Far Forward Liquid Argon Experiment for the forward physics facility

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Workshop on Neutrinos at CERN.
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Introduction

- FLArE is a liquid argon time projection chamber with fiducial mass of 10 tons at 0 degrees to the ATLAS IP.
- The Forward Physics Facility and FLArE technical design has gone through tremendous progress. Several documents are in preparation.
- The science case, initial detailed simulations, the technical design (and options), and integration can be ready in a short time if the project is given the go-ahead.
- The technical team over the last 2 years are:

  (BNL) Steve Linden, Milind Diwan, Matteo Vicenzi, Yichen Li, Connor Miraval, Larry Bartoszek, Aleksey Bolotnikov.

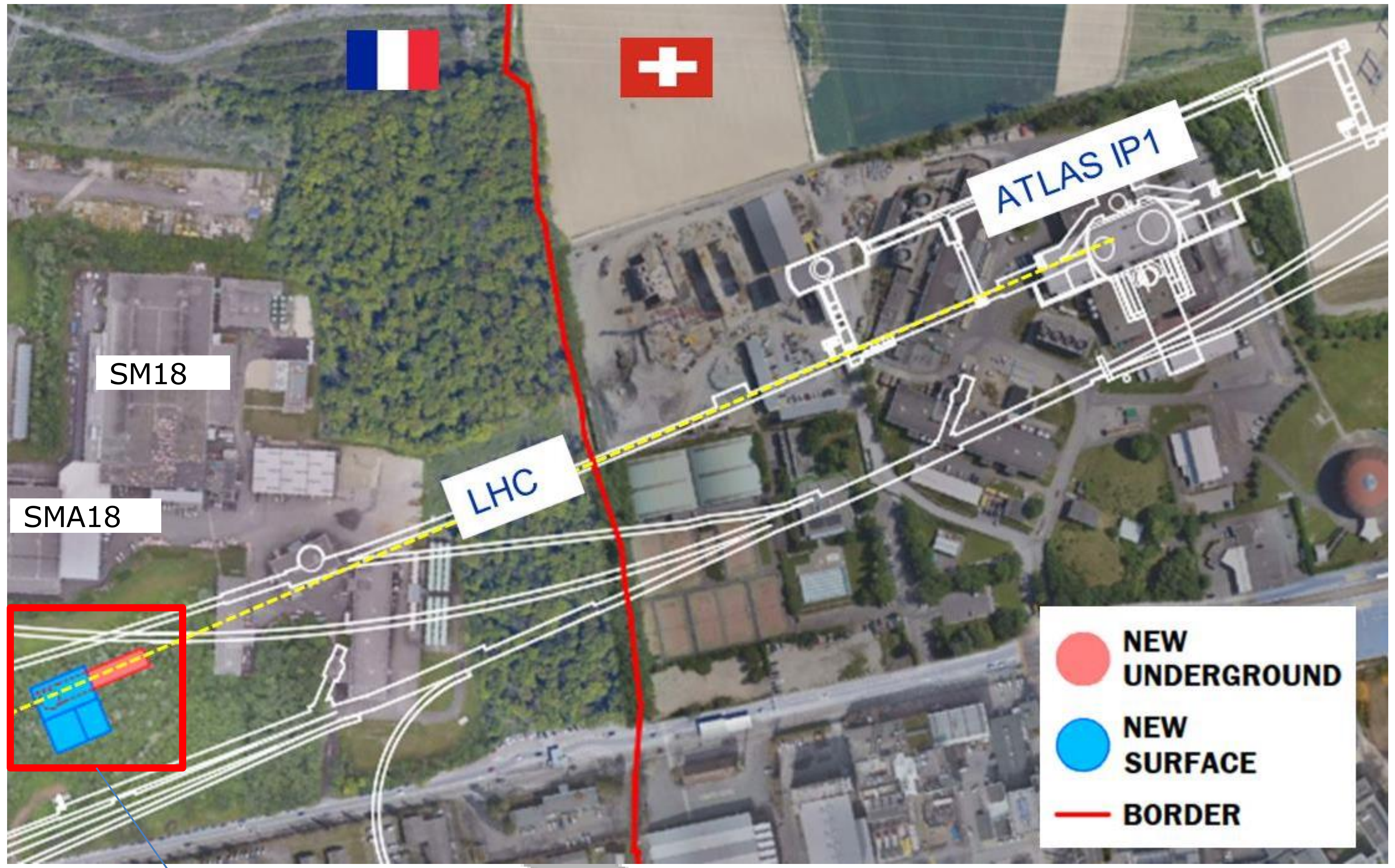
  (UCI) Wenjie Wu, Jianming Biang,

  (Liverpool) Kostas Mavrokoridis, George Stavrakis, Adam Roberts

  (CERN) Jamie Boyd, Julien Prosic, Anastasiya Magazinik, Johan Bremmer, F. Resnati.

  In addition: Sebastian Trojanowski, Alan Barr, Olivier Salin… Jonathan Feng…

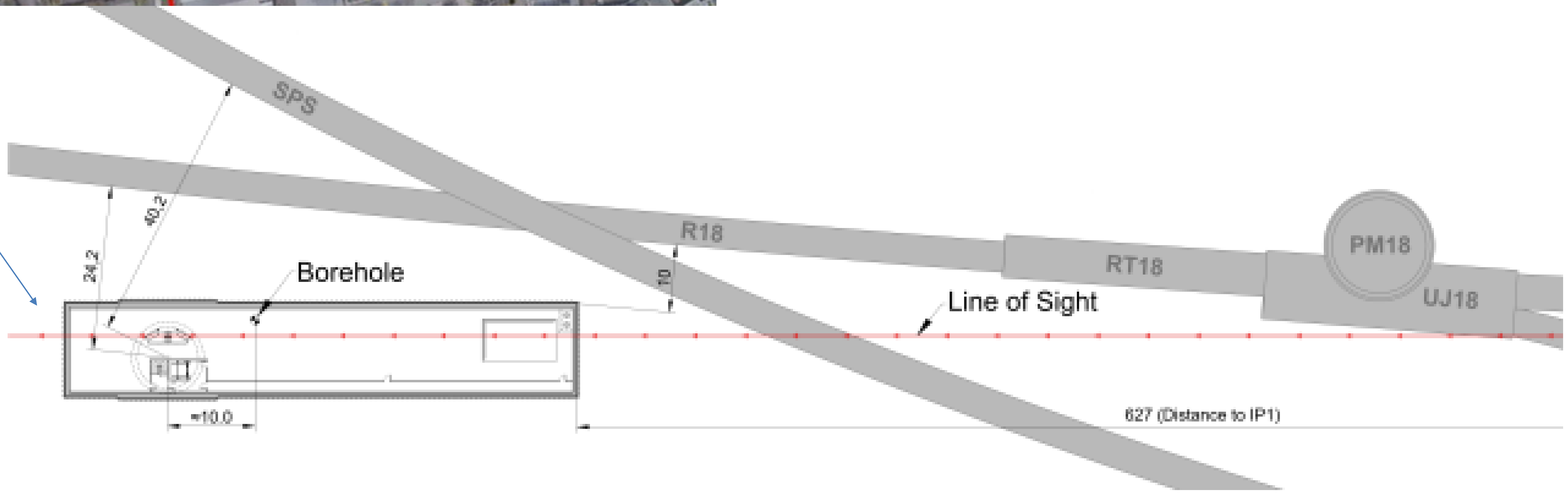
Overview

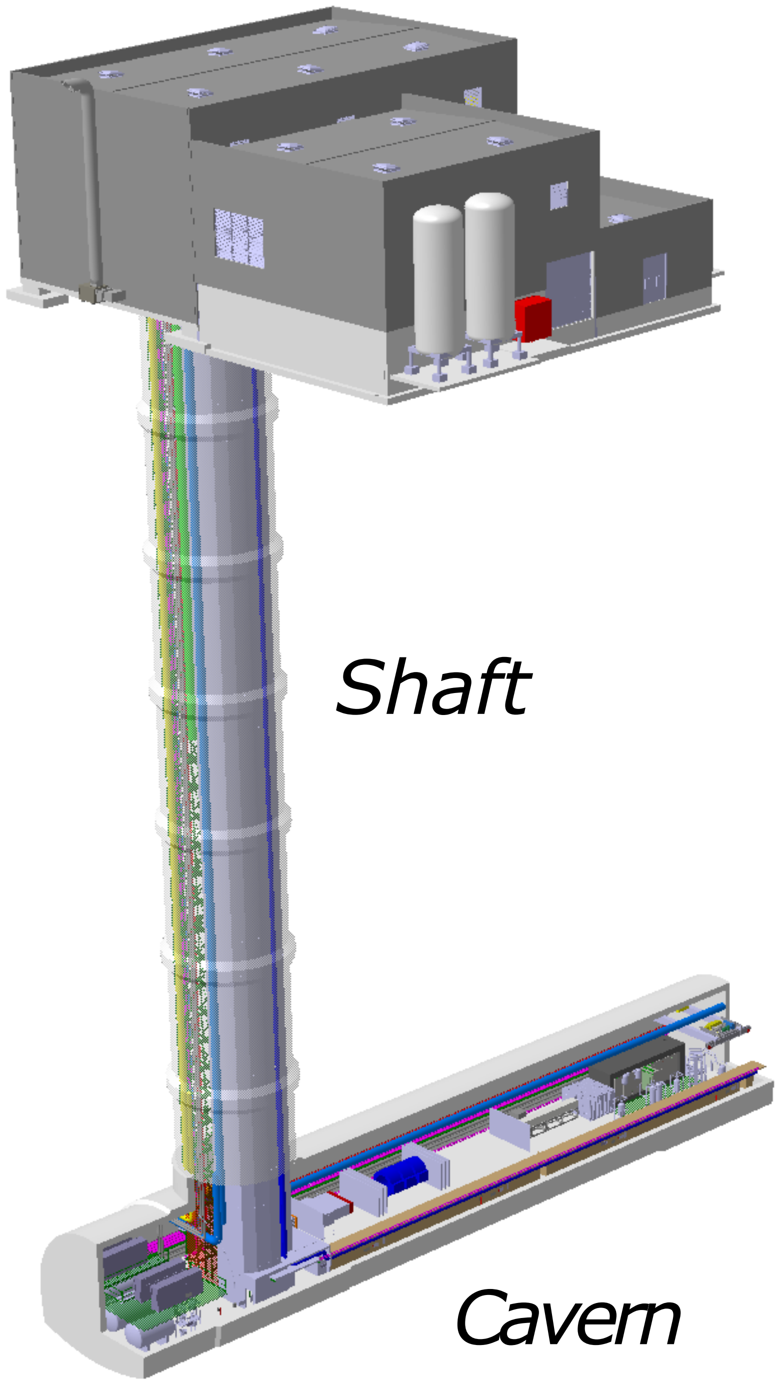


- FPF - Forward Physics Facility:

To build a new facility to test new physics

- Final location to respect constraints:
  - ✓ 627 m from ATLAS IP1 on the French side of CERN land
  - ✓ 90 m depth
  - ✓ 10 m away from the LHC tunnel

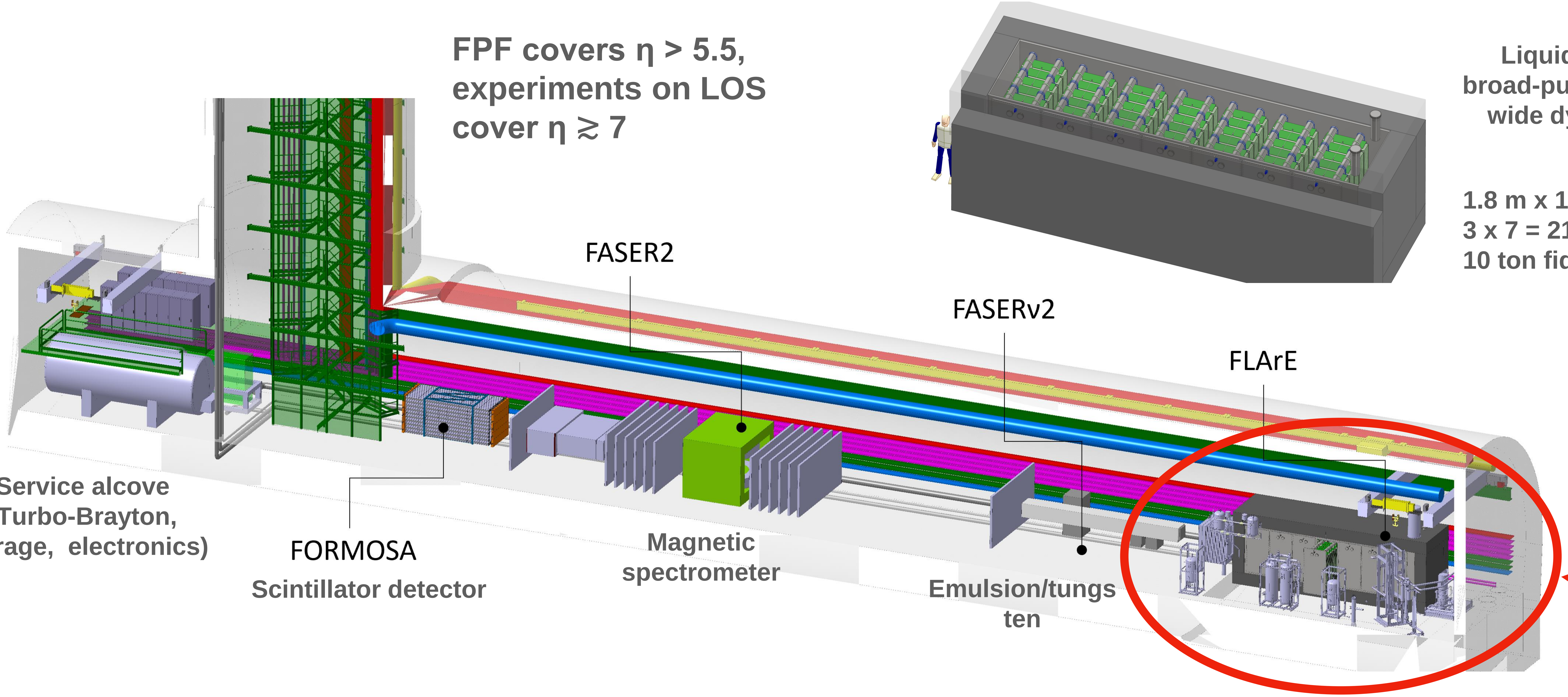




FLArE @ Forward Physics Facility

Baseline design

FPF covers η > 5.5, experiments on LOS cover η ≳ 7

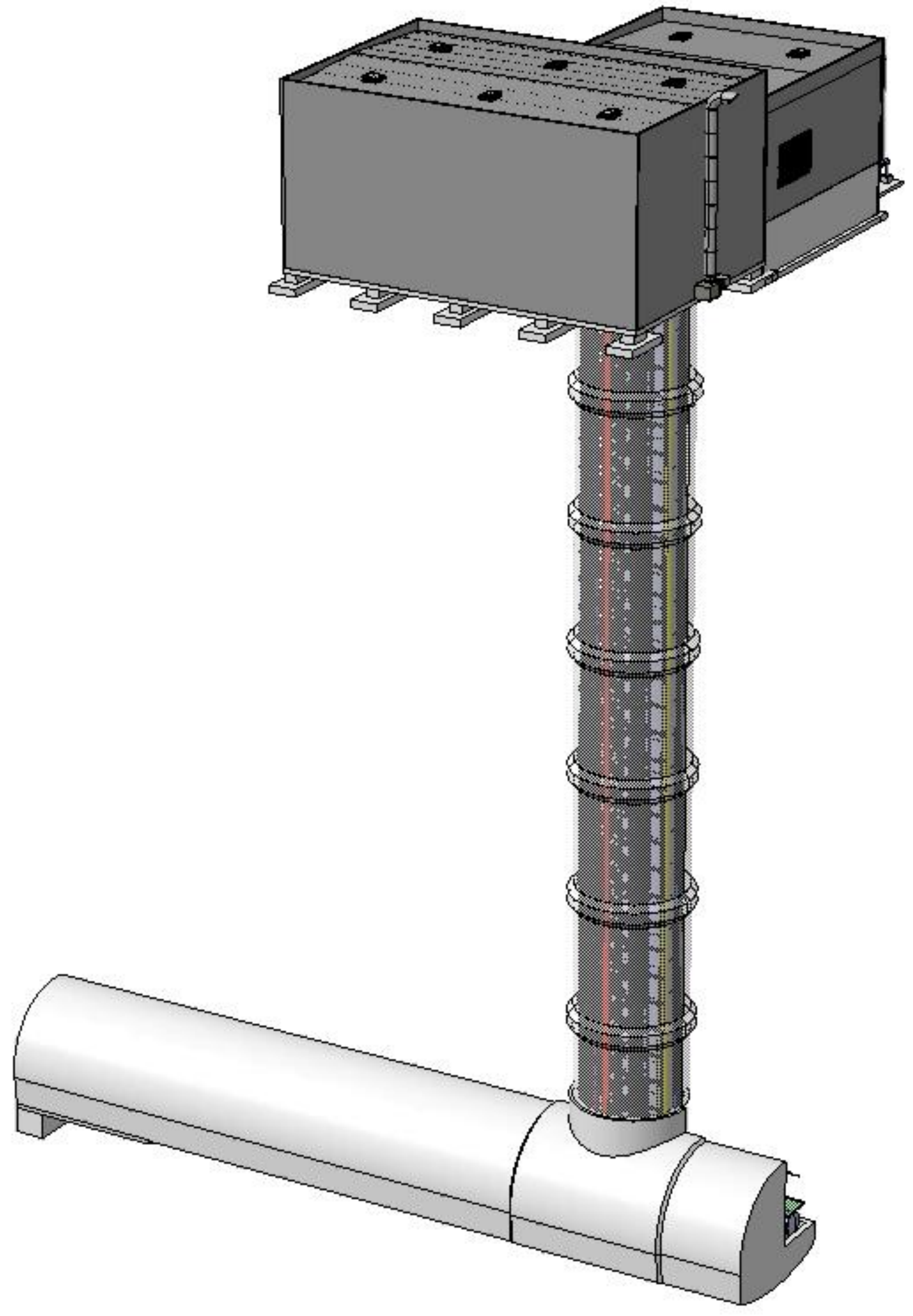


Liquid Argon TPC broad-purpose detector, wide dynamic range

1.8 m x 1.8 m x 7 m
3 x 7 = 21 modules
10 ton fiducial

Good energy containment (high density), high spatial resolution (for τ neutrinos) and low threshold (for DM scattering)

Integration



FLArE is at the upstream end of hall in a pit to minimize ODH issues.

Baseline design has foam insulated cryostat with side installation of TPC modules. Hadron absorber with Fe/Scint.

The cryo system has an industrial cooler(Turbo Brayton), LAr and LN2 storage ; all sized to be installed thru shaft.

A conceptual plan for installation exist.

Design will follow integrated safety procedures.

Scientific Requirements

FASERnu2 (Tungsten/emulsion) and FLArE are complementary detectors that cover neutrino physics.
The FASER2 magnetic spectrometer provides the needed coverage for muon measurements for both.

Label	Description
OG-1	Measure the neutrino flux for all flavors
OG-2	Measure the neutrino cross-section for all flavors
OG-3	Search for neutrino-philic new physics
OG-4	Charm and QCD measurements
OG-5	Detection of direct light dark matter scattering
OG-6	Operation in high-rate environment

Table 2: Summary of the overarching physics goals for FLArE.

We start from a set of overarching physics goals, from which we derive eleven measurement requirements.

FASERnu2 has high spatial resolution for tau physics. FLArE has a live target and containment for resolution and dynamic range. Both will have excellent muon tracking.

Label	Description	Event rate	Rationale	Threshold	$\Delta E/E$	Supports
MR-1	Measure CC ν_μ events.	203k – 268k	FLArE must be able to identify and reconstruct ν_μ-Ar events.	10 GeV	30%	**OG-1** **OG-2** **OG-3**
MR-2	Measure CC ν_e events.	36k – 113k	FLArE must be able to identify and reconstruct ν_e-Ar events.	10 GeV	30%	**OG-1** **OG-2** **OG-3** **OG-4**
MR-3	Measure CC ν_τ events.	1.5k – 4k	FLArE must be able to identify and reconstruct ν_τ-Ar events.	10 GeV	30%	**OG-1** **OG-2** **OG-3** **OG-4**
MR-4	Measure $\nu - e$ elastic scattering.	110	Flux can be extracted exploiting the well-known cross-section for $\nu - e$ elastic scattering.	1 GeV	10%	**OG-1** **OG-2** **OG-4**
MR-5	Measure inverse muon decay (IMD).	440	Flux can be extracted by exploiting the $\nu_\mu + e$ process with well-known cross-section.	11 GeV	20%	**OG-1** **OG-2** **OG-4**
MR-6	Measure low-ν events.	1% of CC rates	Flux can be extracted by exploiting the flat energy dependence of low recoil events.	-	10%	**OG-1** **OG-2** **OG-4**
MR-7	Measure neutrino tridents	25	FLArE must be able to search for neutrino tridents.	100 GeV	30%	**OG-3**
MR-8	Measure sterile neutrino oscillation	1.5k – 4k	FLArE must be able to search for sterile neutrino oscillations with tau neutrinos.	10 GeV	10-20%	**OG-3**
MR-9	Measure low-energy electron recoils	BSM	FLArE must be able to search for DM scattering on electrons.	< 1 GeV	10%	**OG-5**
MR-10	Measure low-energy nuclear recoils	BSM	FLArE must be able to search for DM scattering on nucleons	< 1 GeV	10%	**OG-5**
MR-11	Assess muon-induced background.	-	FLArE must be able to monitor the muon-induced background.	-	-	**OG-6**

Table 3: Summary of the measurement requirements for FLArE. Event rates are per 3000 fb^{-1} (total expected luminosity) and 10 ton of liquid argon (FLArE fiducial mass). Please note that 1 fb^{-1} corresponds to roughly one day of HL-LHC operations.

Scientific Requirements

Label	Description	Specification	Rationale	Subsystem	
CR-1	Fiducial mass	$m \sim 10$ ton	FLArE fiducial mass must be enough to collect sufficient statistics for potential new physics signatures as well as neutrinos of all flavors.	TPC	✓
CR-2	Muon ID	Efficiency $\gtrsim 50\%$, purity $\gtrsim 80\%$	FLArE must be able to tag muons using combined information from all subsystems.	TPC, HadCal, External Spectrometer	✓
CR-3	Electron ID	Efficiency $\gtrsim 50\%$, purity $\gtrsim 80\%$	FLArE must be able to tag electron showers in the TPC.	TPC	IP
CR-4	Tau ID	Efficiency $\gtrsim 20\%$, purity $\gtrsim 60\%$	FLArE must be able to tag tau leptons in the liquid argon volume via their decays.	TPC	IP
CR-5	Muon momentum	$\delta_p < 5\%$	FLArE must be able to reconstruct the muon momentum using combined information from all subsystems.	HadCal, External Spectrometer	✓
CR-6	Event containment	$\gtrsim 80\%$	FLArE must be be able to contain fiducial events within its active volume to collect all the available visible energy.	TPC, HadCal	✓
CR-7	Phase space coverage	$\gtrsim 80\%$ coverage	FLArE must be able to cover most of the phase space limiting event topologies or kinematics where the hadron shower is not contained.	TPC, HadCal	✓
CR-8	Lepton kinematics	Efficiency $\gtrsim 50\%$	FLArE must be able to reconstruct the lepton kinematics with good efficiency.	TPC, HadCal, External Spectrometer	✓
CR-9	Vertex kinematics	$\delta_x \sim \mathcal{O}(1\ \text{mm})$, $\delta_\theta \sim \mathcal{O}(1^\circ)$	FLArE must be able to reconstruct vertex kinematics resolving track angle and momentum for the outgoing particles with sufficient resolution.	TPC	reco
CR-10	Scintillation timing	$\delta_t \sim \mathcal{O}(\text{ ns})$	FLArE must be able to achieve a ns-level scintillation timing resolution to separate the pile-up of interactions per bunch crossing.	TPC	✓

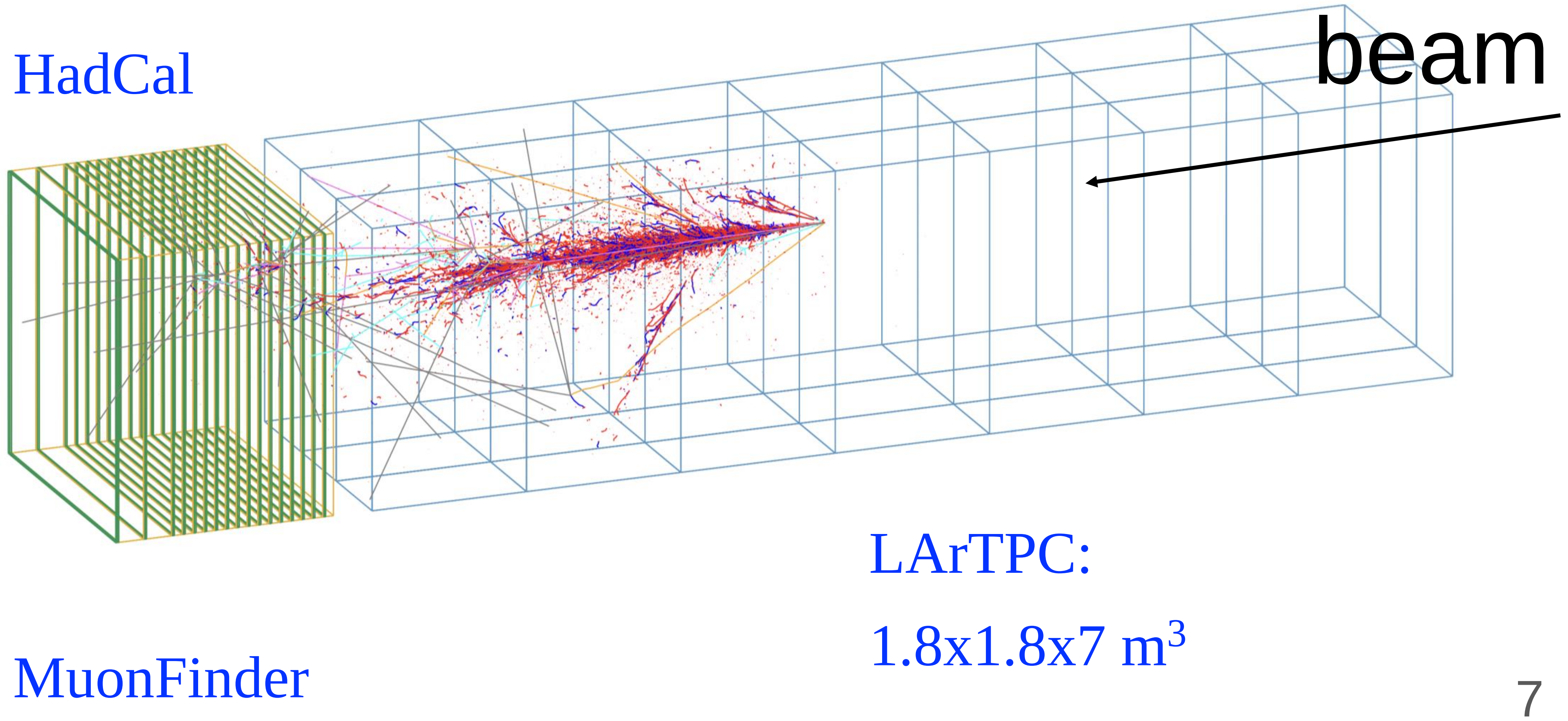
Table 4: Summary of the capability requirements for FLArE. An initial set of specifications has been derived based on feasibility estimates of the current design. These are conservative, and driven mostly by neutrino physics.

These capability requirements are meant to justify the design choices we make in the rest of the document.

Statistical techniques for tau are promising.

Trigger and daq is in progress.

Initial simulation ready.

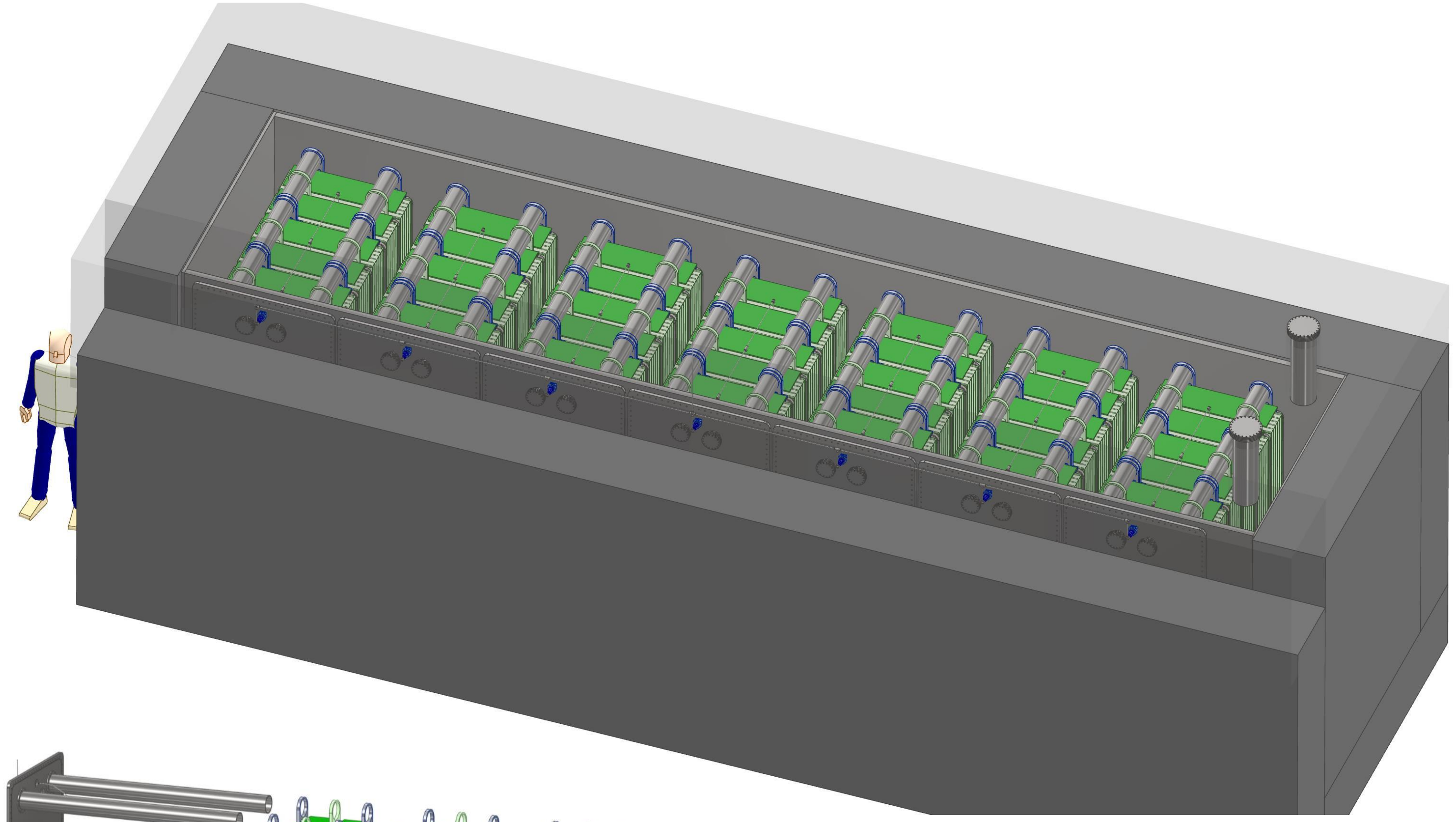


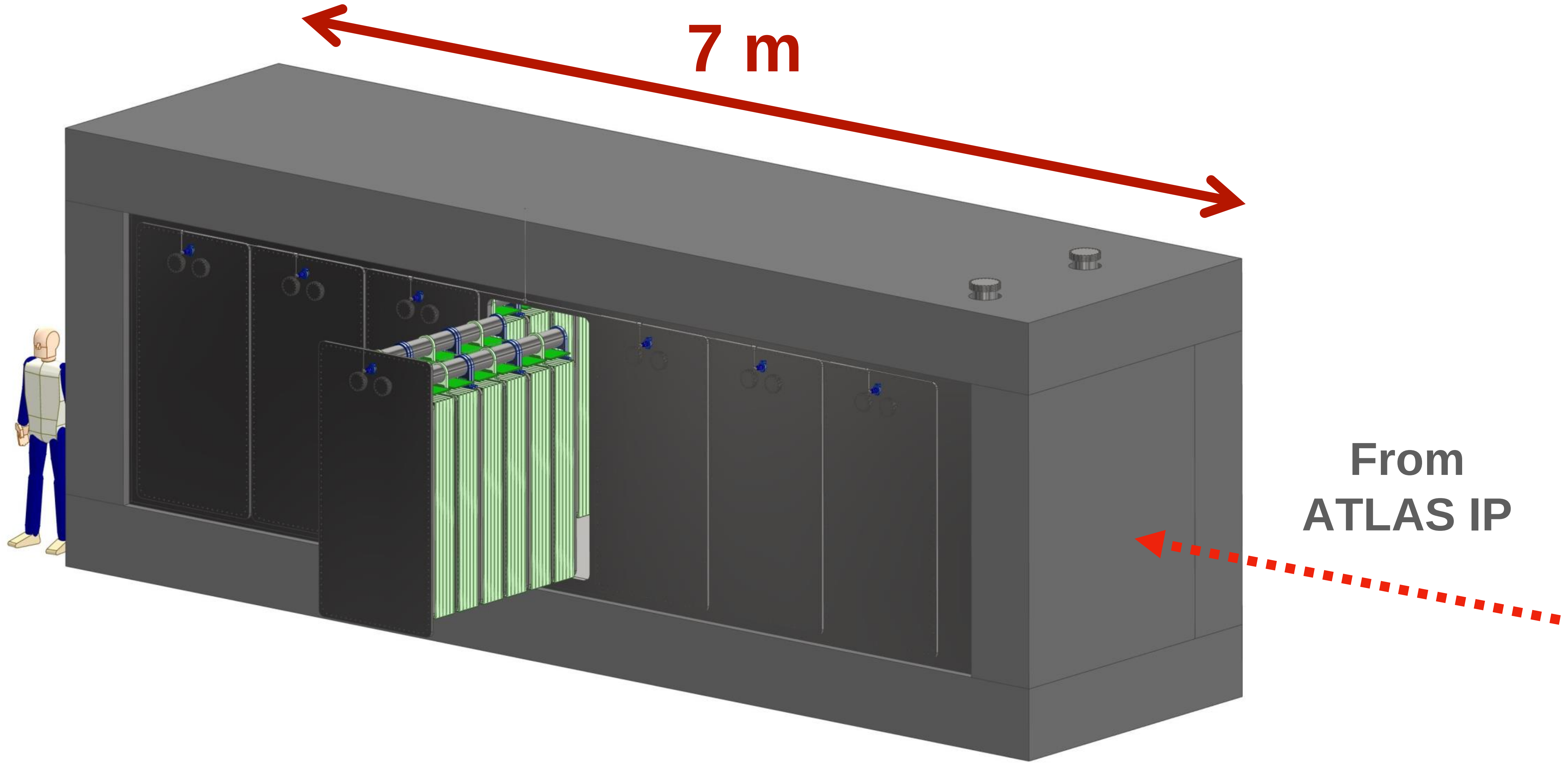
Basic detector requirements for FLARE from studies

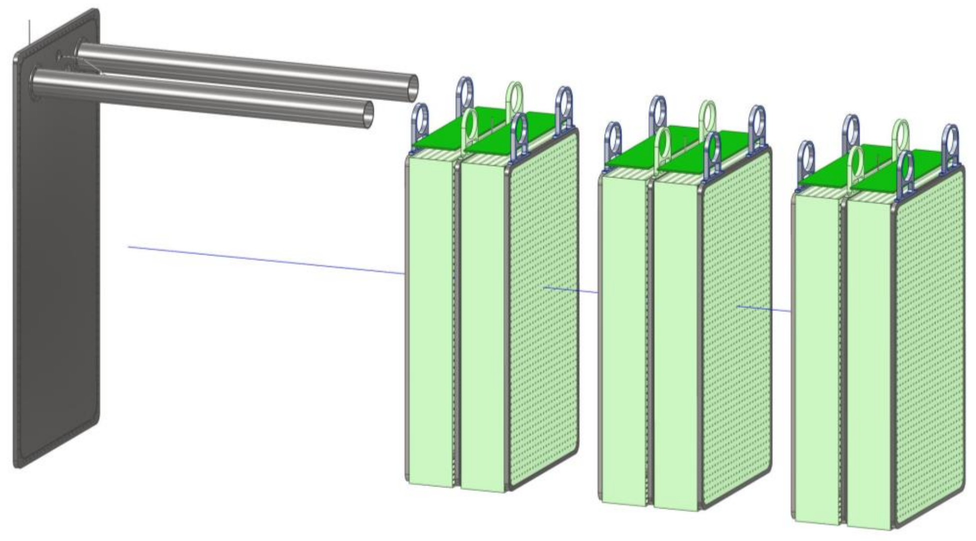
Item	Technical Issue	Choice
Liquid fill	LAr or LKr or LAr/LXe mix	LAr rad length 14 cm. LKr is radioactive and has space charge problem.
Cryostat and TPC dimensions	Keep the total to active volume ratio small. Need to fit into FPF space and ease of installation	Foam insulated flat walled cryostat with side installation. Easy to procure. (cylinder also possible)
Event containment	Events the back of the LAR need to be contained and showers measured. Muons tag needed	Place a steel/scint detector in the back. ~40 tons, magnetized. To be optimized.
Cryogenics	Cryostat must be kept cold underground. Difficult to bring LN2 down.	Use Turbo-Brayton TBF-175 local LN2 cooling unit. Installation studied.
TPC gap size	Muon rate from the ATLAS IP is ~1 Hz/cm2. Space charge needs to be kept limited or corrected.	Keep gap ~0.3 m. Space charge ~(gap/field)^2
Cathode/anode	Channel count for spatial resolution and scintillation light for trigger needs to be considered	Keep cathode transparent to light, Use pixellation for high spatial resolution.
Photon readout	Need to trigger on contained neutrino events. Cannot use PMTs due to space limitations	Use VUV SiPMs and optically separate modules.
SiPM density, timing resolution and trigger	This requires detailed simulations and R&D. **A minimum density is needed for recognizing contained events versus muons for trigger.** Timing resolution is needed to associate with LHC bunch.	
Electronics	Cold electronics for low noise. optimize for spatial resolution.	Need < 1 mm resolution in drift dimension; large dynamic range ~ 20 MIP.
Alternative photonic readout	If the space charge and high trigger rates can be managed then ARIADNE becomes attractive	This requires a different arrangement for installation. Readout will be optical.

FLArE Detector design

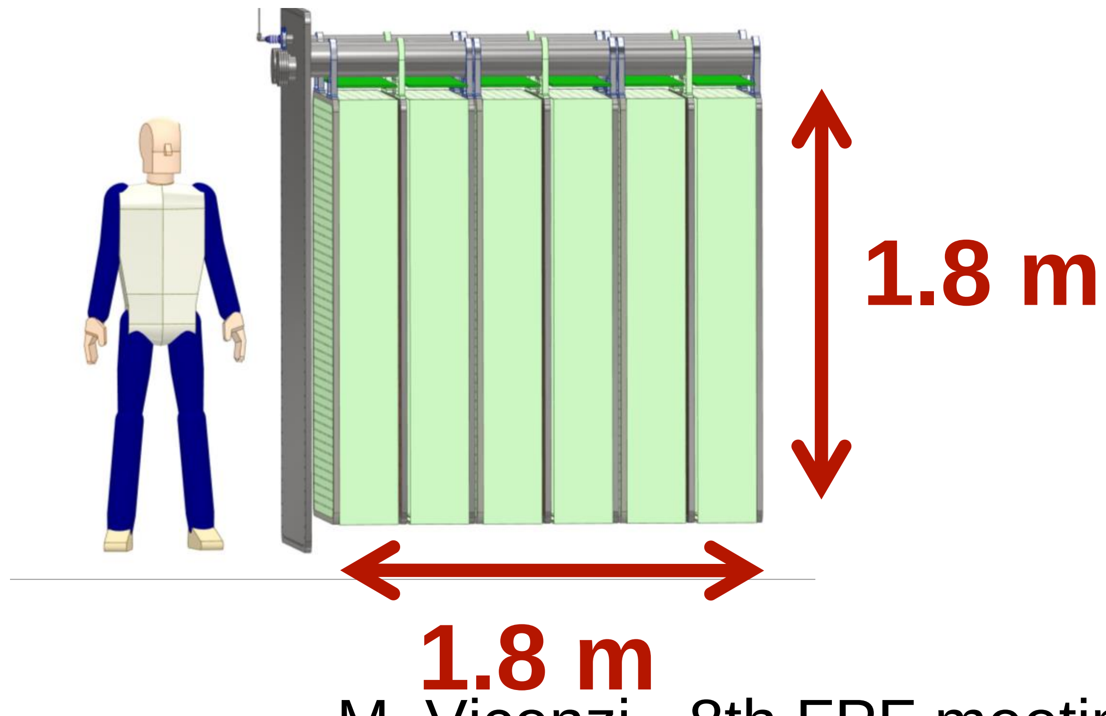
Baseline: foam-insulated cryostat, “filing cabinet” concept
10-ton fiducial LAr mass, 30-ton active volume







Modules “hanging” from the door, installed from the side of the cryostat



3x7 modular LAr TPC: segmentation for light collection (trigger) and background mitigation (small drift gap ~30cm).

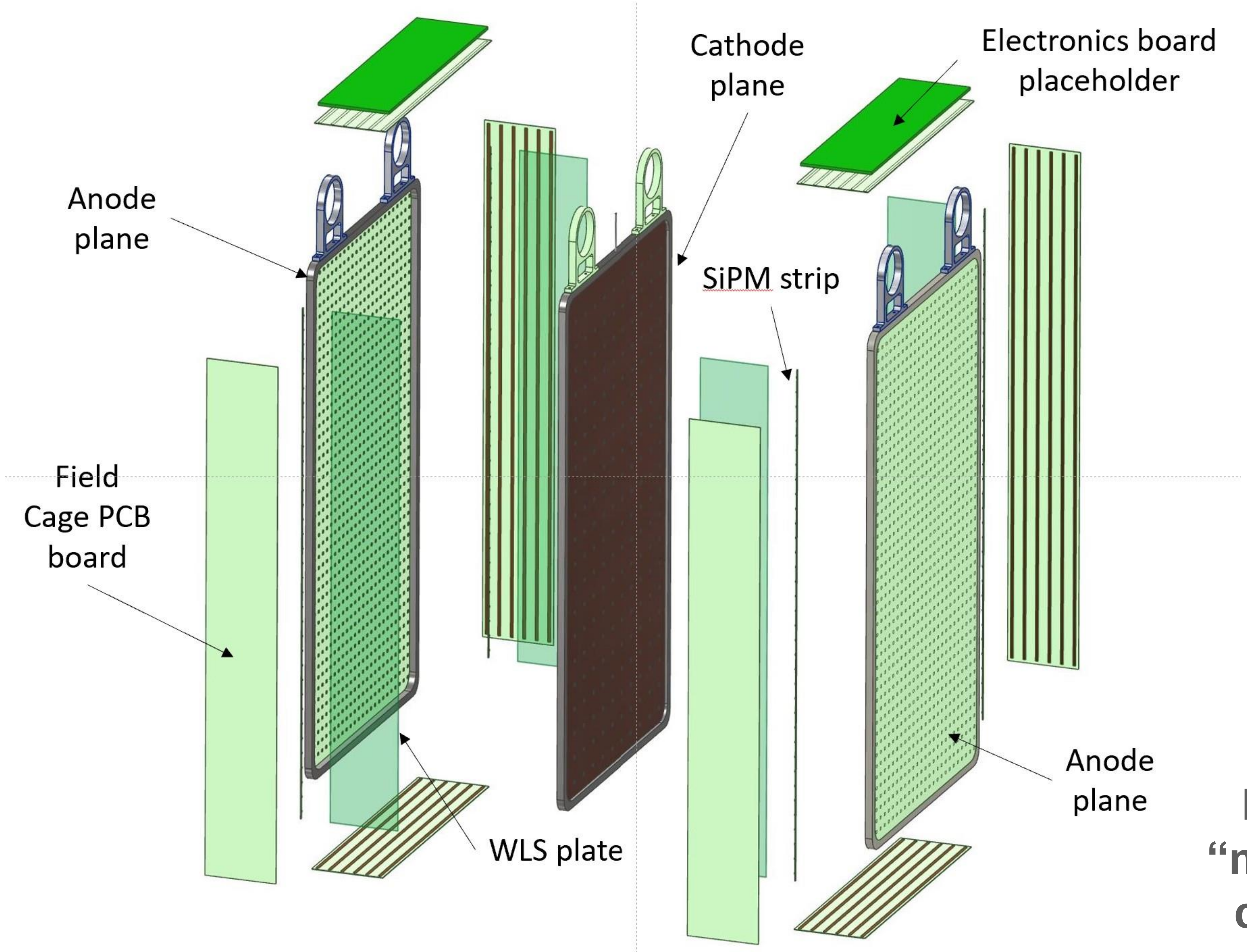
LAr volume: **1.8 m x 1.8 m x 7 m**

Limited space in the cavern, baseline option is **side installation** (“filing cabinet” cryostat).

TPC modules

Inspired by the DUNE near detector concept

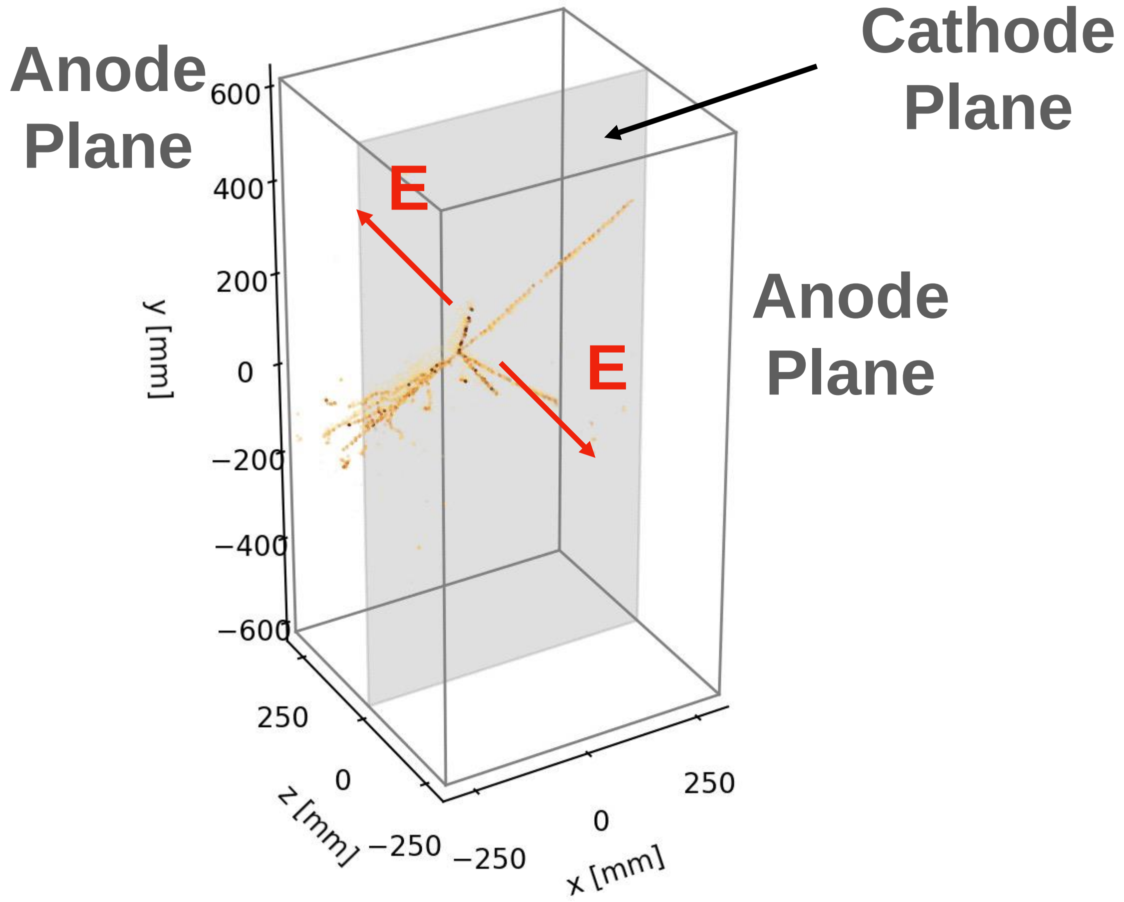
https://doi.org/10.3390/instruments5040031



Lawrence Berkeley National Laboratory
University of Bern

Each module is two "mini" TPCs, sharing a cathode plane in the middle

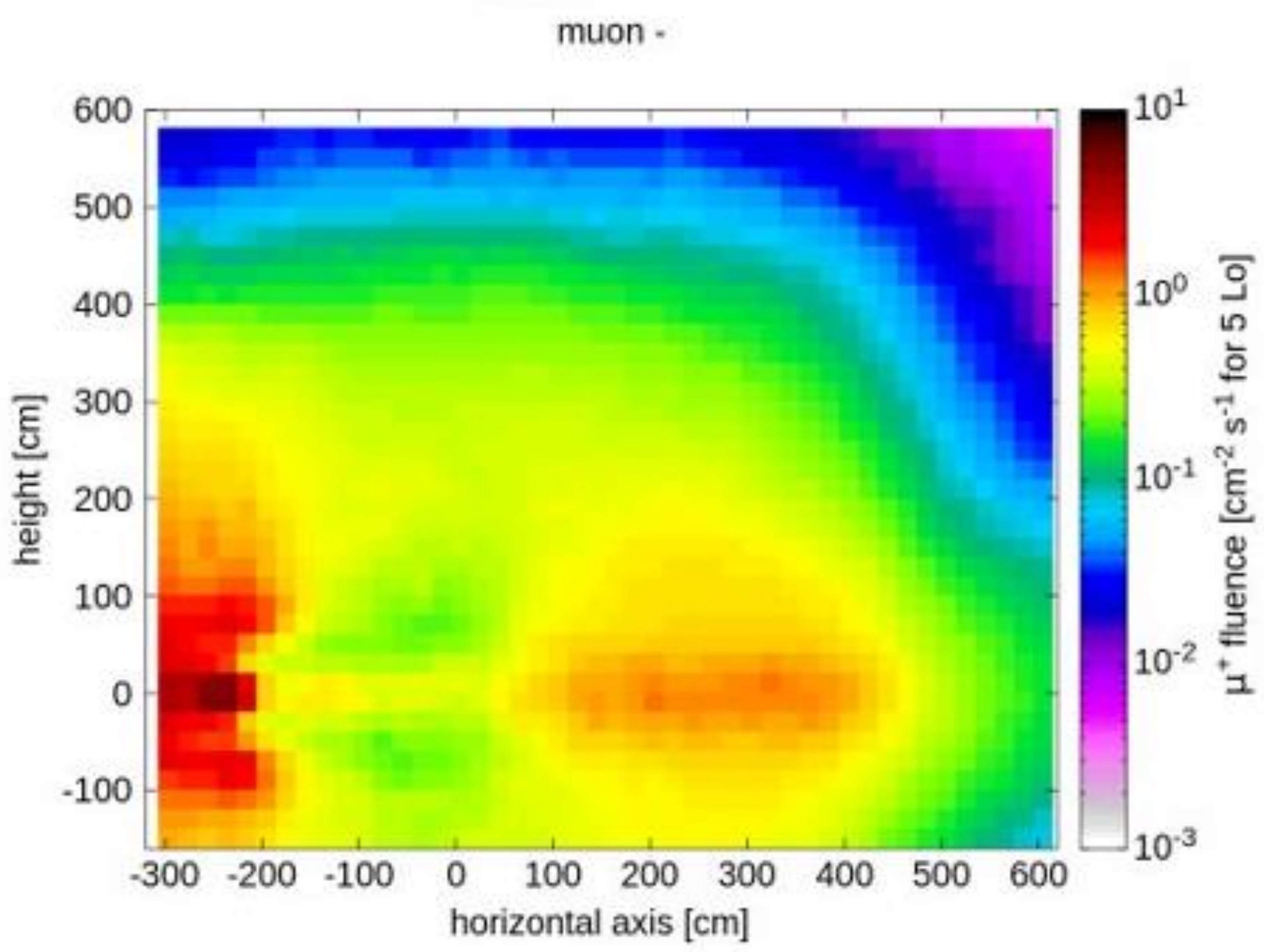
Drift gap ~30 cm

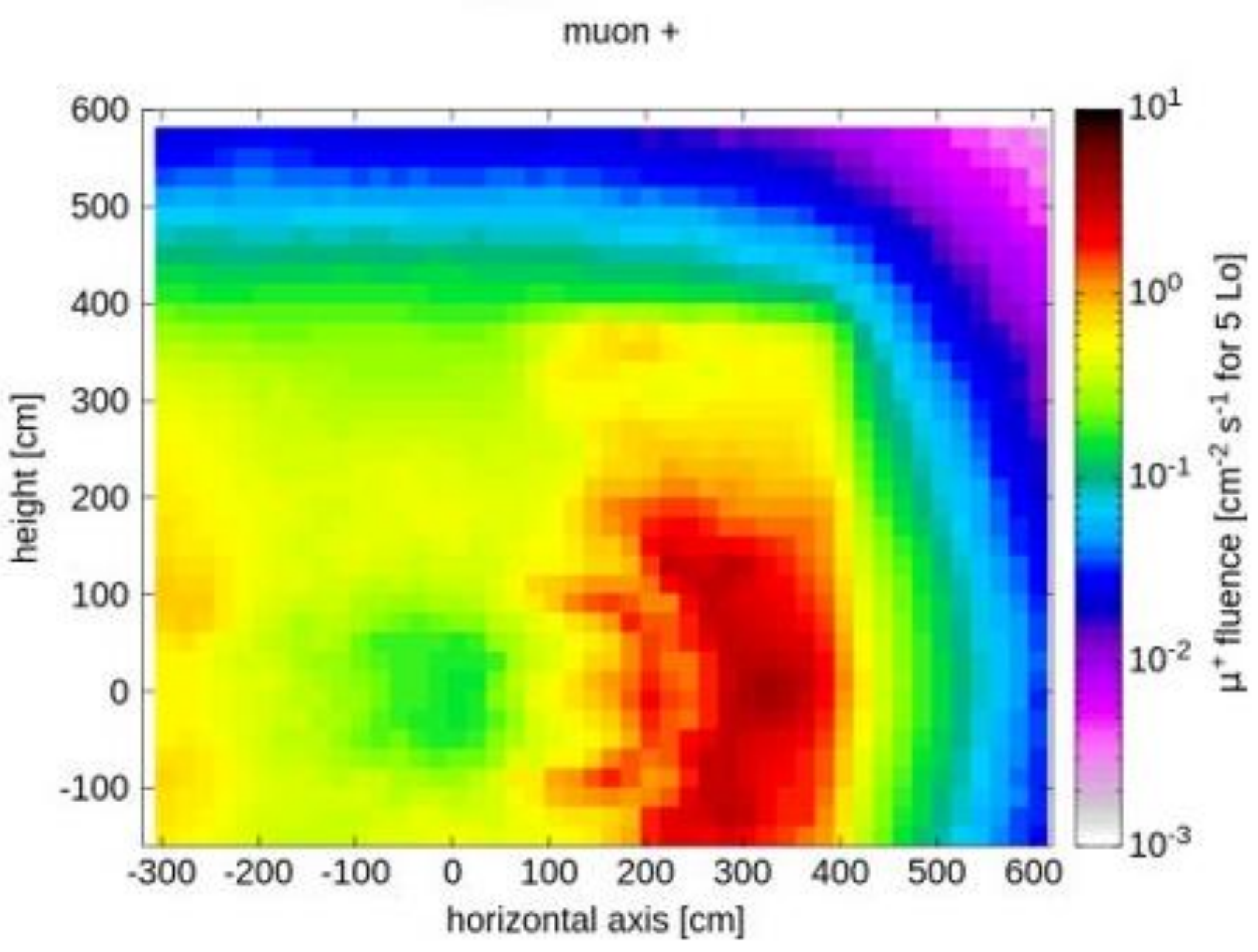


Pixellated anode: ~72000 channels/anode
Photodetection: ~50 SiPMs/anode
Cathode HV: ~15kV (E ~ 500V/m)

Space Charge

~0.5 Hz at LOS.





Significant flux of muons makes space charge a concern.

Space charge is the underlying distribution of charge in the detector volume.

Ionizing particles produce not only electrons (which are removed from the volume relatively quickly) but also positive ions (which are removed much more slowly).

With a constant flux of ionizing particles, a persistent positive charge density builds up.

E-field near the anode is reduced, near the cathode is increased.

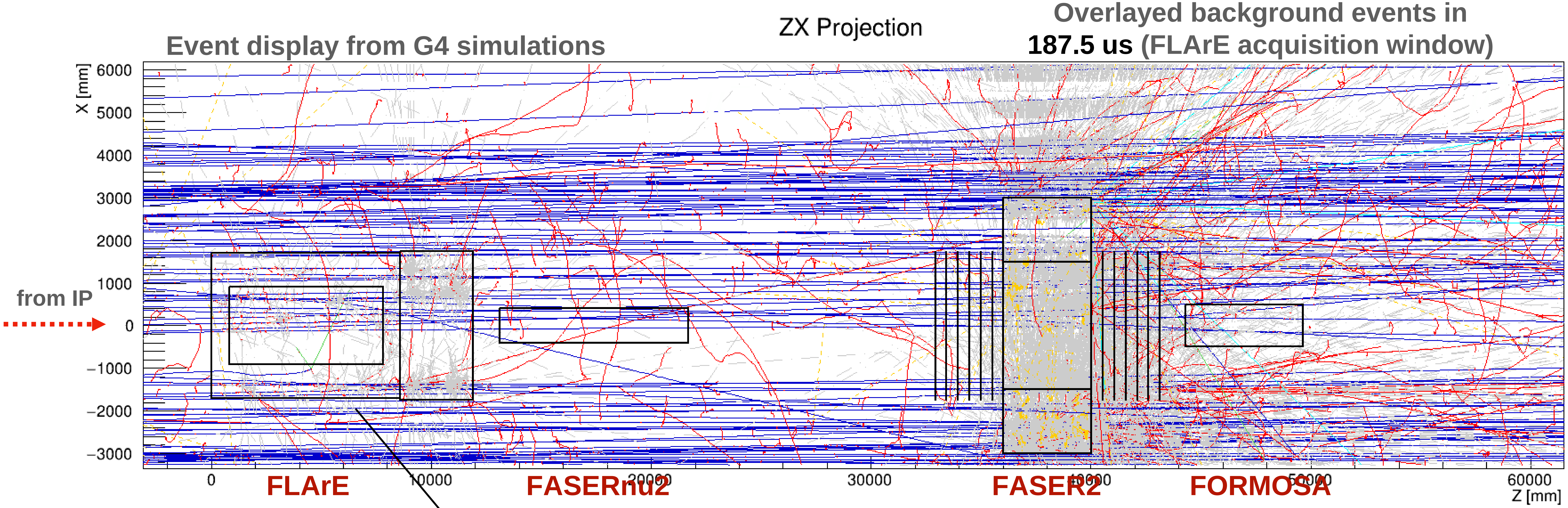
For gap of 30 cm, we conclude that space charge is not an issue. For vertical 180 cm drift, there will be distortions of ~20-30% (dependent on luminosity) that must be corrected.

*S. Palestini and F. Resnati. Space charge in liquid argon time-projection chambers: a review of analytical and numerical models, and mitigation methods. JINST, 16:P01028, 2021, 2008.10472

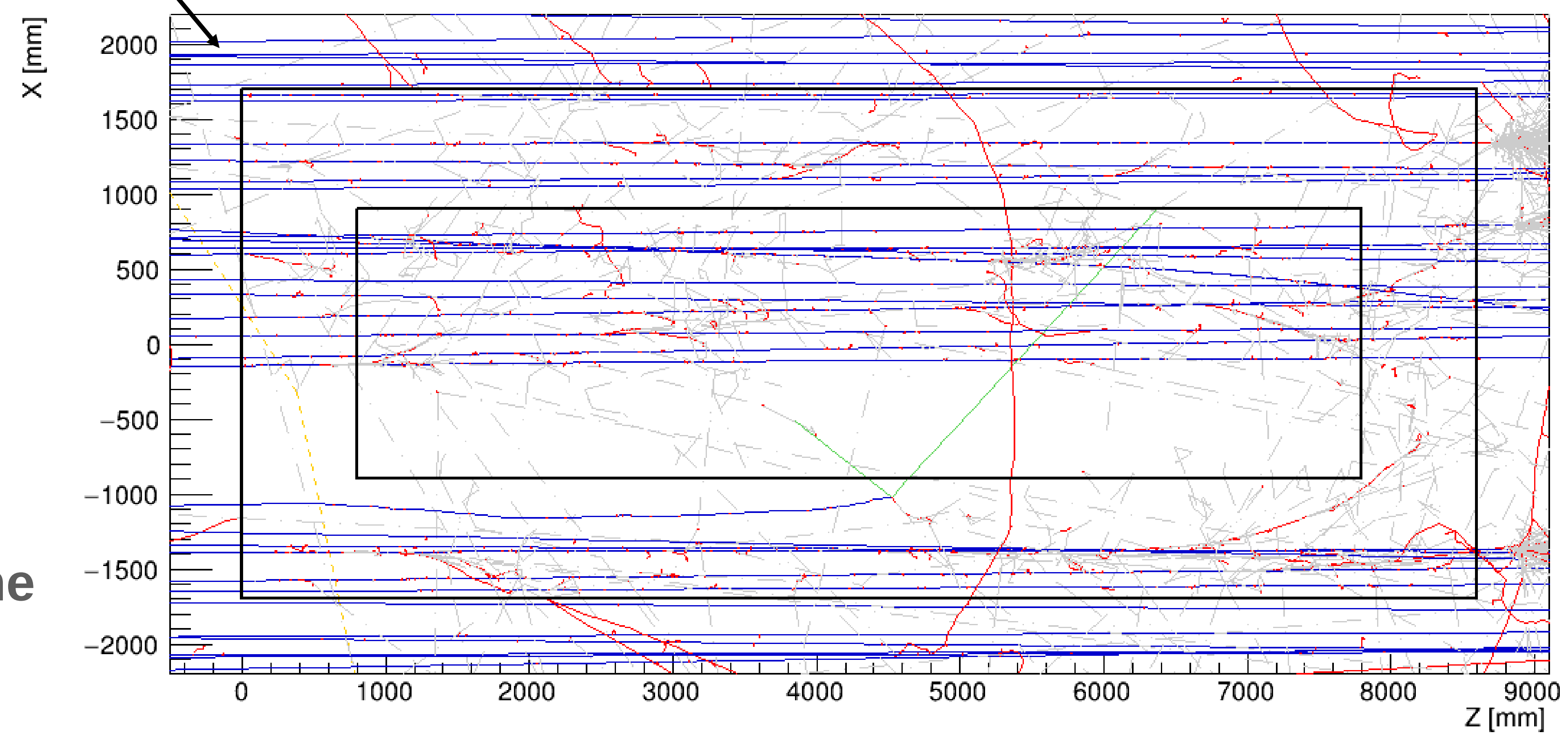
Event display (I) (Trigger studies are needed to deal with the muon background)

Event display from G4 simulations

Overlayed background events in **187.5 us** (FLArE acquisition window)



Zoom on FLArE volume



$\mu^{\pm}$: blue
$e^{\pm}$: red
n: orange
γ: gray

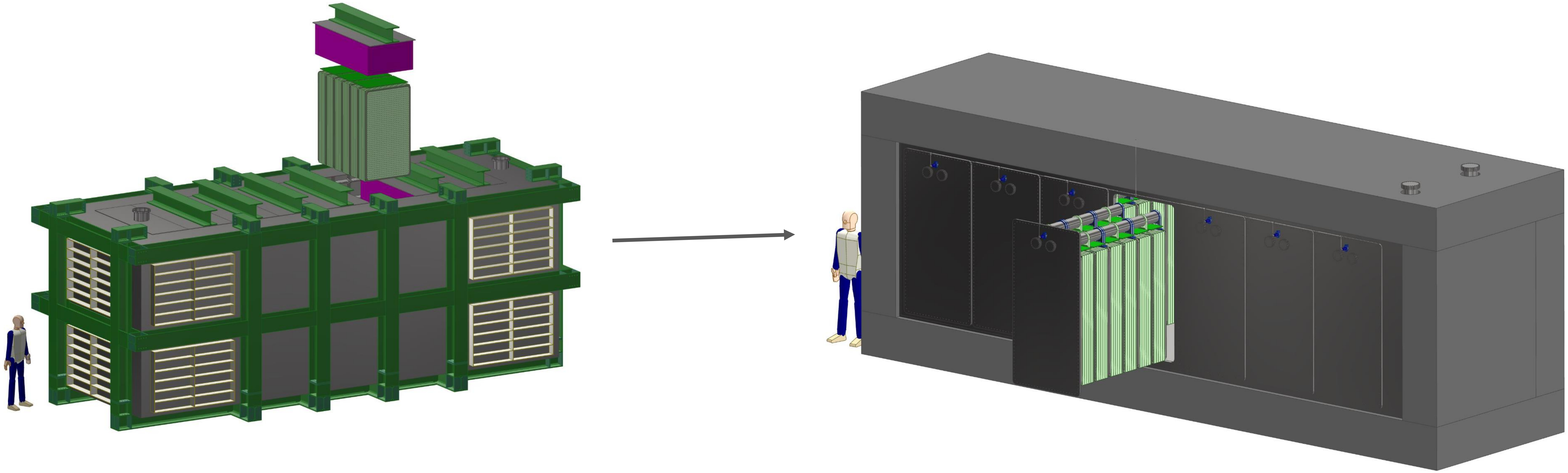
p: black
π^{0}: magenta
$\pi^{\pm}$: cyan
other: green

TPC Design

The TPC design has been modified from top-installation to a side-installed “filing cabinet” design.

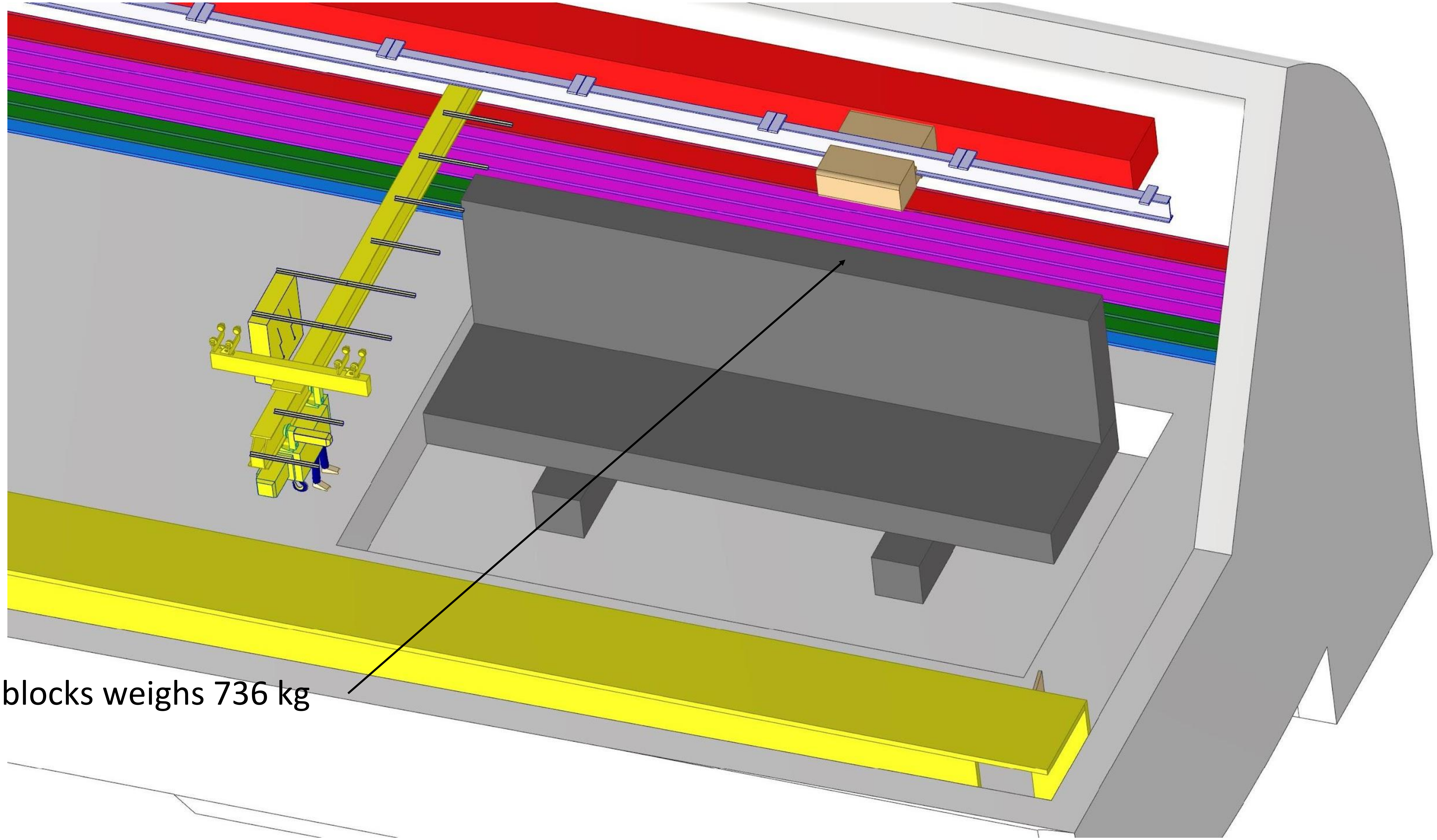
This avoids issues with crane height in installation from above, while the modules remain easily removable for repair.

The GTT membrane cryostat has been replaced with a foam-insulated cryostat.



Installation

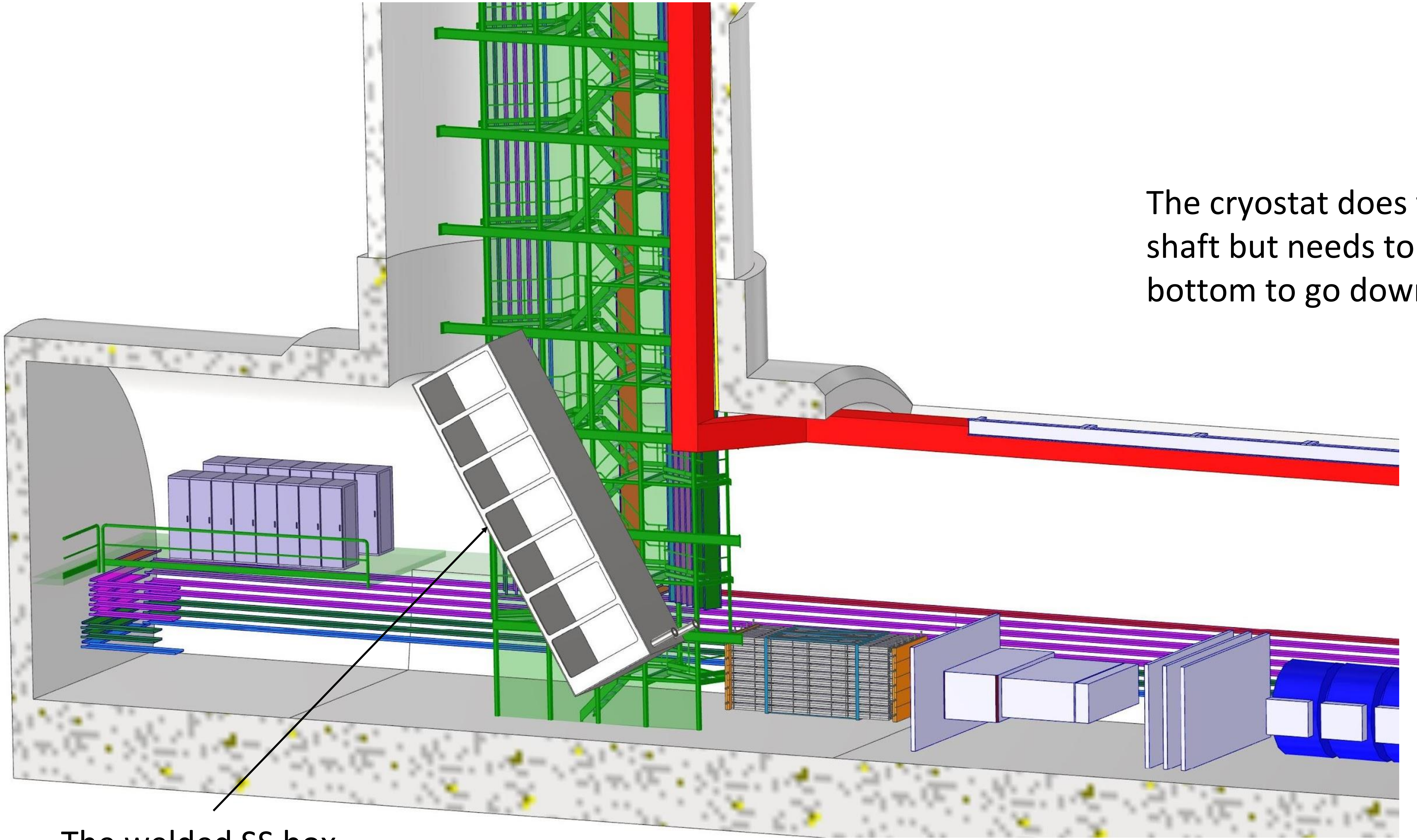
Foam supports, bottom, and back blocks are installed.



This blocks weighs 736 kg

Installation

Lowering the cryostat box down the access shaft

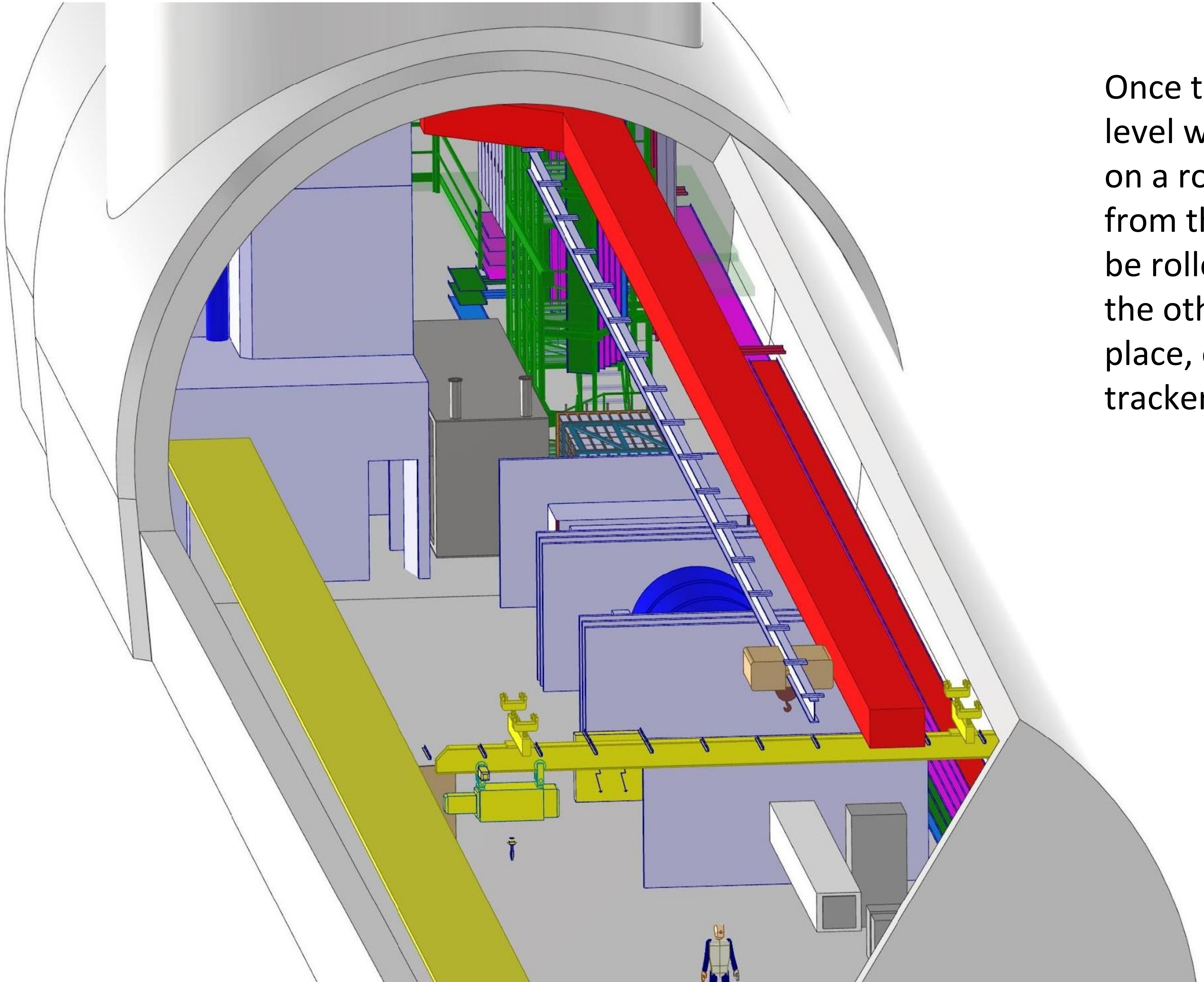


The cryostat does fit down the access shaft but needs to be rotated at the bottom to go down the drift

The welded SS box weighs 19.78 tonnes

Installation

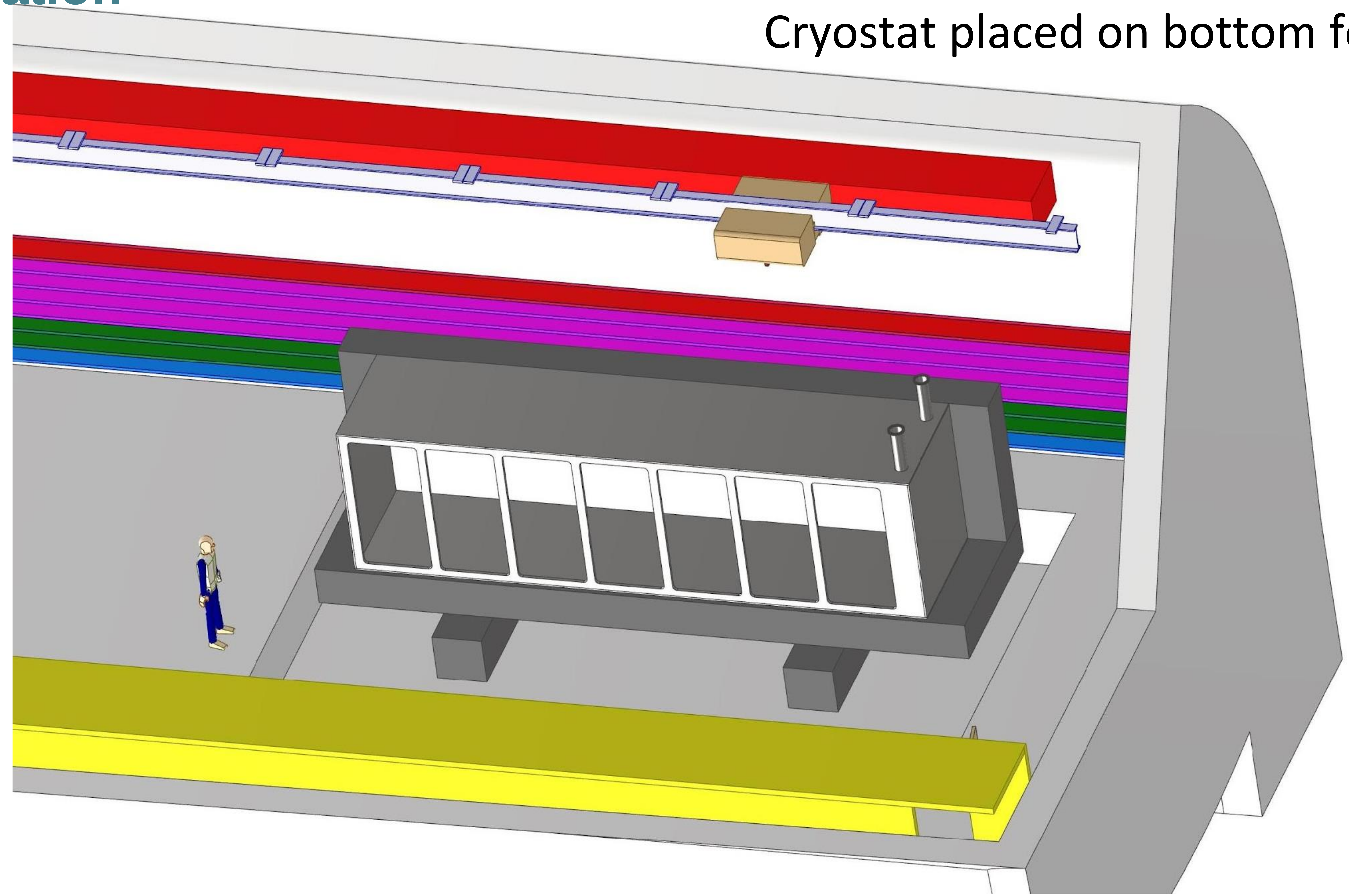
View showing that the cryostat must be the first item in the beam line



Once the cryostat is rotated level with the floor and placed on a rolling dolly, it is clear from this picture that it cannot be rolled down the tunnel with the other beam elements in place, especially the FASER 2 tracker planes.

Installation

Cryostat placed on bottom foam



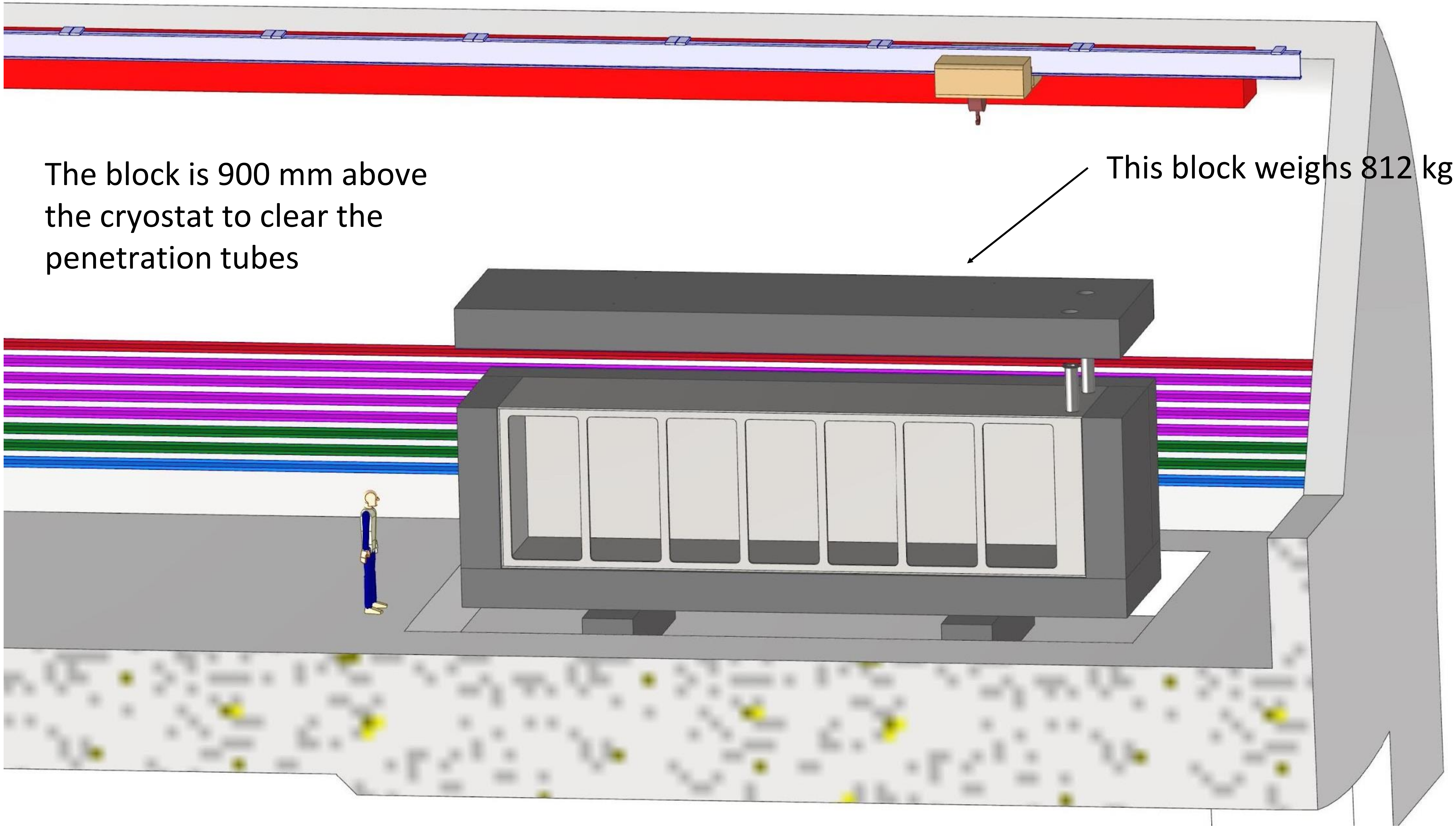
It is a judgement call about whether the back foam or the cryostat gets placed on the bottom foam first. It depends on the fixturing required to do the moves.

Installation

Placing the top block of foam above the cryostat

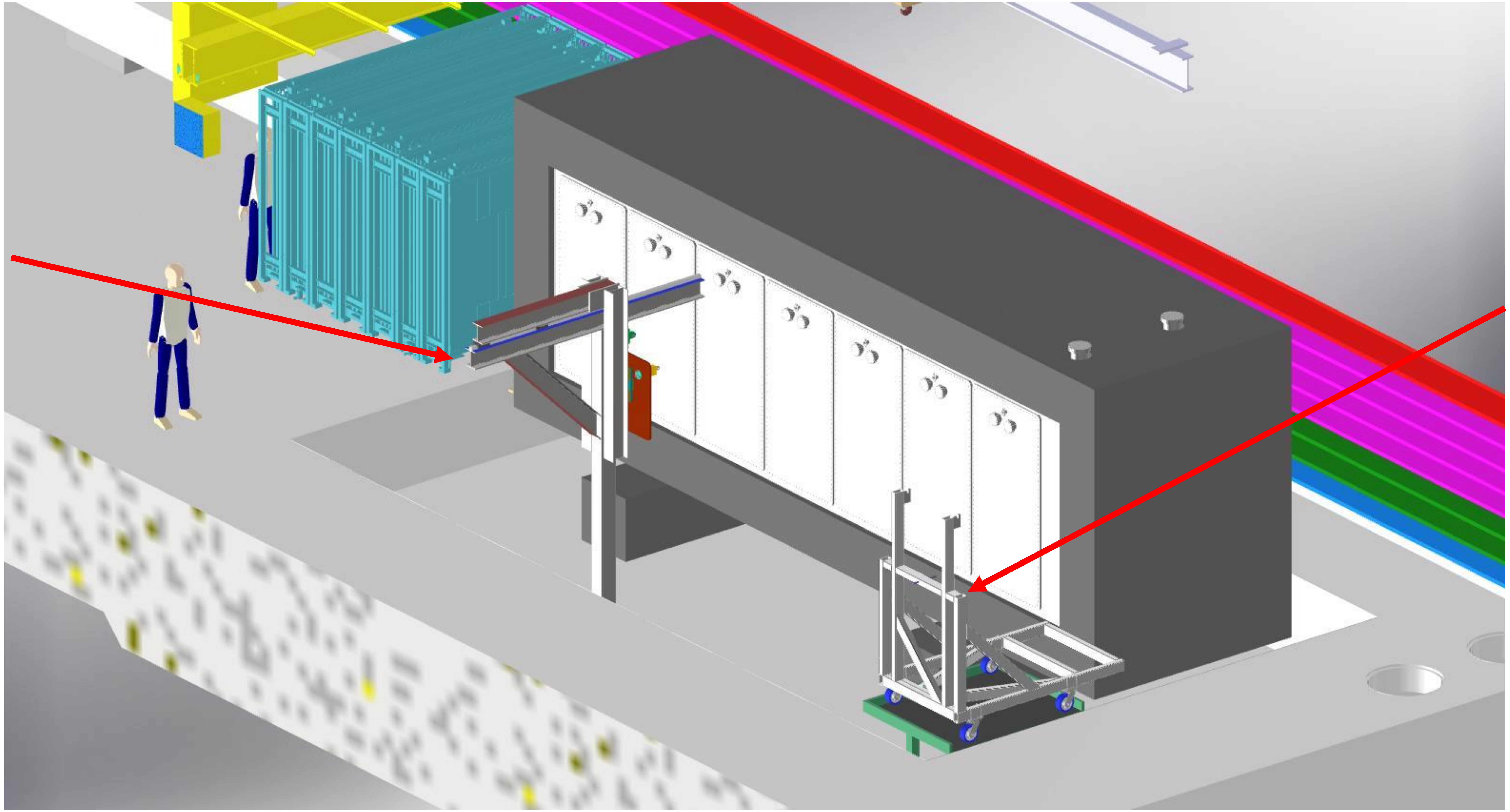
The block is 900 mm above the cryostat to clear the penetration tubes

This block weighs 812 kg



Removal procedure shown (installation is the same, in reverse). The hadron calorimeter will be installed after the TPC. (Baby Mind concept adapted)

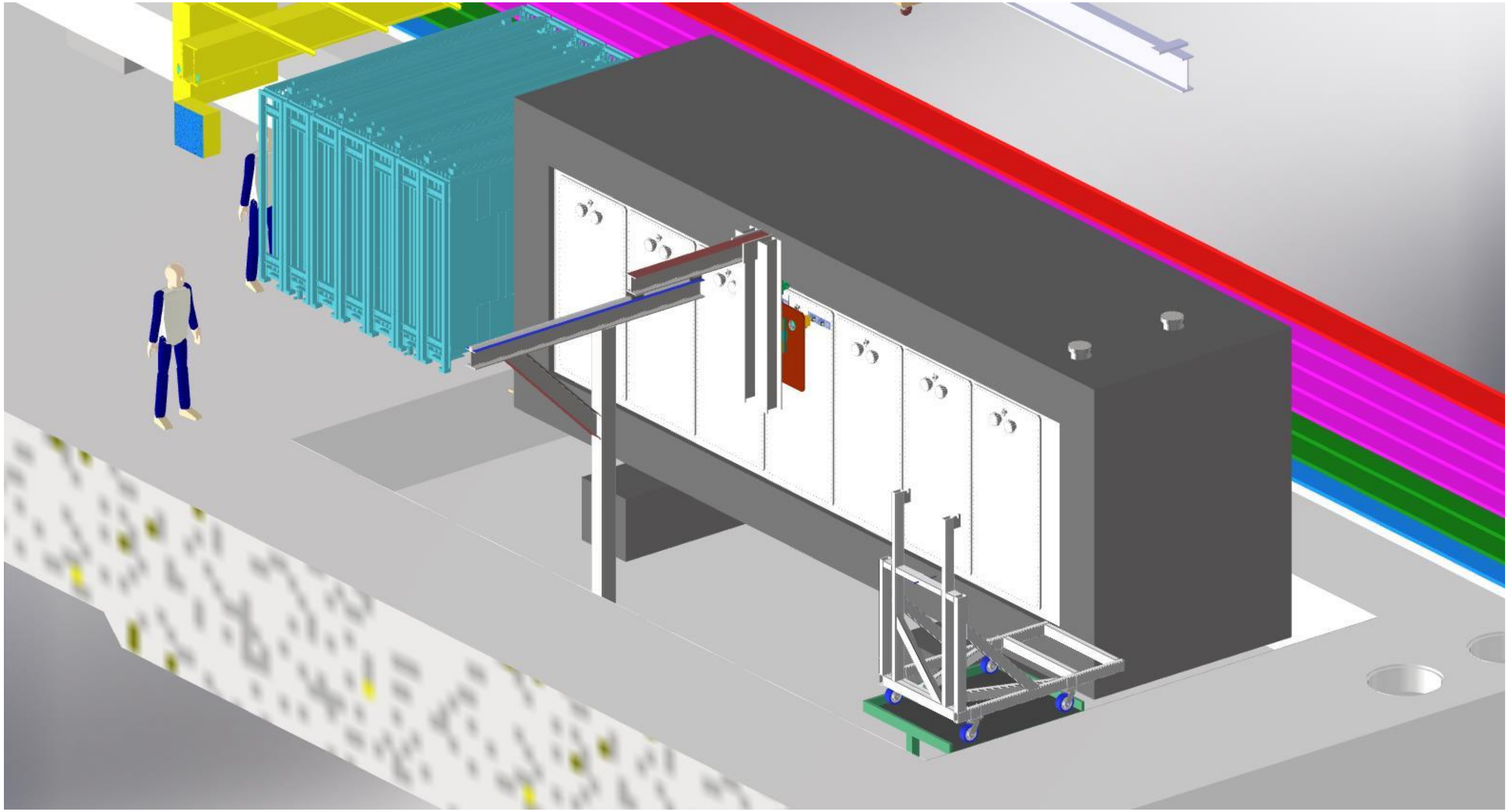
Installation Machine



TPC assembly cart

Installation

Installation machine pins to attachment lugs on the face of the TPC module.

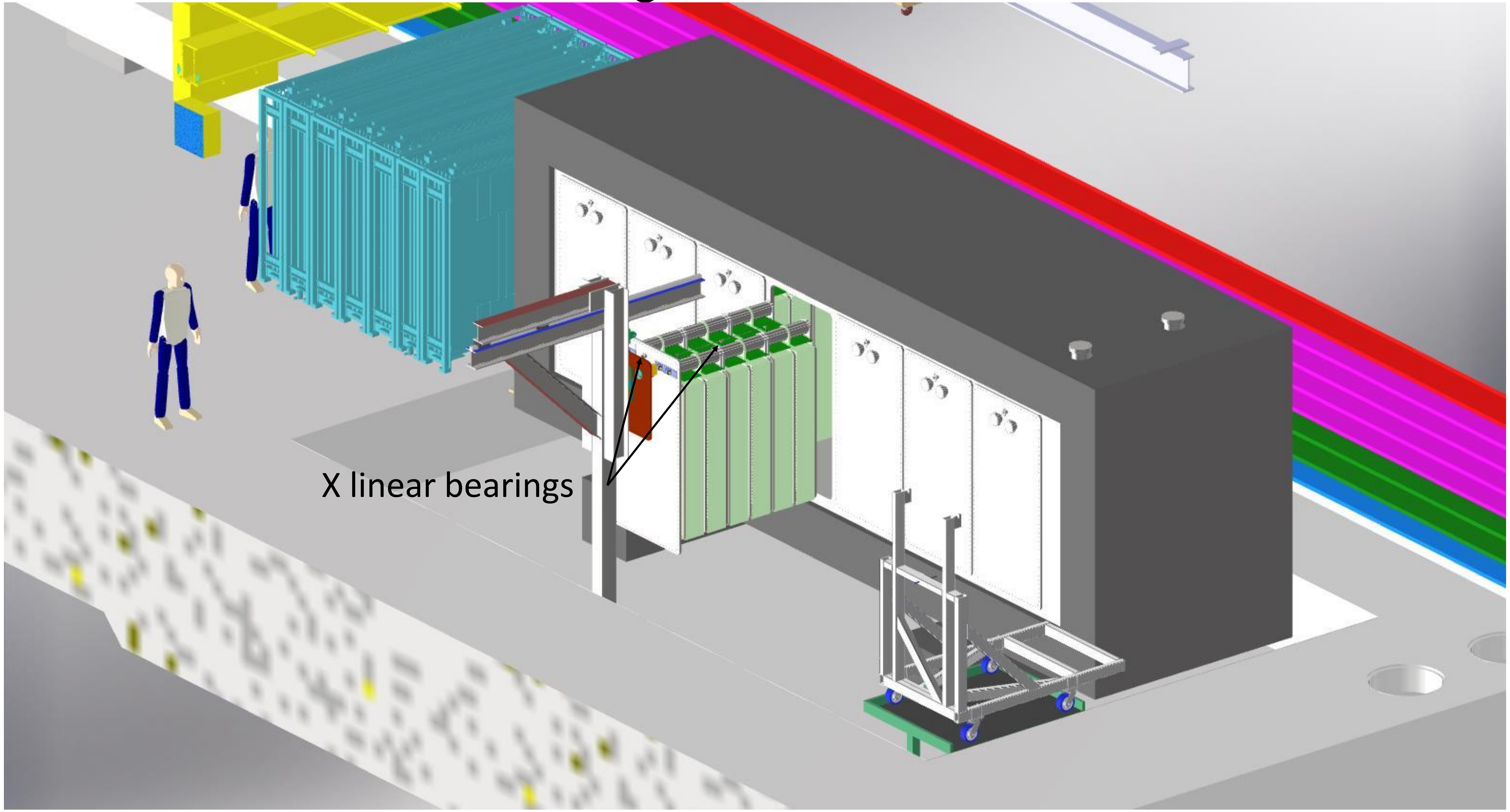


The adjustments of all of the degrees of freedom on the installation machine line up the machine to the position of the TPC module lift points.

If the modules are sealed with bolts and a Jetseal metal o-ring, all bolts are removed at this point. If the modules are welded into the cryostat, the weld must be ground.

Installation

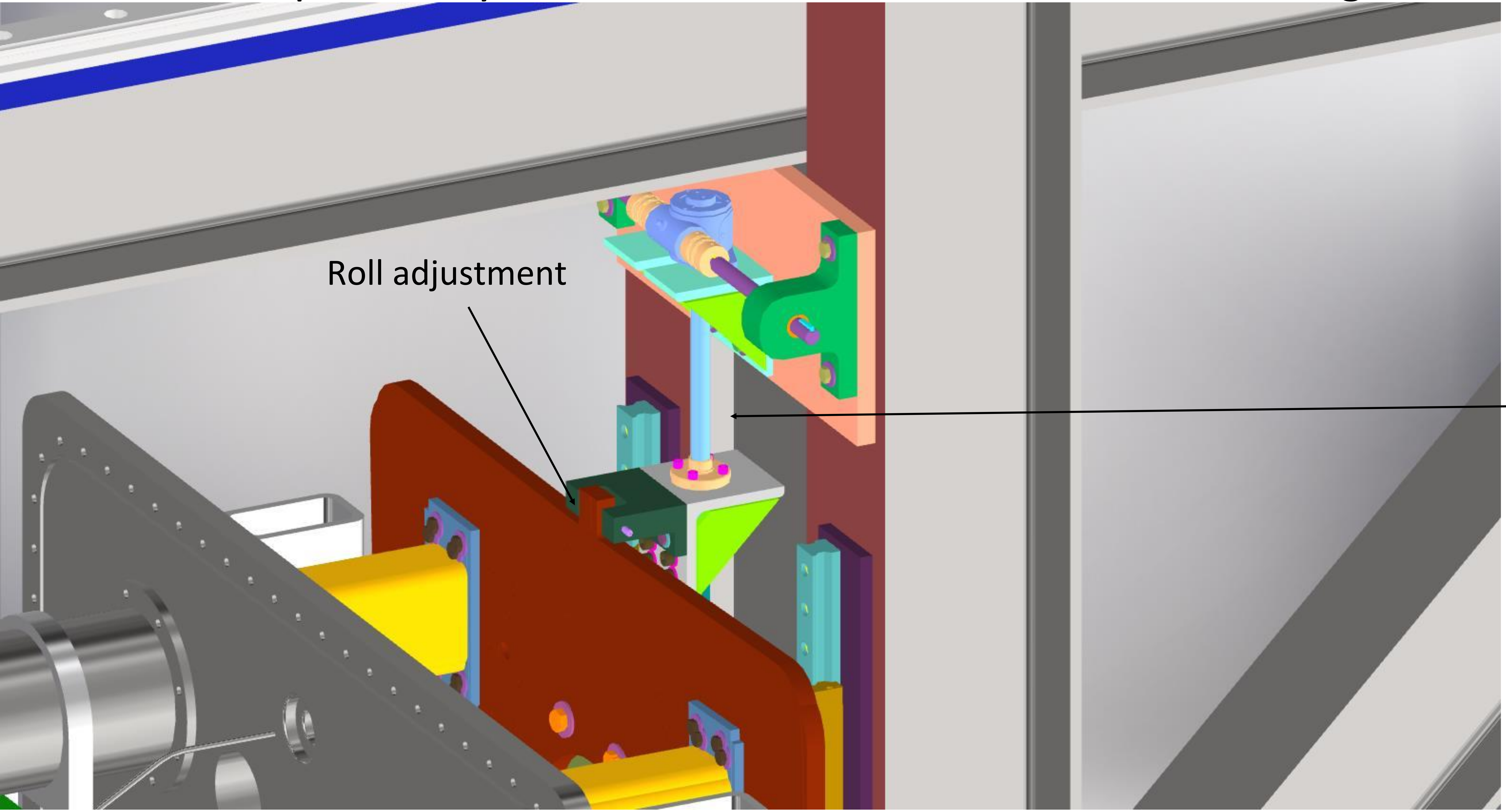
The TPC Module is translated out of the Cryovessel on the Installation Machine's linear bearings on the X axis.



TPC modules weigh 1,114 kg

Installation

Close-up of roll, yaw, and Y translation mechanisms, looking US and to beam left



The rod ends on the ends of the yellow arms that attach to the TPC lift brackets can be extended or retracted to provide yaw adjustment

Y adjustment

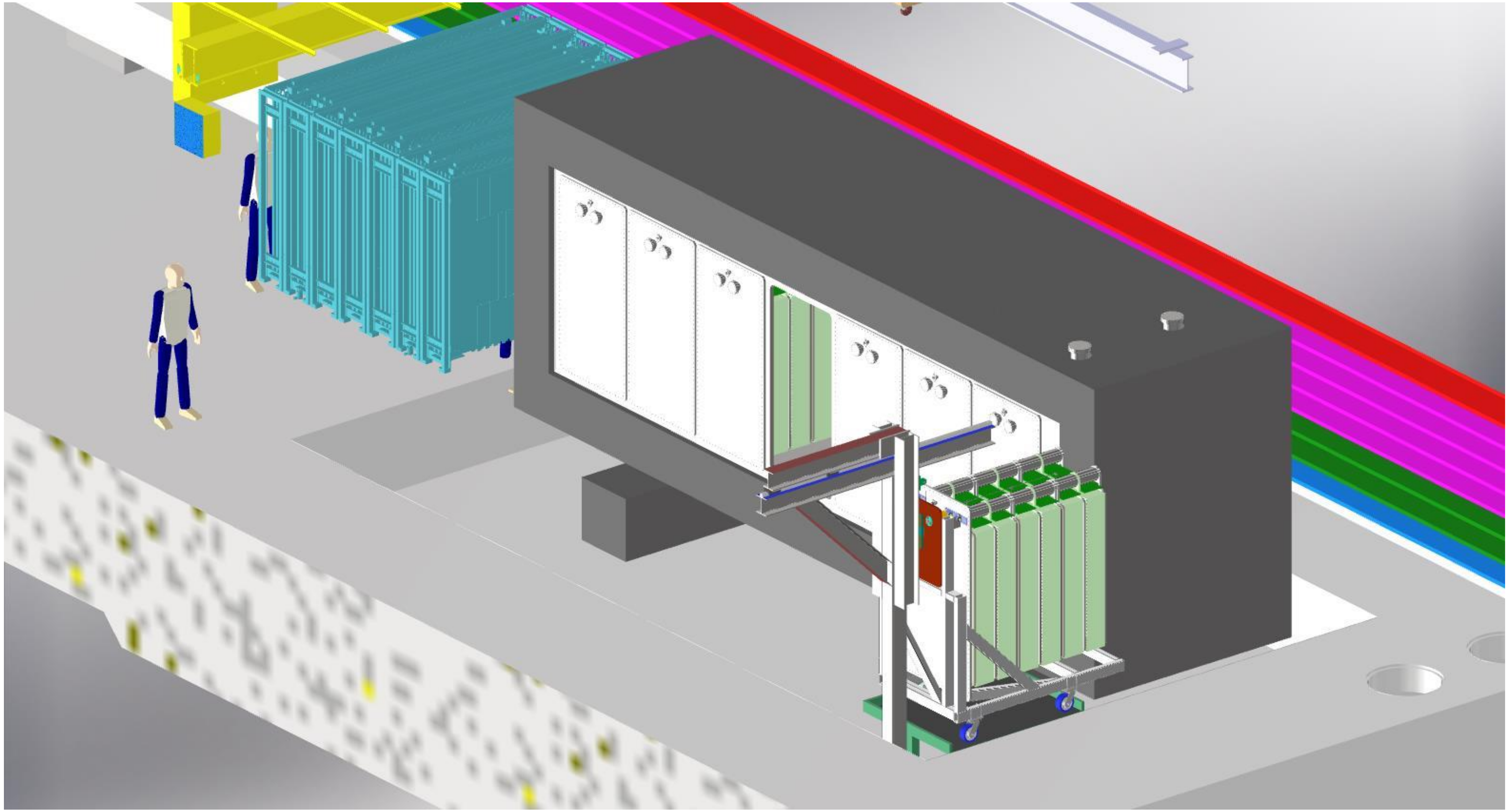
Roll is accommodated by a turret bearing not visible behind the red plate.

This mechanism is a conceptual model adapted from the installation machine built for the EXO cryostat. It will need further engineering to ensure the stability and capacity of the mechanism.

The EXO machine was all manually operated, being smaller and manipulating a smaller mass. It remains to decide which axes are motorized.

Installation

The Installation Machine translates the TPC Module to the Assembly Cart. The Installation Machine lowers the TPC Module onto open hooks of the Assembly Cart.



The handoff takes place by adjusting the Installation Machine to transfer the load to the Assembly Cart, then the pins are removed from the attachment lugs connected to the Installation Machine.

Alternative Design: Optical Readout

- An alternative design using an ARIADNE-style optical readout is also being considered (see Kostas's talk yesterday).
- Technology already well developed and demonstrated.
- Liverpool would deliver the light readout plane and the optical system for FLArE.
- This design offers ~20% cost savings.
- Challenge: Not modularized. The longer drift length means more diffusion and space charge.

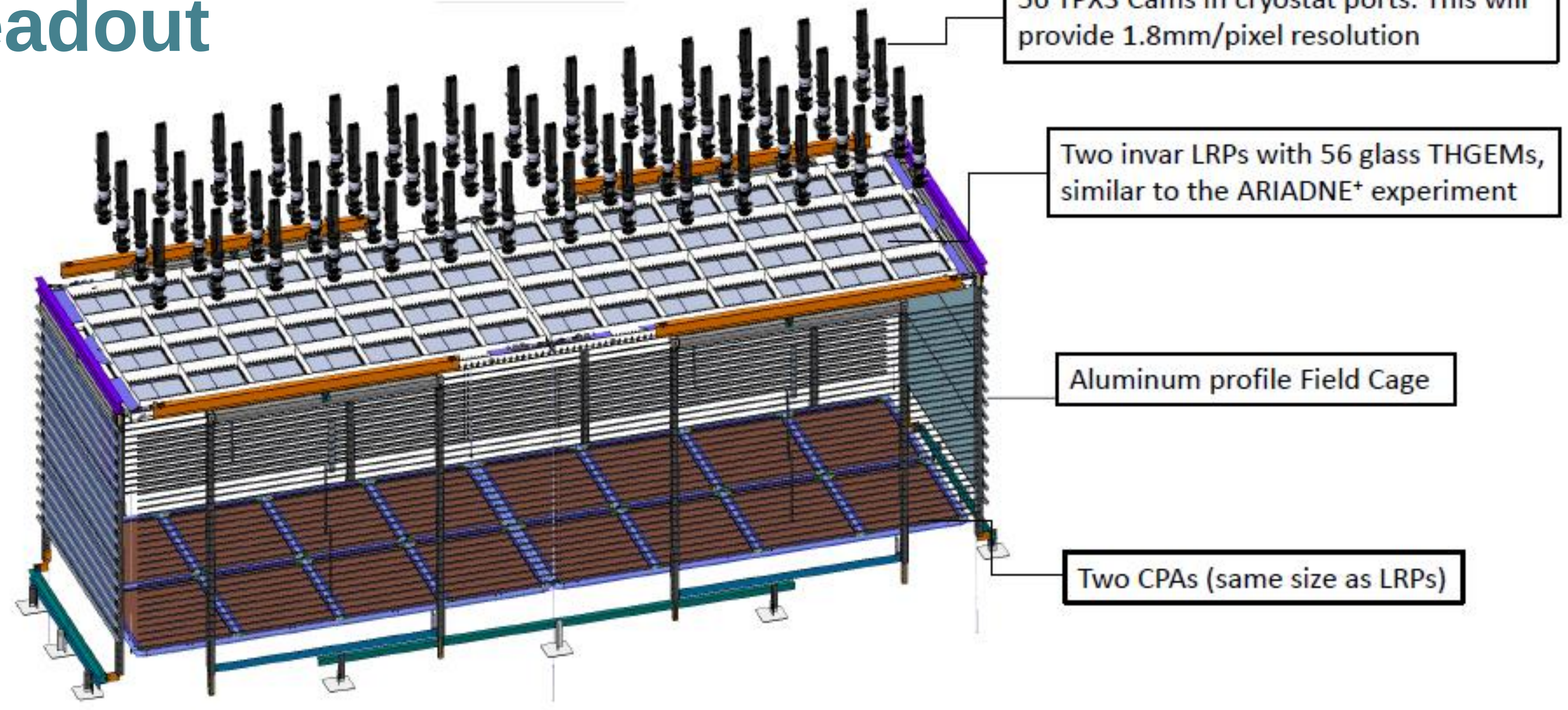


Figure 27: A conceptual model of a 3D optical dual-phase TPC option for FLArE.

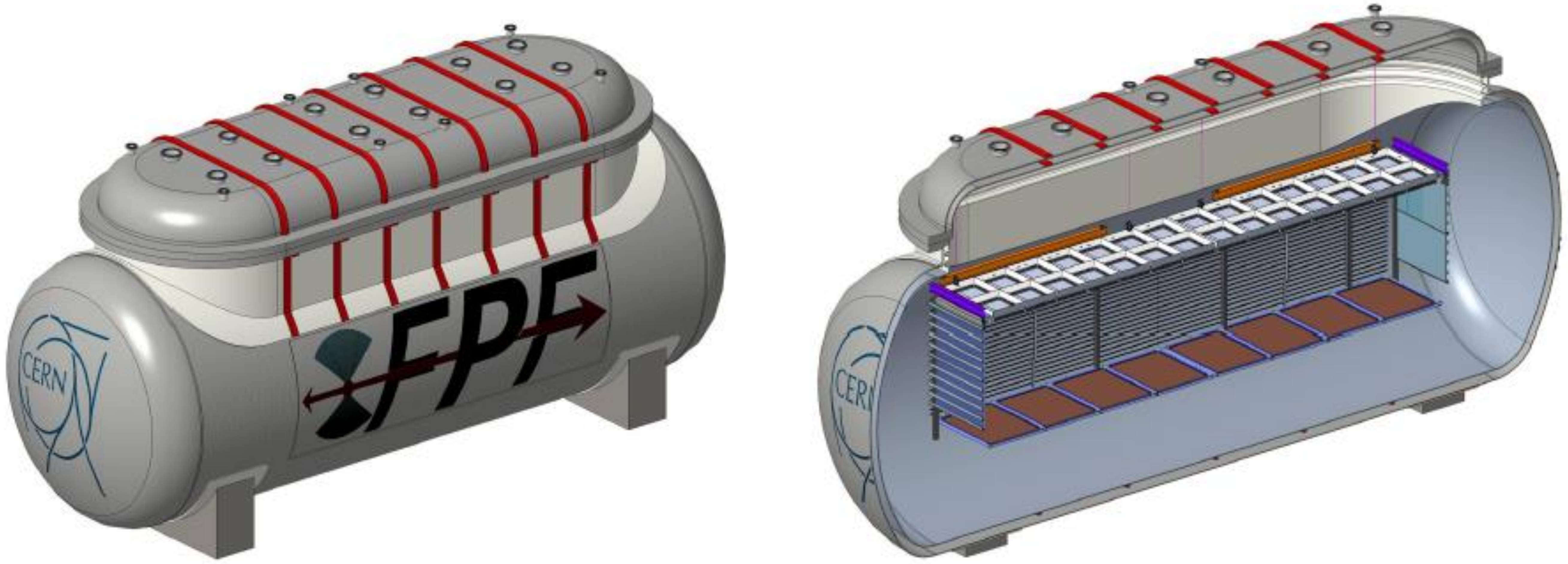


Figure 28: A conceptual model of a vacuum jacketed commercial cryostat with a reopen-able lid for the dual phase fast optical readout option. The cryostat lid will open with hydraulic arms instead of a crane since there is not enough height clearance.

Cryogenics and Heat Load

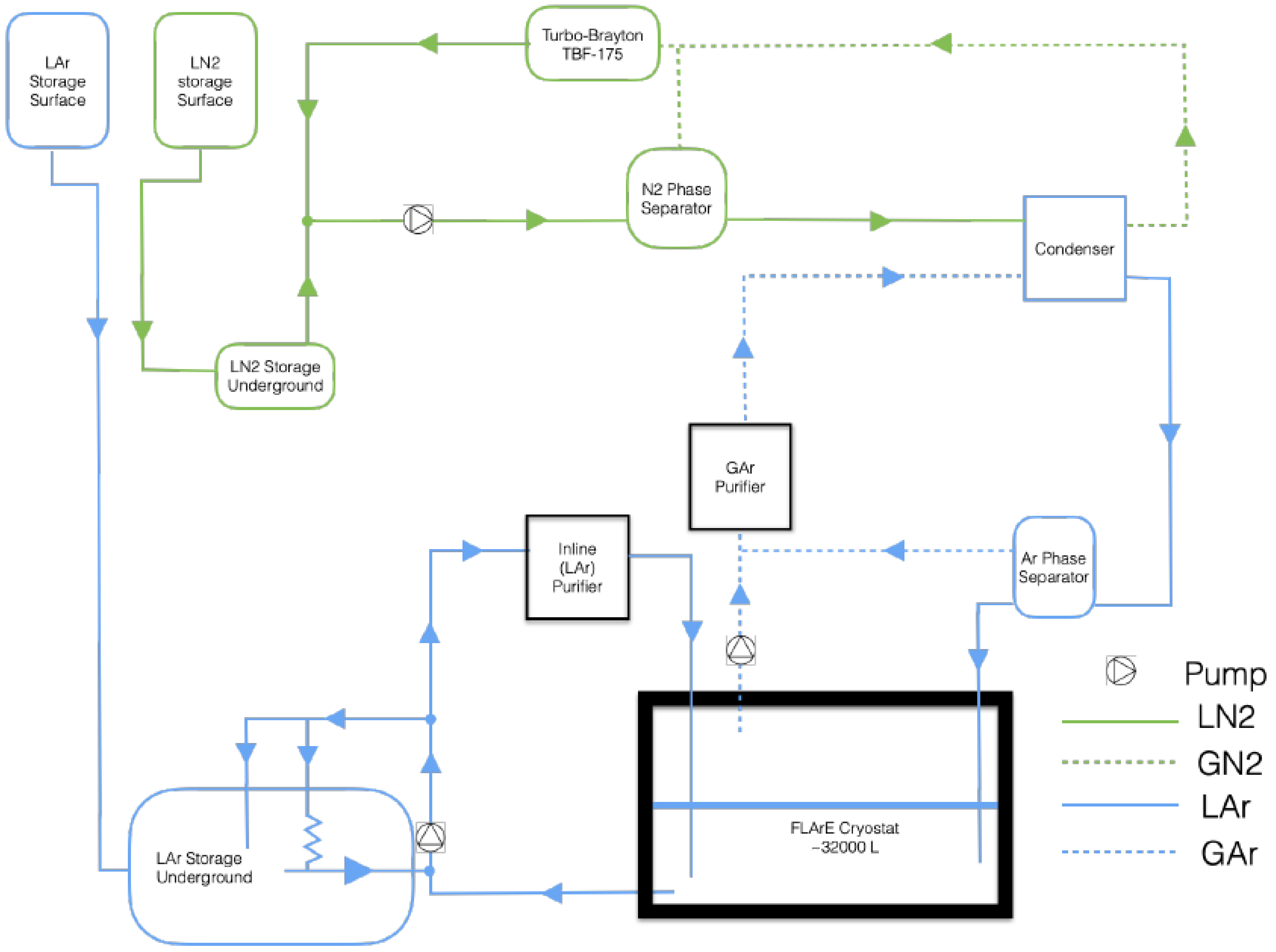


Figure 8: The cryogenic system schematic of FLArE Cryostat.

Conceptual cryogenics design uses a commercially-available Turbo-Brayton for cooling. Max. cooling power 16.5 kW at 77 K.

Circulation system continually purifies argon. Uses now-standard LAr purification strategy of filters, molecular sieves, and getters.

Preliminary estimates of heat load are: 2.7 kW from environment and 2.4 kW from electronics.

Electronics and R&D for the an anode.

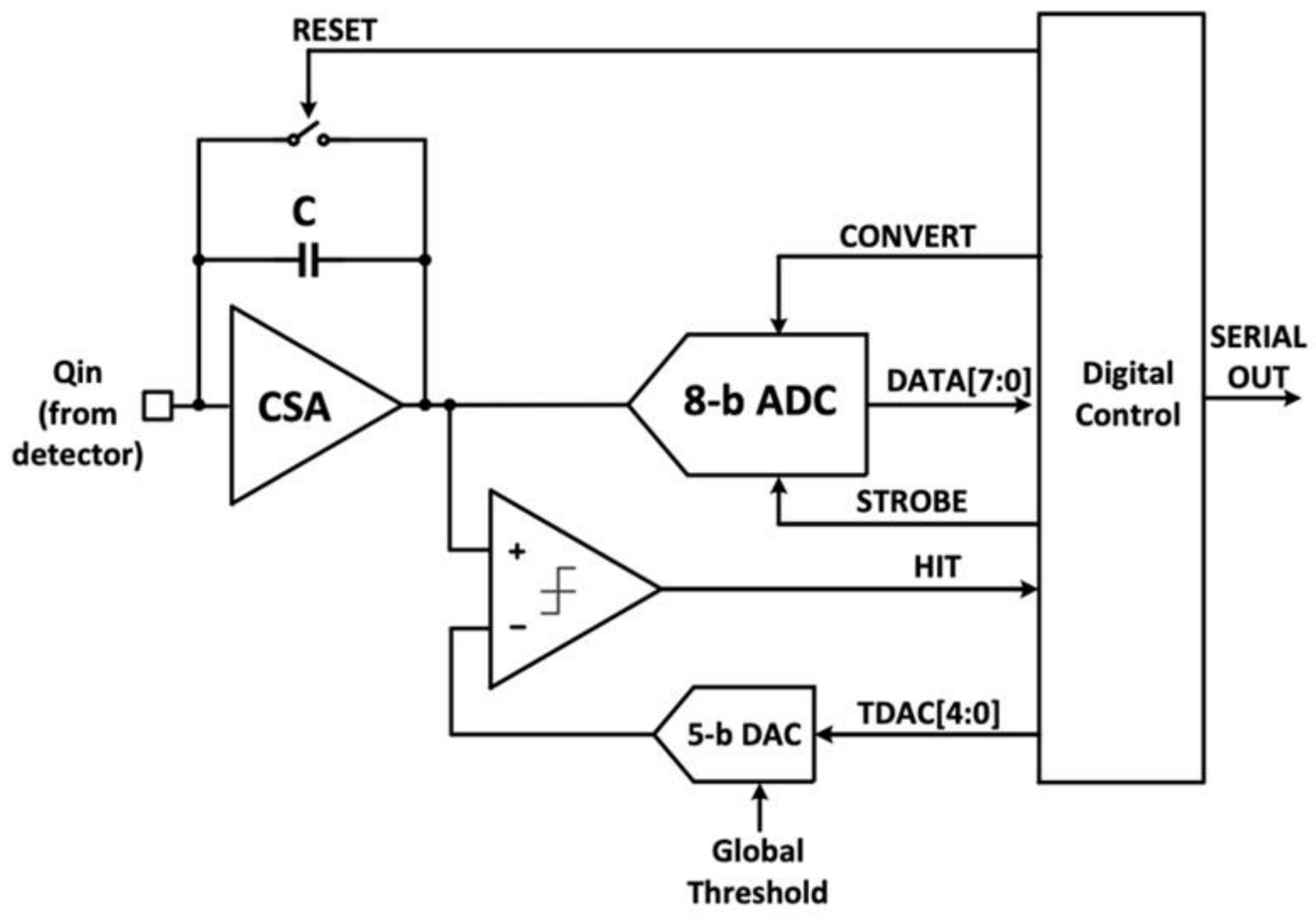
Options for charge readout:

LArPix: Developed for DUNE near detector. Similar to conventional charge-sensitive amplifier with external reset. Digitization and readout only occur when amplitude exceeds a threshold.

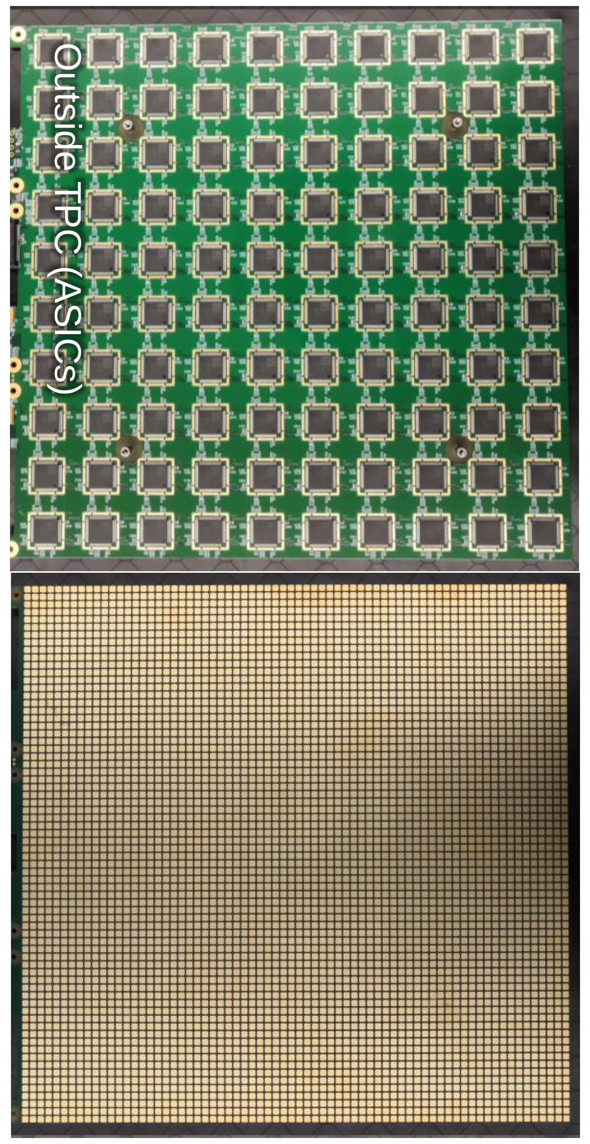
We benefit from huge development in the DUNE-ND enterprise. (redundancy, timing, power, cost are being optimized).

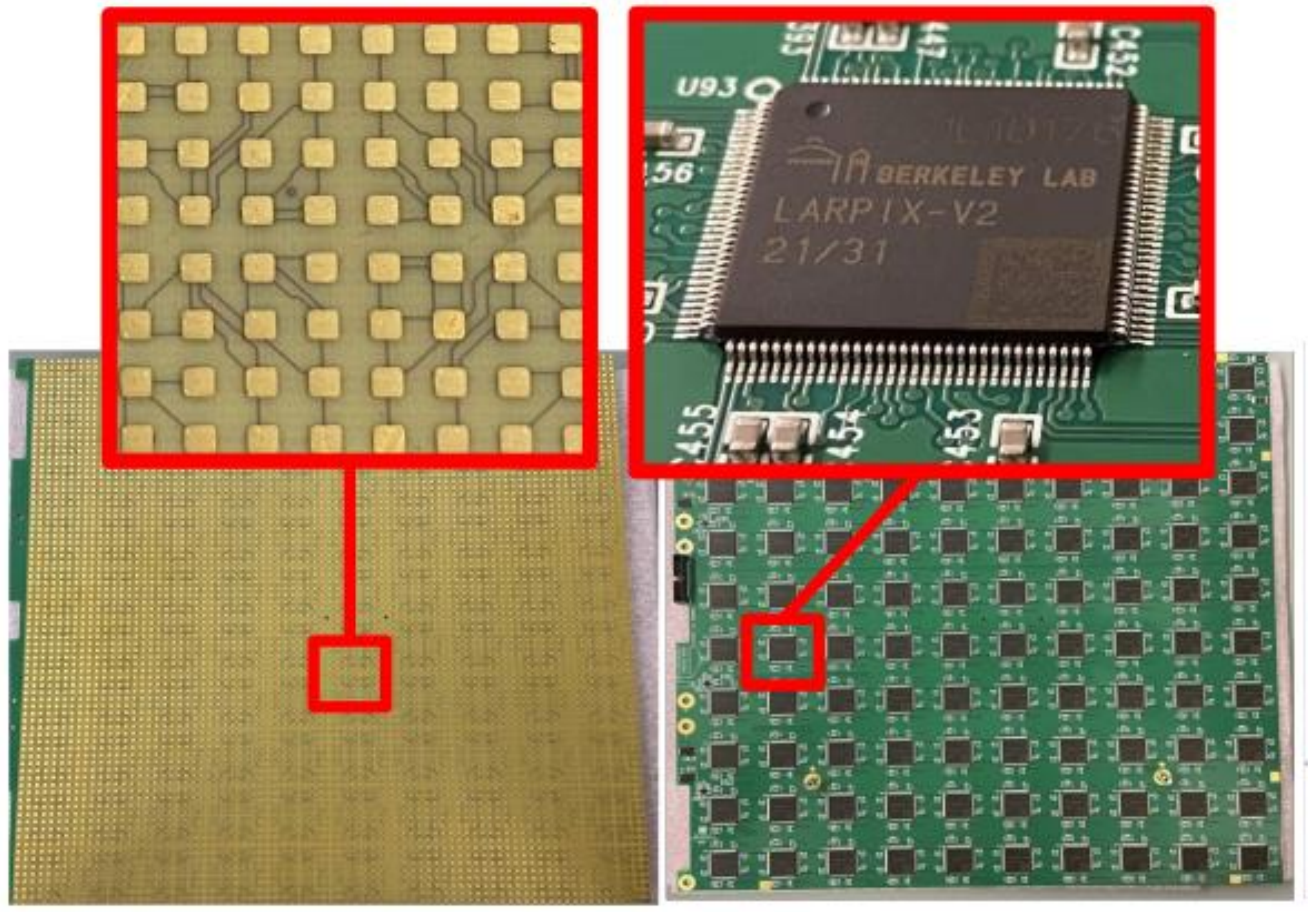
Q-Pix: Developed by Q-Pix consortium. Integrates until a threshold is reached, then resets and reports the time. This is in development, but could be very interesting for FLARE.

Anode geometry needs to be optimized to reduce the tails on the induction signals.



Block diagram of the LArPix ASIC





From Brook Russell (DUNE-ND)

Conclusion

- Please see talks from Matteo Vicenzi and Steven Linden at the 8th FPF workshop: https://indico.cern.ch/event/1473651/overview
  - Headline physics interest for FPF and FLARE is
    - Neutrinos in the 1 TeV range: ~200-500 events/ 10 ton/day
    - Tau neutrino flux and associated heavy flavor physics: ~1-2 events/10 ton/day
    - Light dark matter search with decays and interactions.
- Preliminary examination of event rates and backgrounds suggests that a LAr detector is feasible and ground-breaking.
- A LArTPC requires an advanced readout for ultimate spatial resolution, and a trigger system that can find contained events in the presence of muons. Timing could associate events with the ATLAS bunch crossing (studies are needed).
- A very preliminary estimate for FLArE based on DUNE ND is ~11 MCHF (core cost).
- Facility integration is at a conceptual stage, but appears feasible with little interference to the HL-LHC.
- We expect the project to be very international with substantial US involvement.

US Snowmass energy frontier recommendation.

- Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades. — Energy Frontier Report (2022)

- P5 report certainly recognized this, but recommended that the FPF experiments be considered in a separate small experiment portfolio.