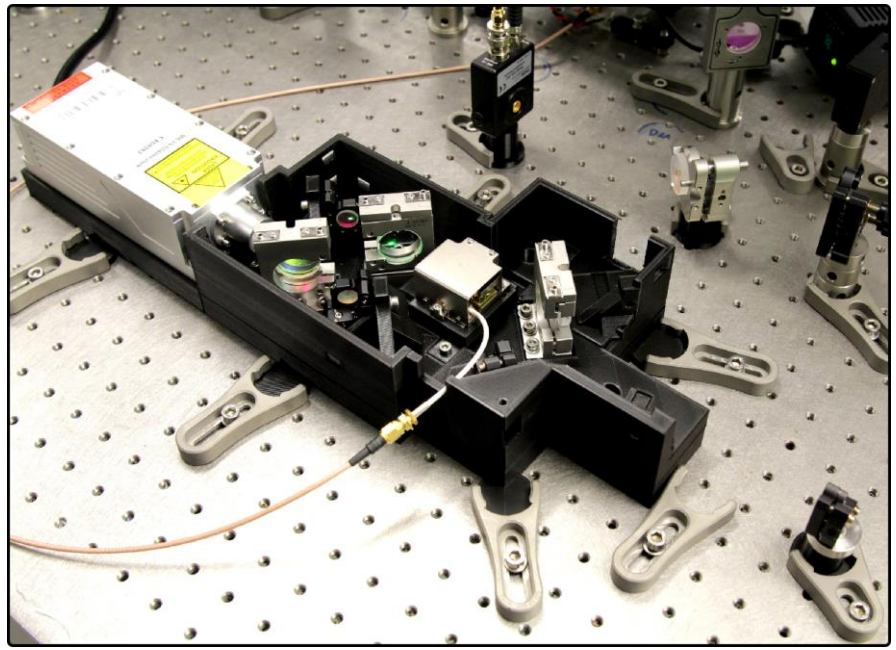
1. Detect VIS and IR signals
2. Downmix PD signal to fit ADC bandwidth
3. Perform IQ-Demod. to obtain ϕ_ω and $\phi_{2\omega}$
4. Calculate $\Delta\phi = 2 \cdot \phi_\omega - \phi_{2\omega}$ and solve Ciddor-equation for Δp



Experimental Setup II

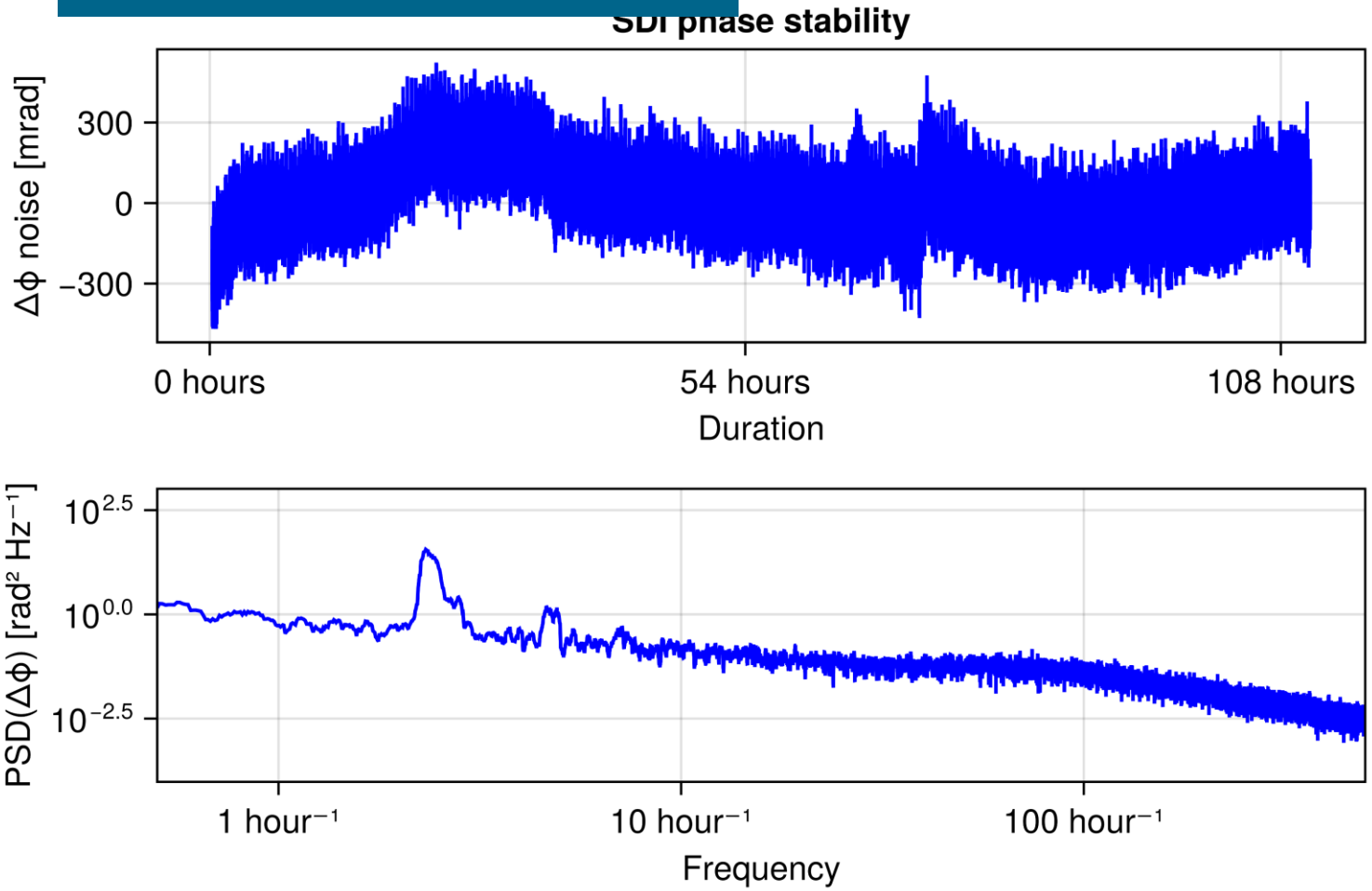
Air Pressure Measurement

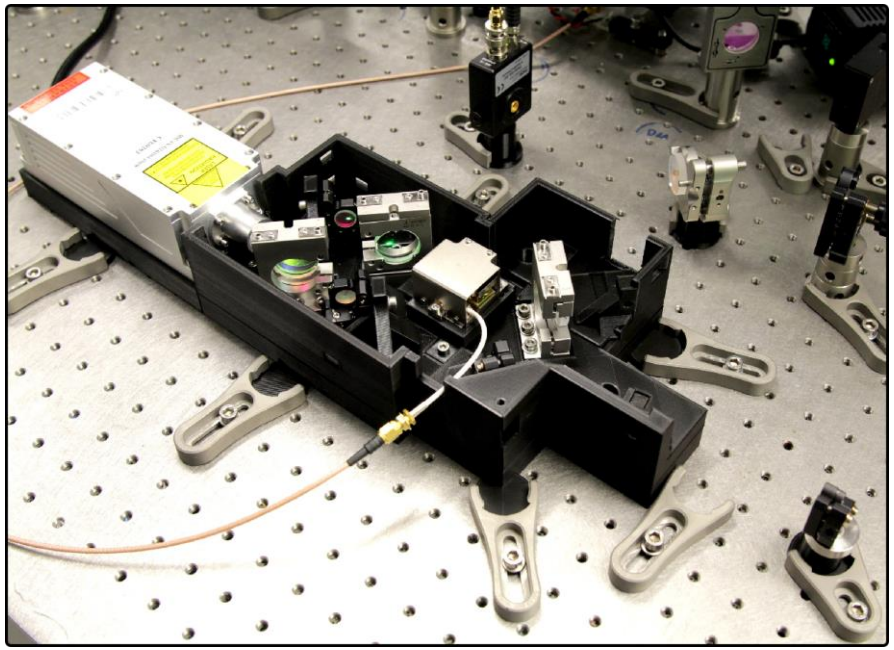




- Footprint: approx. 50 x 30 cm
- Probe arm length: approx. 3.2 m
- Bandwidth: 30 Hz

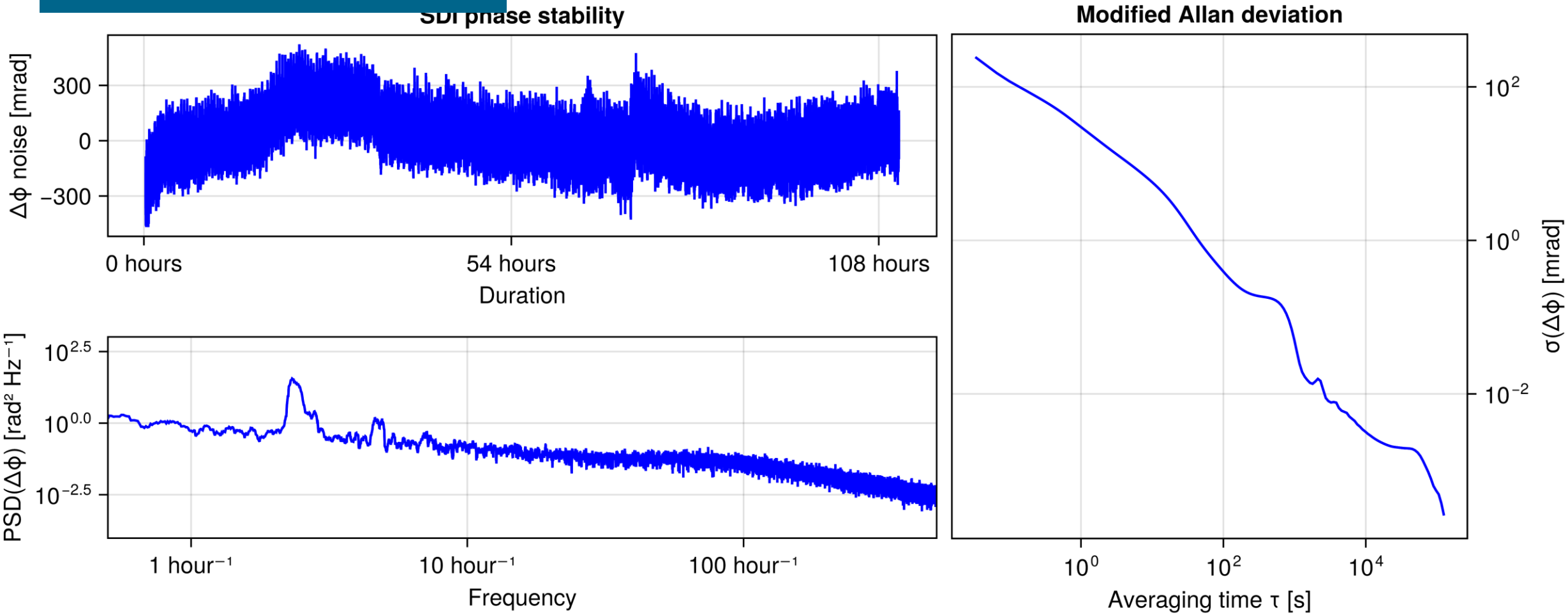
Experimental Setup II





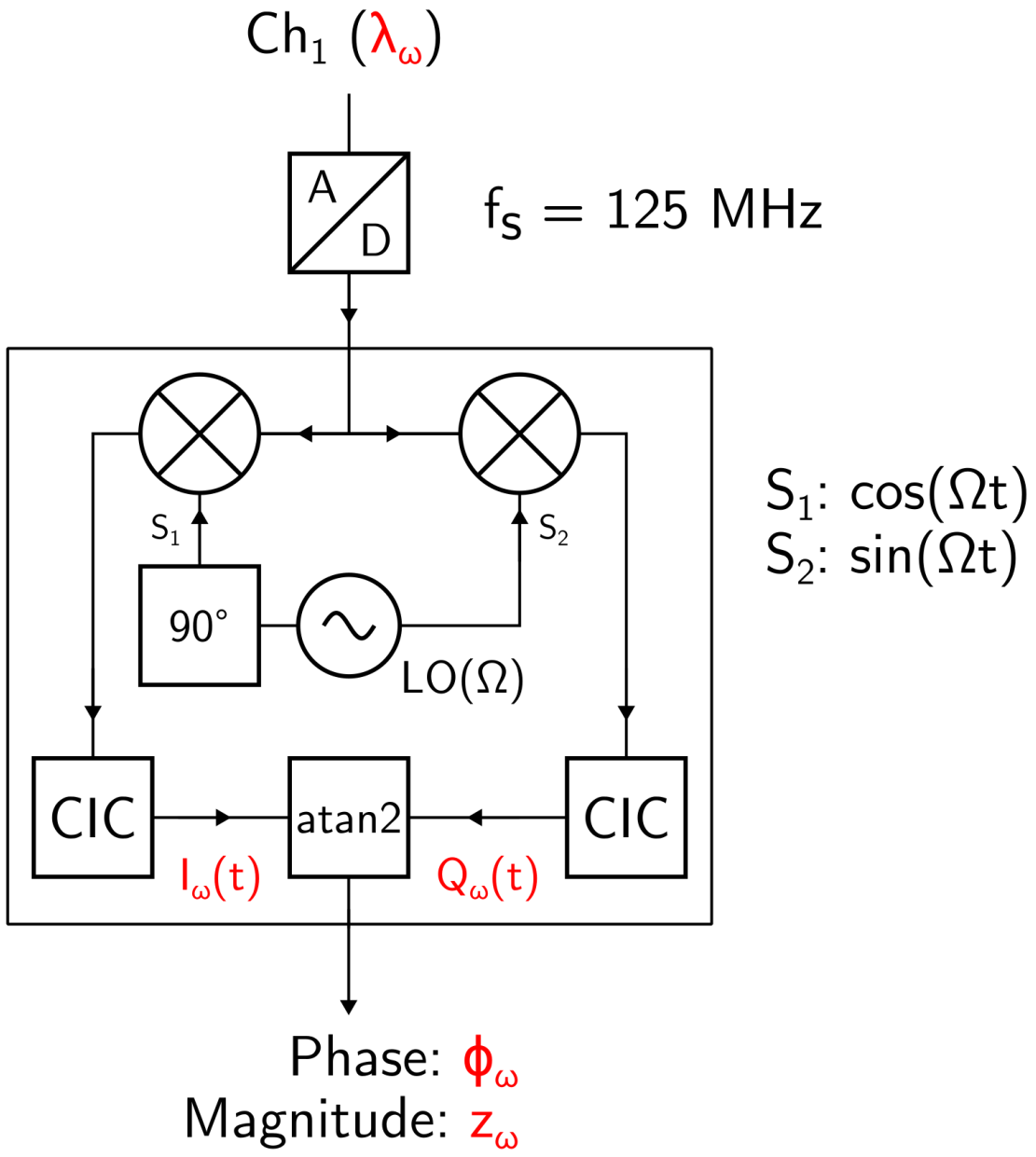
- Footprint: approx. 50 x 30 cm
- Probe arm length: approx. 3.2 m
- Bandwidth: 30 Hz

Experimental Setup II



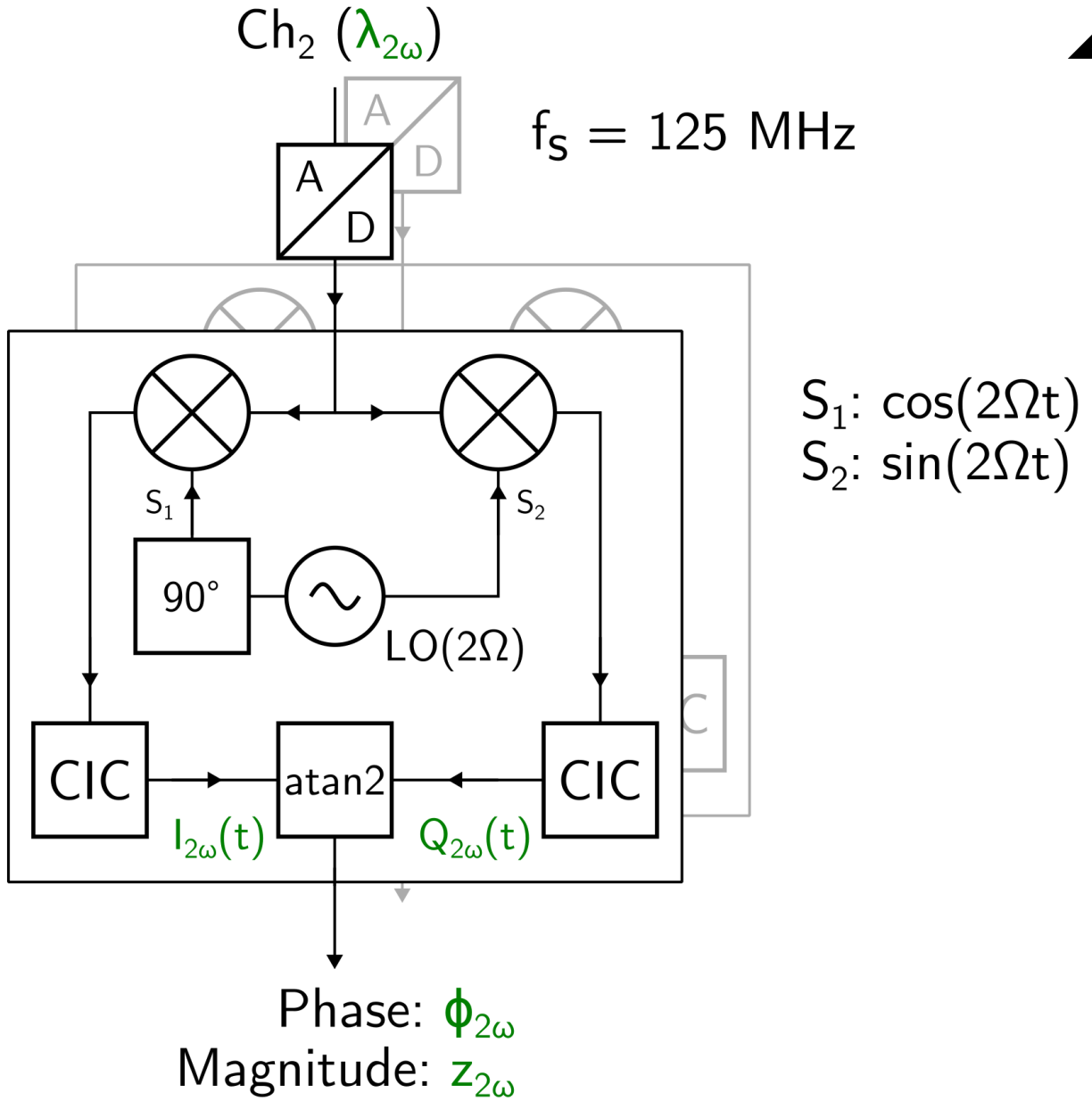
Real-Time Measurement

- IQ demodulation of FM signal



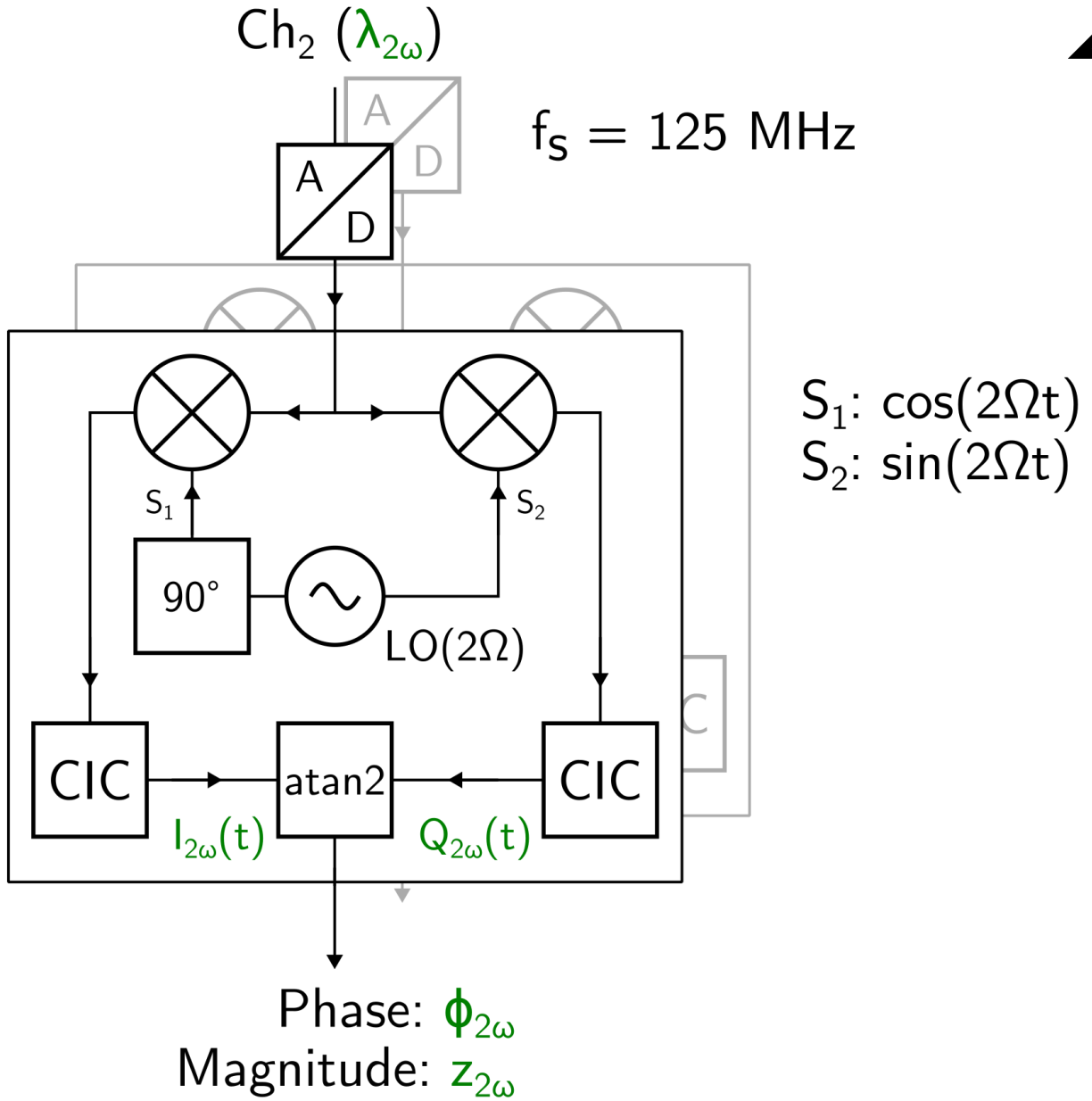
Real-Time Measurement

- IQ demodulation of FM signal
  - Two similar signal processing chains for ϕ_ω and $\phi_{2\omega}$



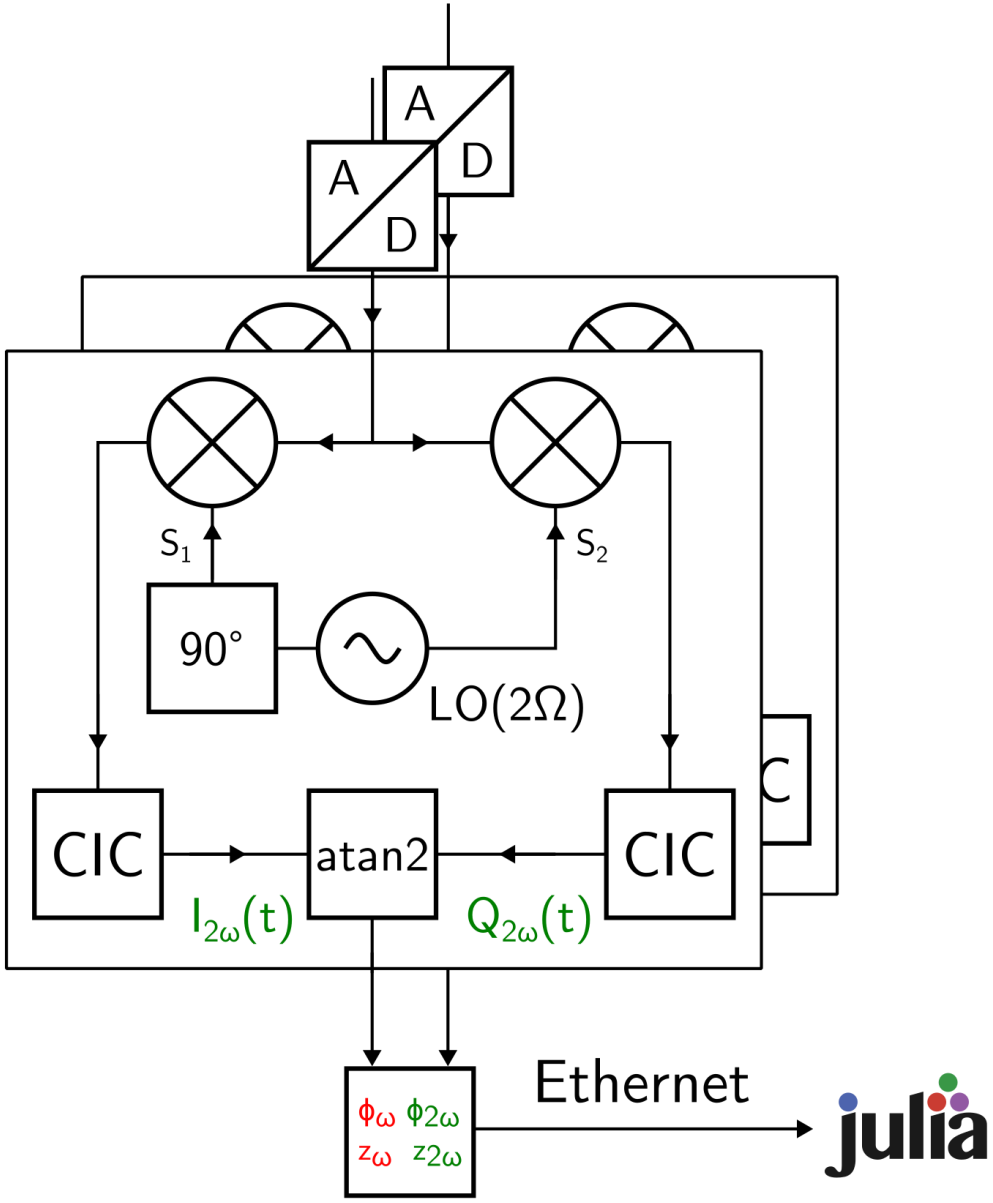
Real-Time Measurement

- IQ demodulation of FM signal
  - Two similar signal processing chains for ϕ_ω and $\phi_{2\omega}$
- Demodulator design
  - Evaluation at Ω and 2Ω to minimize electrical crosstalk
  - $\frac{f_s}{8}$ and $\frac{f_s}{16}$ at roots of cascaded integrator-comb filter (CIC)



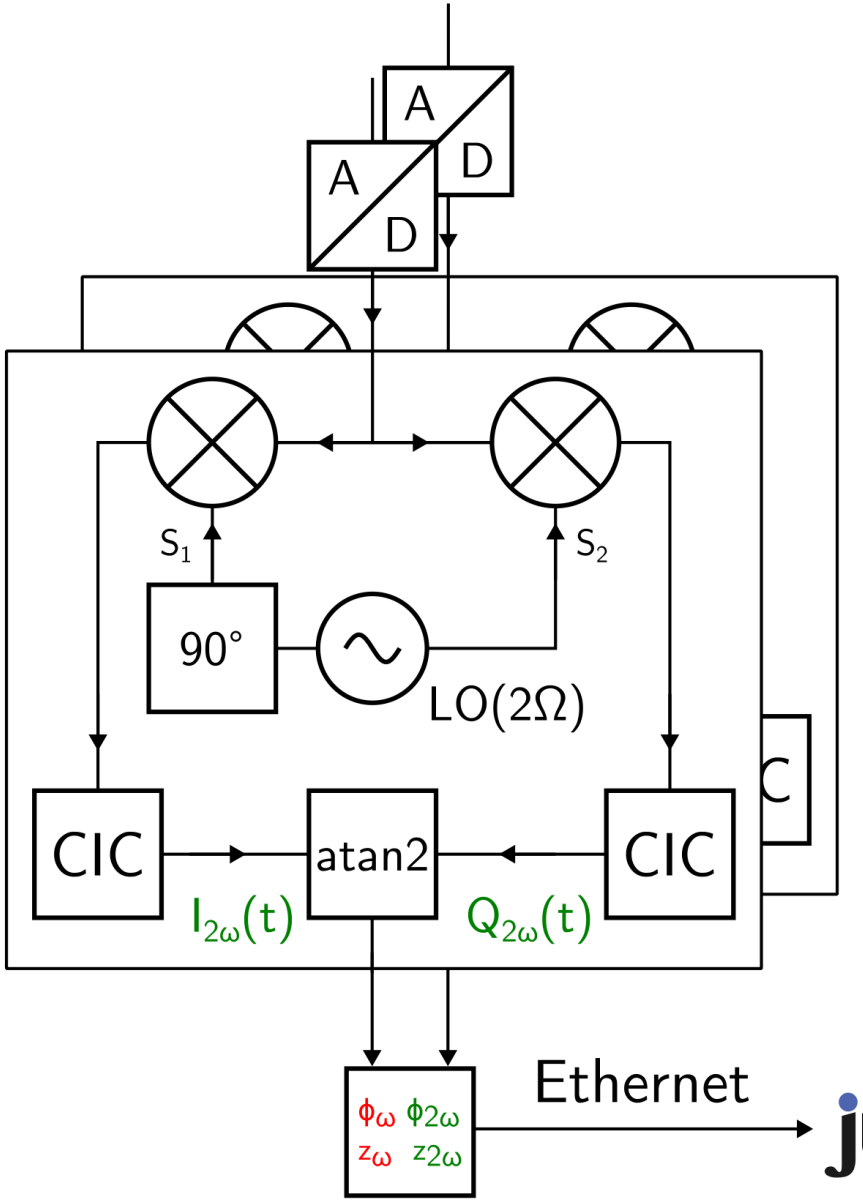
Real-Time Measurement

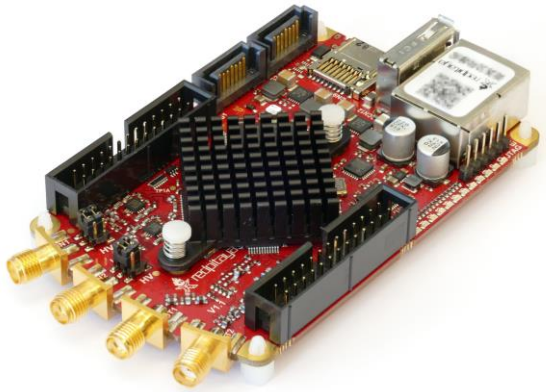
- IQ demodulation of FM signal
  - Two similar signal processing chains for ϕ_ω and $\phi_{2\omega}$
- Demodulator design
  - Evaluation at Ω and 2Ω to minimize electrical crosstalk
  - $\frac{f_s}{8}$ and $\frac{f_s}{16}$ at roots of cascaded integrator-comb filter (CIC)
- Calculate $\Delta\phi = 2 \cdot \phi_\omega - \phi_{2\omega}$
  - Bandwidth ≈ 488 kHz



Real-Time Measurement

- IQ demodulation of FM signal
  - Two similar signal processing chains for ϕ_ω and $\phi_{2\omega}$
- Demodulator design
  - Evaluation at Ω and 2Ω to minimize electrical crosstalk
  - $\frac{f_s}{8}$ and $\frac{f_s}{16}$ at roots of cascaded integrator-comb filter (CIC)
- Calculate $\Delta\phi = 2 \cdot \phi_\omega - \phi_{2\omega}$
  - Bandwidth ≈ 488 kHz
- RedPitaya STEMlab 125-14



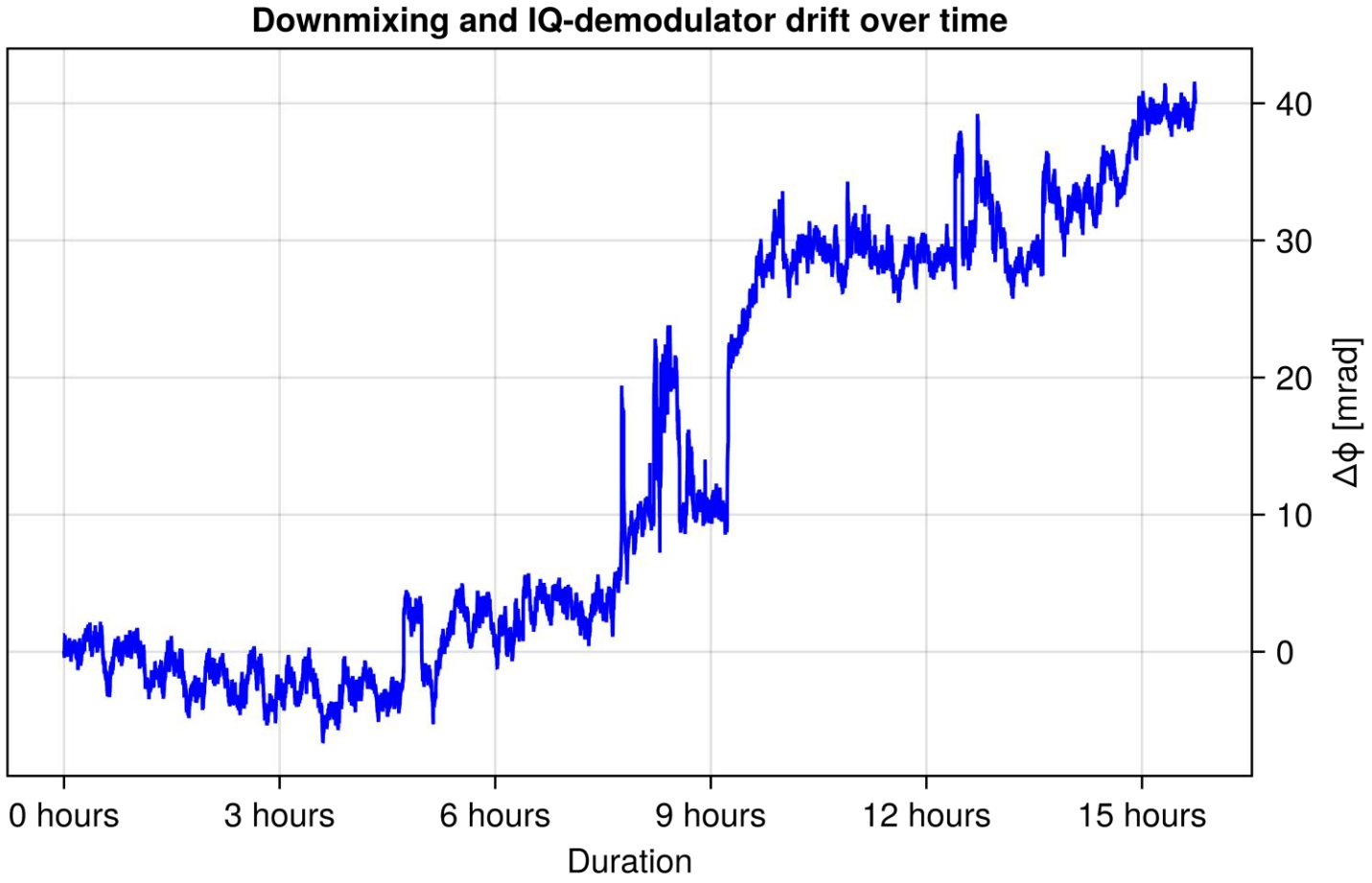


RedPitaya PCB
Geek3 (2019)
CC BY-SA 4.0

Real-Time Measurement

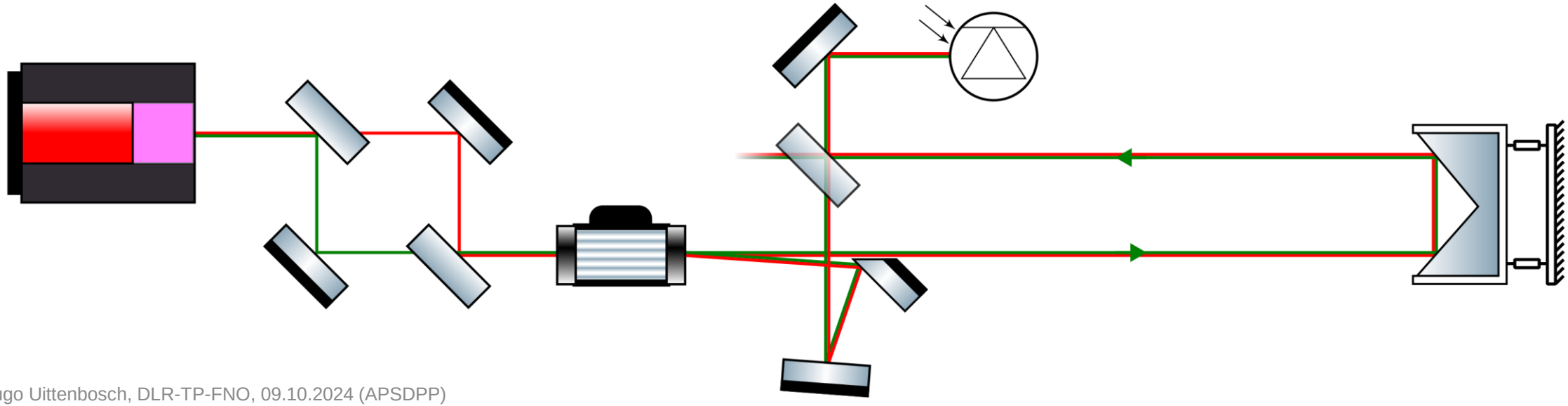
Related publications:
- K.J. Brunner et al., J. Instrum. **13** P09002 (2018)
- J. Zhang et al., Plasma Sci. Technol. **26** 085603 (2024)

- IQ demodulation of FM signal
  - Two similar signal processing chains for ϕ_ω and $\phi_{2\omega}$
- Demodulator design
  - Evaluation at Ω and 2Ω to minimize electrical crosstalk
  - $\frac{f_s}{8}$ and $\frac{f_s}{16}$ at roots of cascaded integrator-comb filter (CIC)
- Calculate $\Delta\phi = 2 \cdot \phi_\omega - \phi_{2\omega}$
  - Bandwidth ≈ 488 kHz
- RedPitaya STEMlab 125-14



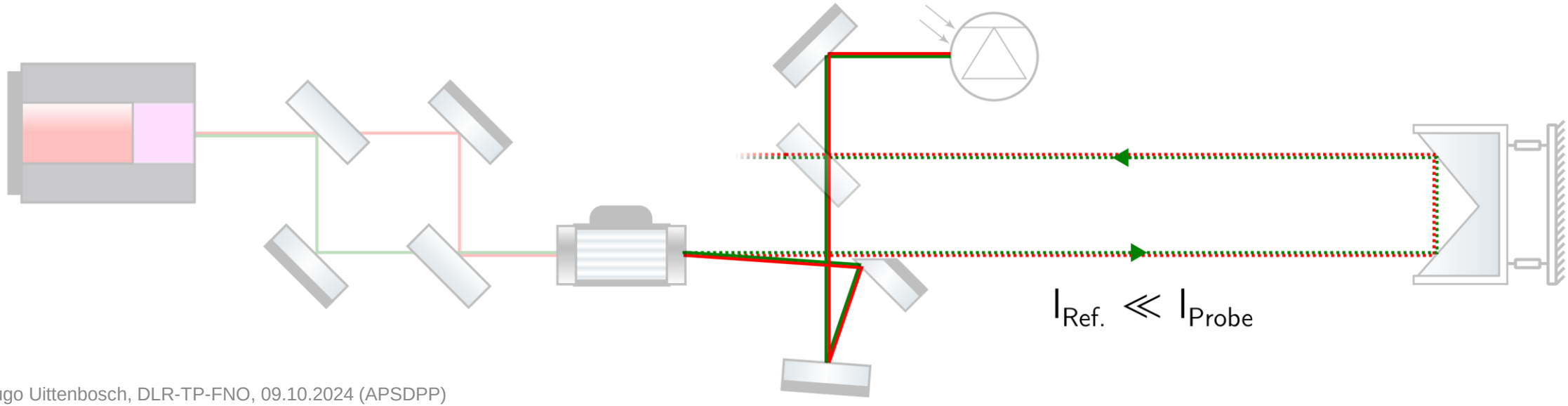
Robustness Improvements

- Interferometric contrast optimization



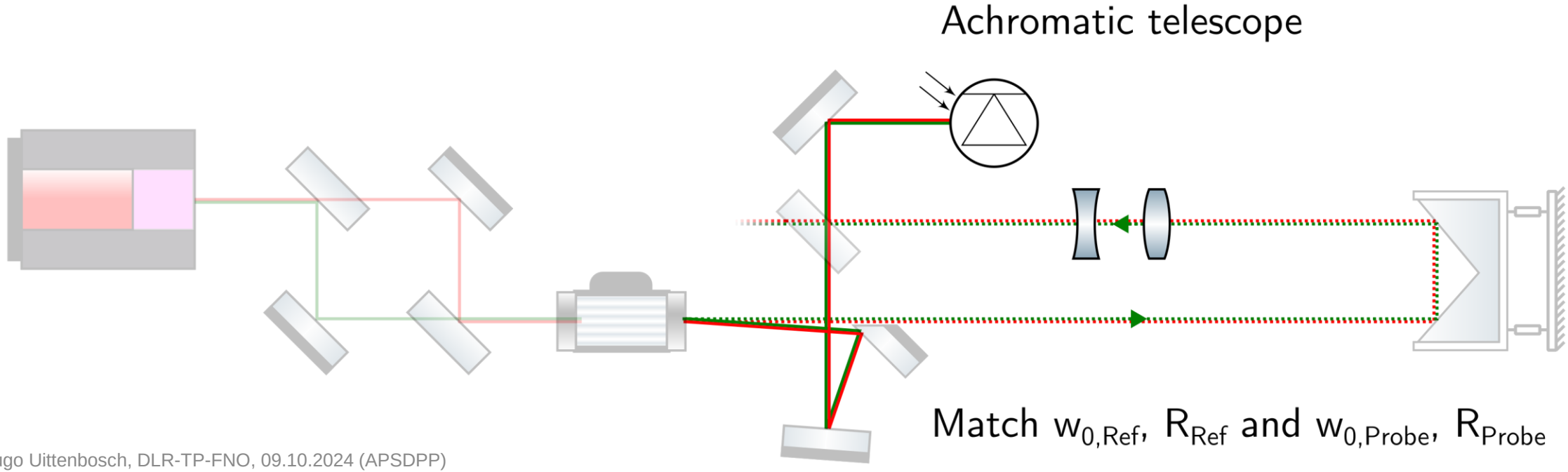
Robustness Improvements

- Interferometric contrast optimization
  - Unequal armlength interferometer
  - Gaussian beam propagation



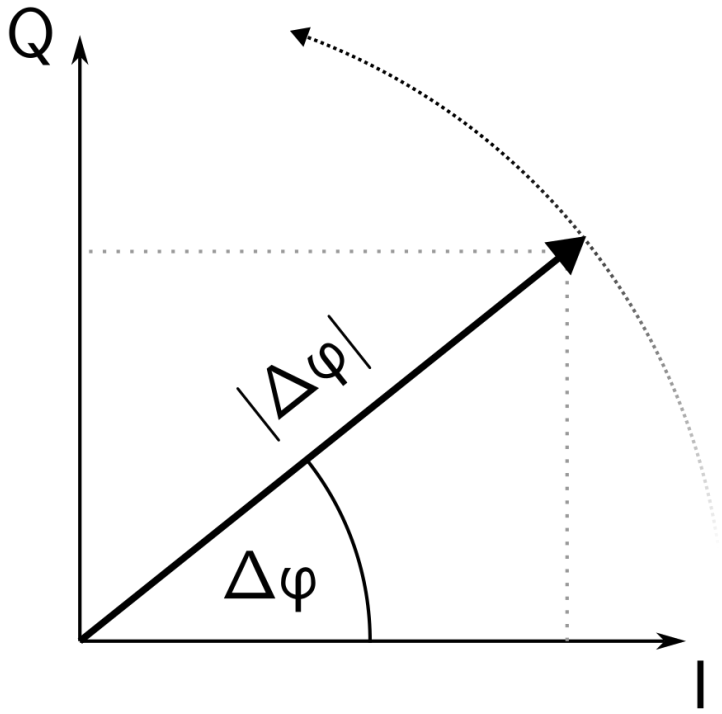
Robustness Improvements

- Interferometric contrast optimization
  - Unequal armlength interferometer
  - Gaussian beam propagation
  - Phase front matching at photodetector

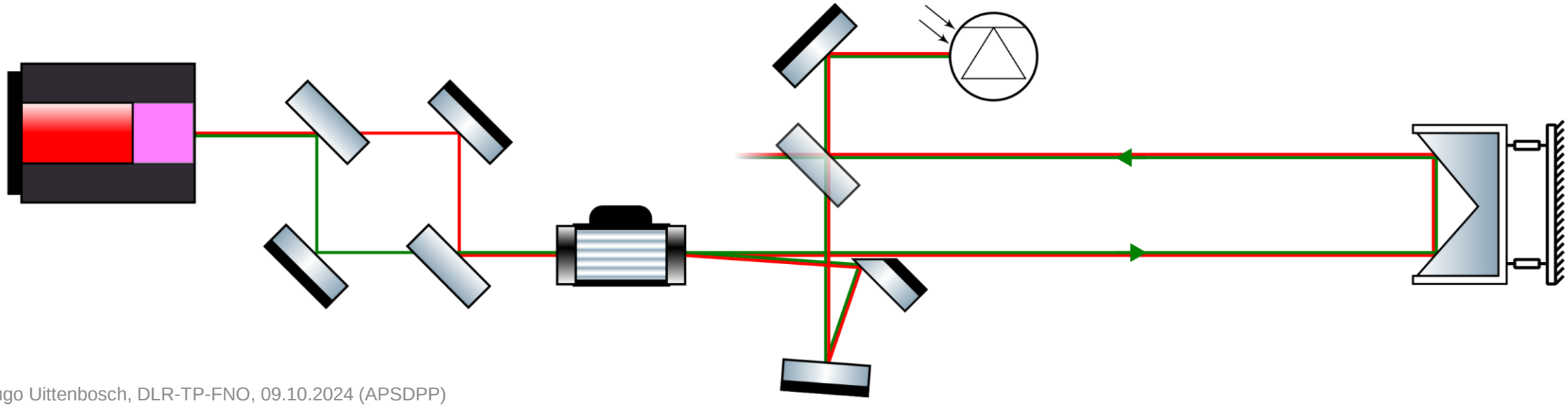


Robustness Improvements

- Parasitic phasor calibration

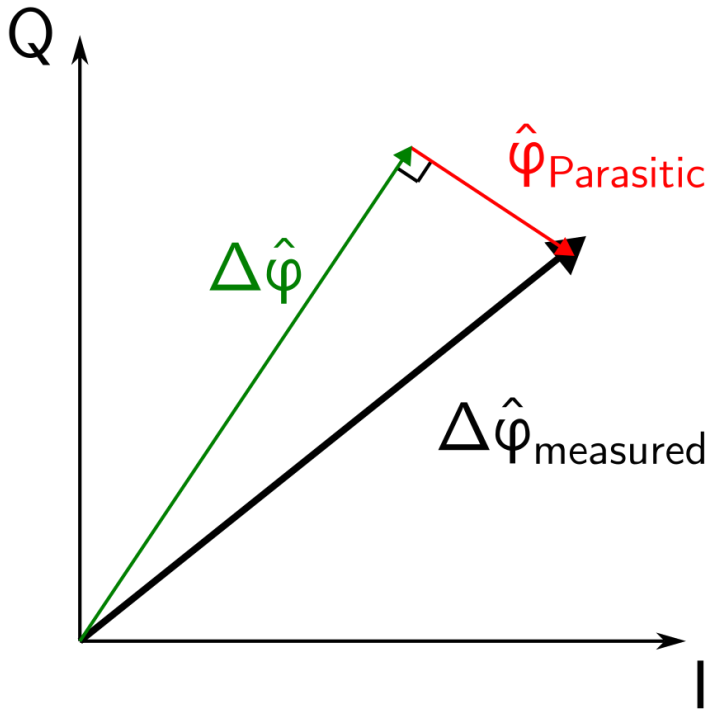


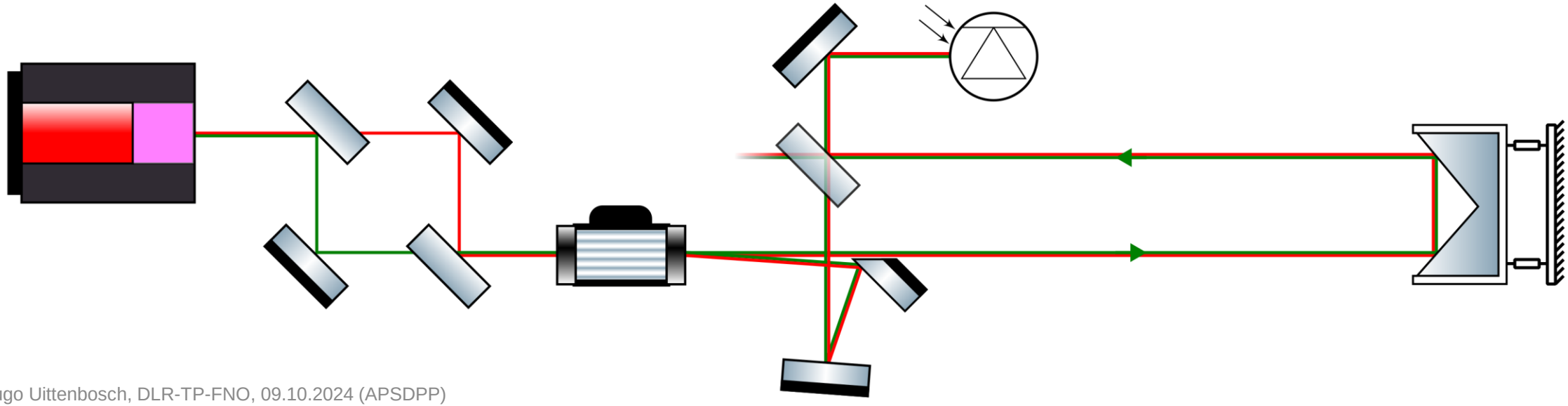
$$\Delta\hat{\varphi} = |\Delta\varphi| \cdot e^{\Delta\varphi \cdot j}$$



Robustness Improvements

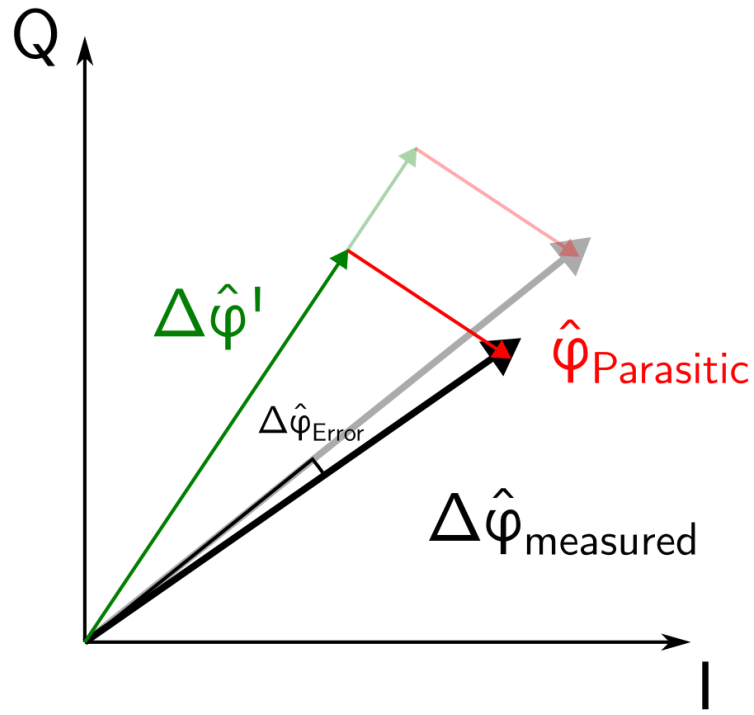
- Parasitic phasor calibration
  - Additional phasors due to e.g. etalons

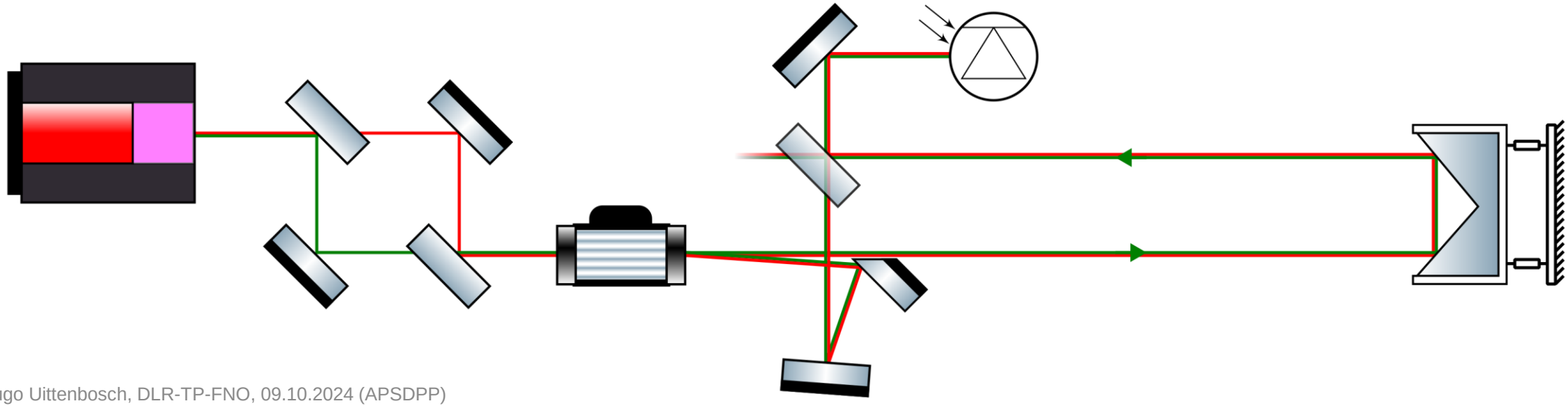




Robustness Improvements

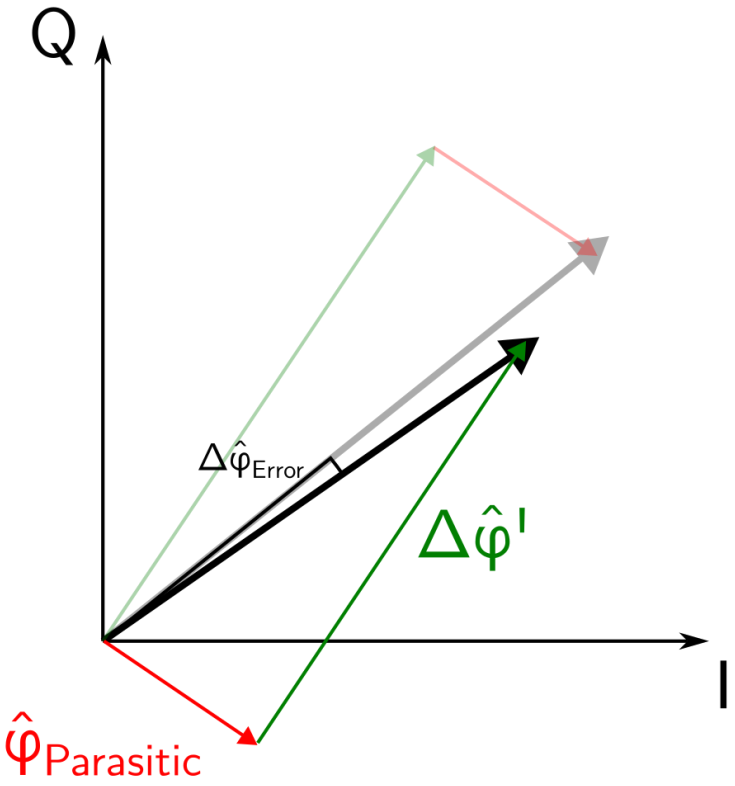
- Parasitic phasor calibration
  - Additional phasors due to e.g. etalons
  - Magnitude change can cause phase change

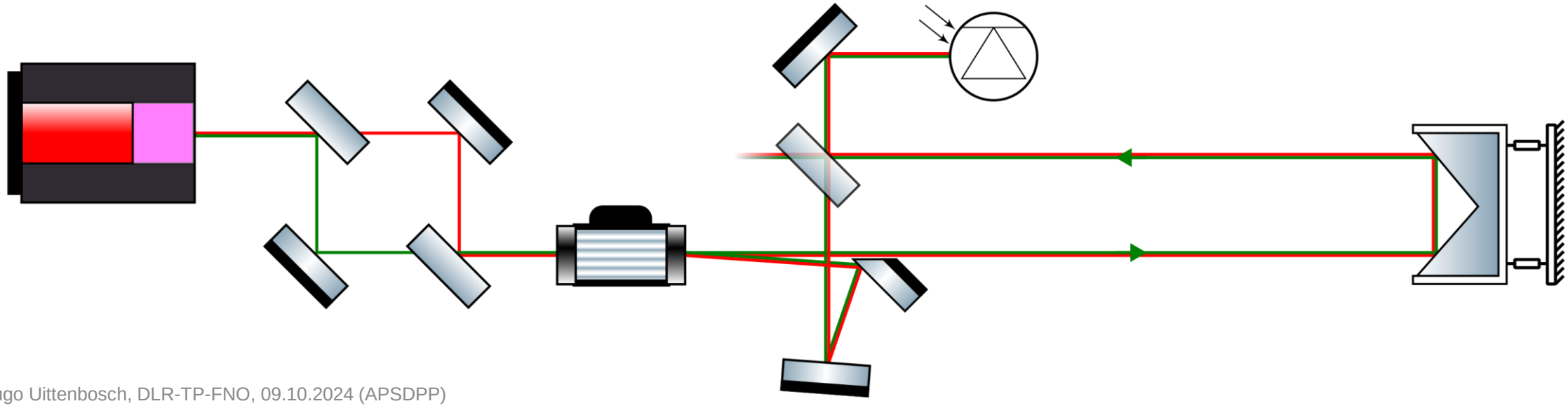




Robustness Improvements

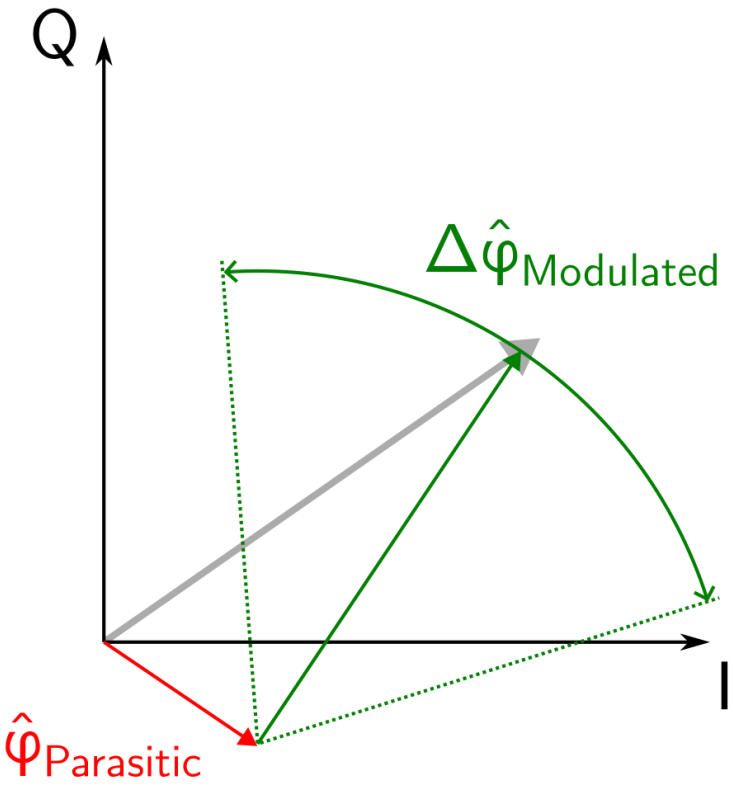
- Parasitic phasor calibration
  - Additional phasors due to e.g. etalons
  - Magnitude change can cause phase change

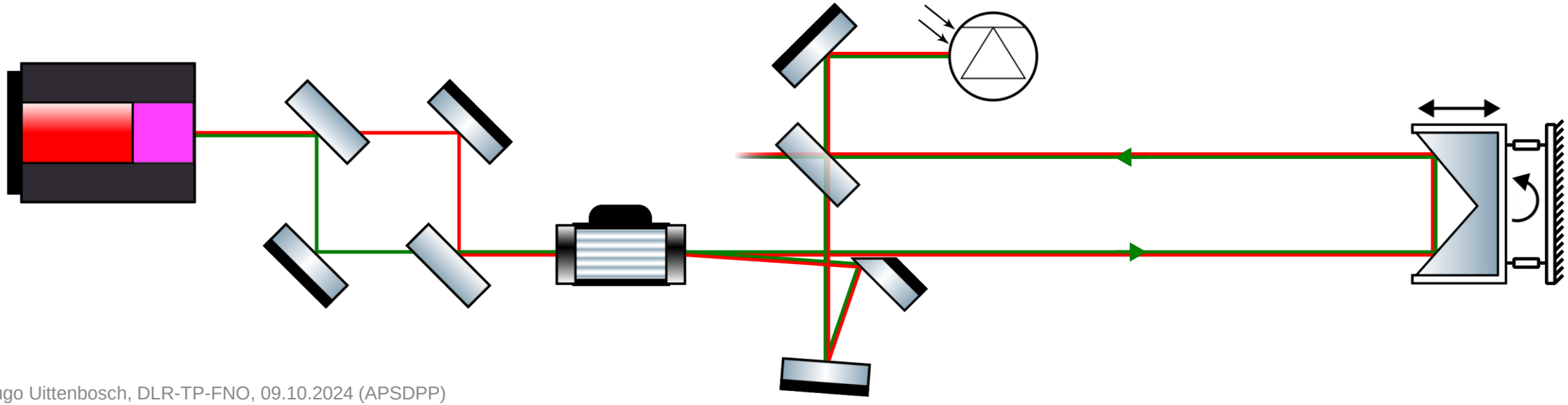




Robustness Improvements

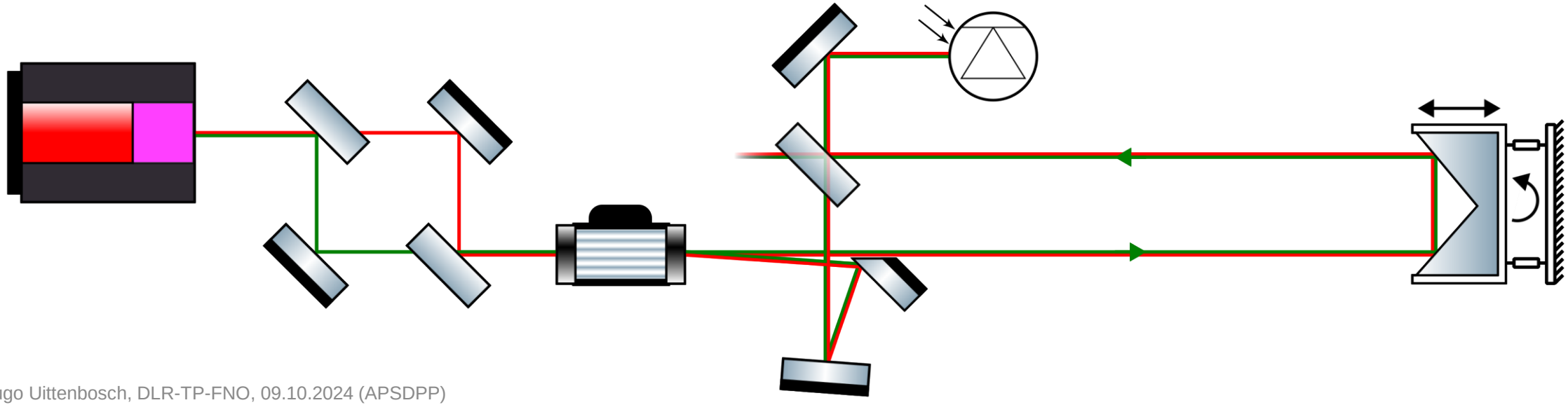
- Parasitic phasor calibration
  - Additional phasors due to e.g. etalons
  - Magnitude change can cause phase change
  - Detection and calibration of unwanted phasors





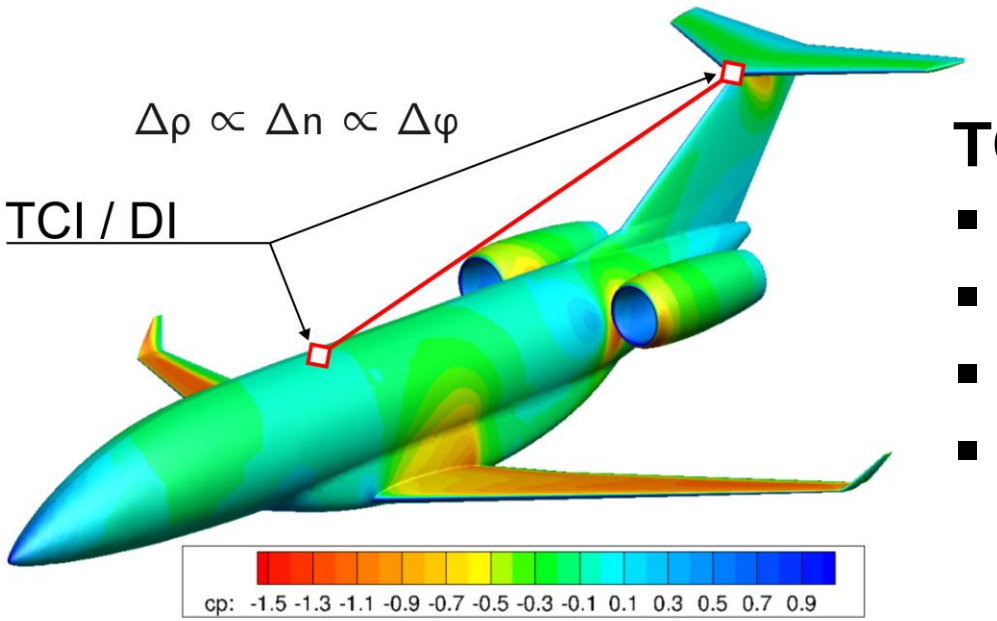
Robustness Improvements

- Misc.
  - Phase jump correction ($\Delta\phi > 2\pi$)
  - AOM material (birefringence, optical activity)



Summary

A. Ronzheimer, DLRK 450117 (2017)



TCI for density measurement in aviation

- Measurement outside of aerodynamic influence
- Mechanical robustness
- Capable of high accuracy
- Self-diagnosis capability

Outlook

- System integration
  - Custom PCB for mixing electronics
  - Integrated optical sensor head
- Relative to absolute measurement?