STATUS OF CERN-ATS/TE PARTICIPATION IN THE DUNE PROJECT

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

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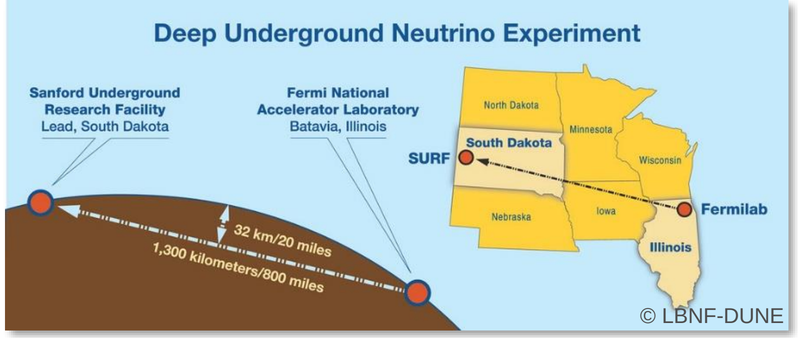
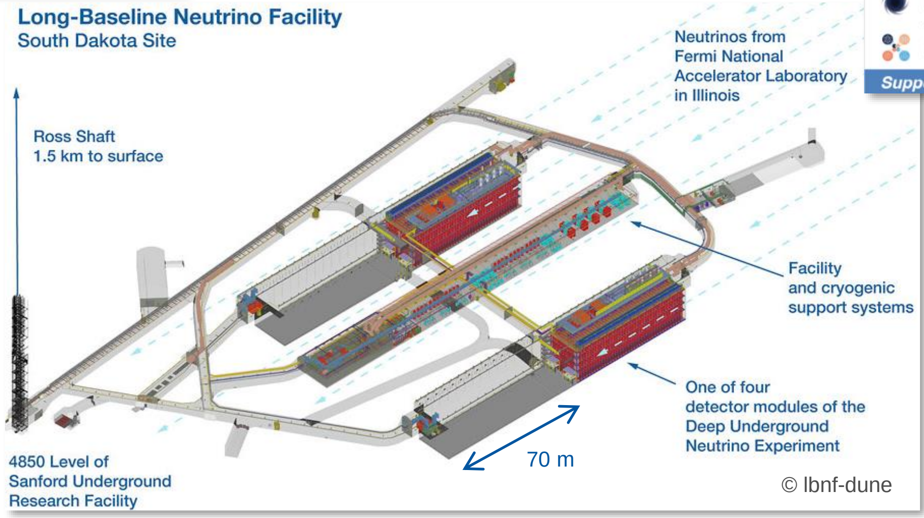
Introduction

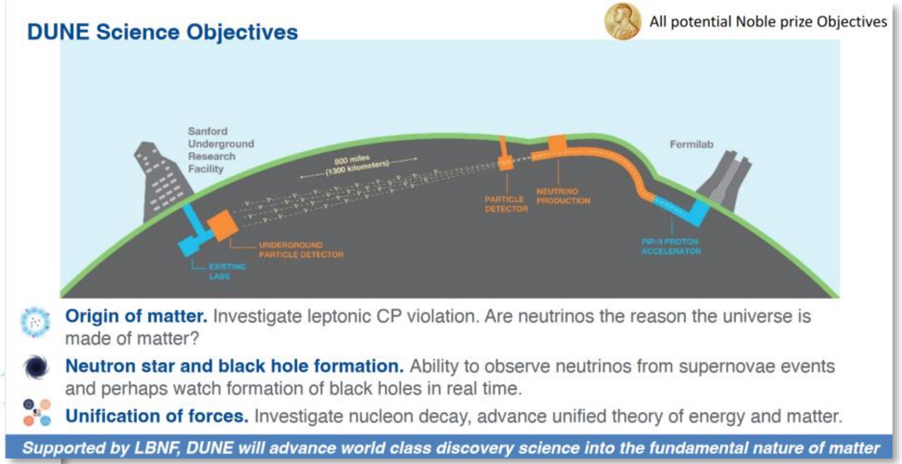
An international collaboration (DUNE) has been set-up to perform a comprehensive investigation on neutrino oscillations. Idea: Shoot a neutrino beam from Fermi Lab to Sandford Lab, covering a distance of 1300 km and detect neutrinos with a liquid argon based detector with a total argon mass of 70 kTon. 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



Far site caverns



@LBNF/DUNE

4 x 17 kT
of LAr as active medium

Intro video:
https://www.youtube.com/watch?v=nv13DswIKr8

1. Principles

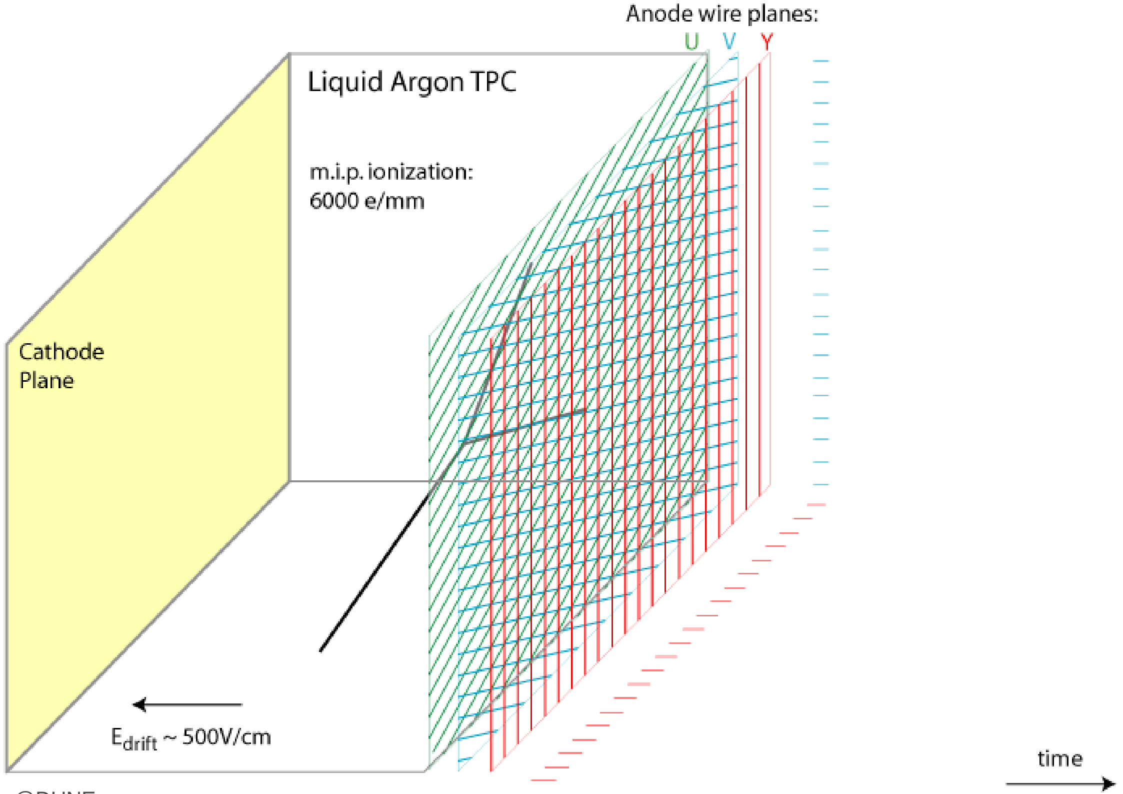
Detection principle

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.

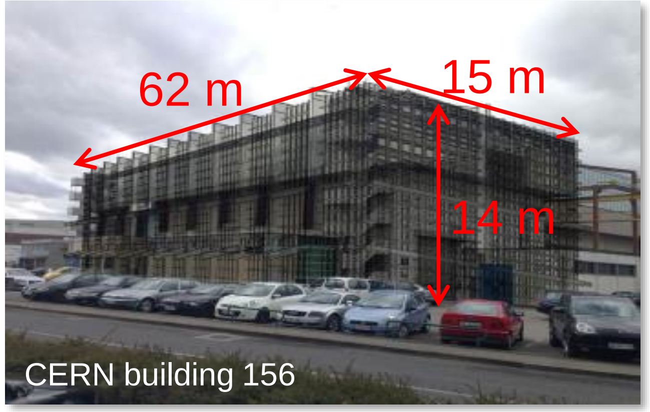


@DUNE

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 (500V/cm) 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;

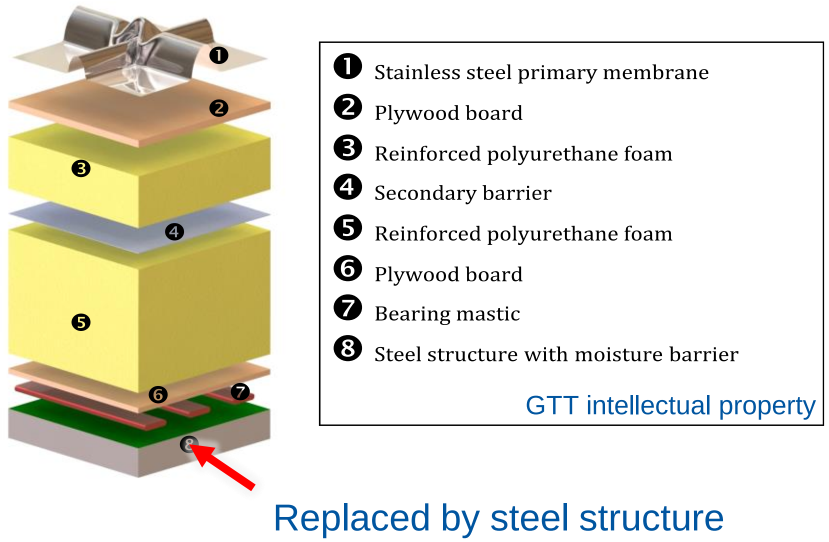


CERN building 156

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.



Prototyping

Can the membrane cryostat principle fulfill the demands?

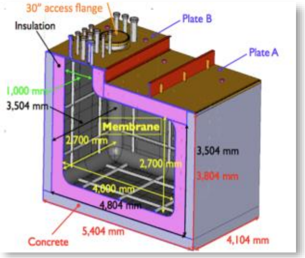
- Can a detector be mounted in such a structure?
- Is heat load through insulation indeed < 7.5 W/m^2?
- What will be the long term temperature / pressure stability in cryostat volume?
- Can demanded purity levels be reached (> 3 ms of free electron life time)?
- Can the safety levels for use in the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

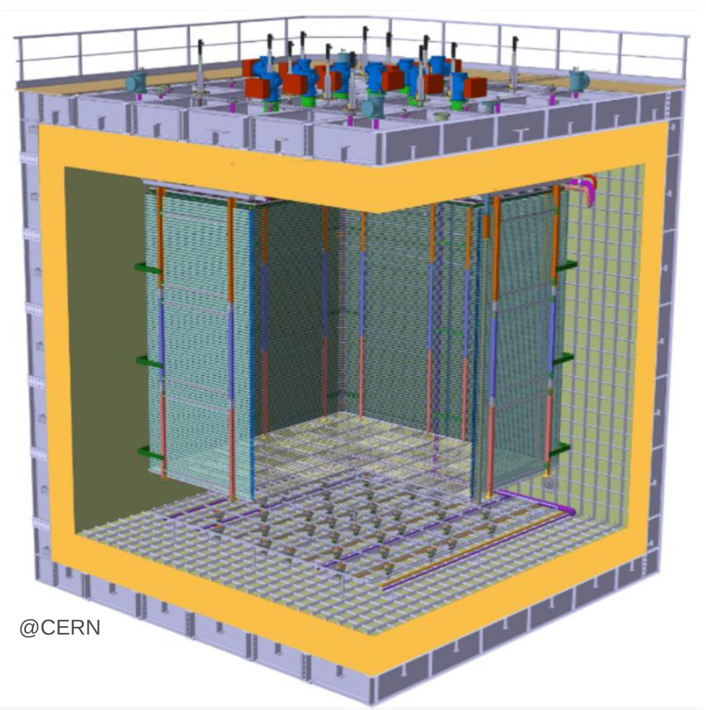
ProtoDUNE DP

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

2. ProtoDUNE

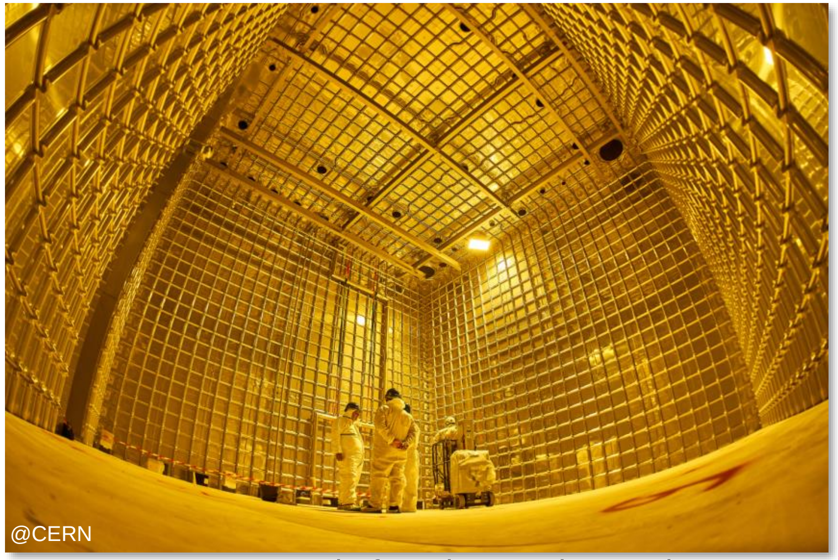
ProtoDUNE

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:

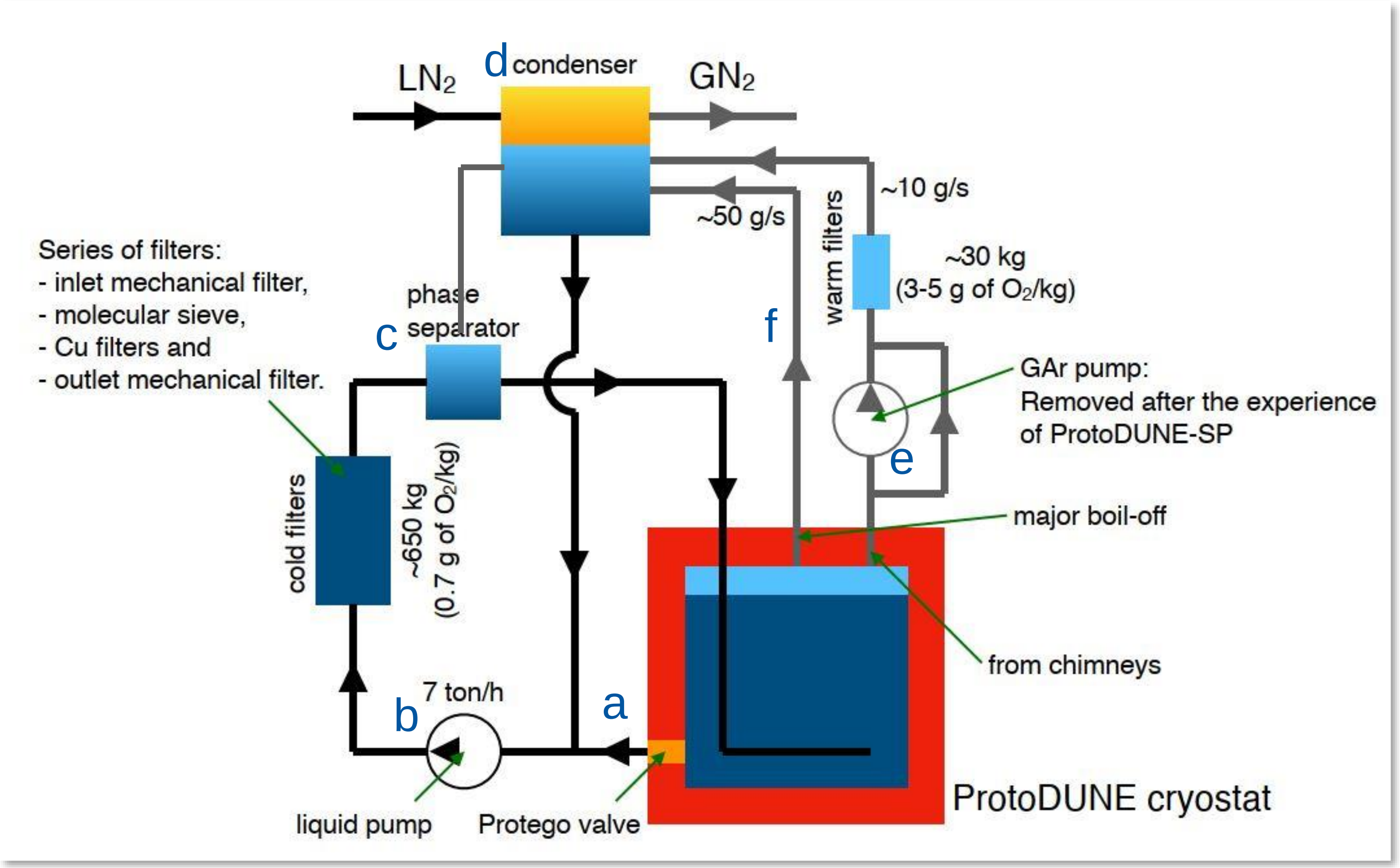
1. Keep liquid argon in cryostat (8 x 8 x 8 m^3) in stable conditions, without any boiling within the sensitive detector volume (6 x 6 x 6 m^3);
2. Guarantee a max temperature gradient of 0.5 K between any two points in the liquid argon bath;
3. Guarantee a continuous operation of the cryogenic system, 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

ProtoDUNE Cryogenic system principles and REx



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 2018-2020

Filling

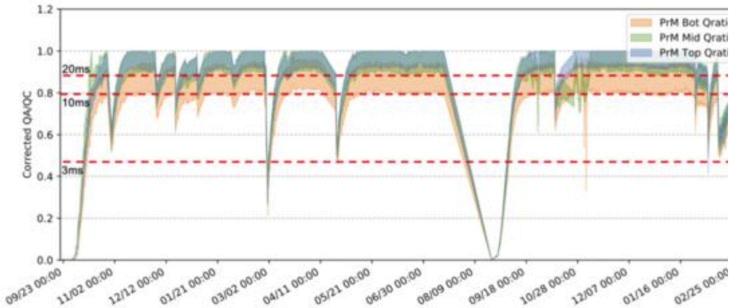
800 tons to be delivered per cryostat, 20 to 40 tons per day. Argon coming from Dortmund (Germany) area, delivered per train and truck. Total time to fill one cryostat takes about 5 full weeks.

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

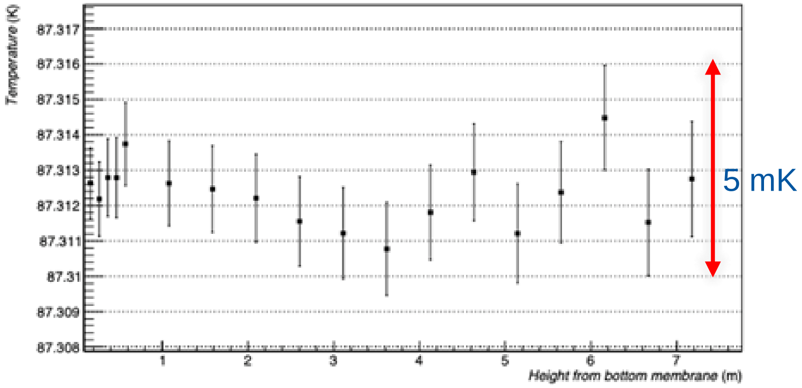


Thanks to F. Resnati

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

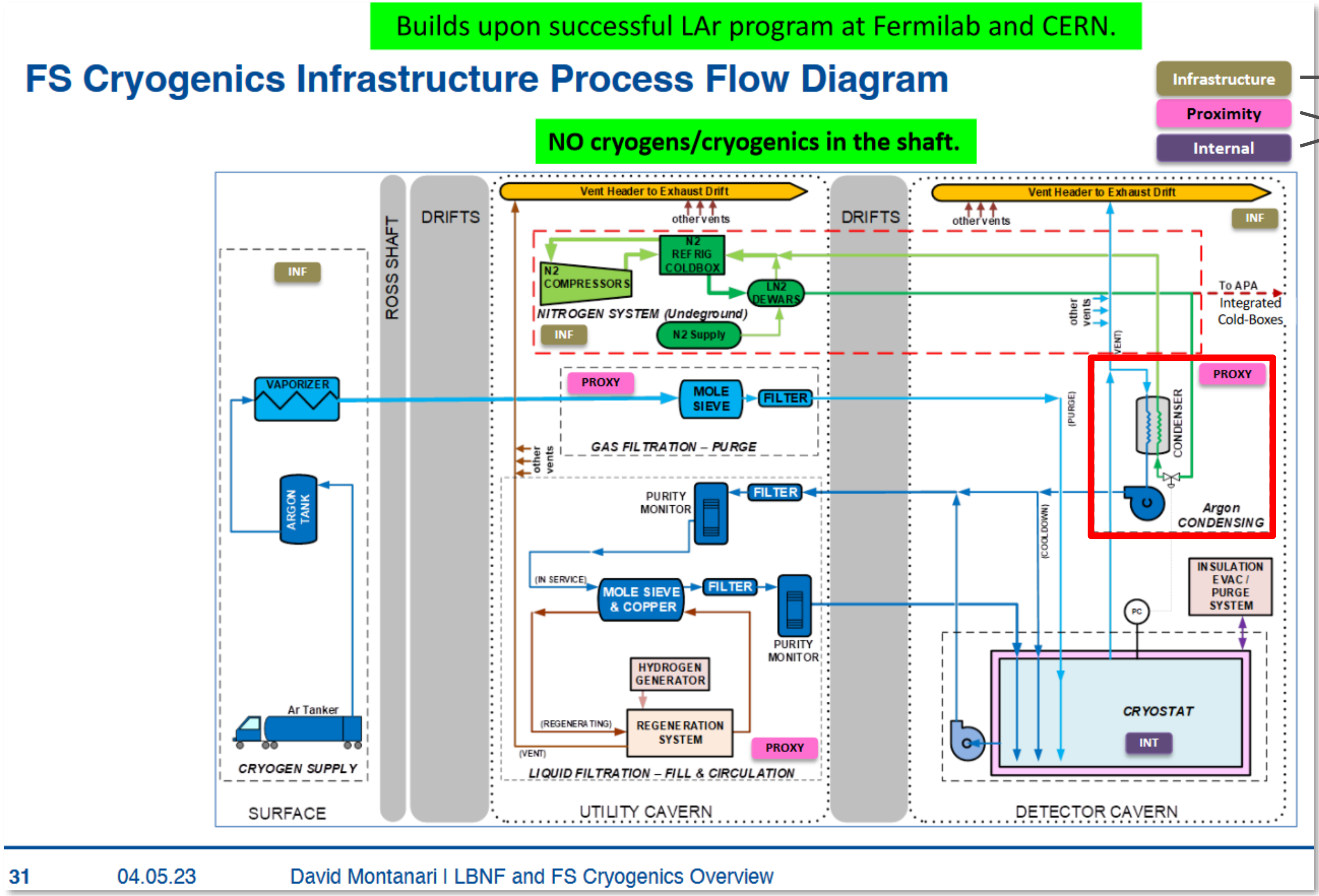
@ DUNE:
17 kilo tons
Total filling time: approx. a year
Liquid produced underground

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

@ DUNE:
DT < 1K

3. DUNE

DUNE cryogenic system overview (1/2)



Infrastructure → US DOE

Proximity, Internal → In-kind Contributions (installed by US DOE)

Conceptual Design developed by Fermilab

based on the principles developed at ProtoDUNE and including the return of experience

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

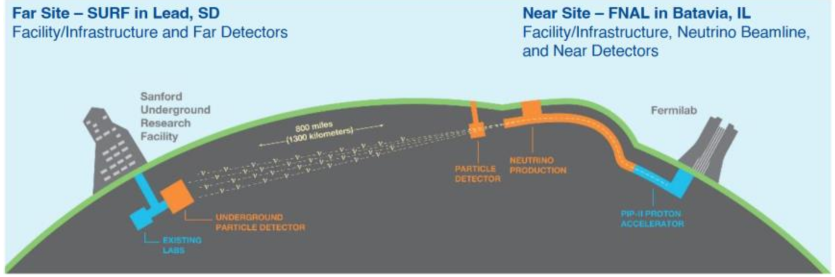
DUNE cryogenic system overview (2/2)

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).

CERN/NP in the LBNF/DUNE Collaboration

The LBNF/DUNE vision is achieved by groundbreaking international partnerships



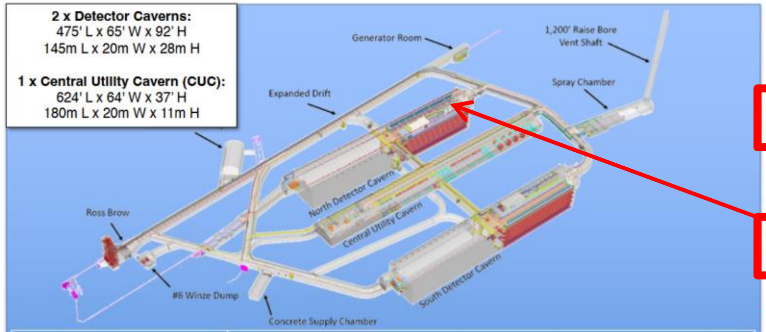
DOE LBNF/DUNE-US Project

- **Long Baseline Neutrino Facility** – facilities with partner in-kind contributions — **LBNF**
- **DUNE-US** – U.S. contribution to the international DUNE experiment
- **International DUNE** - partner contributions to the international DUNE experiment

LBNF and DUNE-US are one DOE Order 413.3B Project

5 04.05.23 David Montanari I LBNF and FS Cryogenics Overview LBNF/DUNE

DOE Project Scope – Far Site



WBS/Subproject	Scope
131.FSCFEXC/FSCF-Excavation	Project management, preliminary and final design, reliability/infrastructure upgrades, pre-excavation systems, and excavation work to support 4 detector modules.
131.FSCFBSI/FSCF-Building & Site Infrastructure	Project management, preliminary and final design, and construction of surface and underground utilities, and infrastructure outfitting of spaces for detector modules.
131.FDC/Far Detectors and Far Site Cryogenic Infrastructure	DUNE-US contributions to two DUNE detector modules; two cryostats & associated liquid argon; cryogenic systems to support two detector modules; installation and integration for two detector modules and cryogenic infrastructure

At the far site, the LBNF project scope includes committed critical in-kind contributions from:

- CERN – Membrane cryostats and portions of argon receiving facility (tanks)
- Brazil/UNICAMP – Argon purification and recirculation systems
- Switzerland/SERI – Argon condensing system
- Poland/WUST – Internal cryogenics systems

and the DUNE International collaboration, consortia, and partners.

Thank you to all our partners!

12 04.05.23 David Montanari I LBNF and FS Cryogenics Overview

*Switzerland contribution is via CERN.

with CERN-NP personnel

FD-1 = HD
FD-2 = VD

FD-1 = HD
2018

Trading of scope in progress 2024

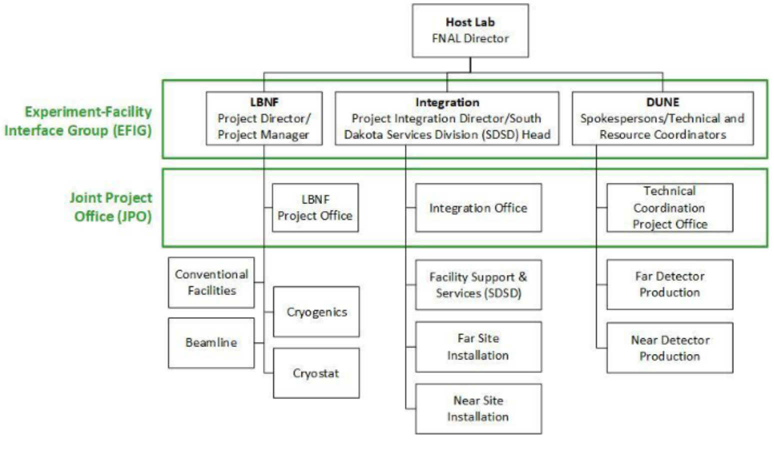


Figure 2.1. LBNF/DUNE organization.

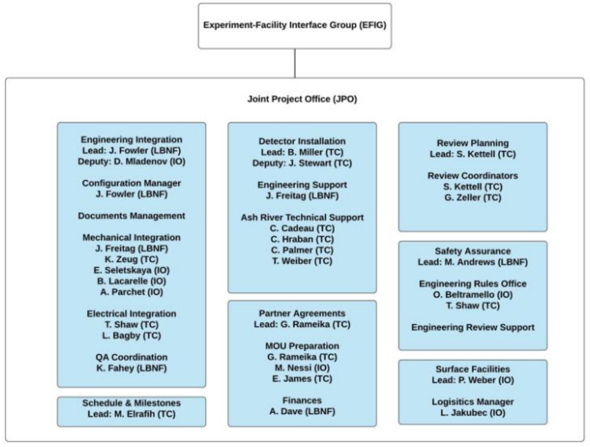
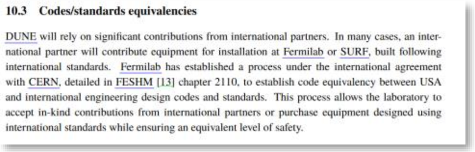


Figure 2.2. JPO global support functions and teams.

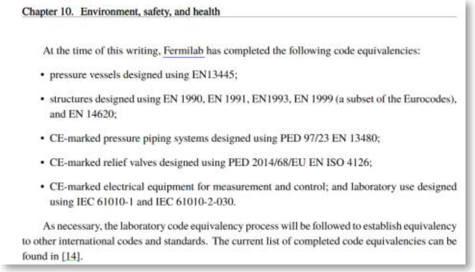
TDR 2020:
https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08009/pdf

CERN/NP in the LBNF/DUNE-US Project



10.3 Codes/standards equivalencies

DUNE will rely on significant contributions from international partners. In many cases, an international partner will contribute equipment for installation at Fermilab or SURF, built following international standards. Fermilab has established a process under the international agreement with CERN, detailed in FESHM [13] chapter 2110, to establish code equivalency between USA and international engineering design codes and standards. This process allows the laboratory to accept in-kind contributions from international partners or purchase equipment designed using international standards while ensuring an equivalent level of safety.



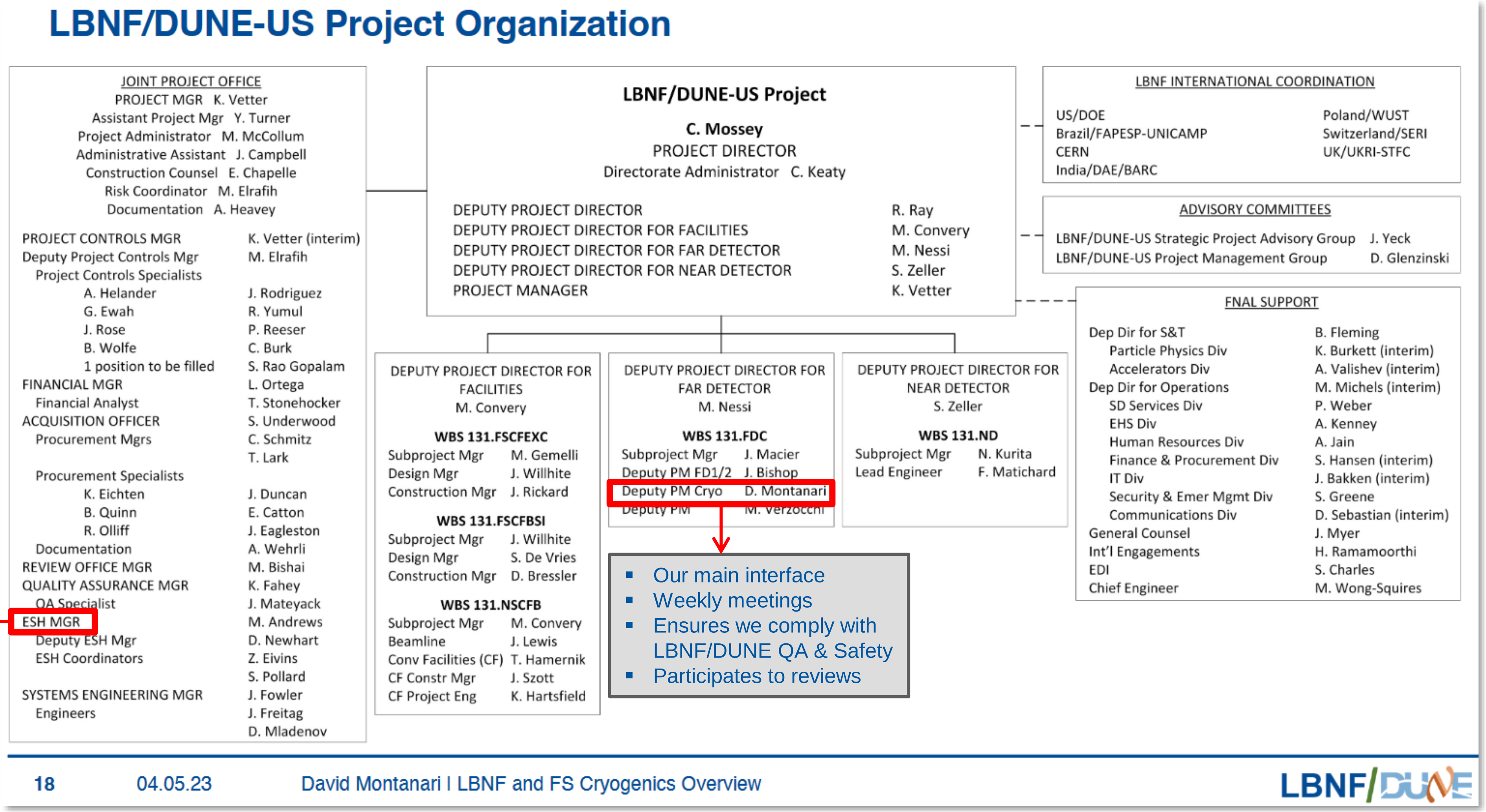
Chapter 10. Environment, safety, and health

At the time of this writing, Fermilab has completed the following code equivalencies:

- pressure vessels designed using EN13445;
- structures designed using EN 1990, EN 1991, EN1993, EN 1999 (a subset of the Eurocodes), and EN 14620;
- CE-marked pressure piping systems designed using PED 97/23 EN 13480;
- CE-marked relief valves designed using PED 2014/68/EU EN ISO 4126;
- CE-marked electrical equipment for measurement and control; and laboratory use designed using IEC 61010-1 and IEC 61010-2-030.

As necessary, the laboratory code equivalency process will be followed to establish equivalency to other international codes and standards. The current list of completed code equivalencies can be found in [14].

Codes/standards equivalencies



- Our main interface
- Weekly meetings
- Ensures we comply with LBNF/DUNE QA & Safety
- Participates to reviews

Perspectives towards DUNE proximity cryogenic system (1/3)

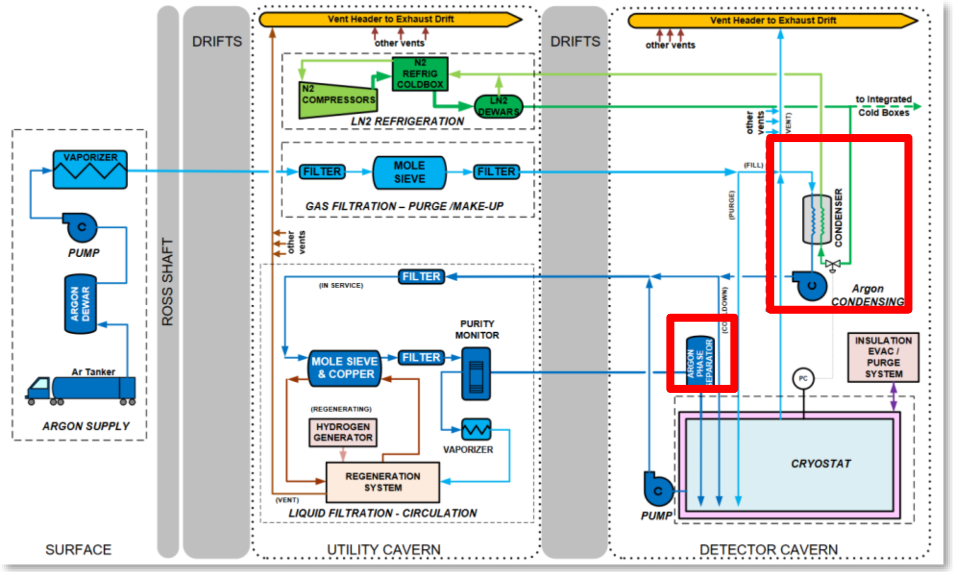
CERN Neutrino Platform (/TE-CRG-CL) is responsible for the design and production of Proximity Cryogenics Condensation System (installation not included)

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



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 send condensed liquid to purification
- To pass LAr through a phase separator before being injected in the cryostat

Constraints

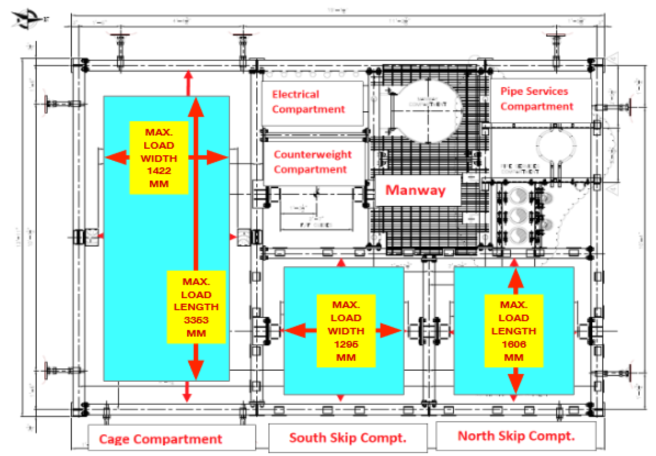
- Access shaft imposes assembly underground and limits size of equipment

→ several similar units working in parallel

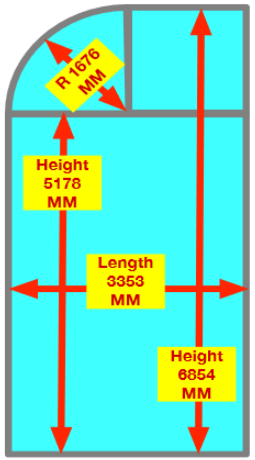
Perspectives towards DUNE proximity cryogenic system (2/3)

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

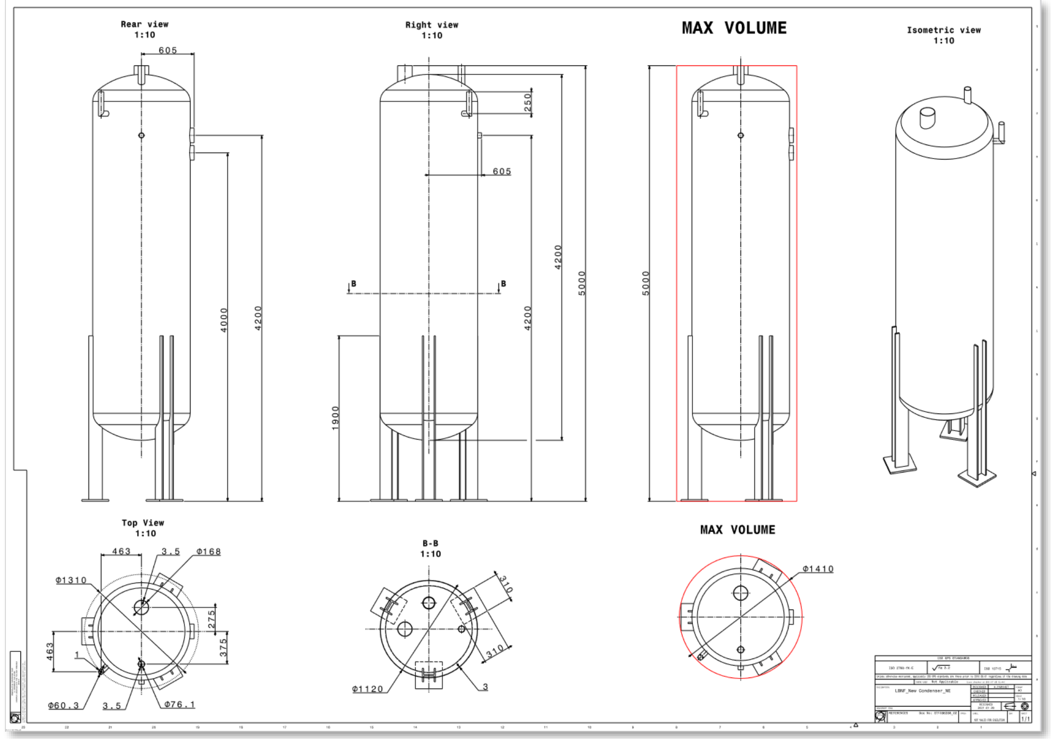
ROSS SHAFT AND SKIP COMPARTMENT UNDERSLUNG LOAD ENVELOPES[1)2)]:								
DIMENSIONS	MAX. WEIGHT		LENGTH		WIDTH		HEIGHT	
	MT	LBS	MM	FT	MM	FT	MM	FT
ROSS SHAFT MAX. LOAD ENVELOPE	6.1	13500	3353	11.0	1422	4.7	6854	22.5
ROSS SOUTH SKIP MAX. LOAD ENVELOPE	10.0	22000	1606	5.3	1295	4.2	15000	49.2



SHAFT LOAD ENVELOPE VIEW



CAGE UNDERSLUNG LOAD ENVELOPE

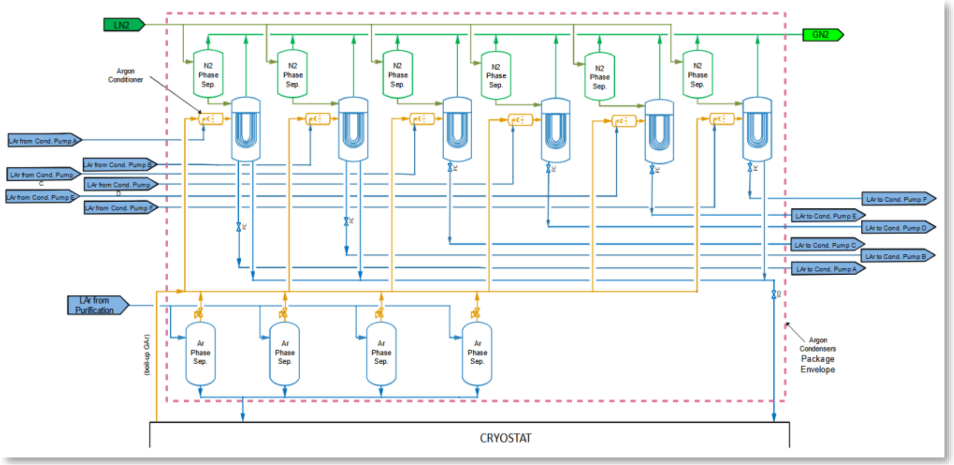


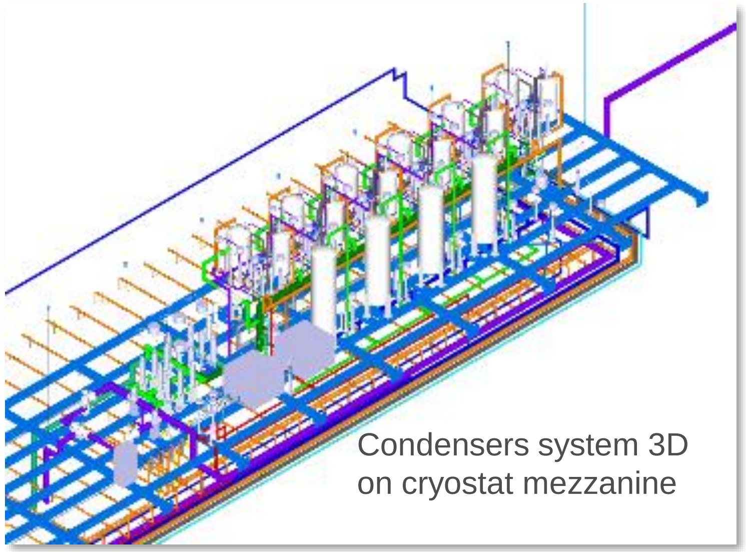
Perspectives towards DUNE proximity cryogenic system (3/3)

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

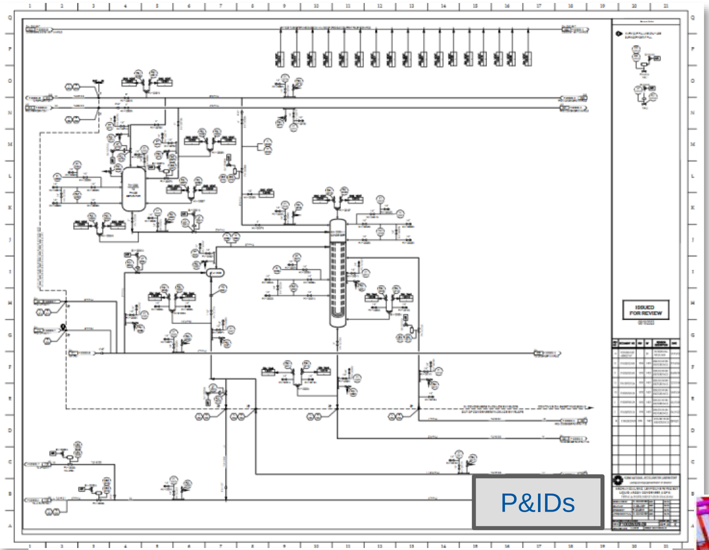




Condensers system 3D on cryostat mezzanine

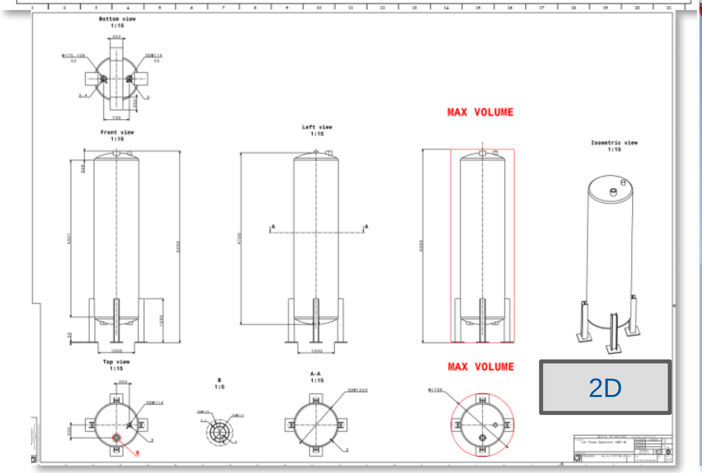
Conceptual Phase / Engineering status (1/2)

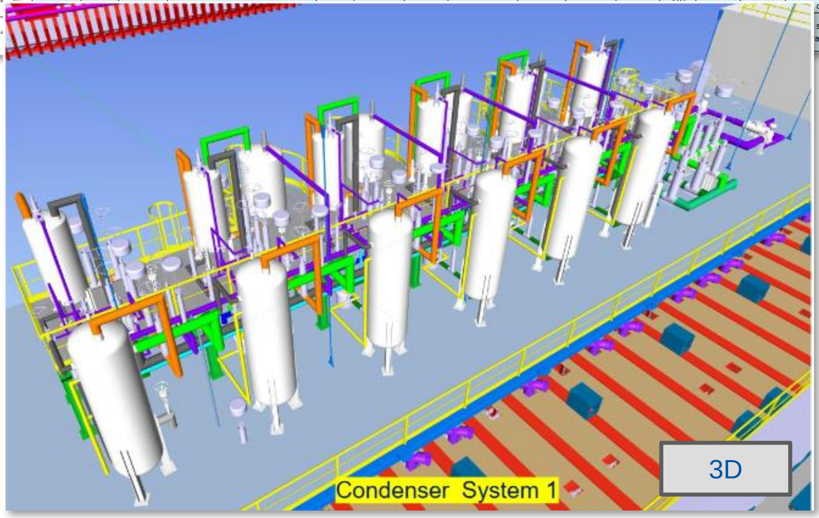
Fermilab cryo team performed Conceptual Design up to Procurement Readiness Review (July 2023)

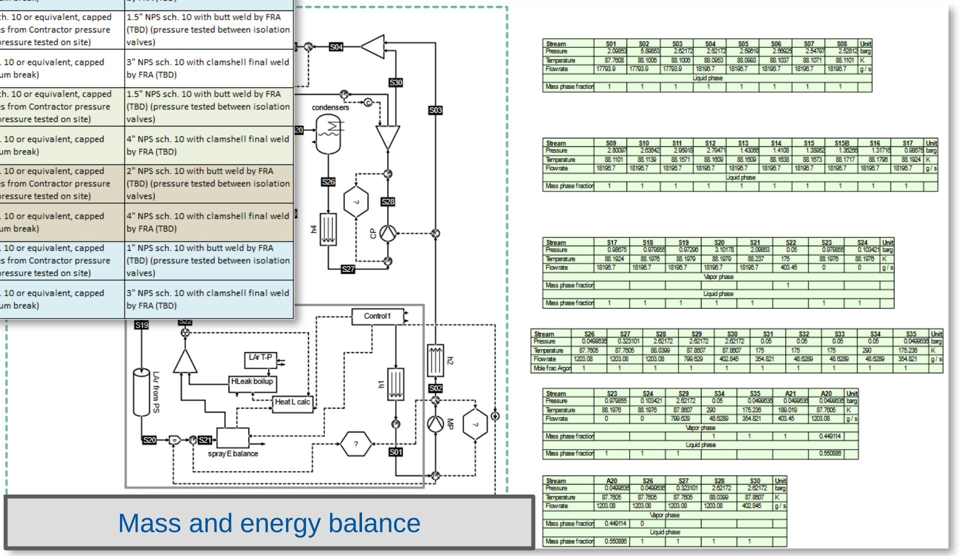


LBNF Argon Condensers System 1
Interface Control Table

LBNF Interface Points on P&IDs F10028329 rev. K								Pressure Rating, barg (psig)		Temperature Rating, K		Flow Rating, kg/s		Connections	
# per P&ID	Drawing Number	Fluid	Description	Location	Type	Line Diameter, inches	Type of insulation	Operating	Design Maximum	Operating	Design Range	Operating	Design Maximum	described as provided by "Subcontractor"	described as provided by FRA (TBD)
TJ 2140	13	N/A	Vacuum Jacketed Insulation	D - 11	Clamshelled Batt Weld	4	N/A	< 20 mTorr	full vacuum	N/A	300	N/A	N/A	4" NPS sch. 10 or equivalent, capped (with vacuum break)	4" NPS sch. 10 with clamshell final weld by FRA (TBD)
TP 2145	13	LAr/GAr	LAr from Argon Condenser Pump to Argon Condenser (A41). The line to prime LAr pump. TL01-S1019	D - 13	Butt weld	1	vacuum jacketed TJ 2145	4.1	10 (145)	88	87 - 310	0.64	0.65	1" NPS sch. 10 or equivalent, capped pipe (comes from Contractor pressure tested, or pressure tested on site)	1" NPS sch. 10 with butt weld by FRA (TBD) (pressure tested between isolation valves)
TJ 2145	13	N/A	Vacuum Jacketed Insulation	D - 13	Clamshelled Batt Weld	3	N/A	< 20 mTorr	full vacuum	N/A	300	N/A	N/A	3" NPS sch. 10 or equivalent, capped (with vacuum break)	3" NPS sch. 10 with clamshell final weld by FRA (TBD)
TP 2150	14	LAr	LAr from Argon Condensers pumps (A39) TP 2155 to Purification	D - 7	Butt weld	1.5	vacuum jacketed TJ 2150	4.1	10 (145)	88	87 - 310	0.6	0.64	1.5" NPS sch. 10 or equivalent, capped pipe (comes from Contractor pressure tested, or pressure tested on site)	1.5" NPS sch. 10 with butt weld by FRA (TBD) (pressure tested between isolation valves)
TJ 2150	14	N/A	Vacuum Jacketed Insulation	D - 7	Clamshelled Batt Weld	3	N/A	< 20 mTorr	full vacuum	N/A	300	N/A	N/A	3" NPS sch. 10 or equivalent, capped (with vacuum break)	3" NPS sch. 10 with clamshell final weld by FRA (TBD)
TP 2155	14	LAr	LAr from Argon Condensers pumps (A39) to TP 2150, then to Purification	D - 8	Butt weld	1.5	vacuum jacketed TJ 2155	4.1	10 (145)	88	87 - 310	0.64	0.65	1.5" NPS sch. 10 or equivalent, capped pipe (comes from Contractor pressure tested, or pressure tested on site)	1.5" NPS sch. 10 with butt weld by FRA (TBD) (pressure tested between isolation valves)
TJ 2155	14	N/A	Vacuum Jacketed Insulation	D - 8	Clamshelled Batt Weld	4	N/A	< 20 mTorr	full vacuum	N/A	300	N/A	N/A	4" NPS sch. 10 or equivalent, capped (with vacuum break)	4" NPS sch. 10 with clamshell final weld by FRA (TBD)
TP 2160	14	LAr	LAr from Argon Condenser (A37) to Condenser Pump (AB)	D - 9	Butt weld	2	vacuum jacketed TJ 2160	0.016	10 (145)	87	87 - 310	0.64	0.65	2" NPS sch. 10 or equivalent, capped pipe (comes from Contractor pressure tested, or pressure tested on site)	2" NPS sch. 10 with butt weld by FRA (TBD) (pressure tested between isolation valves)
TJ 2160	14	N/A	Vacuum Jacketed Insulation	D - 9	Clamshelled Batt Weld	4	N/A	< 20 mTorr	full vacuum	N/A	300	N/A	N/A	4" NPS sch. 10 or equivalent, capped (with vacuum break)	4" NPS sch. 10 with clamshell final weld by FRA (TBD)
TP 2165	14	LAr/GAr	LAr from Argon Condenser Pump (AE) to Argon Condenser (A36). Line	D - 13	Butt weld	1	vacuum jacketed TJ	4.1	10 (145)	88	87 - 310	0.64	0.65	1" NPS sch. 10 or equivalent, capped pipe (comes from Contractor pressure … or pressure tested on site)	1" NPS sch. 10 with butt weld by FRA (TBD) (pressure tested between isolation valves)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	… sch. 10 or equivalent, capped … acuum break)	3" NPS sch. 10 with clamshell final weld by FRA (TBD)







CERN-NP contribution: consultancy & participation to reviews

Conceptual Phase / Engineering status (2/2)

CERN-NP (TE-CRG-CL), as collaboration member, takes owner-ship and responsibility for performance of design
→ reviews and iterates conceptual design

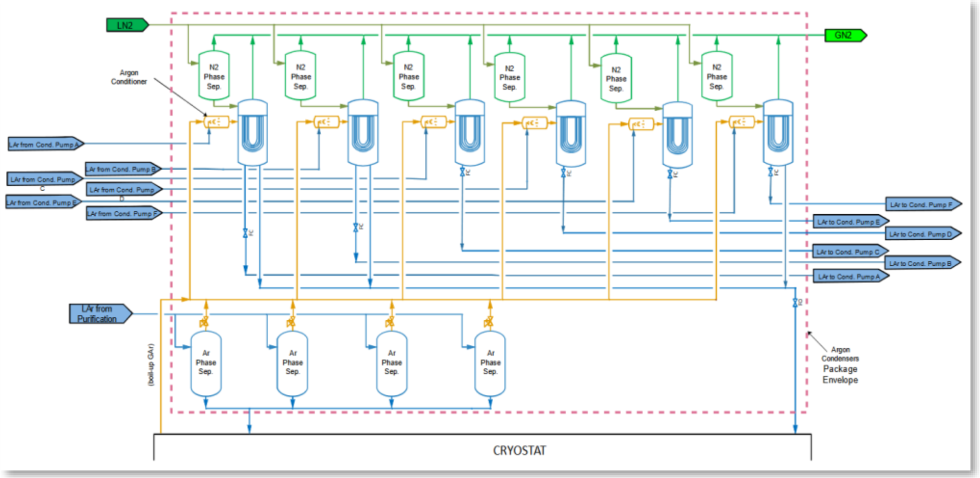
- ✓ Analysed requirements
- ✓ Produced Functional analysis
- ❑ Reviewing PFD/P&ID → iteration required due to new technical design choices
- ❑ Producing Interface Sheets
- ❑ Preparing for desuperheater and condenser pump test @ NP-04

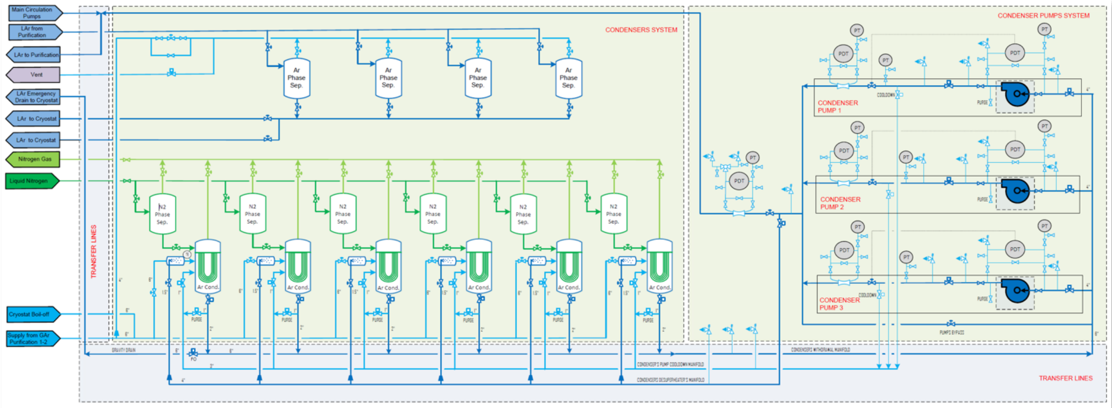
In preparation for :

Market Survey

Technical Specification

Condensers system PFD





PFD of new condenser pump configuration

Conceptual Phase / Management actions status (1/2)

- ❑ Management plan being developped

FUNCTION			NAME
PL	-	Neutrino Platform Project Leader	Francesco LANNI
PCPL	-	Neutrino Platform Proximity Cryogenics Project Leader	Johan BREMER
RO	-	Responsible Officer	Caroline FABRE

- ❑ Workpackages

WP1: Contracts	CFE-JBR
WP2: Quality	CFE-JBR
WP3: Project Management	JBR-CFE
WP4: Process	CFE- x
WP5: Instrumentation	CFE- x
WP6: Assembly	LBNF-PCT
WP7: Risks and availability Analysis	CFE-JBR
WP8: Safety	CFE-PCT
WP9: Mechanical	x -PCT

(1.7 FTE from TE-CRG-CL)

- ✓ PBS

LBNF Proximity Cryogenics Condensation System

PBS proposal								#
Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	product name		Comments
project level	sub-project level	system level	sub system	family	Product			
FD	01	00	00	00	00	Common		common components to the **Far Detector 1**
FD	01	**CR**	00	00	00	Common		common components to the **proximity CRyogenic system**
FD	01	CR	**CS**	00	00	Common		common components to the **Condensation System**
FD	01	CR	CS	**LN**	00	Common		common components to the **Nitrogen transfer Lines**
FD	01	CR	CS	**LA**	00	Common		common components to the **Argon transfer Lines**
FD	01	CR	CS	**SN**	00	Common		common components to the **N2 phase Separator**
FD	01	CR	CS	PN	01	N2 phase separator 1		N2 phase separator system 1
FD	01	CR	CS	PN	02	N2 phase separator 2		N2 phase separator system 2
FD	01	CR	CS	PN	03	N2 phase separator 3		N2 phase separator system 3
FD	01	CR	CS	PN	04	N2 phase separator 4		N2 phase separator system 4
FD	01	CR	CS	PN	05	N2 phase separator 5		N2 phase separator system 5
FD	01	CR	CS	PN	06	N2 phase separator 6		N2 phase separator system 6
FD	01	CR	CS	**SA**	00	Common		common components to the **Ar phase Separator**
FD	01	CR	CS	**DH**	00	Common		common componenents to the **De-superHeater**
FD	01	CR	CS	**CA**	00	Common		common components to the **Argon Condensers**
FD	01	CR	CS	CA	01	Condenser 1		Condenser 1
FD	01	CR	CS	CA	02	Condenser 2		Condenser 2
FD	01	CR	CS	CA	03	Condenser 3		Condenser 3
FD	01	CR	CS	CA	04	Condenser 4		Condenser 4
FD	01	CR	CS	CA	05	Condenser 5		Condenser 5
FD	01	CR	CS	CA	06	Condenser 6		Condenser 6
FD	01	CR	AC	00	00			Liquid argon circulation
FD	01	CR	AC	MC	00			Main circulation box
FD	01	CR	AC	CC	00	Common		common components to the **Condenser Circulation boxes**

Conceptual Phase / Management actions status (2/2)

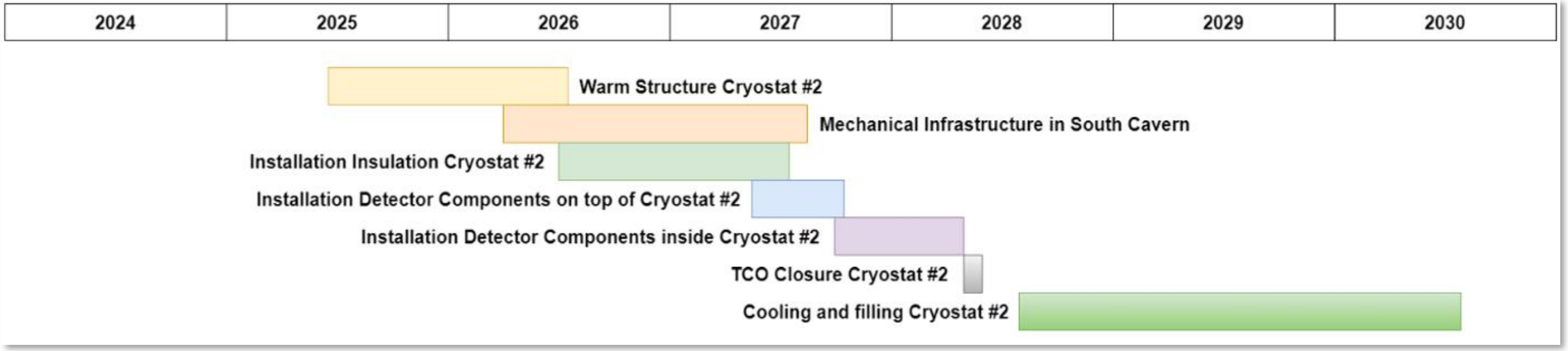
Budget

- ✓ Cost Estimate > Swiss in-kind contribution 2.3 mCHF (2018)

- ❑ CERN – US-DOE negociations in progress:
- → Trading of scope
- → Financing
- → Dedicated collaboration agreement

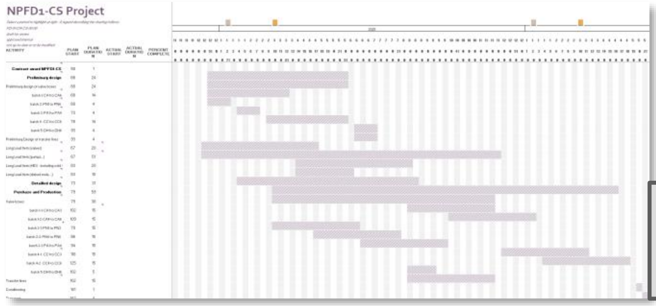
Conceptual Phase / Management actions status (2/2)

Schedule



Milestones

Tender out : 01-02-2025
Contract signed: 01-06-2025
Shipment: 01-02-2027
Delivery: 01-04-2027



NPFD1-CS Schedule to be updated

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

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 Q1 2025; Delivery foreseen in Q2 2027
- The first cryostat cool-down and filling is foreseen to begin in Q2 2028.

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