# An overview of optical benches for mirror metrology and Coating Thermal Noise (CTN) measurement

Laboratoire d'Annecy de Physique des Particules

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ET France Workshop - 01/04/26

# Birefringence characterization of Sapphire substrates

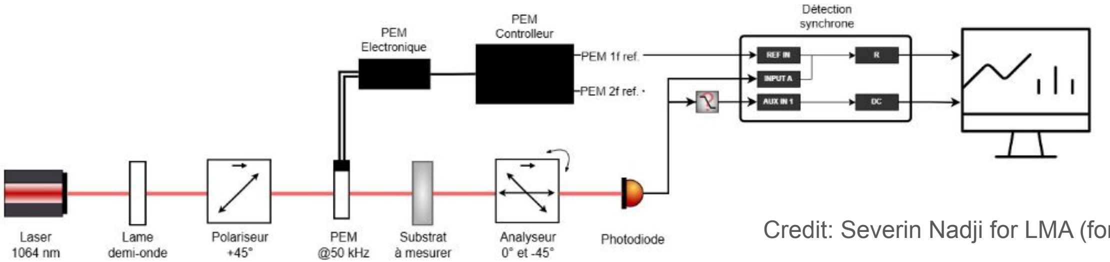
Figure 1: Birefringence bench setup ongoing

Sapphire is a potential candidate for ET but is a **birefringent** material.

➔ Development of a bench to measure birefringence.
  - Adapted to ET sized mirrors.

Principle of operation:

- A **10.5 mW laser** source (1064 nm or 1550 nm) is **polarized** using a Glan-laser calcite polarizer.
- A Photoelastic Modulator (PEM) **modulates the polarization** state of the beam at 50 kHz.
- The **beam** interacts with the **sample** where it experiences a **phase delay** due to **birefringence**.
- A second polarizer converts the **phase delay** to an **intensity modulation**.
- A lock-in **amplifier** detects this modulation to **isolate the signal** at the PEM modulation frequency.
- Measure **retardation magnitude** (Δn x d) and **fast-axis orientation** (ρ).




Credit: Severin Nadji for LMA (for ET Core Optics meeting in March 2026)

# Study micro-scale absorbing defects of mirror coatings

Detect and characterize point absorbers in mirror coatings.

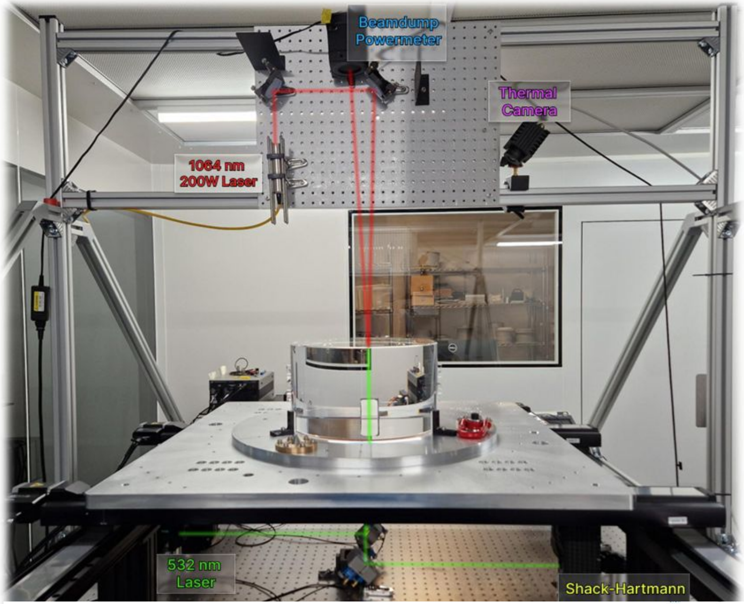
➔ Shared bench with the birefringence measurement (see previous slide).

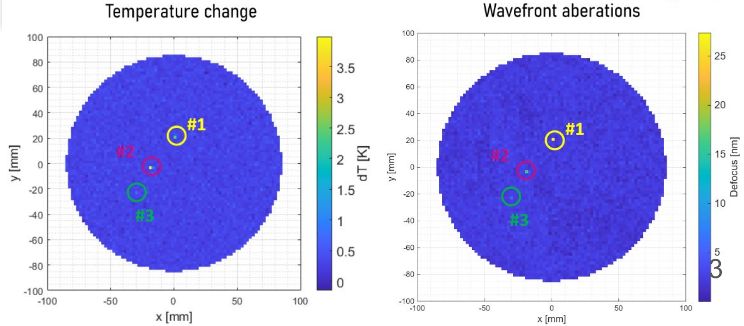
Principle of operation:

- A **200 W laser** (1064 nm) is directed towards the **mirror**.
  - Point absorbers create thermal gradients.
- A **1 mW probe laser** (532 nm) **scans** the **mirror** surface.
- A Shack-Hartmann **sensor** captures **distorted wavefronts**.
- Comparison with thermal camera to **identify point absorbers**

➔ First measurements allowed to assess uniform absorptions above 100 ppm and detect point absorbers.

Next measurement: test on two Virgo's IM spare mirrors.




Credit: Maxime Le Jean, Jerôme Degallaix (for LVK meeting in March 2026) - LIGO-G2600516-v3

# Absorption measurement for crystalline coatings

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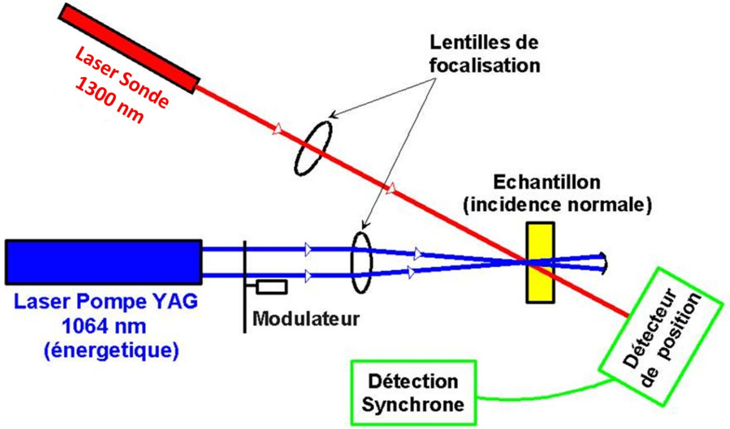
This bench was updated from the previous state of measuring absorption on amorphous samples to be able to measure 200 mm crystalline wafers.

Principle of operation:

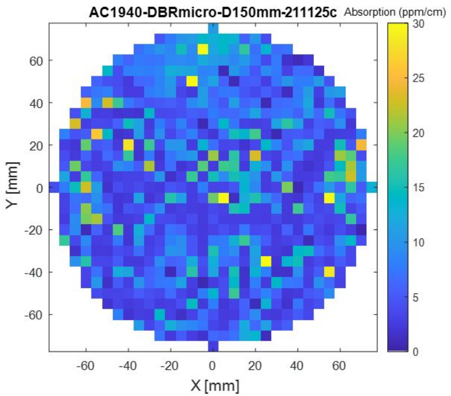
- A **high power laser** (1064 nm) is directed towards the **mirror**.
  - Substrate absorption induces thermal gradients/refractive index gradient.
- A **probe laser** (1300 nm) is pointed at an angle on the **same mirror area**.
  - Wavelength is **transmitted** by the coating.
  - Beam is **deflected** due to the thermal gradient.
- The probe beam’s deflection is detected.




Cartographie Ø150 mm - pas de 5 mm AC1940

Measure AlGaAs 200 mm:

7.4 +/- 7.9 ppm



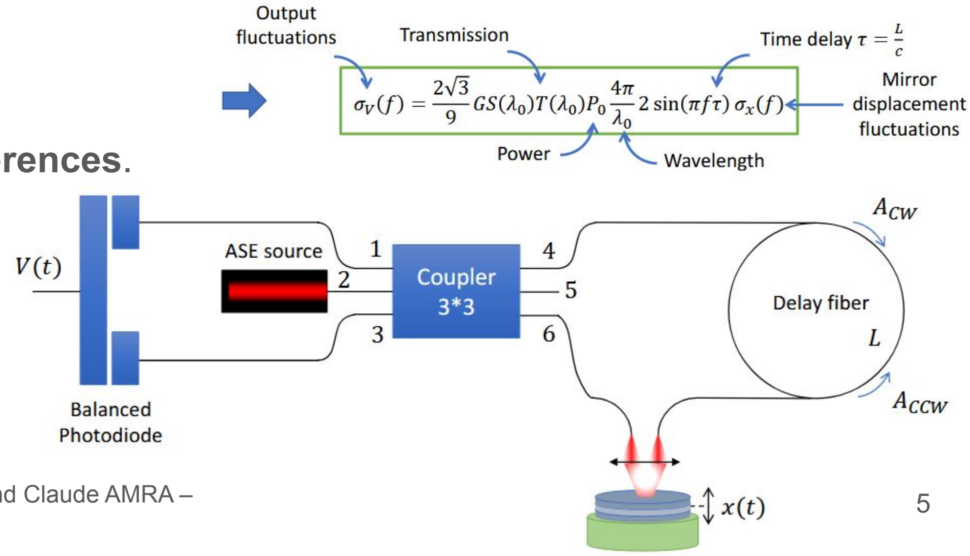

Credit: Laurent Pinard (for MICRONG F2F meeting in January 2026)

# CTN measurement using Cyclic Interferometry

Time-differential measurement of CTN without locking a cavity.

Principle of operation:

- A **laser** (NIR) is injected into a **Sagnac interferometer**.
    - A 3x3 coupler splits it **clockwise (CW)** and **counterclockwise (CCW)**.
- The beam travels through the **delay loop** (L=4 km).
    - A **time delay** is induced.
- Each beam interacts with the mirror.
- The beam **recombines** at the coupler.
    - **Interference** signal sensitive to **phase differences**.
- **CTN** induces **phase difference** between beams.
    - Detected by a balanced photodiode.




Credit: Paul ROUQUETTE, Michael HARTMAN, Myriam ZERRAD, Michel LEQUIME and Claude AMRA – Light scattering group – Virgo Coating Workshop 2025 - VIR-0066A-26

# Development of an optical bench for the measurement of CTN using a resonant cavity

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# Measuring the CTN (MIT) - The cavity

S. Gras and al.
Phys. Rev. D **95**, 022001
Phys. Rev. D **98**, 122001

Massachusetts Institute of Technology

Direct CTN measurement using a laser beam in a Fabry-Pérot cavity.

How to isolate the mirror sample's CTN from the cavity mirrors' CTN?

- Use of a 3-mirrors folded cavity with the sample mirror in the center.
- The effect of the CTN on the beam increases as the beam size on the mirror decreases.
    - A large beam size on the input and output mirrors is required.
    - And a smaller beam size on the mirror sample.

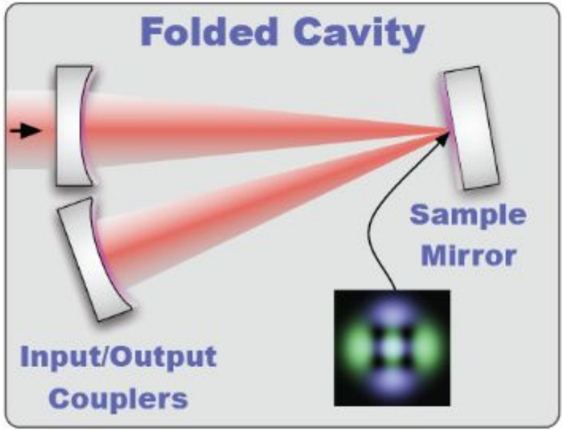



Figure from Phys. Rev. D **95**, 022001

# Measuring the CTN (MIT) - Multimode readout

Massachusetts Institute of Technology

How to isolate the CTN from parasitic noises?

S. Gras and al.
Phys. Rev. D **95**, 022001
Phys. Rev. D **98**, 122001

- Many parasitic noises will dominate over the CTN.
  - The laser frequency and power noise.
  - The cavity length variations (due to vibrations).
- Use of co-resonating transverse modes in the cavity : TEM00 (fundamental), TEM02 et TEM20 (high order modes “**HOM**”).
  - Dominant parasitic noises common to each modes.
  - **HOM** TEM02 and TEM20 scan different areas of the sample.
  - Extraction of the CTN = measuring the frequency difference between the modes 02 and 20.

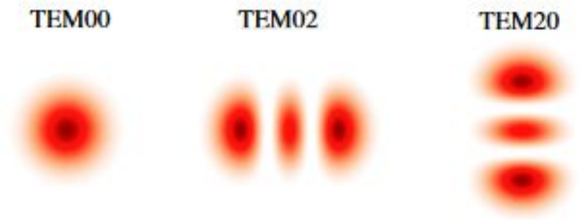
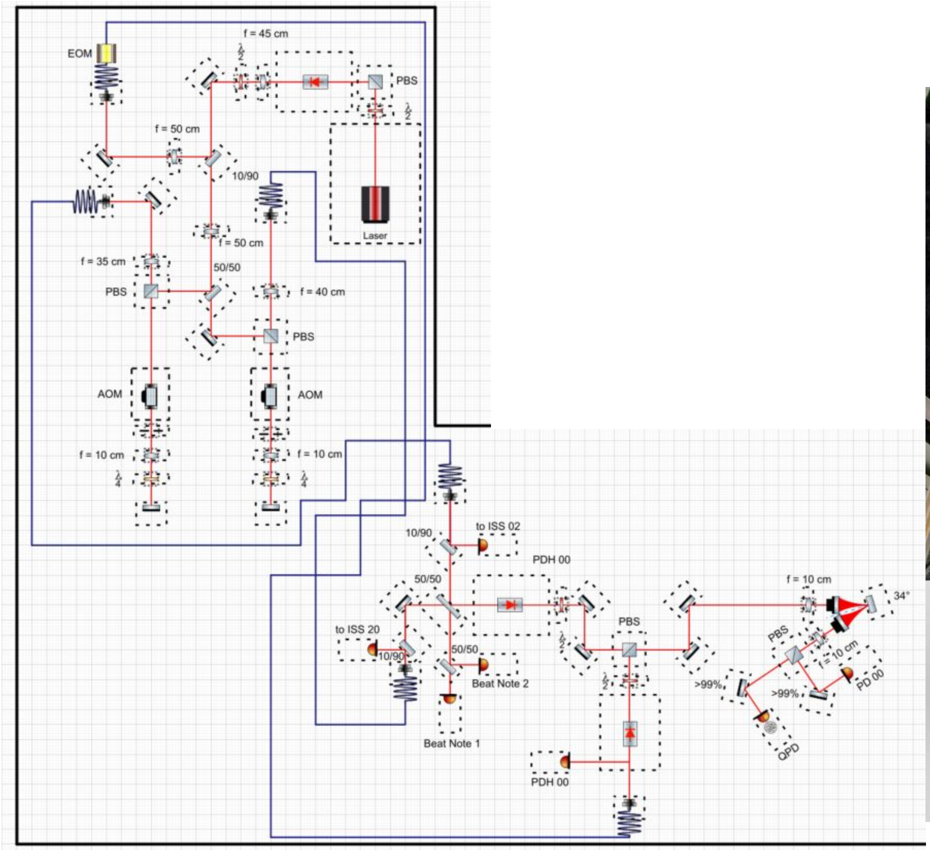
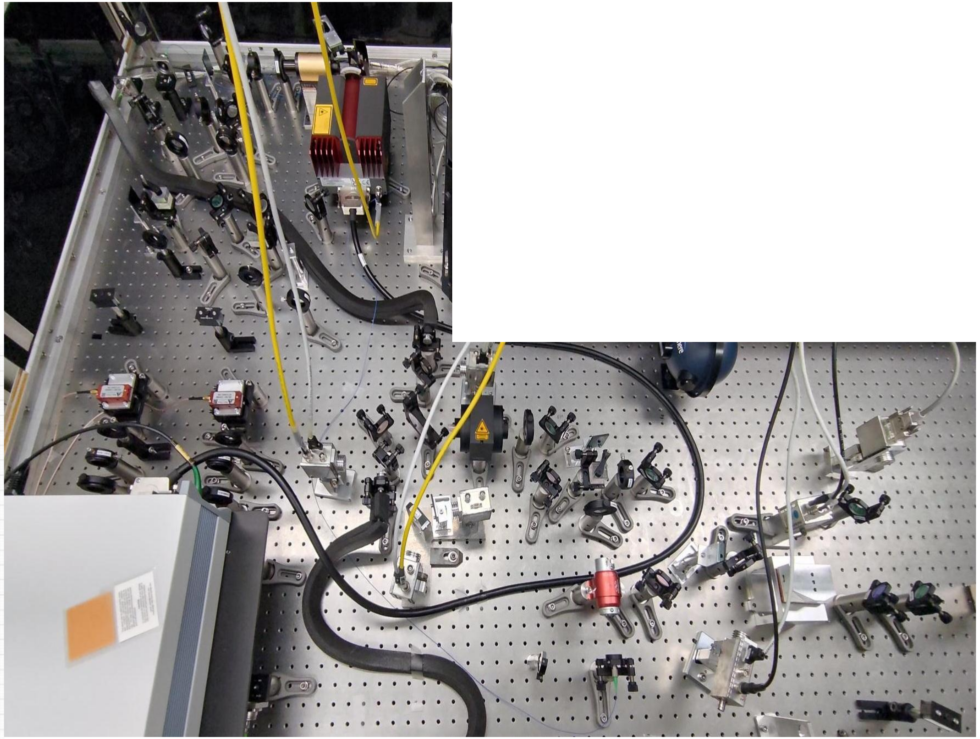



Figure from Phys. Rev. D **95**, 022001

# Optical setup at LAPP for the CTN measurement



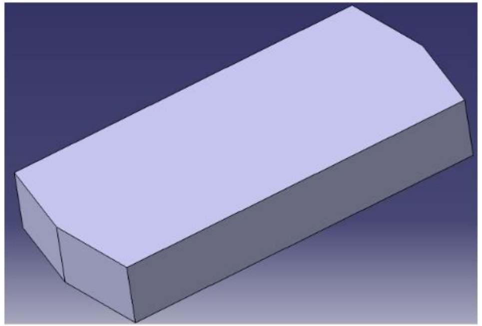



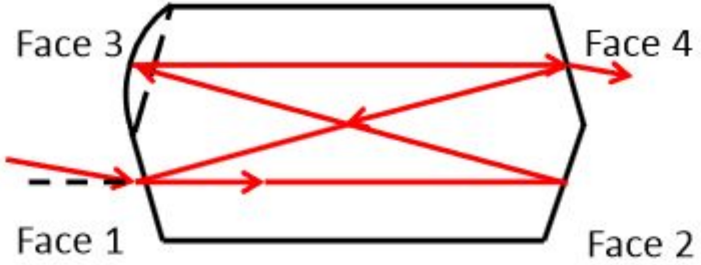
# Study of a test cavity - OMC

We test the setup with a test cavity.

An Output Mode Cleaner (OMC):

- Monolithic silica block.
  - Less sensitive to vibrations than the MIT cavity.
- 4 reflective surfaces = mirrors.
  - We measure the total thermal noise of the cavity (including thermo-refractive noise which is expected to be dominant in this case).



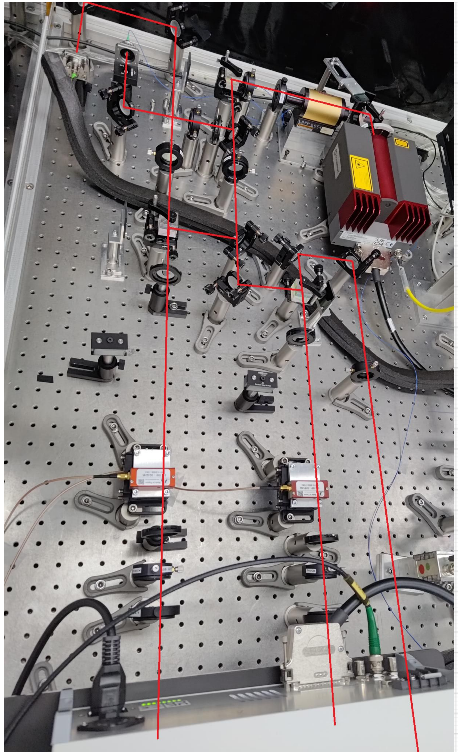



Figures from ⟨tel-01489175v2⟩

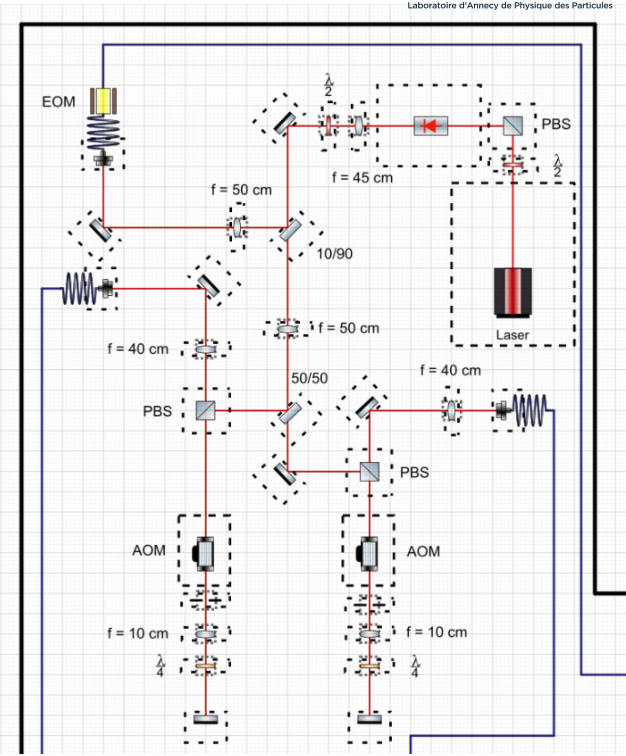
# Generation of the beams
## Pre-fiber part

Laser Nd-YaG (1064 nm) with 1 W of power split in 3 beams:

- Beam 1 (TEM00) phase modulated with fibered Electro-Optic Modulator (EOM) at 18.75 MHz.
- Beam 2a (TEM02) frequency shifted using Acousto-Optic modulator (AOM) at 200 MHz.
- Beam 2b (TEM20) frequency shifted using AOM at 208 MHz.
- Each beam is injected in a fiber.



Current state

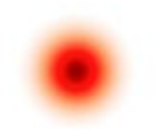



Layout

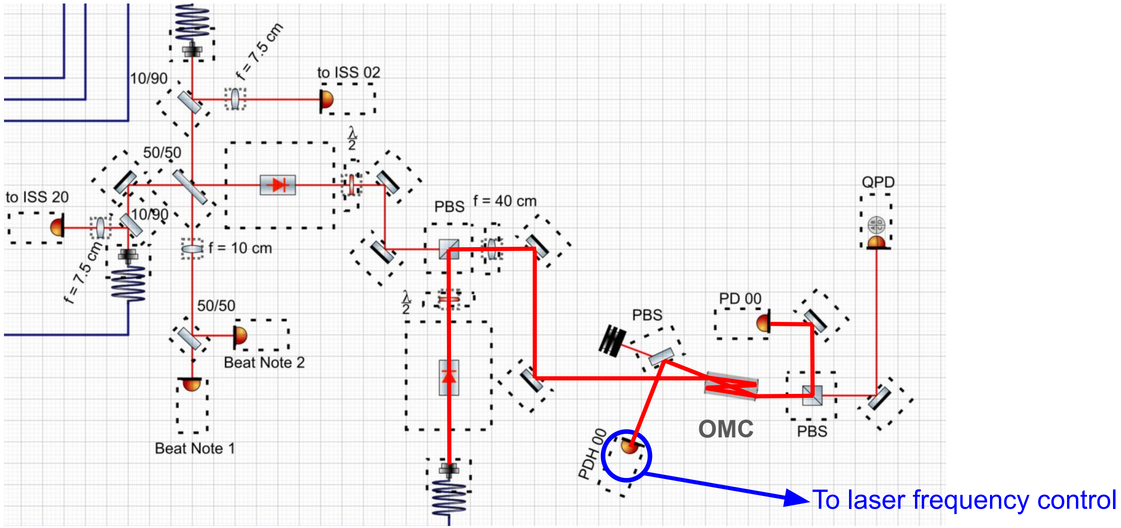
# Lock of the laser frequency to the cavity’s TEM00

## Beam 1

TEM00

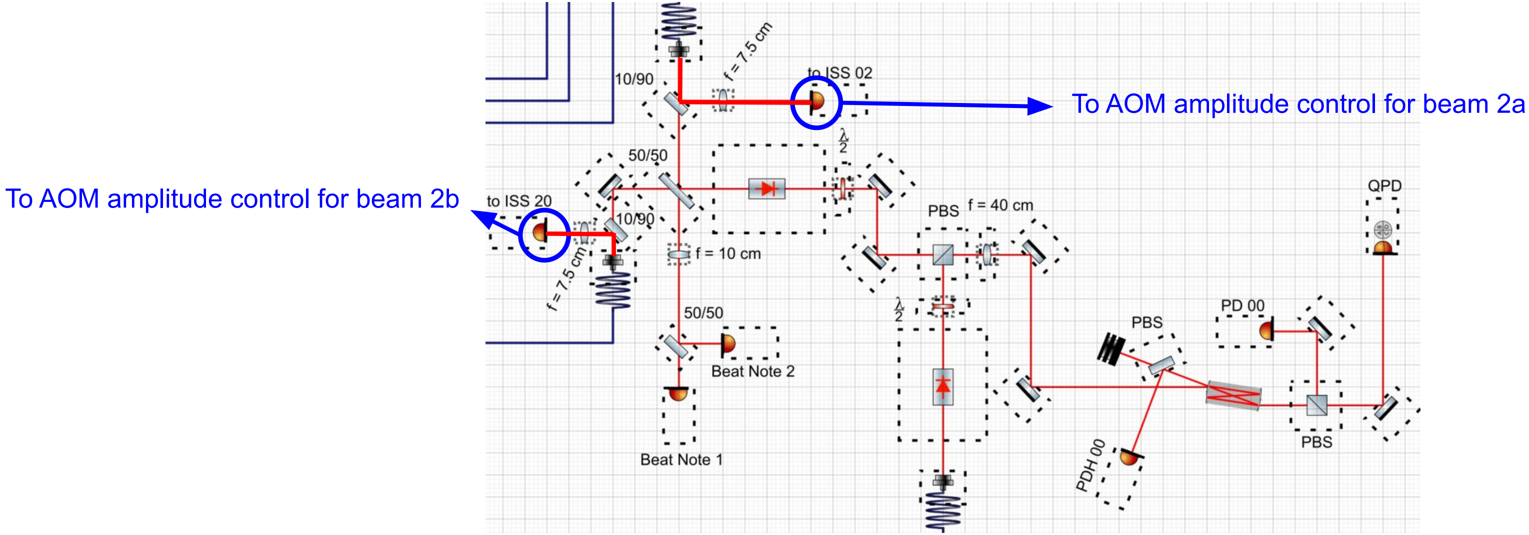


- **Beam 1**, phase modulated at 18.75 MHz, is output from the fiber and injected in the cavity.
- The reflected beam from the cavity is detected by a photodiode.
- Using the Pound-Drever-Hall technique (**PDH**), the demodulated signal is used to lock the laser at the resonant frequency of the **TEM00** of the cavity.
- Control loop implemented digitally (UGF @ 10 kHz).



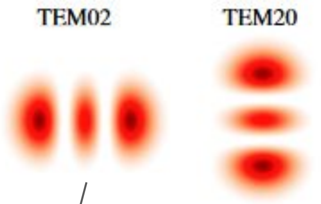
# Intensity stabilization of beams 2a & 2b

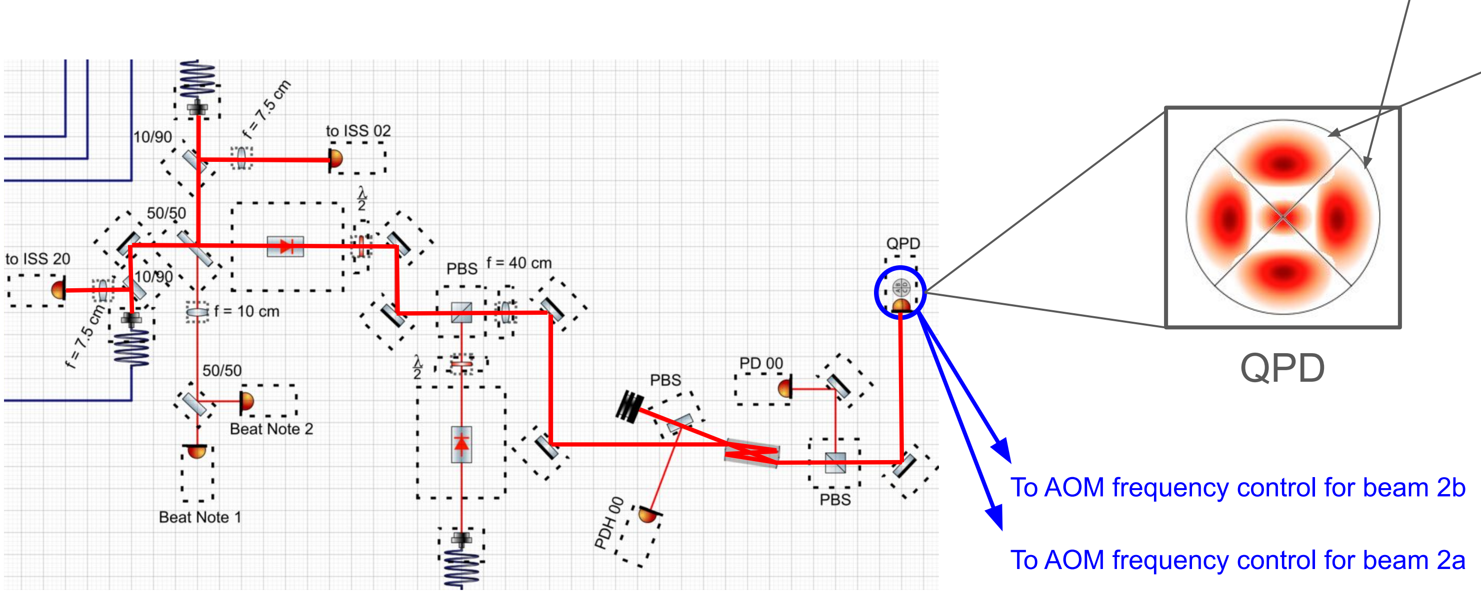
- **Beams 2a & 2b** are output from the fibers.
- For each beam, a fraction of the power is detected by a photodiode.
- The signal is used to stabilize the intensity of the beam by acting on the **AOMs amplitudes**.
- Intensity Stabilization Servo (**ISS**) implemented analogically (UGF @ 40 kHz).



Frequency lock of beams 2a & 2b to the cavity's TEM02/20

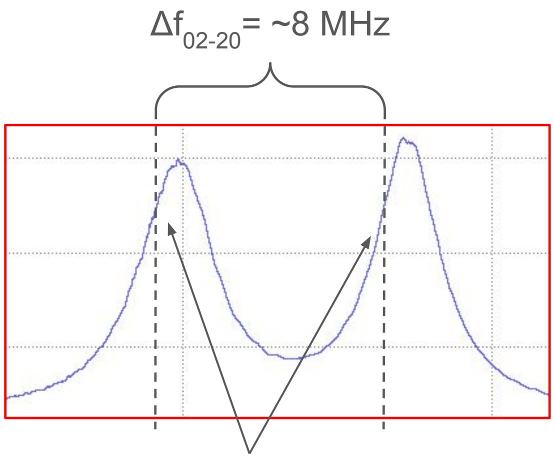
- Using a quadrant photodiode (**QPD**), **2a & 2b beams** are frequency locked to the **TEM02/TEM20** of the cavity by acting on the **AOMs frequencies**.
- Control loop implemented digitally (UGF @ 1.3 kHz).
  - To be implemented analogically to improve the bandwidth.



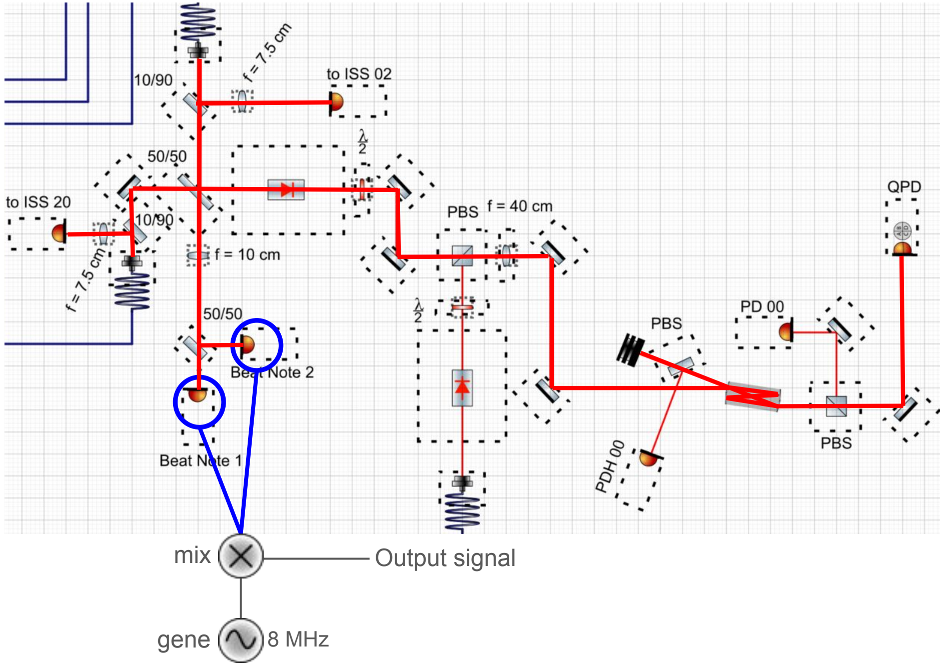



# Measuring the CTN using the Beat Note signal of beams 2a & 2b

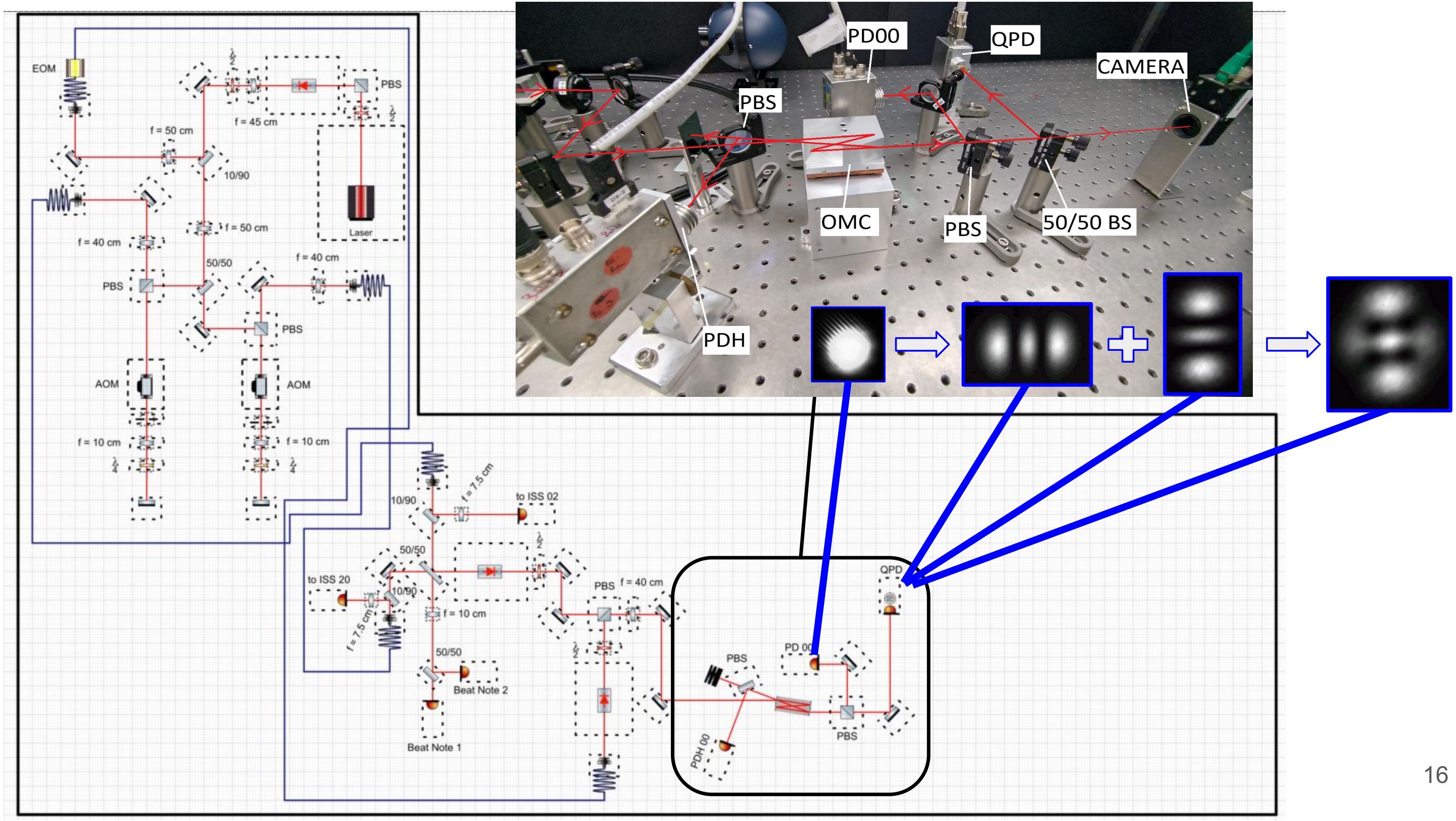
- Beams 2a & 2b interfere on beat note(s) photodiodes.
- The frequency difference between the two beams produce a beat note signal at **~ 8MHz**.
- The **CTN** is extracted by demodulating this signal with an external source at ~8 MHz and measuring frequency fluctuations.




**Lock at 70% of the modes peak = best sensitivity to measure frequency fluctuations**

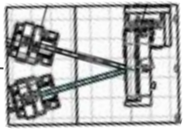


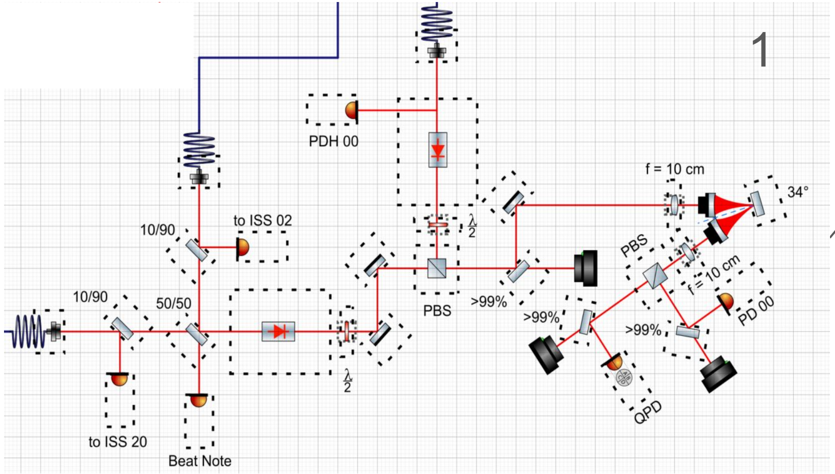
# Current state of the setup at LAPP

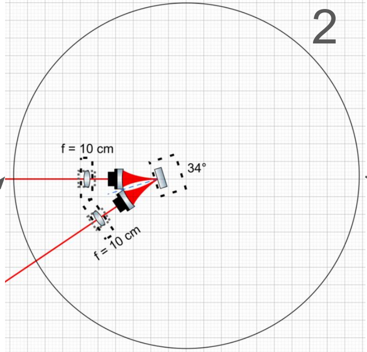


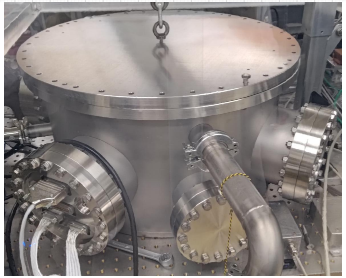
# Goals of the MICRONG experiment at LAPP

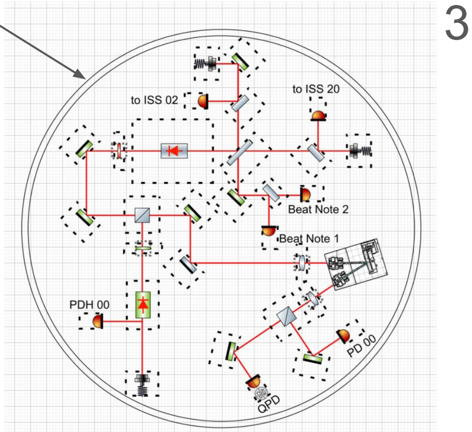
- **In-air** measurement of the OMC.
  - Tested with low finesse OMC (280*) but signal not sensitive enough to measure CTN.
  - **Now** testing with higher finesse OMC (10000*).
- Building a **3 mirror folded cavity** (work in progress).
- Moving under **vacuum** of the **cavity** for more test.
- Moving under **vacuum** the **detection + cavity** part (post-fibers).








* Coated at LMA