KBTM

# Optical sensors & Data Synchronization

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20 November 2025

**Kibble Balance Technical Meeting**
**special session “knowledge transfer”**
**20 November 2025, BIPM**

# Operations of Kibble balances

- **Original Kibble balance**
  - Single position weighing phase, constant velocity measurement
- **Joule balance**
  - Multiple position weighing phase, velocity measurement integrated over a single whole trajectory
- **Compact micromotion Kibble balance**
  - Multiple position weighing phase, oscillating mode velocity measurement

- ✓ Weighing measurement common to all operation modes
- ✓ Position sensors common to all operation modes (the compact micromotion Kibble Balance do not measure parasitic coil motion)
- ✓ Synchronization of voltage and velocity measurement (velocity phase) critical for original Kibble balance

# Measured quantities

- **Weighing phase:**
  - **Main quantities:**
    - Current in the coil (voltage drop across a standard resistor)
    - Free fall acceleration
- **Velocity phase:**
  - **Main quantities:**
    - Voltage induced across the coil
    - Coil velocity
- **Both phases:**
  - **Control:**
    - Balance beam angular position
  - **Secondary quantities:**
    - Parasitic coil motion (i.e. translation and rotation: six degrees of freedom)
    - Environmental parameters

# Measured quantities: Position sensors requirements

- **Weighing phase:**
  - **Main quantities:**
    - Current in the coil (voltage drop across a standard resistor)
    - Free fall acceleration
- **Velocity phase:**
  - **Main quantities:**
    - Voltage induced across the coil
    - Coil velocity
- **Both phases:**
  - **Control:**
    - Balance beam angular position
  - **Secondary quantities:**
    - Parasitic coil motion (i.e. translation and rotation: six degrees of freedom)
    - Environmental parameters

- ✓ Accurate
- ✓ High resolution
- ✓ Measurement Range: ~ cm
- ➢ Optical interferometer

- ✓ Low drift
- ✓ High resolution
- ✓ Measurement Range: ~ 10 µm

# Measured quantities: Synchronization requirements

- **Weighing phase:**
  - **Main quantities:**
    - Current in the coil (voltage drop across a standard resistor)
    - Free fall acceleration
- **Velocity phase:**
  - **Main quantities:**
    - Voltage induced across the coil
    - Coil velocity
- **Both phases:**
  - **Control:**
    - Balance beam angular position
  - **Secondary quantities:**
    - Parasitic coil motion (i.e. translation and rotation: six degrees of freedom)
    - Environmental parameters

- ✓ Static measurement, sensitive to the variation of free fall acceleration
- ✓ Sync. requirement: ~ 1 s
- ✓ Method: sync. software clocks

- ✓ Dynamic measurement, sensitive velocity noise and Bl variation
- ✓ Sync. Requirement: ~ µs
- ✓ Method: hardware trigger / arming

- ✓ Sync. Requirement: < ms
- ✓ Method : hardware trigger or sync. software clocks

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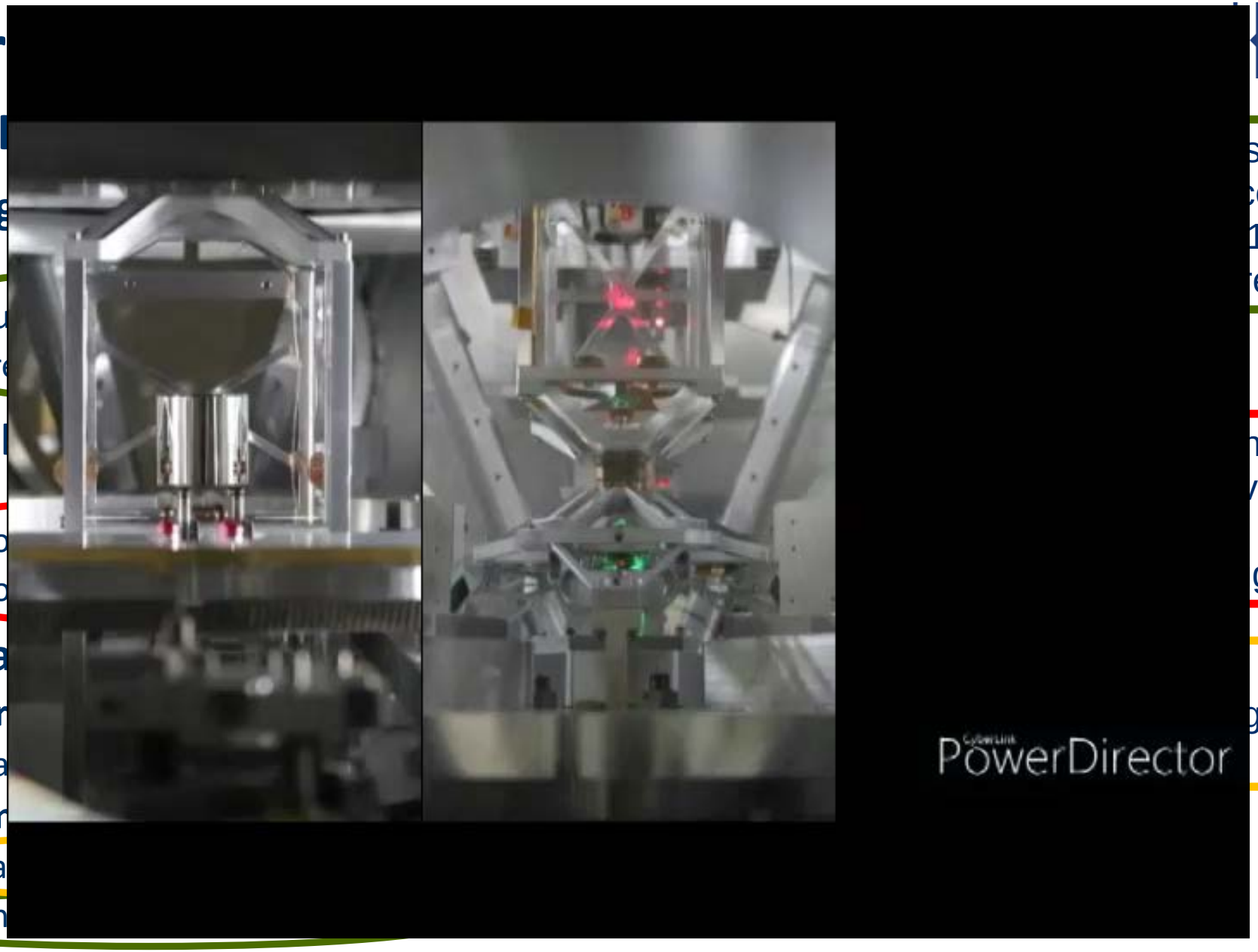


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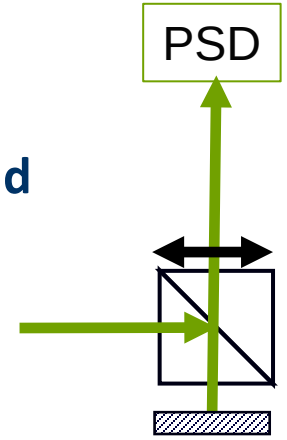
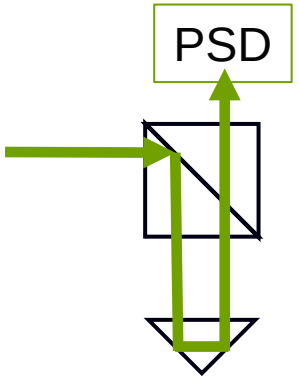
# Monitoring the coil motion

- **Rotations:**
  - Measurement range: 1 mrad
  - Resolution: 1 µrad
  - Autocollimators






- **Translations:**
  - Measurement range: 1 mm
  - Resolution: 1 µm
  - Shadow detectors
  - Position sensitive detectors associated with corner cube

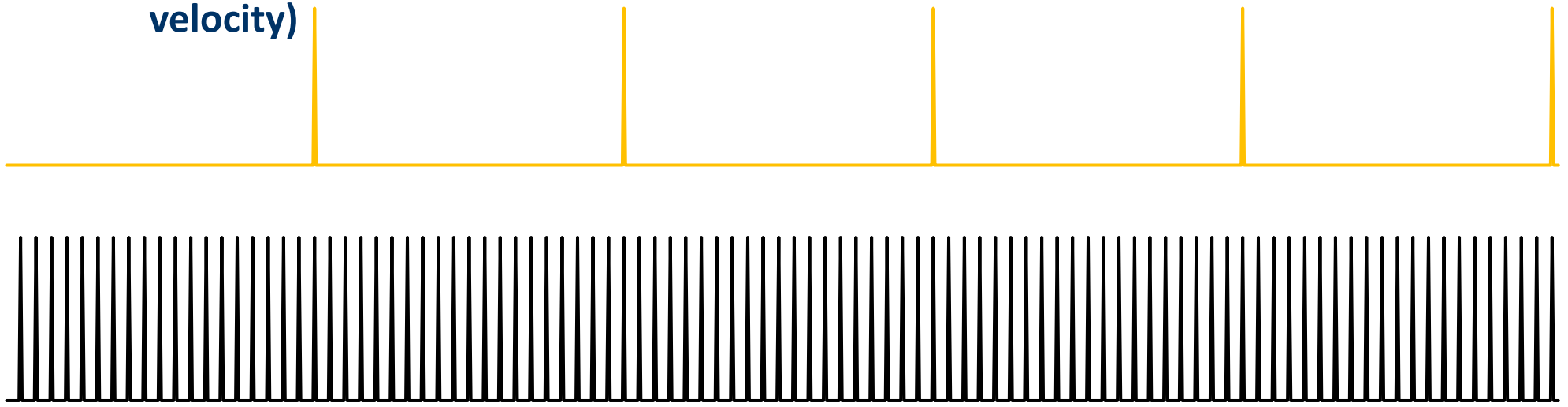




**Vertical alignment required for velocity phase**

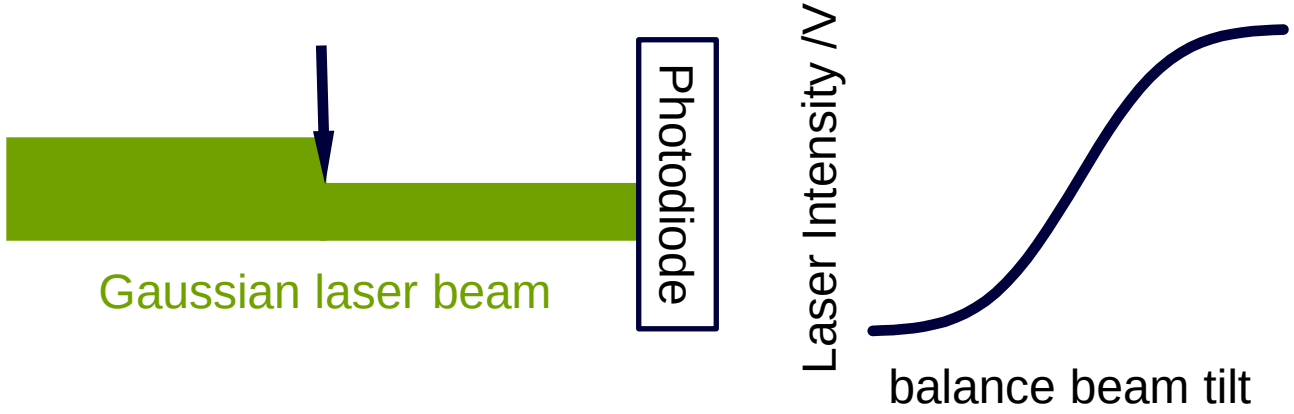
# Synchronization of rotation / translation measurements

- Sensors outputs: voltage
- Voltage sampling with acquisition board (DAC).
- Hardware trigger
  - Software average
  - Synchronization limited by sampling frequency of the DAC.
  - 0.1 ms achievable : sufficient for correlation with the main quantities (i.e. voltage and velocity)



# Measuring the beam inclination (for control purpose)

- **Balance beam used as force comparator only (weighing phase):**
  - Measurement range: 1 mrad
  - Resolution: < 100 nrad
  - Shadow detector, autocollimator




- **Balance beam used as force comparator and motion control:**
  - Measurement range: 150 mrad
  - Resolution: < 100 nrad
  - Optical interferometer

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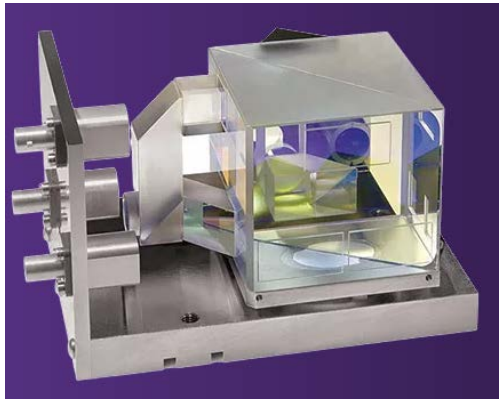
# Measuring the vertical motion of the coil

- Accuracy: $10^{-9}$ (relative) level
- Measurement range: 100 mm
- Measurement resolution: 1 pm
- ➢ High accuracy optical interferometer
  - ➢ Homodyne Michelson interferometer
  - ➢ Heterodyne Michelson interferometer

# Commercial interferometers

- Various operation modes  (homodyne, heterodyne, frequency modulated, Fabry-Perot…)
- Resolution down to 1 pm
- High sample rate
- Low non-linearity available (depending on the system)
- Limited accuracy (laser frequency stab, non-linearity…)



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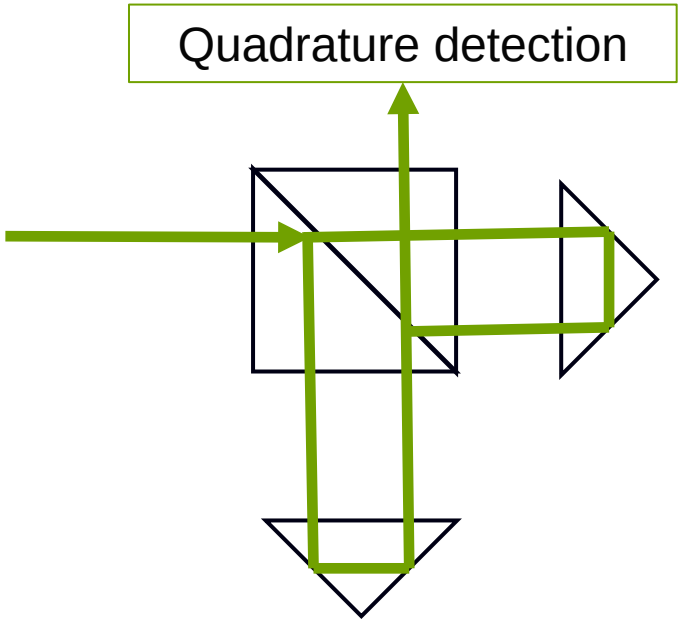
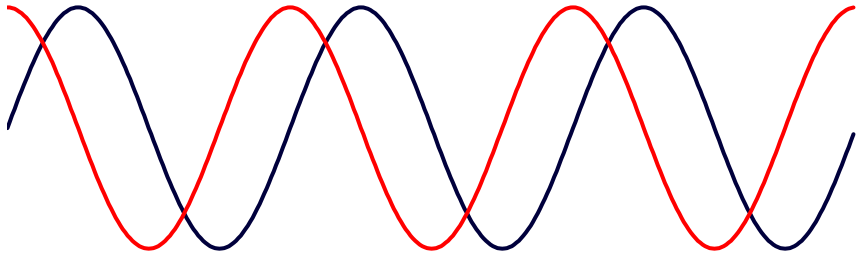
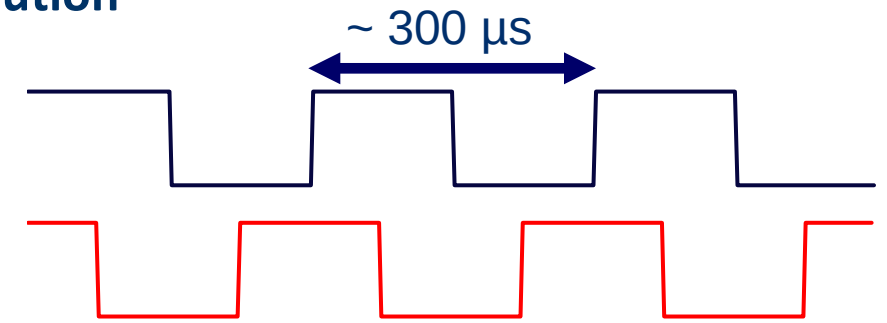
SIOS Meßtechnik GmbH

# Homodyne interferometer

- Based on frequency stabilized laser
- Simple and compact
- Quadrature detection required
- Measured frequency : 0 Hz to 5 kHz
- Phase measurement:
  - integer fringe number only, due to non-linearity
  - Time stamp requirement : 2 Channels / ~ ns resolution





# Homodyne interferometer

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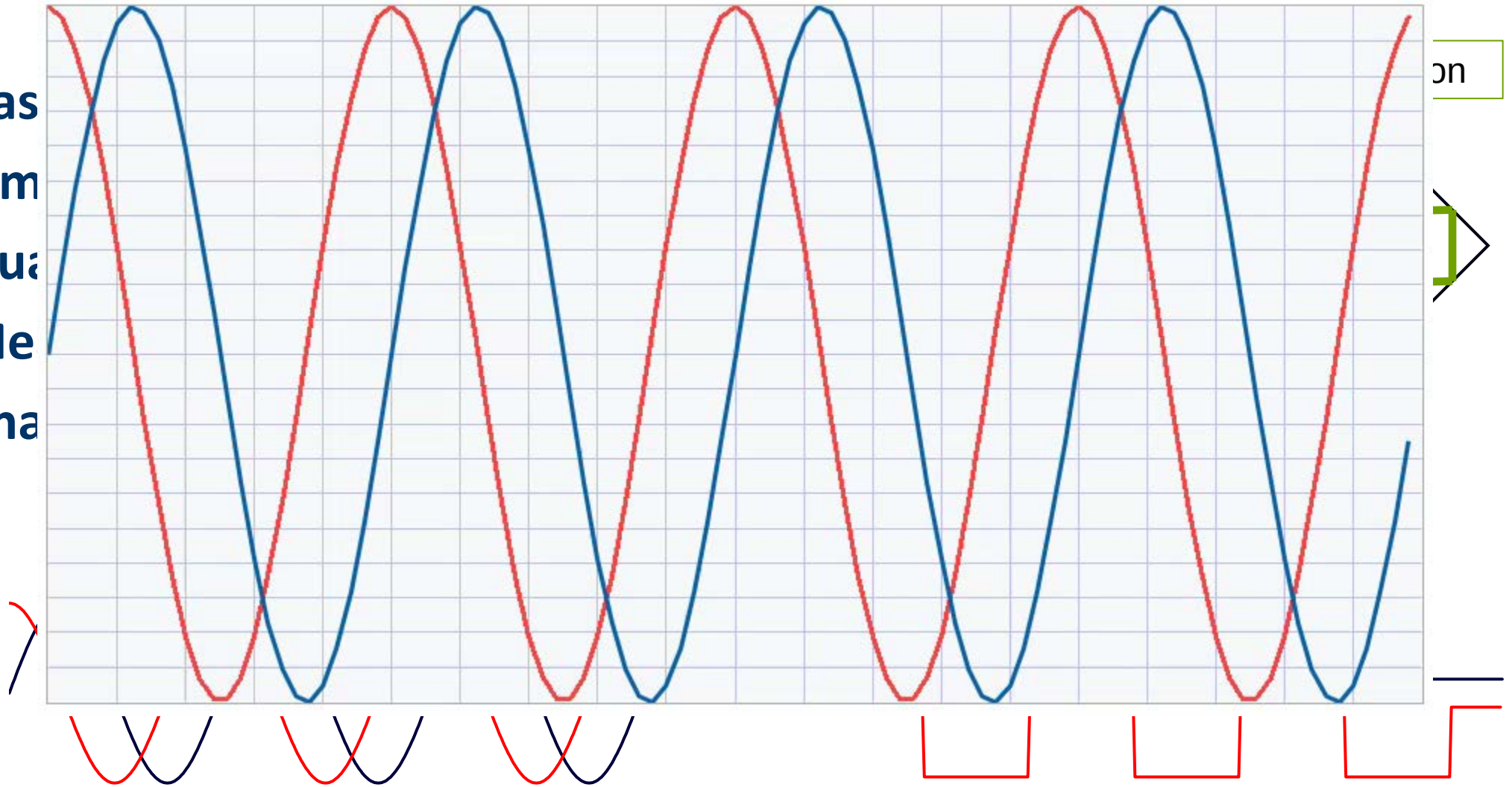
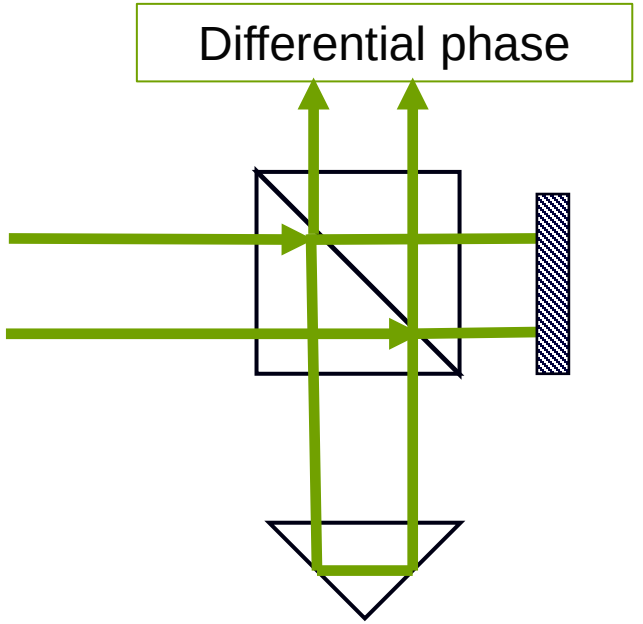
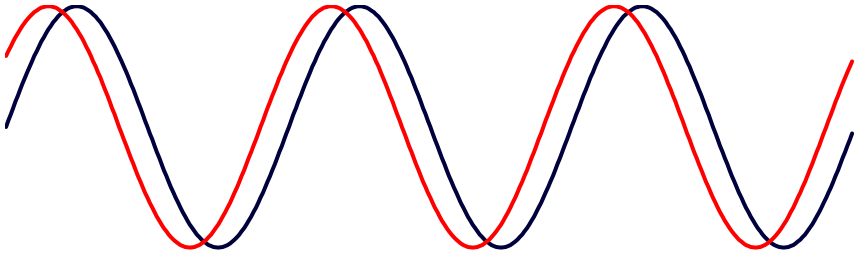
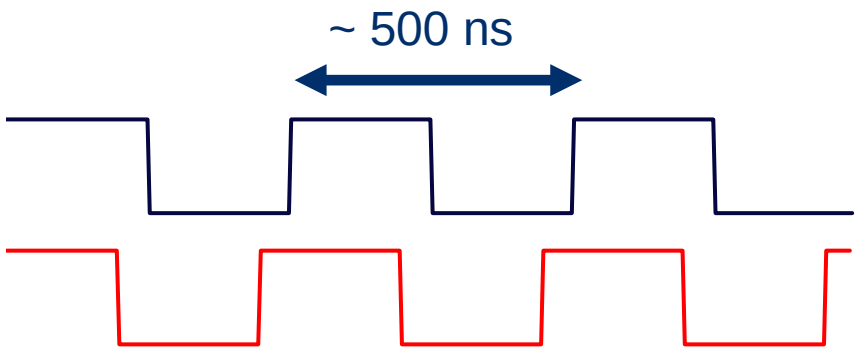


# Heterodyne interferometer

- Based on frequency stabilized laser
- Double input beam for non-linearity suppression
- Measured frequency : about 2 MHz ($\nu_{het}$)
- Phase measurement:
  - Continuous
  - Sampling rate $\nu_{het}$
  - Optical phase equal to the phase difference between the two outputs
  - Time stamp requirement : 2 Channels / ~ ps resolution





# Heterodyne interferometer

- Bas
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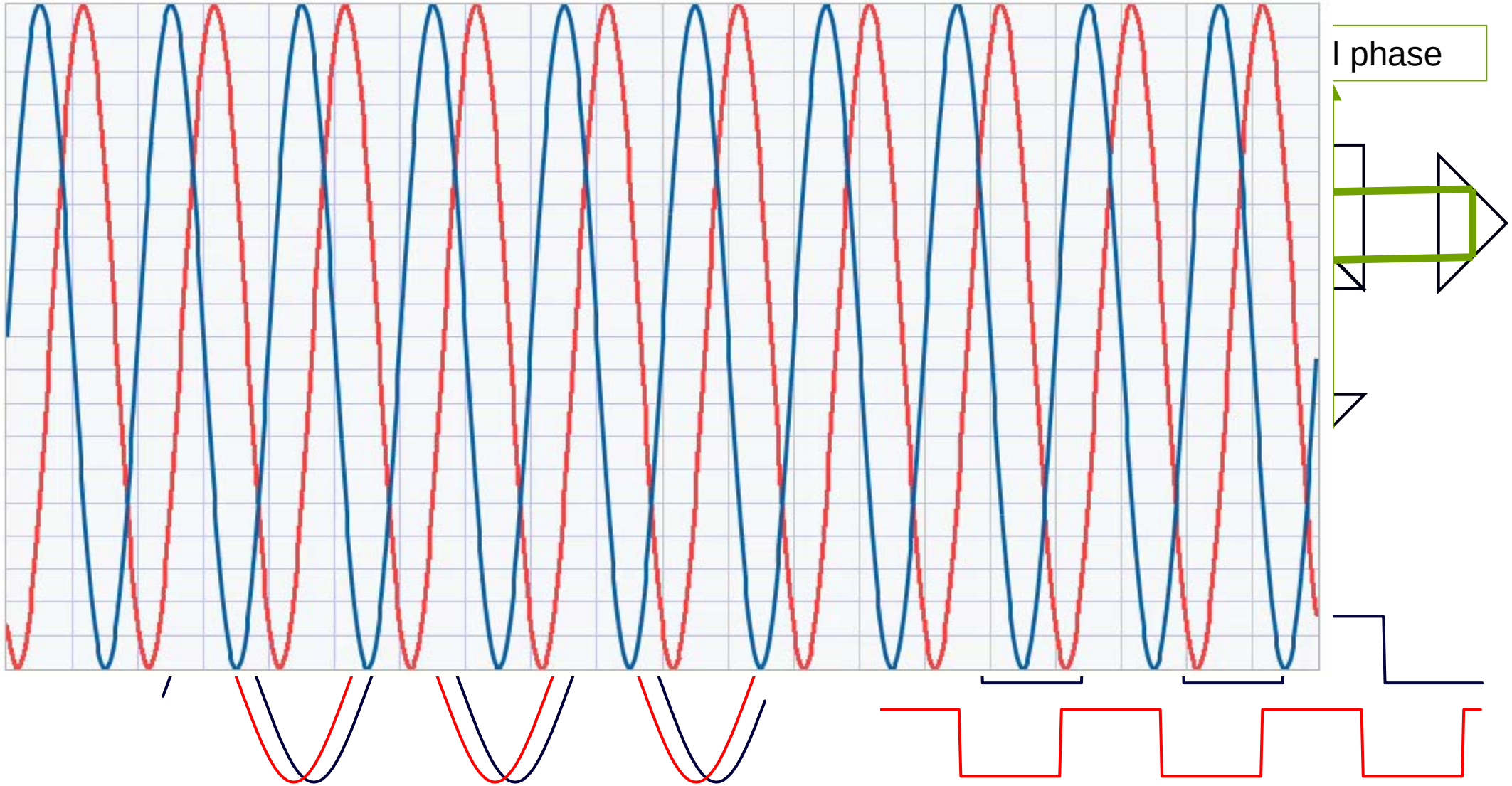
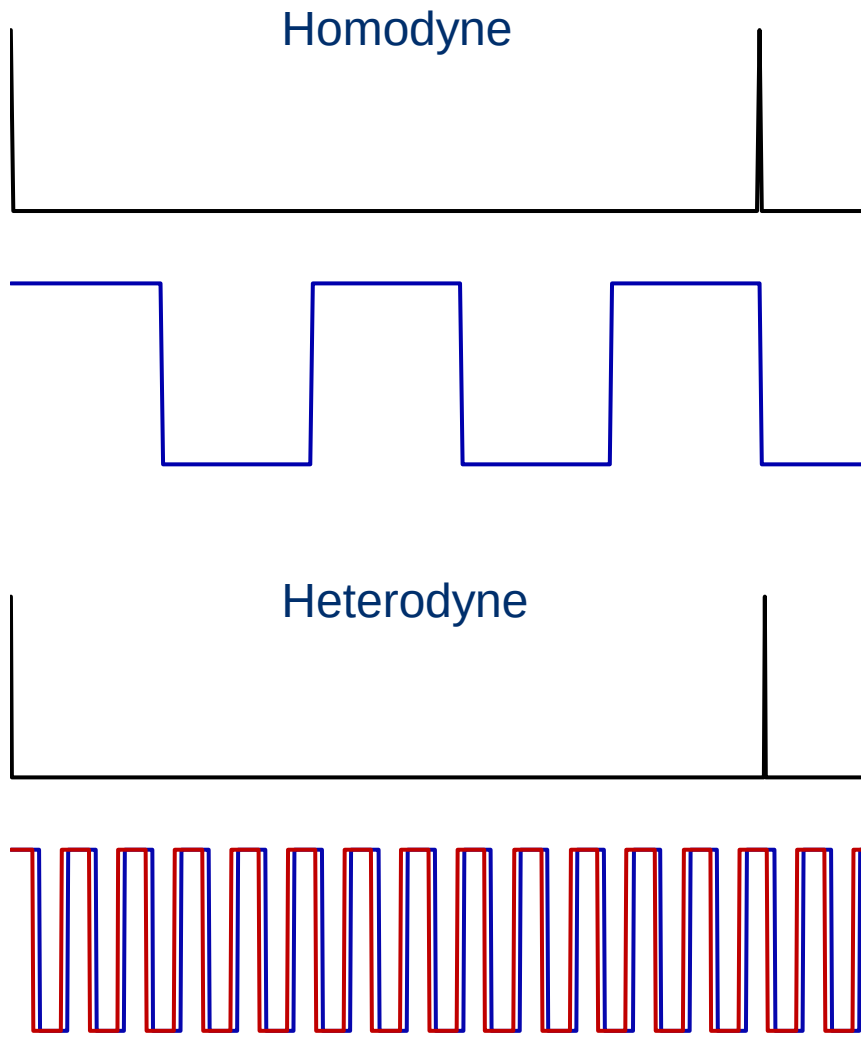


# Homemade Interferometer For velocity phase

- **Accuracy of the laser frequency**
  - **Requires the use of a well stabilized frequency laser**
  - **Usually, HeNe or Nd:YAG stabilized on $I_2$ transitions**
- **Control of the non-linearity**
  - **Interferometers usually affected by non-linearity**
  - **Several options to overpass the non-linearity**
    - Homodyne interferometry: measurement of integer fringe number only
    - Heterodyne interferometry: use of specific scheme with two inputs to reduce the non-linearity
- **Choice between interferometers types**
  - **Homodyne interferometers: simple, large signal period**
  - **Heterodyne interferometers: more complex (phase resolution), short signal period**
  - **Synchronization requirements**

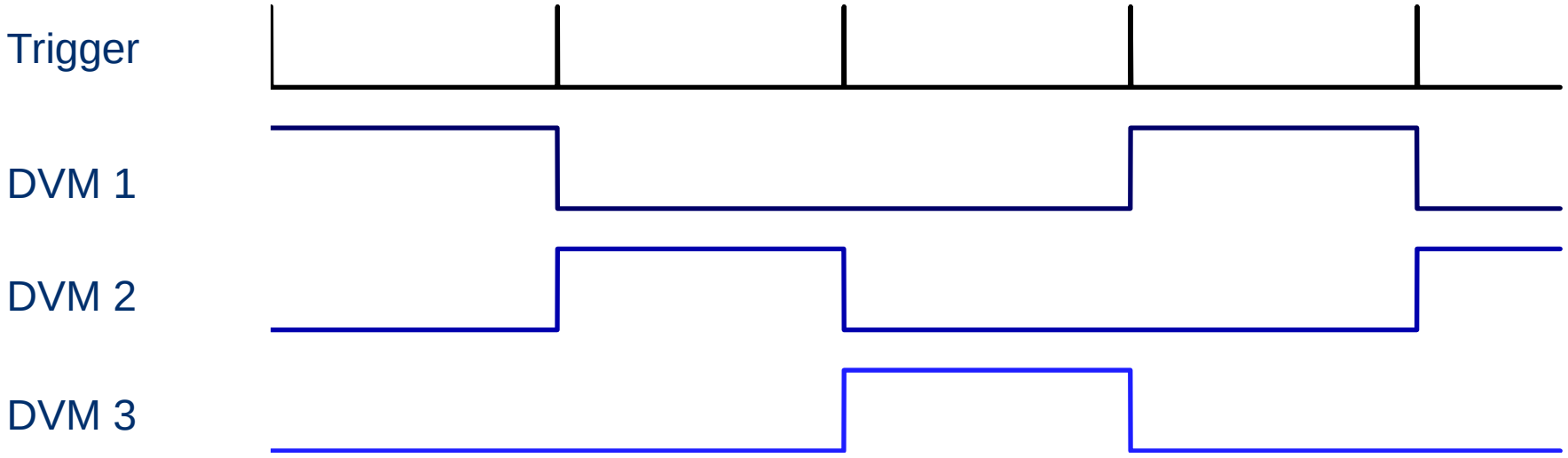
# Voltage / Velocity(ies) Synchronization

- **Synchronization**
  - **< µs: Distinction between Arming / Synchronization**
  - **Depends on the operation of the measuring system**
  - **Delay between arming and measuring: ~ signal period**
    **Depends on the jitter**
- **Homodyne Interferometer**
  - **Homodyne frequency lower than 5 kHz**
  - **Hundreds of µs level synchronization**
- **Heterodyne Interferometer**
  - **Heterodyne frequency greater than 1 MHz**
  - **Sub µs level synchronization**



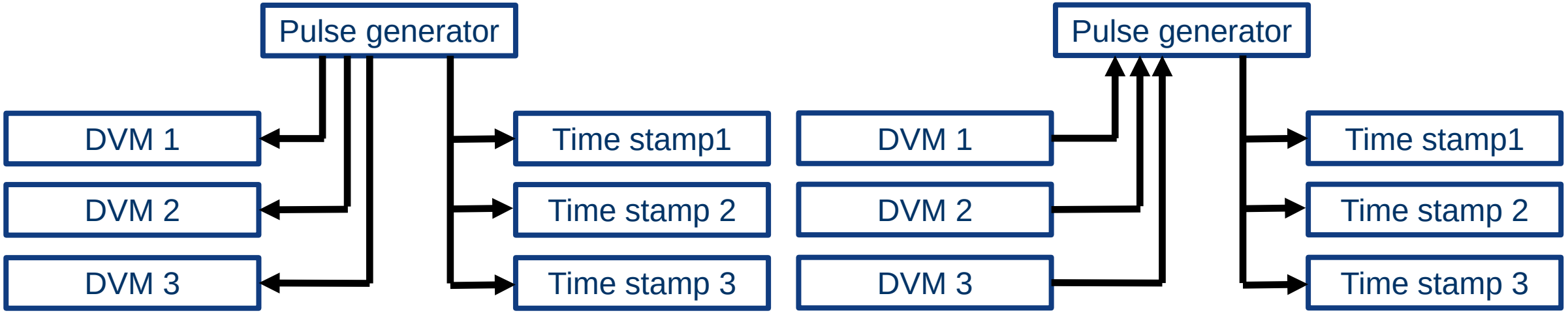
# DVM’s requirements for synchronization

- High resolution / High accuracy
- DVMs with external Arming (Keysight 3458a)
- DVMs associated for continuous measurement



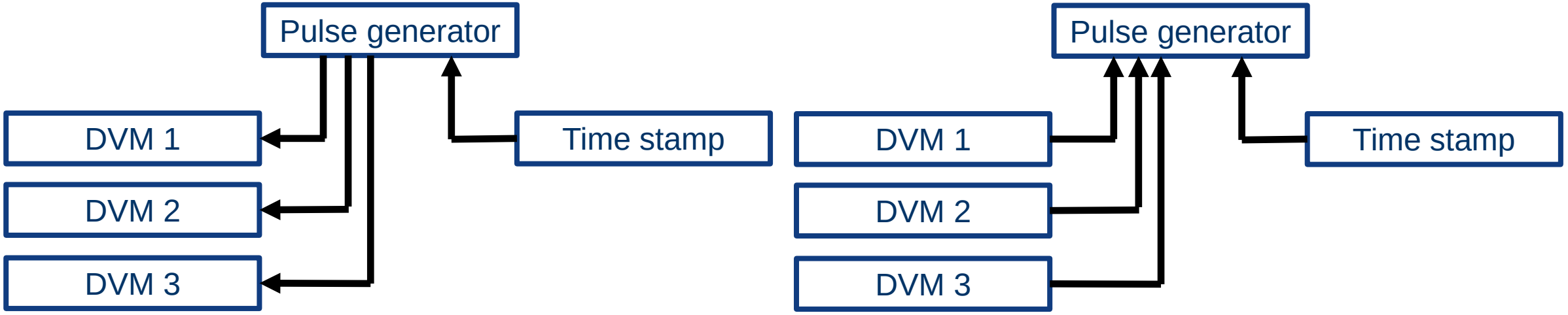
# Synchronization scheme with heterodyne interferometers

- Measured frequency allows µs synchronization
- Interferometric measurement externally triggered
- Use of multiple interferometers

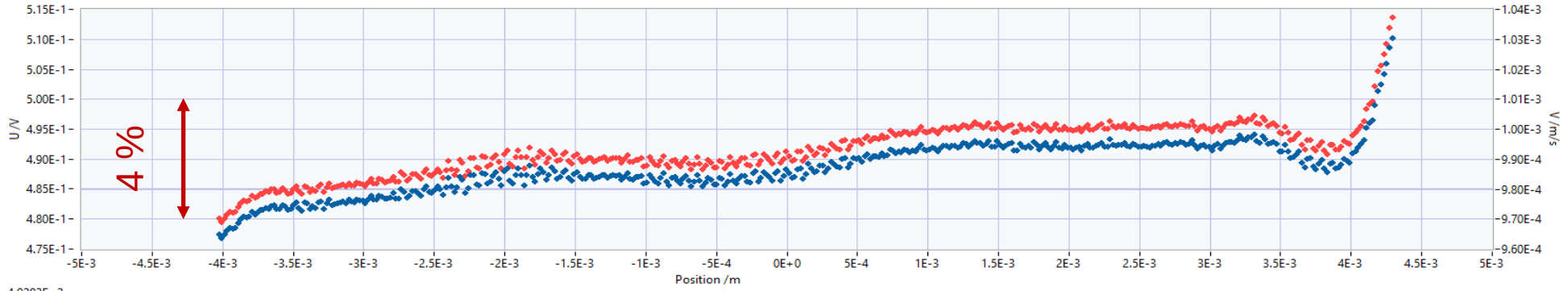


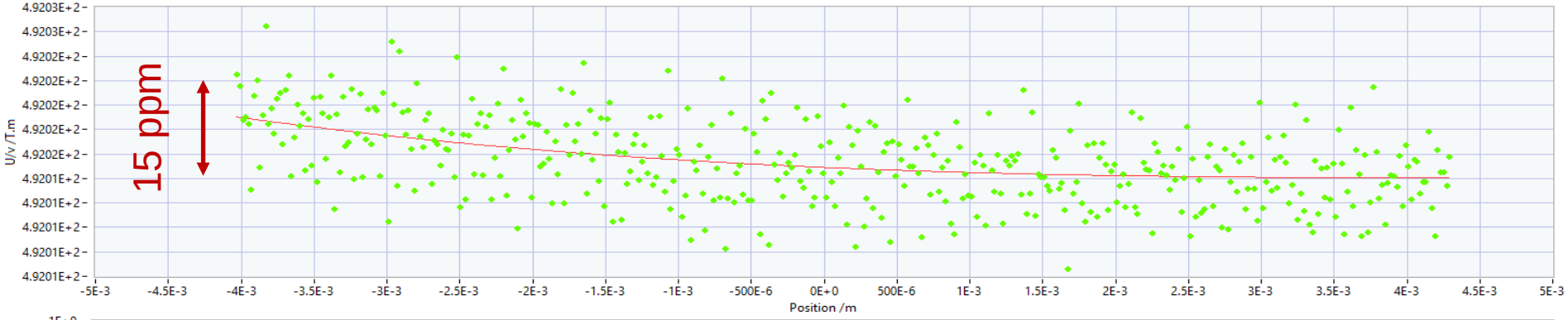
# Synchronization scheme with homodyne interferometers

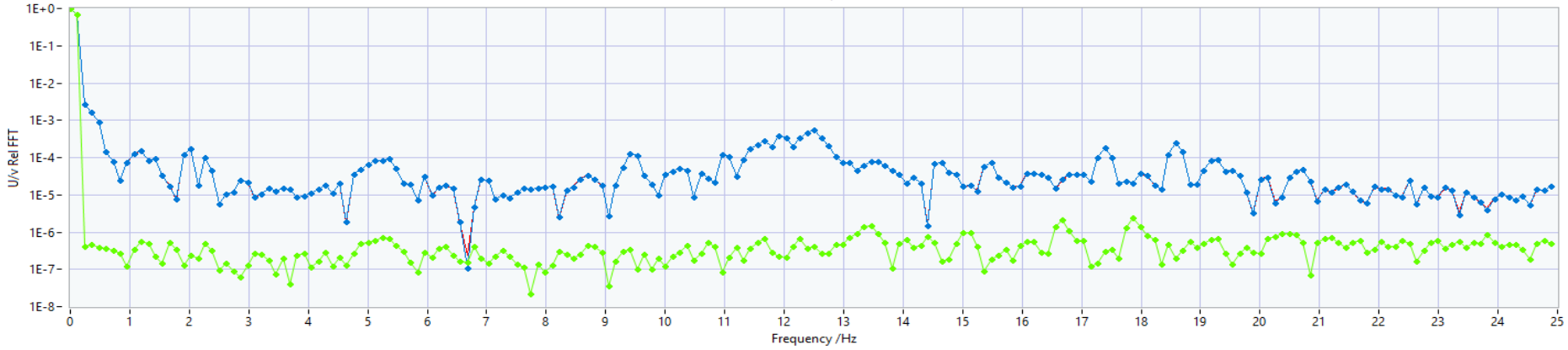
- Measured frequency not compatible with µs level synchronization
- Requirement for high stability of velocity
- Use of interpolation
- Interferometric signal used as master clock for trigger
- Only compatible with single interferometer



# Measurement example: velocity phase



# Summary

- **Monitoring the coil position:**
  - Typical requirement in resolution: µm, µrad
  - Typical requirement in synchronization capability: ms
  - Commercial devices (position sensors / autocollimators) available
- **Velocity measurement:**
  - High accuracy interferometer required
  - Both homodyne / heterodyne Michelson interferometers options
  - Interferometer choice related to synchronization requirements

# Thank you.

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