GRAIN: progress report

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on behalf of

GRAIN working group
Biweekly meetings (recorded): Thursday 11:00 on specific arguments
Mailing List: dune-nd-sand-grain@fnal.gov
Indico page: https://indico.fnal.gov/category/1403/

SAND Technical meeting– 21 Jun 2022

OUTLINE

- Overview of the activities

Focus today on:

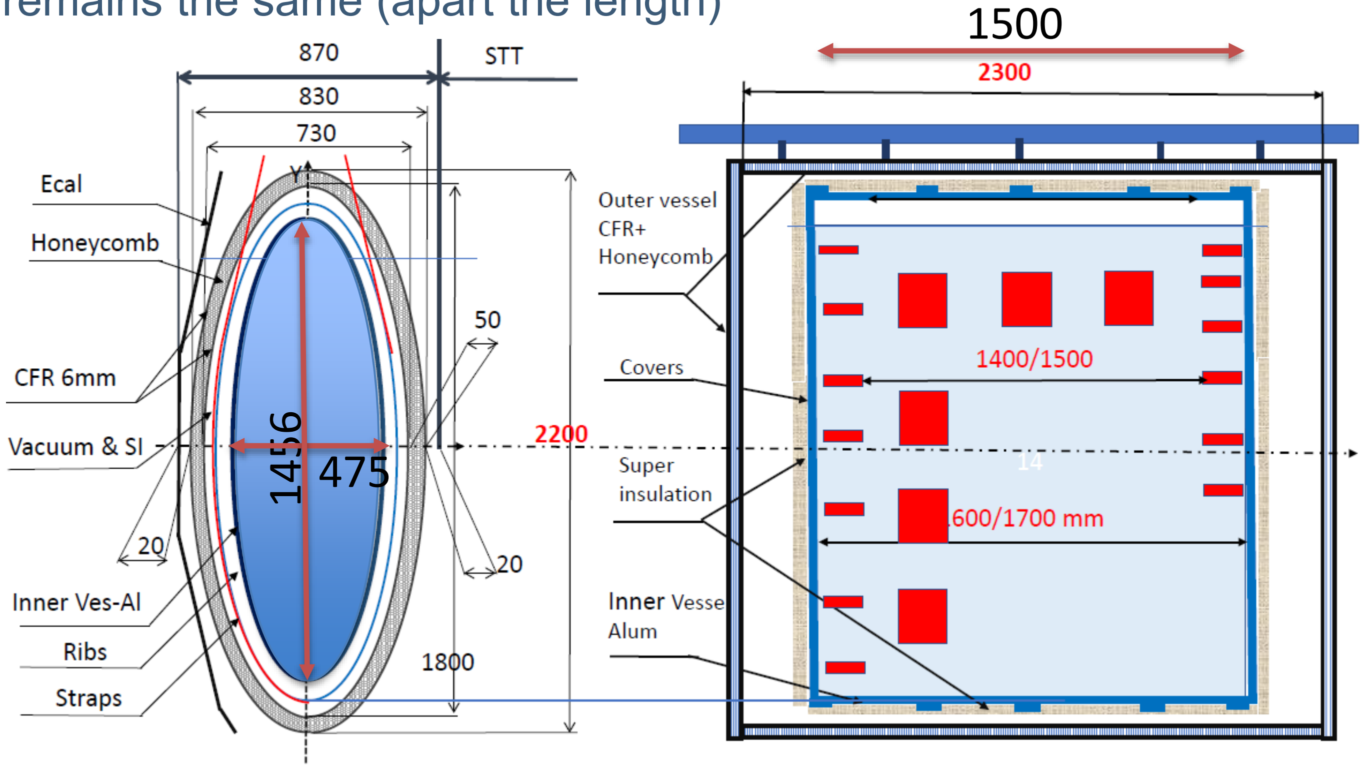
- Cryostat prototype
- Cryogenic readout electronics
- Timeline

Material for internal vessel

- Up to now, internal vessel was assumed to be made of Aluminum:
  - Mechanics needs particular care
  - Steel-Aluminum transition is critical
- Sergio B. proposes to use Steel instead:
  - Most of the stopping power is due to Liquid Argon
  - Probably the current 12 mm of Aluminum thickness can be replaced by 6 mm Steel
  - Big advantage for mechanics
  - Also cryogeny in simpler (avoid Al/Steel transition)
  - External vessel does not change
- Need carefull simulation

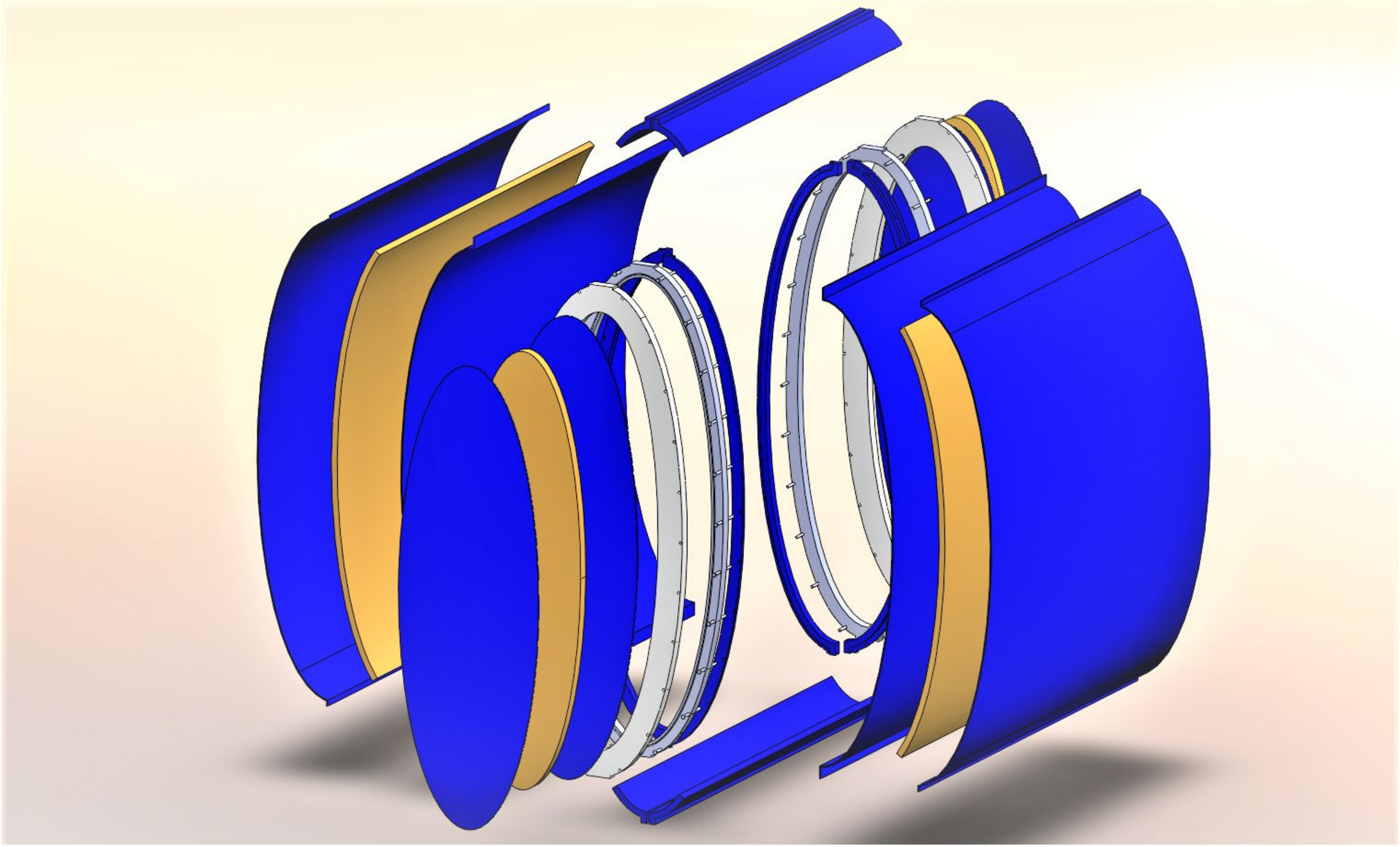
GRAIN updated geometry

- In order to fix some starting point, let's go on with the geometry that was simulated with great details and complying Fermilab rules
  - Change only the length from 1300 to 1500 mm, in order to guarantee a Lar fiducial volume close to 1 Ton
  - Mechanics Team is working to produce and verify this new design, including the change of material
  - External vessel remains the same (apart the length)



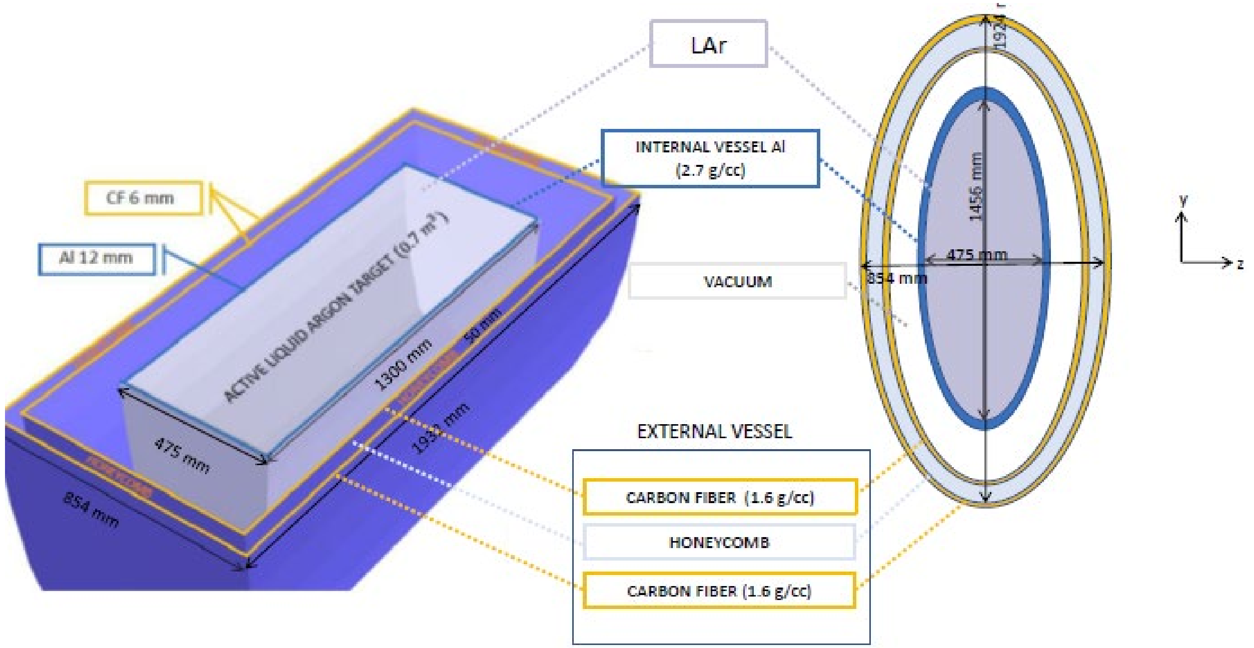
Grain Cryo 1 ton Lar fiducial volume - tentative dimensions

Design of external vessel – preliminary!!



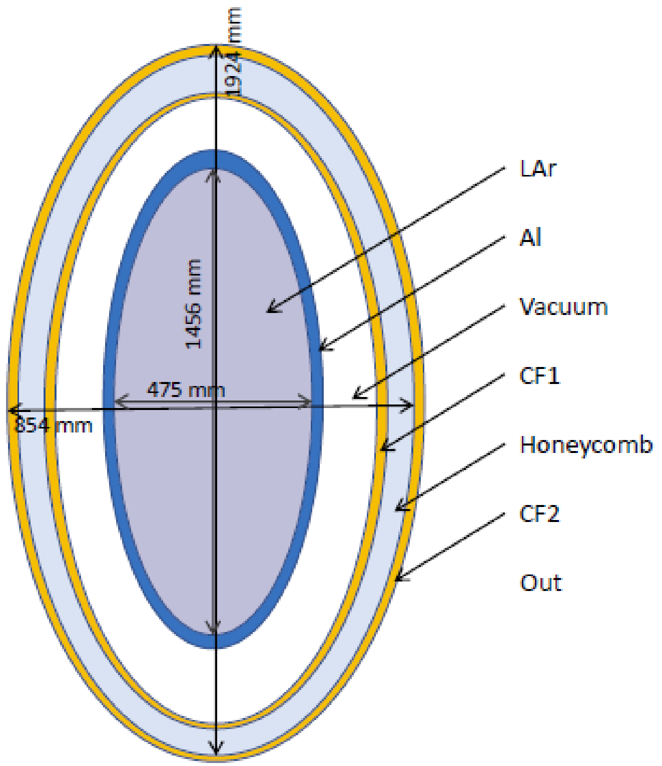
Simulation studies

- Neutrinos energy spectrum from FHC LBNF beam
- 90k interactions of ν_μ (ν_e) generated with Genie (v.2) in Lar volume of GRAIN
- Final state particles propagated through SAND with EDepSim

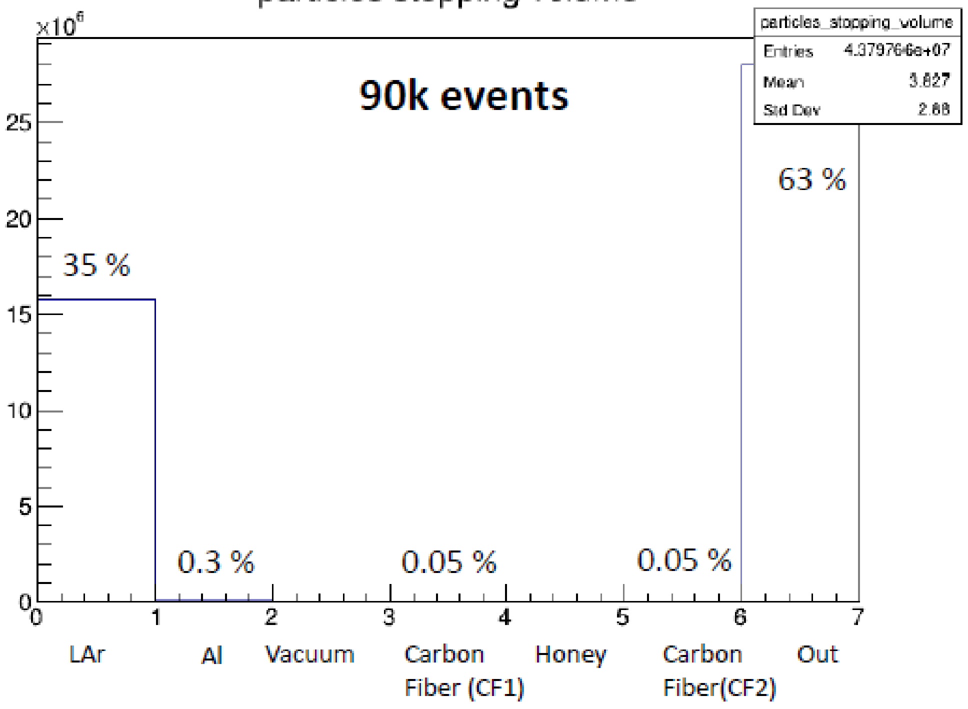


Interaction in and out GRAIN (ν_μ)

ALL TRACKS (primary, secondary, charged and neutral)



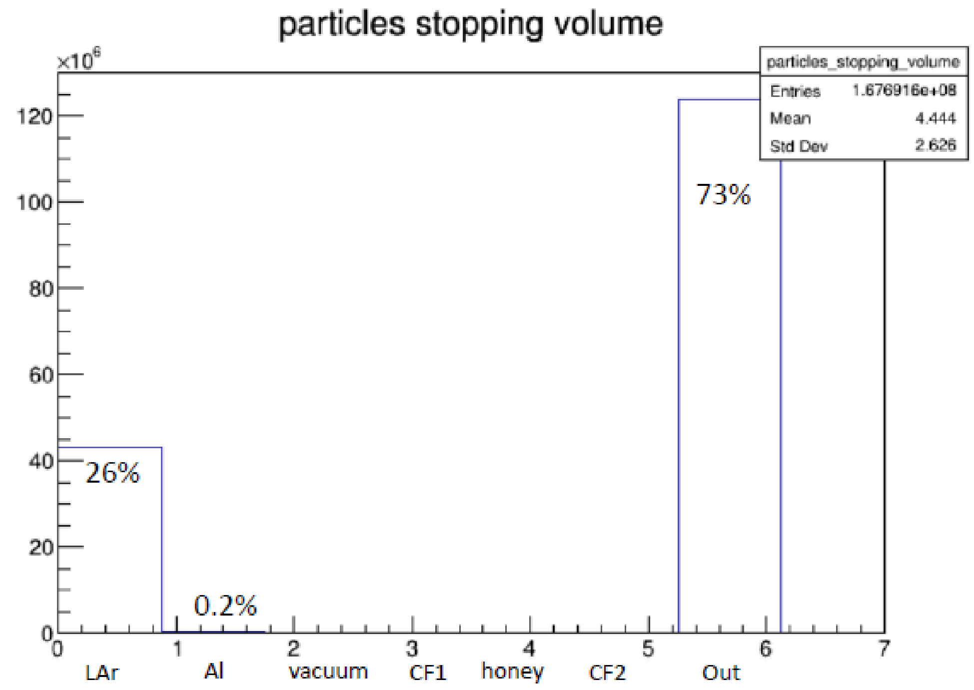
$\nu_\mu - Ar$ interactions



Interaction in and out GRAIN (ν_e)

ALL TRACKS (primary, secondary, charged and neutral)

$\nu_e - Ar$ interactions



Preliminary summary

$\nu_\mu - Ar$ int.	LAr	Al vessel	CF vessels	Out of GRAIN
μ	2.3 %	0.3 %	0.1 %	97.3%
Primary p	80 %	3.6 %	1.4 %	15 %
Primary n	40 %	4.4 %	2.2 %	52 %
Primary $\pi^{+/-}$	40 %	4.2 %	2.2 %	54 %

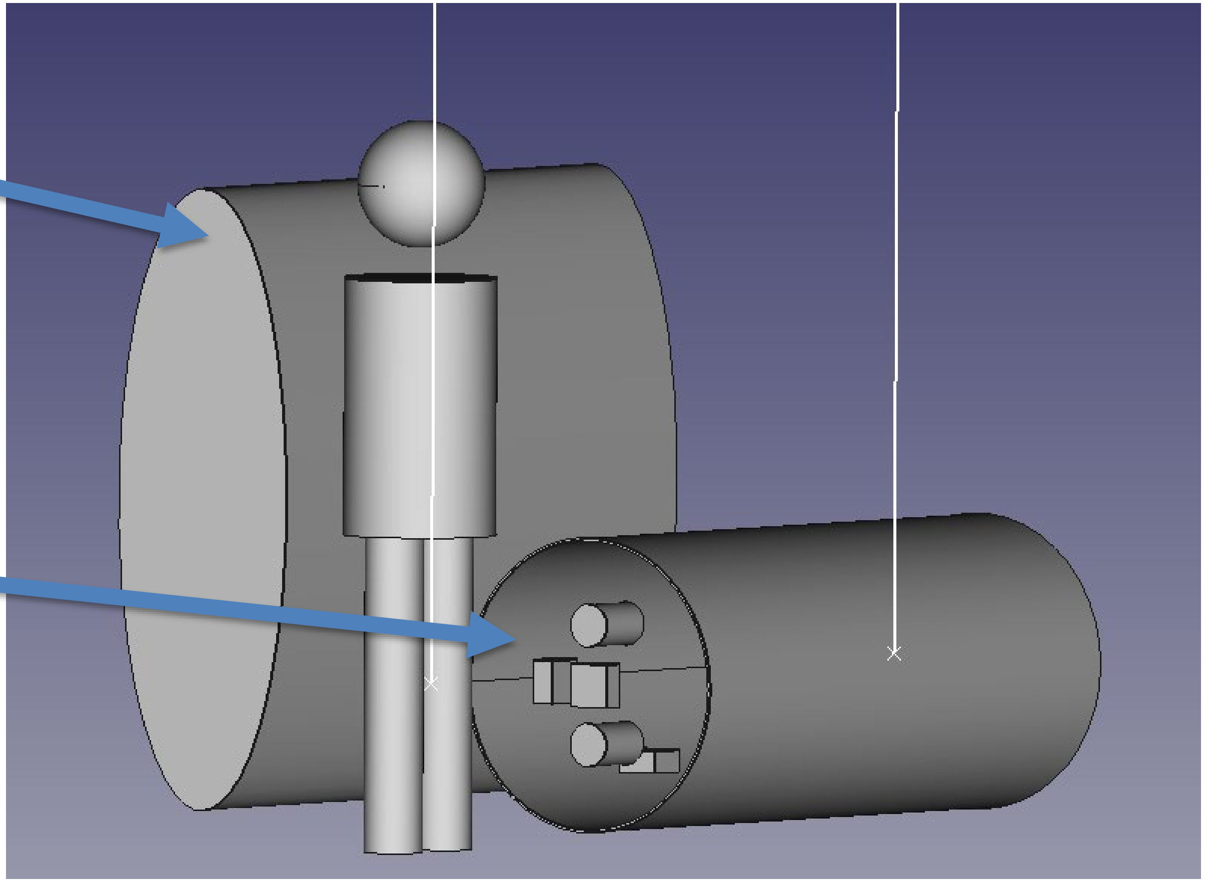
$\nu_e - Ar$ int	LAr	Al vessel	CF vessels	Out of GRAIN
e	26.8 %	5.6 %	3 %	64.6 %
Primary p	78 %	3.7 %	1.6 %	16.9 %
Primary n	38.7 %	4.1 %	2.2 %	56.9 %
Primary $\pi^{+/-}$	36.2 %	4.1 %	2.2 %	55.1 %

Proposal for GRAIN prototype

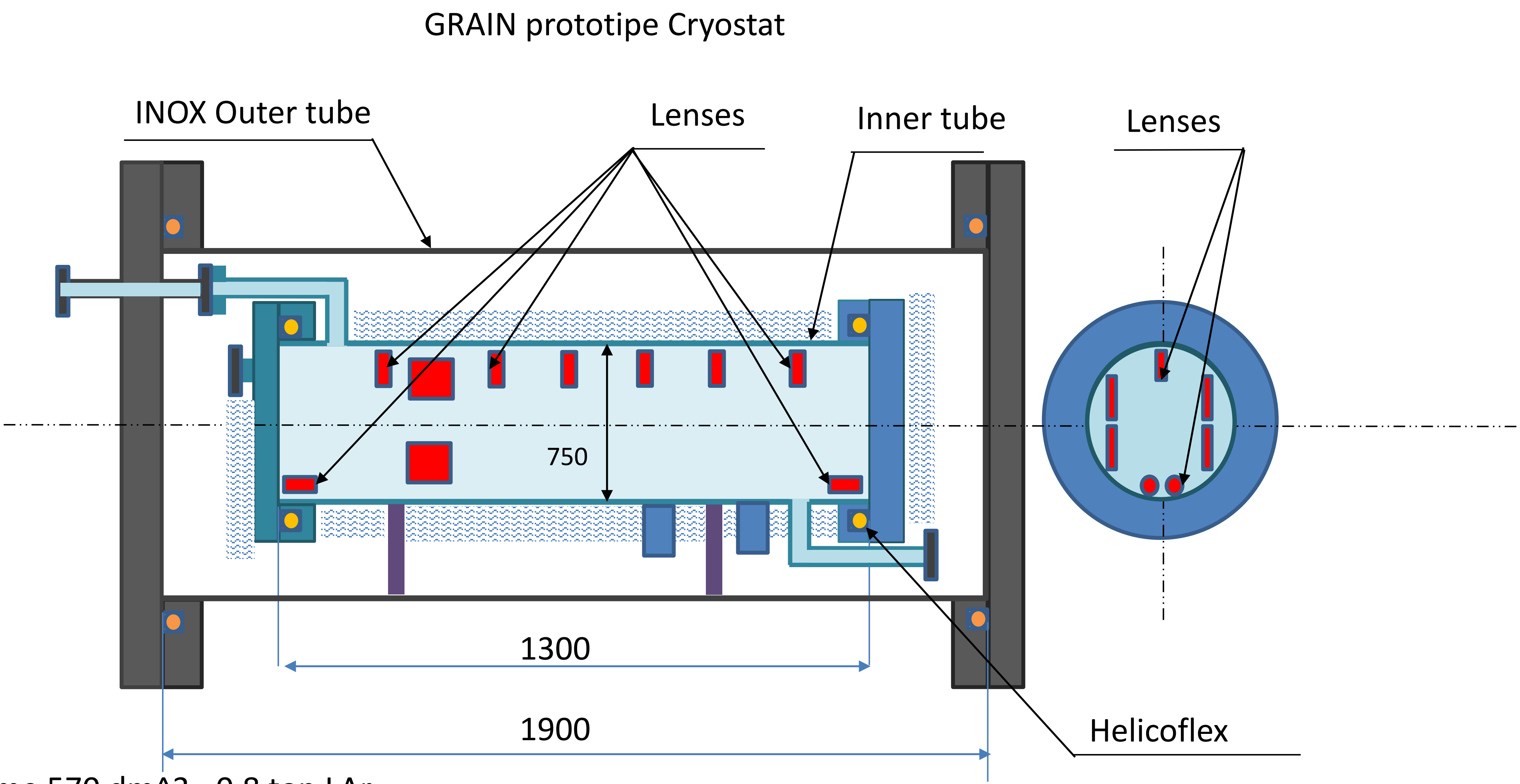
- Two options were discussed:
  - **Full scale** prototype (Sergio B. proposal)
    - “Final” geometry
    - Good test for cryogeny
    - Some parts will be reused in final detector
    - It needs a big external vessel (try to find something already existing in some INFN labs)
  - **Small scale** (Giuliano L. team proposal)
    - Tubular geometry
    - Less expensive
    - External vessel is a simple tube around the internal one (see next slide)

After discussion in GRAIN WG the Full scale prototype seems the preferred solution and LNL the best place were to build and install the prototype

Internal vessel represented for the two options

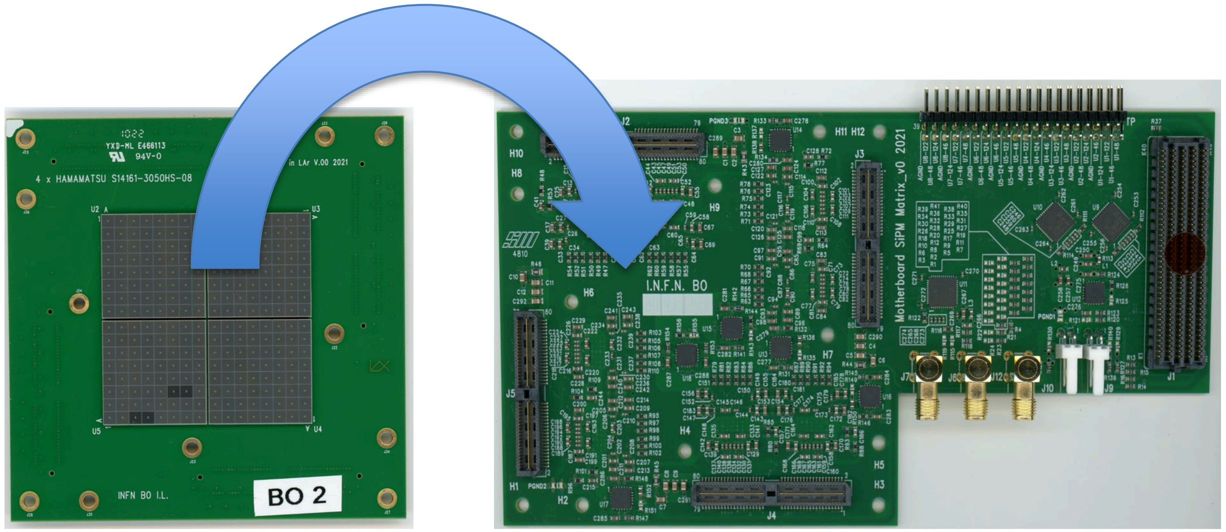


Small prototype proposal



Inner volume 570 dm^3= 0,8 ton LAr

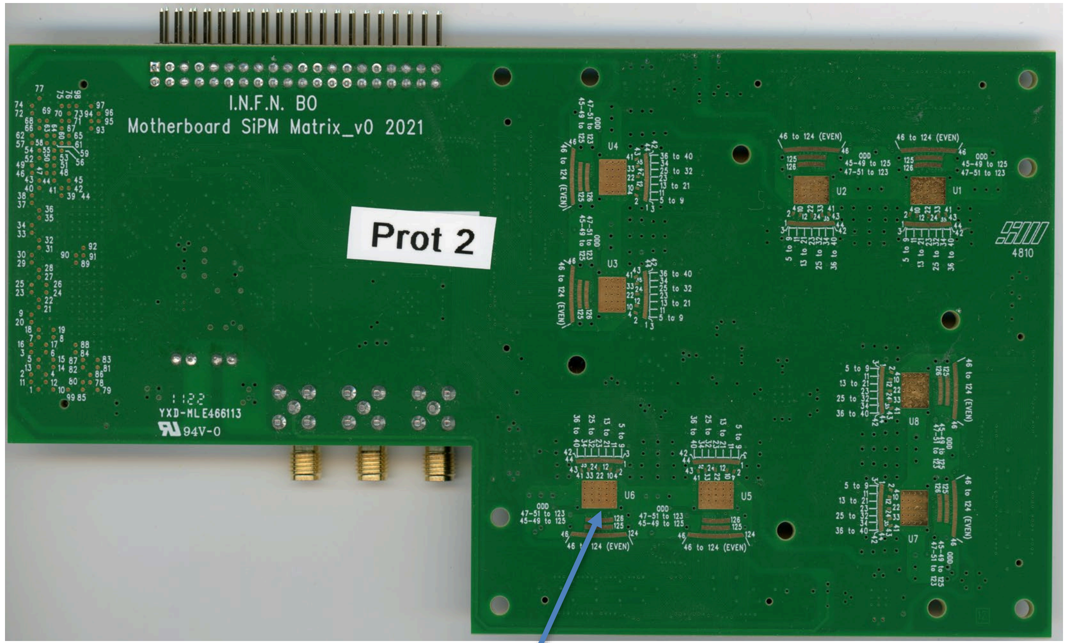
Camera demonstrator



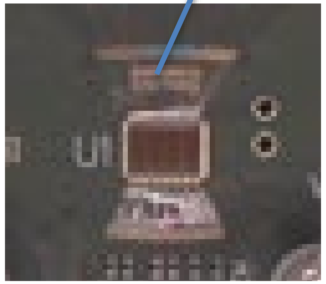
- Matrix of SiPMs mounted on a mezzanine board
- Motherboard contains 8 ASIC (256 ch in total)
- DAQ with FPGA on demo board

Considerations on ASIC

- For this prototype we used the already available ASIC (“Alcor”) developed by INFN-Torino for other target applications
- It features Time Over Threshold frontend and High Rate capability (that implies high power consumption)
- This ASIC as it is now, does not fit perfectly with our needs: dynamic range starting from few photons, lower rate, high multiplicity of channels, but hopefully will allow to start dealing with real data.
- ASIC development for our specific case is critical..

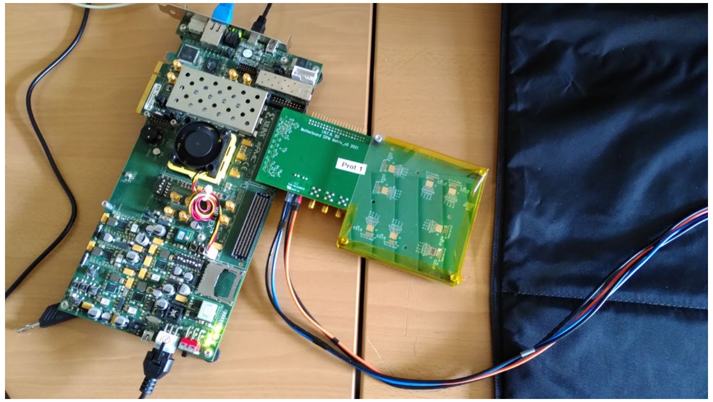


8 ASIC
Wire-bonded



Preliminary test and debug on electronics

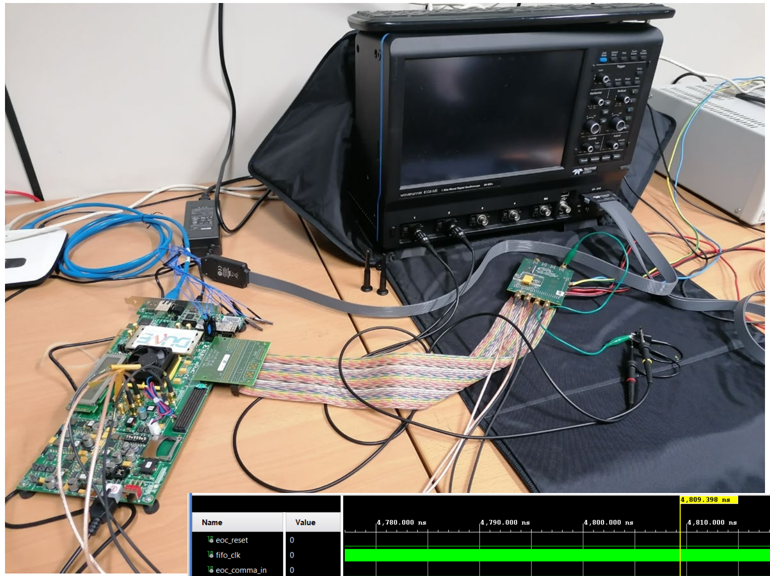
- Write firmware for communication with Alcor ASICs with SPI serial interface – done
- Correctly configure internal Alcor registers (many parameters!) – we are in contact with the designer of the ASIC to set correct parameters for analog sector
- Read data words from LVDS links and unpack data – done
- Repeat above tests in Liquid Nitrogen – to be done
- Measure IV curves of each SiPM of the matrix in Liquid Nitrogen – to be done
- Connect sensor Mezzanine to Motherboards and test acquisition – to be done

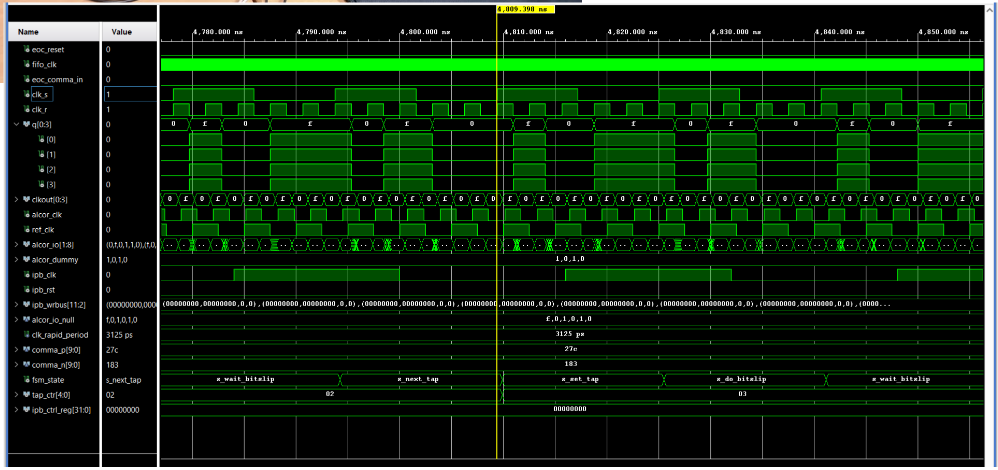


Firmware development

- Firmware interface with ALCOR is under development
  - Test on single ALCOR demoboard
  - Target XilinX VC707, Virtex 7

  - *Already implemented features*:
    - IPbus 2.0 over ethernet with client PC
    - Low jitter clock distribution
    - SPI based slow control of ALCOR
    - LVDS data links @ 640 Mbps from ALCOR
  - *Partially completed*:
    - Fully featured ALCOR emulator for simulation
    - Readout of data frames over Ipbus
  - *To be developed:*
    - Data merging and formatting
    - DAQ and Trigger logic





Some consideration related to schedule

Physics cases:
- only calorimetry
- vertex reconstruction
- track reconstruction

Simulation of GRAIN inside SAND:
- Track matching with STT
- Calorimetry

Simulation of scintillation:
- Yield
- Timing
- Propagation
- Xenon doping

Detector prototype:
- Lens
- Masks
- Sensor Matrix
- Readout

Constraints to mechanics:
- minimal Lar Fiducial
- Thickness of LAr
- Thickness ext vessel
  + material (carbon fiber)
- Thickness int vessel
  + material (aluminum)

Detector design:
- Lens
- Masks
- Electronics (ASIC)

Simulation of det. response:
- Lens (Geant4?)
- Masks
- Electronics (Alcor ASIC)

Reconstruction:
- 3D Lens
- 3D masks voxel
- 2D masks

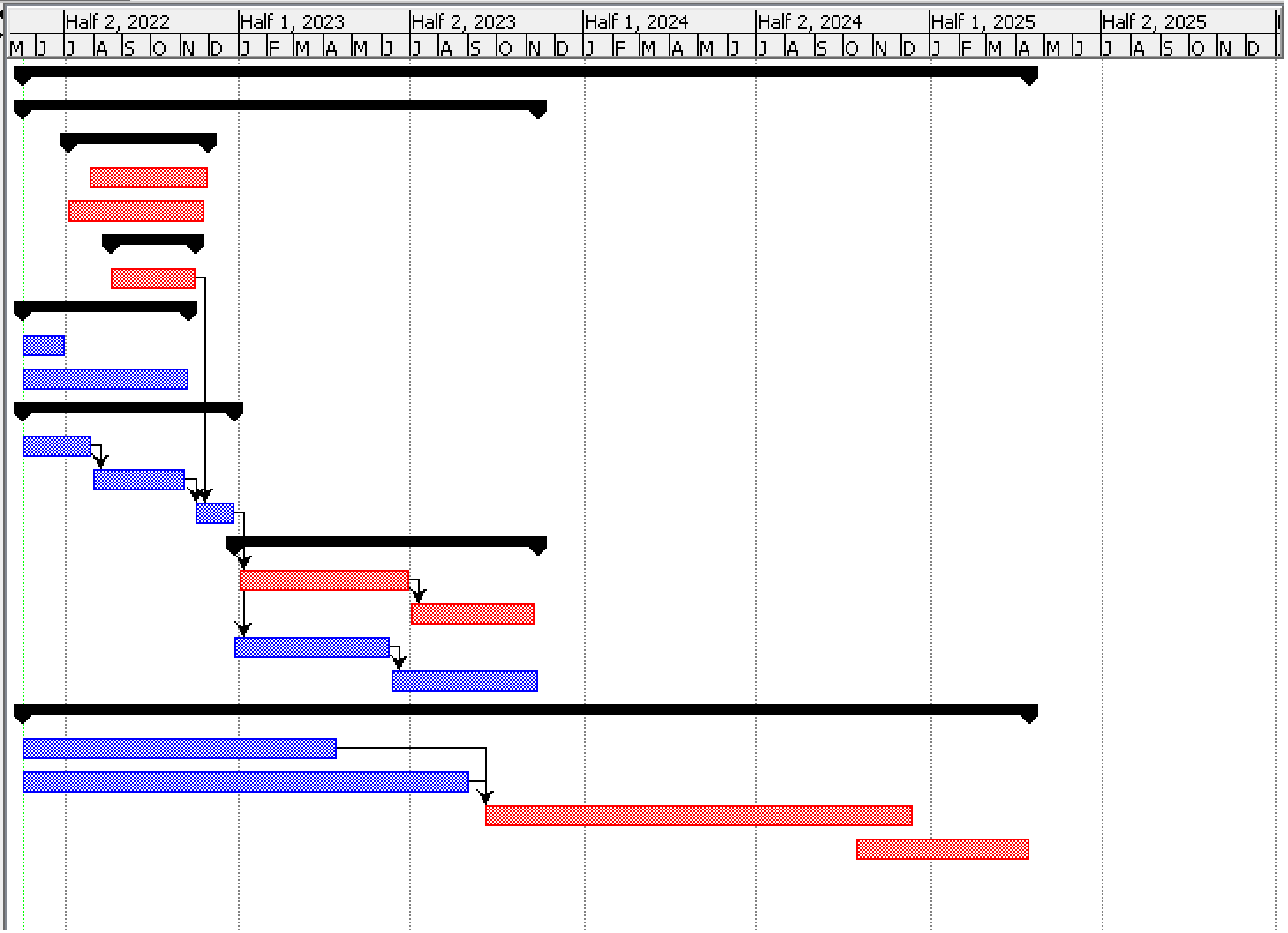
Mechanical design:
- Internal vessel
- External vessel
- Flanges
- Pipe connections
- Protoype

Cryogeny:
- Recirculation
- Purification
- Integration in SAND

Test det. prototype:
- ARTIC setup
- Supports
- Artificial light
- Cosmic trigger
- Detector installation

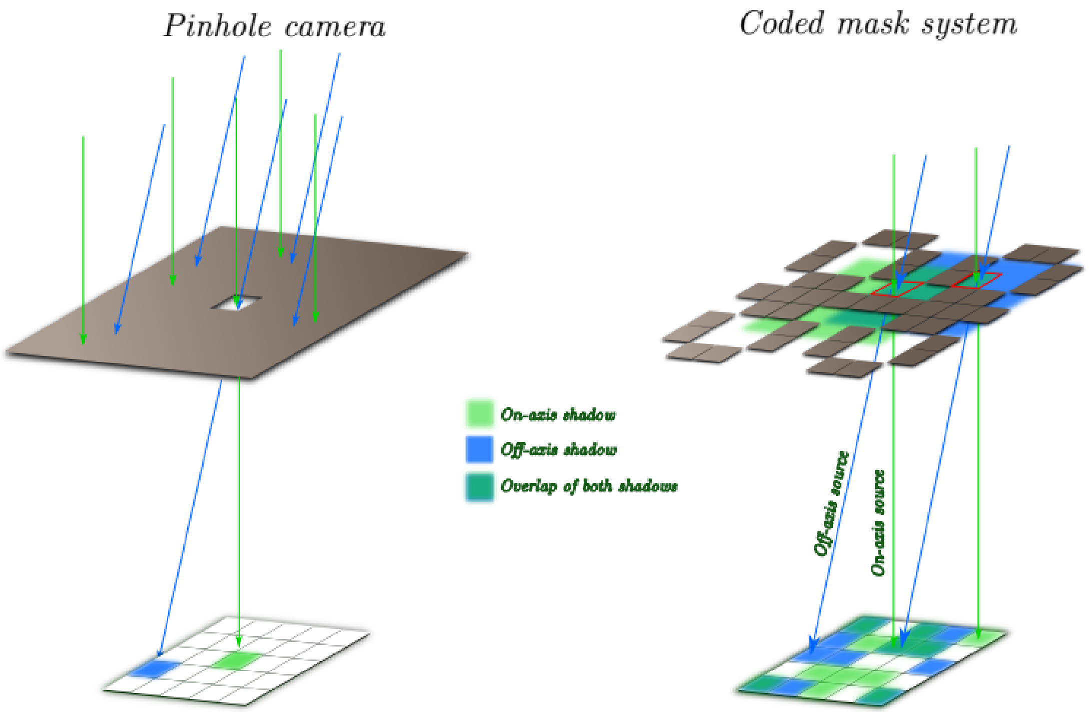
Timeline preliminary

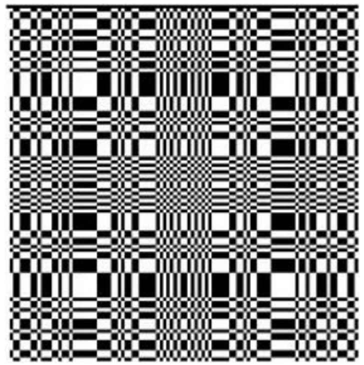
	Duration	Name
1	762 days?	⊟GRAIN
2	390 days?	⊟Prototyping
3	106.375 da...	⊟Mechanics
4	90 days	Flanges
5	104 days	Supports for detectors
6	64.125 days	⊟Photosensors
7	64.125 days	Procurement and WLS coating
8	126 days	⊟Optics
9	33.25 days	Prototype of lens and cryogenic tests
10	126 days	Prototype of coded aperture mask
11	161 days?	⊟Cryogenic electronics
12	54 days?	Production of electronics based on ALCOR
13	70 days	Firmware and debugging of motherboard
14	29 days	Calibration of SIPM matrix in dark box
15	229 days	⊟Test in ARTIC LAr+ Xenon cryostat
16	130 days	Test of lens with light source
17	94.125 days	Test of lens with scintillation light
18	118 days	Test of coded aperture masks with light source
19	111 days	Test of coded aperture masks with scintillation light
20	762 days	⊟Design of cryostat mechanics
21	239 days	Preliminary design and mechanical simulations
22	339 days	Cold electronic feedthrough
23	324 days	Prototype
24	133 days	Final design



Backup

Optics: coded aperture masks





Coded aperture mask techniques were developed as the evolution of a single pinhole camera

- matrix of multiple pinholes to improve light collection and reduce exposure time

Image formed on sensor is the superimposition of multiple pinhole images.

Advantages:

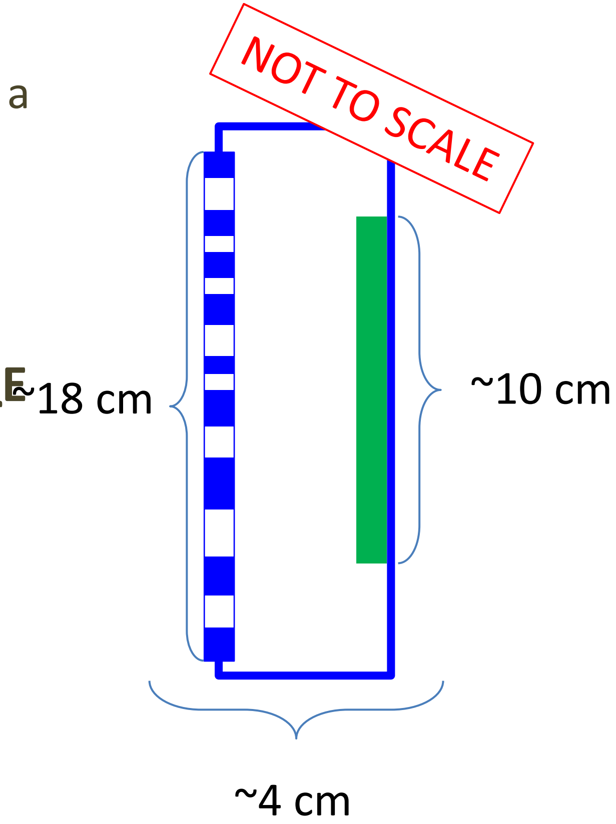
- Good light transmission (50%)
- Good depth of field
- Small required volume

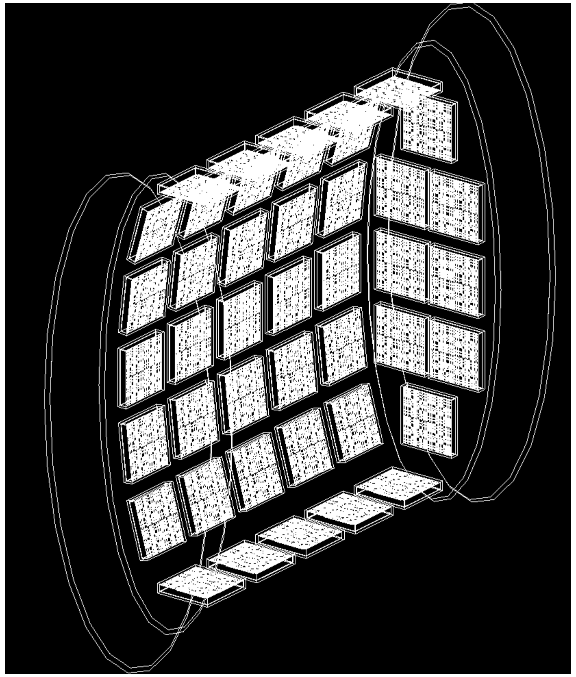
Mask geometry in GRAIN

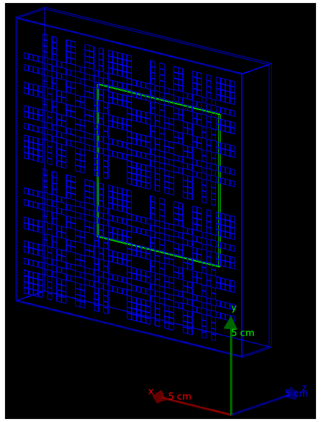
- **Old GRAIN geometry (to be updated):**
  - x, y, z = 130 x 146 x 48 cm^3

- **76 cameras, covering most of the available surface:**
  - 25 cameras on each curved (YX) face arranged in a 5x5 grid
  - 5 cameras on top/bottom
  - 8 cameras on each side (YZ) face

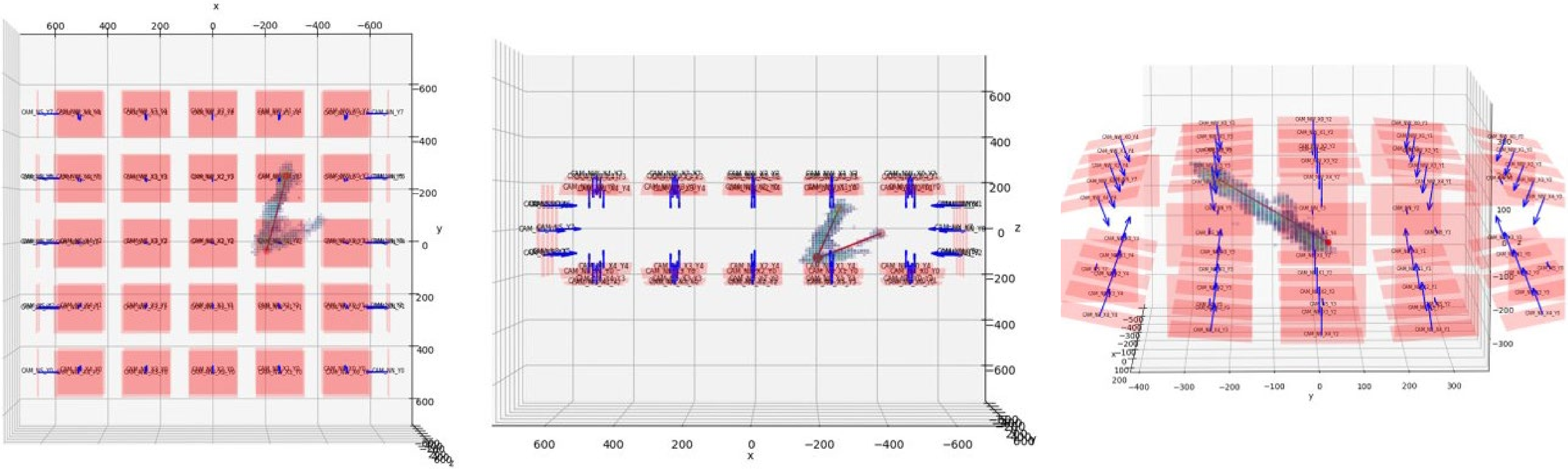
- **32x32 matrix sensors, 3.2 mm pixels and 25% QE**







3D reconstruction with masks

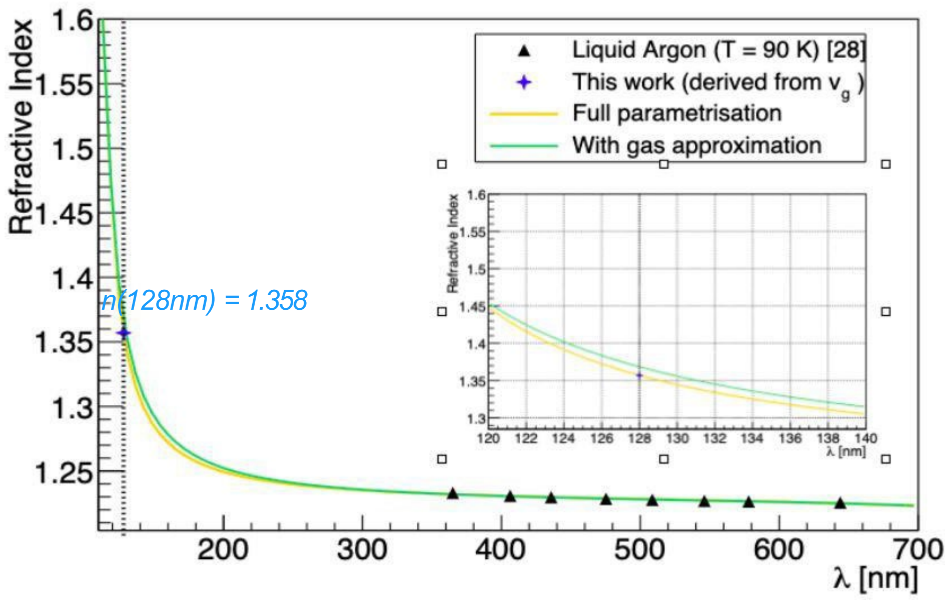


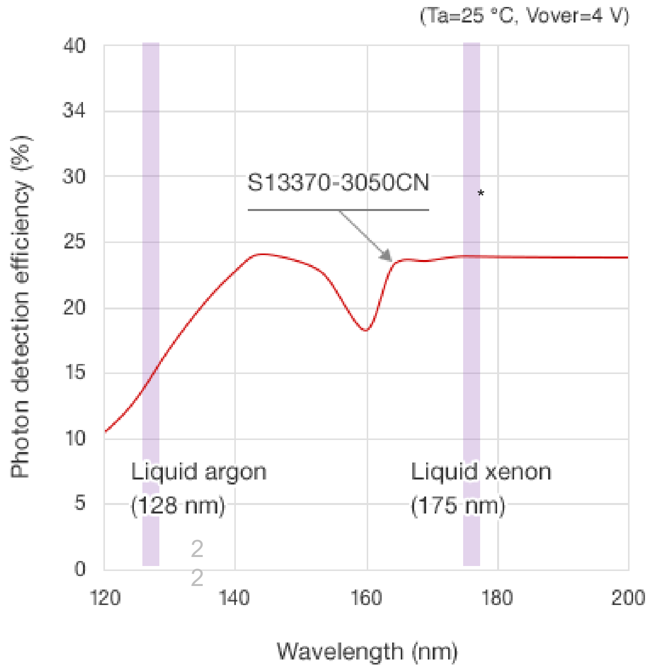
Optics: lens

Challenges for VUV optical system

- Transmittance at 128 nm problematic
- Low SiPM efficiency at 128nm at 10-15 %
- LAr Refraction Index similar to optical glasses

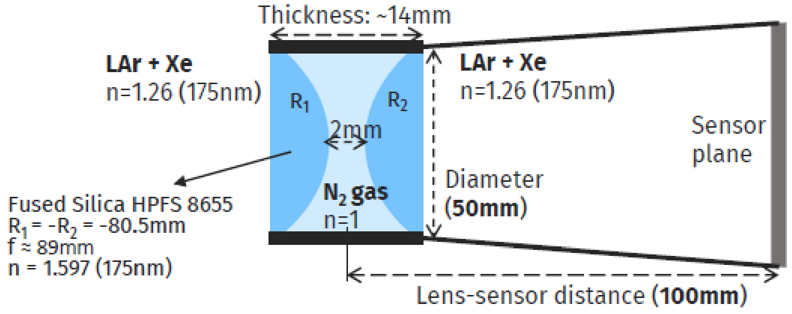
- Fixed focus optics has to cover the whole depth of the detector



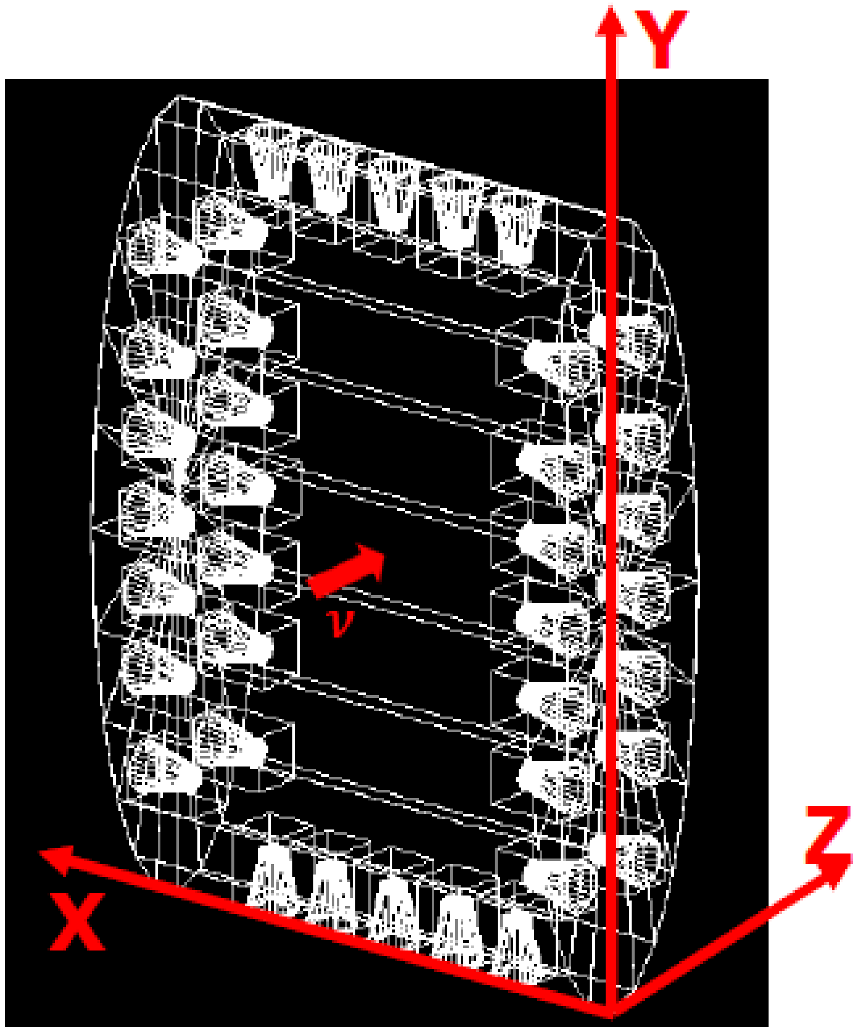


Lens geometry

- GRAIN geometry:
  - but Lx= 1000mm (to be updated to new dimension)
- Lens cameras inside the LAr volume
- 38 cameras, for maximum coverage
  - 14 pairs on the sides
  - 5 pairs on top/bottom
- Assume 32x32 matrix sensor, with 2 mm pixels and 20 % QE



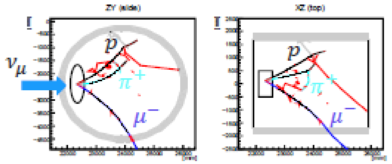
GDML:

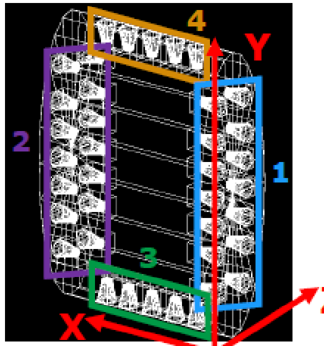


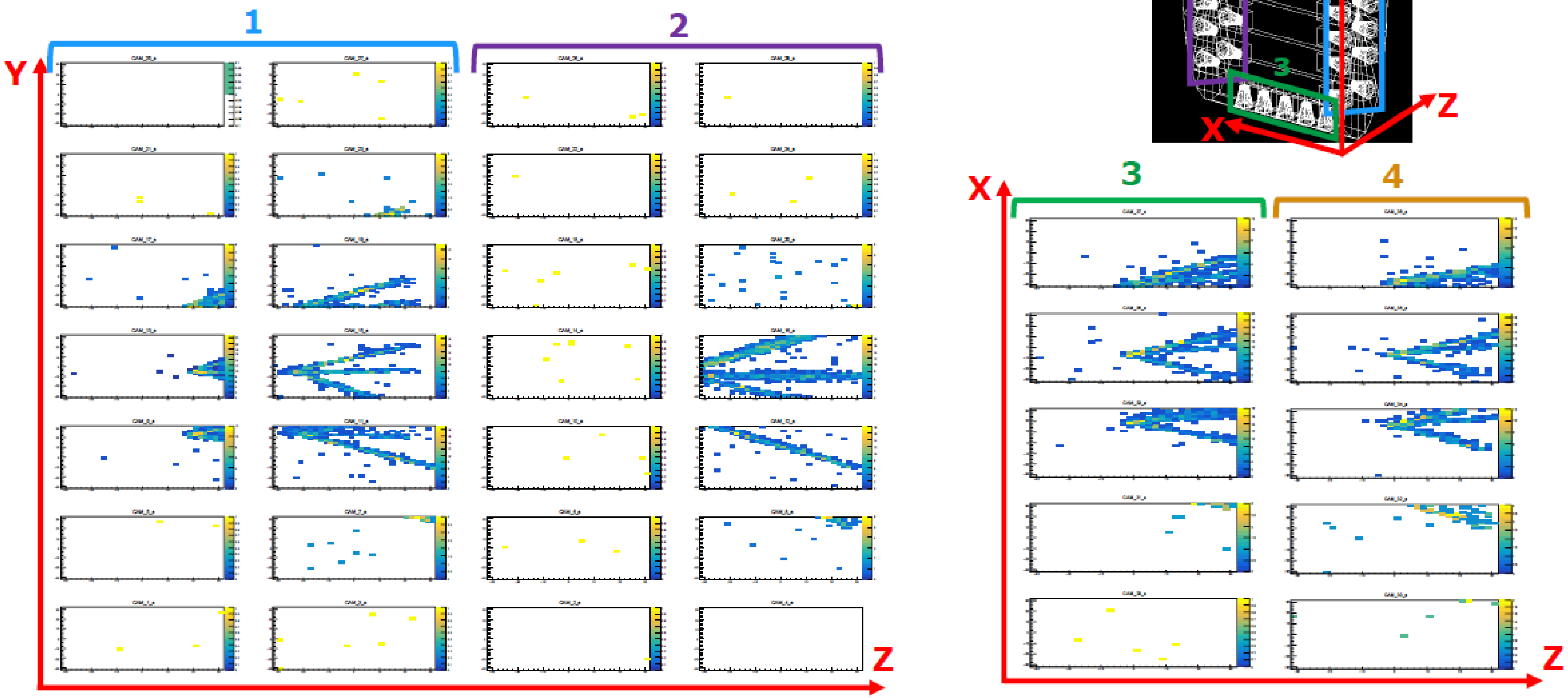
An example

Event in GRAIN

- Example of $\nu_\mu CC$ interaction inside GRAIN







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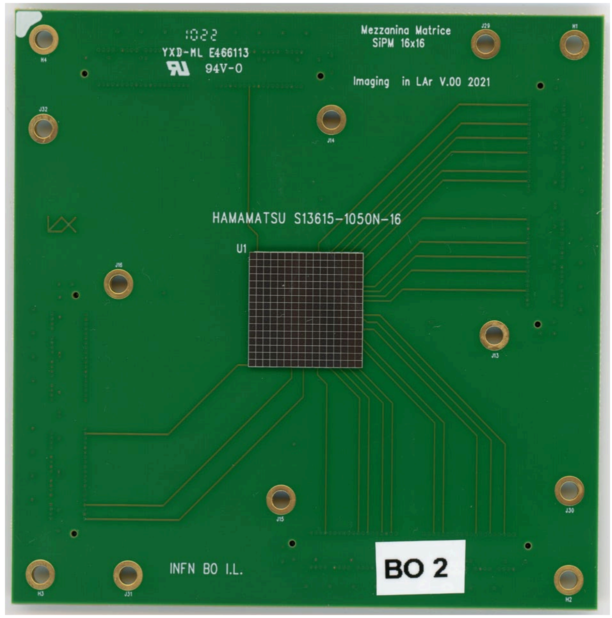
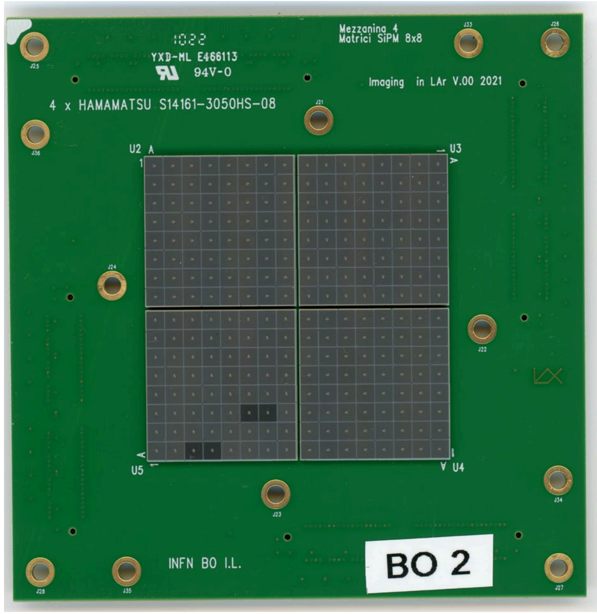
Photosensors

- Matrices of Silicon PhotoMultipliers
  - From Hamamatsu different models and sizes
  - Choose to work now with 16x16 matrices of 1x1 mm^2 or 3x3 mm^2 SiPM
  - 256 is the maximum channel count we can afford with presently available electronics (ASIC)

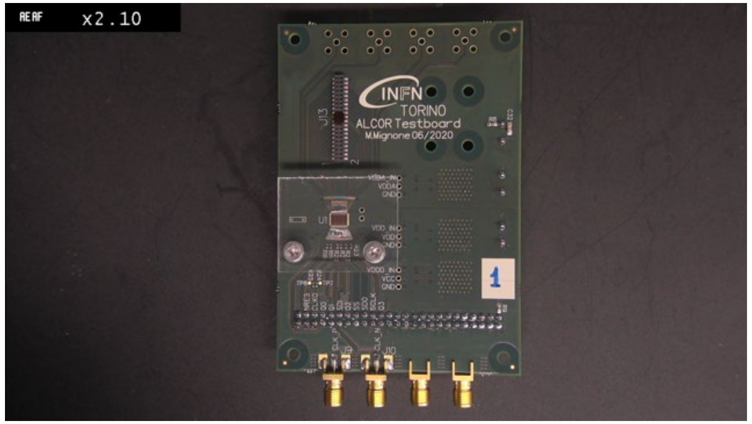


~ 2 cm



~ 5 cm

Cold readout electronics



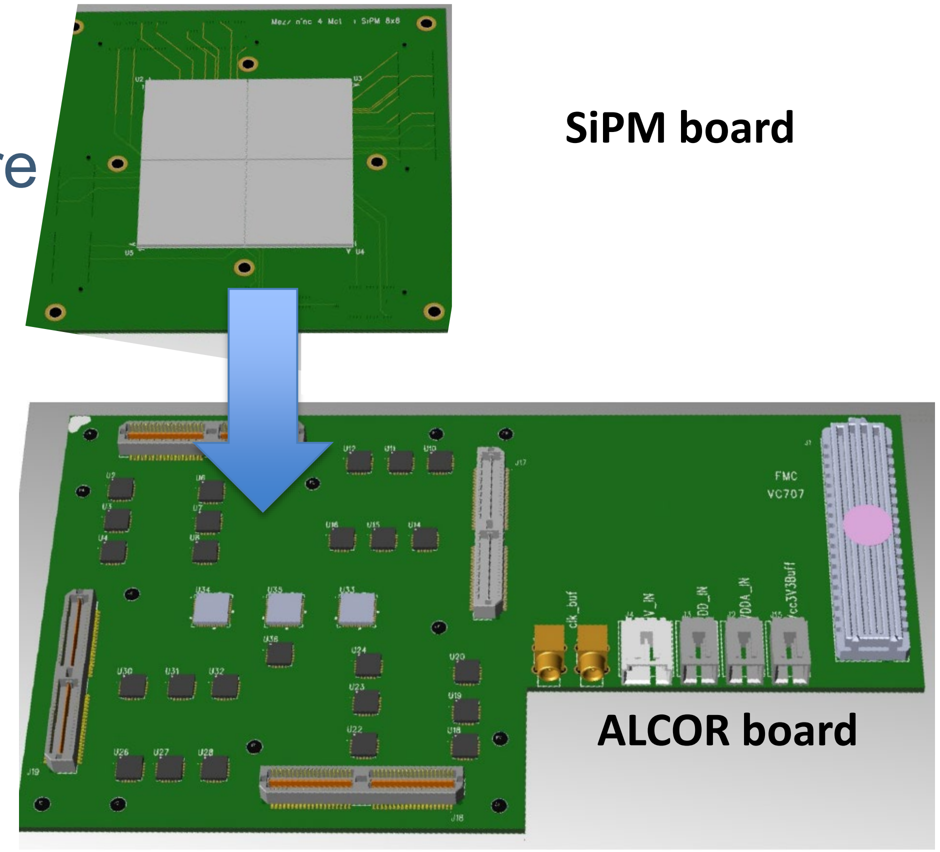
- The ALCOR ASIC by INFN Torino
  - Can operate in cryogenic conditions
  - 32 Channels, each with multiple TDCs
  - <100ps TDC resolution, amplitude from Time-Over-Threshold

- Quite a few limitations, first chip of its kind:
  - Yet to be demonstrated in the full system
  - High power consumption per channel (several mW)
  - Insufficient density, limited number of physical channels per output lane

A stack of boards

- To allow easy swapping of the matrices, they are mounted on a separate board

- The motherboard contains 8 ALCOR ASICs, for a total of 256 readout channels

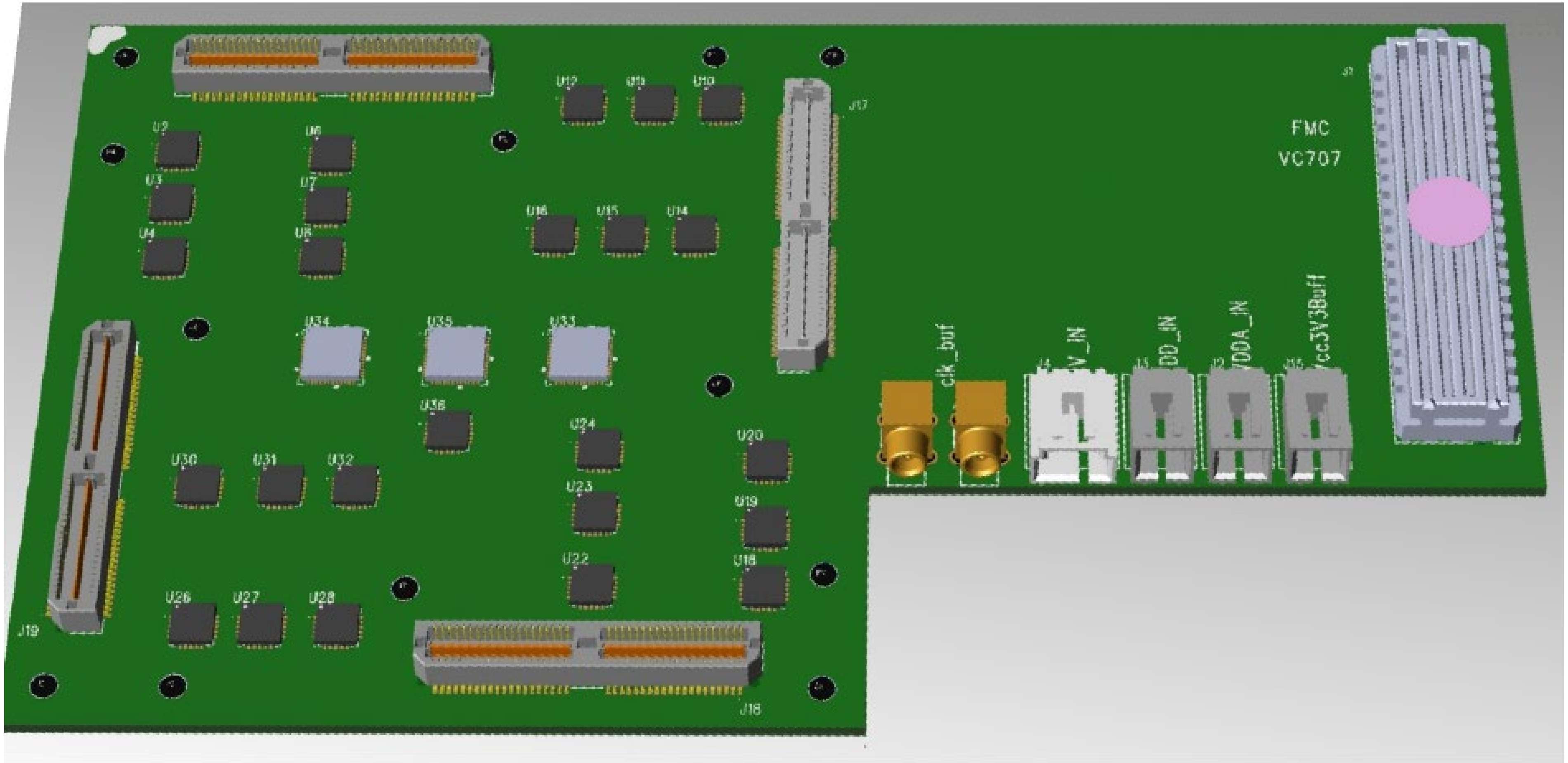


SiPM board

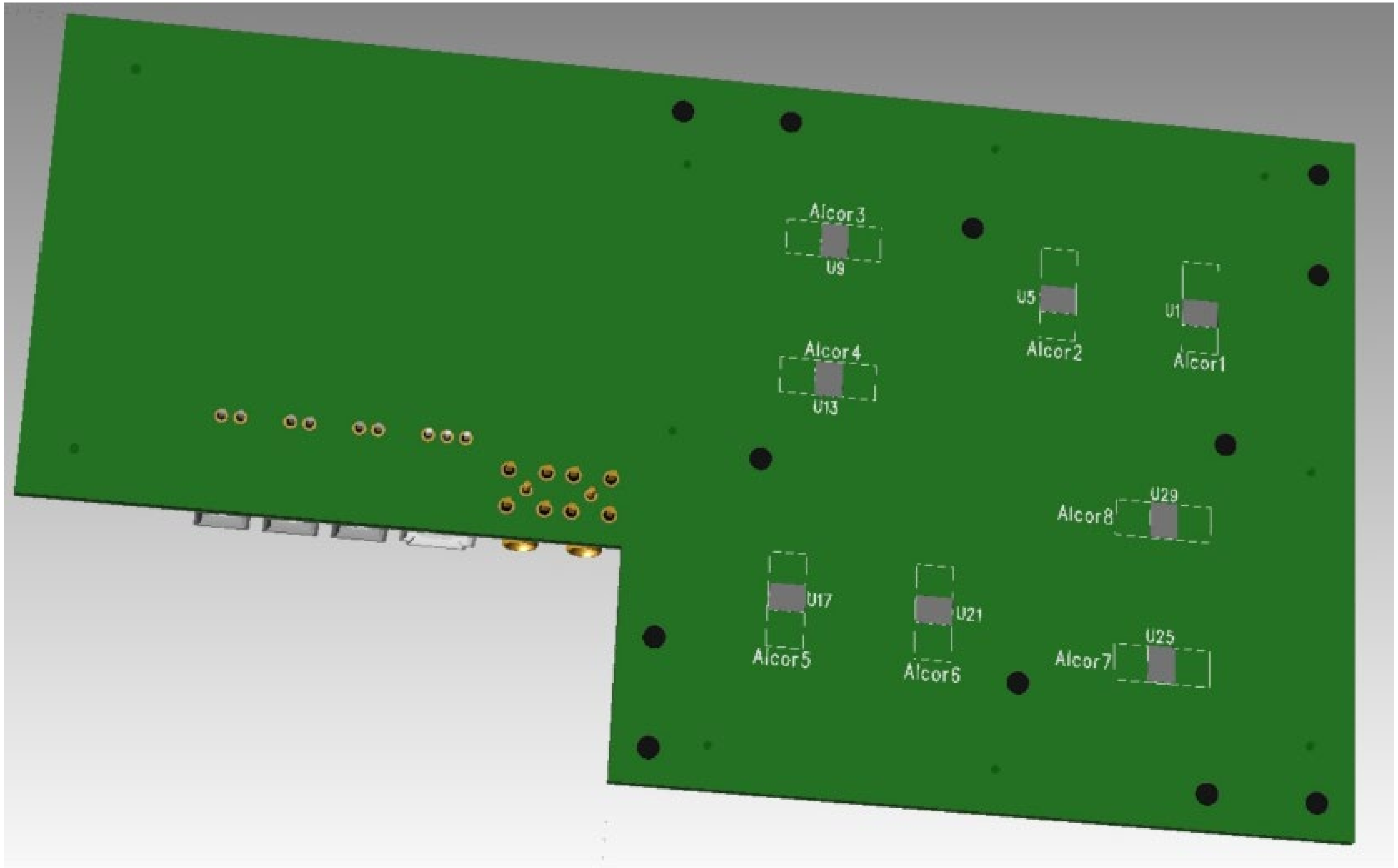
ALCOR board

Cryo reliability of connectors and cable has been tested in Liquid Nitrogen with a mechanical mock up

ALCOR board (top)



ALCOR board (bottom)

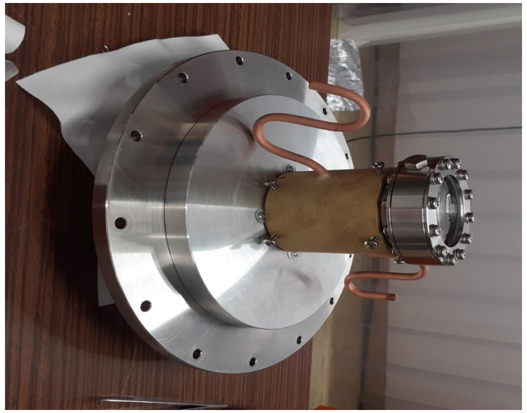


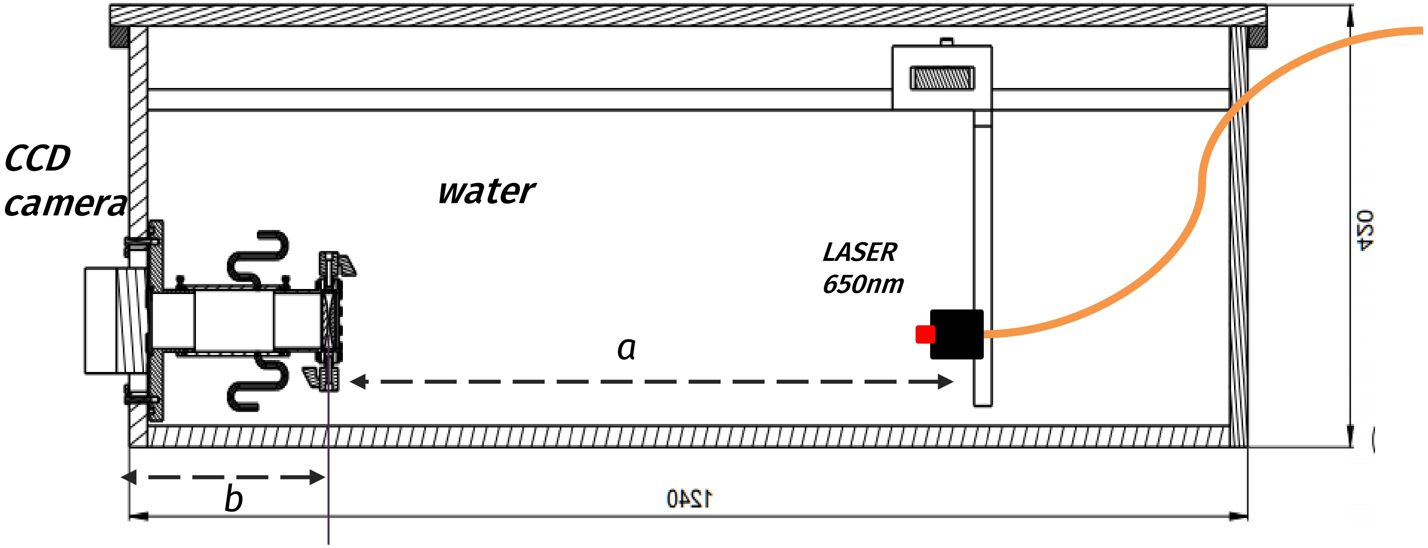
Back End FPGA

- Commercial, choice dictated by ALCOR connectivity
- Each ASIC requires12 LVDS pairs, of which 6 @320MHz/640 Mbps DDR
- Could go slower, but cannot decouple TDC clock from I/O clock
  - Some slow pairs can be buffered
  - Some tuning was needed to select LVDS buffer working in cryo conditions
- Still about 70 pairs => Requires full HPC FMC
- Very few boards have this fully routed
- Selected XilinX VC 707, somewhat old but quite powerful
  - Use commercial Twinax FMC extension cable for better integrity

Lens prototypes

- Lens produced by **GestioneSILO.**
  - Materials: **Fused Silica HPFS 8655. (n=1.57)**
  - $R_1 = R_2 = -80.5$mm
  - f ≈ 89mm in LAr (n=1.26-1.4)
- Visible light source (650 nm)
  - trasported on fiber
  - Movable position inside the box volume
  - The distance between the lens system and CCD can be changed
- In water → (n_lens=1.45 n_water=1.33, bigger focal length f=118 mm)



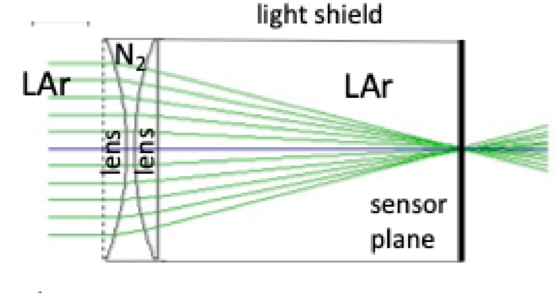


Lens integration with photosensor

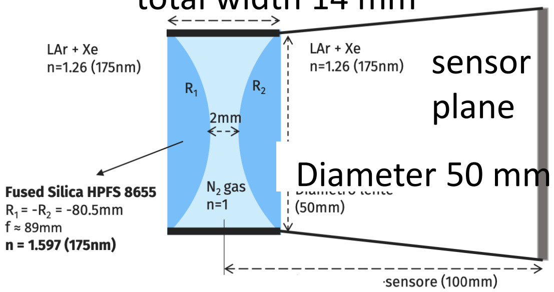
3 prototypes:

- Type A: the same of the simulations (focal 89 mm)
- Type A: similar (focal 89 mm) but bigger Ø = 60 mm
- Type B: Single bi-convex lens (focal 64 mm)

TYPE A



total width 14 mm

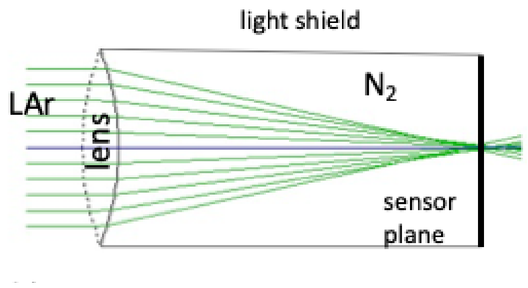


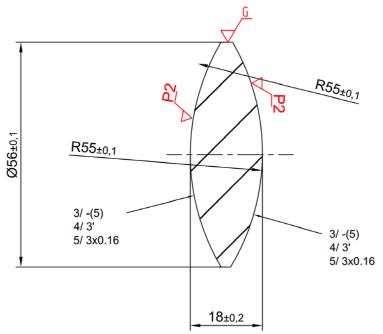
sensor plane

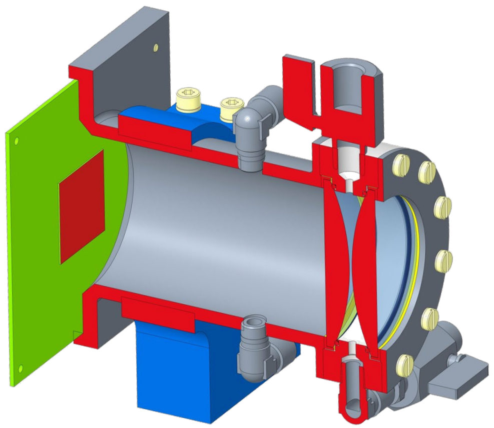
Diameter 50 mm

lens-sensor plane distance = 10 cm

TYPE B







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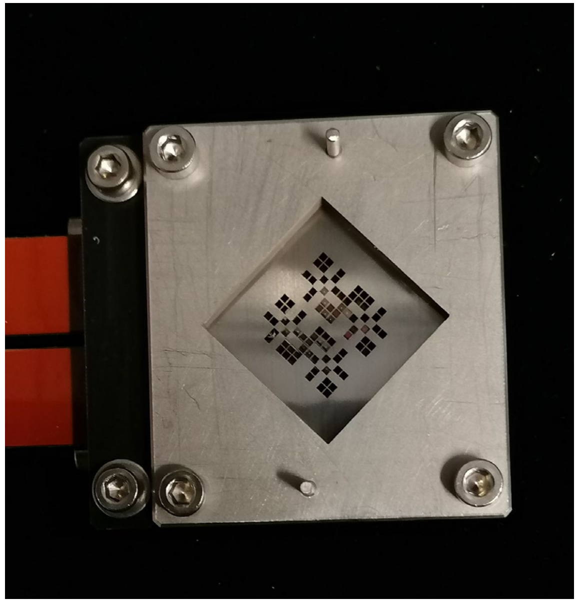
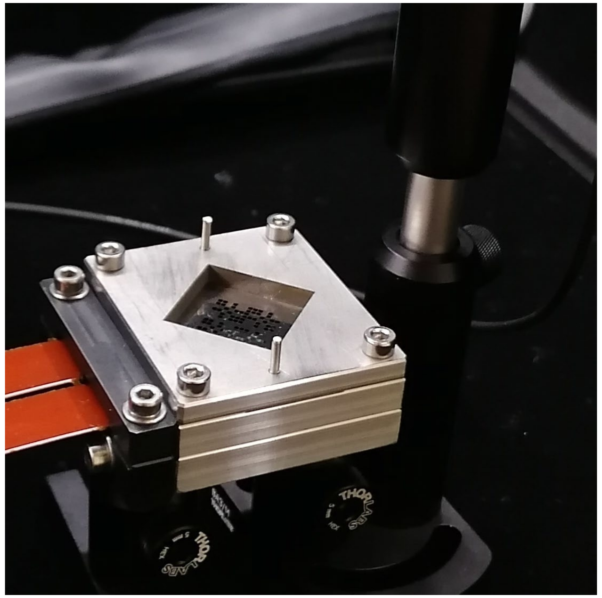
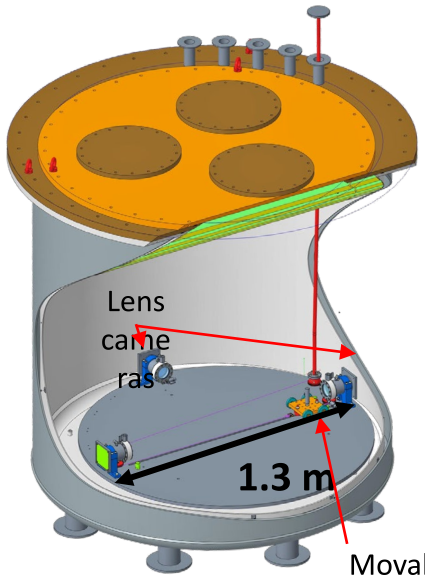
Coded aperture mask prototype

- We will profit of the experience in the design and production of a warm demonstrator based on an 8x8 SiPM matrix (in 2021)
- Mask built in stainless steel:
- Support and positioning structure: we will use aluminum for the new prototype.





Test in ARTIC (artificial light source)

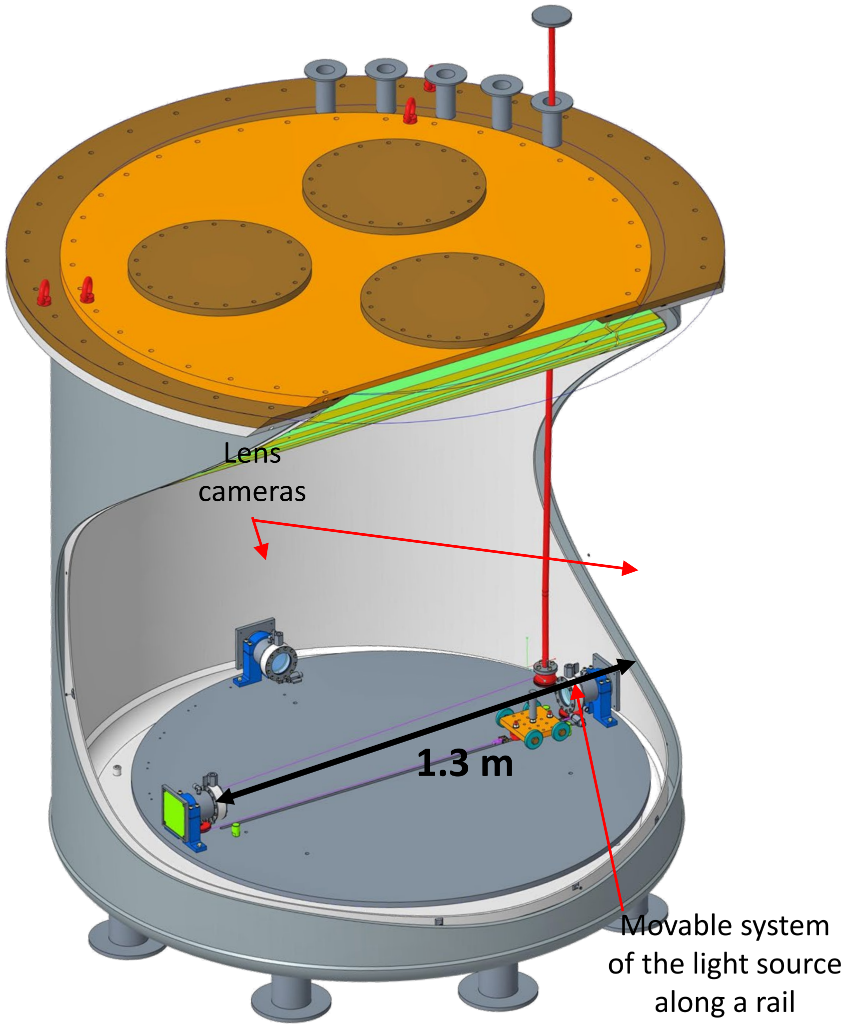


- Build a first simple working set up (readout, reflections, cryogenics)

- Tune simulation parameters
- Check current simulation results

- Evaluate:
  - the Point Spread Function by point source light
  - the reconstruction capability by using two faced detectors

Test in ARTIC (in Lar+ Xenon)



- Test with cosmics
- with more detectors (3 or more?)

…many things to be done…

-- NOT BEFORE SUMMER 2023 --

Some considerations on the schedule

- The mechanics needs some input from the detector design: number of cameras, cables, heat dissipation…etc
- On the other hand, the design of electronics needs some input from the mechanics and cryogeny: allowed heat dissipation, number of copper lines allowed through the feedthrough….
- We have some boundary conditions to respect: LAr fiducial mass of about 1 T, power consumption of about 1kW
- Optical imaging of scintillation light in LAr is a new technology: we need some preliminary prototype to fix some starting point before going on with a realistic design
  - Test new detectors
  - Tune simulation with real data
  - Use simulation to find optimal detector configuration and electronics requirements (dinamic range, time window,

Power estimate

- Channel count for full readout, mask-only:

  76 x 1024 = 88824

- Power budget:

  ~1000 W

- Passive heat load from cables:

  ~200 W (suboptimal ALCOR I/O)

- Available for electronics:

  10 mW/ch

- Power consumption from Alcor test board (1 ASIC, 2 LDOs)

- Non configured/standby:

  540 mW, 17 mW/ch

- Configured, clocks running:

  860 mW, 27 mW/ch