LARGE SIZE NOBLE LIQUID DETECTORS: DUNE AND PROTODUNE

Challenges, prototyping program, operational experience, and perspectives towards the design and construction of the DUNE first cryostat and associated cryogenic system, due to start operation in 2027.

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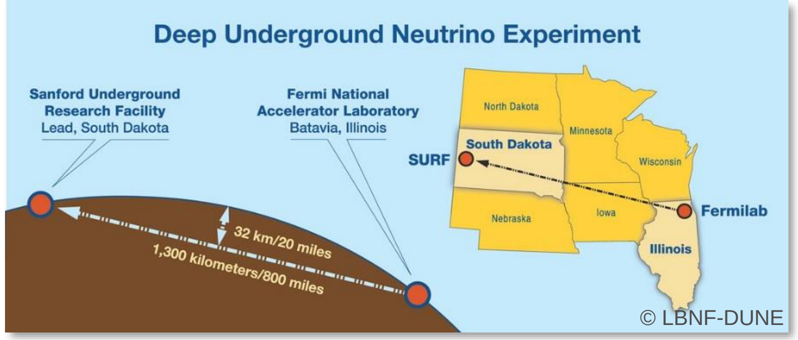
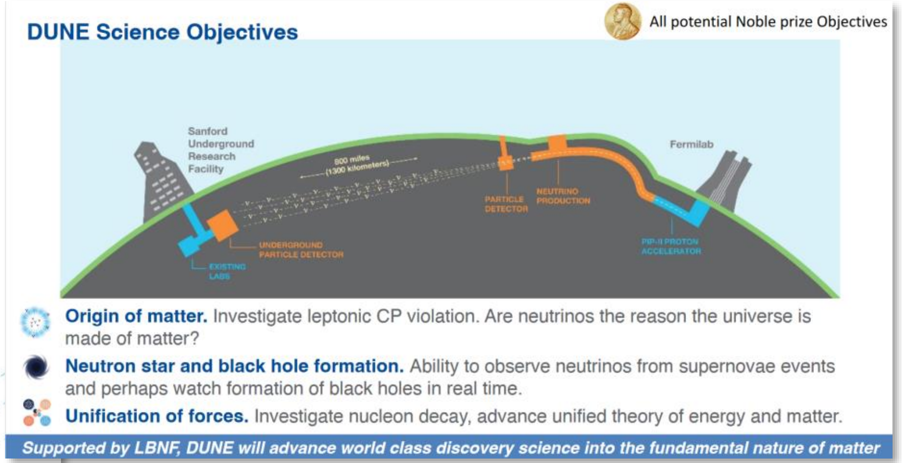
NP02 vertical drift cryostat and associated cryogenic system in CERN's EHN1 test beam hall

Introduction

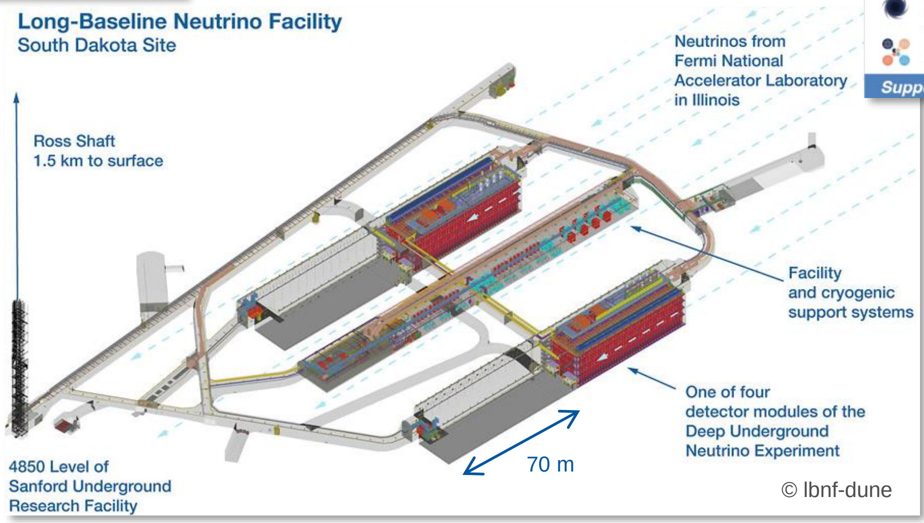
An international collaboration (DUNE) has been set-up to perform a comprehensive investigation on neutrino oscillations. Idea: Shoot a neutrino beam from Fermi Lab to Sandford Lab, covering a distance of 1300 km and detect neutrinos with a liquid argon based detector with a total argon mass of 70 kTon. The detectors will be placed in caverns at 1.5 km below the surface.



Neutrinos from Fermilab to South Dakota through the earth, no tunnel necessary



@LBNF/DUNE



Far site caverns

4 x 17 kT
of LAr as active medium

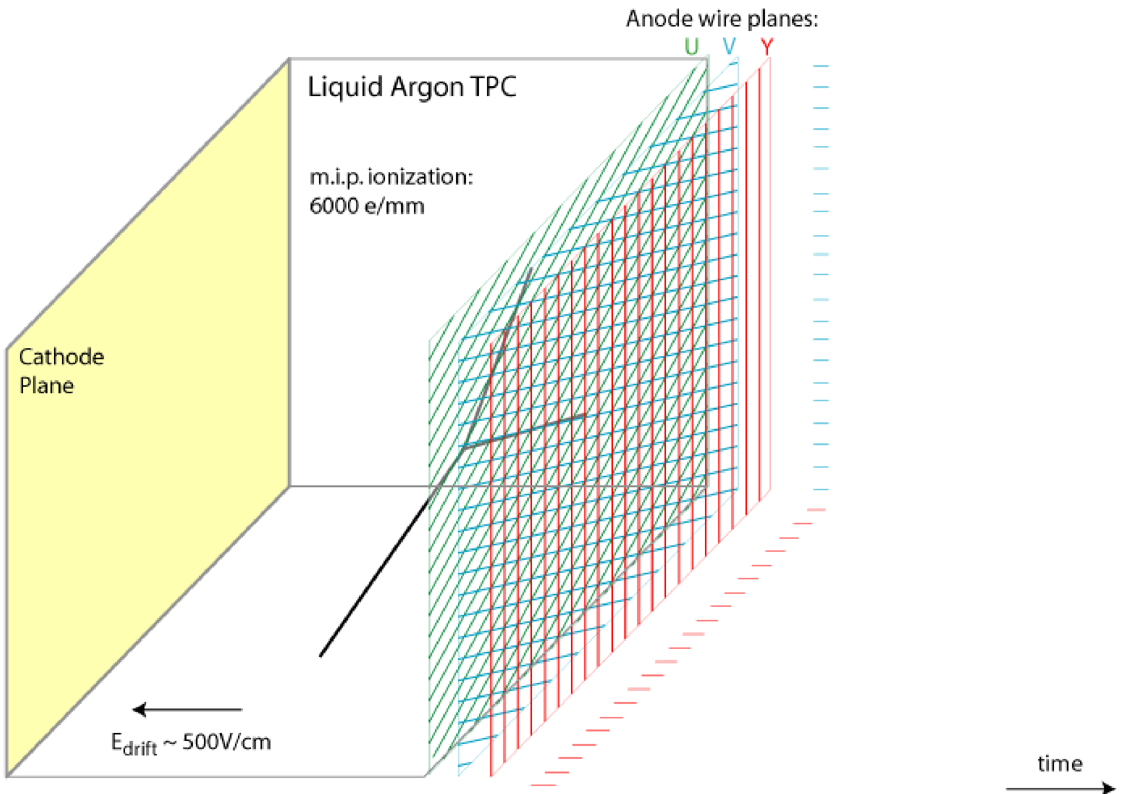
Detection principle

Neutrino has interaction with argon atoms creating secondary particle(s). These particles are liberating valence electrons along their travel through the detector;

Along the path through the detector about 6000 free electrons are created per mm;

These electrons are moving to the anode plane, while the much heavier positive ions move relatively slow in this field;

Together with the scintillation light detected by the photo multipliers, the track of the neutrino in the detector can be reconstructed.

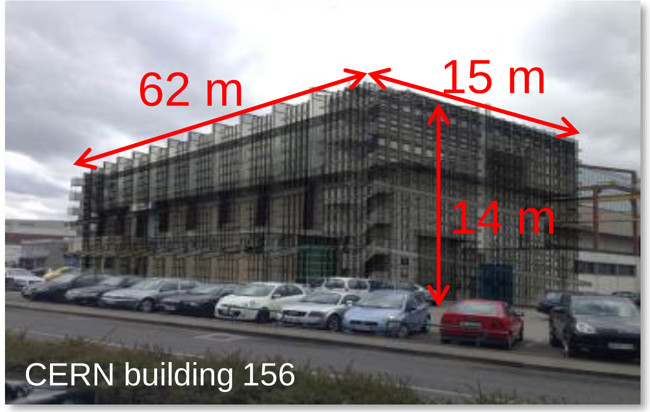


@DUNE

Detection principle

For this operational principle to function:

1. Need of very pure argon to have a "long" free electron lifetime. "long" means milli-seconds, which corresponds to an oxygen equivalent purity in the parts per trillion level;
2. Need to be able to put a HV field of 300 kV over the sensitive argon volume;
3. The temperature gradient over the liquid argon volume shall be below 1 K;
4. Need of relatively long liquid argon bath and relative large argon surface perpendicular to the neutrino beam (increase chance of interaction);
5. Trigger and exclusion systems are vital seen the large number of cosmic particles arriving at the detector;



CERN building 156

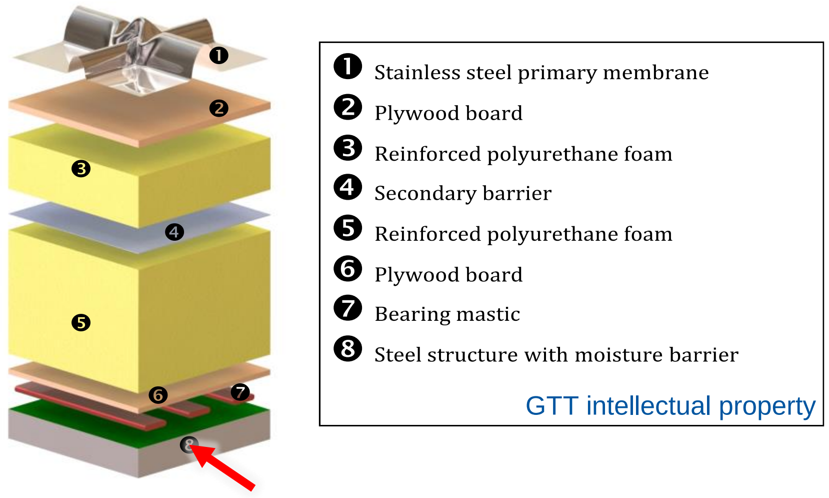
Cryostat Principle

Cryostat and Cryogenics collaborators were demanded

- To develop, prototype and build cryostats conform to the physics demands, and which also guarantee the highest safety level for use in the underground caverns;
- To develop, prototype and construct a cryogenic system, which guarantees stable conditions in the large liquid argon baths, and an argon purity level in ppt oxygen equivalent level

Seen the detector size and the underground installation: a non-vacuum insulated cryostat option (membrane cryostat) would be preferable:

1. No degradation possible by “vacuum rupture”, and no continuous vacuum pumping needed;
2. However: heat-load of about 7.5 W/m^2, higher than in case of vacuum insulated cryostats;
3. However: cryostat cold volume shall not go into an under pressure;
4. Qualified technique used for liquid natural gas (111 K) transport by ship and land storage.



Replaced by steel structure

Prototyping

Can the membrane cryostat principle fulfill the demands?

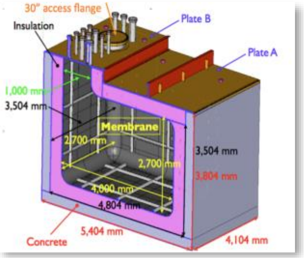
- Can a detector be mounted in such a structure?
- Is heat load through insulation indeed < 7.5 W/m^2?
- What will be the long term temperature / pressure stability in cryostat volume?
- Can demanded purity levels be reached (> 3 ms of free electron life time)?
- Can the safety levels for use in the underground areas be guaranteed?

Prototyping!

1 x 1 x 3
17 m^3

26 T
Program finished (CERN)

35 T



@Fermilab

35 T
Program finished (Fermilab)

ProtoDUNE SP

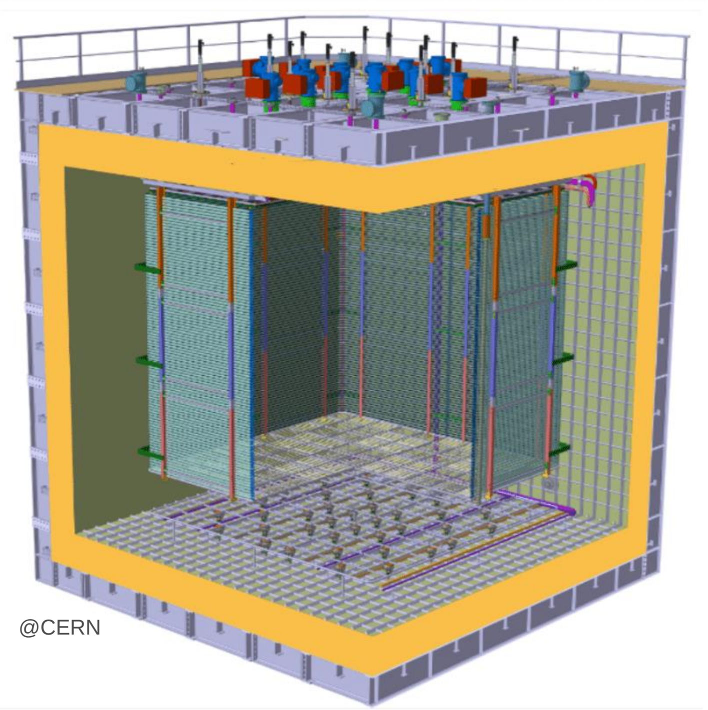
740 T
Cool-down in June 2018
(NP04, CERN)

ProtoDUNE DP

740 T
Cool-down in December 2018
(NP02, CERN)

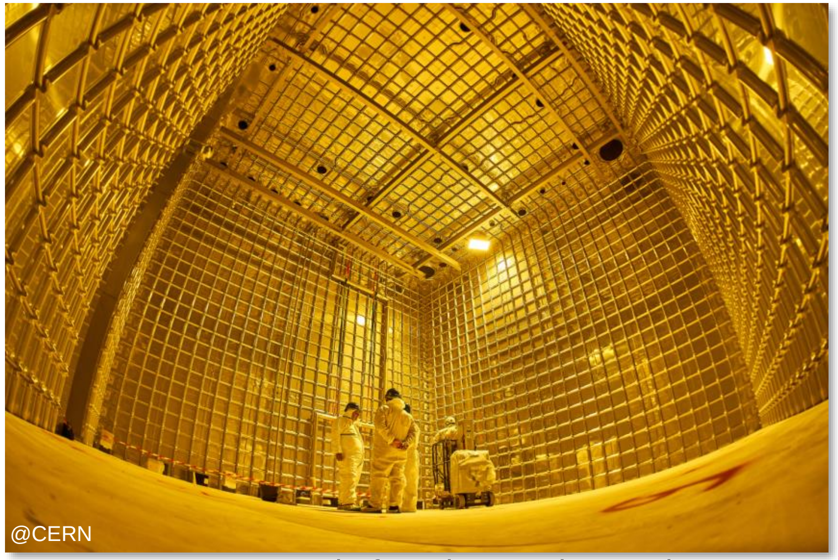
ProtoDUNE

At CERN a special building and its infrastructure have been put in place to test the two ProtoDUNE cryostats. These cryostats have an internal argon volume of 8 x 8 x 8 m^3 (external 10 x 10 x 10 m^3) and are equipped with prototype detectors and cryogenic system. These prototypes shall also be used to check the mounting principle of such a system (structural, how to leak check successfully, how to install detectors,…)



Cryostat on the design table

The experimental area



NP04 cryostat before detector integration

Demands to cryogenic system

Cryogenic system requirements:

1. Keep liquid argon in cryostat (8 x 8 x 8 m^3) in stable conditions, without any boiling within the sensitive detector volume (6 x 6 x 6 m^3);
2. Guarantee a max temperature gradient of 0.5 K between any two points in the liquid argon bath;
3. Guarantee a continuous operation of the cryogenic system, over a long period (years);
4. Guarantee a purity level of the liquid argon bath at the100's ppt oxygen equivalent;

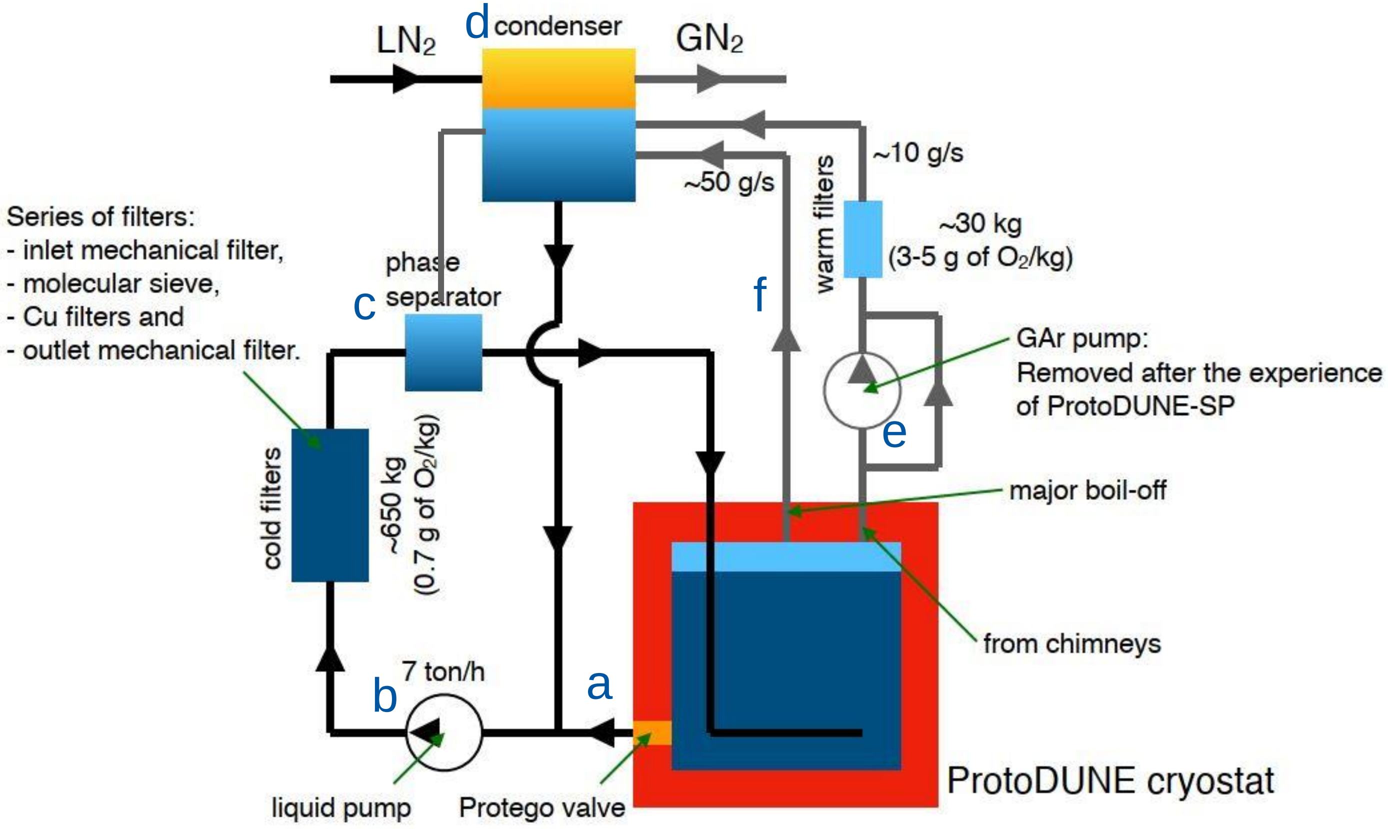
Purity rule: « argon should not see a warm surface before entering the cryostat»

→ Continuous recirculation and purification in the liquid and in the gas phases with the use of Molecular Sieve (H_2O) and active Cu pellets (O_2)

→ The liquid argon delivered to the experiments was accepted on the following conditions:

$O_2 <$ 2 ppm; $N_2 <$ 2 ppm; $H_2O <$ 1 ppm

Cryogenic system principles



Thanks to F. Resnati

a) Cryostat safety valve, closes liquid outlet in case predefined events take place
b) Liquid argon circulation pump: used to purify in liquid phase;
c) Phase separation of argon coming from purification system. Liquid returned to cryostat, at slightly higher temperature;

d) Gaseous argon condensed by nitrogen evaporation via a shell and tube heat exchanger, and brought to inlet circulation pump (purity!);
e) Signal chimney warm gas flow, caused by argon vaporization in the cryostat
f) Argon cold gas evaporating from the cryostat

ProtoDUNE operational results

Filling

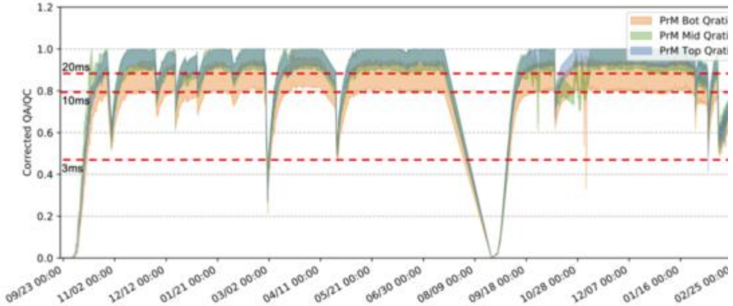
800 tons to be delivered per cryostat, 20 to 40 tons per day. Argon coming from Dortmund (Germany) area, delivered per train and truck. Total time to fill one cryostat takes about 5 full weeks.

Thanks to D. Duchesneau

Purity

1. Piston purge: gas displacement of 1.2 m/h (no turbulences and no back diffusion): <1 ppm O2
2. When filling, liquid passed through purification system: ~10 ppb O2
3. In stable state, after 5 volumes recirculated reached electron lifetime > 7 ms corr. < 40 ppt O2

Cryostat purity level in liquid argon

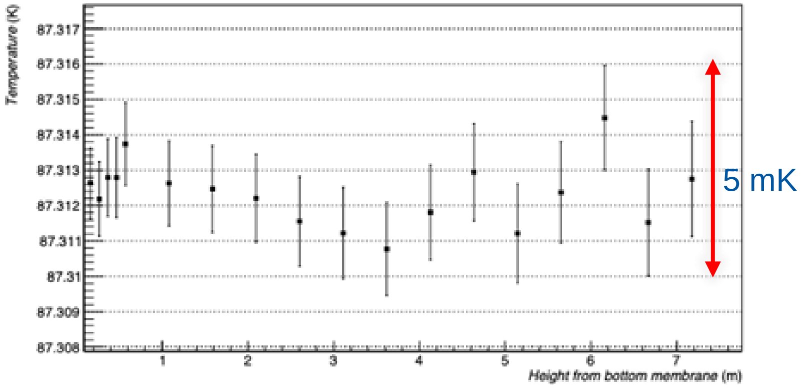


Thanks to F. Resnati

Homogeneity

After several weeks of stable operation, regulating the absolute argon gas layer pressure, while circulating for purification.

T gradient (in height) over cryostat volume



Thanks to F. Resnati

Principles validated for DUNE scaling up in size and complexity

@ DUNE:	**@ DUNE:**	**@ DUNE:**
17 kilo tons Total filling time: approx. a year Liquid produced underground	> 10 ms free electron lifetime < 30 ppt O2	DT < 1K

Perspectives towards DUNE first cryostat

CERN Neutrino Platform is responsible for the design, production and installation of 2 cryostats

The cryostat components are being procured.

Status:

- Metal structure cryostat 1: production completed, being transported to South Dakota (SD)
- Metal structure cryostat 2: in production. Delivered to SD by the end of the year
- Insulation and containment system (for both cryostats): in negotiation phase, contract will soon be signed
- Contract for the construction of the metal structure underground: soon in tendering phase
- Contract for the installation of the insulation: tendering will start beginning of next year

The metal structure of the first cryostat at Horta Coslada (Spain)

and in the harbour

Thanks to F. Resnati, D. Mladenov

Perspectives towards DUNE cryogenic system (1/2)

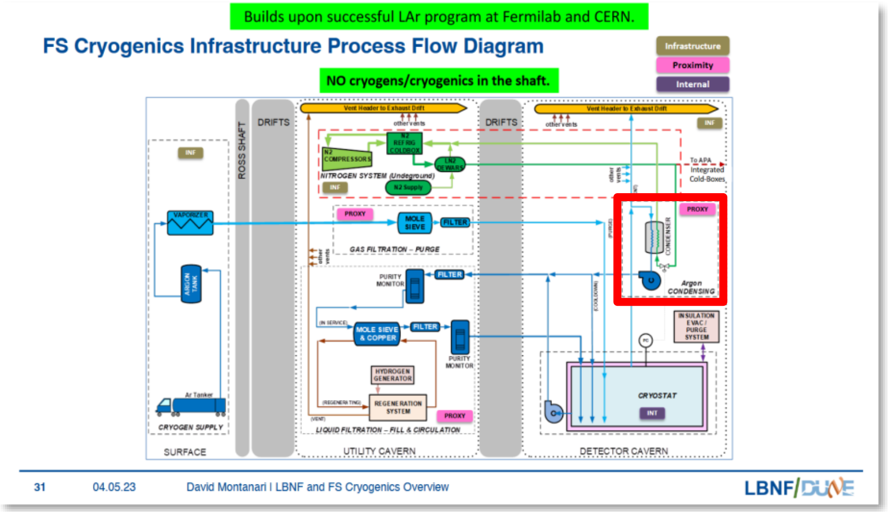
CERN Neutrino Platform is responsible for the design and production of the Proximity Cryogenics Condensation System (installation not included)

Scope

The argon condensers system.

Need

To re-condense the cryostat boil-off in Cool-down, Filling and Steady State operation and send it to the LAr purification system before returning it to cryostat



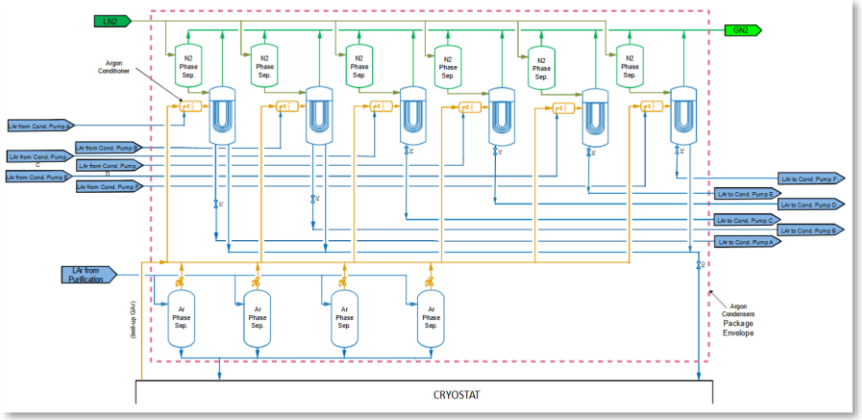
Constraints

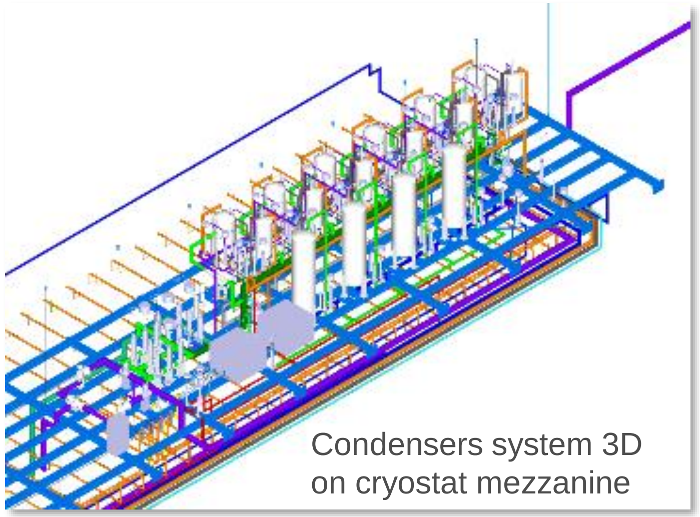
- Access shaft imposes assembly underground and limits size of equipment
- Scaling in cooling power → several similar units working in parallel

Equipment

- Batch 1: 6 identical tube-in-shell argon condensers (50 kW each)
- Batch 2: 6 identical nitrogen phase separators
- Batch 3: 4 identical argon phase separators
- Batch 4: 6 identical argon pump boxes (500 g/s each)
- Batch 5: 6 identical distribution valve boxes and de-superheating systems
- Batch 6: LN2 and LAr transfer-lines with diameters ranging up to DN250, 700 m overall length
- Approx 135 cryogenic valves ranging DN40 to DN150

Condensers system block diagram





Condensers system 3D on cryostat mezzanine

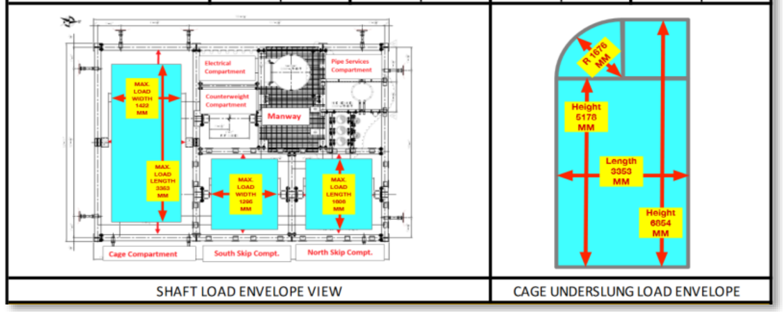
Perspectives towards DUNE cryogenic system (2/2)

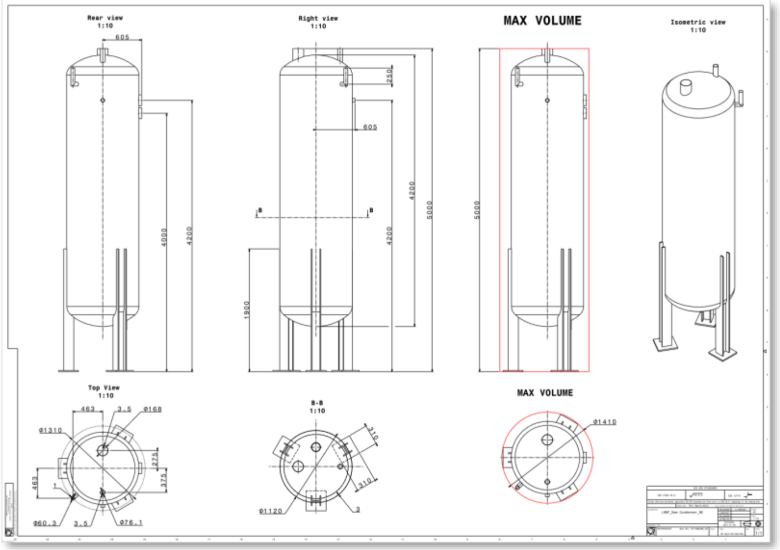
Dimensional constraints

Shaft constraints

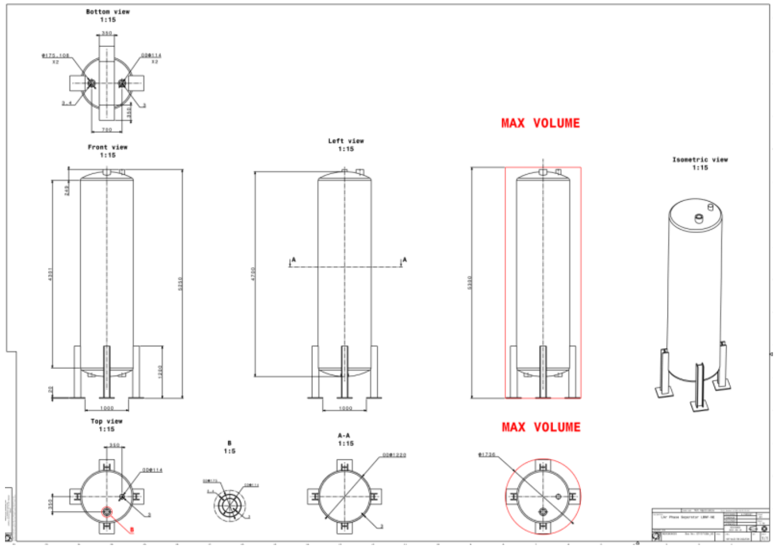
ROSS SHAFT AND SKIP COMPARTMENT UNDERSLUNG LOAD ENVELOPES[1)2)]:

DIMENSIONS	MAX. WEIGHT		LENGTH		WIDTH		HEIGHT	
	MT	LBS	MM	FT	MM	FT	MM	FT
ROSS SHAFT MAX. LOAD ENVELOPE	6.1	13500	3353	11.0	1422	4.7	6854	22.5
ROSS SOUTH SKIP MAX. LOAD ENVELOPE	10.0	22000	1606	5.3	1295	4.2	15000	49.2





Argon condensers: approx. 1.3 m3 LN2, 1.8 m3 LAr
Sizes: 2.5 to 5 m height; 1.2 m diameter



Argon phase separators: 1.6 to 4 m3
Approx 3 valves each

Conclusions

- The DUNE experiment will operate with four 17 kT cryostats in an underground area. Prototyping of the foreseen equipment has been performed;
- Two large volume liquid argon filled membrane cryostats (0.8 kT) have been operational at CERN for several years;
- The developped principles have been validated;
  now: scaling up in size and complexity for DUNE
- The first two cryostats are in production;
- The proximity cryogenics condensation system will be in tendering phase in Q4 2024; Delivery foreseen in Q3 2026
- The first cryostat cool-down and filling is foreseen to begin in Q3 2027.


Photo: Matthew Kapust, Sanford Underground Research Facility

https://news.fnal.gov/2024/02/excavation-of-colossal-caverns-for-fermilabs-dune-experiment-completed/