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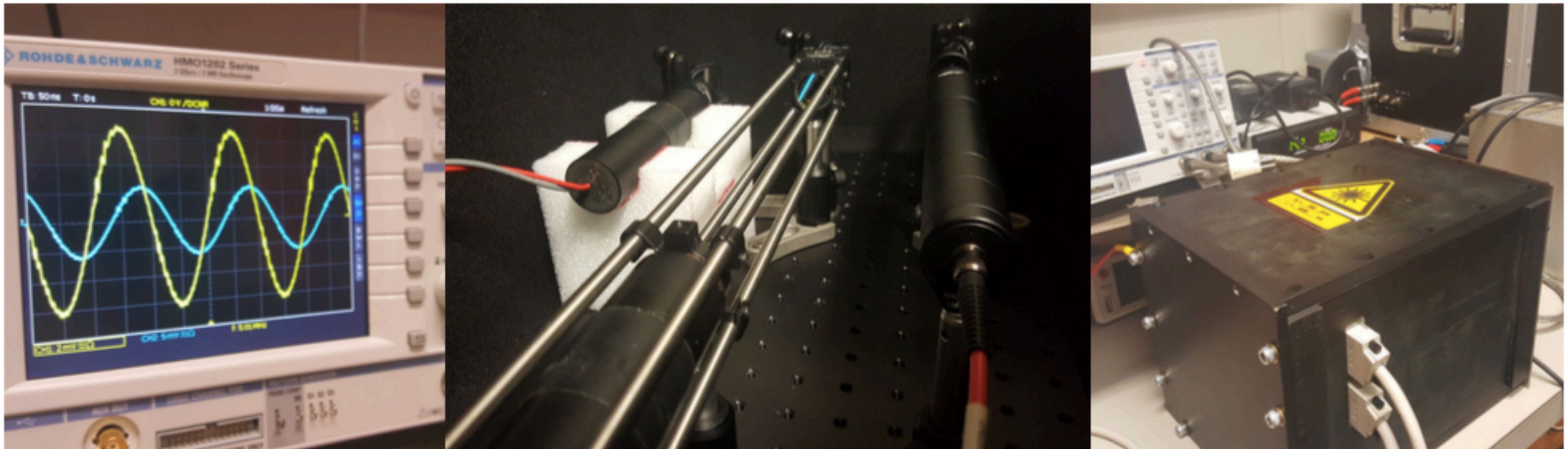
Kepler Center for Astro and Particle Physics



Cavity enhanced long light path attenuation length measurement

An alternative approach in measuring the attenuation in the liquid scintillator for JUNO

Tobias Heinz , 18.09.17

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Outline

- Motivation
- Properties of optical cavities
- Measurement of attenuation length
- First results
- Next steps

Motivation

Attenuation length cannot be measured precisely with commercial available UV-vis spectrometers due to small decrease in intensity (the intensity drops to 99,6% of initial intensity after 10 cm in medium with attenuation length of 25 m)

- Need long light path to be able to measure attenuation length of LS
- But: very impractical to build cells with lengths of several meters
- Solution: use optical cavity to extend light path

Optical Cavity

An optical cavity is an arrangement of mirrors so that light is reflected multiple times

- An optical cavity is characterized by mirror reflectivities R_1, R_2, the radii of curvature r_1, r_2 and the distance between both mirrors L
- The light path is only closed inside of cavity for certain combinations of r_1, r_2 and L

Stability criterion

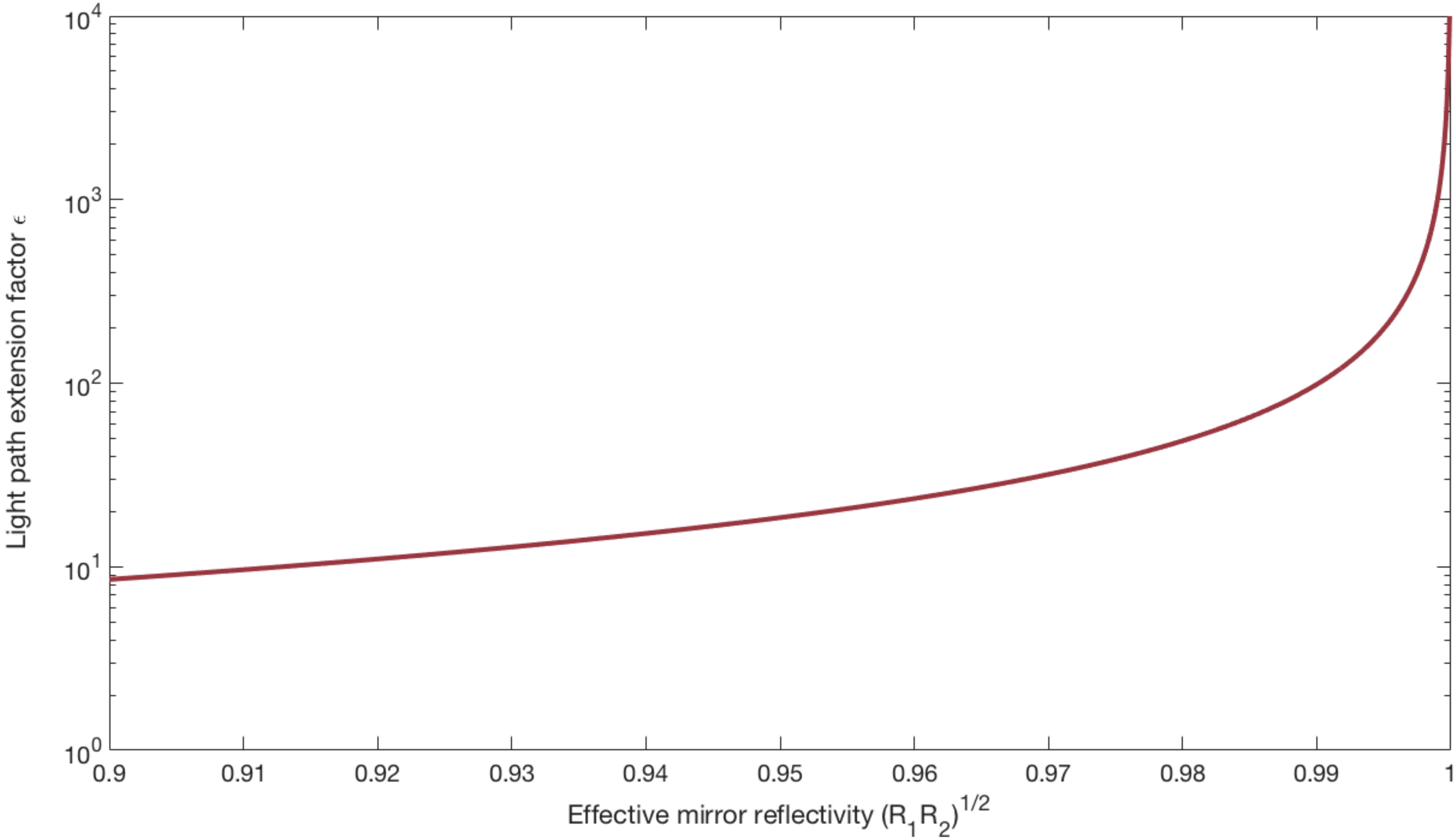
$$0 \leq \left(1 - \frac{L}{r_1}\right)\left(1 - \frac{L}{r_2}\right) \leq 1$$

Optical Cavity

- Photons are reflected multiple times inside of cavity
  - Depending on the mirror reflectivities R_1, R_2 the average light path is extended by a certain factor

Light path extension factor

$$\epsilon = \frac{2R_1R_2}{1-R_1R_2}$$



LPE factor for cavity with effective mirror reflectivity $\sqrt{R_1 R_2}$

Optical Cavity

- Photons are reflected multiple times inside of cavity
  - Depending on the mirror reflectivities R_1, R_2 the average light path is extended by a certain factor

Light path extension factor

$$\epsilon = \frac{2R_1R_2}{1-R_1R_2}$$

- Effective average light path is given by:

Effective light path

$$L_{\text{eff}} = (1+\epsilon)L$$

Parameters of cavity mirrors

In Tübingen we use two identical concave cavity mirrors

- Radius of curvature: -50 cm
  - Possible cavity lengths from 0 to 1 meter

- Reflectivity: 0.95
  - LPE factor: ~18.5

➢ Effective light path up to ~19.5 m possible

Measurement of attenuation length

The output intensity is a superposition of waves with various numbers of round trips

- Attenuation length cannot be measured with Beer‘s law

Two possibilities:

- Modulated intensity method:
  - initial intensity is modulated sinusoidally
  - output intensity is phase-shifted sine wave
    - Phase-shift occurs due to attenuation inside of cavity

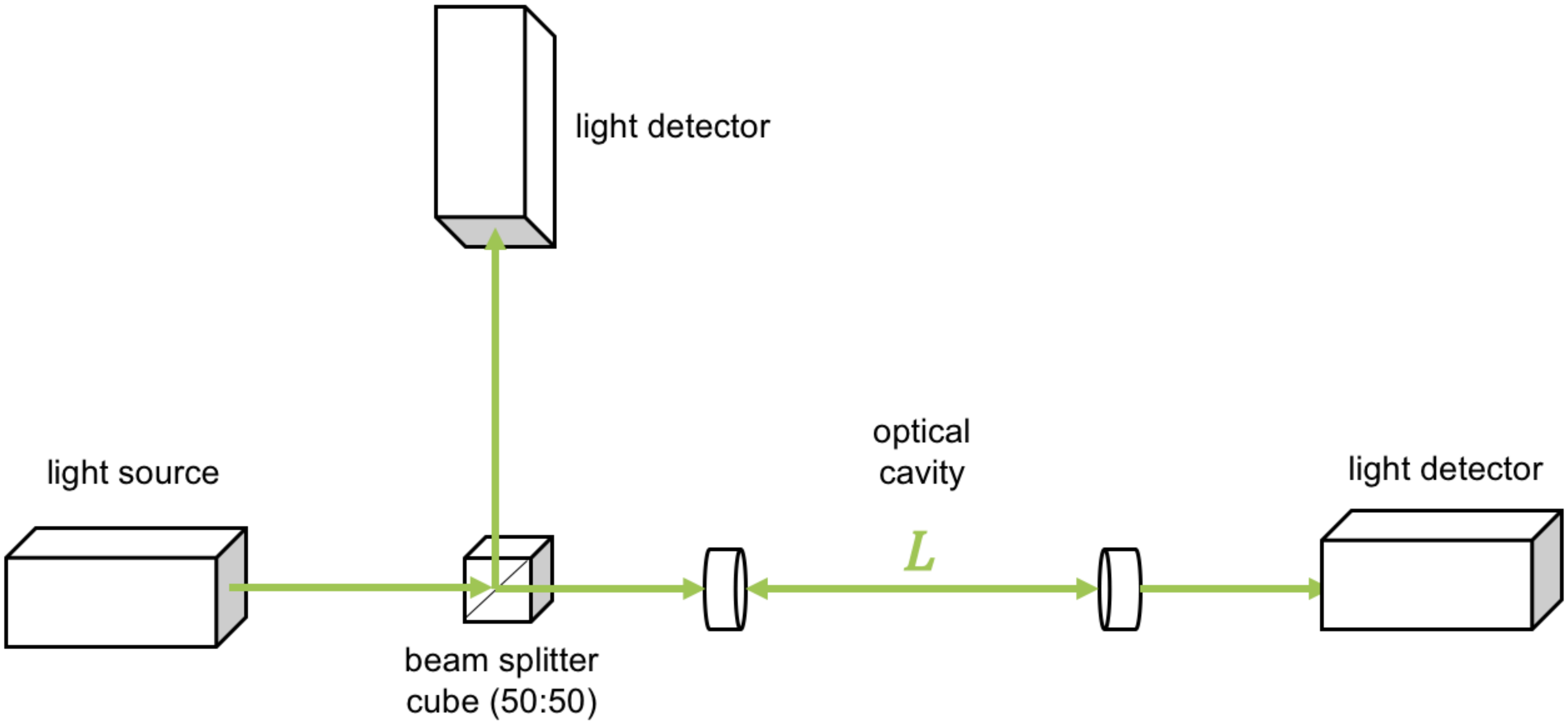
- Ring down measurement:
  - build up intensity inside of cavity
  - turn off light source
    - output intensity will drop exponentially
    - time constant of exponential decrease depends on attenuation

CELLPAL measurement

Modulated intensity method was chosen:

- ability to sweep modulation frequency
  - more data due to relation between phase-shift and modulation frequency
- the attenuation has an impact on amplitude and phase-shift of output intensity
  - two ways to determine attenuation length with one measurement

Schematic illustration of setup



CELLPAL measurement

Input intensity

$$I_{\mathrm{in}}(t) = I_0 \left[1 + \alpha \cdot \sin\left(-\omega t\right)\right]$$

measured with detector in front of cavity

Output intensity

$$I_{\mathrm{out}}(t) = I_0' \left[1 + \alpha' \sin\left(-\omega t + \phi\right)\right]$$

measured with detector behind cavity

CELLPAL phase-shift measurement

Phase-shift between detector signals

$$\Delta\phi = \frac{2\pi f \Delta L}{v_g} + \arctan\left(\frac{A_{eff}\sin\left(\frac{4\pi f L}{v_g}\right)}{1 - A_{eff}\cos\left(\frac{4\pi f L}{v_g}\right)}\right)$$

$$\text{with } A_{eff} = R_1 R_2 \exp\left(-\frac{2L}{L_{att}}\right)$$

f: modulation frequency

ΔL: net distance between both detectors

v_g: group velocity

L_{att}: attenuation length

CELLPAL amplitude measurement

Output amplitude

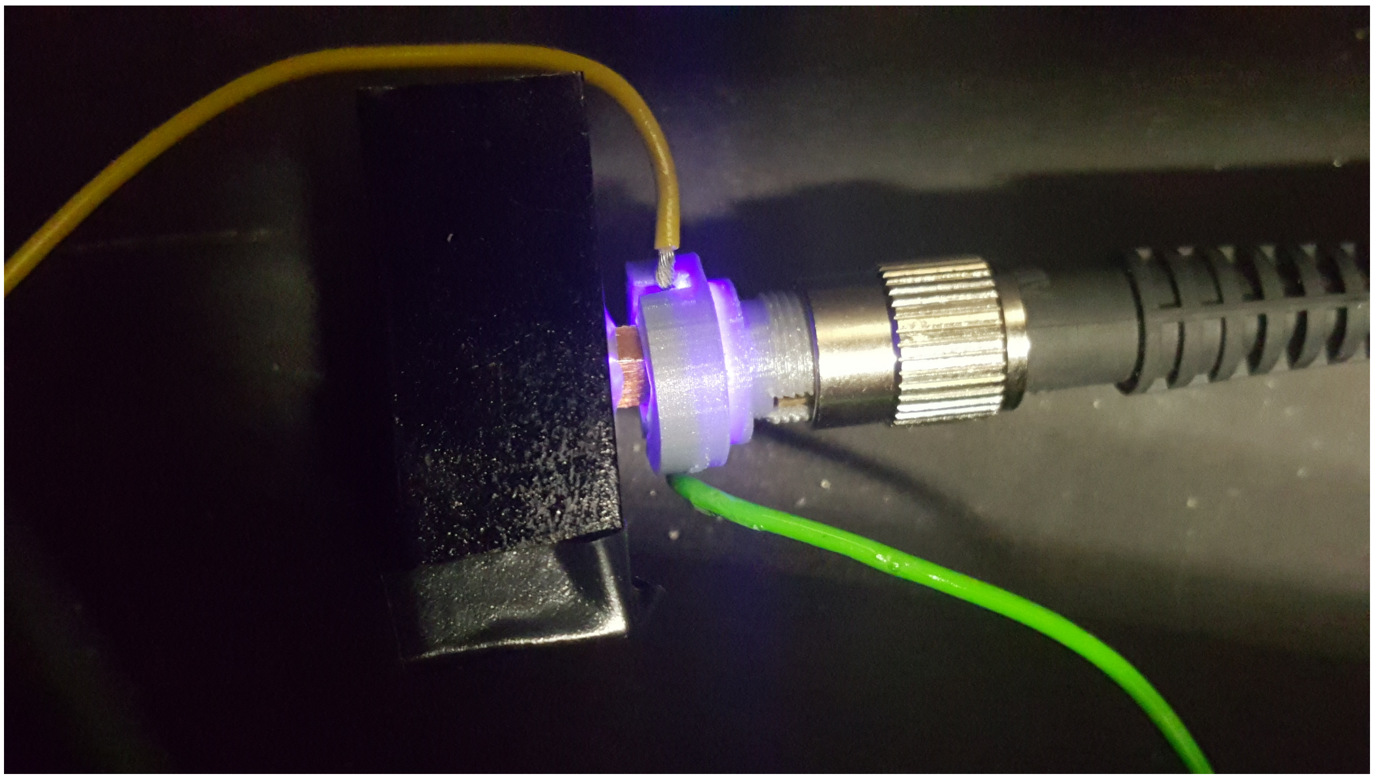
$$I_0' = \frac{(1 - R_1)(1 - R_2)\exp\left(-\frac{L}{L_{att}}\right)}{1 - A_{eff}} I_0$$

$$\alpha' = \frac{(1 - A_{eff})\,\alpha}{\sqrt{1 - 2A_{eff}\cos\left(\frac{2\omega L}{v_g}\right) + A_{eff}^2}}$$

$$\text{with} \quad A_{eff} = R_1 R_2 \exp\left(-\frac{2L}{L_{att}}\right)$$

Current setup in Tübingen

- Light source: High Power LED (420 nm) coupled to fiber



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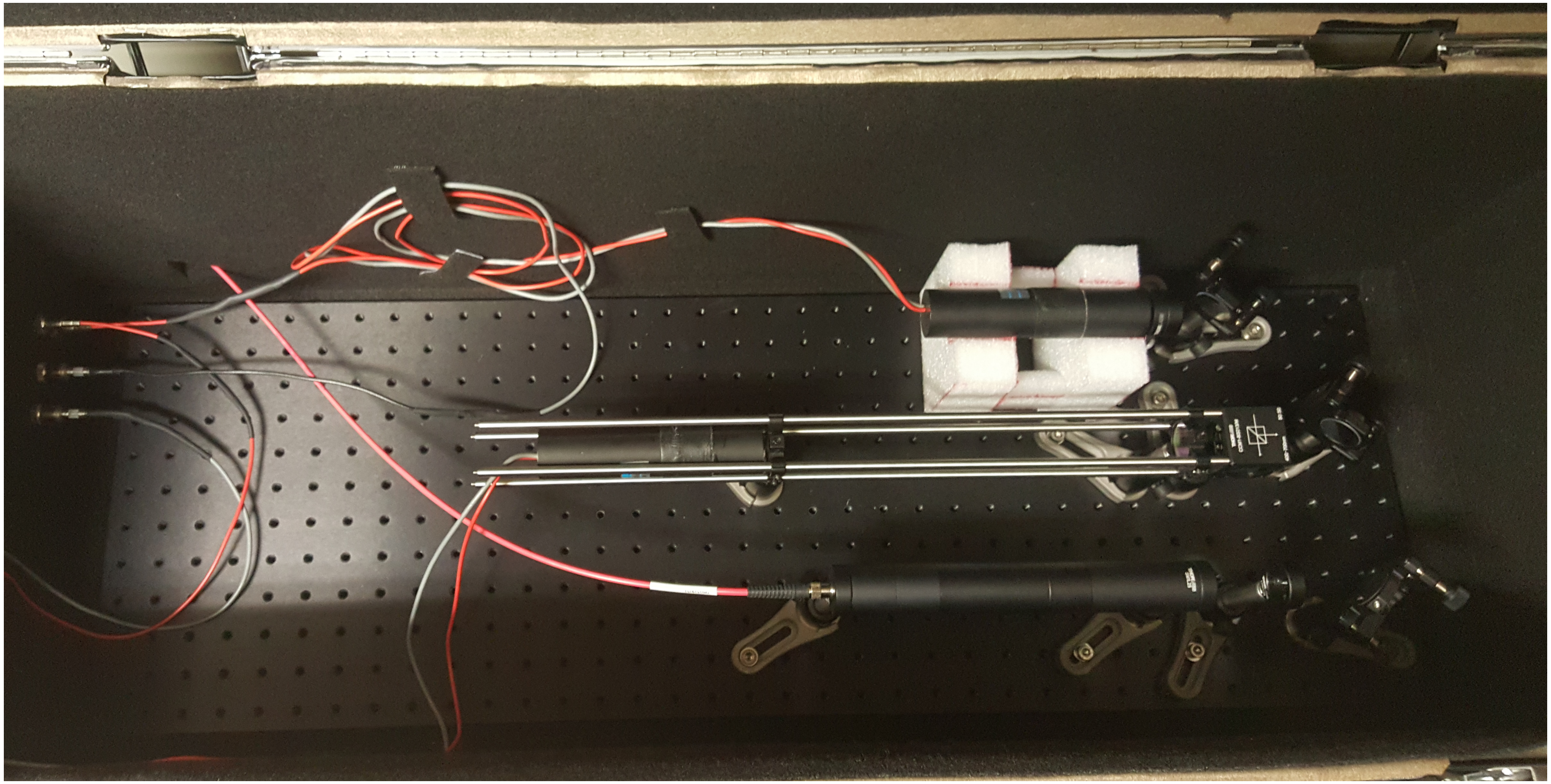
Current setup in Tübingen



setup placed inside darkbox with nickel-copper shielding

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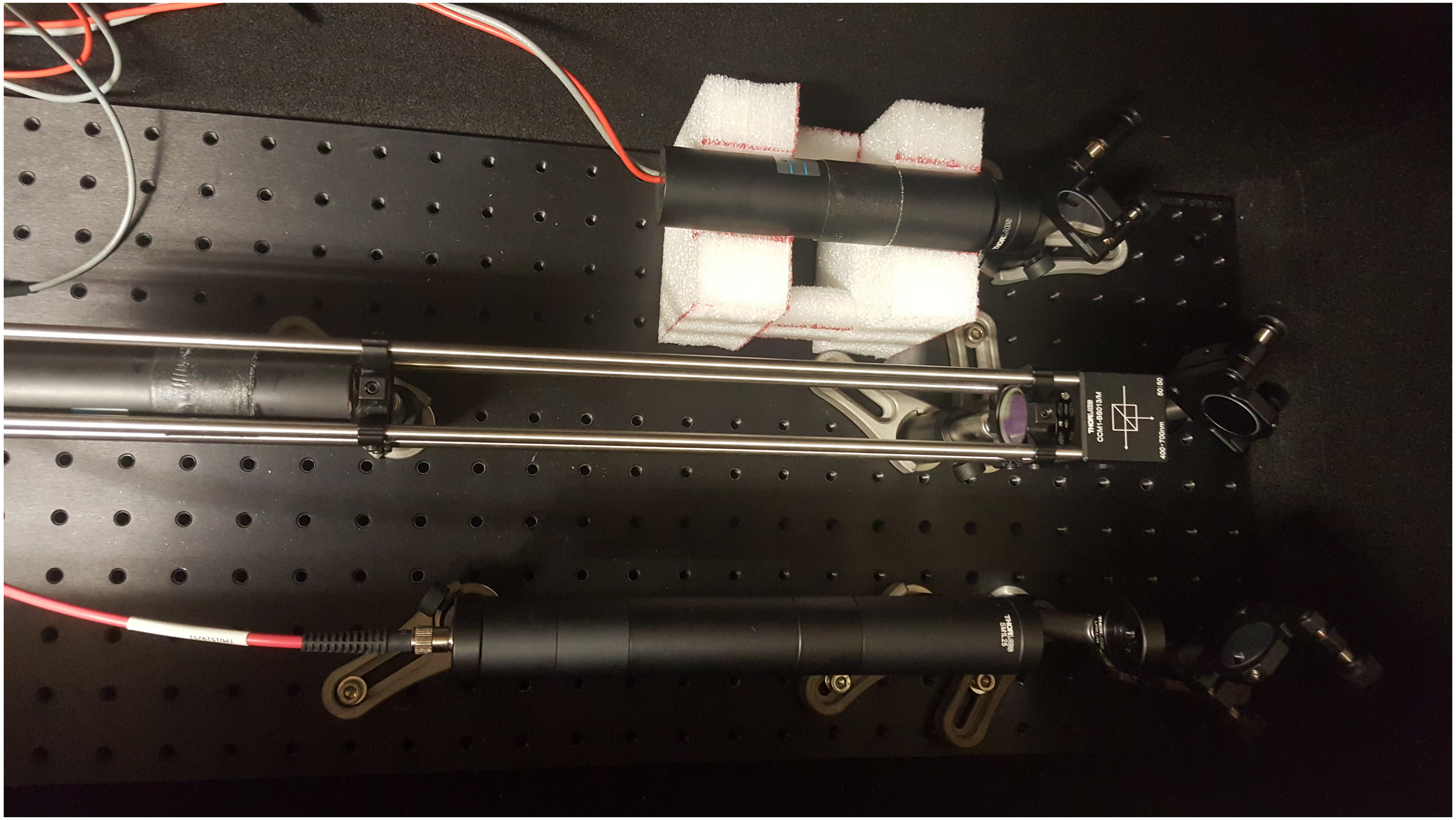
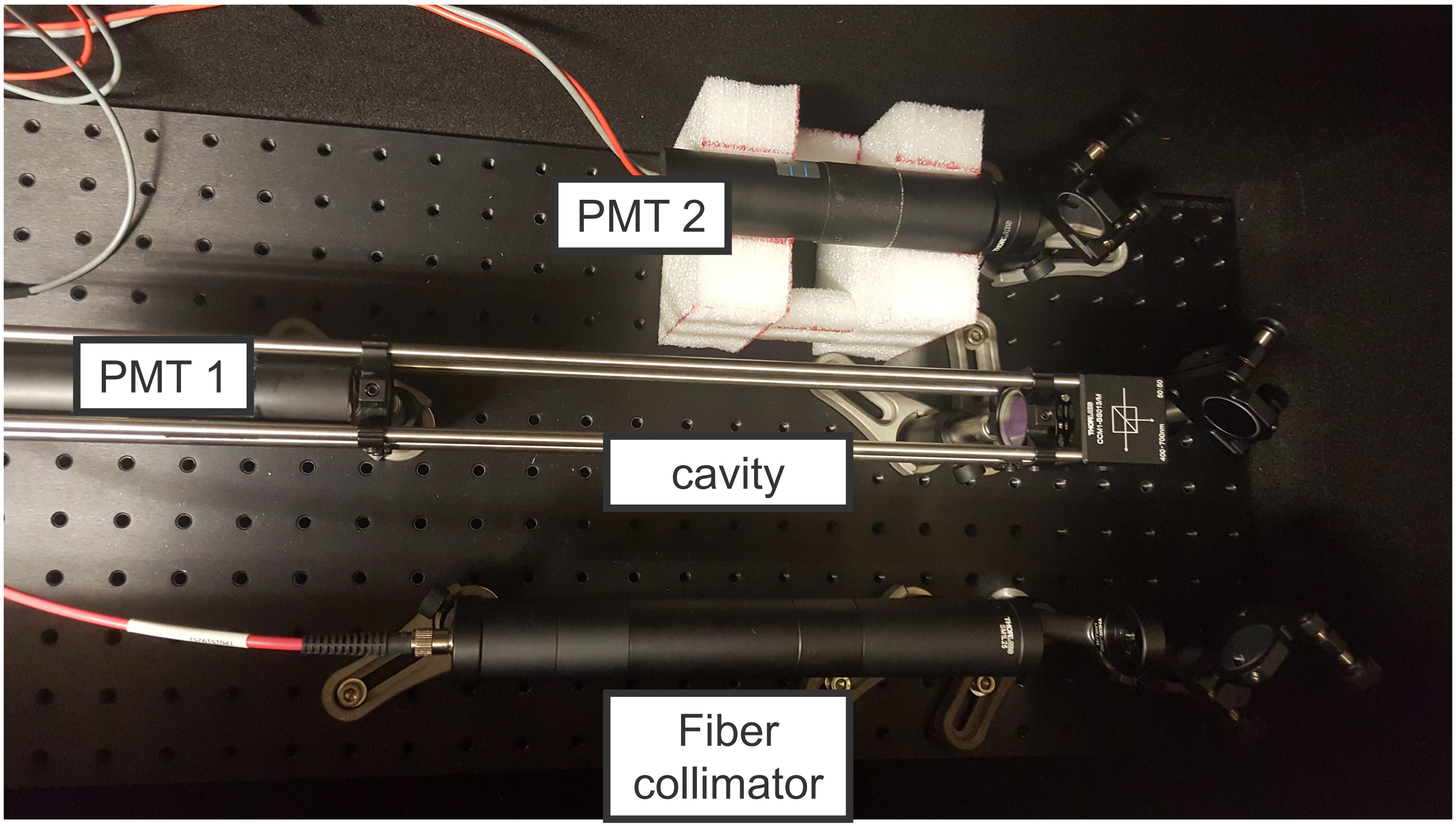
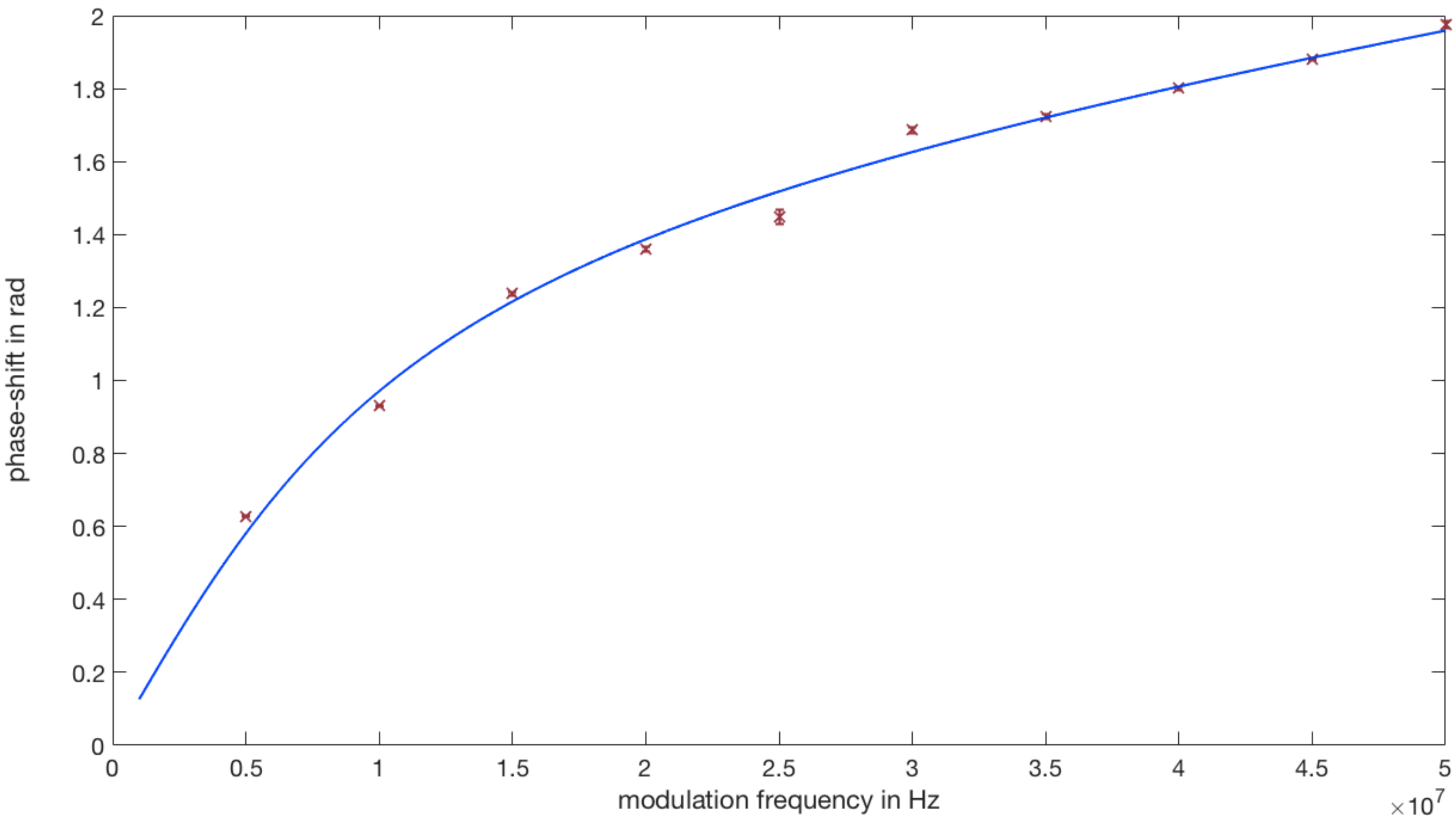
Current setup in Tübingen



Current setup in Tübingen



First results – Laser as light source/photodiode as detector



Measured phase-shift (red) and fit (blue) as function of modulation frequency

First results – Laser as light source/photodiode as detector

- The measured data points were fitted with the function for $\Delta\phi(f)$:
  - values used in calculation:
    - cavity length: 0.25 m
    - attenuation length in air: 5000 m
    - speed of light in air: 299 700 000 m/s
  - fit parameters:
    - mirror reflectivity
    - net distance between detectors

Results of fit

$$R = 0.956 \pm 0.004$$

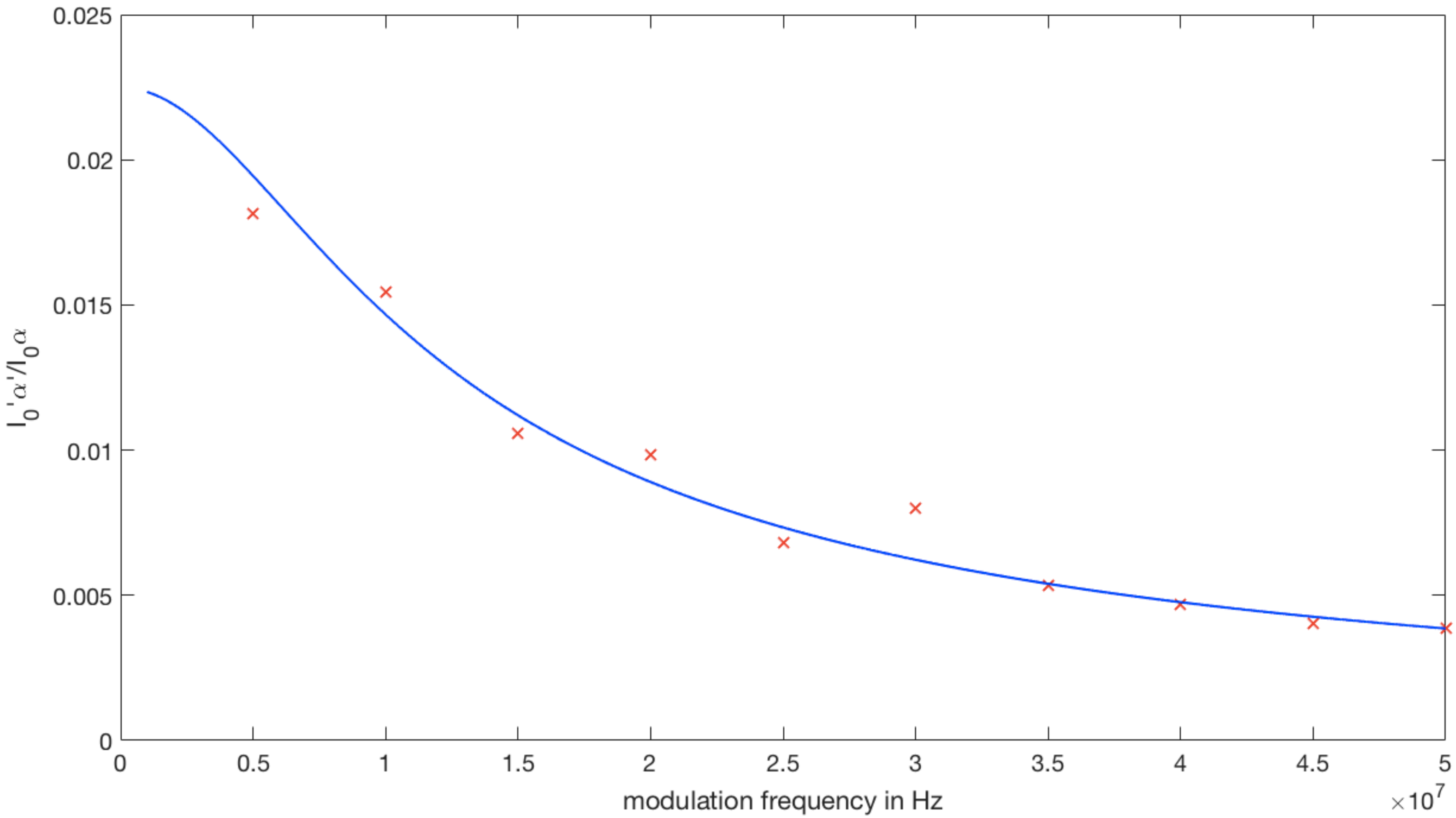
$$\Delta L = 0.78\,\mathrm{m} \pm 0.07\,\mathrm{m}$$

Value of manufacturer

$$R = 0.95 \pm 0.005$$

➢ method seems to work!

First results – Amplitude measurement in Laser/PD setup



Measured amplitude ratio (red) and fit (blue) as function of modulation frequency

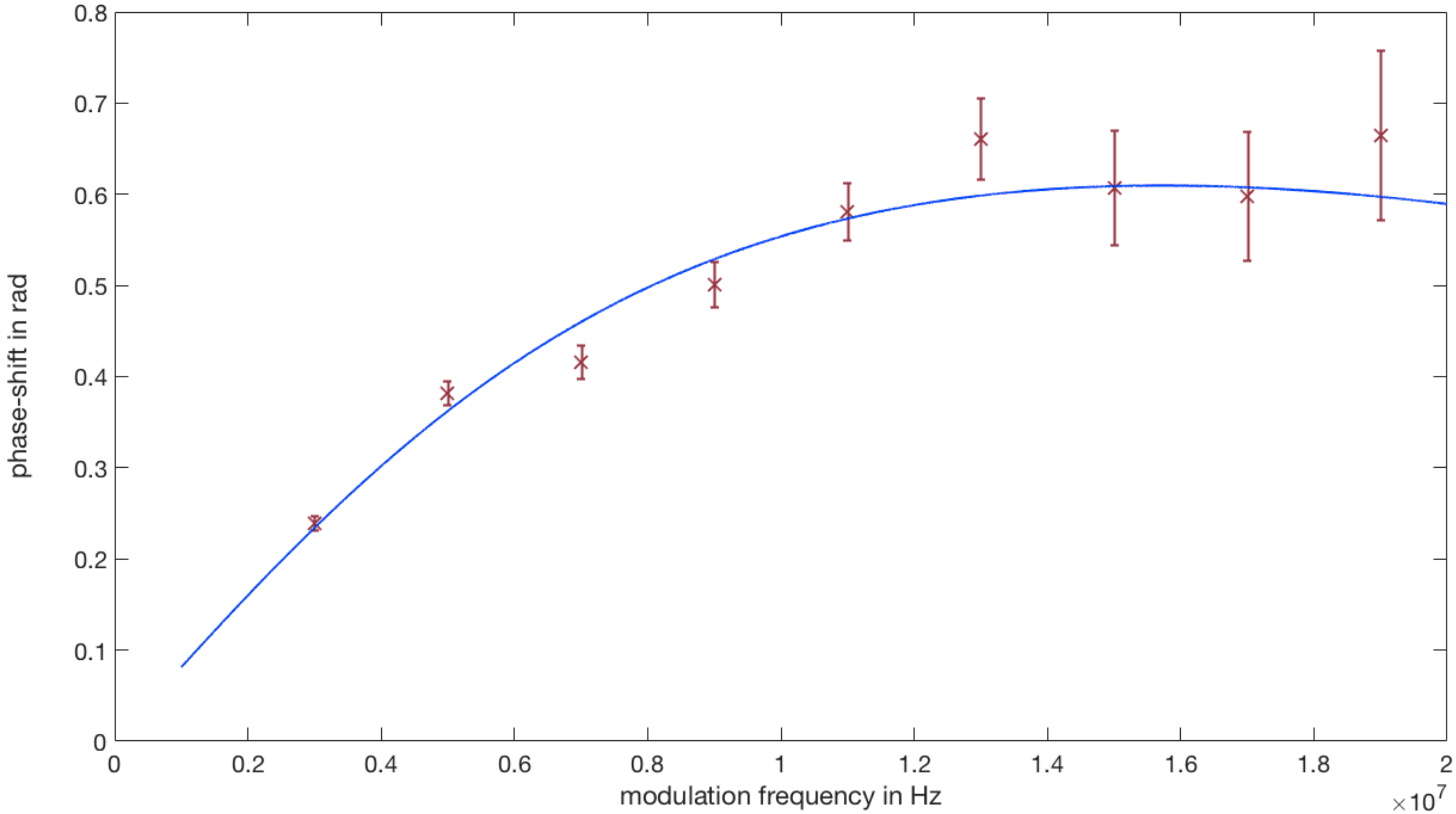
First results – Amplitude measurement in Laser/PD setup

- The measured data points were fitted with the function for $\frac{I_0'\alpha'}{I_0\alpha}(f)$ with the same values used in calculation as before
- Mirror reflectivity as fit parameter

Result of amplitude fit

$$R = 0.956 \pm 0.002$$

First results with current setup



Measured phase-shift (red) and fit (blue) as function of modulation frequency

First results with current setup

- Same values used in calculation as before

LED/PMT setup result

$$R = 0.953 \pm 0.006$$

First results with current setup

- Same values used in calculation as before

LED/PMT setup result

$$R = 0.953 \pm 0.006$$

Laser/PD setup result

$$R = 0.956 \pm 0.004$$

Result of amplitude fit

$$R = 0.956 \pm 0.002$$

Value of manufacturer

$$R = 0.95 \pm 0.005$$

➢ reproducable results with both setups!

Next steps

- Build cavity which is able to be filled with LS
- Reflectivity of mirrors in LS should be known precisely
  - need experimental method to measure mirror reflectivity in liquid with refractive index >1

Thank you.

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Backup

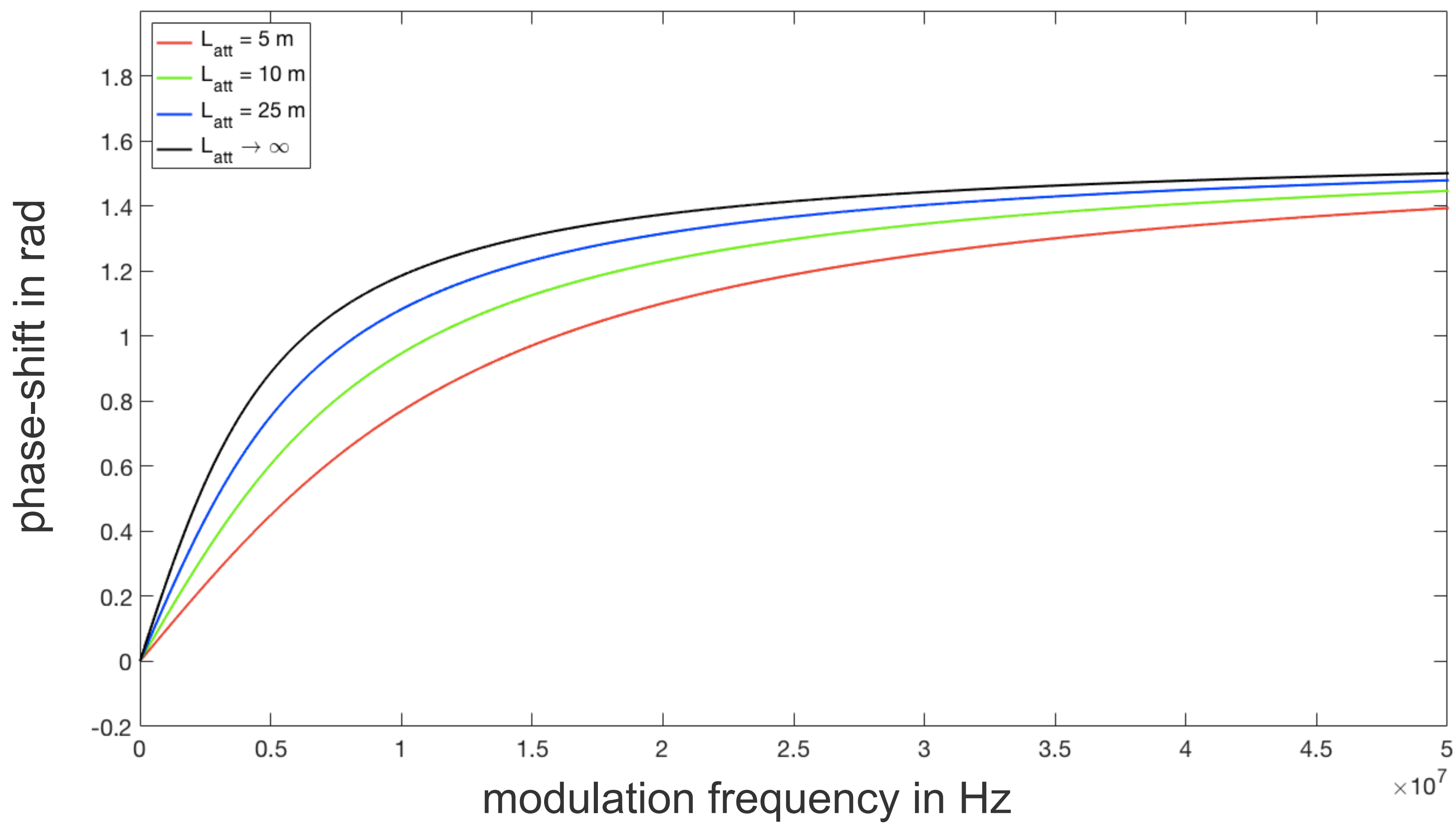
CELLPAL ring down time measurement

- After light source is turned off, the output intensity drops exponentially: $I(t) = I_0 e^{-t/\tau}$
- Ring down time depends on mirror reflectivity R, cavity length L and attenuation length L_{att}

Ring down time

$$\tau = \frac{L}{c\left[1 - R + \frac{L}{L_{\mathrm{att}}}\right]}$$

Frequency dependence of phase-shift for different values of attenuation length in 40cm cavity



Frequency dependence of amplitude for different values of attenuation length in 40cm cavity