HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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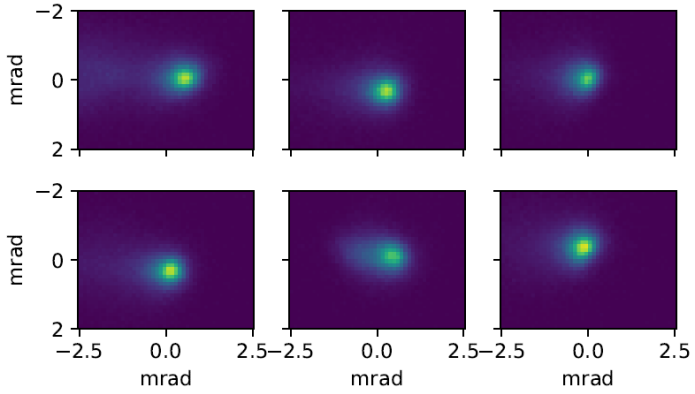
Predictive Beam Steering and Machine Learning at JETi200

Alexander Sävert

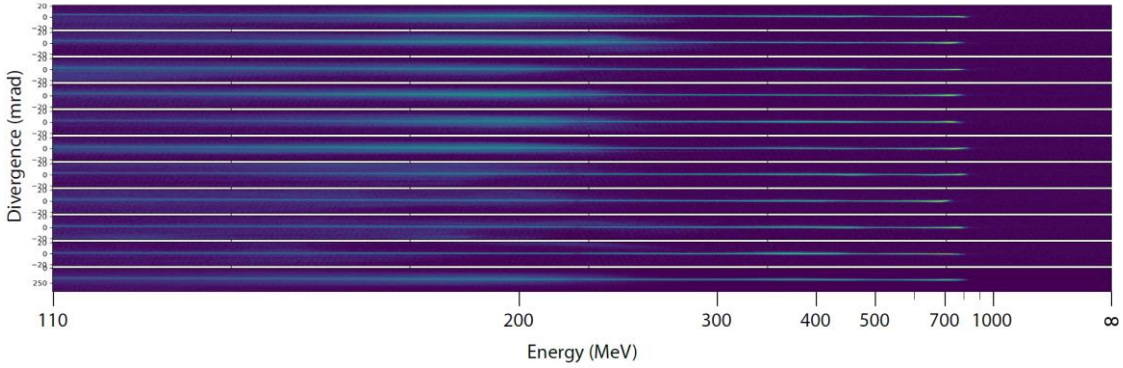
GeV electron bunches

Electron bunch profile



pointing fluctuations on
same order as divergence

Electron bunch spectrum



GeV beams with ultra low
beam divergence < 0.5 mrad^2

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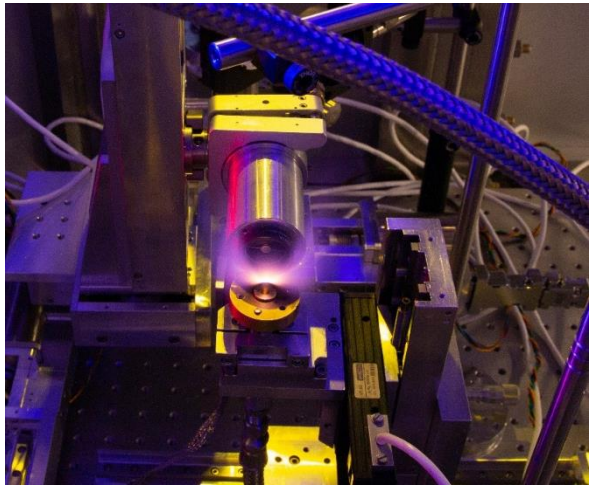
Bayesian Optimizing of LWFA



Laserparameters for optimization

- Energy
- Focussing (shape, position)
- pulse duration (chirp)
- temporal intensity contrast

Experimentalparameters for optimization

- target gas
- target length
- focus position

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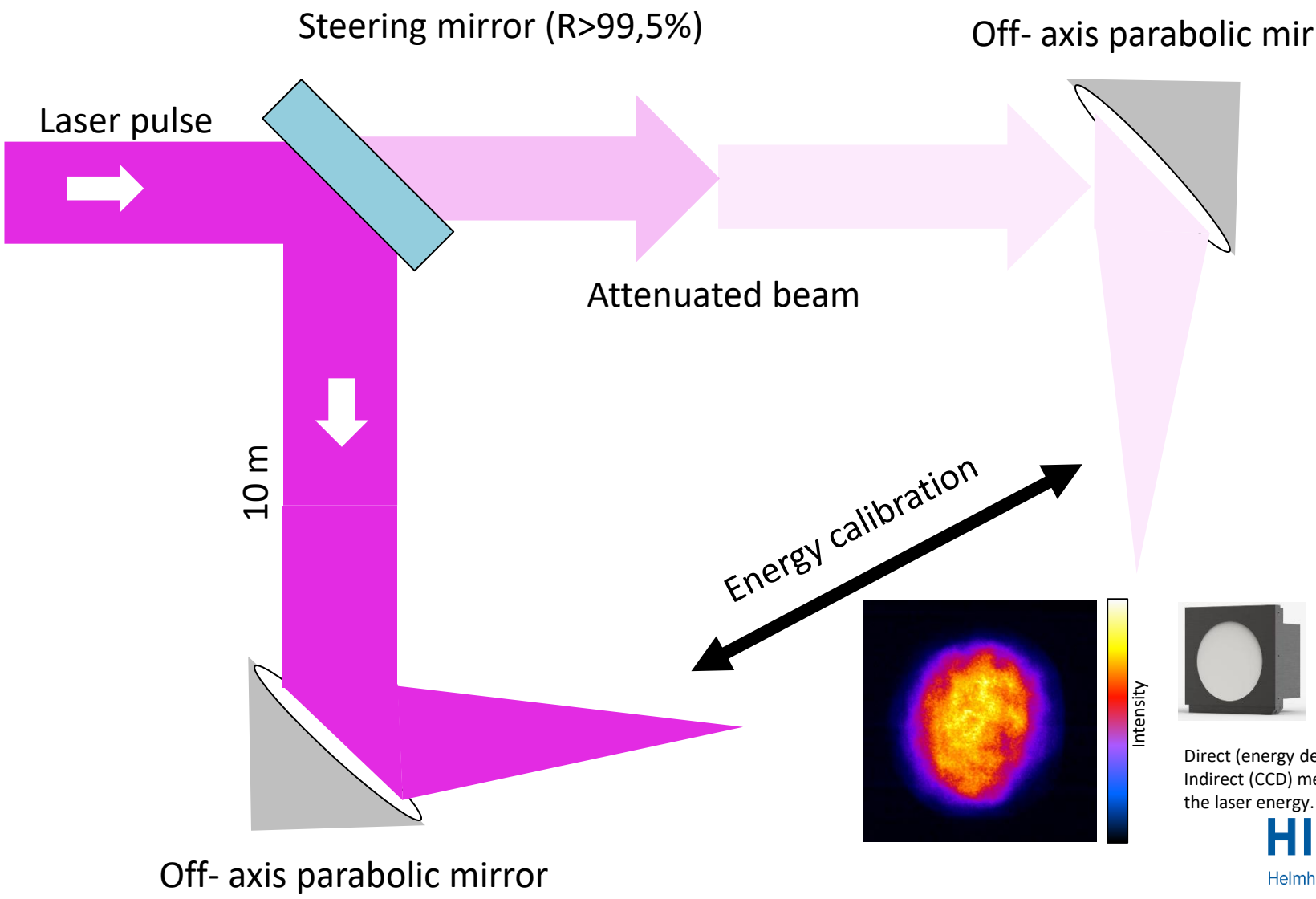
Pulse characterization @ full power



Direct (energy detector) or Indirect (CCD) measurement of the laser energy.

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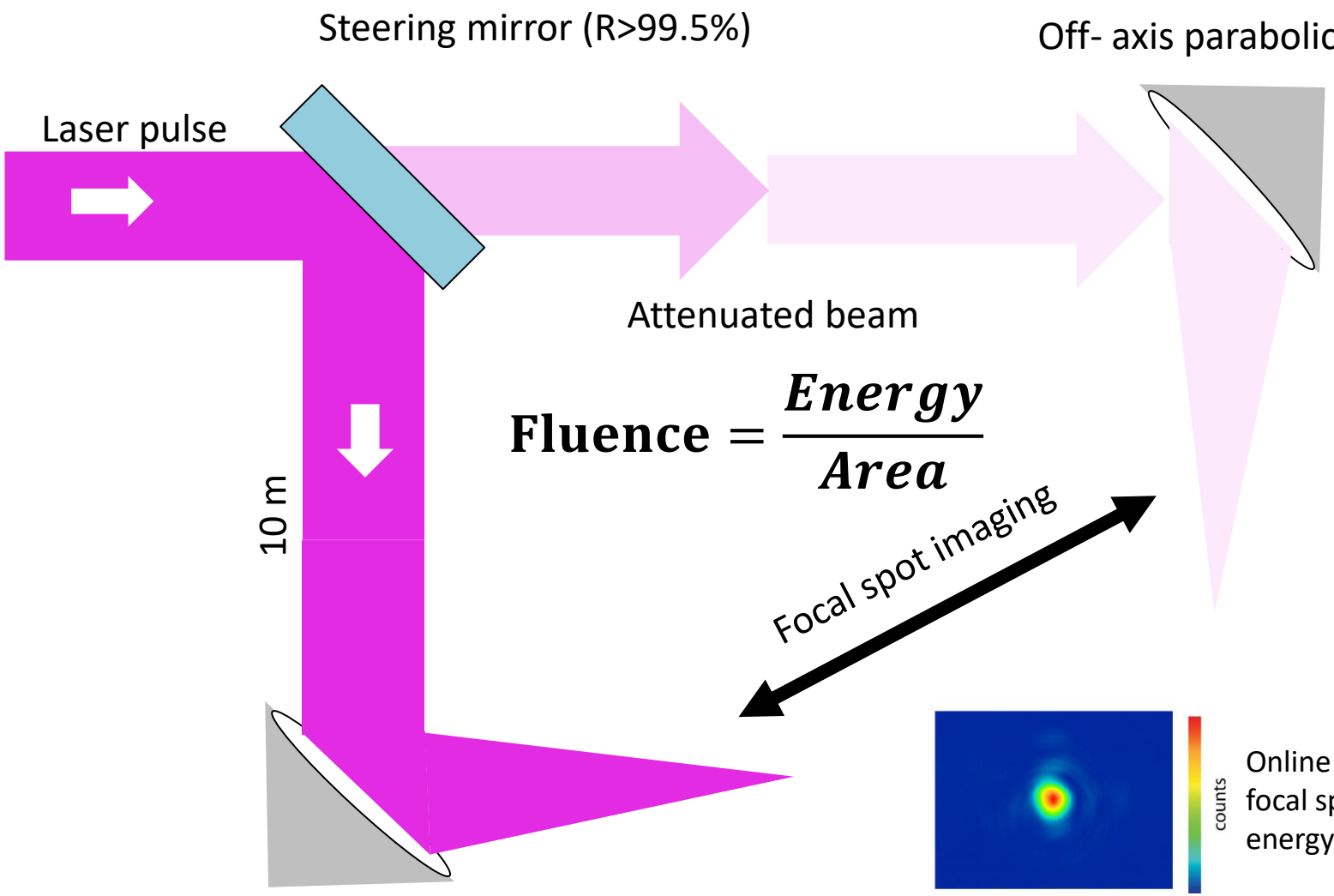
Pulse characterization @ full power



$$\textbf{Fluence} = \frac{\boldsymbol{Energy}}{\boldsymbol{Area}}$$

Online evaluation of the focal spot (area, position energy content) .

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Pulse characterization @ full power

Steering mirror (R>99.5%)

Off- axis parabolic mirror

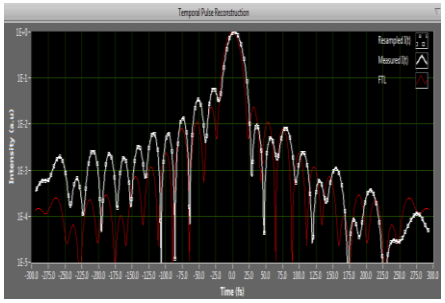
Laser pulse

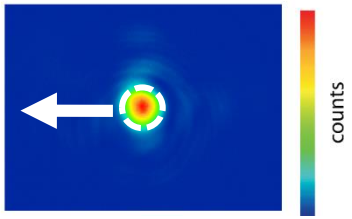
Attenuated beam

Dispersion compensation

10 m

$$Intensity = \frac{Energy}{Pulse\ length \times Area}$$





Off- axis parabolic mirror

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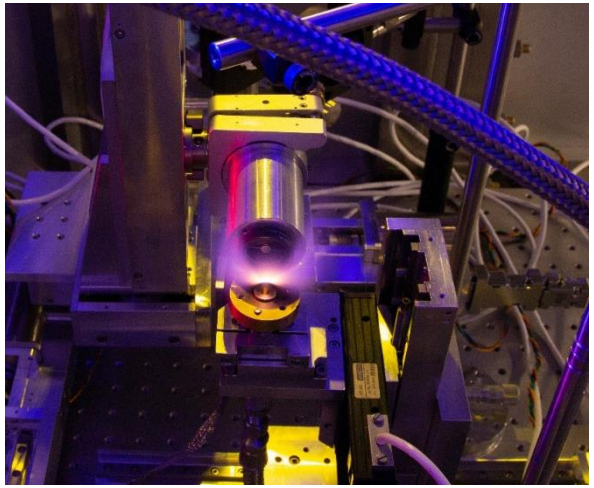
Optimizing LWFA



Laserparameters for optimization

- Energy
- Focussing (shape, **position**)
- pulse duration (chirp)
- temporal intensity contrast

Experimentalparameters for optimization

- target gas
- gas pressure
- gas doping
- target length
- focus position

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HI Jena extension

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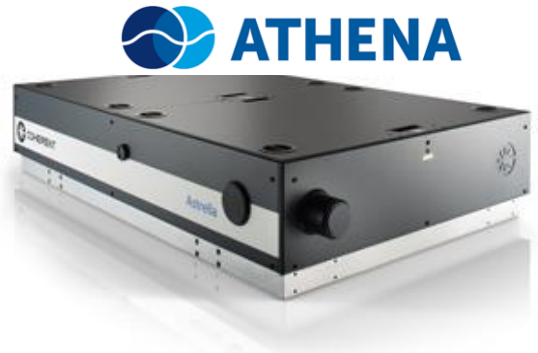
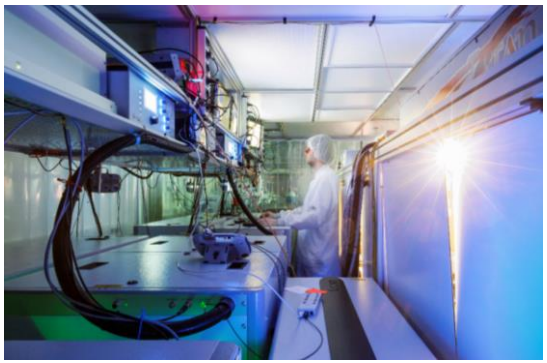
High intensity lasers @ HI Jena & IOQ (2023)

JETi ONE



Wavelength:	0,8-7 µm
Energy on target:	0,5 mJ
Pulse duration:	few cycle
Peak power:	
Repetition rate:	1 kHz

JETi200



Wavelength:	800 nm
Energy on target:	5 J
Pulse duration:	17 fs
Peak power:	300 TW
Repetition rate:	5 Hz

POLARIS

Wavelength:	1030 nm
Energy on target:	16 J (54 J)
Pulse duration:	100 fs
Peak power:	160 TW
Repetition rate:	1/50 Hz

Goal: synchronisation of all beams in space (<1 µrad (rms)) and time (<20 fs (rms))

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State of the art synchronisation < 20 fs (2025)

EFRE EUROPA FÜR THÜRINGEN
EUROPÄISCHER FONDS FÜR REGIONALE ENTWICKLUNG

Thüringer Aufbaubank

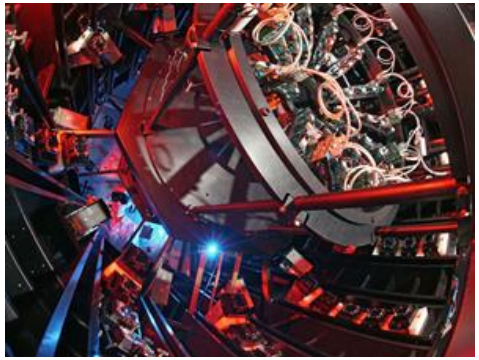
MASTER oscillator @ 1550 nm (lowest noise)

stabilized optical fiber links

JETi ONE

JETi200

POLARIS



New 140 m² Target Area

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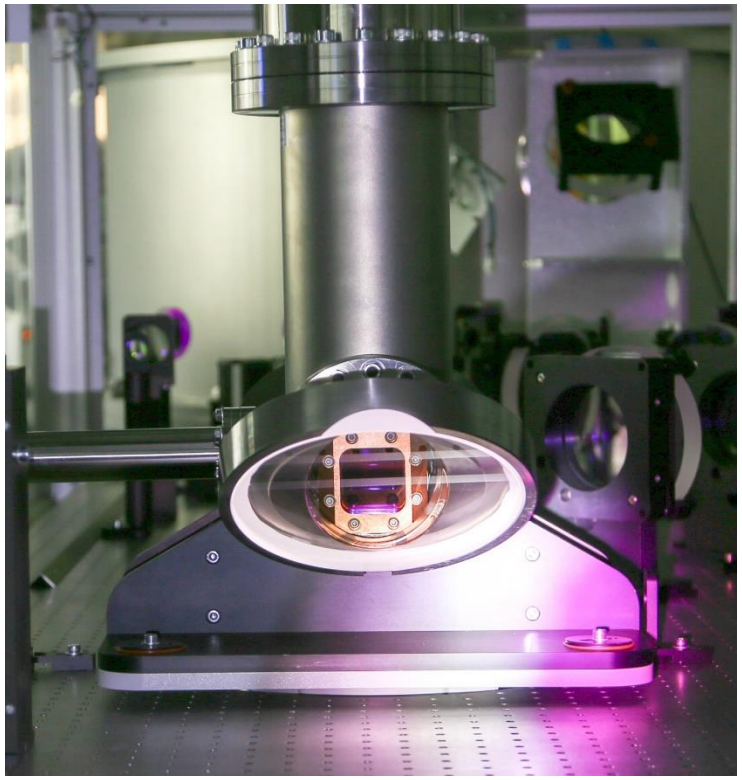
Laser pointing reduction: Cryo cooled power amplifier



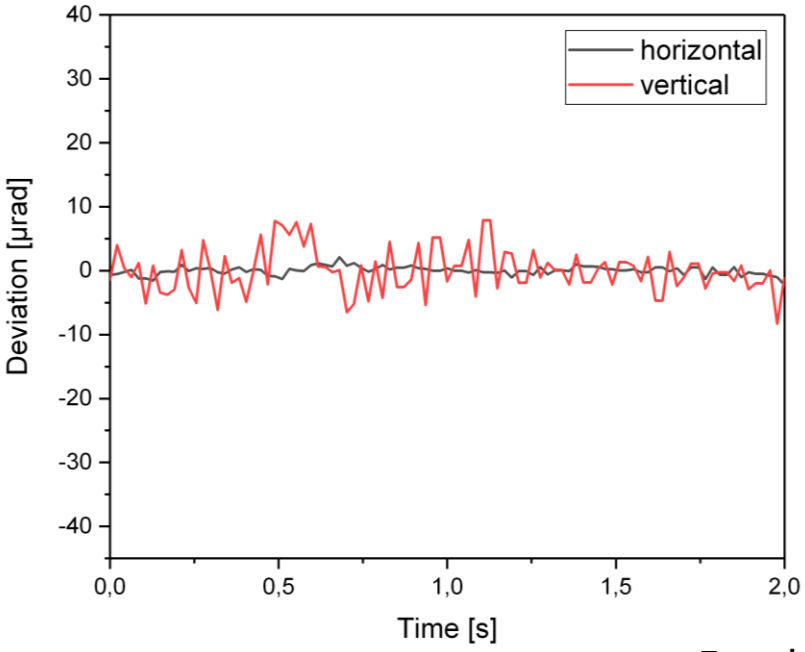
- 100 W pumping power @532 nm
- target temperature 90 K to reduce the thermal lens of the Ti:Sapphire crystal

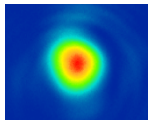
old: Helium expander cryo head ARS DE-110

new: Cryo Spectra K100150

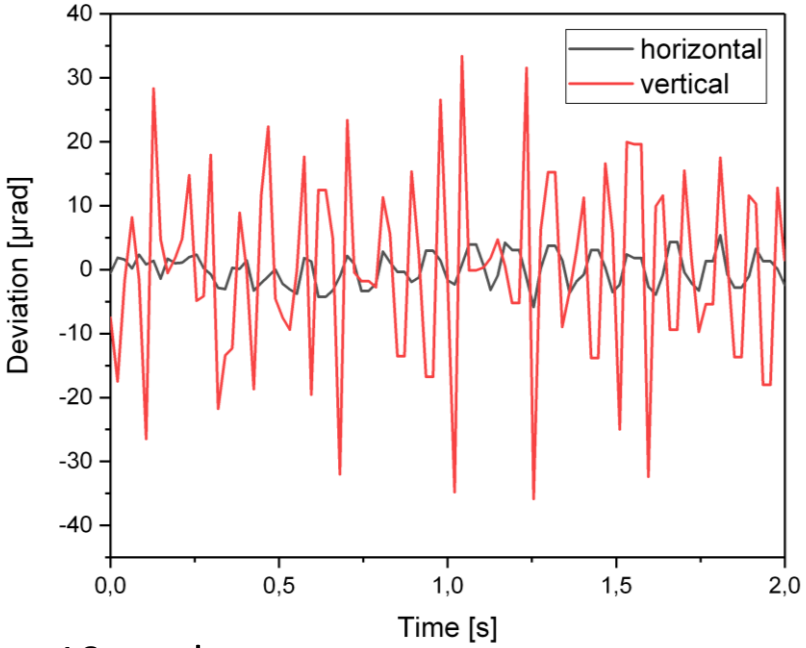
Beam stabilization (short term drift)

just laser & laboratory alone





cryo cooling switched on



Focal spot diameter: ~10 µrad

- **Short term jitter > 30 Hz**
- **Long term drift only depends on environment (temperature, humidity, air pressure)**

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Beam pointing prediction and active beam stabilization for < 1 µrad

Challenge:
Low-repetition rate/ single shot experiments with small pointing jitter

For kHz-laser systems straight forward, small, *continuous* beams, fast piezo mirrors.

For reasonable stable (drift only) systems, e.g 10 Hz JETi200 CPA1 XPW frontend

- **Pilot beam with sufficient high repetition rate and power**
- **Same beam properties as main beam**
- **Detection within the beam line, close to the experiment**
- **typically leaking light through a mirror used for online diagnostics**

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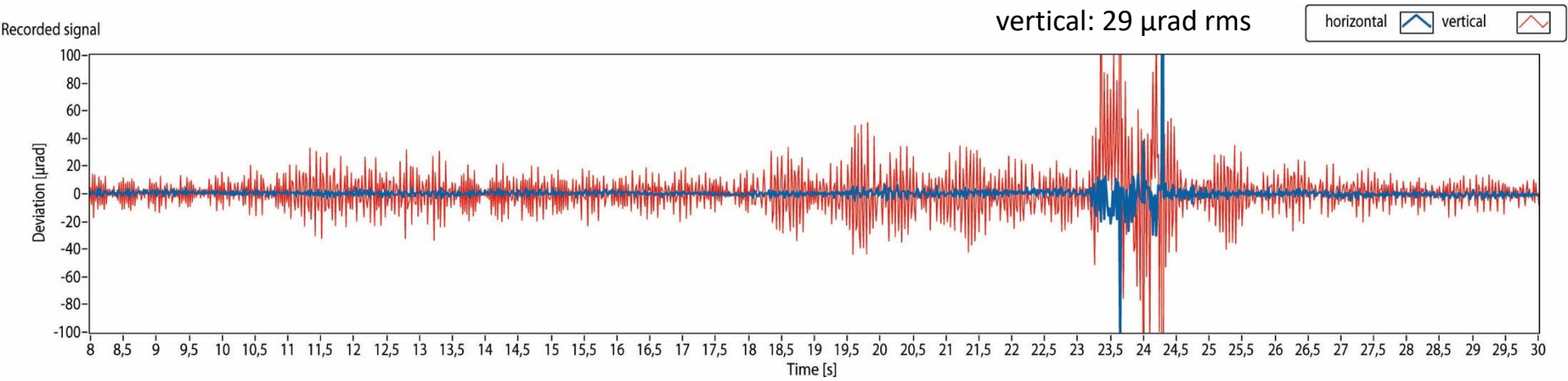
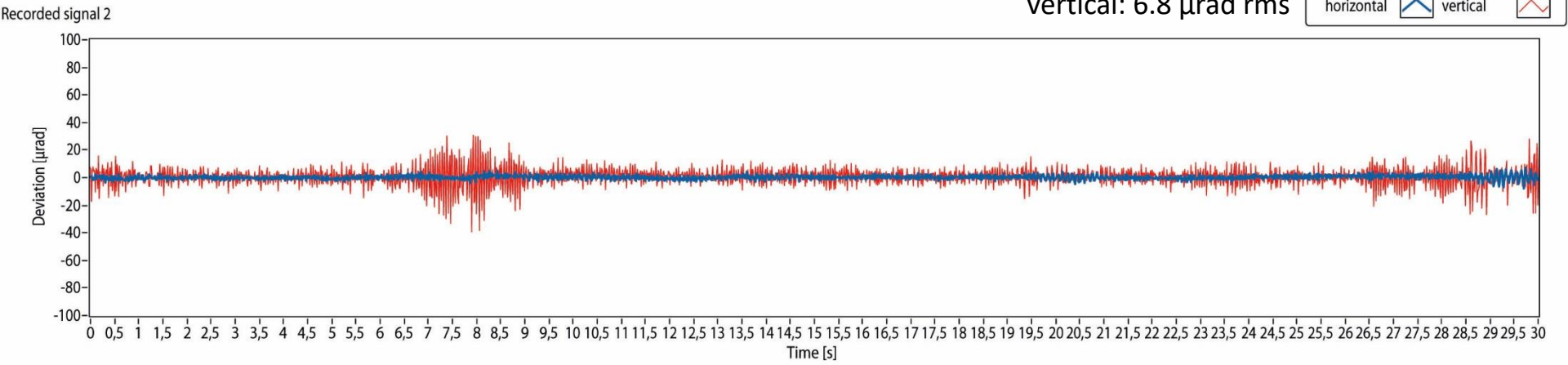
Active beam stabilization with cryo cooling

stabilization OFF
horizontal: 6 µrad rms
vertical: 29 µrad rms



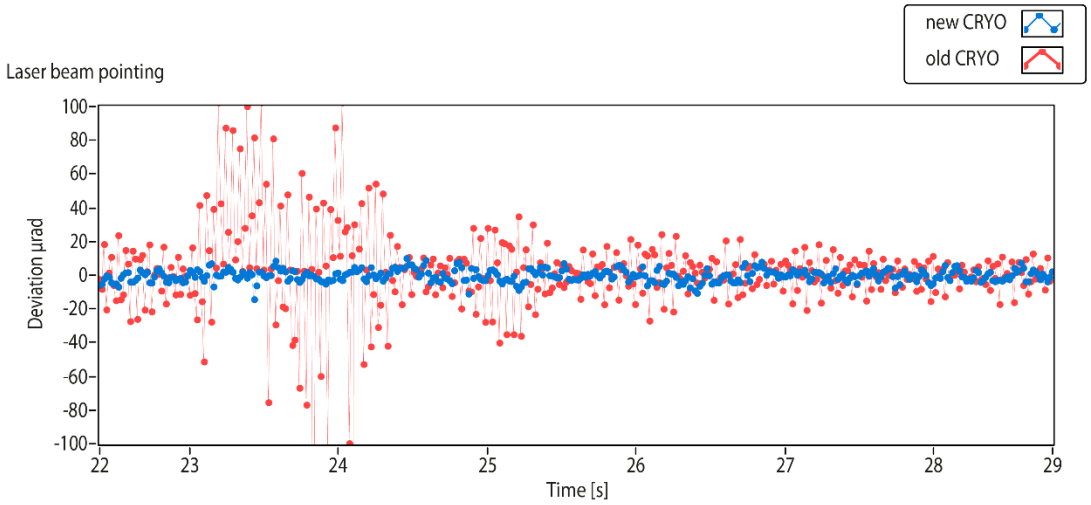
stabilization ON
horizontal: 1.5 µrad rms
vertical: 6.8 µrad rms

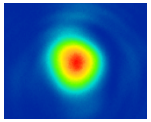


New Cryo head (installation summer 2022)

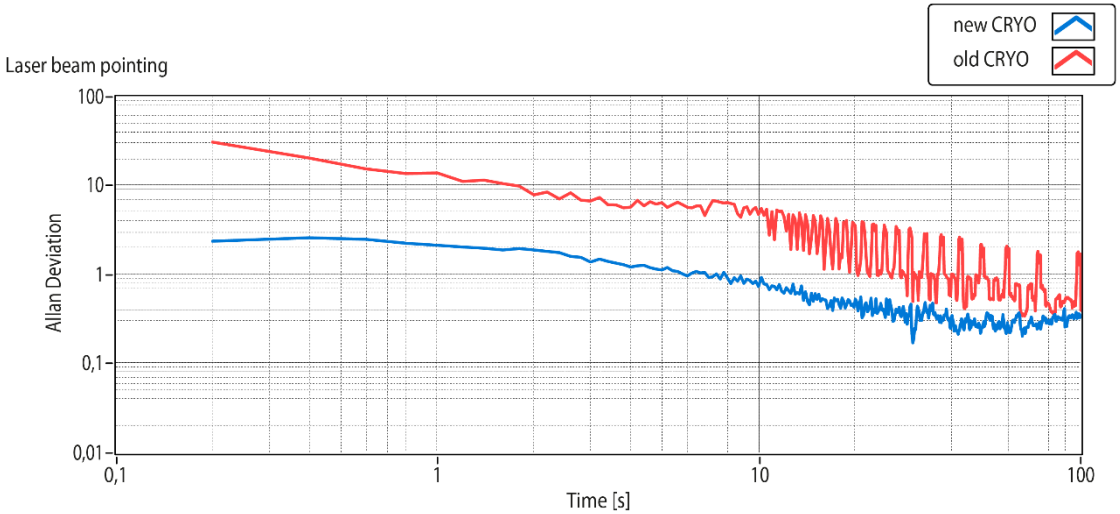
- no vibrations anymore

Installation of new CRYO cooler





Focal spot diameter: ~10 µrad
old CRYO jitter: 30 µrad (rms)
new CRYO jitter: 4 µrad (rms)



Long term drift only depends on environment. (temperature, humidity, air pressure)

Beam pointing at full power is sufficient to hit a 1 µm sphere with a 2 µm diameter focal spot reliable.

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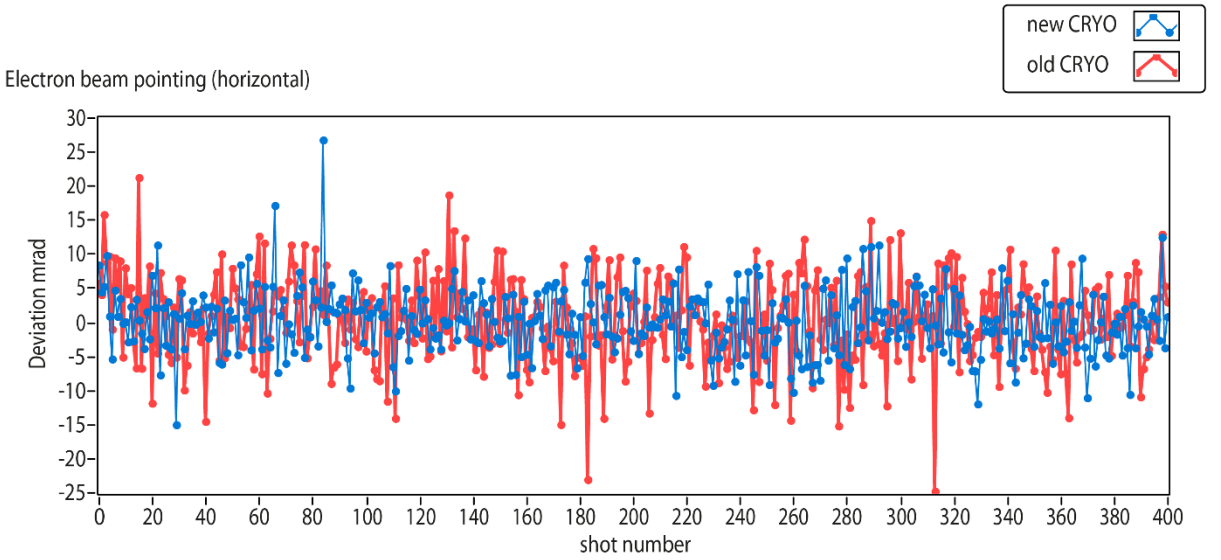
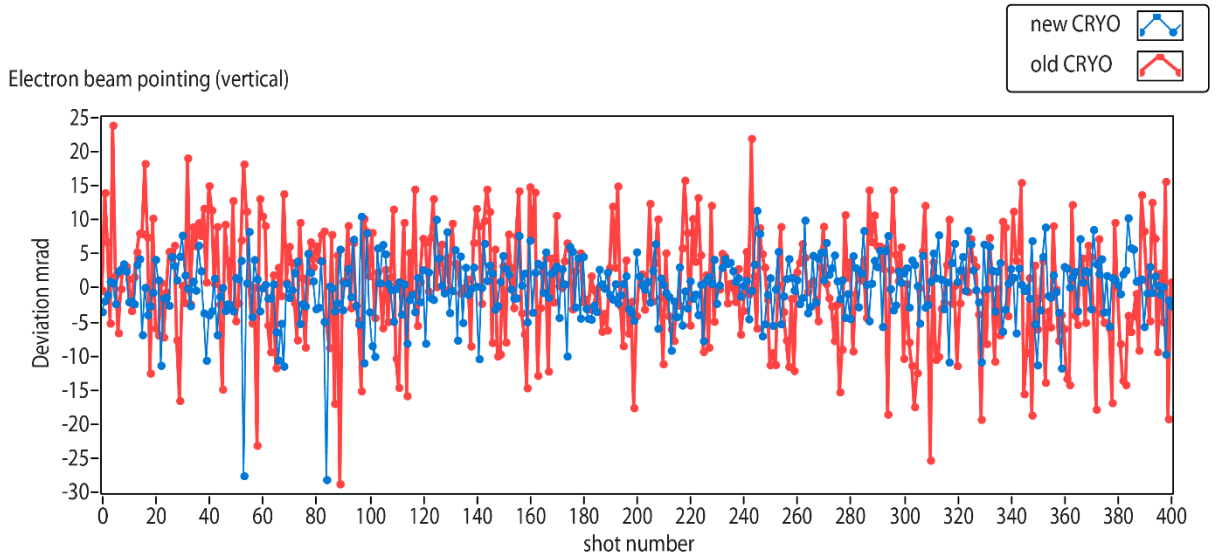
LWFA experiments beam pointing

emittance campaign

- LWFA with ionization injection (95% helium, 5% nitrogen)
- super sonic gas jet

Jitter for electron bunches is **m**rad while for the laser beam is **µ**rad.





horizontal direction
old CRYO jitter: 6.5 mrad (rms)
new CRYO jitter: 4.7 mrad (rms)

vertical direction
old CRYO jitter: 8.4 mrad (rms)
new CRYO jitter: 4.6 mrad (rms)

Technical implementation @ JETi200

JETi200 – Double CPA system

- use residual oscillator beam after pulse picking (front end 10 Hz): P_{pilot} > 200 mW
- beam is coupled in before the multi pass amplifier in CPA2 via thin film polarizer
  no additional stretcher necessary, pulse duration > 6 ps due to dispersion
- same beam path in the laser chain and uses all the expansion optics
- Fast 3“ piezo mirror after the last amplifier
- Detection with 4 quadrant diode (up to 10 kHz) after 99:1 beam splitter in beamline

  - **Pilot beam with sufficient high repetition rate and power**
  - **Same beam properties as main beam**
  - **Detection within the beam line, close to the experiment**
  - **typically leaking light through a mirror used for online diagnostics**

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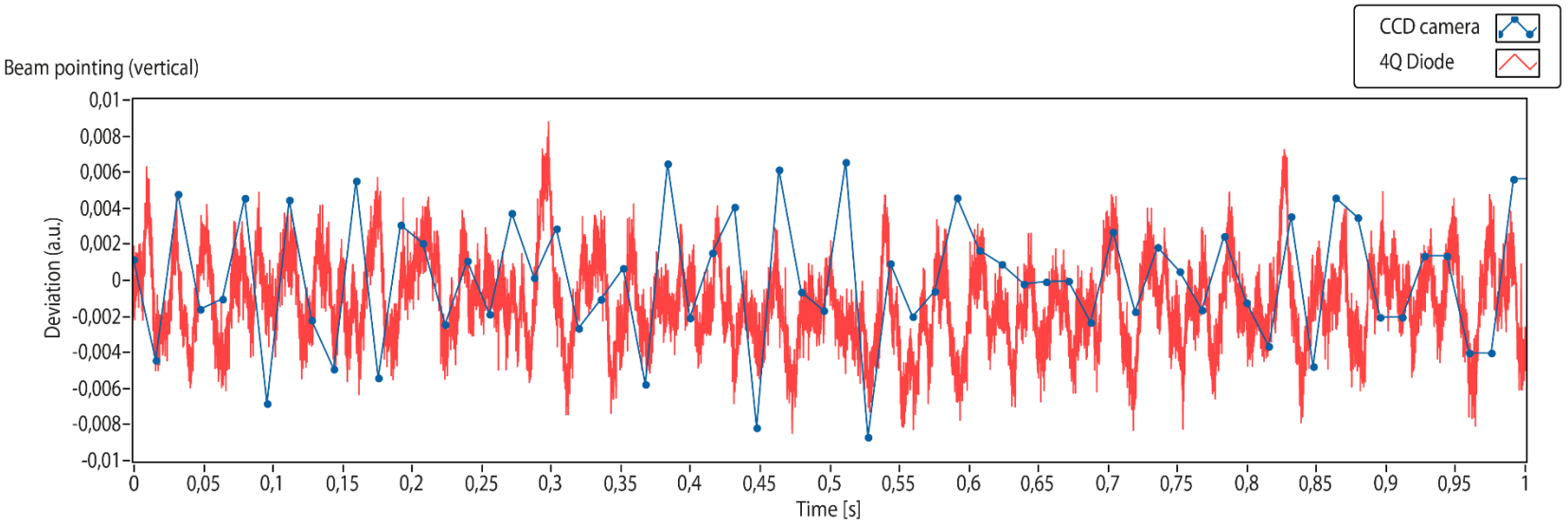
Details



- Disturbances (10 ms) same order as piezo mirror frequency
- 4Q diode needs to be blocked during high power shots

No active readjustment possible, hence, beam prediction is necessary !

Using **L**ong **S**hort-**T**erm **M**emory neural networks to predict time series up to 200 ms into the future.

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Looking 200 ms into the future

- JETi200 operates at nominal 5 Hz
- from pulse picking to target ca. 700 µs -> would allow us to directly pick the right pulse when pilot beam is in the right position
- many experiments require a pre-trigger e.g. for gas cell valves 40 ms before
- use time scale of the pre-trigger for beam prediction

Details

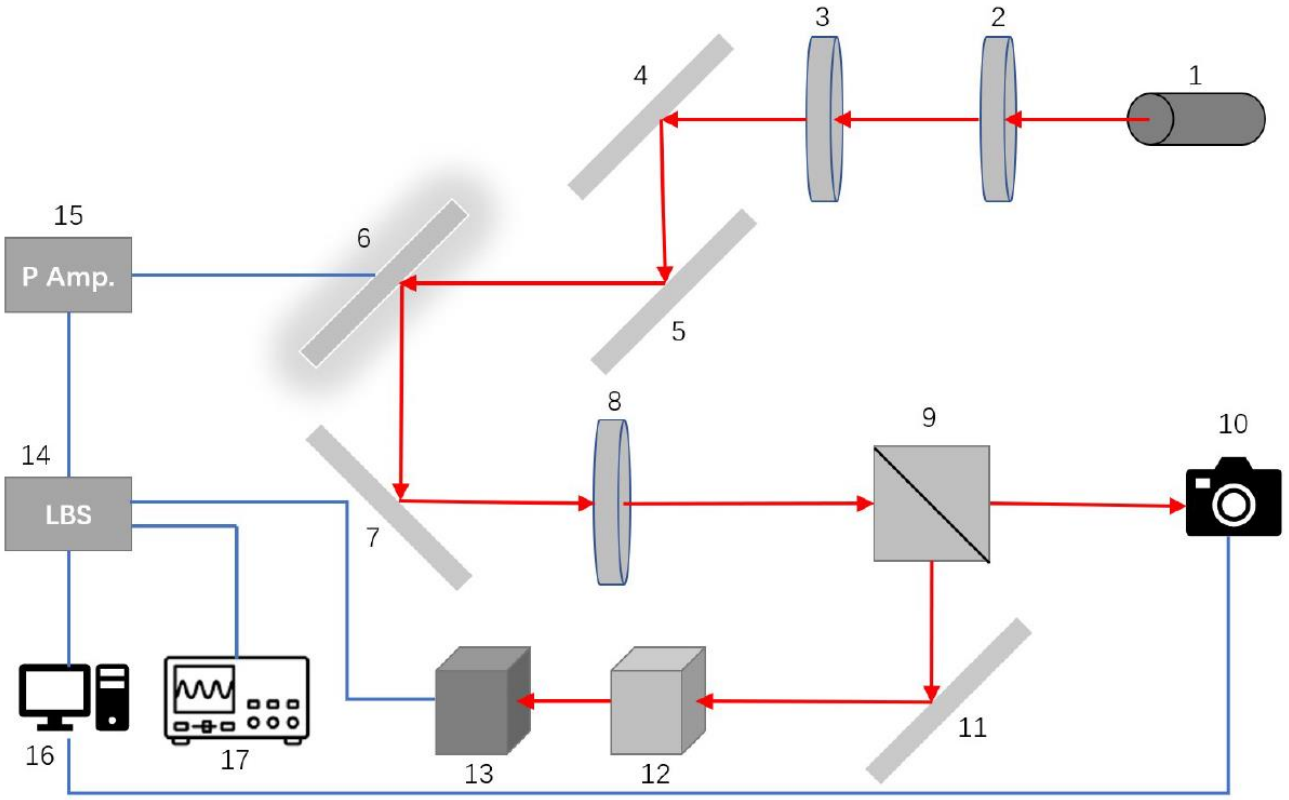


Figure 2.1: Schematic view of the experimental setup

Response time piezo mirror mount

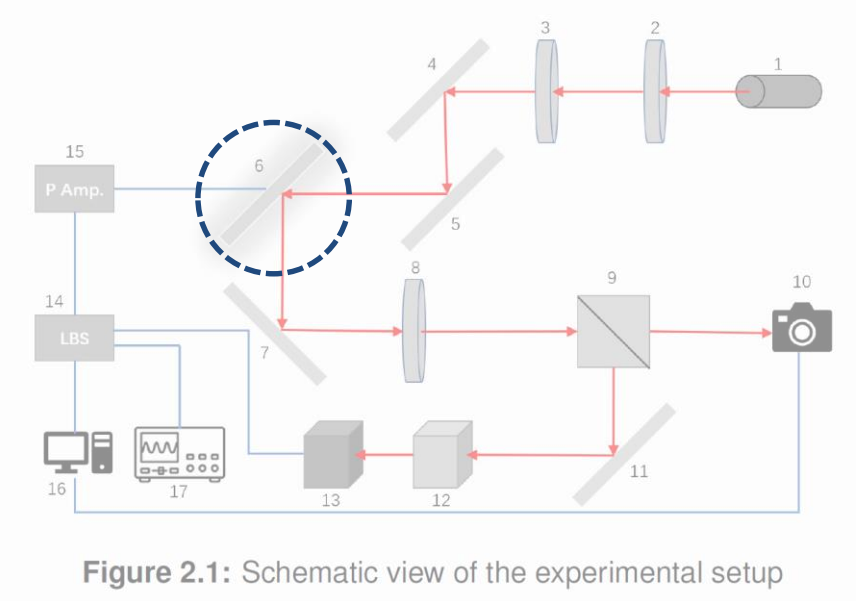
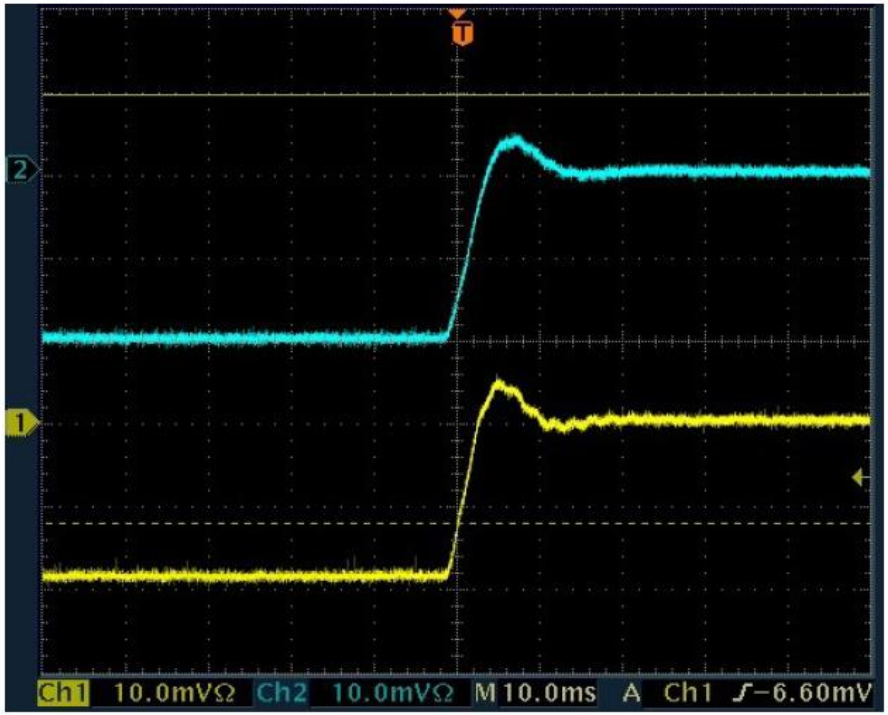
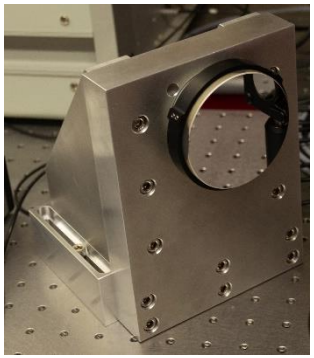


Figure 2.1: Schematic view of the experimental setup





3“ Piezo mirror mount
resonance frequency: ~ 1.7 kHz

Rise time: 4 ms
Final state: 15 ms

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Response time 4QD shutter

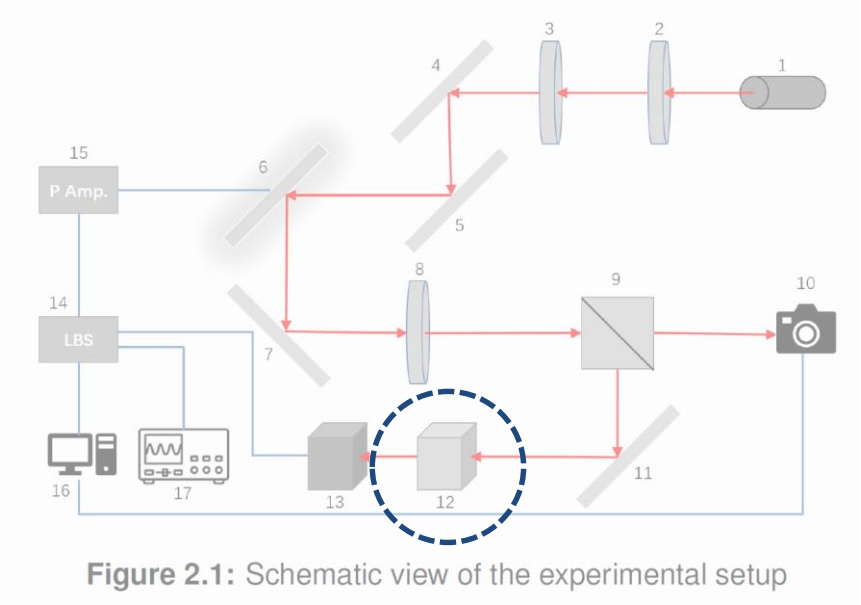
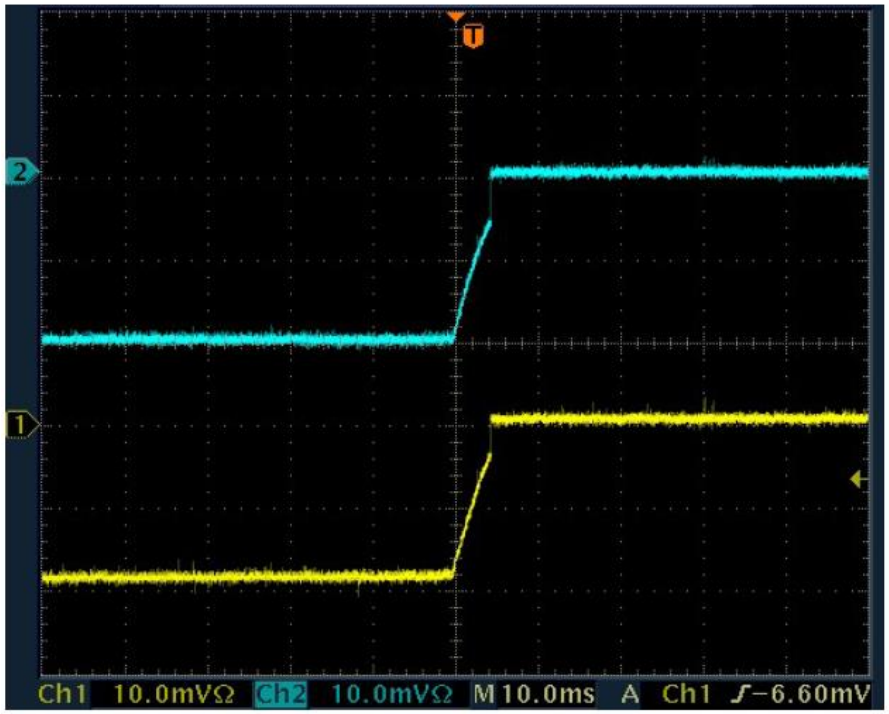


Figure 2.1: Schematic view of the experimental setup



shutter speed: 5 ms

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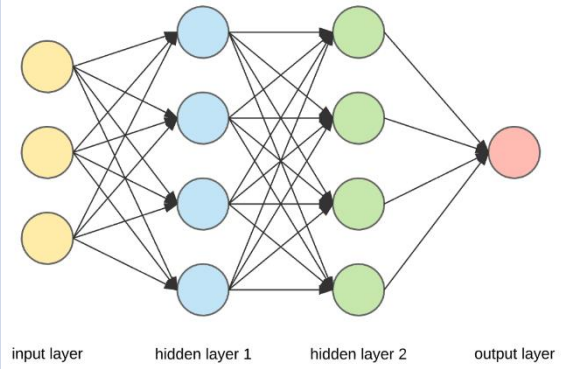
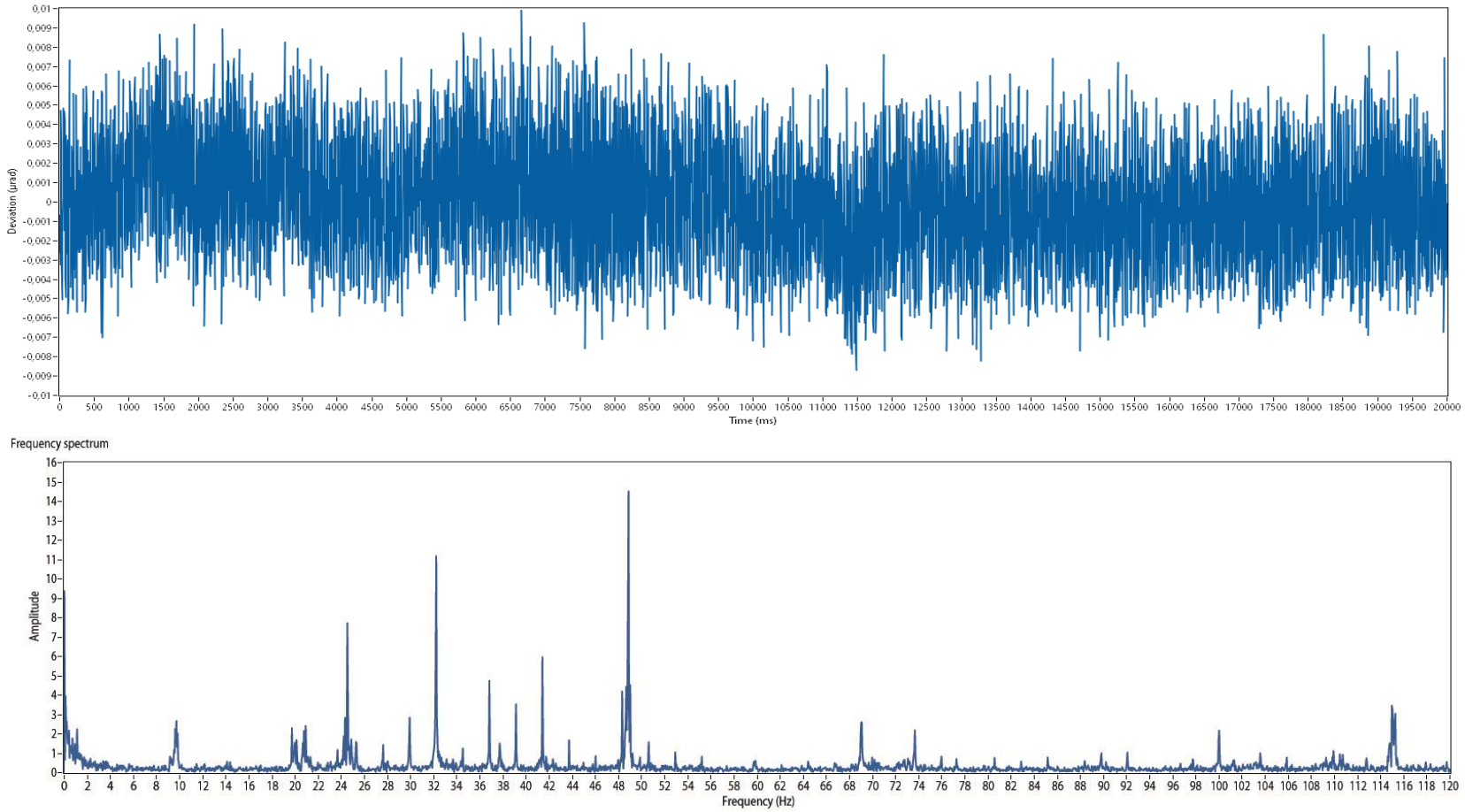
Methods for prediction

- has to be fast enough (analysis + mirror motion+ spare time) < 200 ms

Machine learning / Neural network	Autocorrelation search
„real“ prediction 	searching for similar signals from a database fast but not accurate

Frequency analysis: 20 s @ 1 kHz



characteristic frequencies: **48.9 Hz, 32.2 Hz, 24.6 Hz, 41.5 Hz, 36.8 Hz, 115 Hz**

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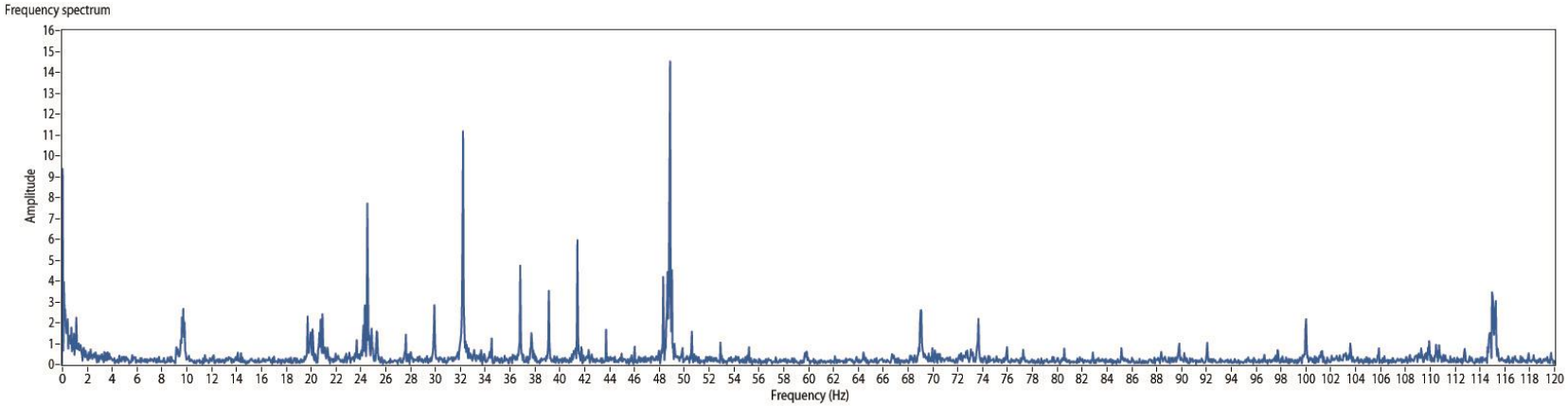
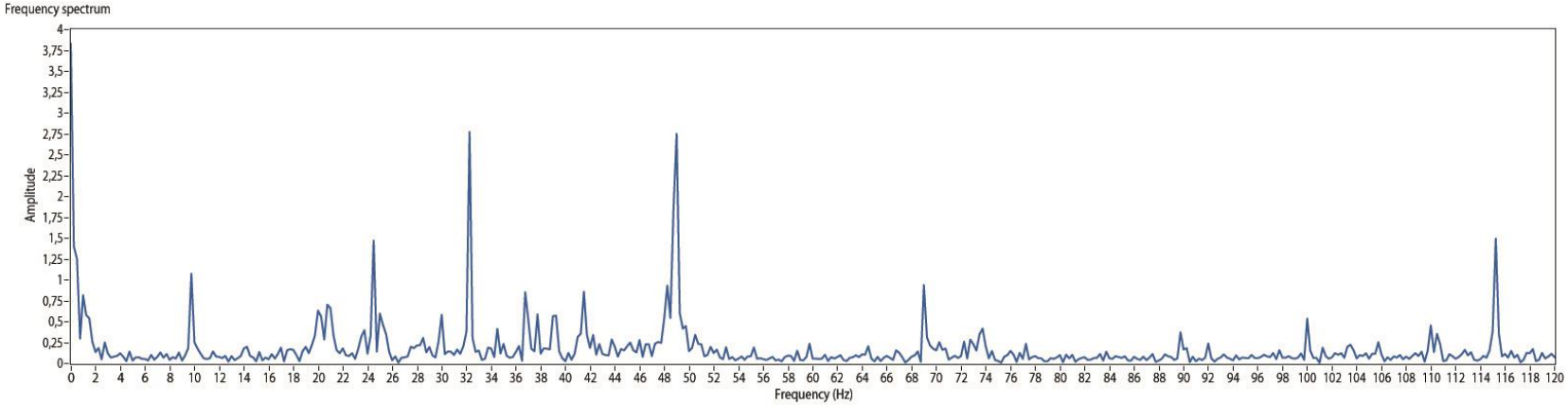
Frequency analysis evolution: 0 – 4 s





characteristic frequencies: **48.9 Hz, 32.2 Hz, 24.6 Hz, 41.5 Hz, 36.8 Hz, 115 Hz**

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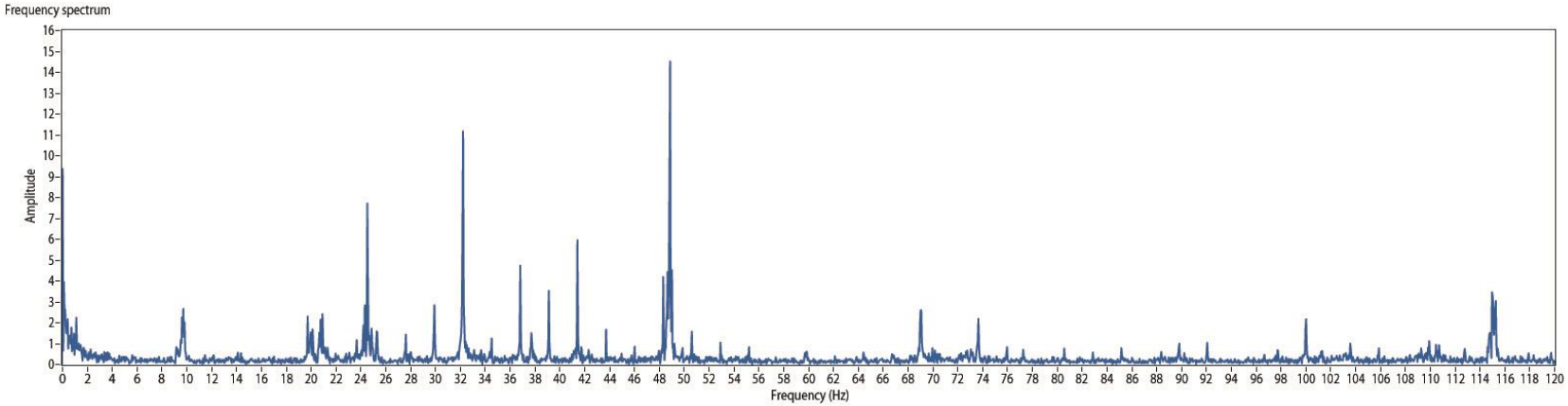
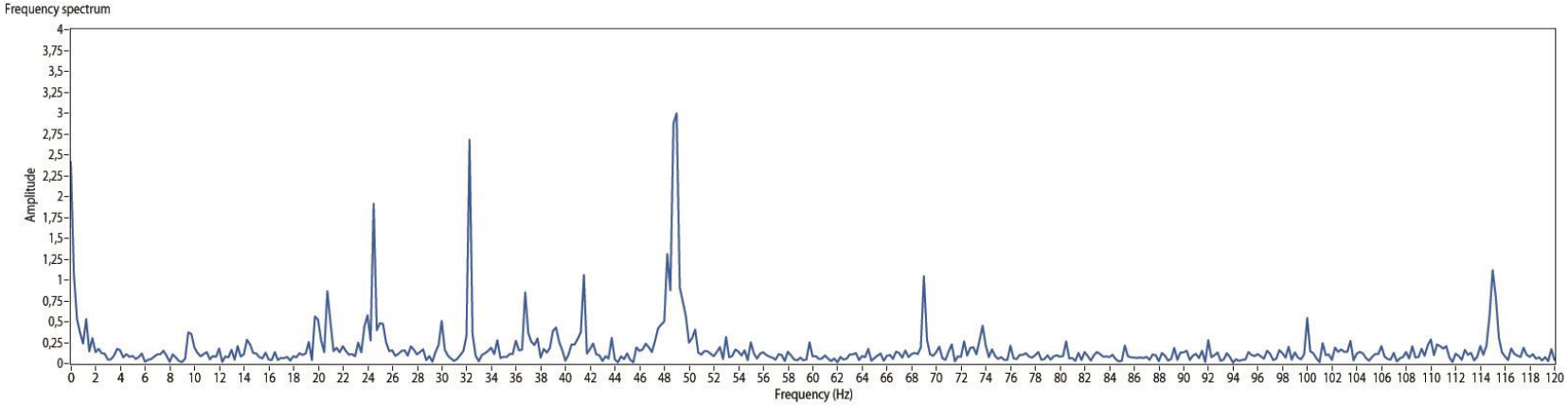
Frequency analysis evolution: 4 – 8 s





characteristic frequencies: **48.9 Hz, 32.2 Hz, 24.6 Hz, 41.5 Hz, 36.8 Hz, 115 Hz**

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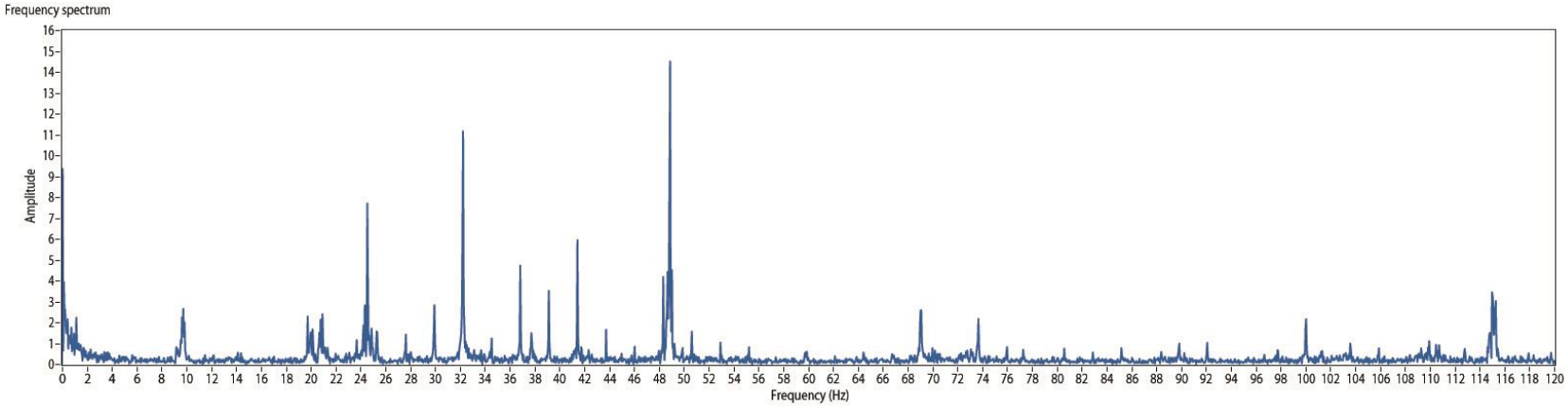
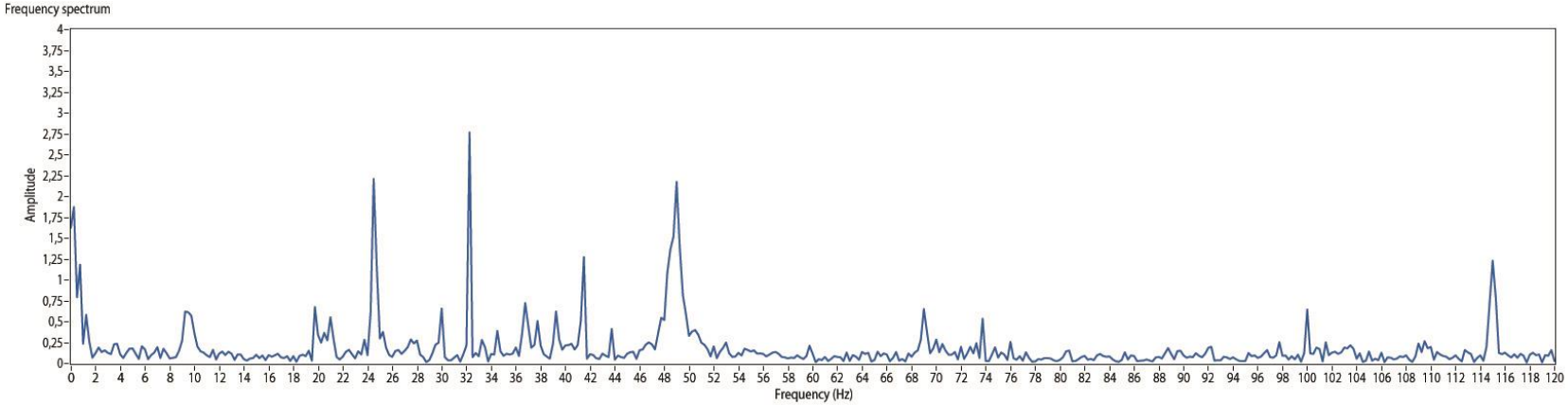
Frequency analysis evolution: 8 – 12 s





characteristic frequencies: **48.9 Hz, 32.2 Hz, 24.6 Hz, 41.5 Hz, 36.8 Hz, 115 Hz**

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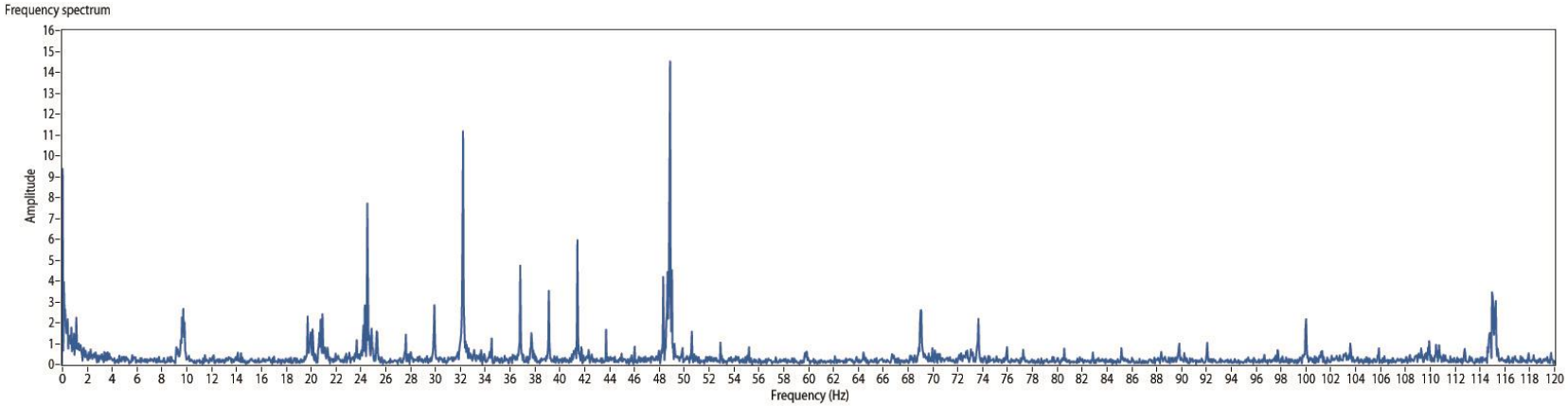
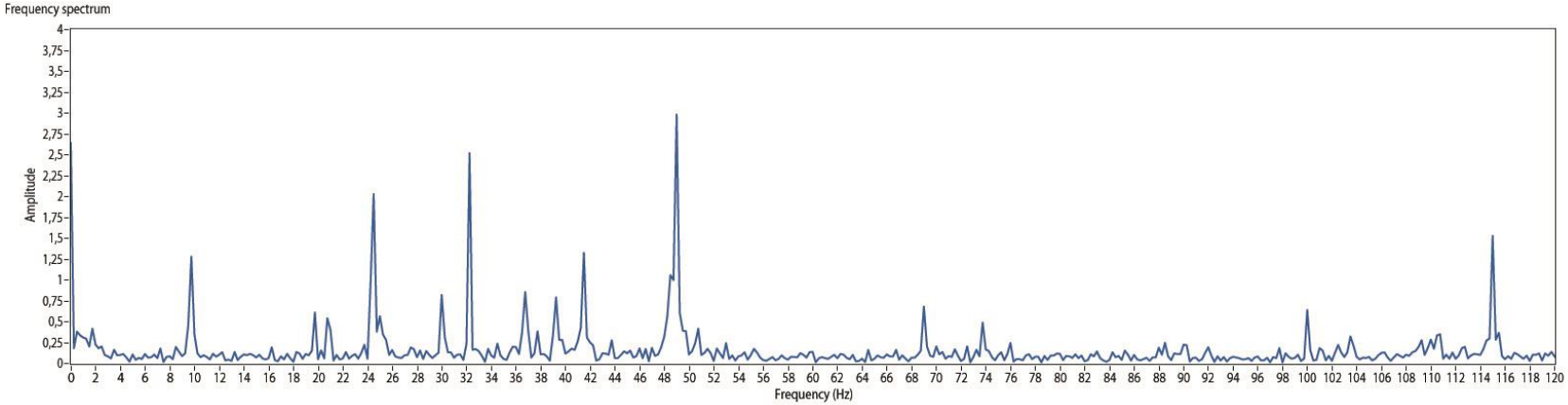
Frequency analysis evolution: 12 – 16 s





characteristic frequencies: **48.9 Hz, 32.2 Hz, 24.6 Hz, 41.5 Hz, 36.8 Hz, 115 Hz**

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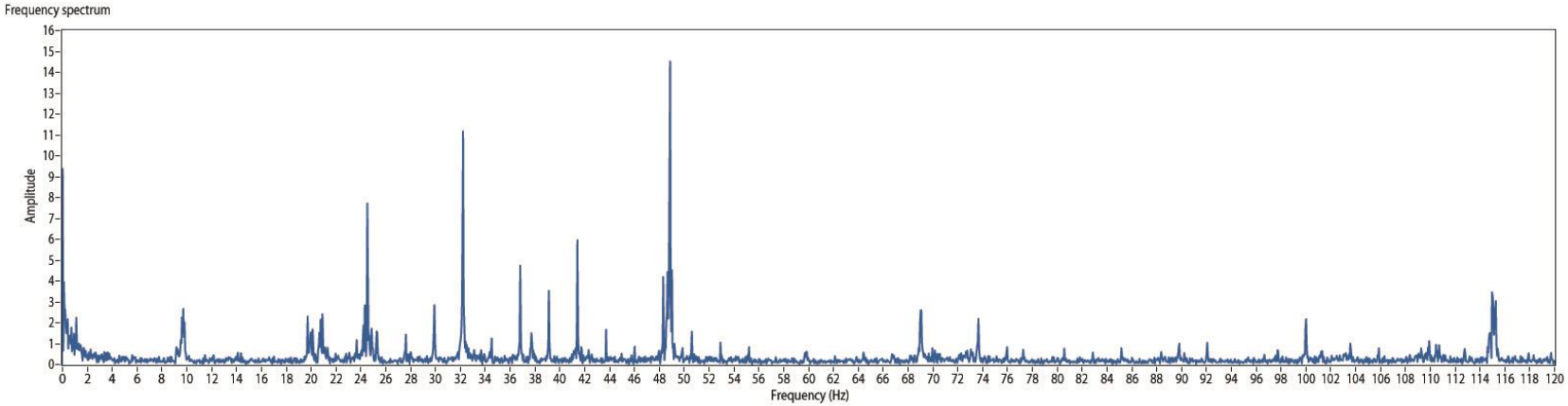
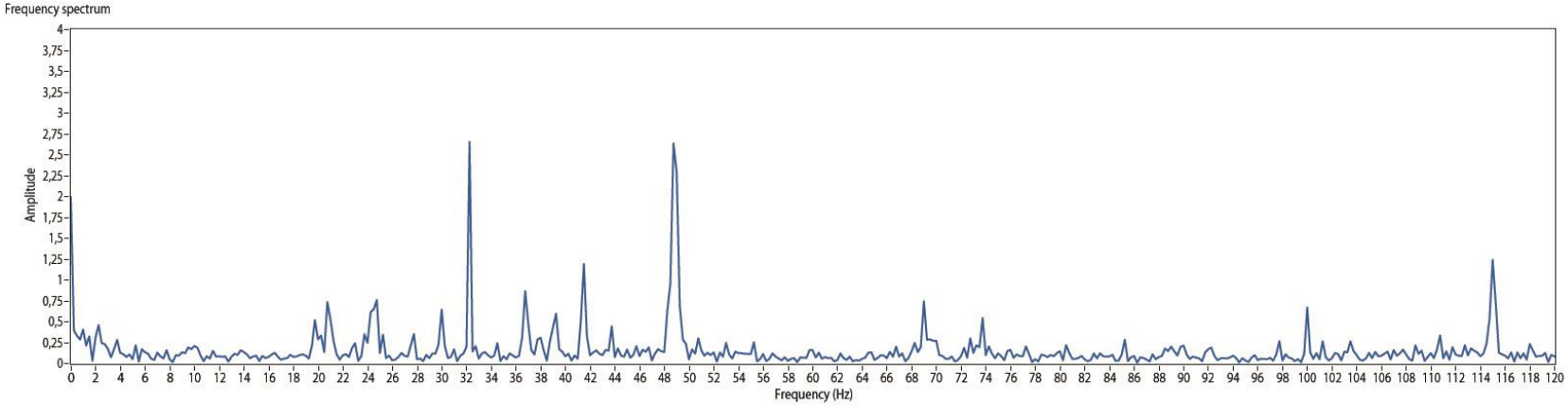
Frequency analysis evolution: 16 – 20 s





characteristic frequencies: **48.9 Hz, 32.2 Hz, 24.6 Hz, 41.5 Hz, 36.8 Hz, 115 Hz**

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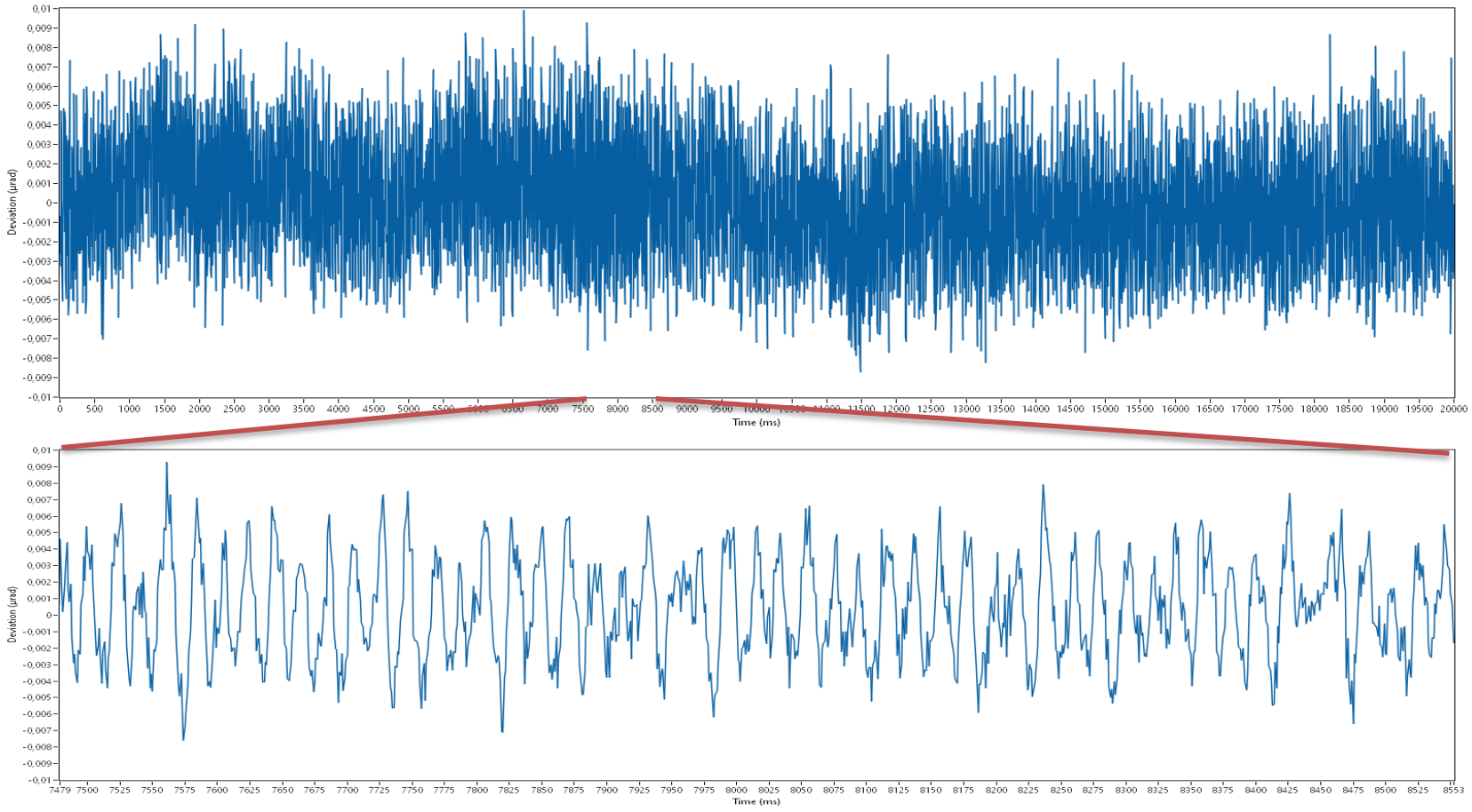
Key parameter: training data @ 1 kHz



- Using tensorflow libraries in python
- multiple sets with different lengths (typical 1000-20000 points)

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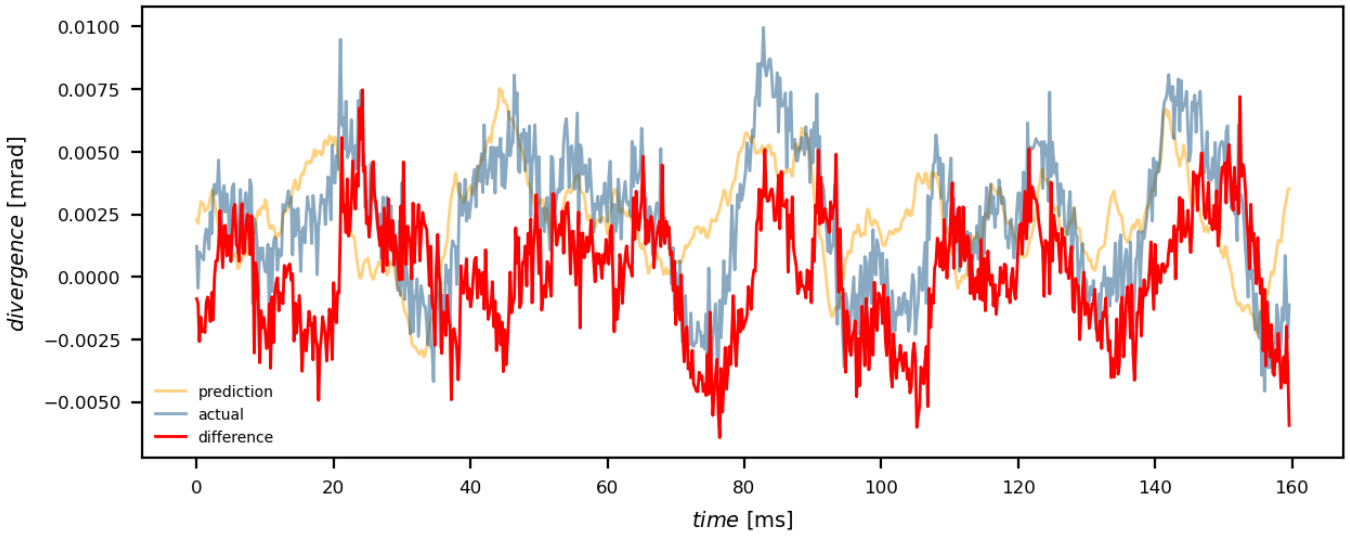
Sampling resolution 1 kHz



- 2000 pts for 200 pts prediction (first 2 s of measurement)
- comparison @ 6s

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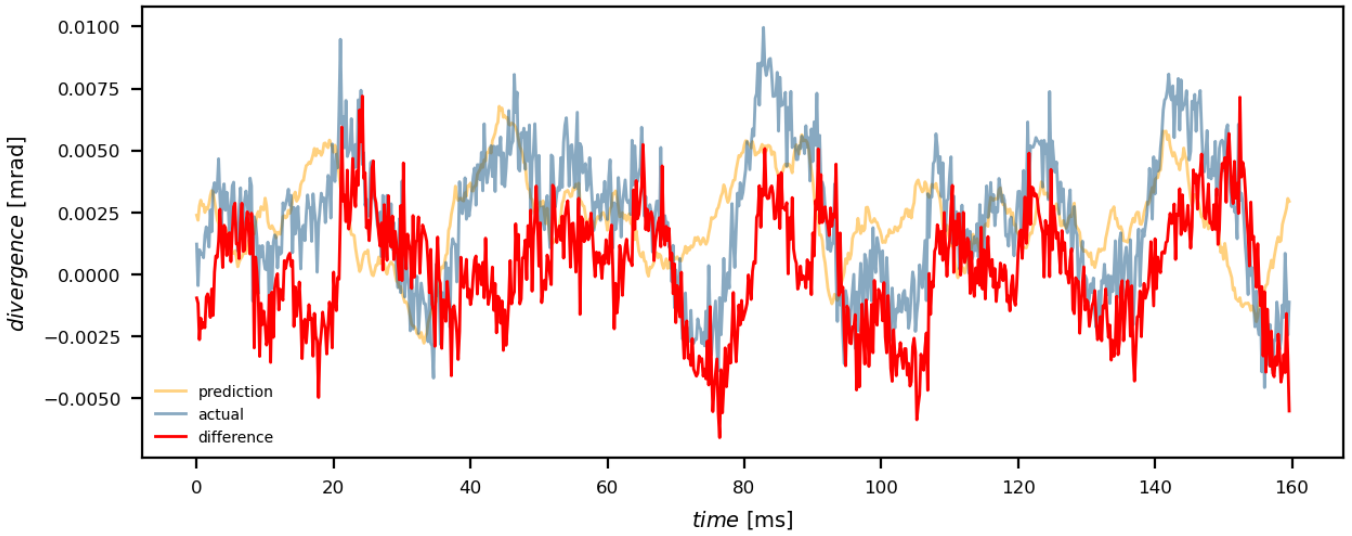
Sampling resolution 1 kHz



- 10000 pts for 200 pts prediction (first 10 s of measurement)
- comparison @ 6s
- longer sets didn´t contribute to better predictions

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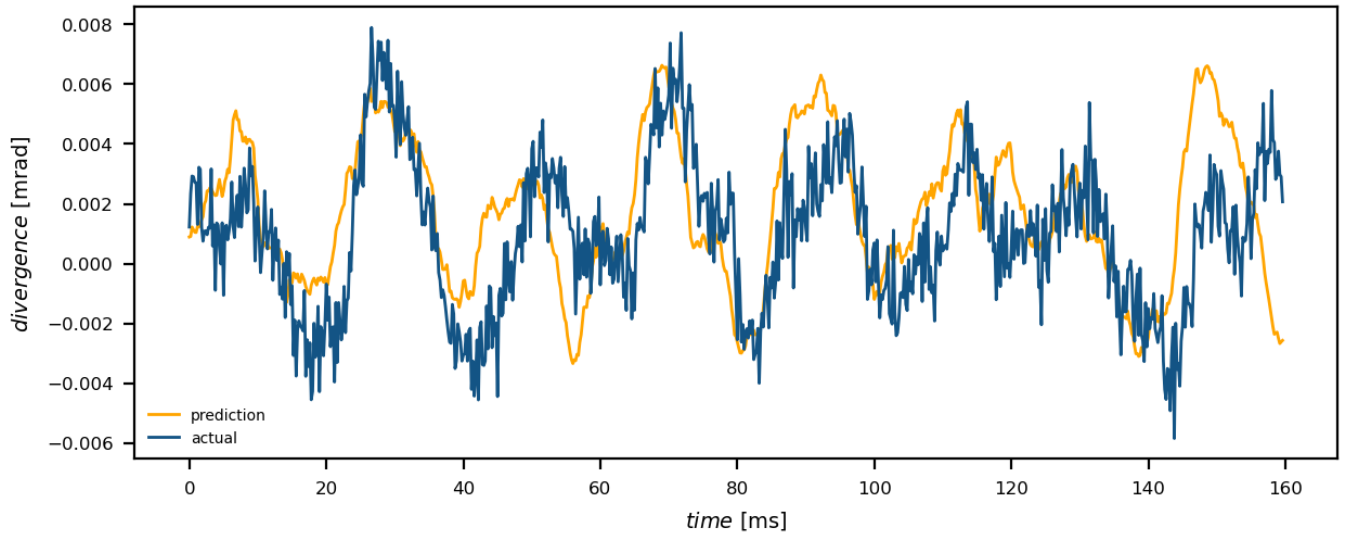
Sampling resolution 5 kHz



- 50000 pts for 200 pts prediction (first 10 s of measurement)
- comparison @ 6s (within trainings set)

We can only predict what has happened at some point in the past.
(slamming doors, …)

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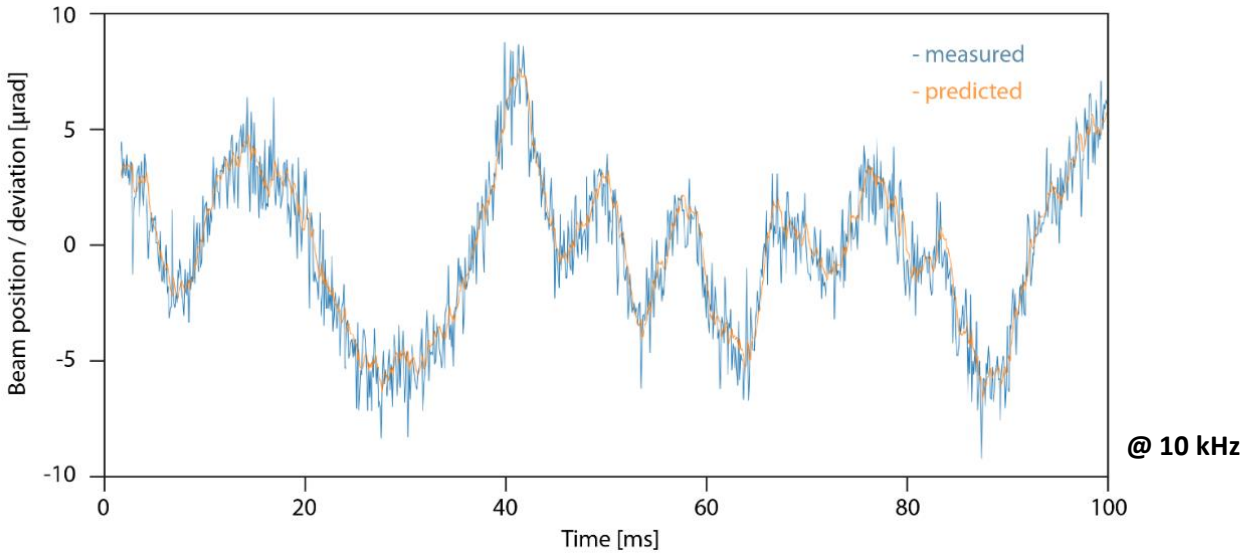
Beam pointing prediction and active beam stabilization

First tests (Labview, python with tensor flow/ pytorch) with recorded trainings data and compare to recorded test data



@ 10 kHz

Good news: - It works! up to 2 times RMS-jitter reduction (best case).
- Worst case: no improvement
- Calculation time < prediction time

But: seems not to be long term stable, reinforced learning necessary

Anyway: Installation of hardware and tests later this year .

CONTROL SYSTEM neccessary!

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