Development of charge-based calibration systems for LAr-TPCs in the DUNE Experiment

Nuno Barros, on behalf of the DUNE Collaboration

Technology in Instrumentation & Particle Physics (TIPP) Conference 2023

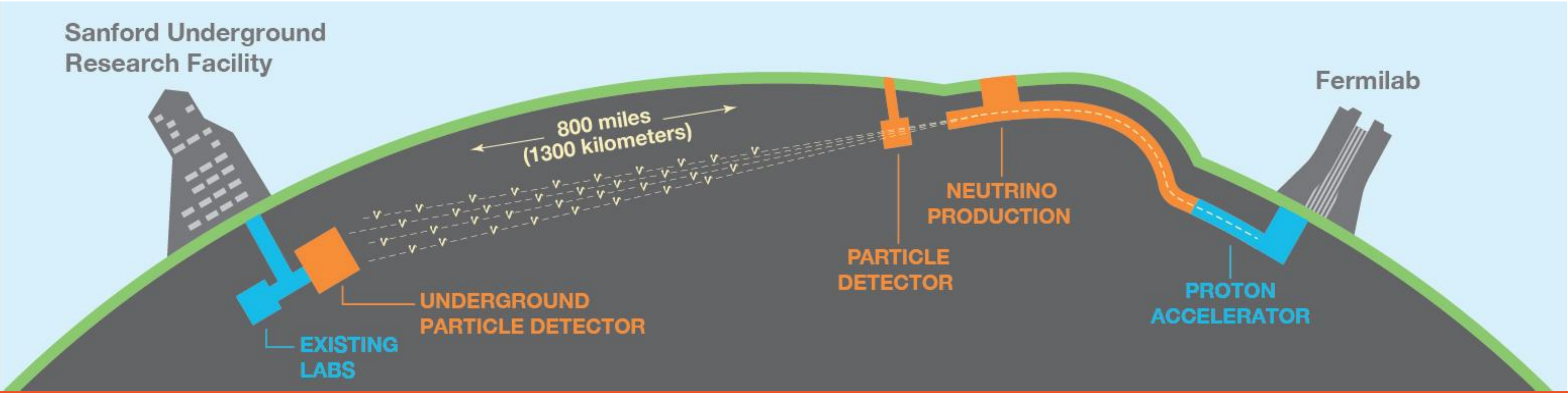
September 5, 2023

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

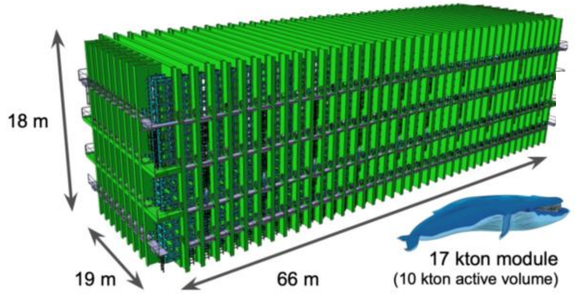
Deep Underground Neutrino Experiment

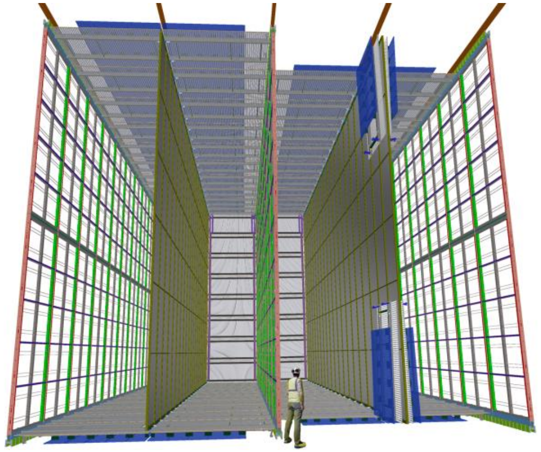
- **DUNE in a nutshell**
  - Fermilab produces intense neutrino and antineutrino beams
    - 1.2 MW (upgradable to 2.4 MW)
  - Near detector characterizes beam and cross-sections
  - Beam reaches SURF, 1300 km away, 1.5 km deep
    - 70 kton far detector, divided in 4 modules

- **Physics goals**
  - Measure neutrino appearance and disappearance
  - Measure mass ordering, CP violation and neutrino mixing parameters in a single experiment
  - Large, deep underground detector is sensitive to rare and low-energy physics (SN bursts, nucleon decay)



Calibrating DUNE





- Calibration challenges for DUNE:
  - Control the response of a huge-size detector, over a long period of time (decade)
  - Highly segmented detector
  - Deep underground location, low statistics from cosmic rays
  - Stringent physics requirements over a wide energy range

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

Particle	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

- Top-level calibration requirements for the physics goals:
  - GeV-scale oscillation physics: energy scale uncertainty < 2% for leptons and 5% for hadrons
  - MeV-scale low-energy physics e.g. supernovae, solar: energy scale uncertainty < 5%

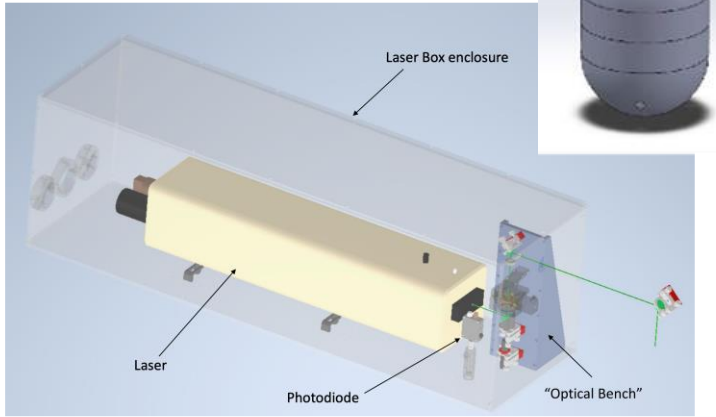
Calibrating DUNE

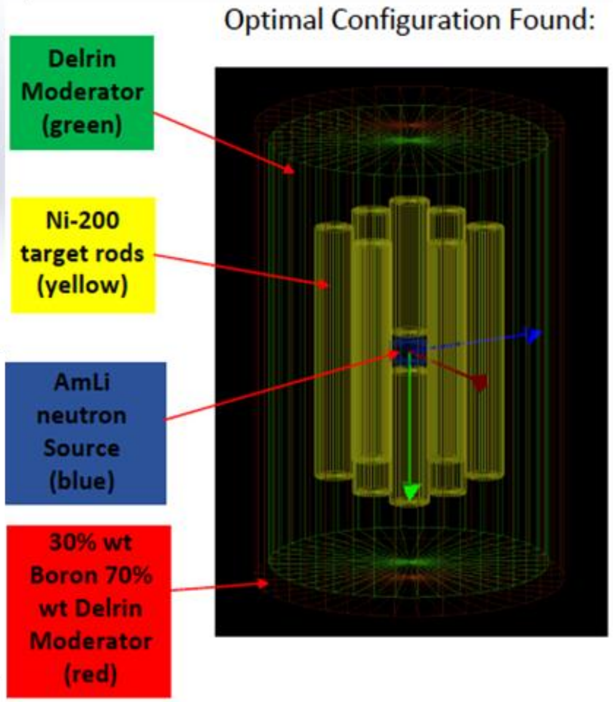
- Goals of the calibration
  - Measure detector model parameters
  - Validate and tune detector response (energy, position, PID,…)
- Sources of calibration
  - “natural” sources: cosmic and beam muons, beam neutrinos, ^{39}Ar
  - deployed sources: laser, external neutrons, radioactive sources

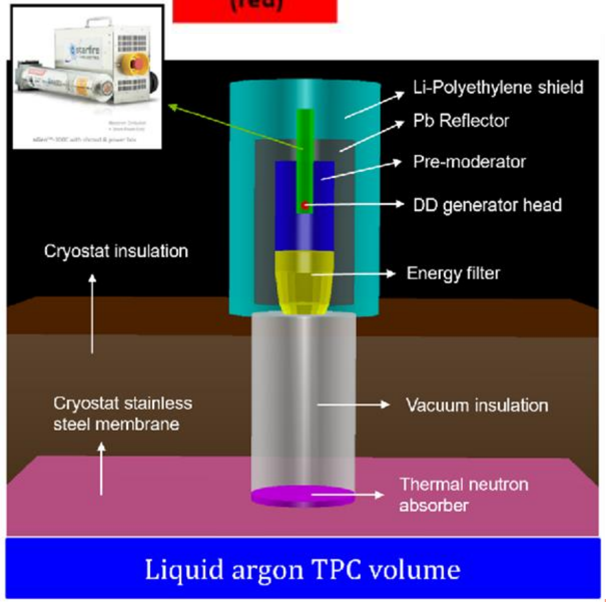
	Deployed sources	**Natural sources**
Detector response	Low energy only (neutrons, sources)	Mostly mid-energy (Michel, π^0, …)
Parameter measurement	E-field, Lifetime, uniformity Problem diagnostic	Lifetime, Response mapping. Always on!

External Calibration systems

- Radioactive sources
  - 9 MeV gamma rays from n-capture in Ni
  - ^{207}Bi source
- Pulsed Neutron Source
  - 6 MeV gamma rays from neutron capture on Ar
- **Ionization Laser System**
  - Ionizing laser tracks produced across the detector to provide independent fine-grained measurements of detector response parameters

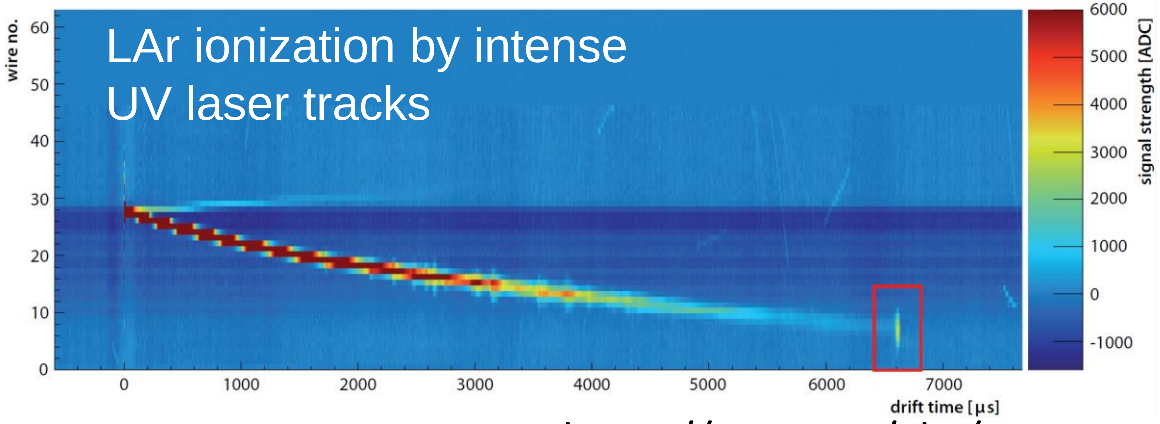




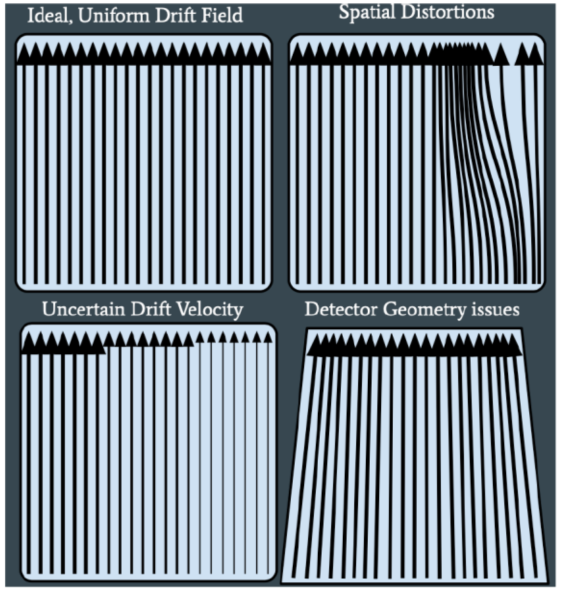


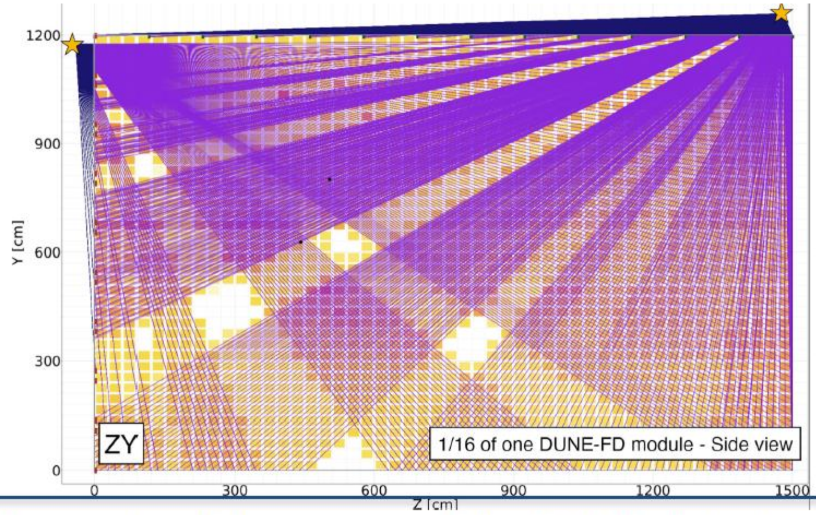
IoLaser – DUNE Ionization Laser System

- Provides an independent fine-grained measurement of detector parameters like drift velocity and electric field
- Diagnoses the detector properties like tilts/shifts of anode and cathode and high voltage issues



https://arxiv.org/abs/1408.6635





Fine-grained laser scan of the DUNE detectors

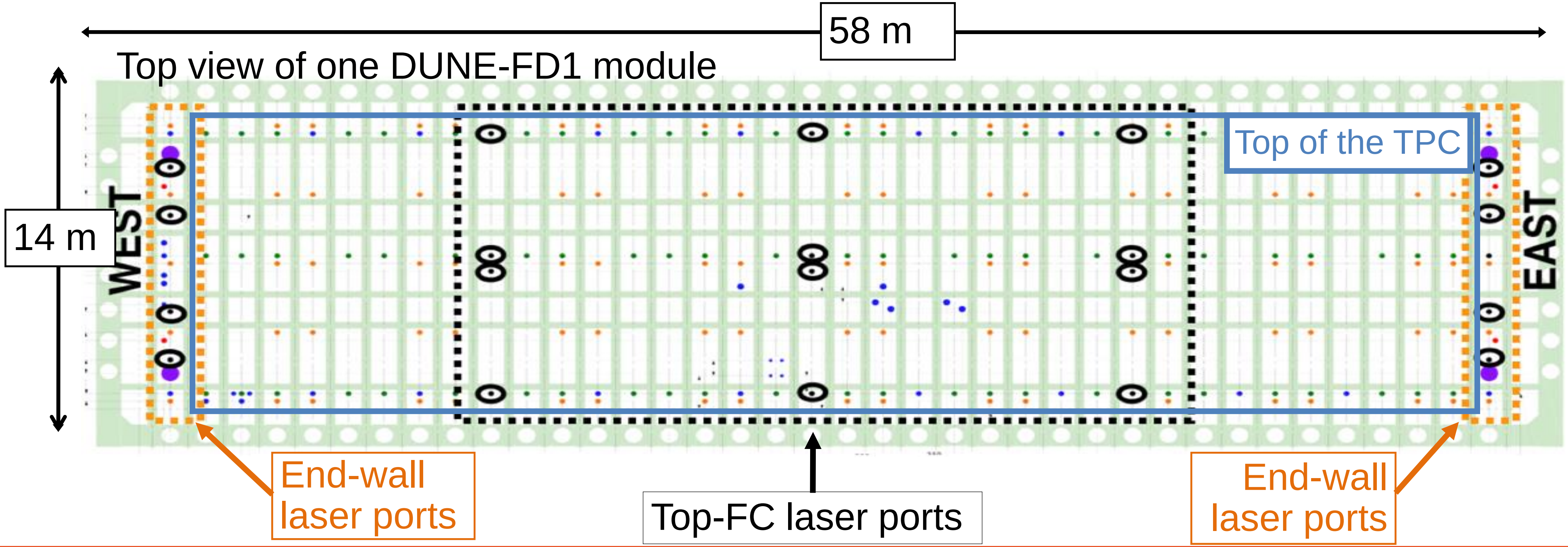
M. Fani, LANL

Straight laser tracks detected as curved when electric field is not uniform

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

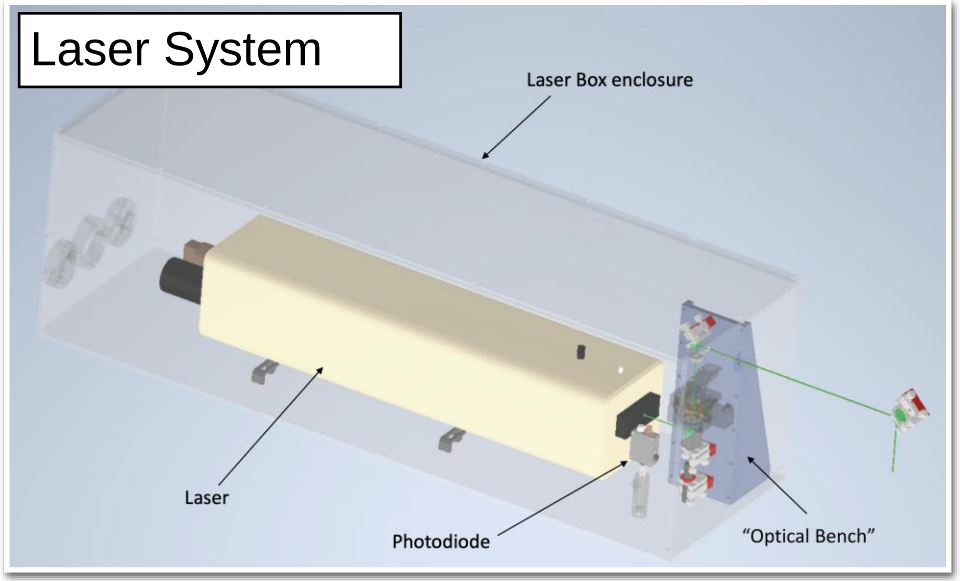
IoLaser in DUNE

- Planning for multiple laser systems on DUNE with ~15 m spacing
- **Two designs** planned to avoid shadowing from detector components: field cage (FC) profiles, I-beams, resistor plates etc.
- For the central ports, field cage penetration is planned for improved coverage



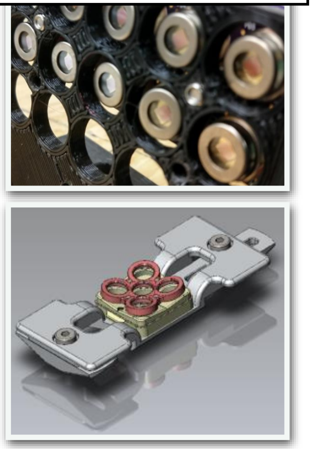
The IoLaser System

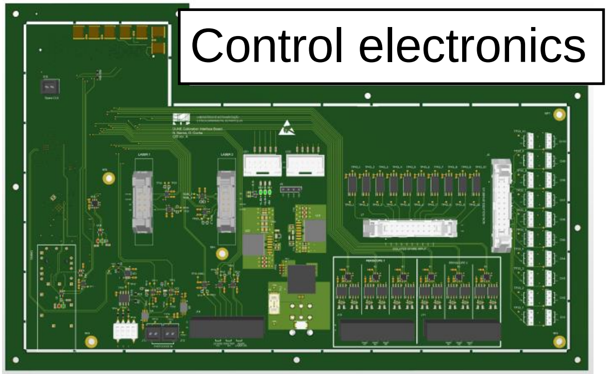
- One laser system, with a laser (Nd:YAG, 266 nm) and a laser box, including an optical bench
- One optical feedthrough and periscope system
- Two laser beam location systems (one active and one passive) to verify beam position requirement
  - Precision of 5 mm over 10 m
- One set of custom electronics for control and monitoring (CIB)



Periscope

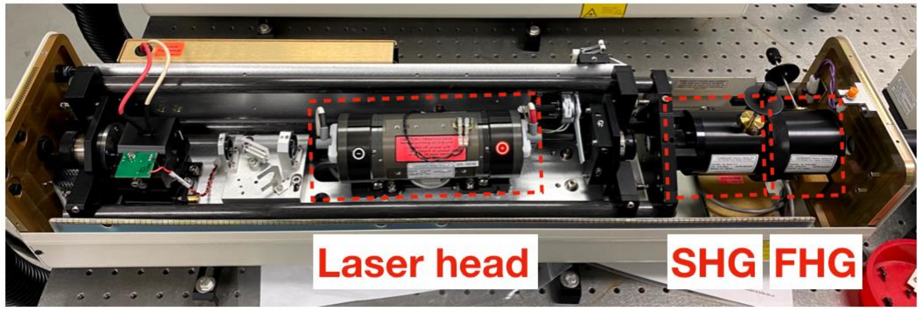
Beam location

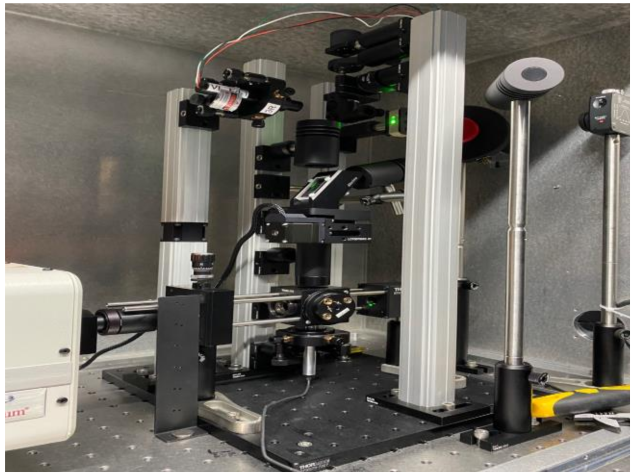


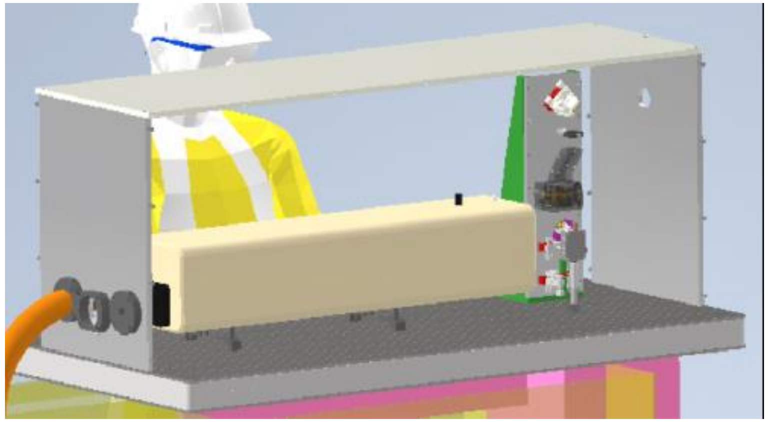


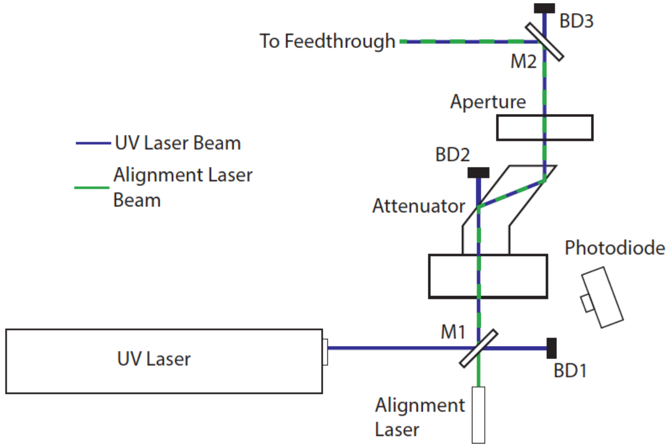
The laser system

- Based on MicroBooNE/SBND design
  - Class-IV UV laser
  - Attenuator to regulate intensity
  - Aperture to limit beam spot
  - Photodiode to monitor pulsing
  - Visible laser to align all downstream
  - mirrors
- Class-IV laser safety rated box enclosure

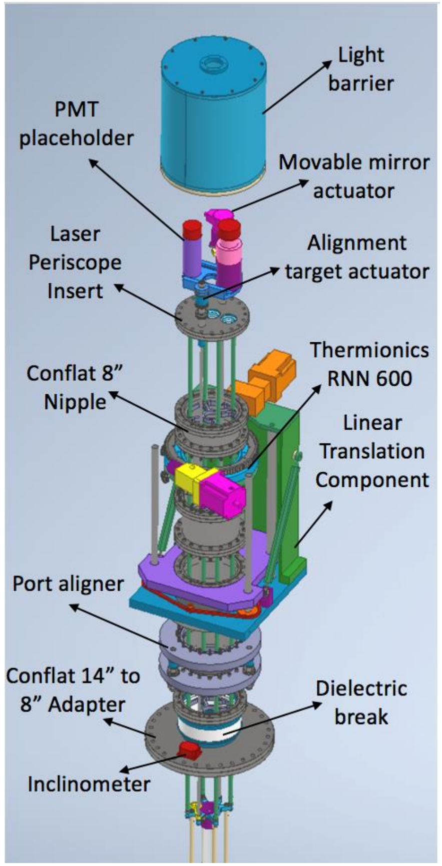








IoLaser periscope – Two available designs

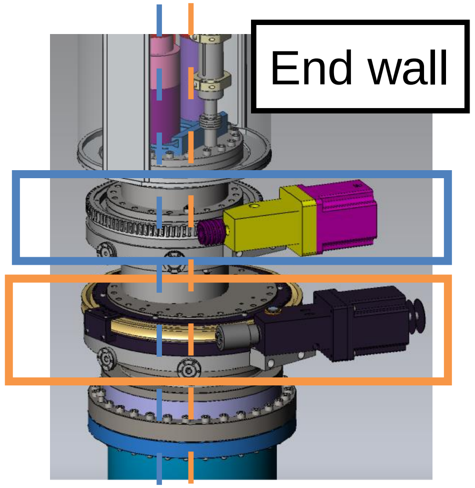


Top-FC

- Top-FC design:
  - FC penetration needed to achieve the required coverage
  - The design includes a retraction feature with 40 cm travel
- End-wall design:
  - Implement two eccentric rotary stages with parallel rotation axes to facilitate the coverage through the obstacles
  - No FC penetration needed

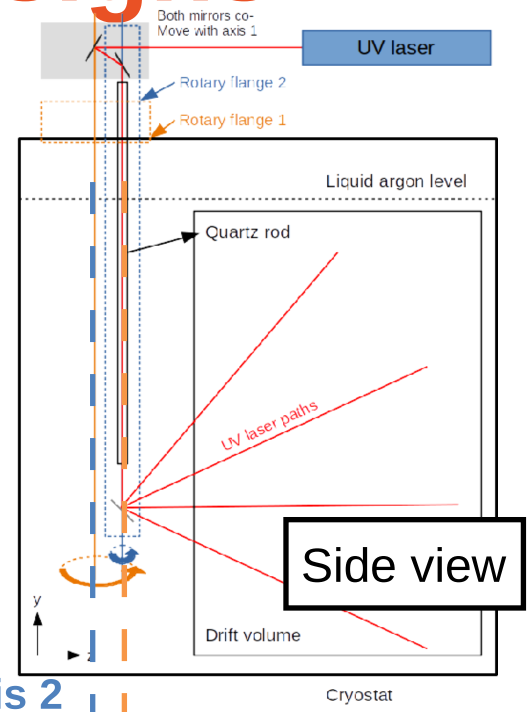
Rotary stage 2

Rotary stage 1



Rotation axis 2

Rotation axis 1



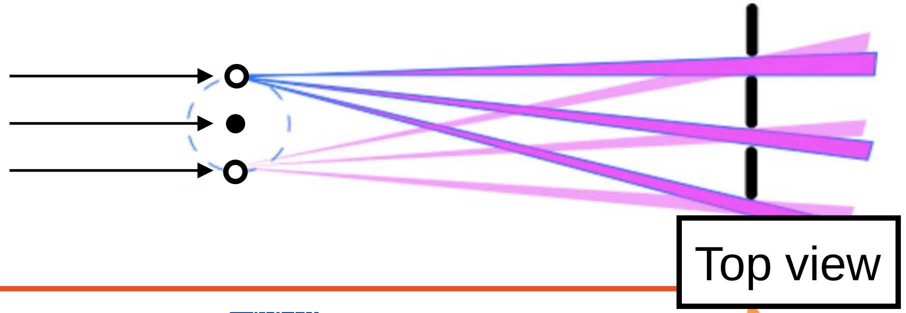
Rotation axis 2

Rotation axis 1

Rotation axis 1

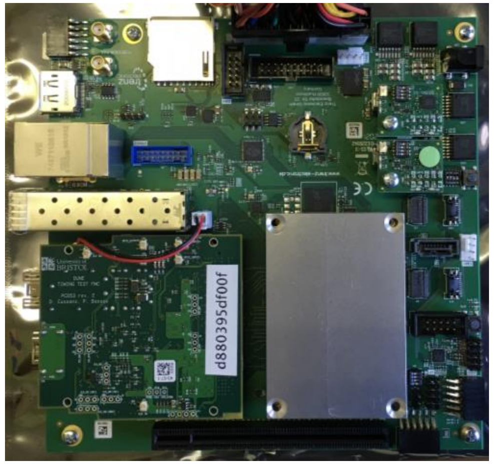
Rotation axis 2

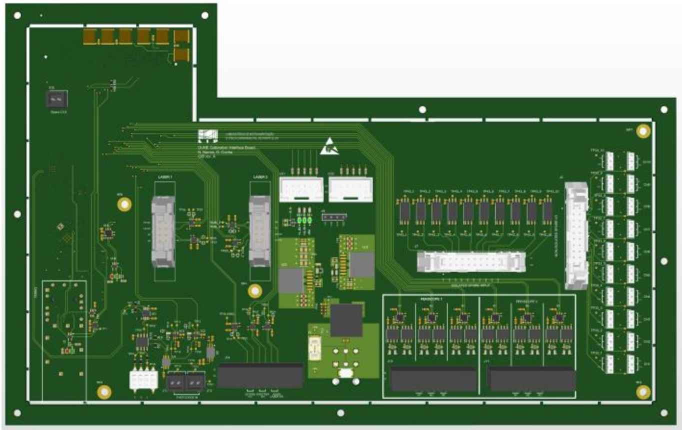
Rotation axis 1

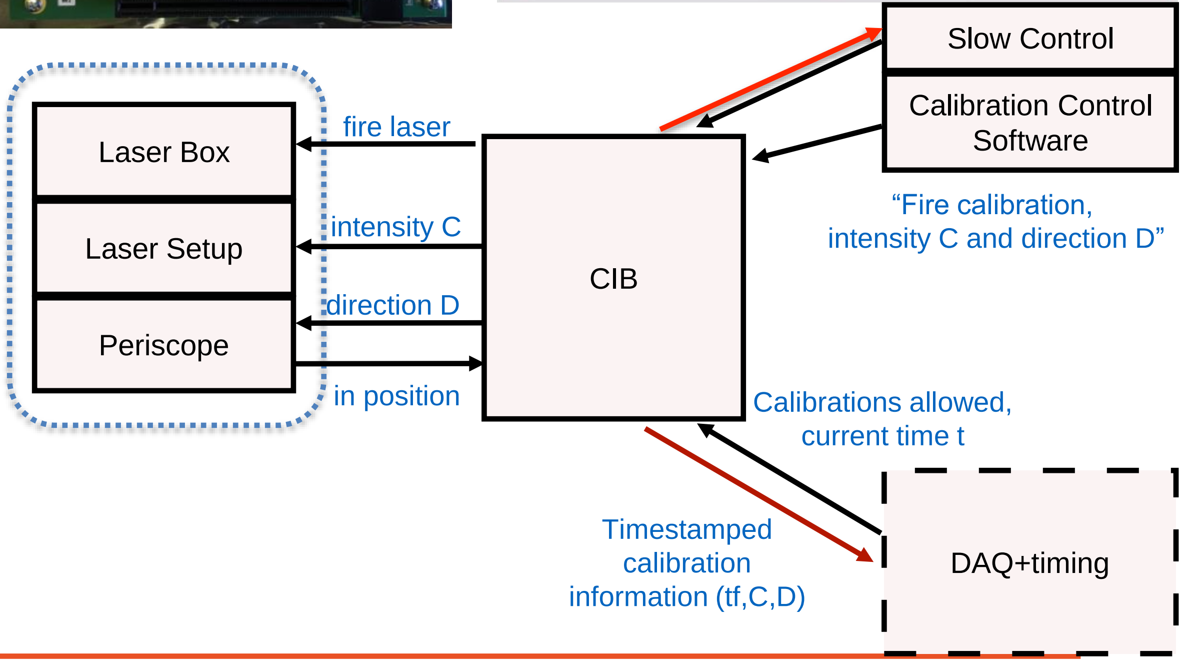


Calibration Interface Board (CIB)

- Custom electronics board with FPGA/CPU to interface Control, DAQ and the IoLaser subcomponents
  - Trenz TEBF0808 with TE803 SoC
    - Xilinx UltraScale+ FPGA + quad-core Cortex-A53 CPU
    - Custom electronics daughterboard with specific interfaces
- Interfaces
  - Timing (FPGA)
    - Receive clock, commands
- Control (CPU/FPGA)
  - Interface between Slow Control (OPC-UA) and all subcomponents
  - Communication with motors/encoders
  - Communication with laser system components
- DAQ (CPU)
  - Receive “fire allowed” signal through the timing system
  - Send firing time and direction

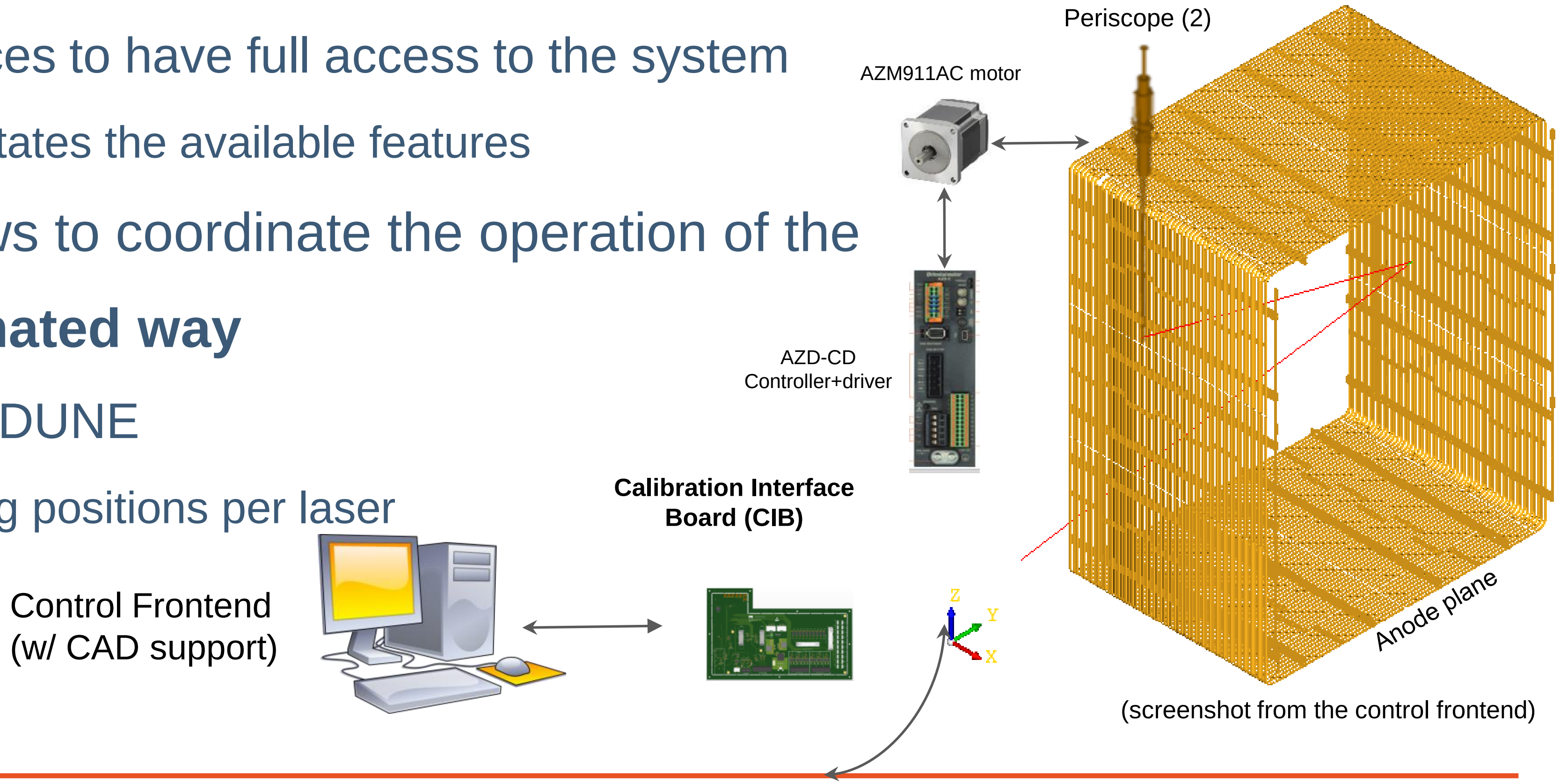






Operation of the IoLaser system

- Through the CIB, all IoLaser components are remotely controlled using custom operator software (implemented with Open-Cascade)
  - Interface shared with Slow Control (OPC-UA)
  - This allows both interfaces to have full access to the system
    - User authentication dictates the available features
- Centralized control allows to coordinate the operation of the whole system in an **automated way**
  - Critical for operation in DUNE
    - Thousands of sampling positions per laser

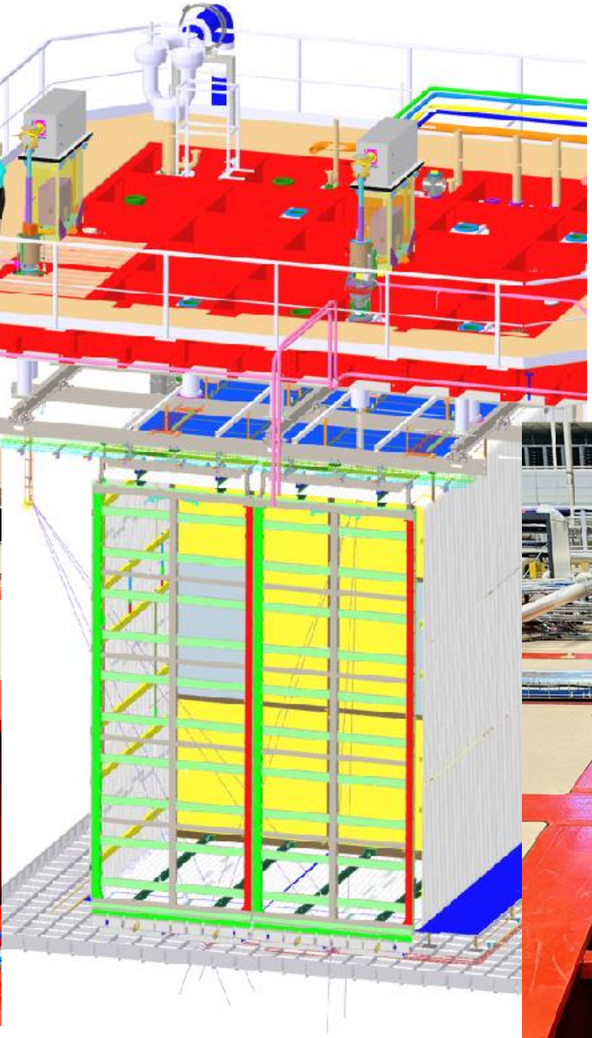


(screenshot from the control frontend)

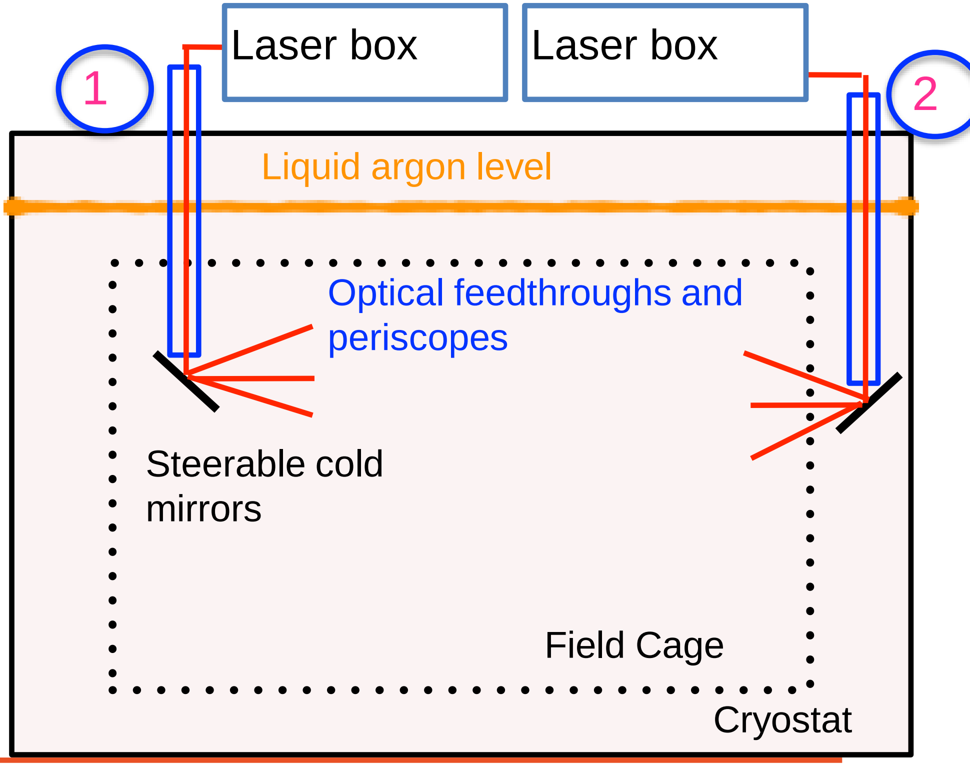
Installation at the CERN Neutrino Platform

- Two complete prototypes being installed in ProtoDUNE-HD
  - P1: internal, retractable
  - P2: external, extra movement
- Third periscope being installed in ProtoDUNE-VD

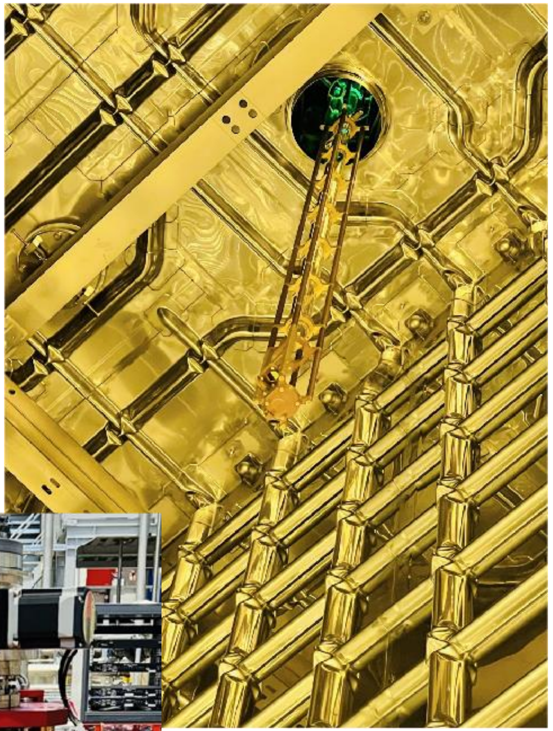
Periscope 2

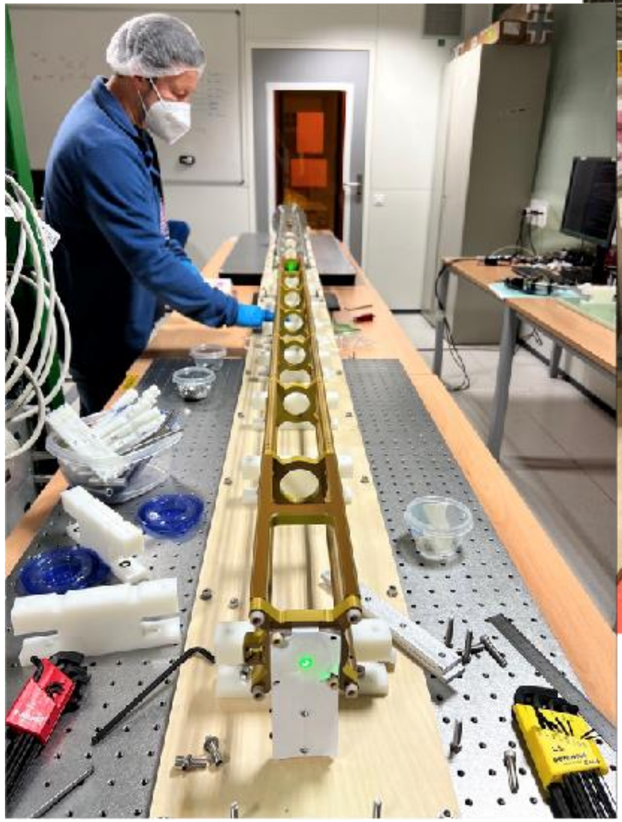


Periscope 1



IoLaser installation at ProtoDUNE





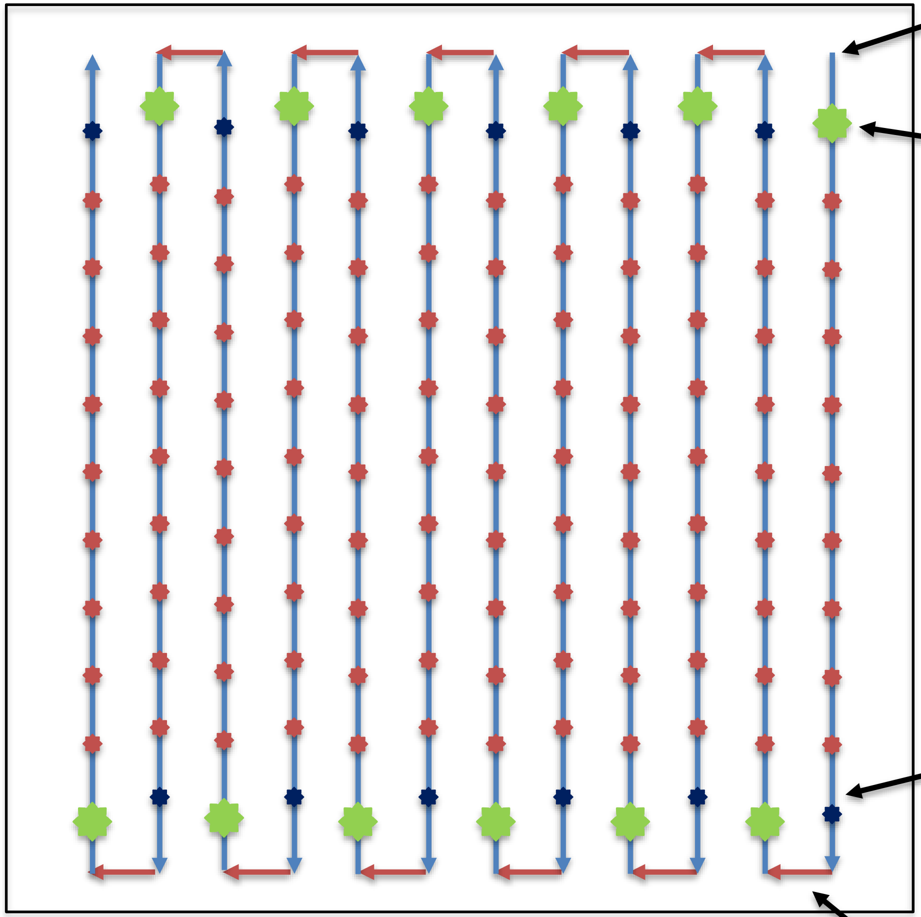
Summary

- The calibration systems play a crucial role for the physics objectives of DUNE
- Various calibration systems under development, both internal (relying on known sources such as muons) and external (relying on specifically designed hardware)
- The IoLaser system has been developed to calibrate the detector charge-readout properties
  - Electron lifetime, field homogeneity, space-charge effects
- These systems build upon past experience and add extra features, to handle the challenges of DUNE
  - In particular the automated operation is a critical aspect for DUNE
- Two fully functional prototypes of each IoLaser systems are being installed at CERN to be operated during ProtoDUNE Run 2
  - Validation of calibration systems in ProtoDUNE Run 2 is a critical step towards DUNE

Backup Slides

IOLaser automated operation

Laser firing at 10 Hz (position determined from motor speed and starting firing position)



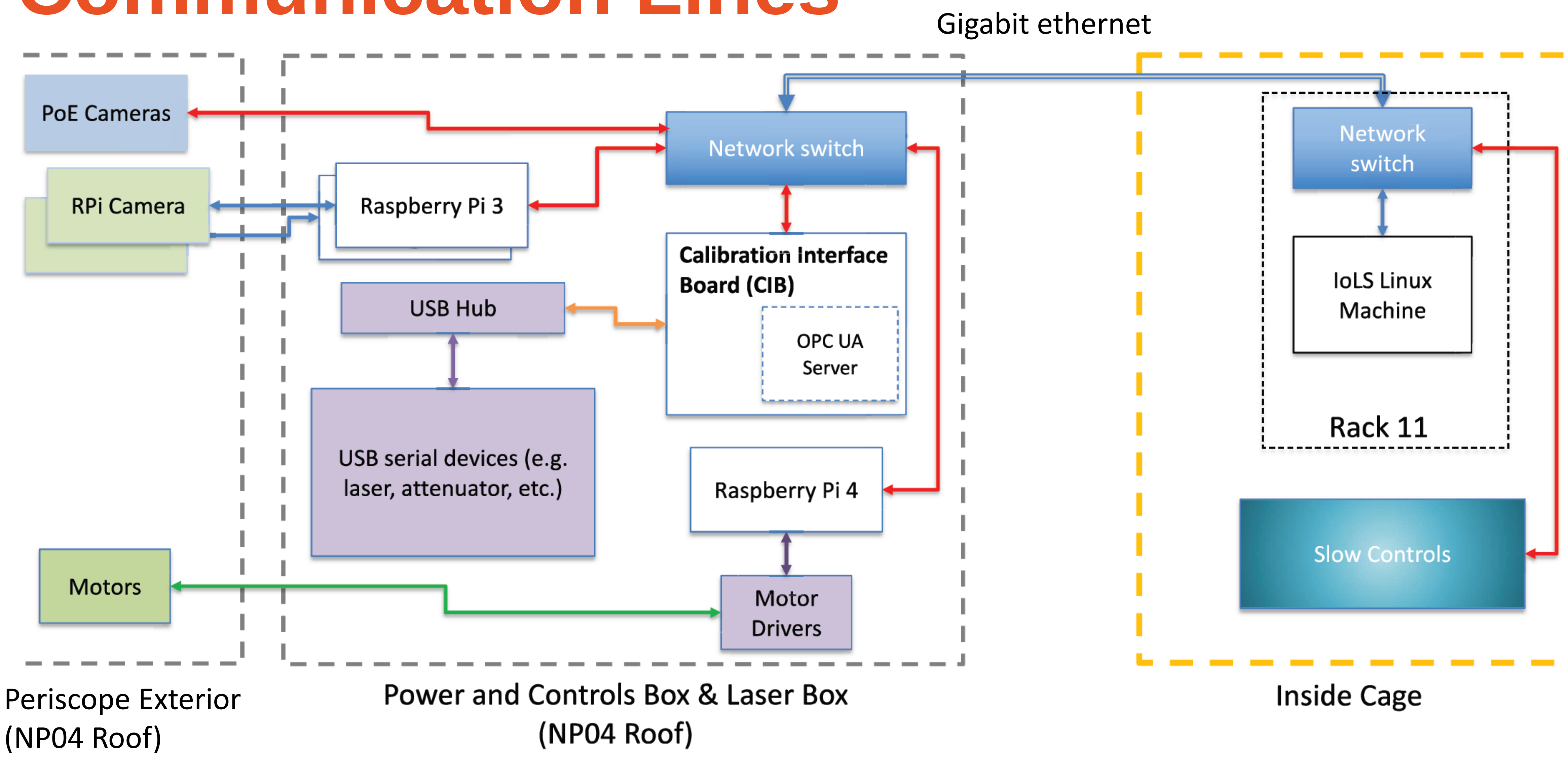
Start motor movement

Start laser firing (once motor is at constant speed)

Stop laser firing (computed from start position and motor configuration)

Mirror repositioning

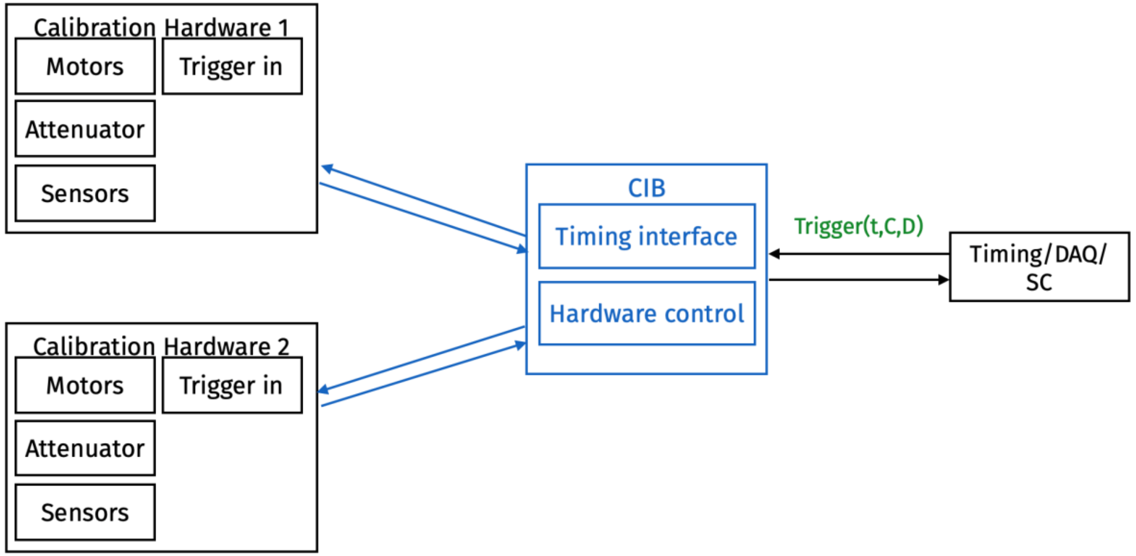
Communication Lines



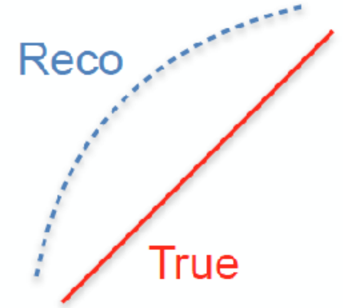
Calibration Interface Board (CIB)

- **Electronics board with FPGA/CPU to interface Control, DAQ and the IoLaser subcomponents**
  - Similar principle as ProtoDUNE-SP I trigger system (CTB)
  - SoC implementing FPGA fast logic and CPU to implement high level processing and ethernet communication with DAQ/SC

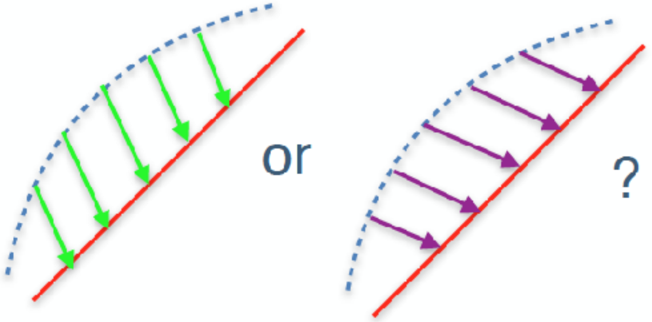
- **Implemented interfaces**
  - **Timing (FPGA)**
    - Receive clock, commands and send firing time
  - **Control (CPU/FPGA)**
    - Interface between Slow Control and different subcomponents
    - Communication with motors/encoders (through ethernet)
    - Communication with laser components
  - **DAQ**
    - Receive “fire allowed” signal through the timing system
    - Send firing time
    - Send laser position/direction



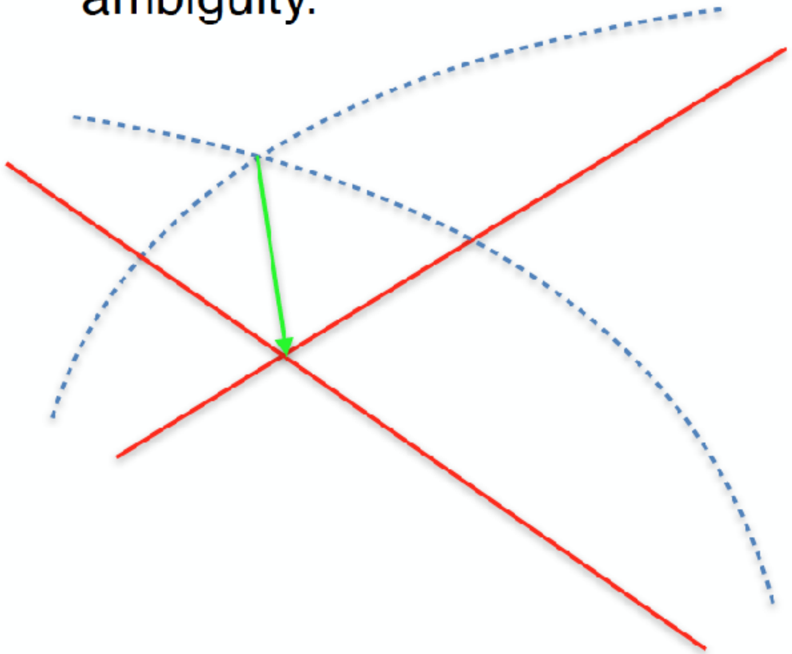
Why Need Crossing Tracks?



- What are the displacements if we see this?



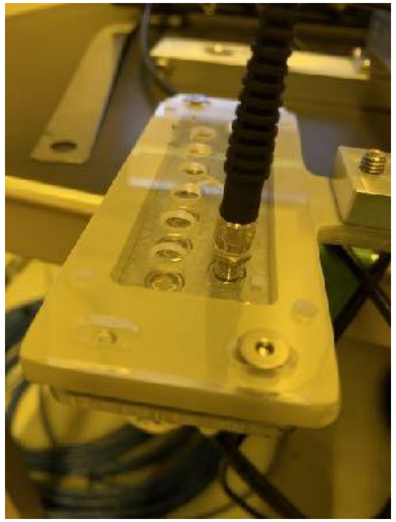
- With tracks from different lasers crossing in the same point, there is no ambiguity.



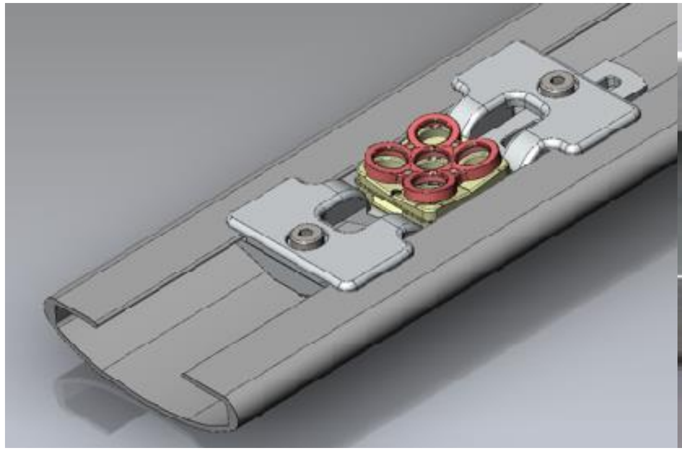
- Hard to get crossing tracks in all volumes, so we need other ways to get displacement

Laser beam location systems

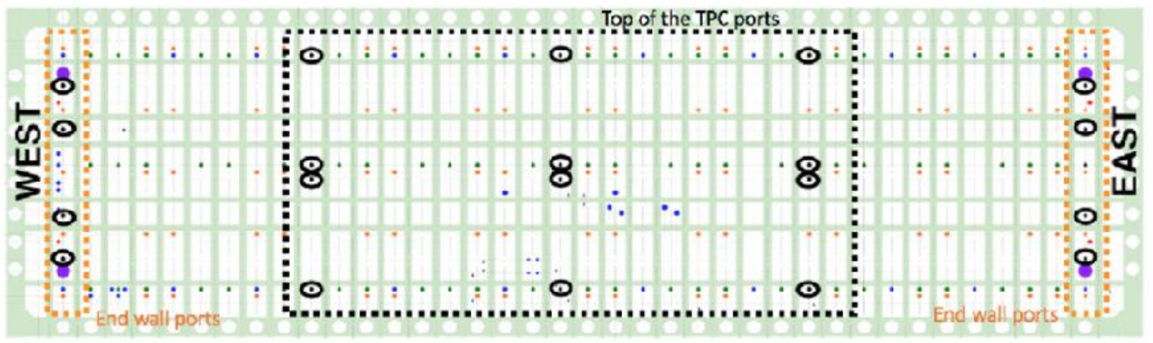
- E-field measurement is based on measuring deviations from straightness of laser tracks
- Two independent in-situ systems:
  - PIN diode
    - Active system with unbiased pin diode assembly at known positions
    - Laser is aimed and use pin diode readout to determine laser beam spot



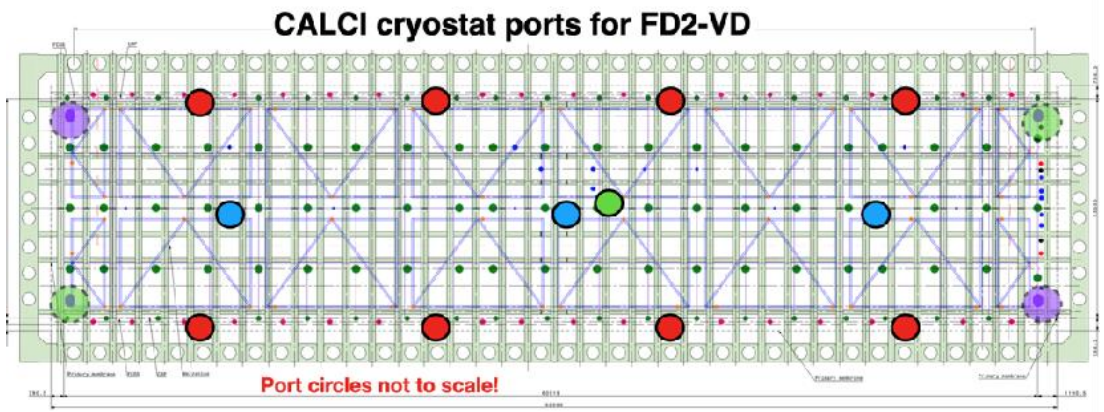
  - Mirror pad System:
    - Mirror assemblies with 5 mirrors at different angles
    - Mirrors in known positions in FC profiles
    - know beam hits them when the TPC sees reflected ionization track (requires TPC data)



Laser at FD1 and FD2



- FD1 available ports:
  - 12 on top of TPC
  - 8 after end-wall

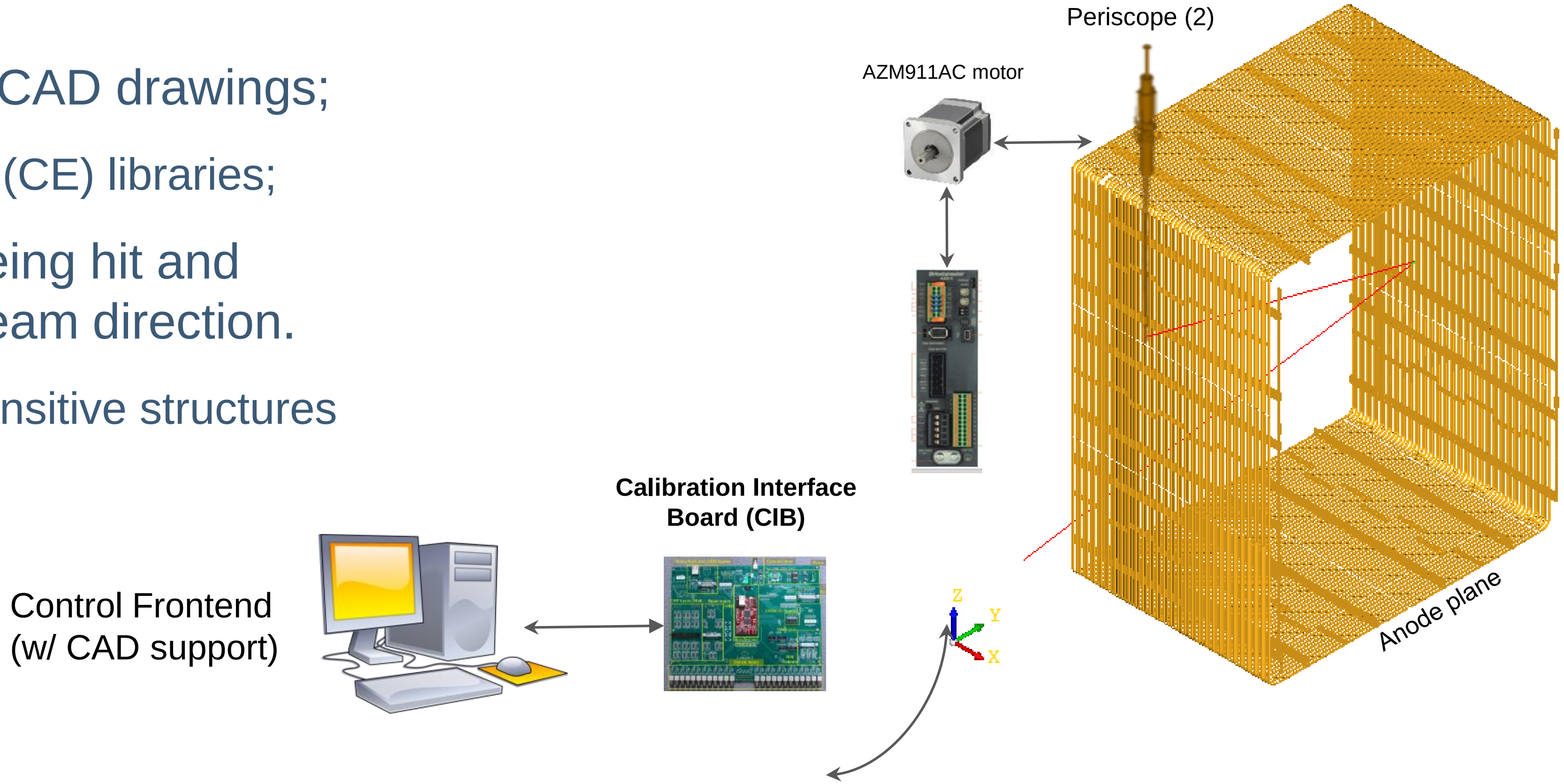


- FD2 available ports:
  - 4 on each side

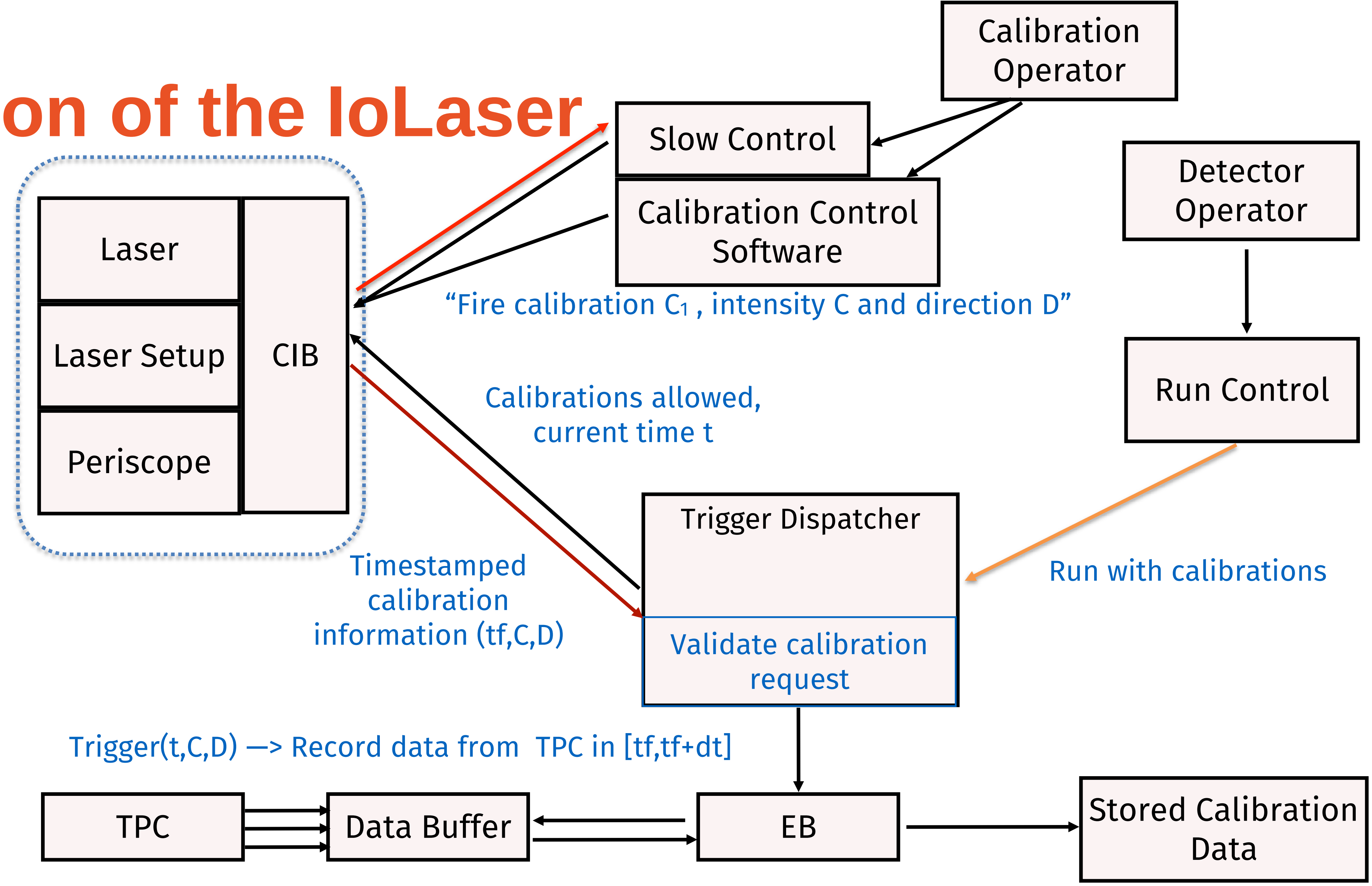
- Working scenario: 10 ports at FD1, 8 ports at FD2, with possible sharing of lasers between some (to reduce cost)
  - double beam coverage (E-field) only in some regions

Control software: user interface

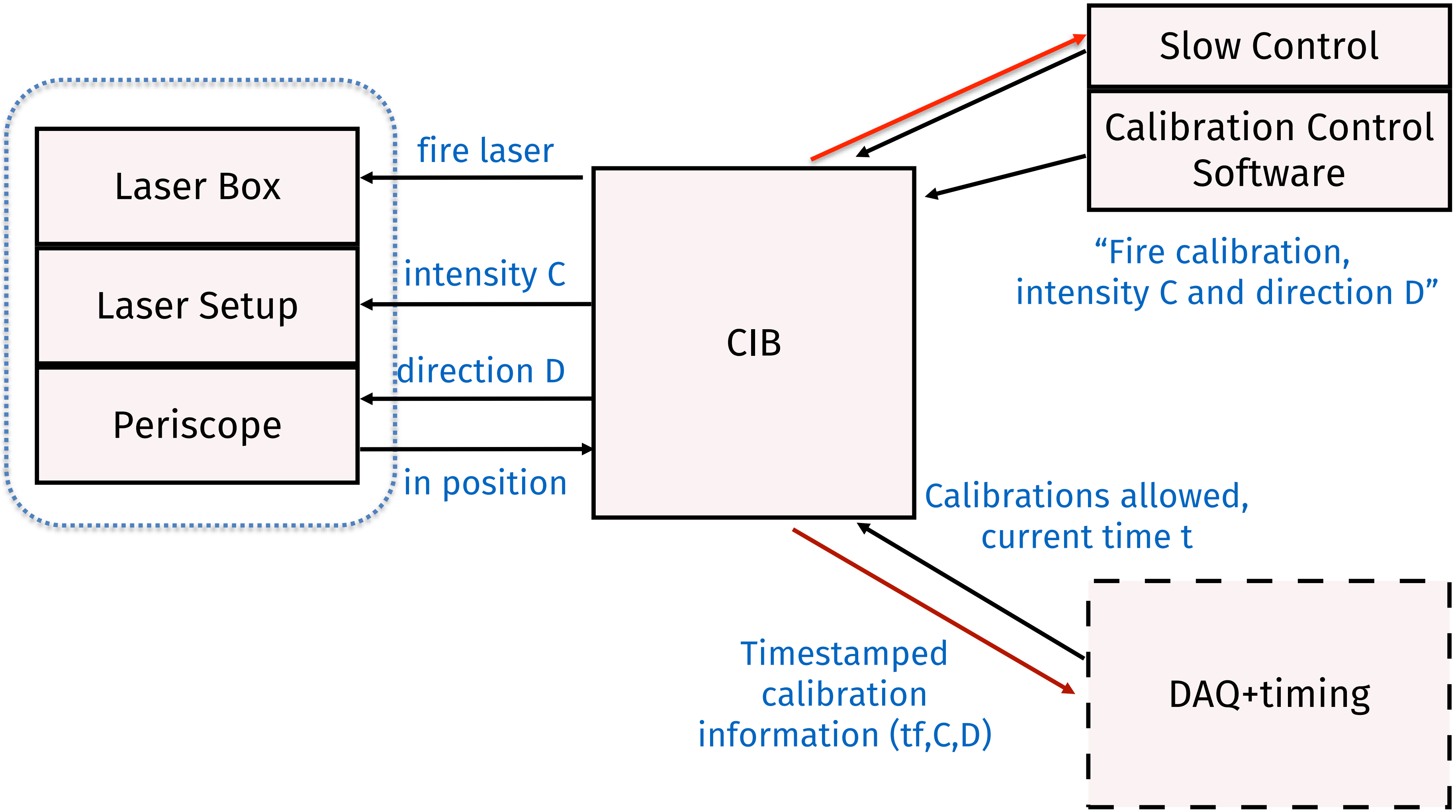
- Frontend to operate/control the periscope and navigate the laser beam through the FC:
  - Uses directly the existing CAD drawings;
    - Based on OpenCascade (CE) libraries;
  - Able to identify the part being hit and determine the reflected beam direction.
    - Critical to avoid hitting sensitive structures (e.g. PDS)



Operation of the IoLaser



Calibration Interface Board



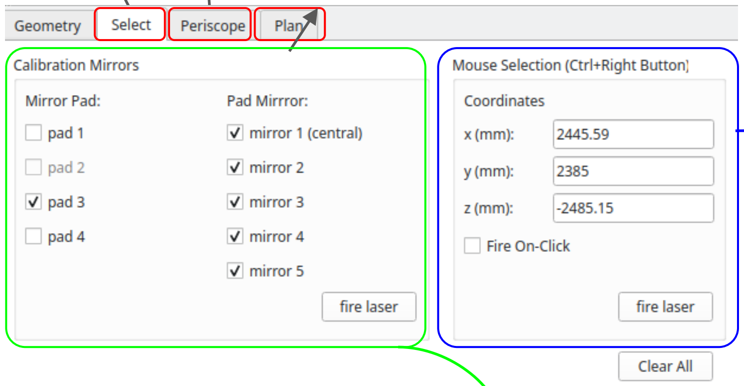
Control software: user interface

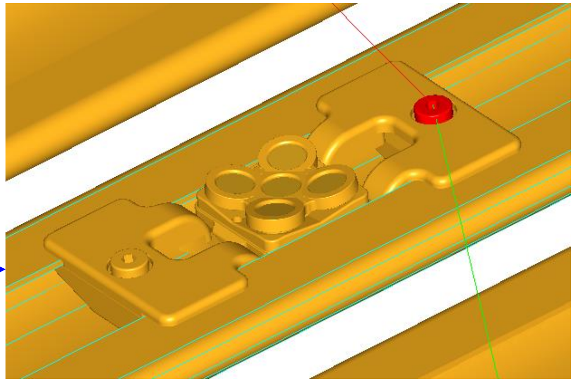
Francisco Neves

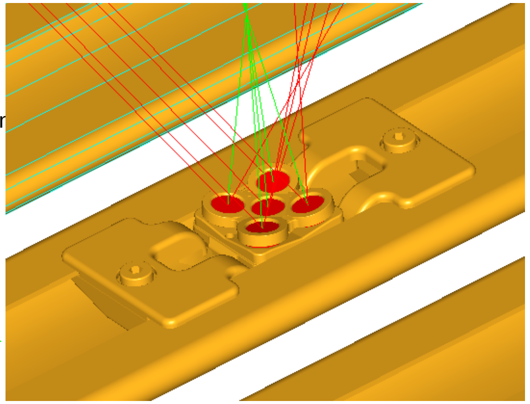
Select mirrors or target points using the mouse

Actuate directly the **periscope** motors (angles/motor steps) - *ongoing!*

Plan a calibration sequence by moving the periscope and firing the laser at predefined positions - *ongoing!*







Note: firing the laser will be interlocked/managed with the CIBs for security!

(screenshot from the control frontend)