Cryogenics for Large Size Noble Liquid Detectors: ProtoDUNE and DUNE

Caroline Fabre (CERN), on behalf of the CERN Neutrino Platform and Fermilab partners

Credits: Johan Bremer; Michel Chalifour; Filippo Resnati, Tiziano Baroncelli

Content

Cryogenics for Detector branch in the CERN cryogenics group

Cryogenics for detectors?

- ❑ as a cooling source for detector superconducting magnets
- ❑ **as active “medium” of detectors for particles energy measurements** like Liquid Ionization Chambers (liquefied rare gases detectors)

Activity range

Design, construction, installation, commissioning, support to operation

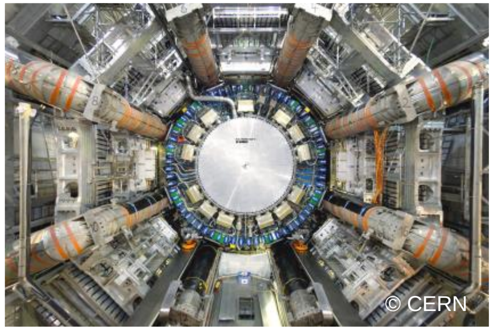
Highlights and Challenges

Developed expertise for liquefied rare gases detectors over past 30 years

is applied to present projects and to future developments,

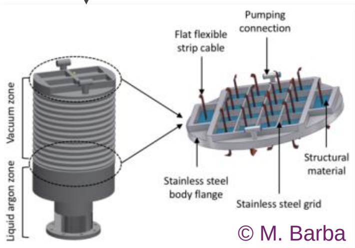
especially in the frame of the **CERN Neutrino Platform**


NA48 - 1996

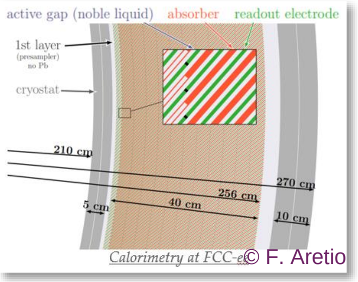


ATLAS - 2005

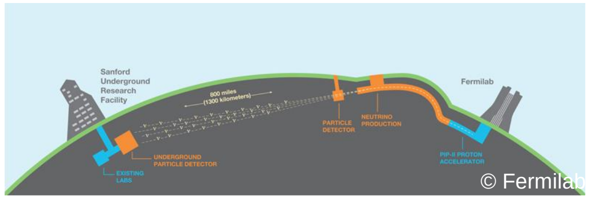

ProtoDUNE - 2018



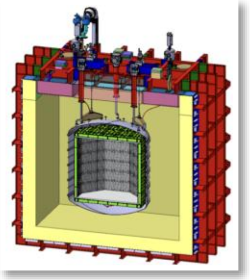
FCC-hh

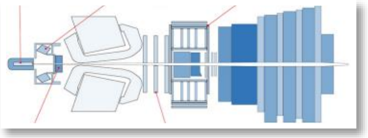


FCC-ee

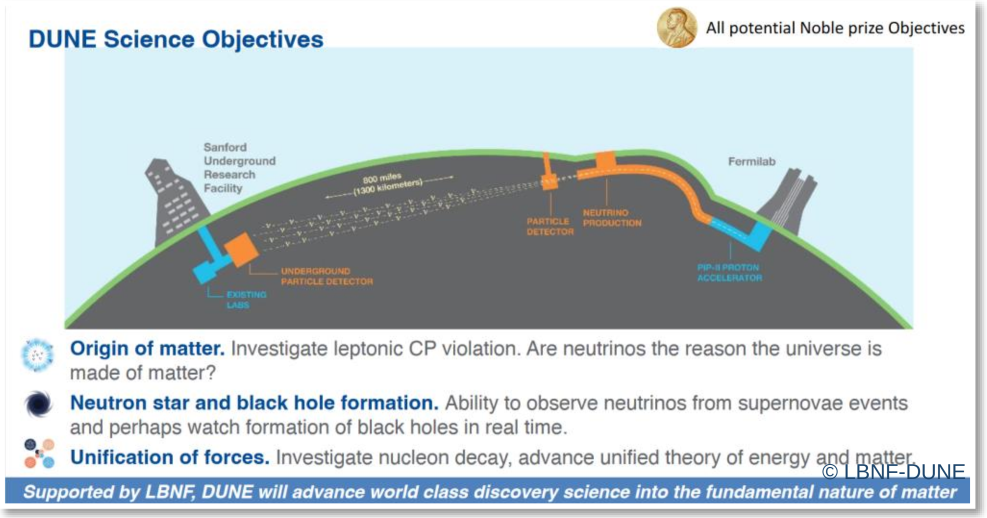


DUNE - 2028

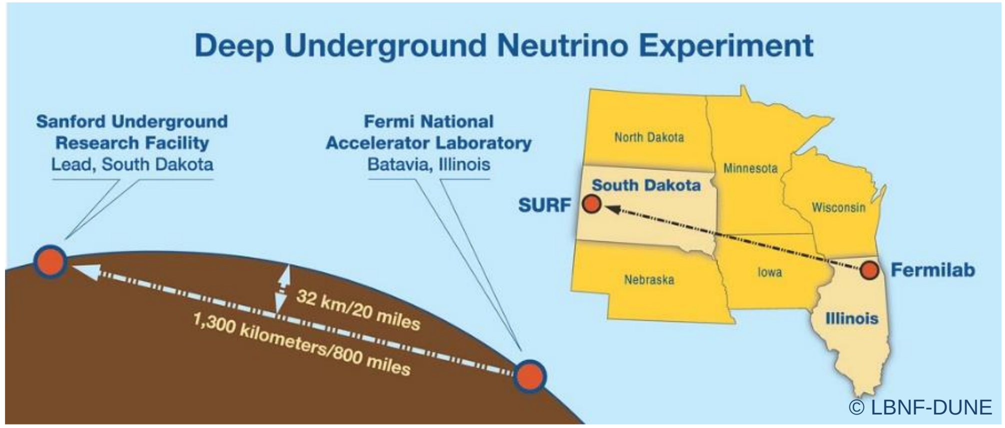

DS-20k - 2025


LHCb II upgrade (2034)

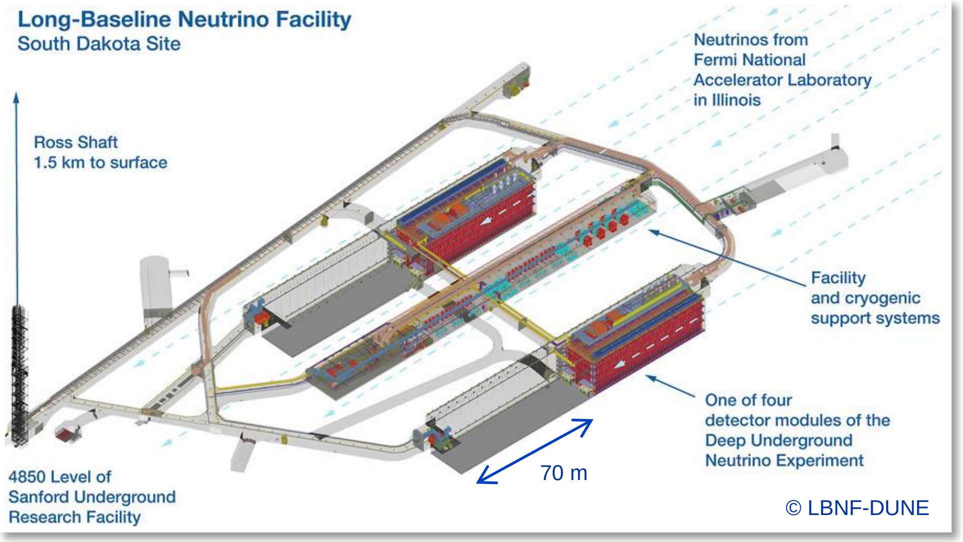
The DUNE project



International collaboration
to investigate
on **neutrino oscillations**



Neutrino beam
from Fermilab to Sandford lab
- straight through the earth,
no tunnel necessary -



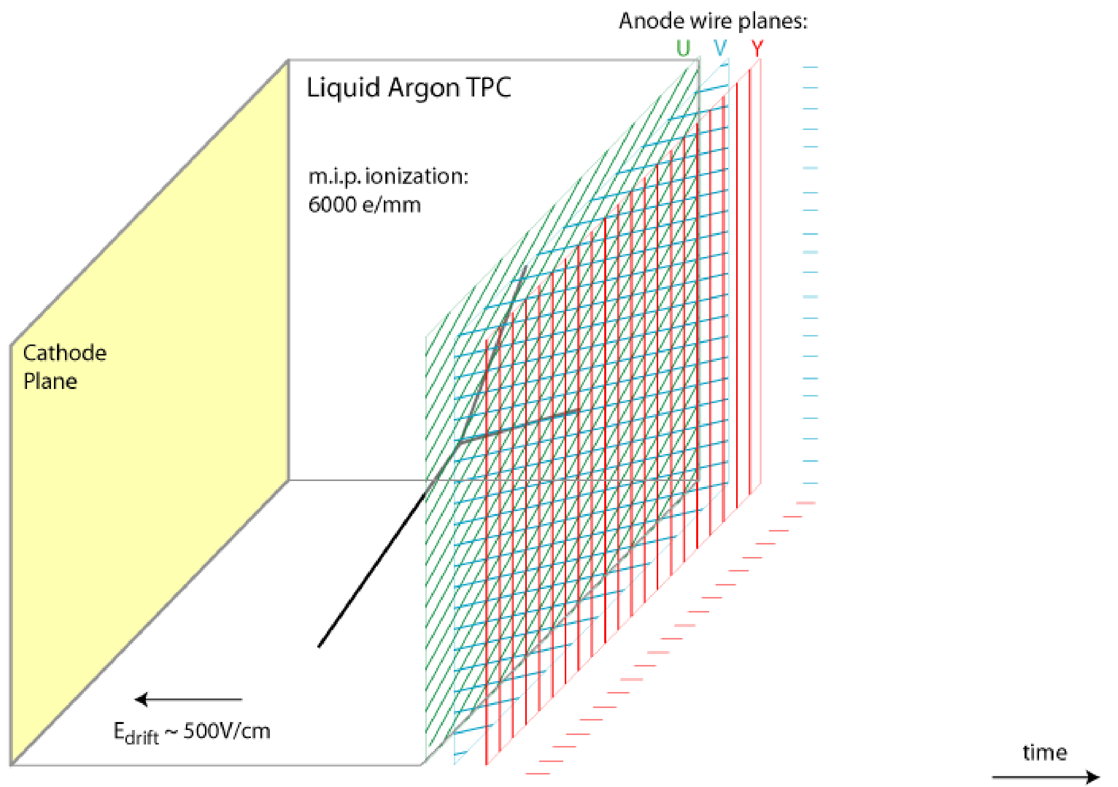
Liquid **argon-based** detector
w 70 kT total argon mass

Detection principle

Liquid Argon Time Projection Chamber:

- Neutrino interacts with argon atoms
- Secondary particles liberate valence electrons
- Electrons are collected to the anode wires
- Scintillation light is detected by photo-multipliers

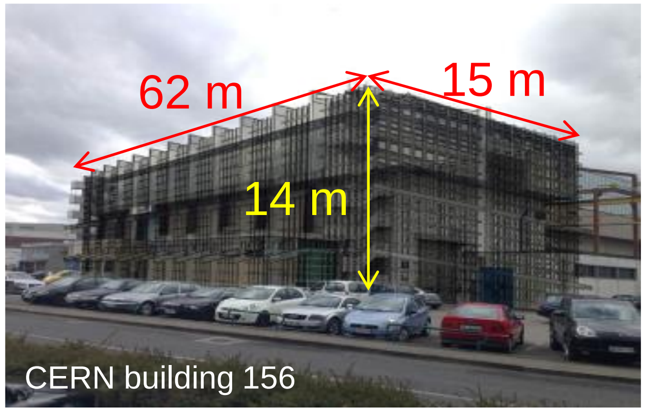
→ **Reconstruct 3D image of the interaction**



© LBNF-DUNE

Requirements

1. To guarantee a «long» free electron life-time : > 3 (10) **ms** → Very **pure** argon : < 100 (30) **ppt** O2 equiv. purity)
2. To put a 300 kV HV field → **No boiling** over the sensitive volume
3. To have a **uniform** reaction over the sensitive volume → A limited T° difference over the detection volume < 1 K
4. To preserve detector properties → **Continuously operated** over long periods
5. To guarantee highest **safety** levels for use in underground caverns → Contain the argon under all circumstances

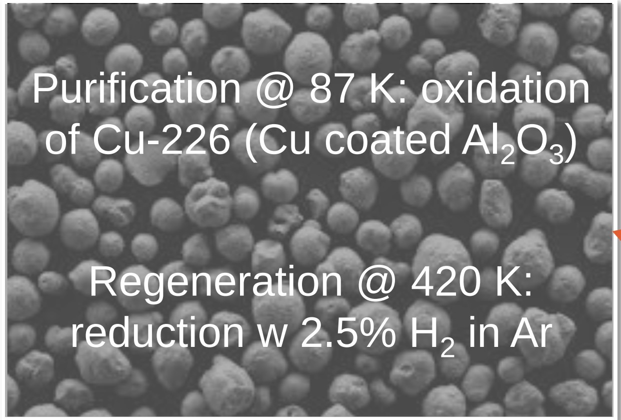


4 cryostats
LAr: 12 500 m^3 – 17 kton
x 500 compared to ATLAS LAr calorimeter

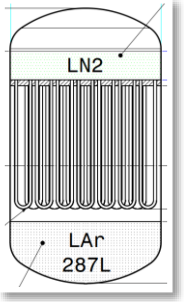
Developments for cryostat and cryogenics

The **argon purification** principle

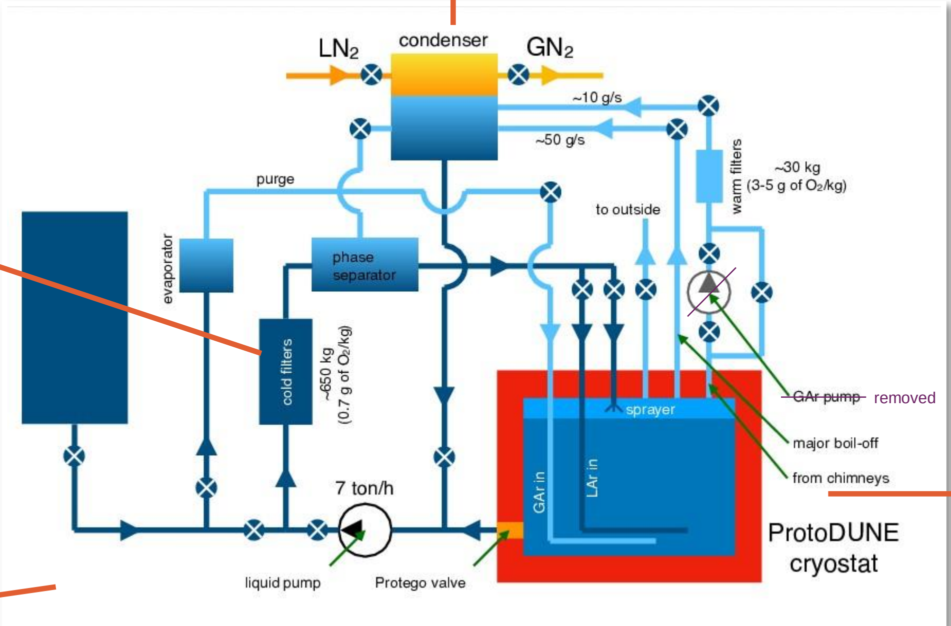
circulation
on active copper pellets



Principle inherited from NA48: 30 years continuous stable operation



The shell and tube **heat-exchanger**: simple, robust and reliable

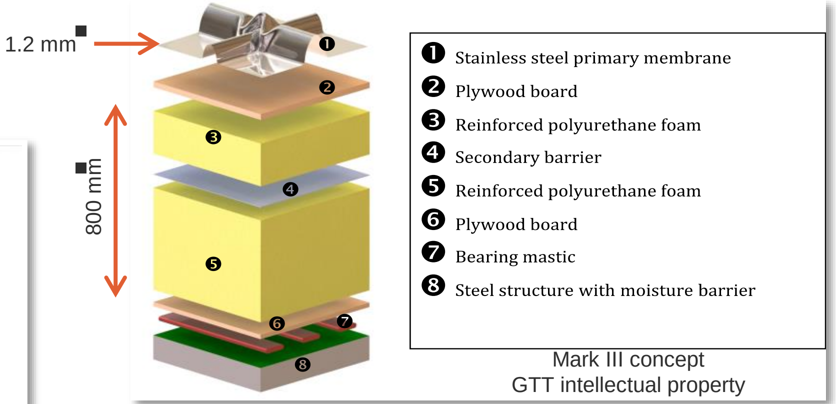


Credits: F. Resnati

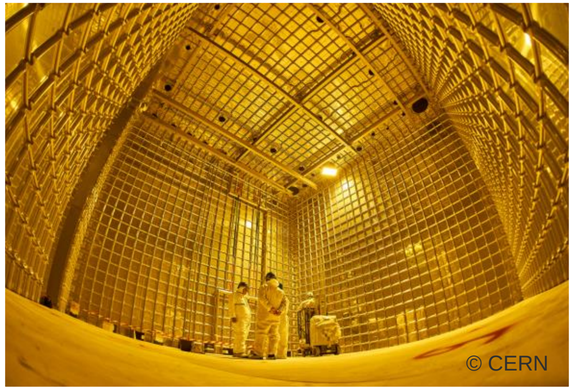
The cryogenic system principle

The **pre-ODH alarms**

The **membrane cryostat** principle developed from a qualified technique for LNG tankers



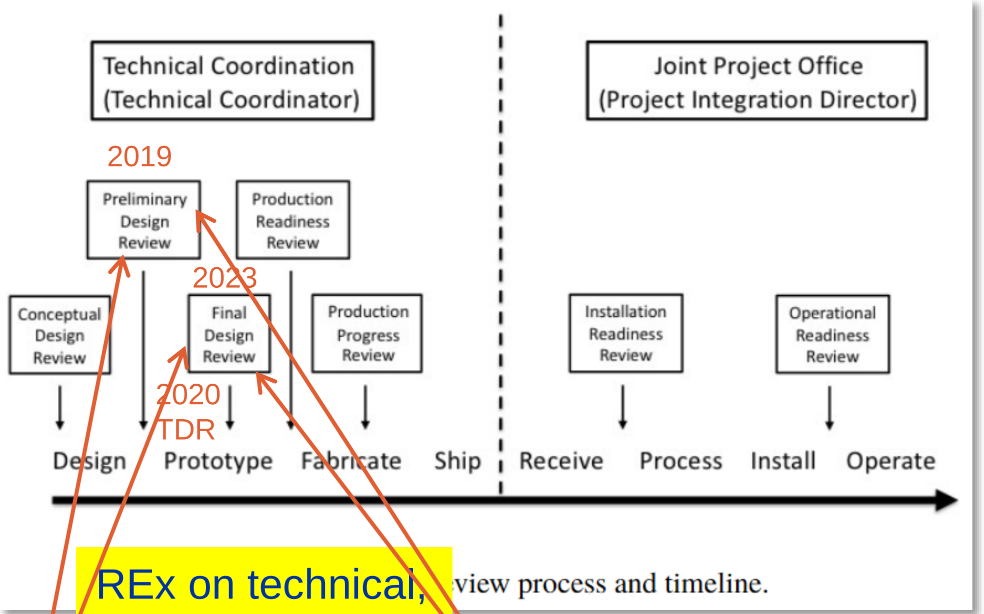
Mark III concept
GTT intellectual property



NP04 cryostat before detector integration

Prototyping

- ProtoDUNE HD & VD: ext 10x10x10 m3 (550 m3, i.e. 1:20 in total LAr mass) equipped with prototype detectors (1:1 scale) and cryogenic system, constructed from DUNE-like modular parts
- To test all principles of cryostat, cryogenics, purification, detector, including how to leak check, install detector, cabling, cool-down, operational results (cosmic and with beam), safety;



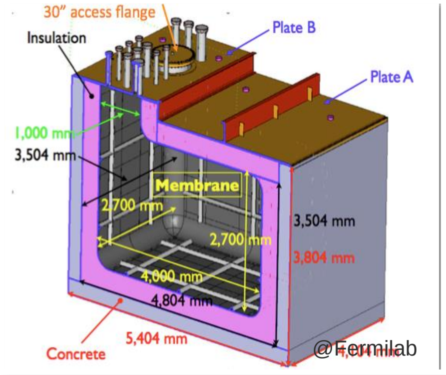
REx on technical, organizational & safety aspects

Sour… iop.org/article/10.1088/1748-0221/15/08/T08009/pdf

ProtoDUNE-HD

ProtoDUNE-VD

26 T – 2016-2017
(CERN)



35 T - 2015
(LAPD, Fermilab)

740 T each - 2018-2021, 2024-2025
(NP04, CERN) (NP02, CERN)

ProtoDUNE operational results

Filling

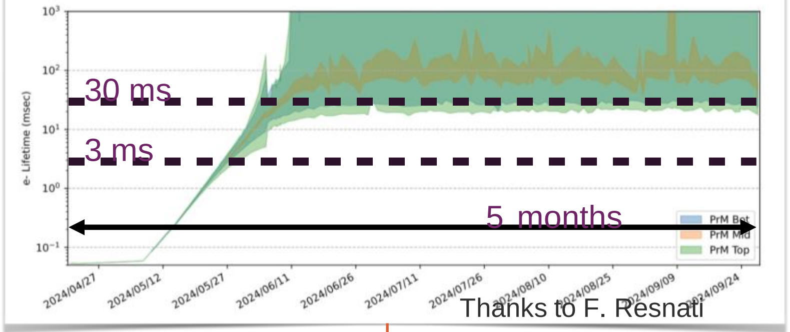
800 tons to be delivered per cryostat, 20 to 40 tons per day. Argon coming from Dortmund (Germany) area, delivered per train and truck. Total time to fill one cryostat takes about 5 full weeks.

NP-04 during filling

Purity

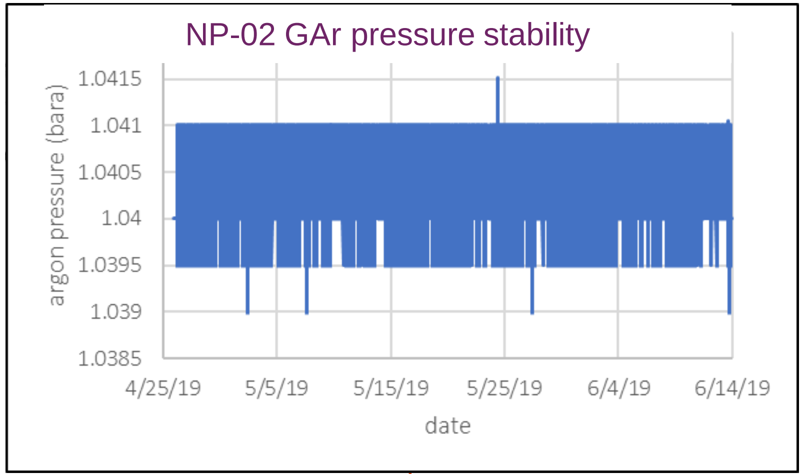
1. Piston purge: gas displacement of 1.2 m/h (no turbulences and no back diffusion): <1 ppm O2
2. When filling, liquid passed through purification system: ~10 ppb O2
3. In stable state, after 5 volumes recirculated reached electron lifetime > 7 ms corr. < 40 ppt O2

Cryostat purity level in liquid argon



Homogeneity / Stability

After several weeks of stable operation, regulating the absolute argon gas layer pressure (stability ~1mbar) , while circulating for purification.



Principles validated for DUNE

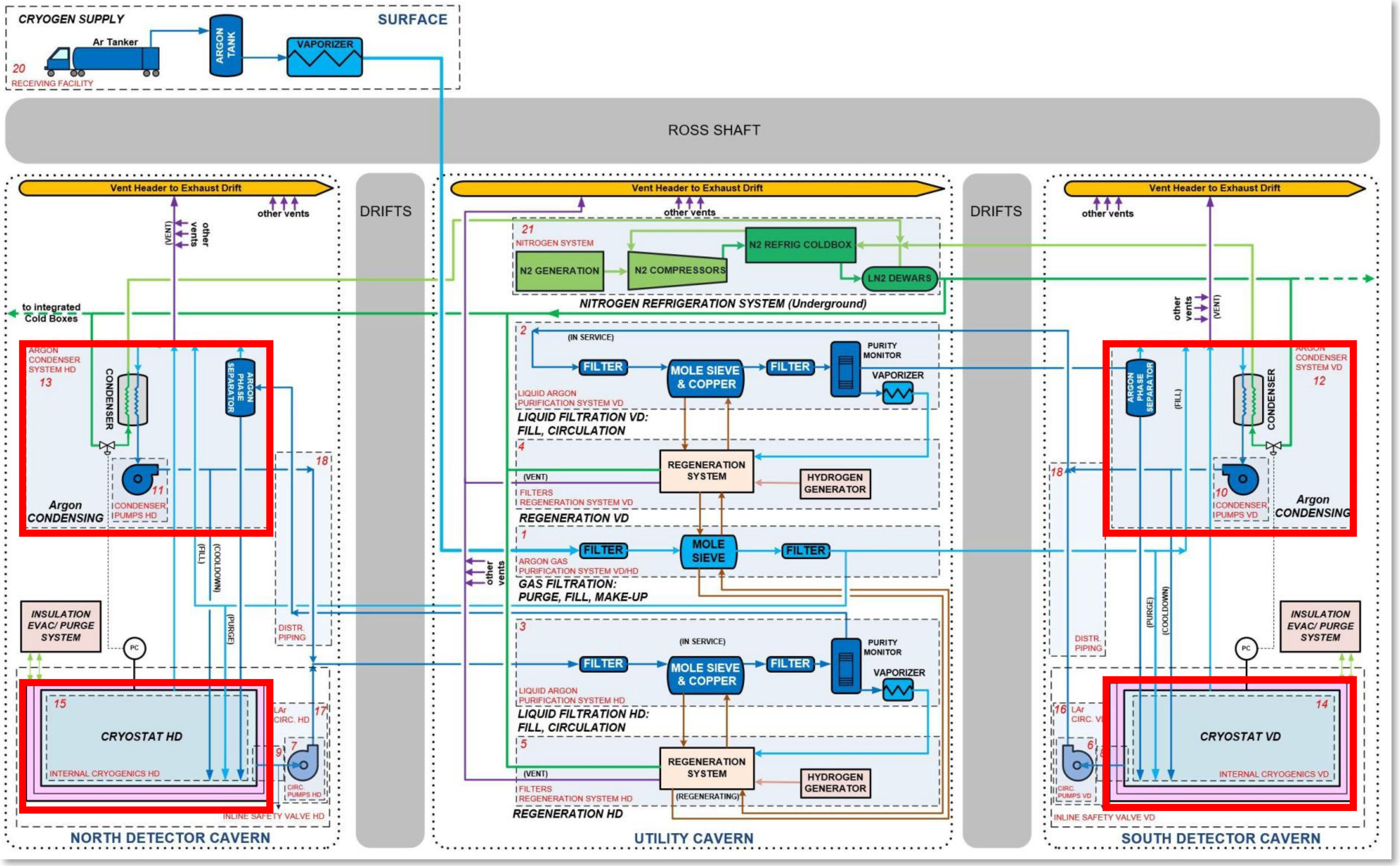
scaling up in size and complexity

@ DUNE:
17 kilo tons
Total filling time: approx. a year
Liquid produced underground

@ DUNE:
> 10 ms free electron lifetime
< 30 ppt O2

@ DUNE:
DT < 1K
DP < 10 mbar

DUNE cryogenic system overview (1/2)



DUNE Process Flow Diagram (‘PFD’).

LBNF cryogenics conceptual design developed by Fermilab

- based on the principles developed at ProtoDUNE by CERN-NP
- including the Return of Experience
- through continuous interactions of the NP and LBNF teams
- and formal participation to reviews

CERN Neutrino Platform responsible for:

- the design, production and installation of 2 cryostats (EP-NU)
- the design and production of 2 Condensers Systems (TE-CRG-CL) (installation not included)

TDR-2020
https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08009/pdf

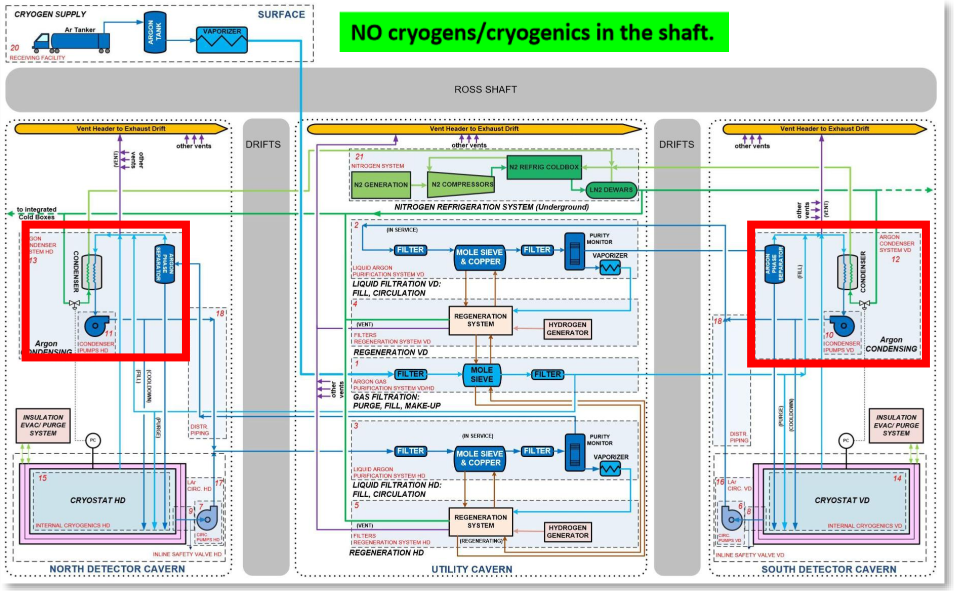
Perspectives towards DUNE Cryogenic Condensers System (1/3)

Scope

The argon condensers system (DCCS).

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



Main functions

- To control a stable cryostat pressure AND to prevent GAr venting (→ to have a stable gas phase density):
  Pressure stability: +/- 5 mbara; pressure: > 50 mbarg
- To recover cryogenics heat loads in steady state: 100 kW @ 88K

Complementary function

(from higher level design choice)

- To fill: **filling** flow rate consistent with available cooling power 300 kW
- To **circulate** condensed liquid to purification
- To pass LAr through a phase separator before being injected in the cryostat

Constraints

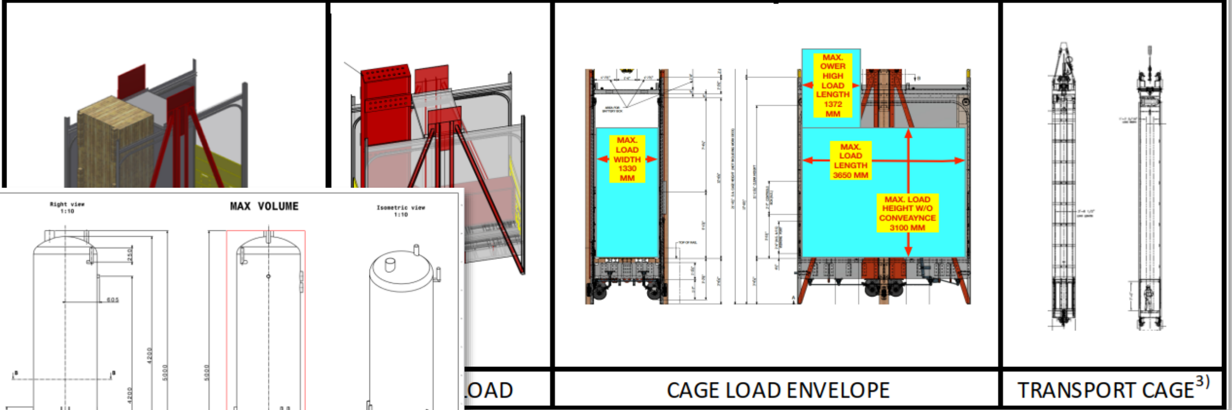
- Access shaft imposes assembly underground and **limits size of equipment**

→ several similar units working in parallel

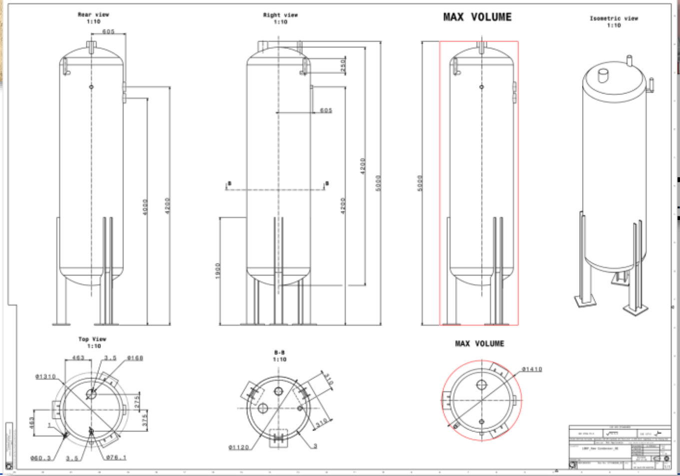
An Additional Challenge

This is how everything has to go down: personnel and material !

ROSS SHAFT LOAD ENVELOPES								
ROSS SHAFT LOAD ENVELOPES[2)]:								https://edms.cern.ch/document/2698746
DIMENSIONS	MAX. WEIGHT		LENGTH		WIDTH		HEIGHT	
	MT	LBS	MM	FT	MM	FT	MM	FT
ROSS CAGE MAX. LOAD ENVELOPE	6.1	13500	3650	12.0	1330	4.4	3100	10.2
ROSS CAGE ROOF OPENING FOR OVER-HIGH LOADS	6.1	13500	1372	4.5	1330	4.4	6000	19.7
ROSS NORTH SKIP TRANSPORT CAGE MAX. LOAD ENVELOPE[3)]	8.4	18520	1422	4.7	1240	4.1	13640	44.8



ALL equipment has to be lowered through the Ross shaft using the dedicated cage



Limiting dimension: width < 1.33 m !

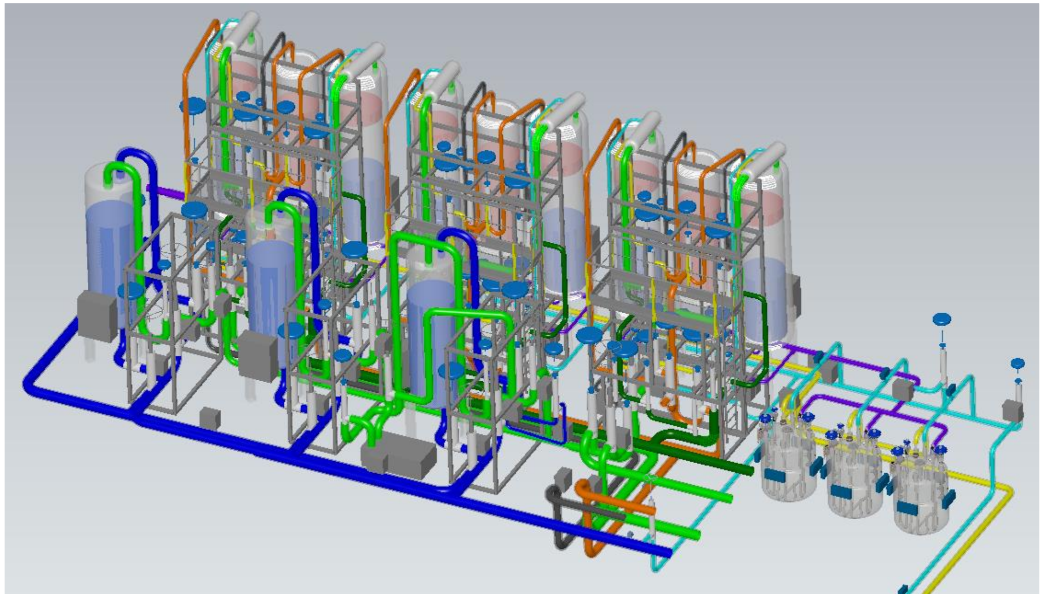
Multiple, identical “thin, long” vessels

Perspectives towards DUNE Cryogenic Condensers System (2/3)

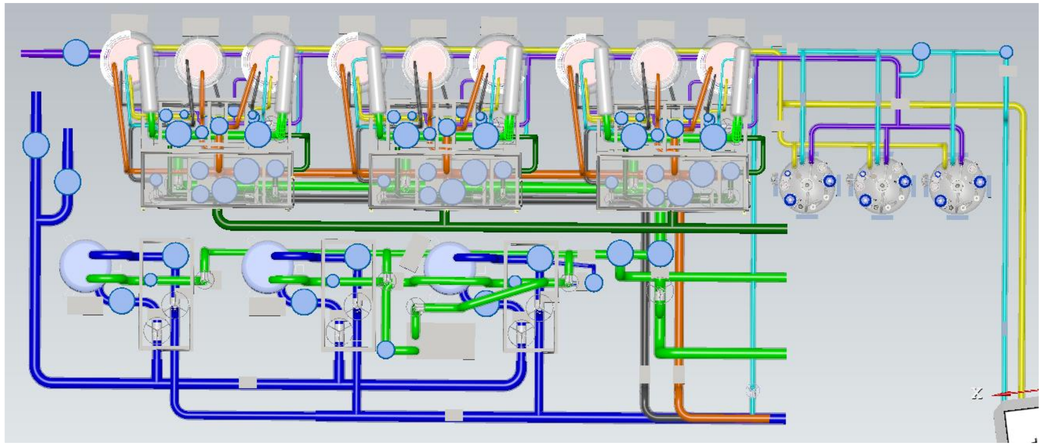
Equipment for 1 system

- 6 identical tube-in-shell argon condensers (50 kW each)
- 6 identical desuperheating systems
- 3 identical nitrogen phase separators
- 3 identical argon phase separators
- 3 identical argon pump boxes (1.3-1.8 kg/s each, 2x**parallel**)
- 3x3 identical valve racks
- LN2 and LAr transfer-lines with diameters ranging DN40 to DN250, 700 m overall length
- Approx 120 cryogenic valves ranging DN32 to DN150

→ **Arranged in repeatable units**



3D model of DUNE Cryogenic Condenser System



Perspectives towards DUNE Cryogenic Condensers System (3/3)

Status

All information required for the DCCS Technical Specification is available, mature and agreed on. (REx)

Development activities:

- P&ID: mature for specs, in configuration management
- Process and physical interfaces: being finalized
- 3D: mature for specs
- Basic design: mature for specs

Tendering:

- Market Survey : published August 2025
- Invitation to Tender: drafting in progress, Q1 2026
- Contact Award: Q2 2026

Milestones:

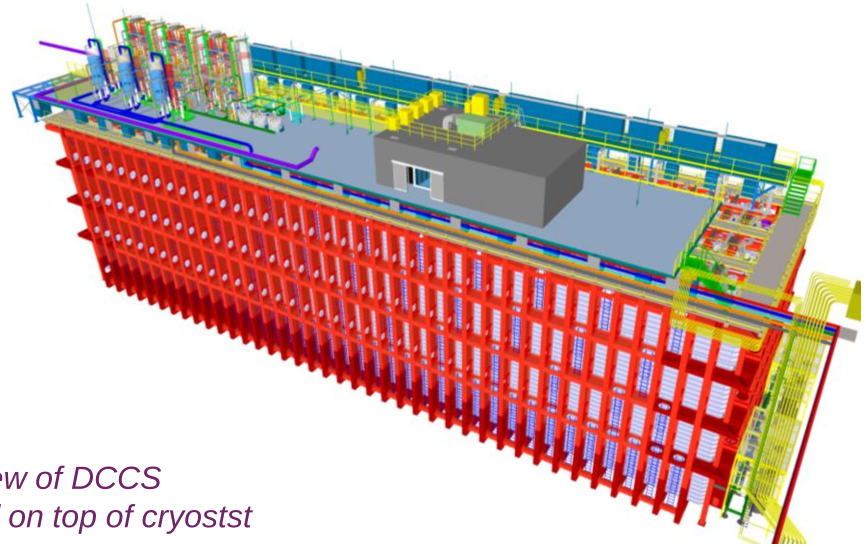
- Delivery of DCCS for Vertical Drift (VD): Q1 2028;
- Delivery of DCCS for Horizontal Drift (HD): Q4 2028
- Cooling and filling of VD cryostat: Q1 2029 (TBC)
- Cooling and filling of HD cryostat: Q1 2030 (TBC)

Subject to availability of installation start date

Conclusions

- The DUNE experiment will operate with four 17kT 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 developed principles have been validated; now: scaling up in size and complexity for DUNE
- The first two cryostats metallic structures are delivered; No official start of installation date available anymore.
- The DUNE cryogenics condensation system will be in tendering phase in Q1-Q2 2026; Delivery foreseen in Q1 2028.

Cryostat steel structure from CERN arrived in Rapid City, SD, March 2025

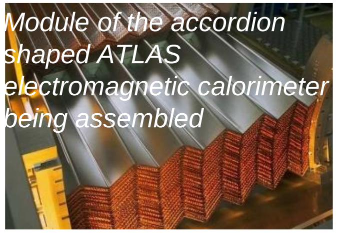


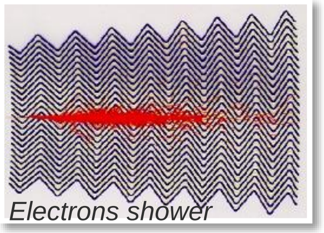
Artistic view of DCCS integrated on top of cryostst

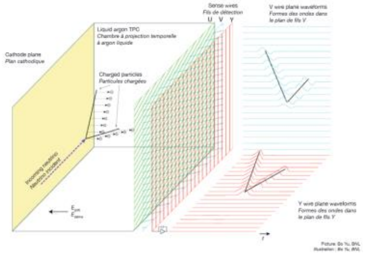
Back-up slides

Cryogenics expertise for large size noble liquid detectors

Cryogenics as active “medium” of detectors for particles energy measurements like Liquid Ionization Chambers


Module of the accordion shaped ATLAS electromagnetic calorimeter being assembled


Electrons shower


Reconstructed 3D image of the neutrino interaction

	Calorimeters	Time Projection Chambers		
Requirements	**ATLAS**	**ProtoDUNE**	**DarkSide-20k**	**DUNE**
to maximize the number of events → **a large volume of a dense noble liquid**	100 m^3 LAr	560 m^3 LAr	500 m^3 LAr	4 x 12 000 m^3 LAr
to have a uniform reaction over the sensitive volume → **a limited T° difference over the detection volume**	88.3 K DT < 700 mK	87.5 K DT < 500 mK	87.5 K	87.5 K DT < 1 K
to put a HV field over the sensitive argon volume → **a subcooled bath to prevent bubbles**	2 kV field 2 mm drift gap	18 kV 3.6 m drift gap	-	300 kV 6 m drift gap
to guarantee a sufficiently long free electron lifetime → **a pure liquid** (oxygen equiv. purity)	> 0,15 ns < 2 ppm	> 3 ms < 100 ppt	> 3 ns < 100 ppb	> 10 ms < 30 ppt
to reduce the noise level (cosmic particles) → **in underground areas**	-100 m @ CERN	-10 m @ CERN	- 1.4 km @ LNGS	- 1.5 km @ Sandford Lab
to preserve detector properties → **continuously operated over long periods**	Since 2005 17 years	2019 1 year	2024 years	2028 years

Commonalities **Scaling in size and complexity**

DUNE cryogenic system overview (2/2)

Selection of cryogenics parameters

Parameter	Value	Note
GAr Purge Flow rate	1,123 m^3/hr	From 1.2 m/hr
LAr filling flow rate	0.8 / 0.5 kg/s	1st /2nd Cryostats (w/ 3 LN2 refrigeration units)
LAr filling duration	257 / 436 days	1st /2nd Cryostats (w/ 3 LN2 refrigeration units)
Cryostat static heat leak	48.7 kW	Each cryostat
Electronics heat load	23.7 kW	Each cryostat
Total estimated heat load	87.1 / 98.2 kW	Each cryostat (only) with 2/4 LAr pumps in operation
Condenser size (per cryostat)	6 x 50 kW = 300 kW	3 LN2 units for cryostats 1 & 2, 4th unit for 3 & 4
Maximum LAr circulation speed (assuming 5 days turnover)	1.73 m^3/min (40 kg/s)	All 4 LAr pumps in operation
Nominal LAr circulation	0.43 m^3/min (10 kg/s)	Only 1 LAr pump in operation
Required LAr Purity	FD-1: 100 ppt (~3.2 ms lifetime). FD-2: 50 ppt (~6 ms lifetime)	O_2 equivalent contamination (O_2, H_2O). ProtoDUNE achieved <10 ppt (**30+ ms** lifetime).