Optical calibration of particle detectors

Using light to “see” particles

G. Cantatore - University and INFN Trieste - PBC Tech WG Optics Workshop - CERN, 10/12/21

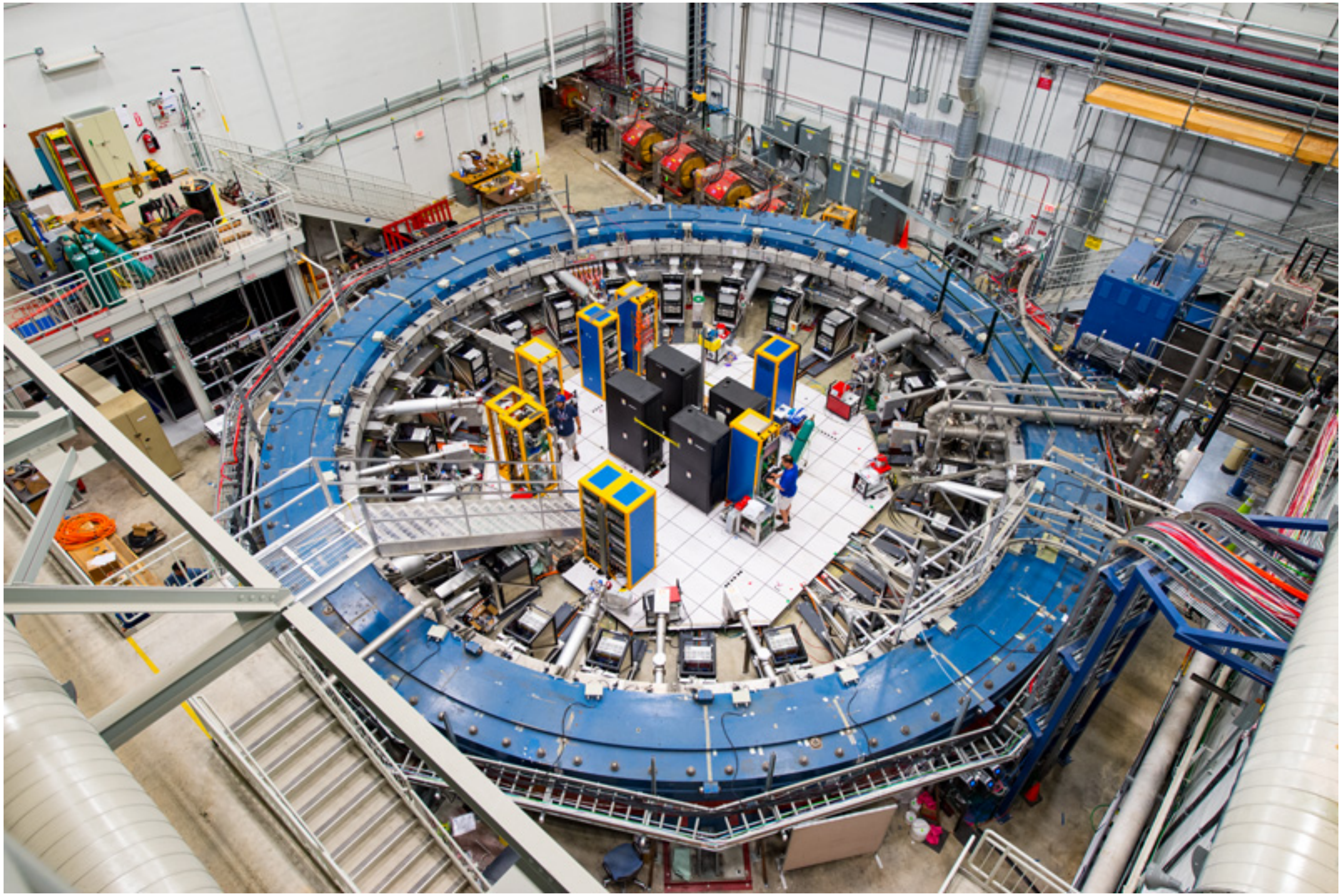
Summary

- VBI
- Laser calibration in Muon G-2
- Optical techniques in the MUonE project
- What we are learning

Introduction

- Using light to "see" particles
  - Optics is becoming a key tool for the task of meeting the ever more stringent requirements of particle detectors
  - High precision measurements are made possible by implementing advanced optical techniques and integrating them in detector systems
- Main areas of interest
  - energy calibration
  - alignment
  - stability monitoring
  - …

Laser calibration in Muon G-2

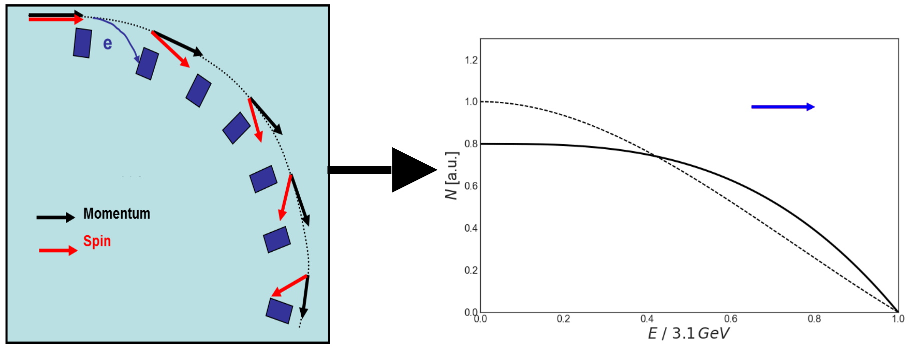


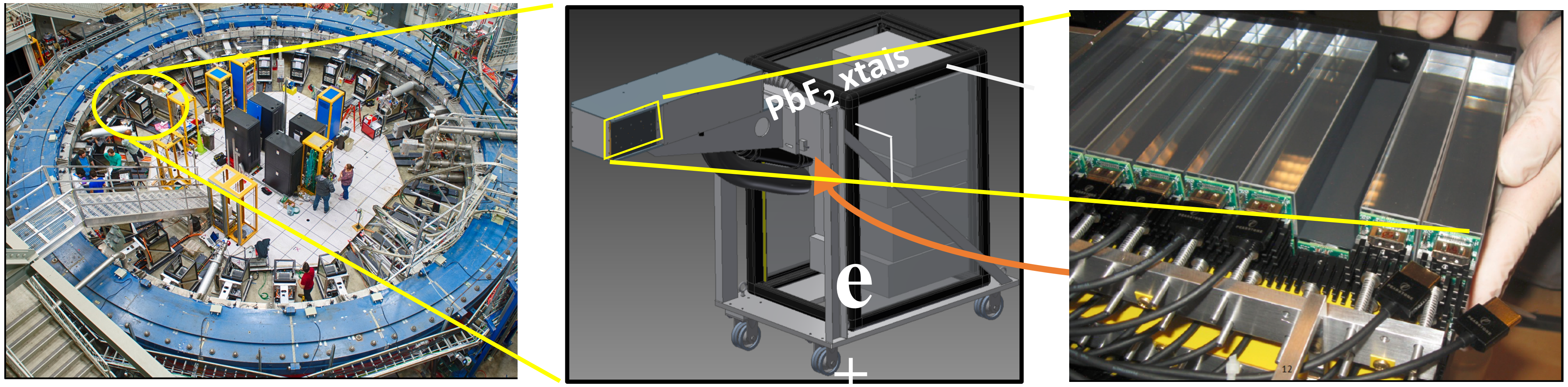
Muon g-2

https://muon-g-2.fnal.gov

Why use a storage ring?

- Parity violation in muon decay → high energy decay positrons are preferentially emitted in the muon spin direction
- Measure the energy spectrum with detectors around the inside of the ring





The laser calibration system

- **The laser calibration system is a key element of Muon g-2, it was practically absent in the previous Brookhaven Lab experiment**

BNL (2001)

Muon g-2 at FNAL

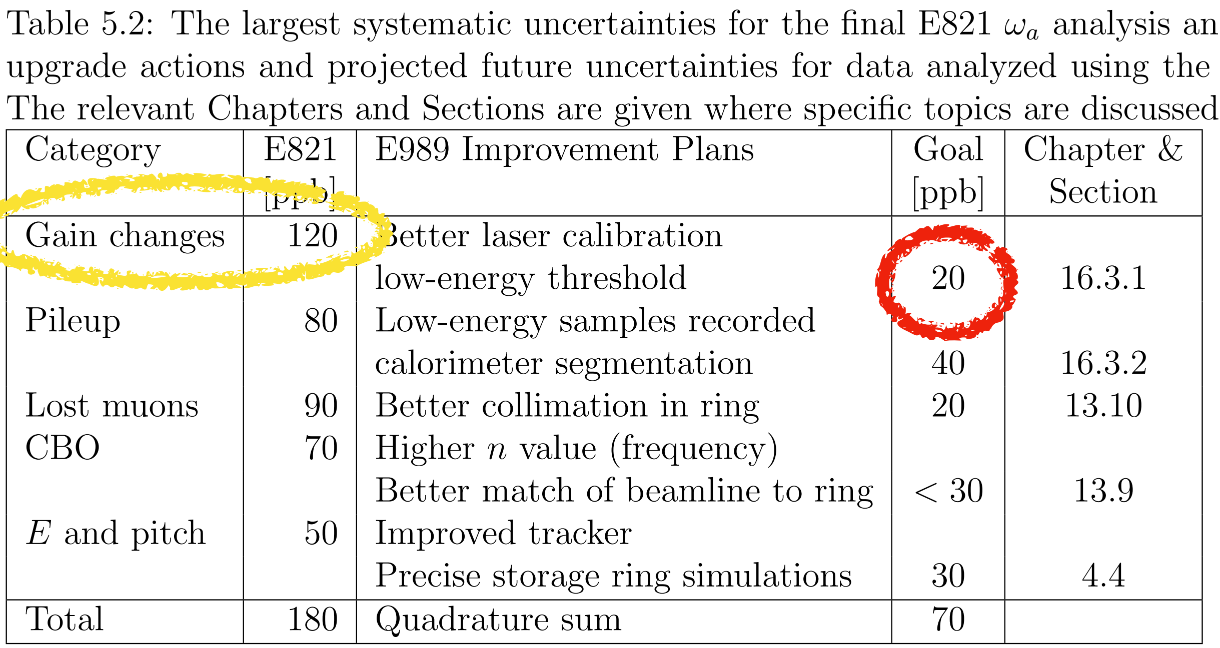


Table 5.2: The largest systematic uncertainties for the final E821 ω_a analysis and proposed upgrade actions and projected future uncertainties for data analyzed using the T method. The relevant Chapters and Sections are given where specific topics are discussed in detail.

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]	Chapter & Section
Gain changes	120	Better laser calibration		
		low-energy threshold	20	16.3.1
Pileup	80	Low-energy samples recorded		
		calorimeter segmentation	40	16.3.2
Lost muons	90	Better collimation in ring	20	13.10
CBO	70	Higher n value (frequency)		
		Better match of beamline to ring	< 30	13.9
E and pitch	50	Improved tracker		
		Precise storage ring simulations	30	4.4
Total	180	Quadrature sum	70	

from Muon g-2 “TDR”

- **Simple working principles:**
  - **a “source monitor” employing a ^{241}Am source as reference gives the absolute calibration of laser pulse amplitudes**
  - **laser pulses are distributed to the calorimeter crystals through a fibre optic network monitored by “local monitor”**
  - **laser pulses illuminate the calorimeter crystals through a “diffuser”, and several pulse sequences are used in order to obtain the gain corrections to be applied to the SiPMs**

Credits for the laser system
Italian collaboration in Muon G-2: INFN Frascati, Napoli, Pisa, Roma 2, Trieste-Udine and INO Pisa

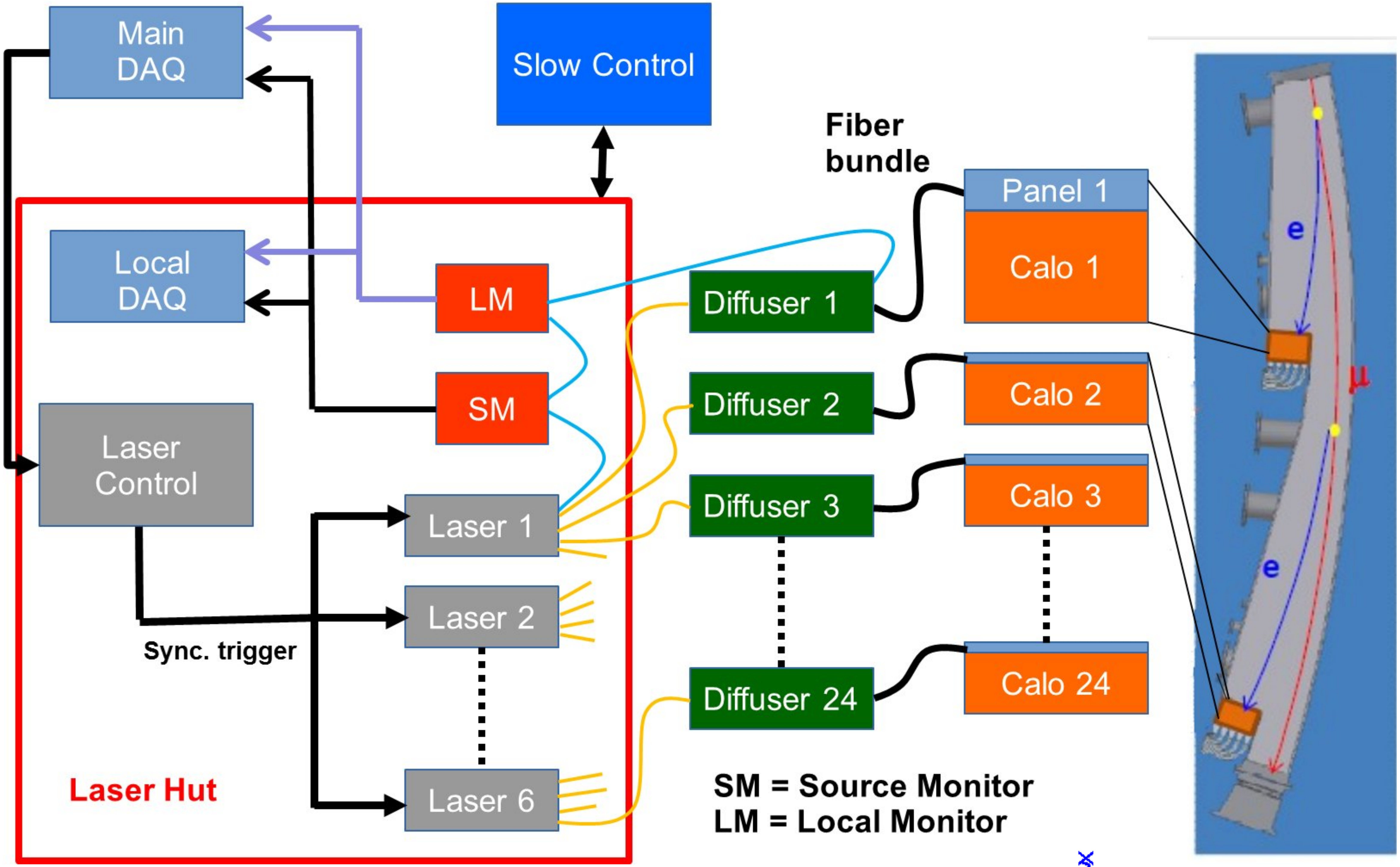
Main requirements and solutions

- **Main requirements for the laser system**
  - **monitoring and calibration of the calorimeters at the 0,04% level on the time scale of a single muon “fill” (700 μs)**
  - **detector gain correction and monitoring at a level <10^{-3} over several hours of running**
  - **synchronization of calorimeters, integral beam counter (“T0 counter”) and beam position monitors (“Fiber Harps”)**
- **Adopted solutions**
  - **laser pulses sent simultaneously to all 54x24=1296 calorimeter crystals**
  - **pulses distributed over a multimode optical fiber network**
  - **continuous monitoring of both pulses and fiber network**
  - **custom timing and control electronics**

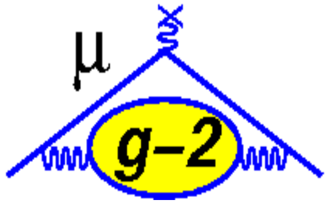
Subsystems

- **Laser heads**
  - generate triggerable 405 nm laser light pulses
- **Diffusers**
  - uniformly distribute light intensity on every single calorimeter crystal
- **Source Monitor (SM)**
  - corrects amplitude fluctuations by comparing the amplitude of the laser pulses with a reference signal generated by a radioactive source
- **Local Monitor (LM)**
  - monitors the stability of the light distribution system using a reference from the SM
- **Custom electronics**
  - interfaces with the beam triggers to control laser pulse generation
  - acquires and stores locally the laser system signals

Laser calibration system layout

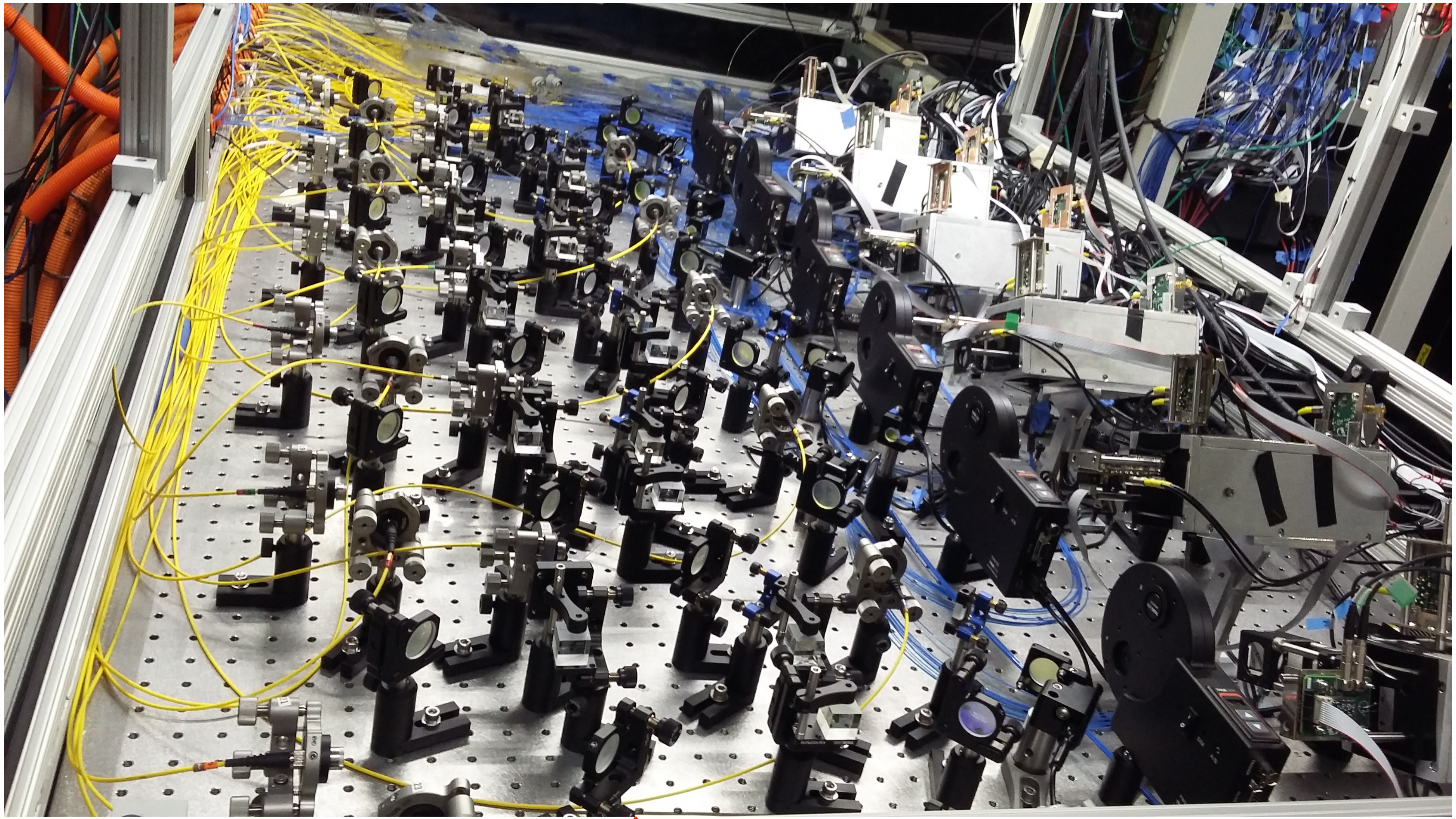


SM = Source Monitor
LM = Local Monitor

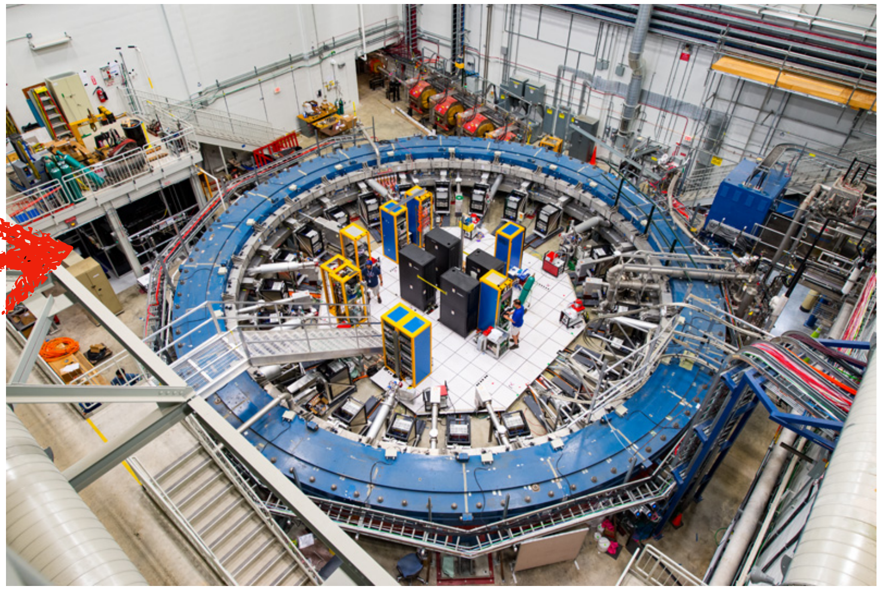


Muon g-2

Optical bench and “Laser Hut”



Optical bench



“Laser Hut”

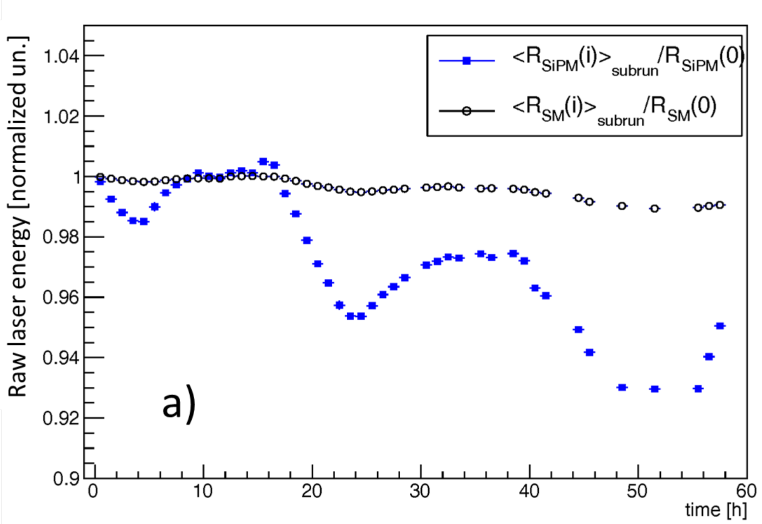
Gain correction example

- **The main cause of gain drifts over long time scales (~seconds) is temperature effects**
- **Correction factor:**

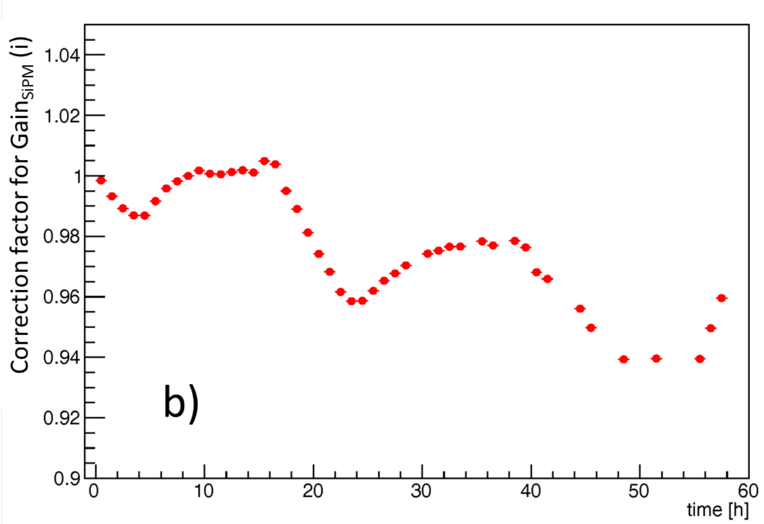
$$G_{\mathrm{SiPM}}(i) = \frac{\langle R_{\mathrm{SiPM}}(i)\rangle_{\mathrm{subrun}}}{R_{\mathrm{SiPM}}(0)} \cdot \frac{R_{\mathrm{SM}}(0)}{\langle R_{\mathrm{SM}}(i)\rangle_{\mathrm{subrun}}}$$

1 subrun = 5 s

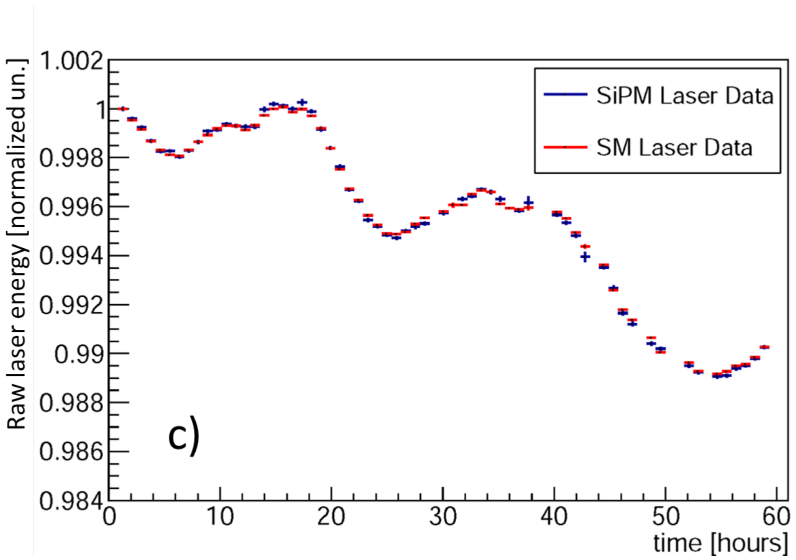
Correction factors



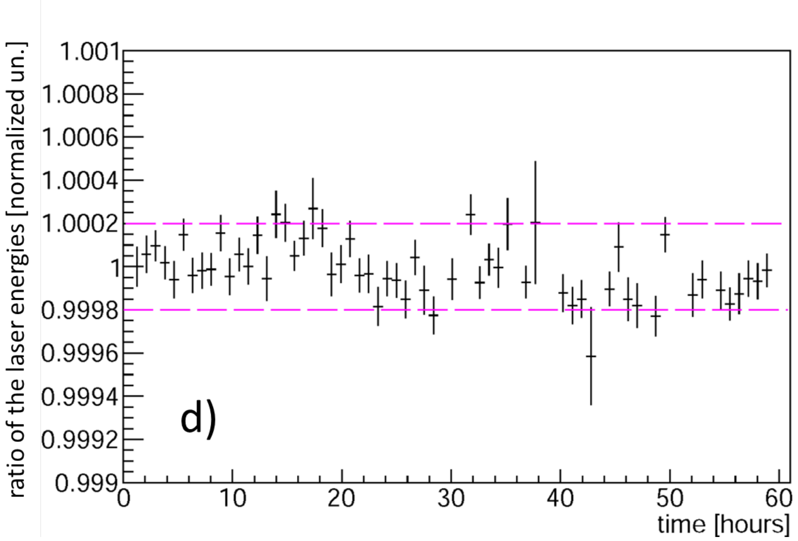
G_{SiPM}



SiPM energies corrected with G_{SiPM}
SM energies = 5 s



Ratio



$+10^{-4}$

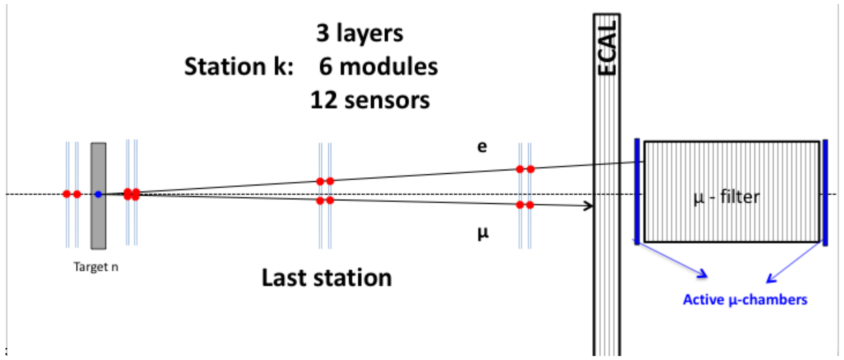
-10^{-4}

Exceeds specs!

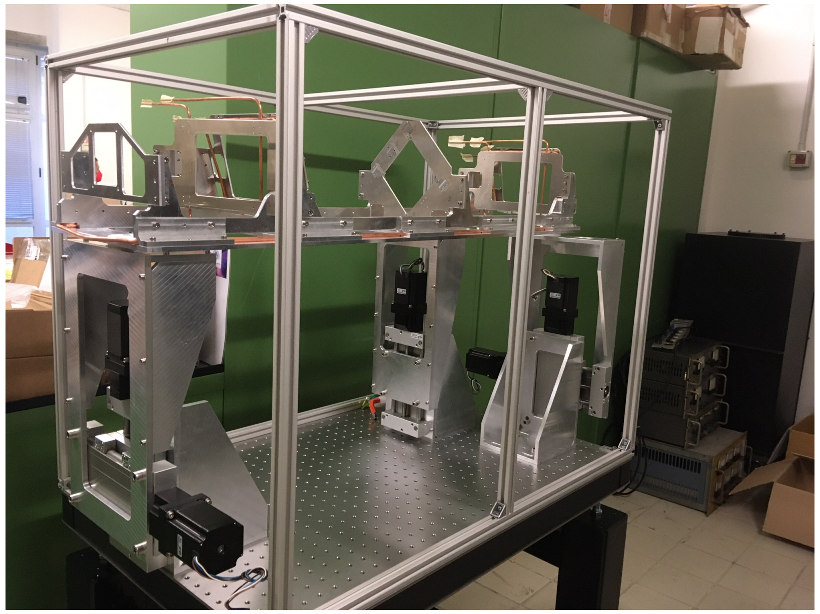
MUonE Project

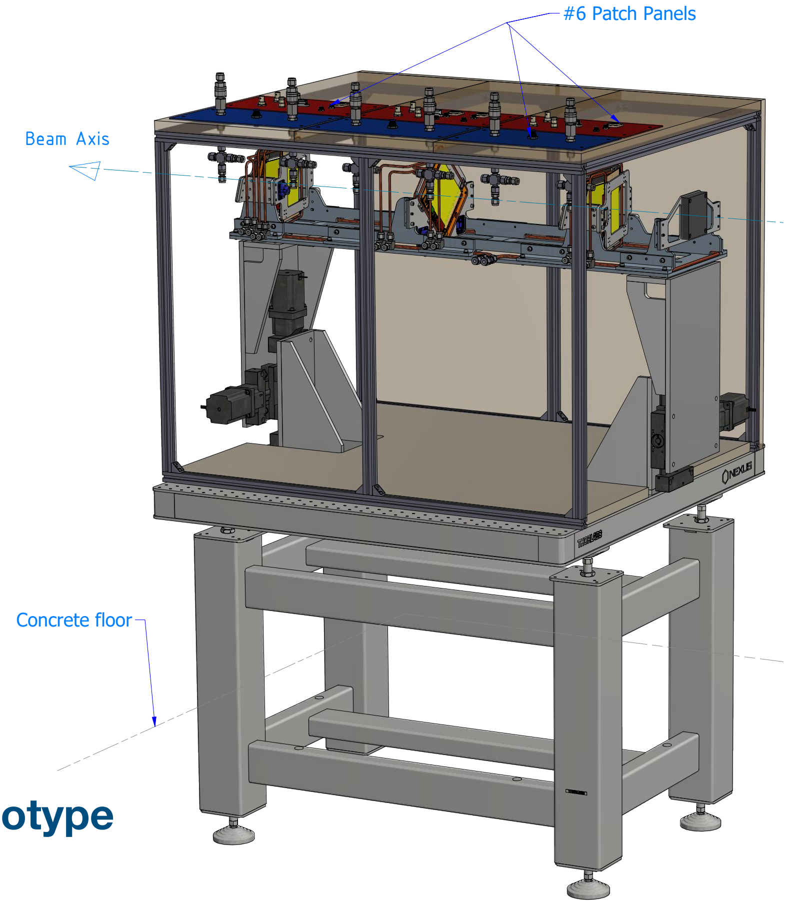
- **Direct determination of the hadronic contibution to the muon gyromagnetic anomaly**
  - **critical for the theoretical interpretation of the recent “Muon G-2” result**
  - **high precision measurement of the scattering angle in μ-e^- elastic scattering**
- **Main characteristics of the apparatus**
  - **muon beam at the CERN North Area**
  - **chain of 40 “tracking stations", each equipped with a fixed target and three Si tracking planes, ending with an ECAL**
- **Critical points**
  - **…**
  - **longitudinal alignment between tracking planes inside a station must be kept stable within 10 microns**

https://web.infn.it/MUonE/



schematic of the “last” tracking station with the ECAL

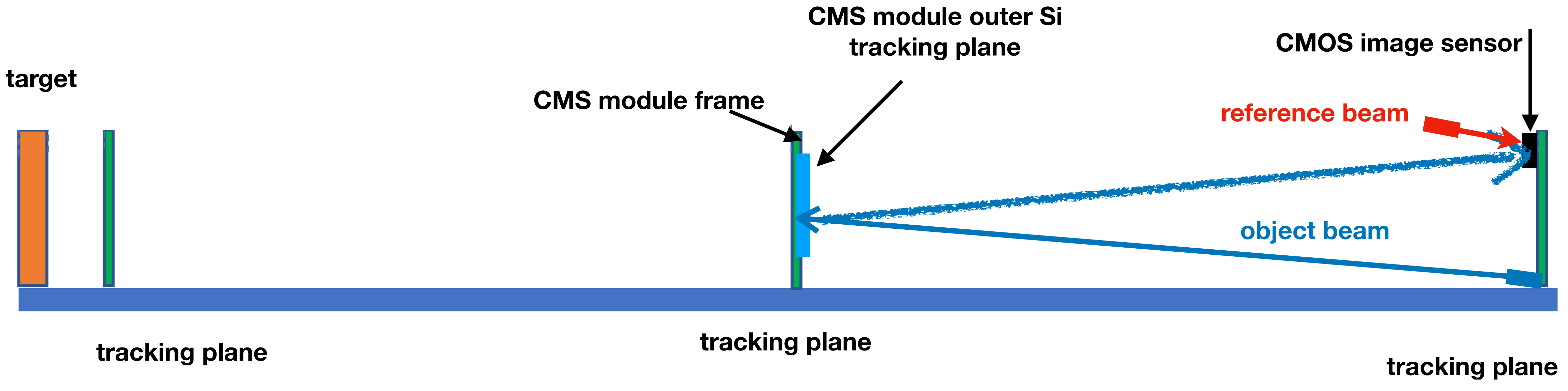




Tracking station prototype

HAM - Holographic Alignment Monitor

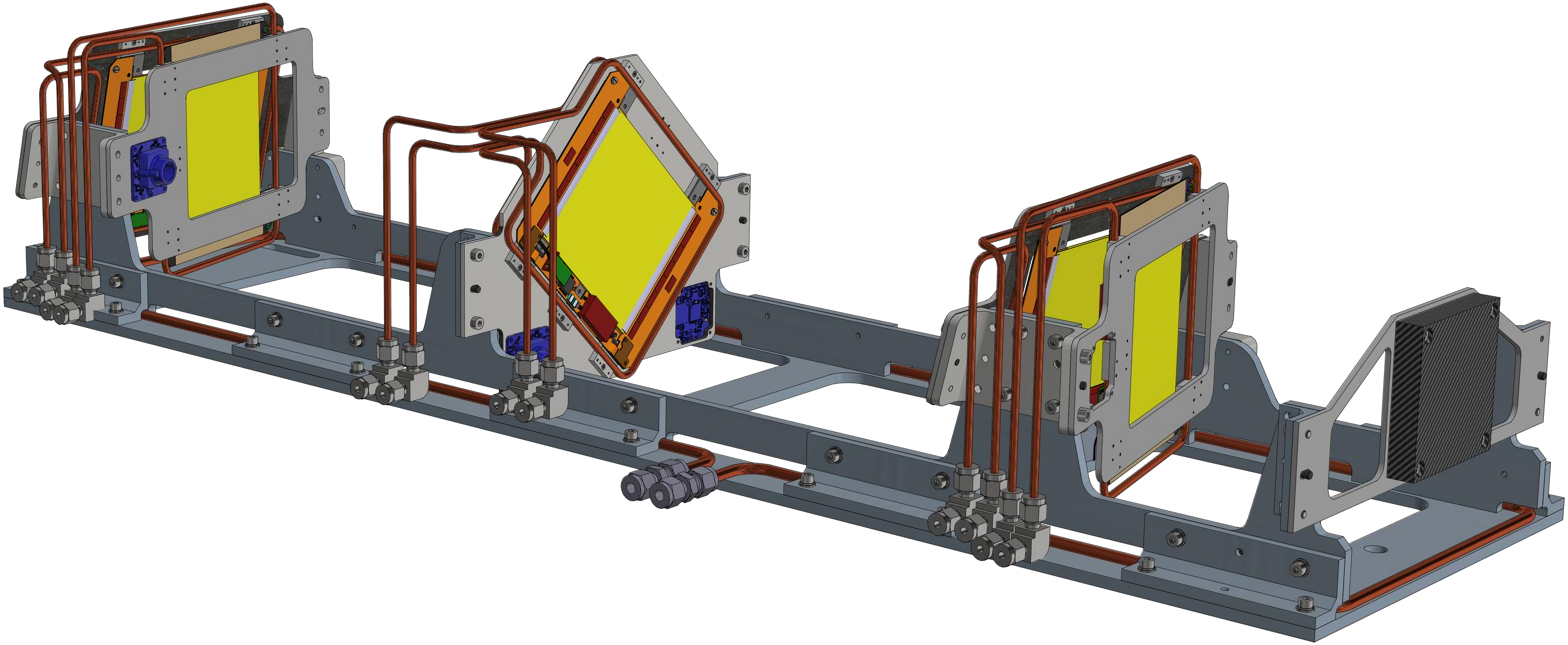
- **Solution to the longitudinal alignment stability requirements**
    - **build the tracker support structure ("frame") in Invar and stabilize temperature inside a protective cover**
    - **monitor the stability by detecting in "real time" possible relative movements between tracking planes**
    - **optical technique of choice: holographic interferometry**
- **HAM Working principle**
    - **Two coherent light beams are obtained by splitting a single laser source, one is the "reference" beam, while the other reflects off the object to be monitored ("object" beam"). Splitting and transport is done via optical fbers ⇒ novelty in holography**
    - **The reference and object beams superimpose on the surface of a CMOS image sensor generating a raw holographic image, which is then reconstructed with a Fourier transform procedure**
    - **Interference takes places between two raw holographic images of the object taken at different times. If the object moves with respect to the light source between the two images, fringes will appear in the reconstructed holographic image of the superposition of the two raw individual images.**



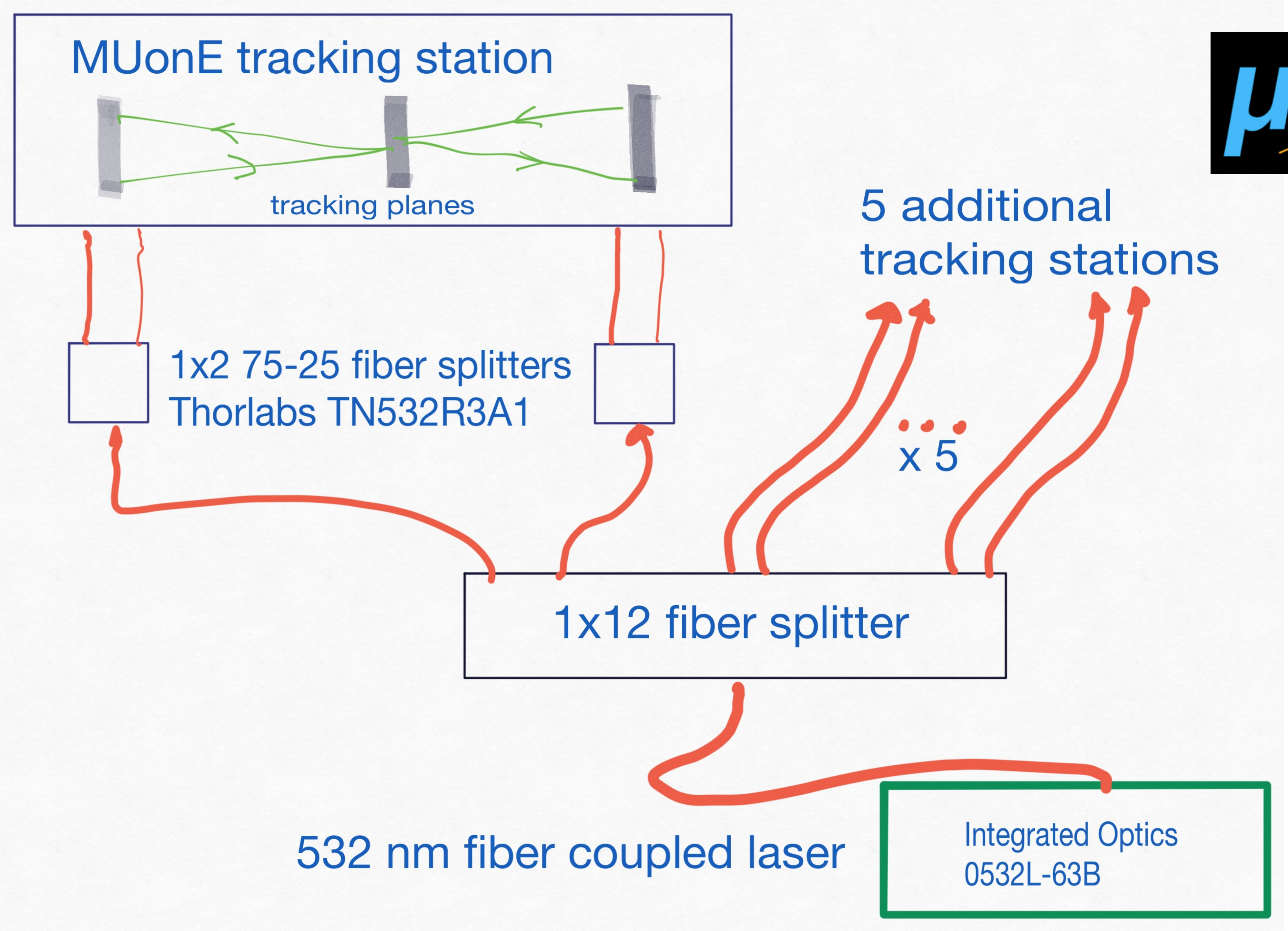
Holography WG in MUonE:
A. Arena and M. Karuza (Univ. of Rijeka and INFN Trieste), G. Cantatore (Univ. and INFN Trieste)

MUonE tracking frame

Station Shaded ISO View



Fiber optic distribution



MUonE tracking station

tracking planes

1x2 75-25 fiber splitters
Thorlabs TN532R3A1

5 additional
tracking stations

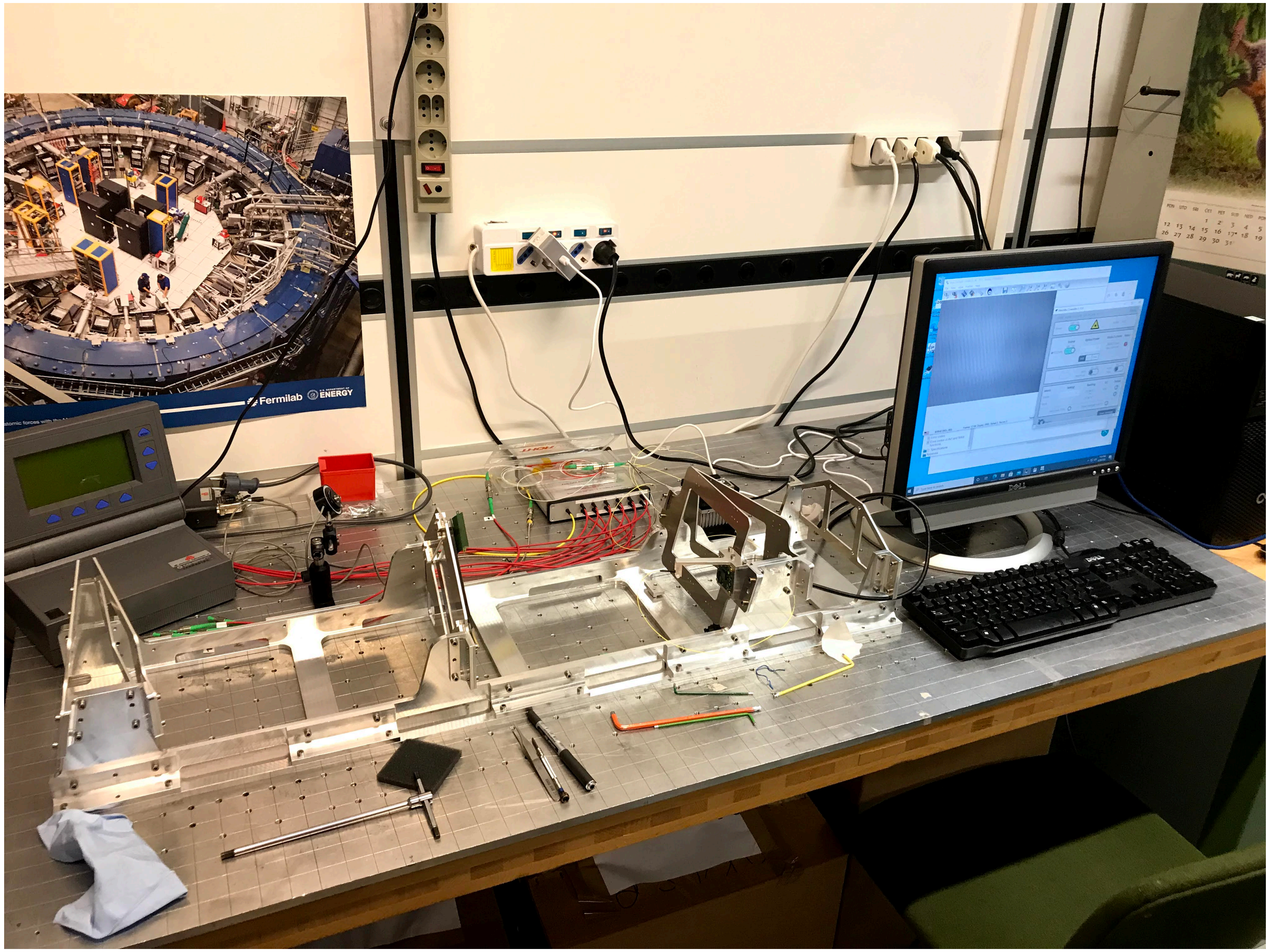
x 5

1x12 fiber splitter

532 nm fiber coupled laser

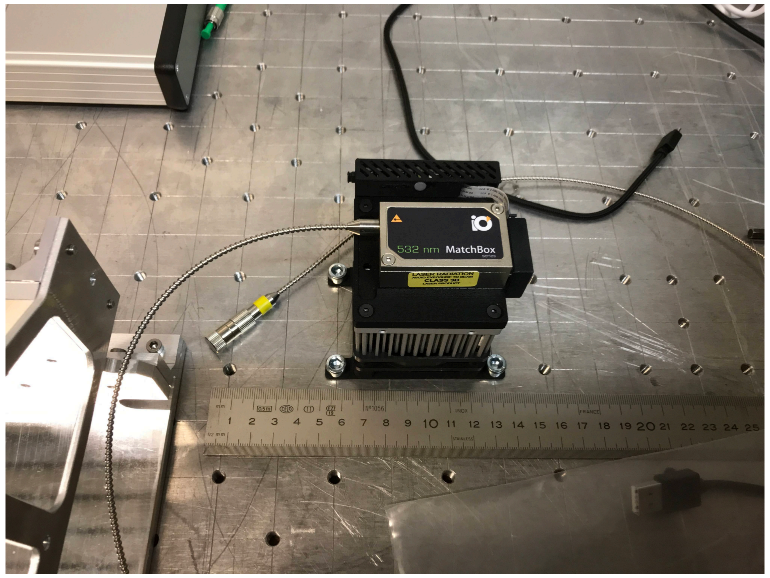
Integrated Optics
0532L-63B

HAM test setup in Trieste

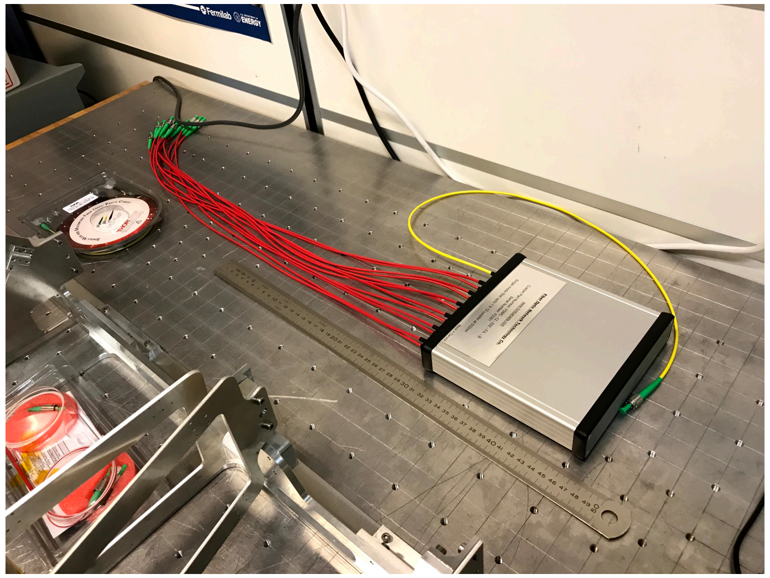


Test setup

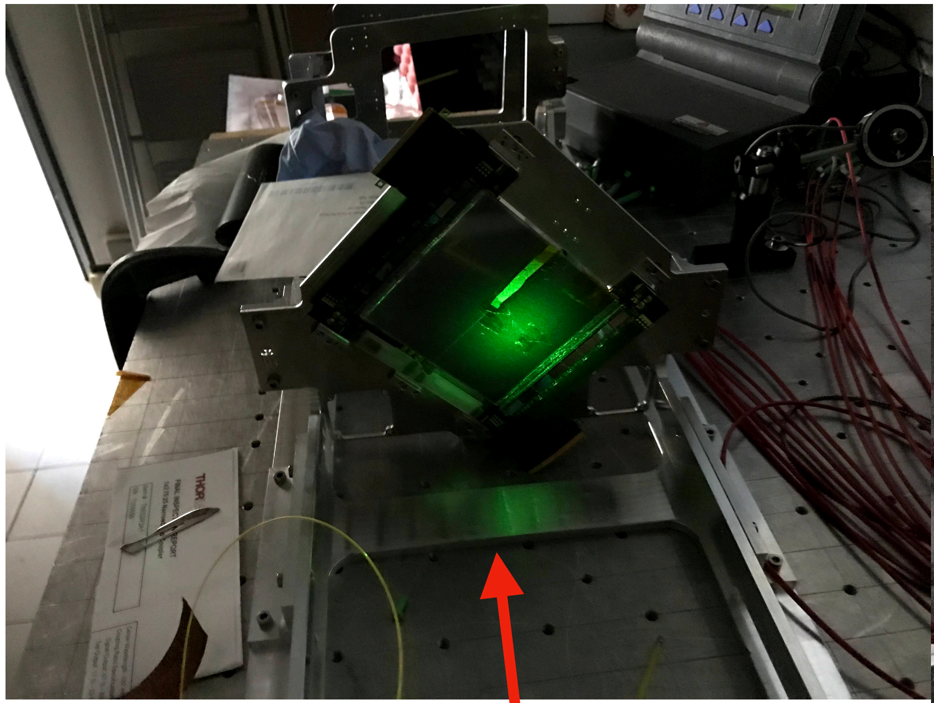
fiber coupled 532 nm laser

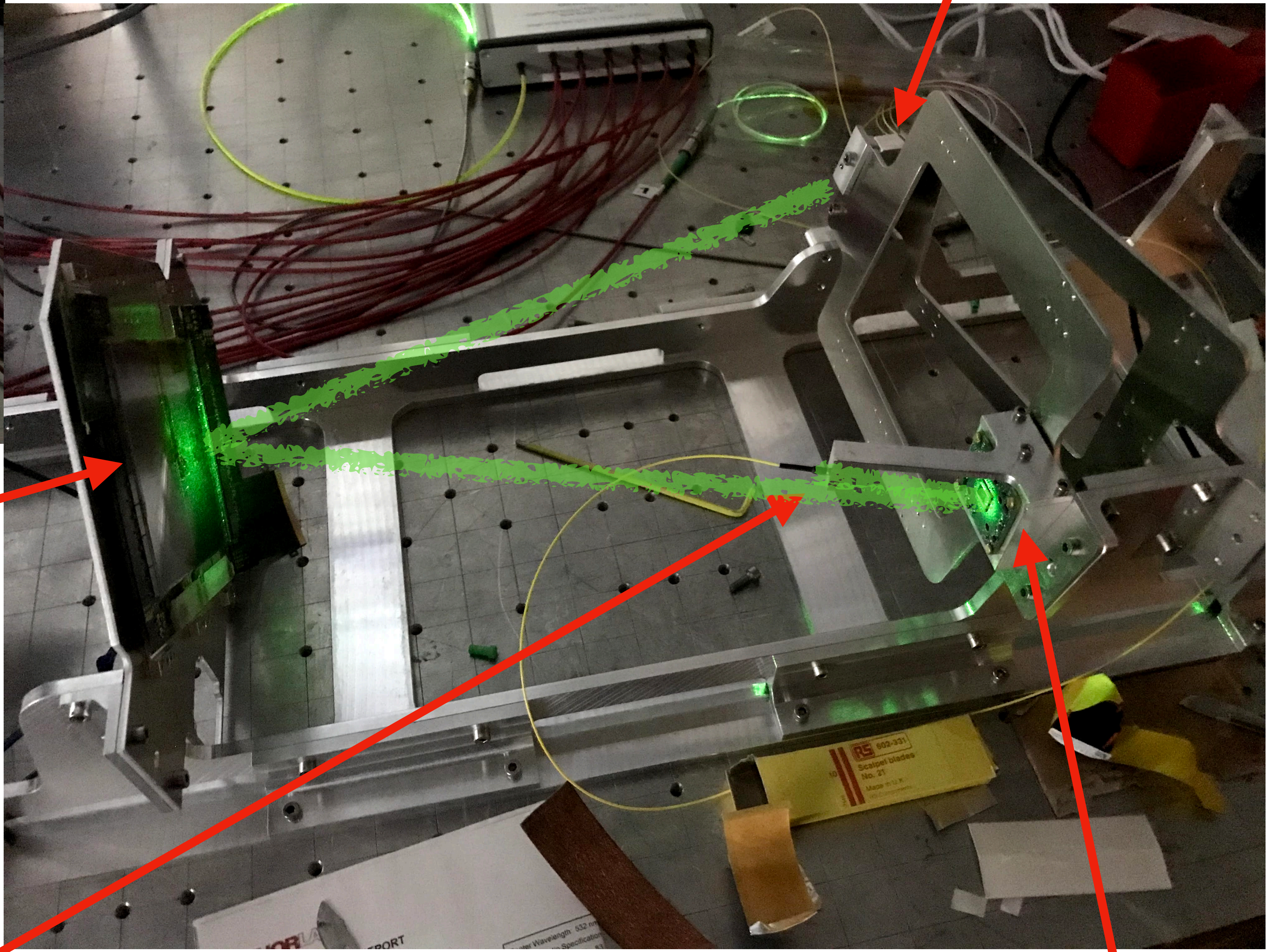


1x12 fiber splitter



HAM tests with a dummy CMS tracking module





Object beam

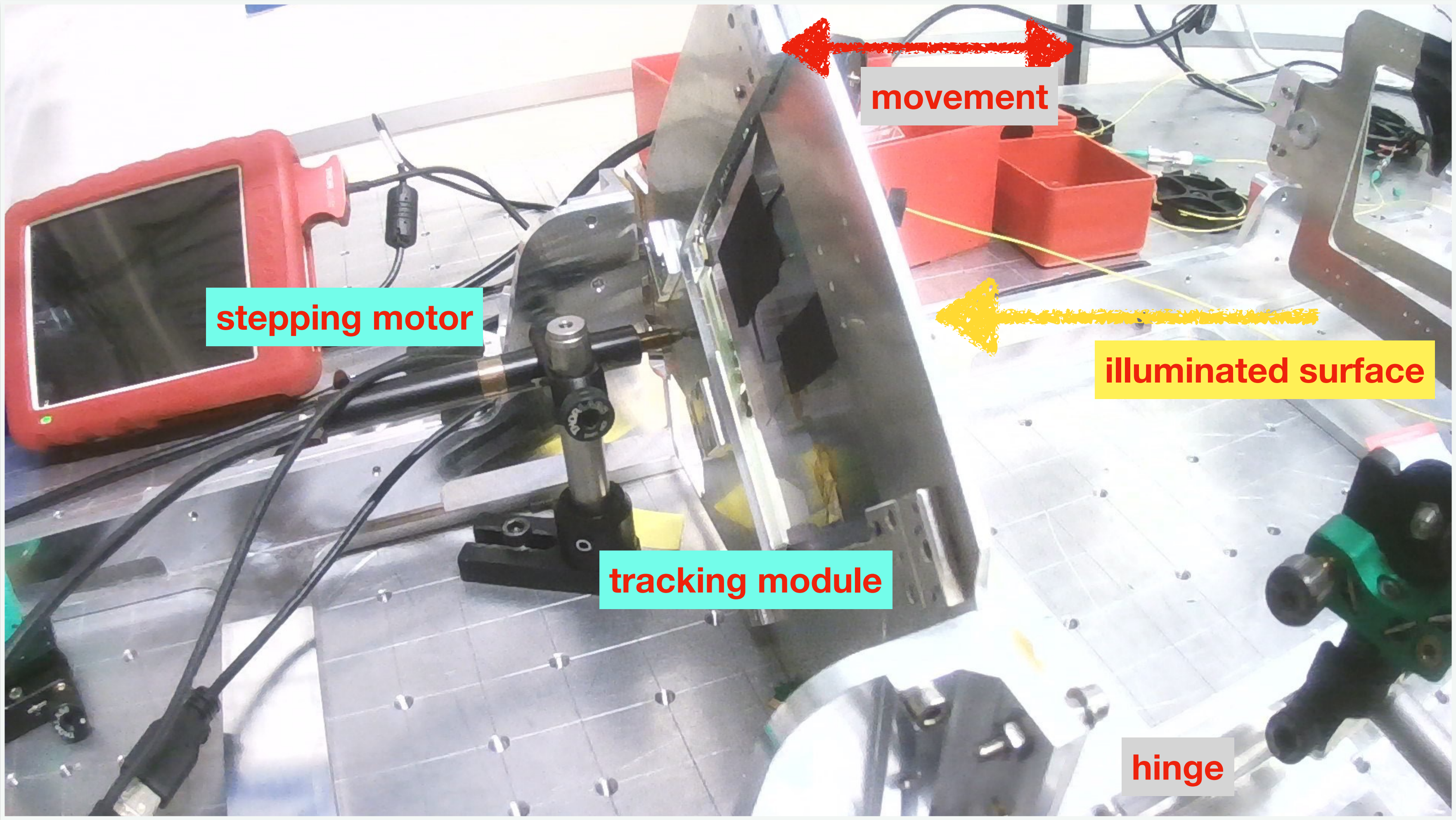
CMS Si tracking module

reference beam

CMOS image sensor

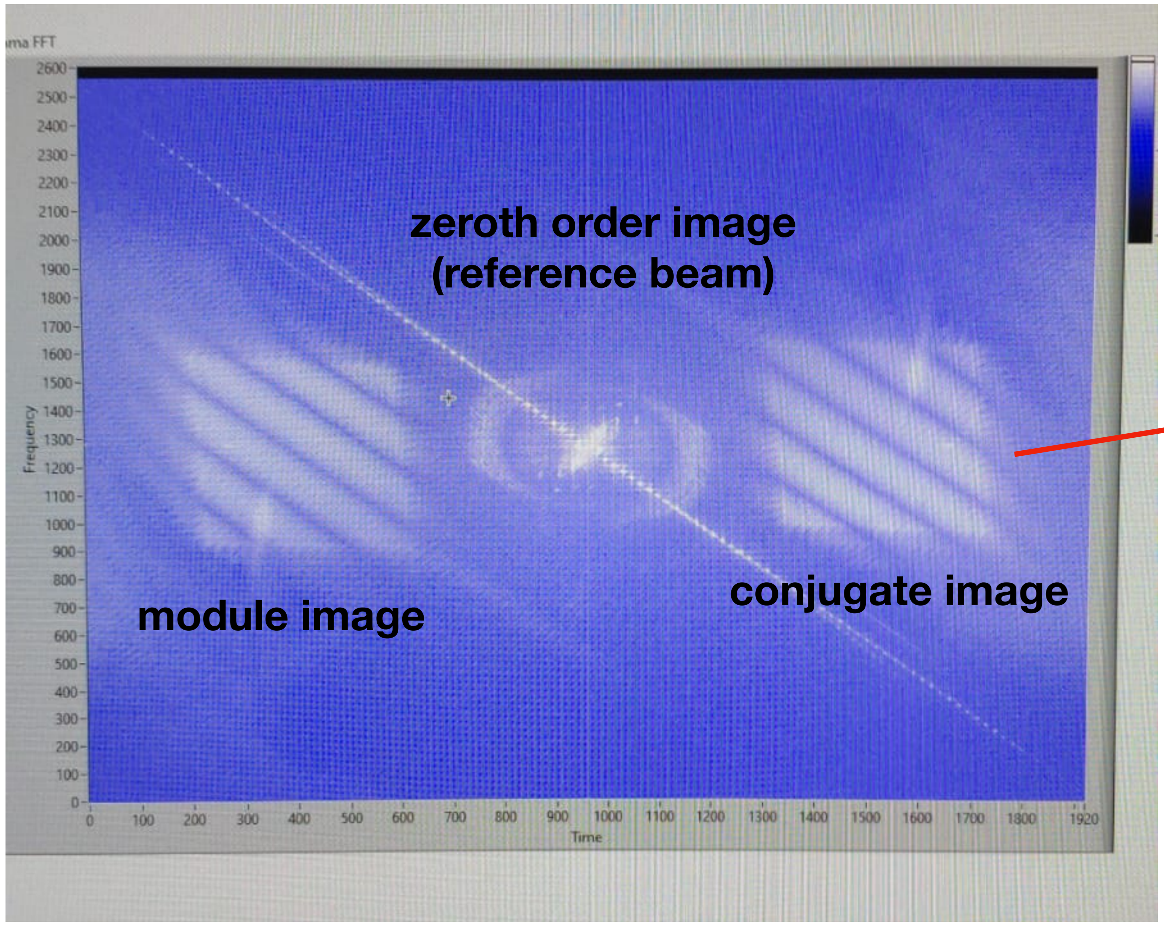
Preliminary calibration tests

- **Controlled tilt movement of the CMS Si tracking module**
  - **calibrated stepping motor actuator with spring loaded counterforce**
  - **labview software for motor control, raw image acquisition and reconstruction**
- **Images are taken at intervals during module movement and superimposed on a “zero”image taken initially**
  - **interference fringes appear revealing relative movements in 3 dimensions**
  - **spatial resolution is given by λ/2 = 256 nm, and the number of observed fringes corresponds to the total sample displacement**



HAM: preliminary results

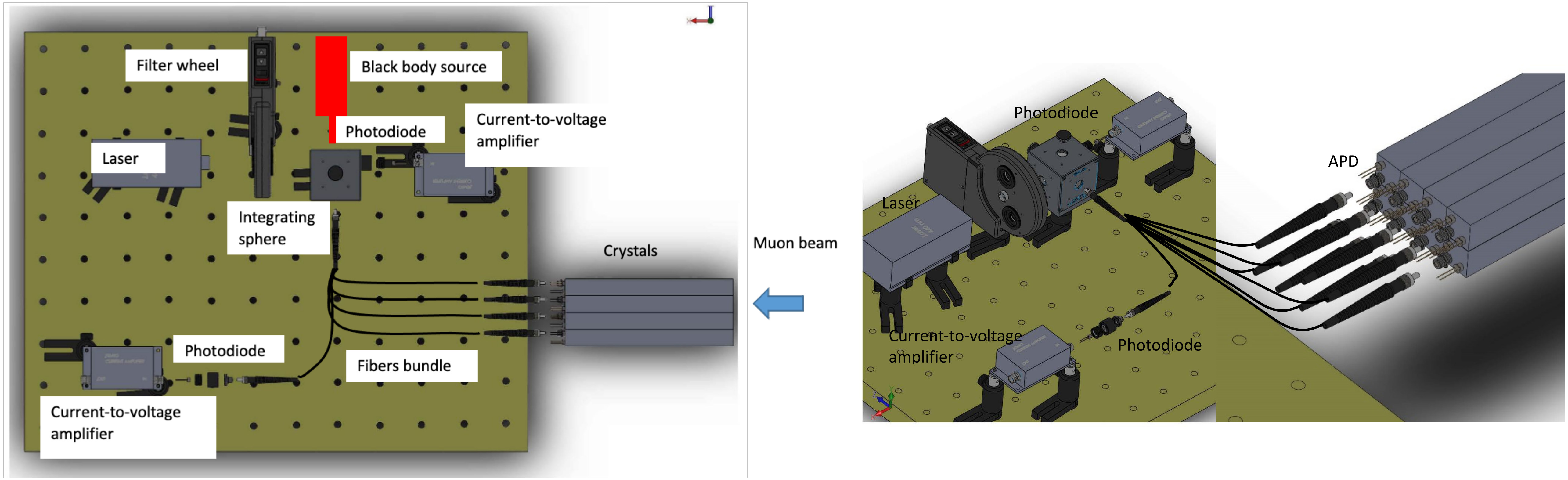
- Sample holographic image of the moving Si module



No. of fringes	Illuminated area displacement (microns)
3	0.8
6	1.6
12	3.2
18	4.7
24	6.3

MUonE ECAL laser calibration

- Energy and gain calibration of the MUonE calorimeter with a pulsed laser system
    - based on the experience from “Muon G-2 (simpler system, only 1 calorimeter)
    - absolute energy calibration with a black body source
- Now in the initial assembly phase



Drawings courtesy of C. Ferrari - INO Pisa

ECAL WG in MUonE:
E. Conti (INFN Padova), C. Ferrari (INO Pisa) and G. Cantatore (Univ. and INFN Trieste)

What we are learning

- Optics is very much alive in experimental particle physics

- Precision requirements for particle detectors are constantly stepping up, and optical techniques are an excellent solution in meeting them

- Our creativity is the sole limitation!

Backup

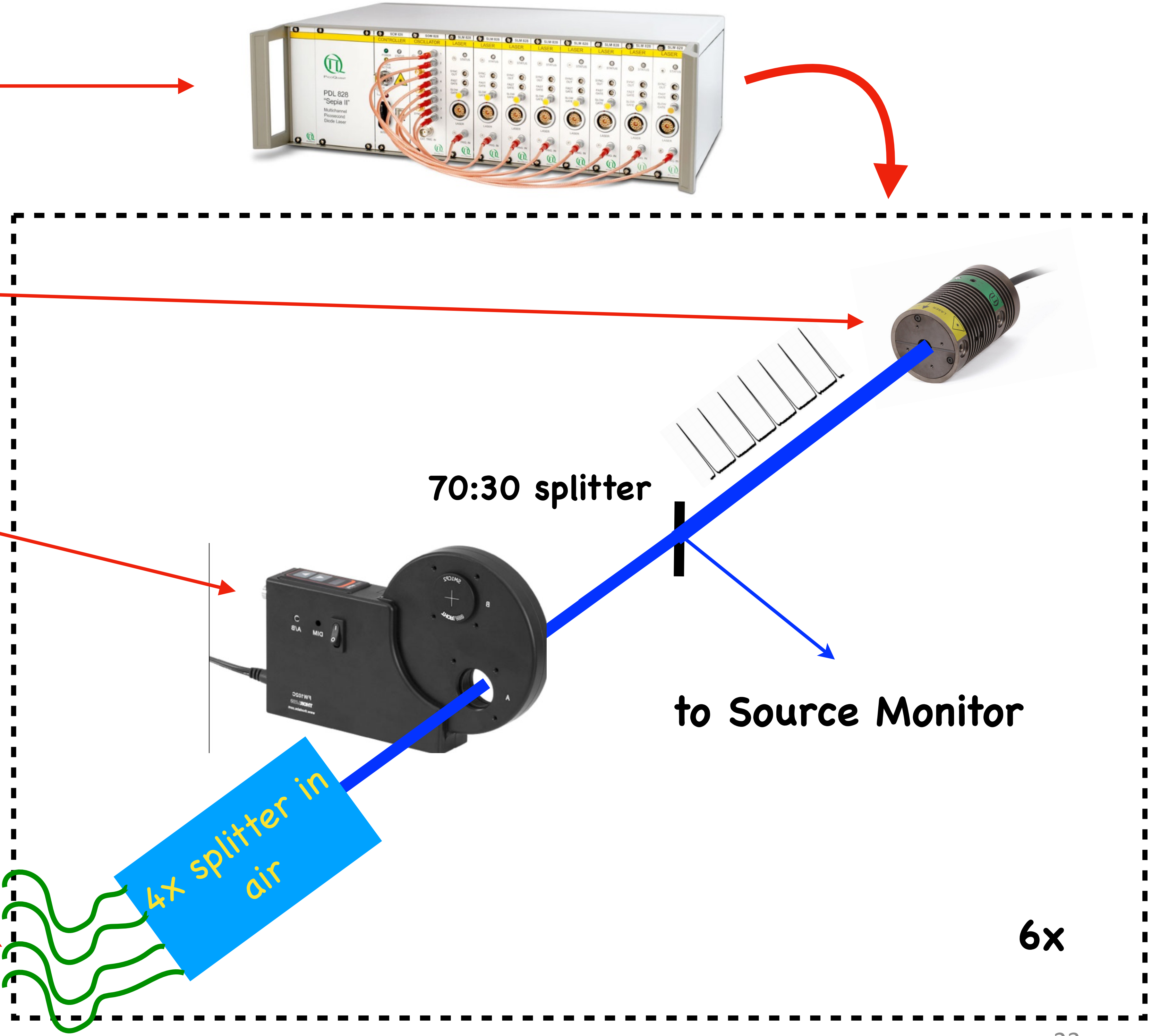
Laser source

Triggerable laser head controller (Picoquant Sepia PDL 828)

Pulsed laser headT, 700 pJ/ pulse, 600 ps (FWHM) (Picoquant, mod. LDH-P-C-405M)

Motorized filter wheel (Thorlabs, mod. FW212CWNEB)

4 “launching” optical fibers (Si, 25 m long, 400 μm dia. Polymicro, mod. FDP400440480)

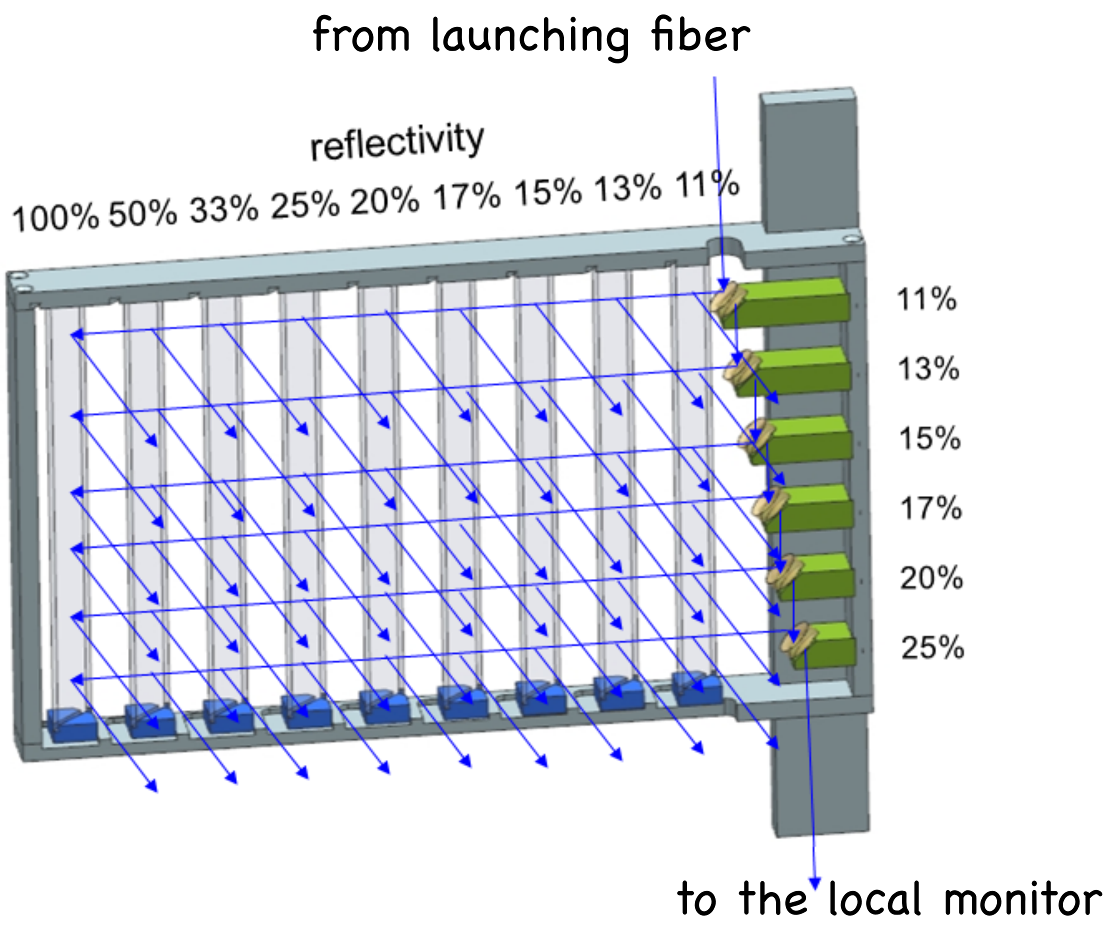


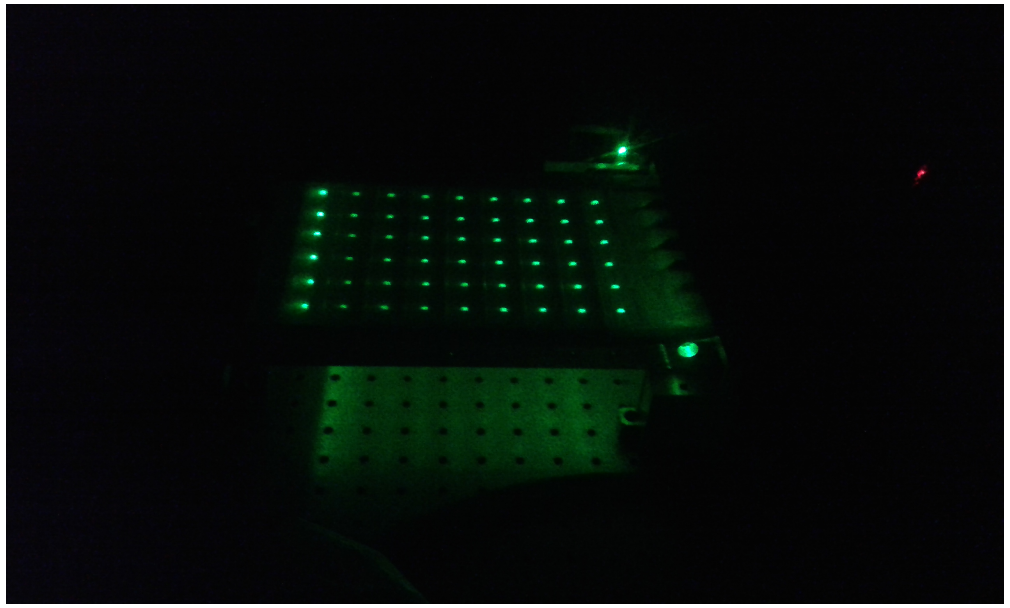
Diffuser - the “PiTs frame”

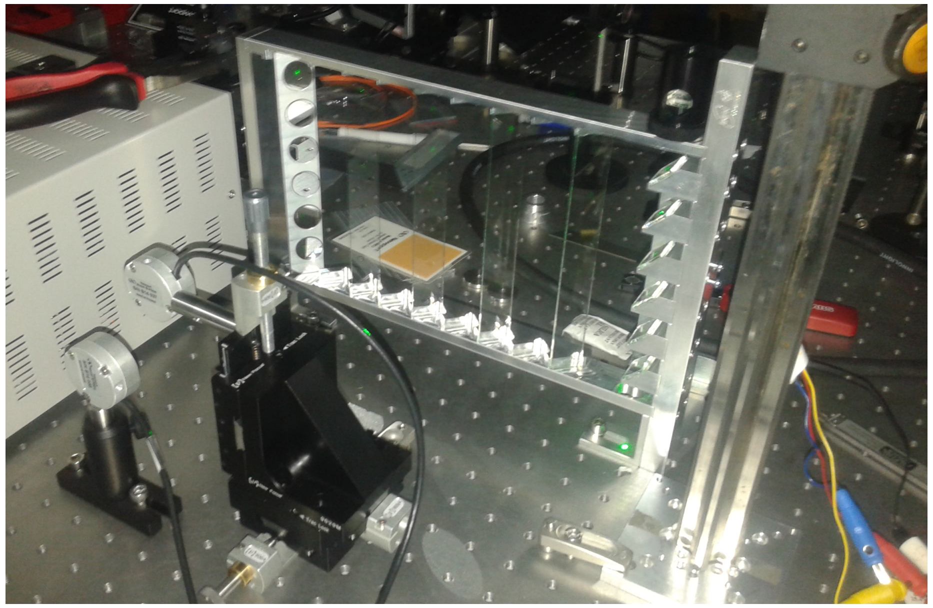
First diffuser prototype: designed in Trieste and tested in Rijeka “

- thin 2 cm frme
- the launching fiber hits a column of beamsplitters having increasing reflectivity
- reflected beams illuminate a grid of rectangular beamsplitters, also having increasing reflectivity, which steer the beams towards the calorimeter crystalso
- the transmitted beam returns to the Local Monitor

Efficient and compact, but assembly is delicate





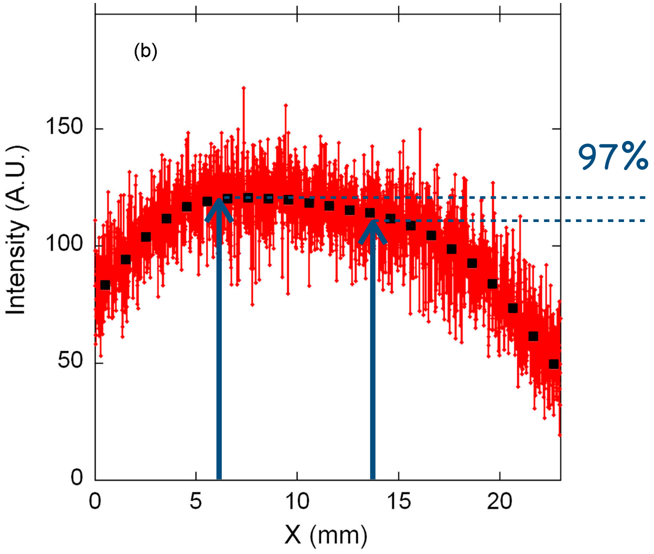


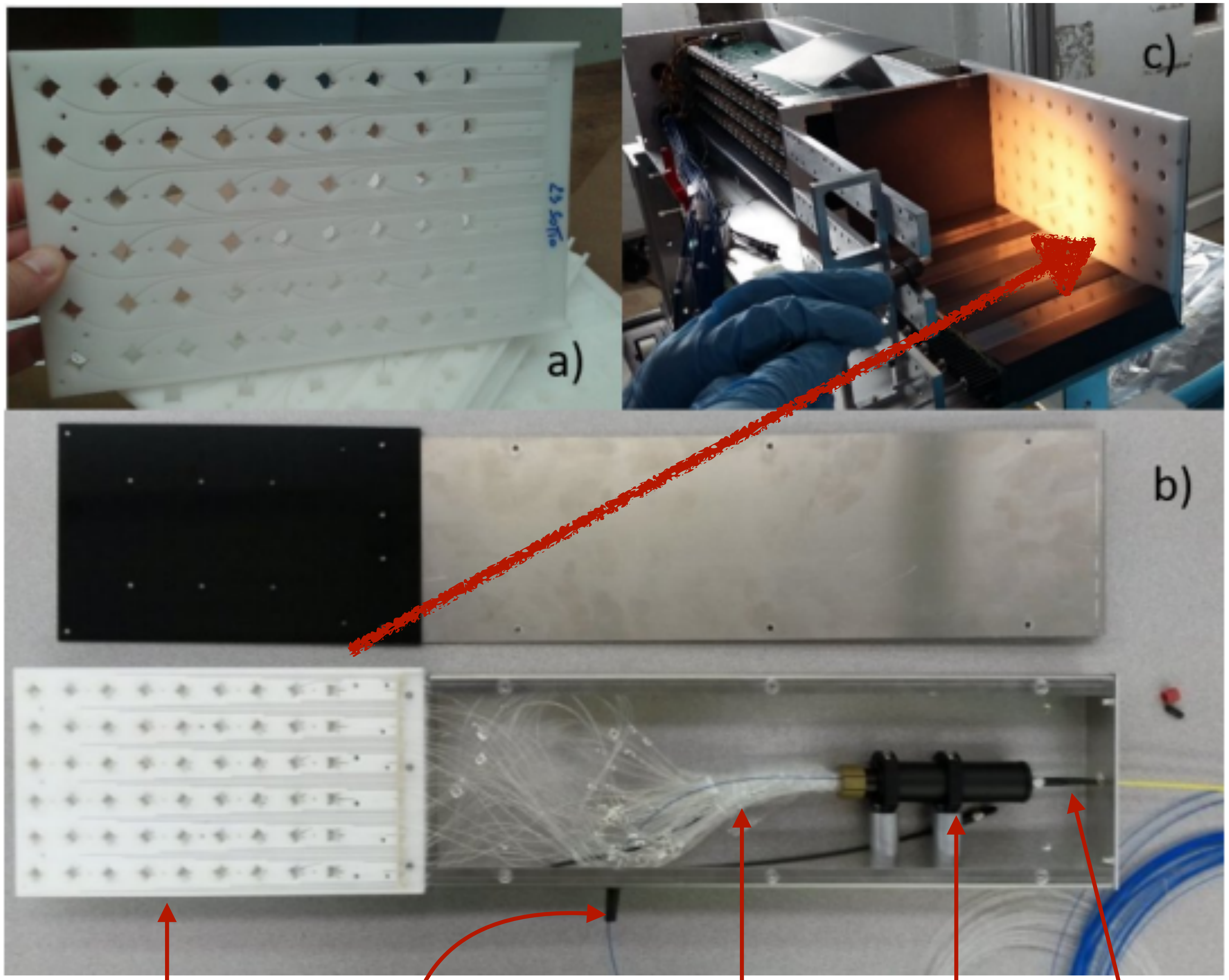
Assembly and uniformity tests in Rijeka

Diffuser solution

Adopted diffuser solution

- light from the launching fiber passes through a pre-diffuser which turns the beam profile from gaussian to flat
- a 54-fiber bundle (+ 2 "return" fibers) collects light after the pre-diffuser and brings it to a distribution panel
- A thin Delrin panel, containing 54 90° reflecting mini-prisms, steers light towards the calorimeter crystals
- the two "return" fibers, one Si and one PMMA, bring light back to the Local Monitor





Delrin panel with 54 mini-prisms

return fibers

fiber bundle

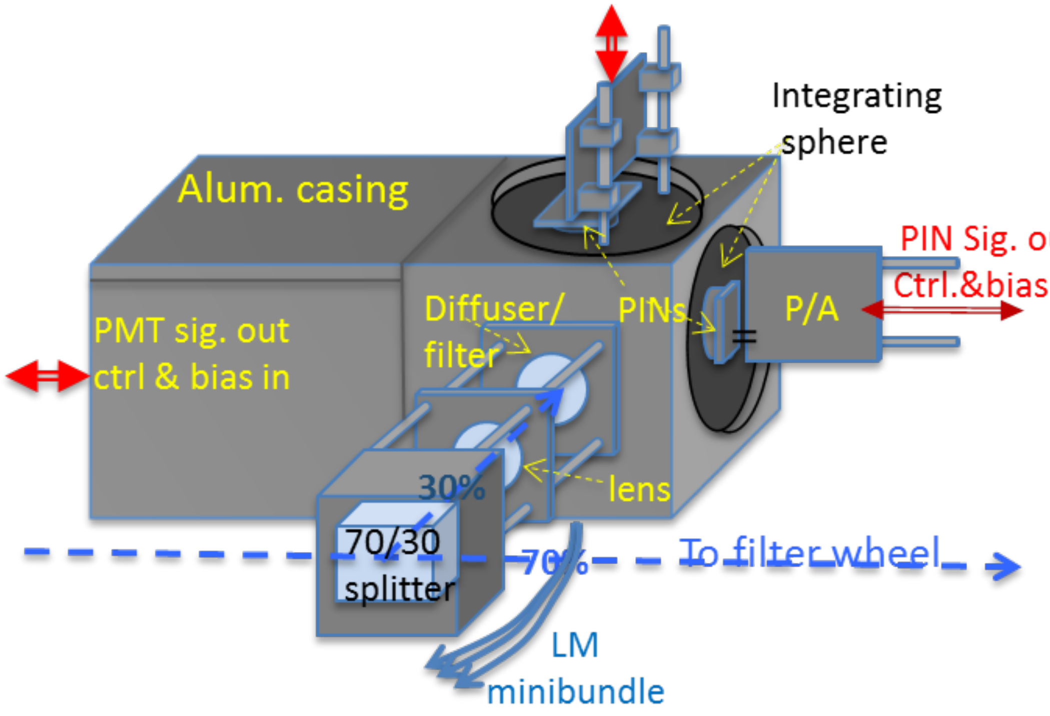
pre-diffuser

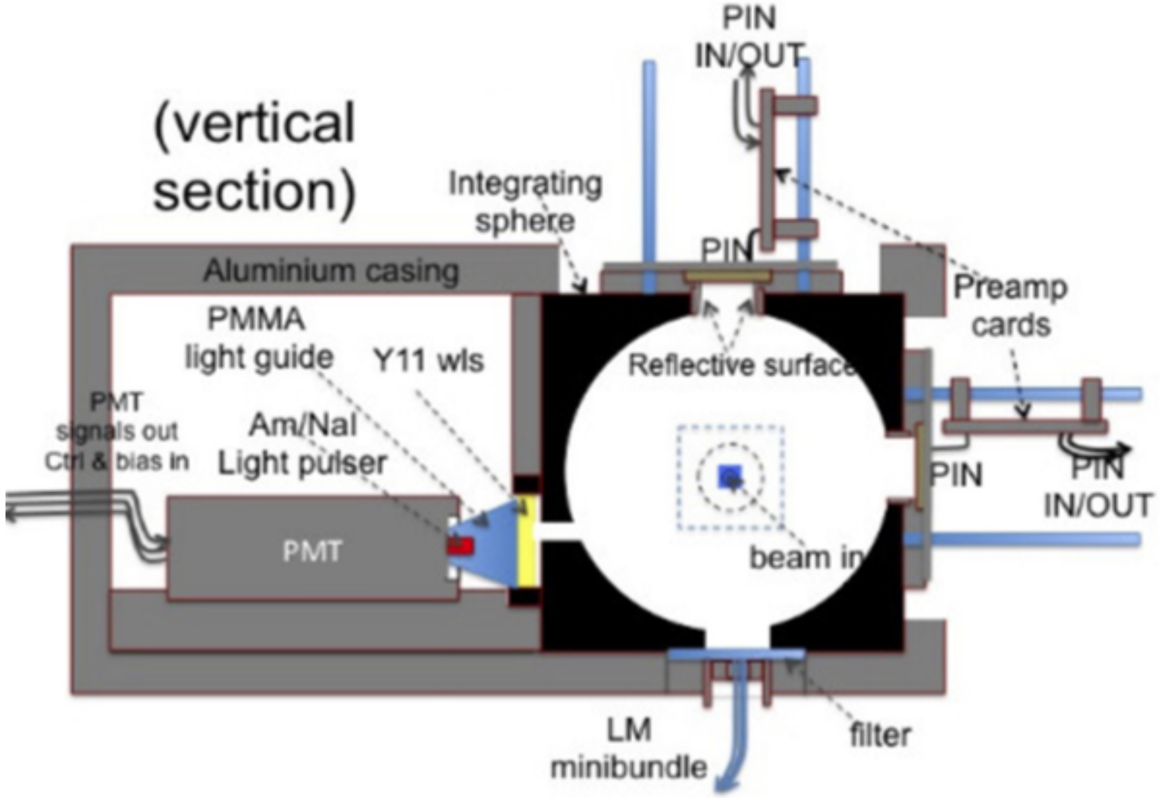
launching fiber

Source Monitor

The Source Monitor monitors the stability of the laser source. There is a total of 6 SM, one for each laser head. Each SM:

- collects 30% of the laser initial intensity and averages out pointing fluctuations by means of an input integrationg sphere
- the 4 sphere outpits are sent to
  - 2 PIN photodiodes
  - a PMT coupled to a NaI scintillator
  - an optical fiber bringing the reference signal to the Local Monitor
- the signal amplitude "seen" by the PMT is calibrated in an absolute way against a low activity ^{241}Am source





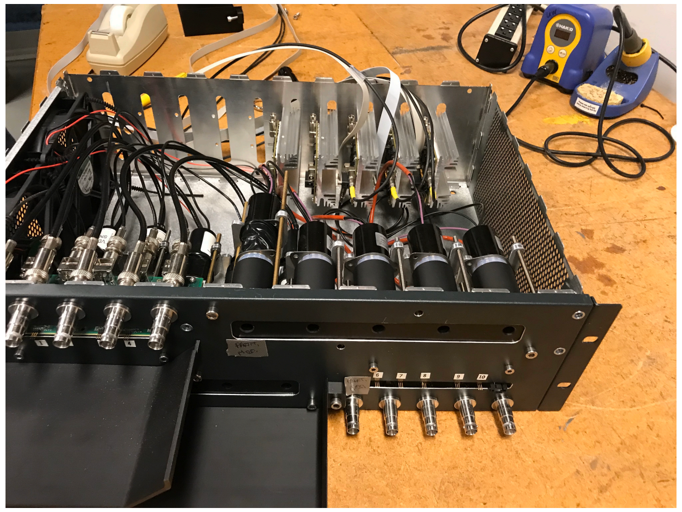
Local Monitor characteristics

Two twin Local Monitor systems

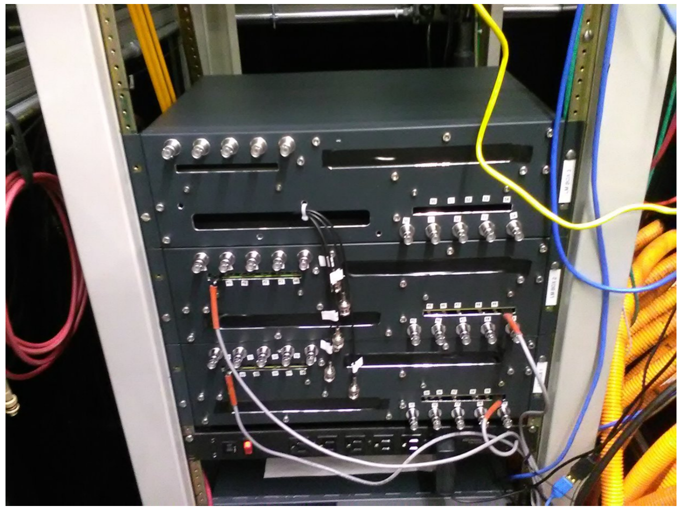
- **main (LM1)**: monitors the 24 Si return fibers
- **redundant (LM2)**: monitors the 24 PMMA return fibers

PMT racks and electronics are placed inside shielded boxes in the Laser Hut, where "return" fibers from the ring terminate

Each LM channel compares the signal from its return fiber with the reference signal provided by a SM

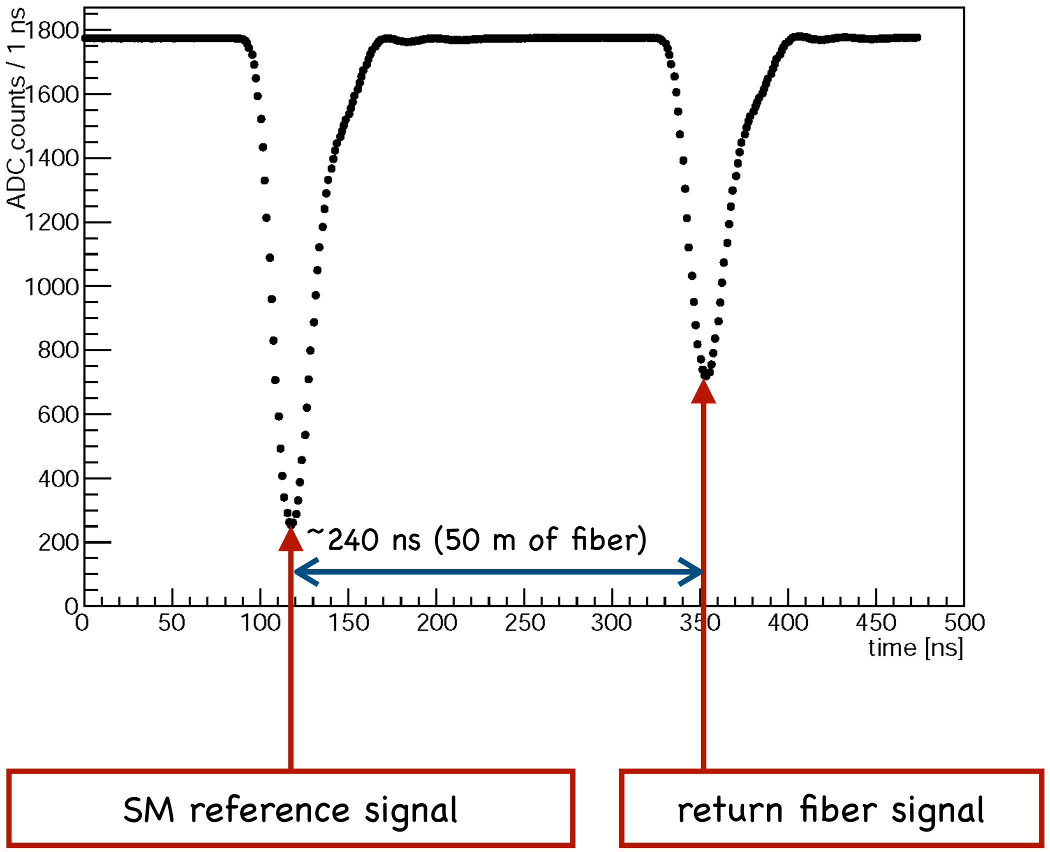


LM PMTs and front-end electronics during assembly



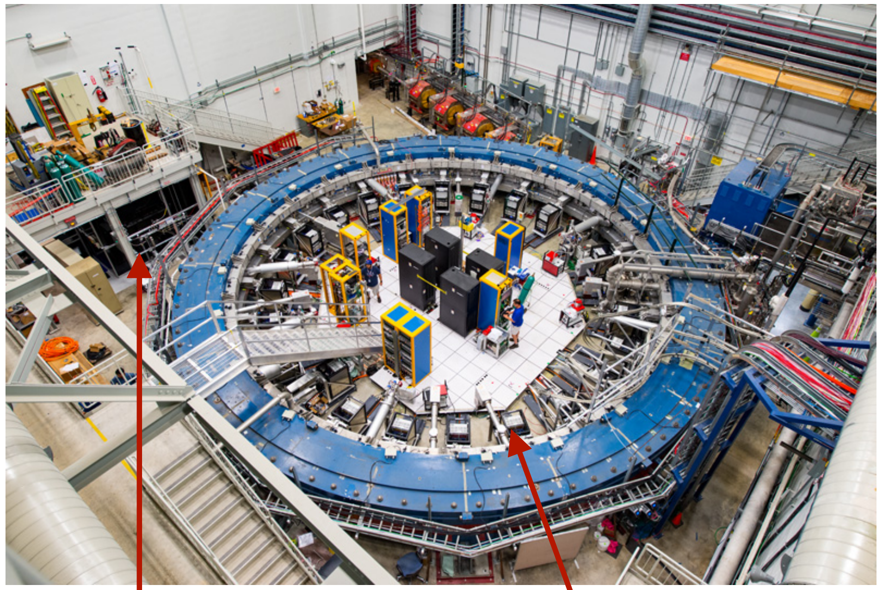
Shielded LM boxes inside the Laser Hut

Typical LM PMT trace



SM reference signal

return fiber signal



Laser Hut

calorimeters