

# The Long-Baseline Neutrino Facility

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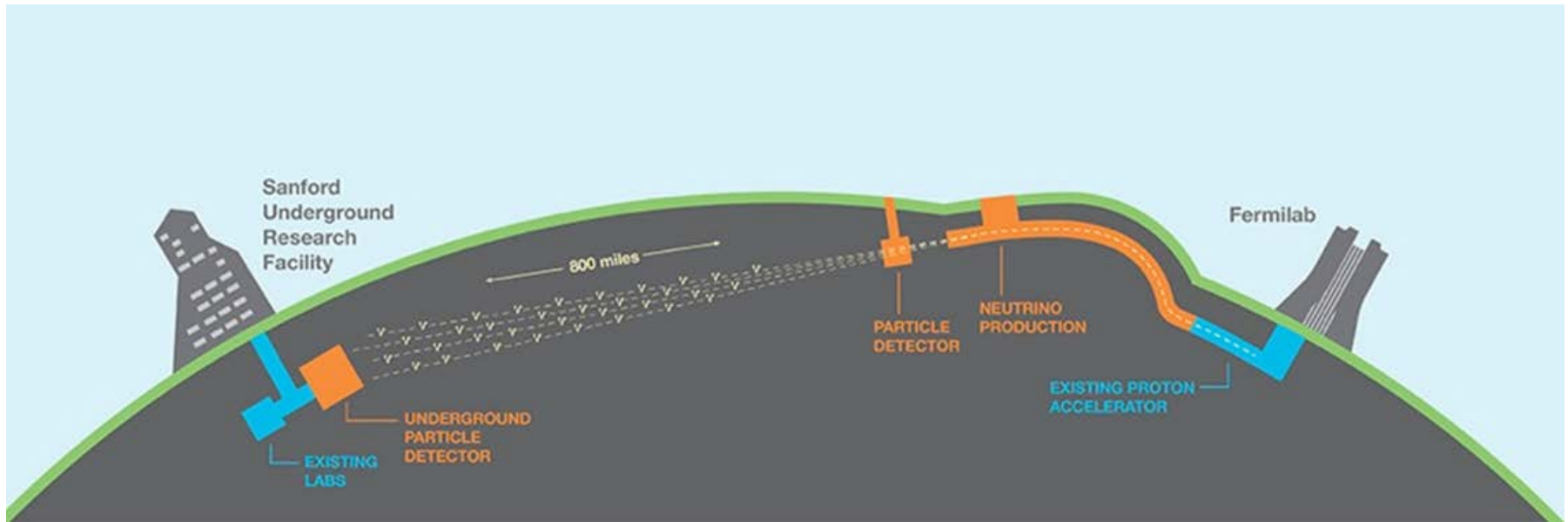


# Outline

- Intro.
- Scope and Strategy.
- Modes of Operations.
- Requirements.
- Cryostat.
- Cryogenic Systems.
- LAr Procurement.
- Schedule.
- Summary.

# Intro: The LBNF/DUNE Project

- The Long-Baseline Neutrino Facility is the **infrastructure** necessary to send a powerful beam of neutrinos 800 miles through the earth, and measure them deep underground at South Dakota's Sanford Underground Research Facility (SURF). LBNF supports DUNE.
- The Dep Underground Neutrino Experiment will be a **game-changing experiment for neutrino science**, potentially transforming our understanding of why the universe exists as it does.
- The **LBNF/DUNE** project will be the **first internationally conceived, constructed, and operated mega-science project** hosted by the Department of Energy in the United States.





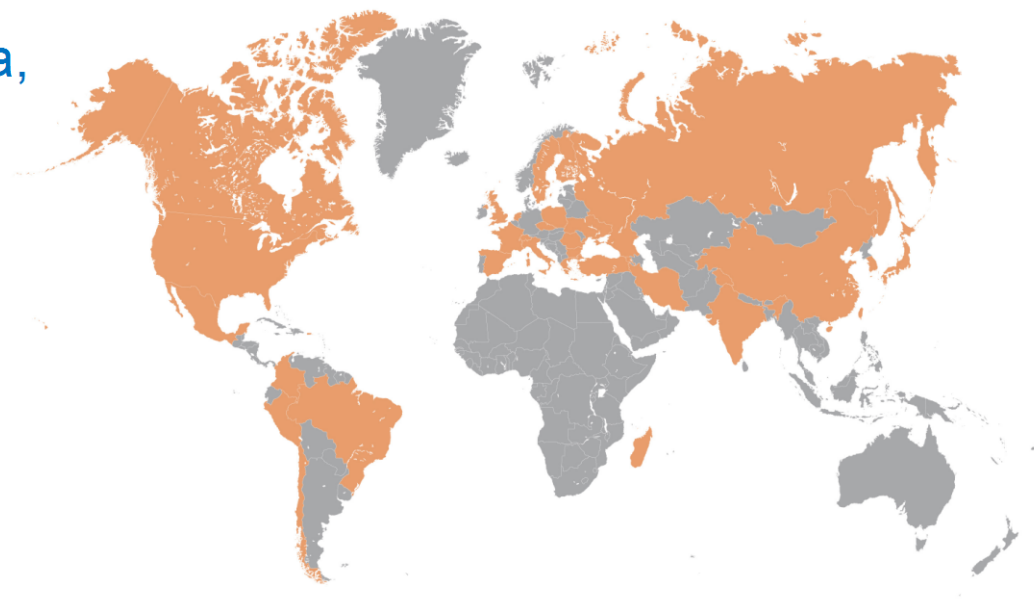
# The DUNE Collaboration

Today:

60 % non-US

**1011 collaborators from 164 institutions in 30 nations!!**

- Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA

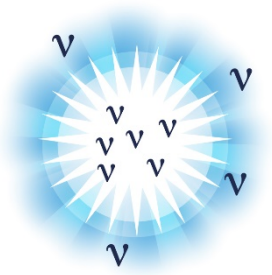


**DUNE is an International Experiment.**

**LBNF is an International Participation with Fermilab as the host Laboratory.**



# Ambitious, Far-Reaching Science Goals



- **Origin of matter**  
Discover what happened after the big bang:  
Are neutrinos the reason the universe is made of matter?



- **Black hole formation**  
Use neutrinos to look into the cosmos and watch the formation of neutron stars and black holes in real time.



- **Unification of forces**  
Move closer to realizing Einstein's dream of a unified theory of matter and energy.



# Neutrinos are Exciting Science!

## The Nobel Prize in Physics 2002



Raymond Davis Jr.  
Prize share: 1/4



Masatoshi Koshiha  
Prize share: 1/4



Riccardo Giacconi  
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiha *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.



## The Nobel Prize in Physics 2015



Photo: A. Mahmoud  
Takaaki Kajita  
Prize share: 1/2



Photo: A. Mahmoud  
Arthur B. McDonald  
Prize share: 1/2

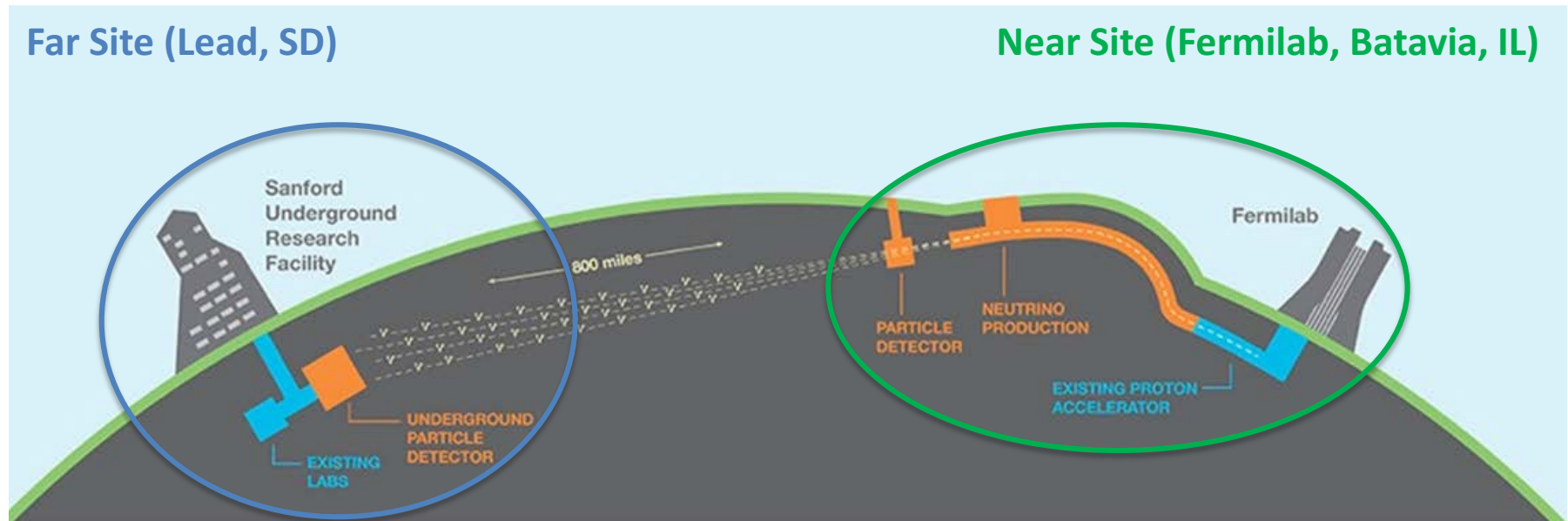
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*





# LBNF

- LBNF includes the Beam Line, the Conventional Facilities and the Cryostat and Cryogenics Infrastructure and has Facilities at two Locations:
  - **Near Site** (at Fermilab, in Batavia, IL) where the Neutrino beam is generated in the accelerator complex, analyzed in the Near Detector and sent through the earth to the target at the Far Site.
  - **Far Side** (at SURF, in Lead, SD) where an out-of-service gold mine (max original depth 8,000 ft) has been repurposed as a research facility. The 4,850 ft Level is already in use for other scientific experiments and will be expanded for the LBNF/DUNE project. Here the Neutrino beam coming from Fermilab reaches its target: the Far Detector, composed of four tanks filled with LAr and Time Projection Chambers (TPCs) to measure the properties of Neutrinos among other things. Detection, Tracking & Studying.







# Detector/Infrastructure Prototyping

## Single-Phase

2015



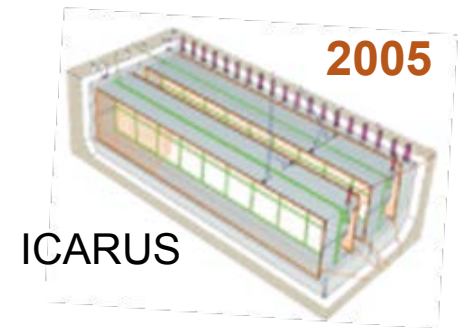
35-t prototype  
38 ton LAr

2018



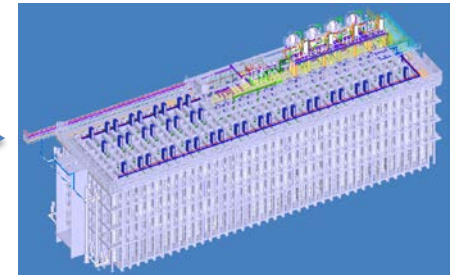
ProtoDUNE SP @ CERN  
760 ton LAr

2005



ICARUS

2024 Ops



DUNE SP  
17,100 ton LAr

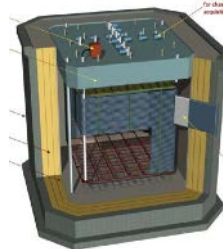
## Dual-Phase

2016



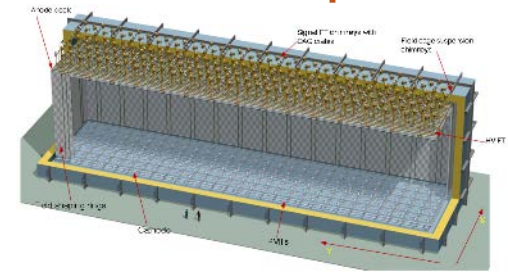
WA105: 1x1x3 m<sup>3</sup>  
23 ton LAr

2018



ProtoDUNE DP @ CERN  
700 ton LAr

2025 Ops



DUNE DP?  
17,100 ton LAr





# SURF: Sanford Underground Research Laboratory (Lead, SD)

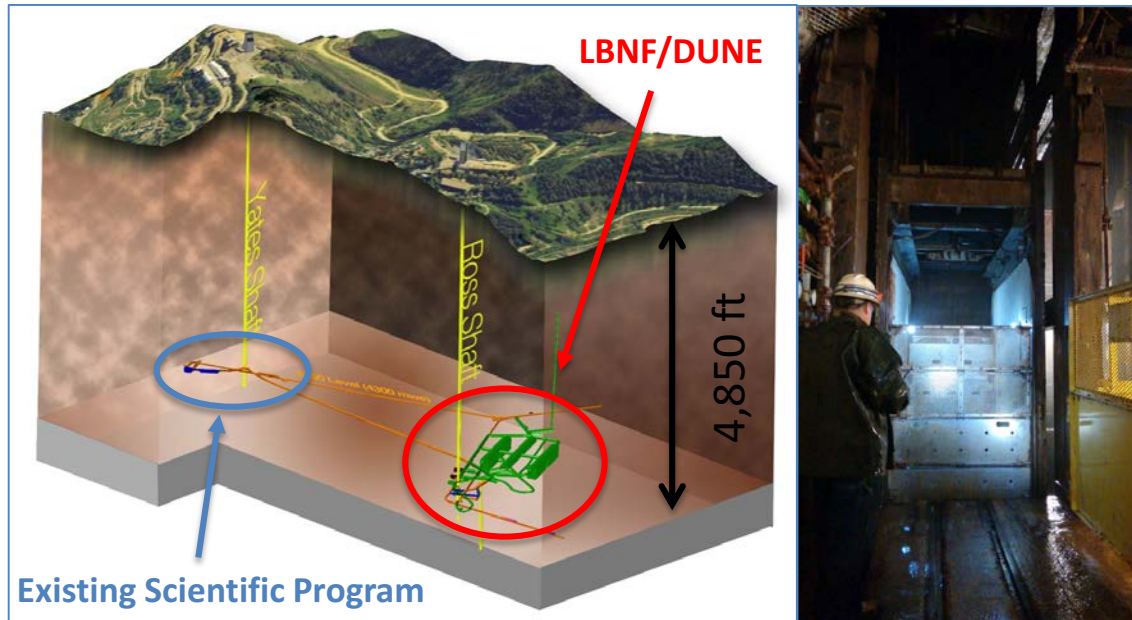


09.13.17

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# Access Conditions at SURF



# Cryogenics Infrastructure Scope and Strategy

- **Cryogenics Infrastructure** to support four 17-kton LAr mass detectors (~70 kton total).
- **International** approach with CERN and Fermilab current main players, but there are very interesting opportunities for others to contribute.
- **Cryostat** includes membrane cryostat and steel support structure, the crane bridges in caverns for cryostat and support structure installation, mezzanines and their supports.
  - Predominantly non-DOE. CERN responsible for 1<sup>st</sup> Cryostat.
  - Responsible parties for remaining cryostats are to be identified.
- **Cryogenic Systems** includes design, procurement of materials, construction and testing of the cryogenic systems for the detector cryostats.
  - Split between DOE and non-DOE.
  - Responsible parties for non-DOE scope are to be identified.
- **LAr procurement** of 70 kton. Split between DOE and non-DOE.
- **Integration** of all components: DOE. CERN integrating detector cavern.
- Participation in the DUNE **prototyping** effort at CERN (ProtoDUNE-SP and ProtoDUNE-DP).

# Modes of Operations

- **GAr Purge:** GAr is slowly flown from the bottom of the tank (initially full of air) to push the impurities out from the top. Reduces contaminants (O<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>O) to ppm level.
- **GAr Circulation:** GAr is circulated in a closed loop and purified through the GAr purification system. Reduces O<sub>2</sub> and H<sub>2</sub>O to sub-ppm level.
- **Cool-down:** a mix of GAr and LAr is flown into sprayers to generate a mist of small liquid droplets that are circulated by another set of sprayers flowing GAr only.
- **Filling:** GAr is transferred from surface and re-condensed underground. Once the cryostat and the detector are cold, LAr flows from the condenser into each cryostat.
- **Steady state operations:**
  - LAr is continuously purified via external LAr pumps (4 in each cryostat, all in service to achieve purity, then fewer to maintain purity).
  - Boil-off GAr is recondensed in the condensers (outside the cryostat) and purified in the LAr purification system before being reintroduced as liquid.
- **Emptying:** at the end of operations, the tank is emptied and the LAr removed.

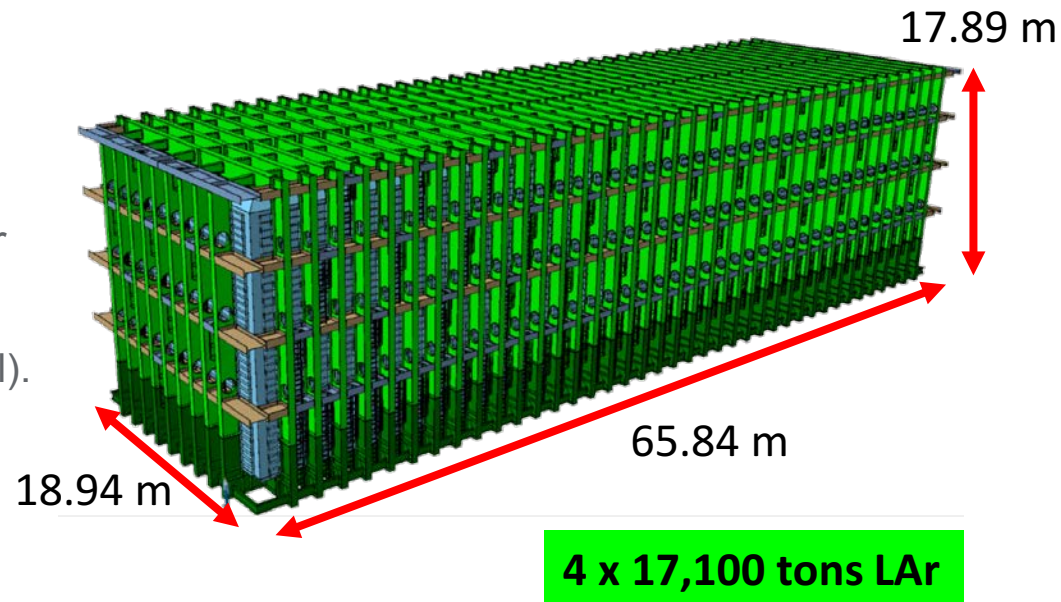
# Selection of Design Parameters

$$\text{Lifetime}[s] = \frac{3 \cdot 10^{-13} [s \cdot \text{parts of Oxygen}]}{\text{Contaminant} [\text{parts of Oxygen}]}$$

Design Parameter	Value (per cryostat)
GAr Flow rate during piston purge	254 m <sup>3</sup> /hr
Maximum cool down rate detector	40 K/hr
Maximum Delta_T any two detector points	50 K
Maximum available cooling power	100 kW
Required electron lifetime	> 3 ms
Required LAr purity (Oxygen equivalent contamination)	< 100 ppt
Maximum liquid turnover (5 days/volume change)	36.12 kg/s
Cryostat operating pressure	130 mBarg
Cryostat design pressure	350 mBarg

# Cryostat

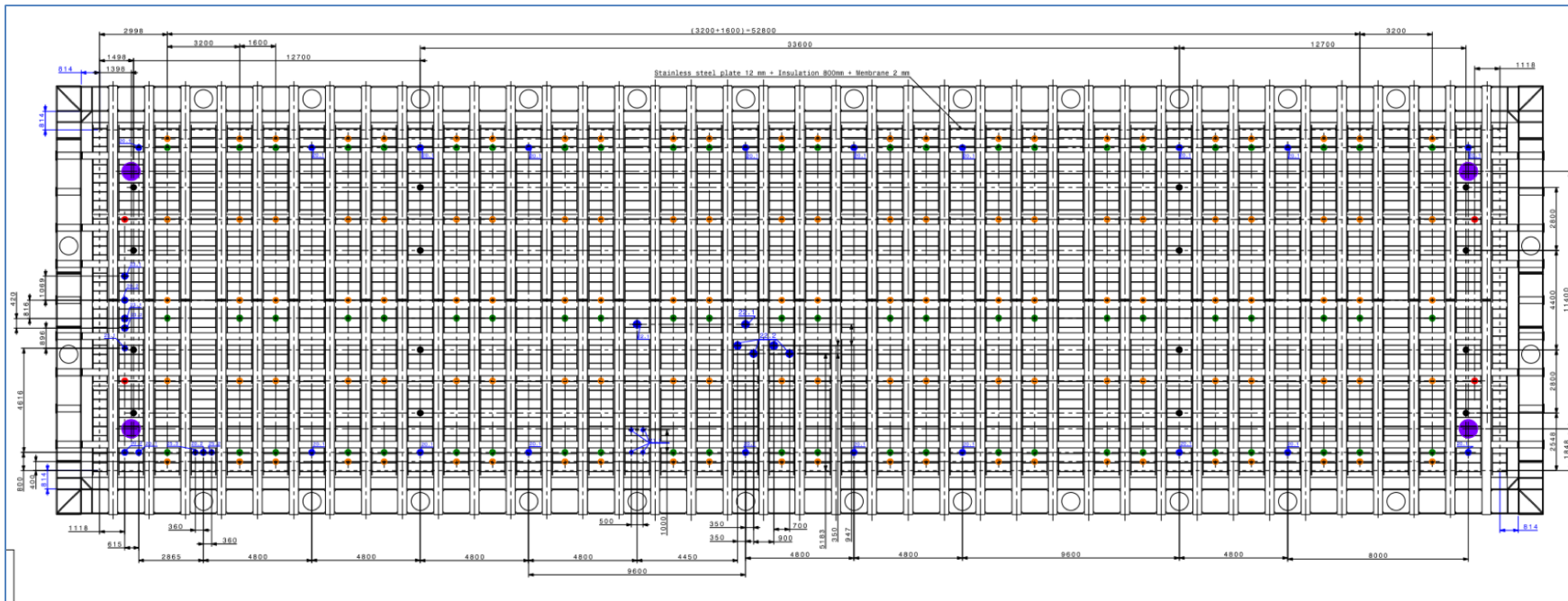
- Membrane cryostat technology.
- 1.2 mm membrane (304L).
- 0.8 m of passive insulation (polyurethane).
- Support structure bears LAr + GAr loads:
  - 12 mm vapor barrier (stainless steel).
  - 1.1 m high I-beams (steel).
- The design includes the feedback from the assembly of ProtoDUNE.



Dimensions of one cryostat	Length (m)	Width (m)	Height (m)
Membrane Internal Dimensions	62.00	15.10	14.00
SS plate Internal Dimensions	63.60	16.70	15.60
External Dimensions of steel structure	65.84	18.94	17.84



## Cryostat feedthroughs (DRAFT)



# Cryogenics Systems

- **Infrastructure Cryogenics (INF):**

- Receive Ar/N2.
- Transport Ar to cavern.
- LN2 refrigeration (compressors, cold boxes, N2 distribution system).

} **DOE**

- **Proximity Cryogenics (PROX) :**

- Circulate and purify LAr.
- Achieve and maintain LAr purity.
- Recondense and purify boil off GAr.

} **Non-DOE**

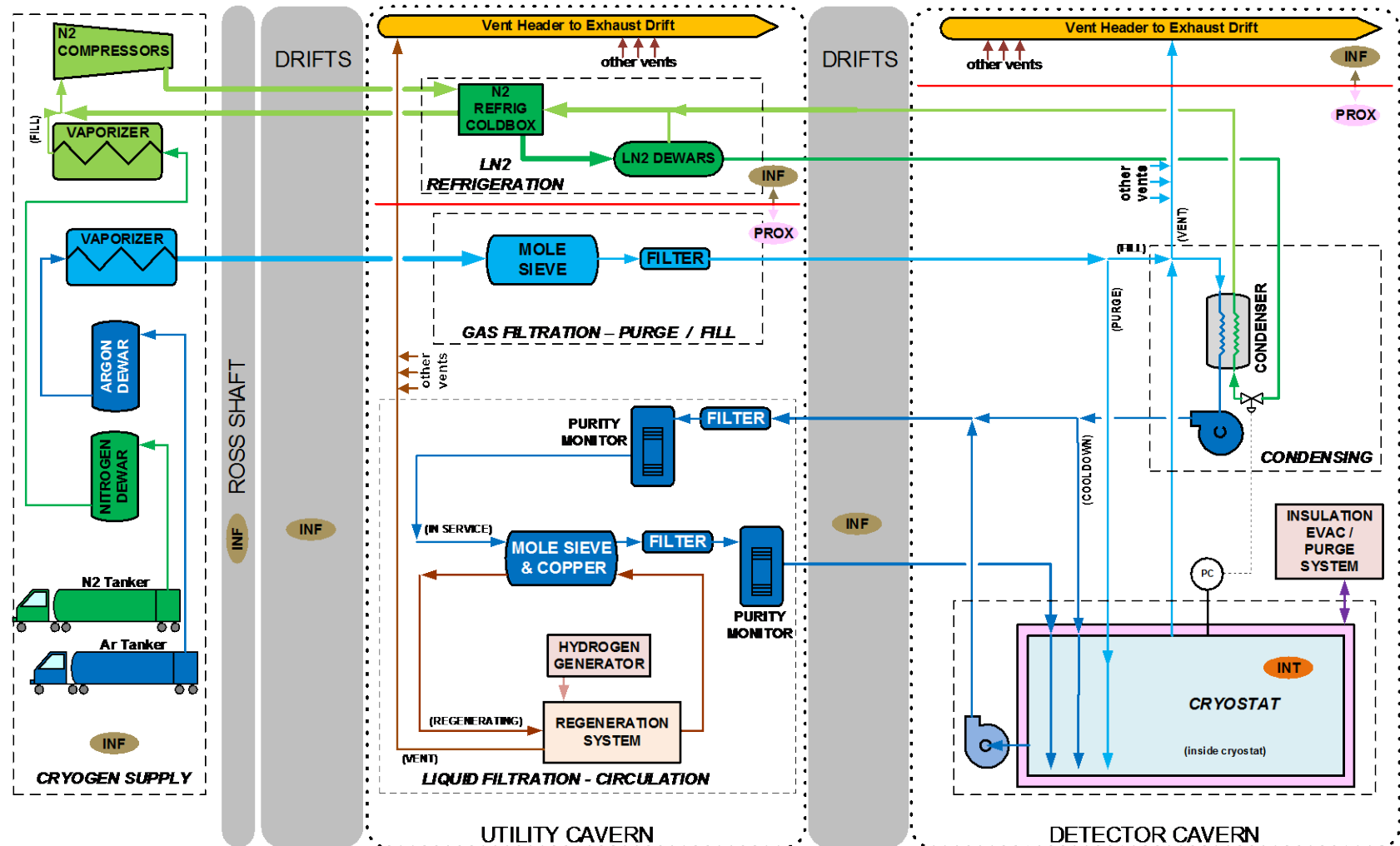
- **Internal Cryogenics (INT):**

- Inside the cryostat.
- Cryostat purge, cool down, fill.
- GAr/LAr distribution.

} **DUNE**

# Cryogenics Process Flow Diagram

**NO cryogenics in the shaft.**

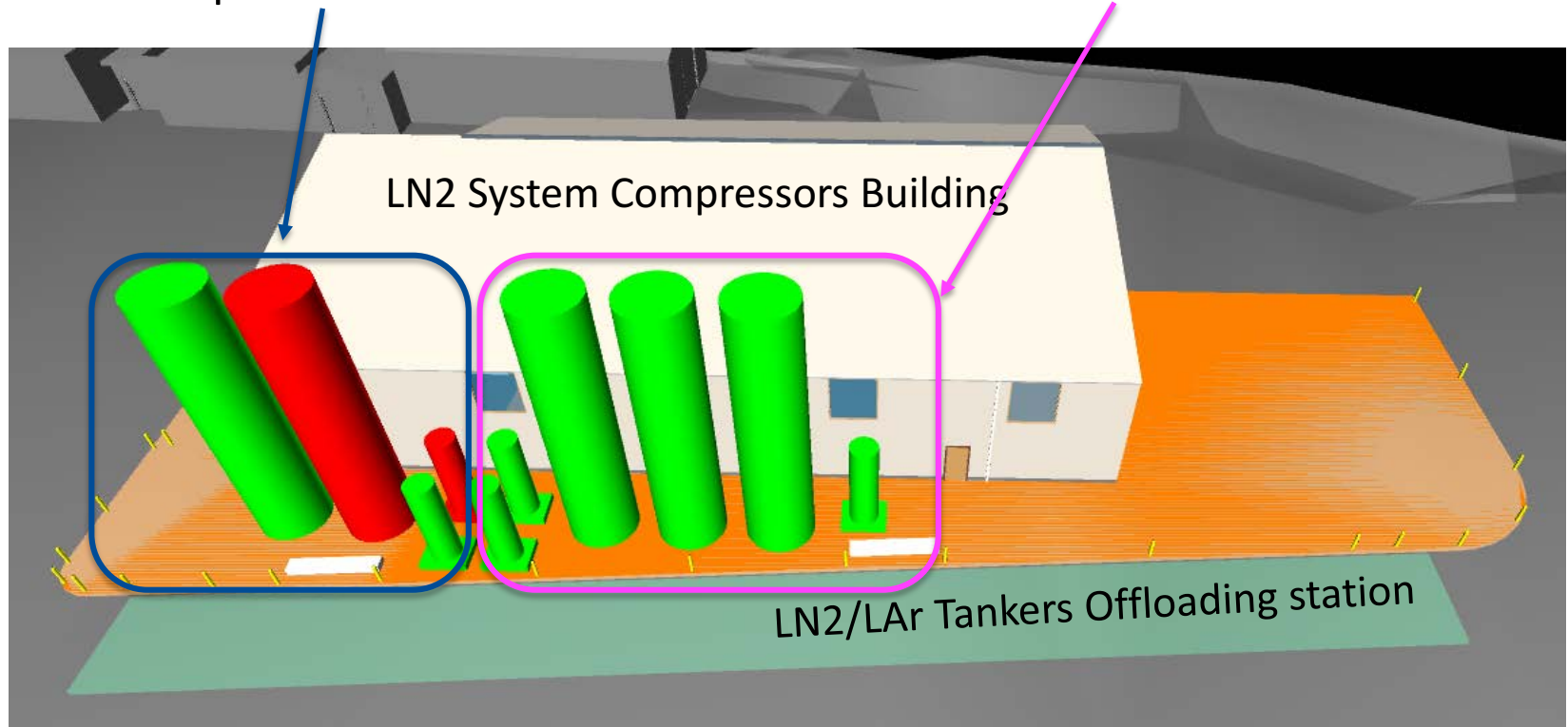


# Infrastructure Cryogenics

# Infrastructure Cryogenics – Receiving Facilities

Current Cryogen Storage  
and vaporizers: 2x50 m<sup>3</sup>

Proposed additional temporary LAr Storage  
and Vaporizers (LAr fill only): 3x50 m<sup>3</sup>



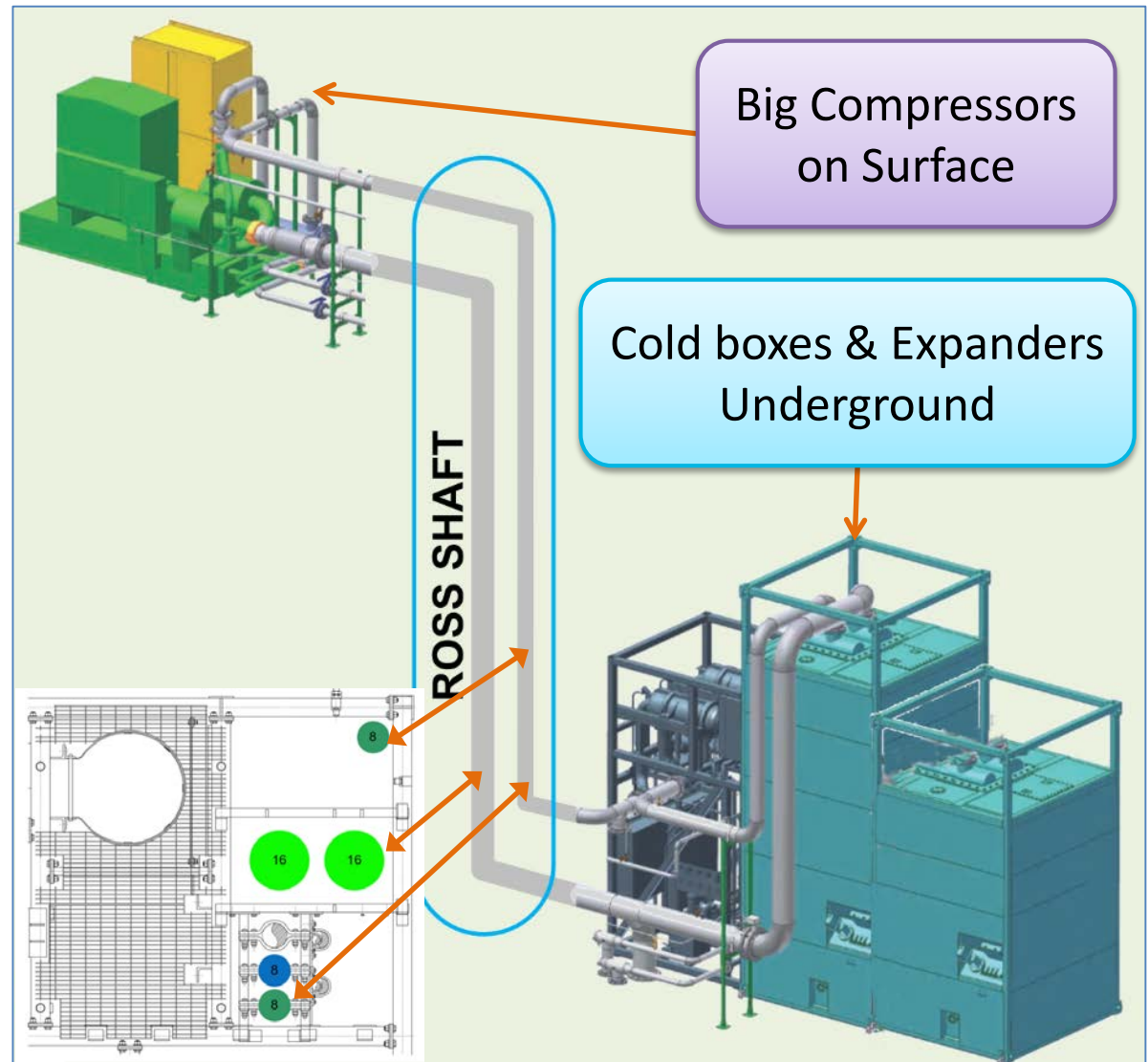
LN2 Storage Tank and  
Vaporizer (1x50 m<sup>3</sup>)

LAr Storage Tanks and  
Vaporizers (4x50m<sup>3</sup>)

**280 tons of LAr storage**

# Infrastructure Cryogenics – LN2 Refrigeration System

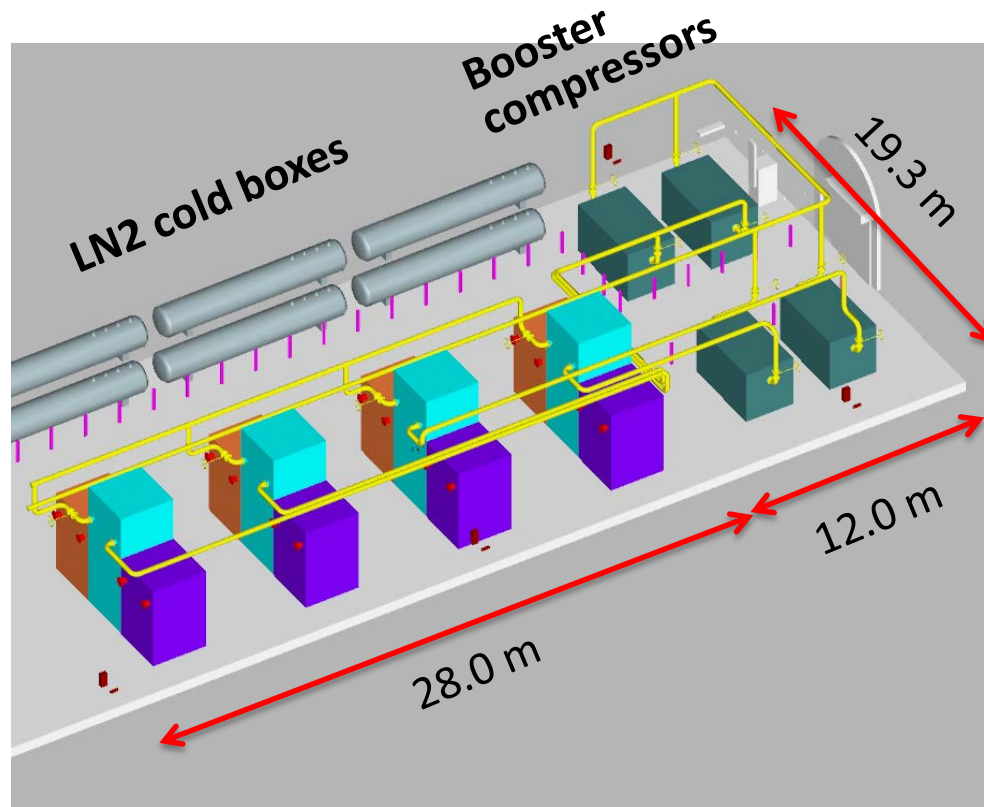
- 4 **Commercial** units:
  - Cold boxes and gas boosters in the cavern.
  - GN2 compressors above ground.
- Units assembled in cavern, based on transport limits.
- 3 units for cryostats 1, 2 and 4<sup>th</sup> unit added for cryostats 3, 4.
- 4x97 kW units.
- Refrigeration model validated with COCO-COFE simulator.





# Infrastructure Cryogenics in Central Utility Cavern (CUC) – LN2 Refrigeration and Storage

- Lifting eyes in the ceiling of CUC for LN2 cold boxes and booster compressors positioning and maintenance.



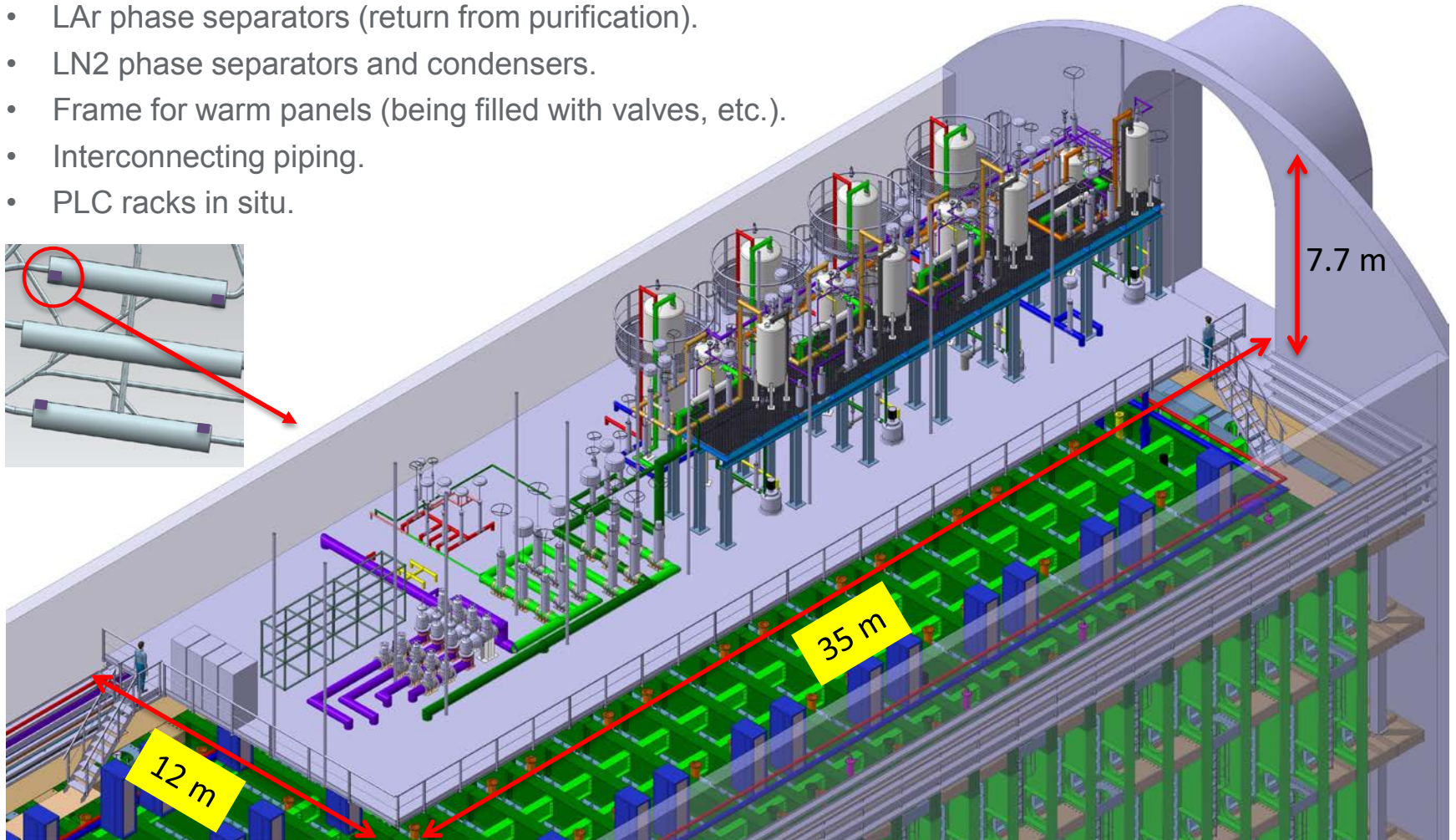
# LN2 Refrigeration System – Procurement Strategy

- Chosen design/fabricate/install phased approach:
  - **Base** → Design (full scope: 4x97 kW units) and Fabrication of first three units only (required for Detectors #1, #2).
  - **Option 1** → Installation and Commissioning of first three units.
  - **Option 2** → Fabrication of 4th unit (required for Detectors #3, #4).
  - **Option 3** → Installation and Commissioning of 4th unit.
- Iterating with DOE on Acquisition Plan (AP) for the whole LN2 system.
- Writing Functional Requirements Specifications (FRS).
- Goal is to issue the Request For Proposals (RFP) to industry by Dec 2017 and award the contract by Jun 2018 (subject to availability of funds).

# Proximity Cryogenics

# Proximity Cryogenics in Detector's Cavern – Mezzanine

- Cryostat Pressure Safety Valves (PSVs), piping and lockout valves.
- Small LAr buffer tanks (for condenser pumps) and condenser LAr pumps.
- LAr phase separators (return from purification).
- LN2 phase separators and condensers.
- Frame for warm panels (being filled with valves, etc.).
- Interconnecting piping.
- PLC racks in situ.

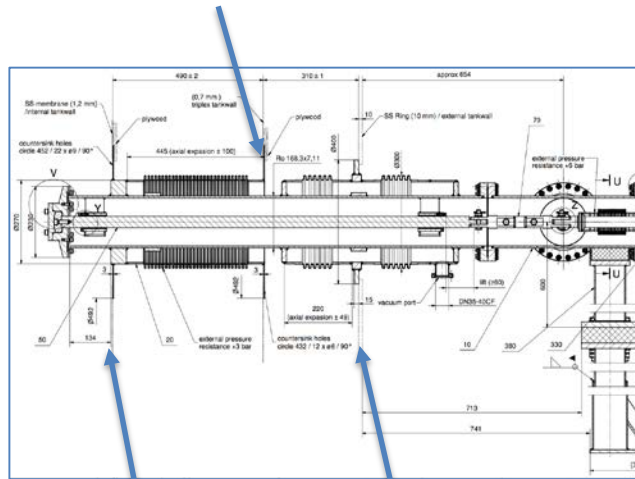




# Proximity Cryogenics in Detector's Cavern – LAr Pumps

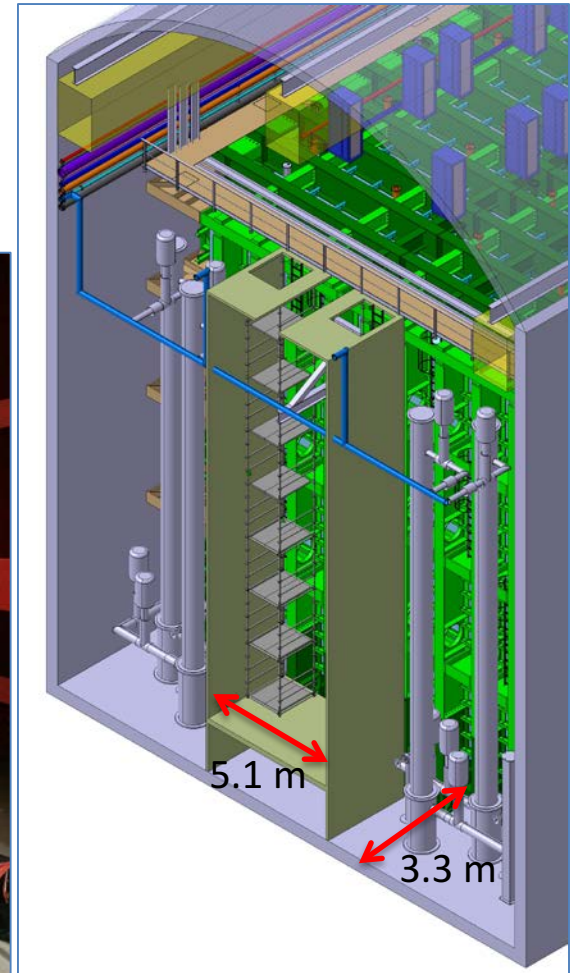
- LAr pumps.
- Concept of Clean Room (CR) for detector installation.
- Inline safety valves (one per penetration). Same as in ProtoDUNEs.

## Cryostat Secondary Barrier

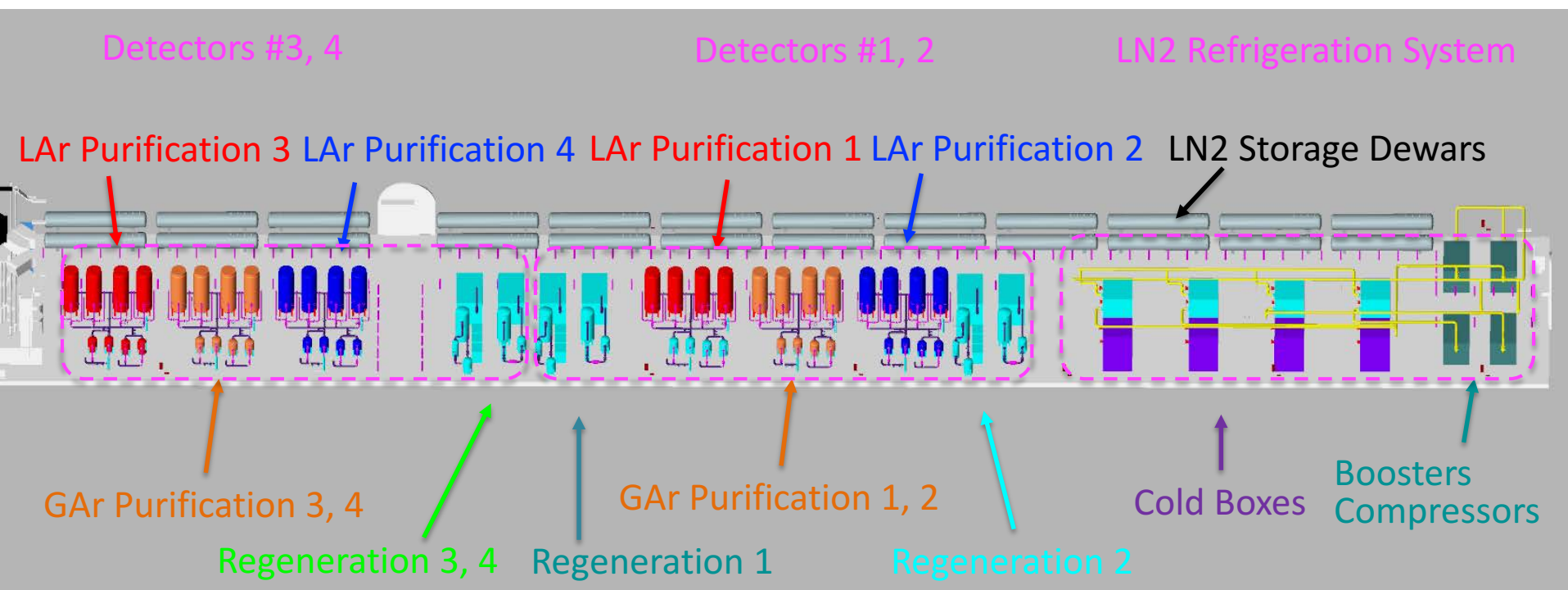


Cryostat Vapor Barrier

Cryostat Membrane



# Proximity Cryogenics in the CUC – Layout





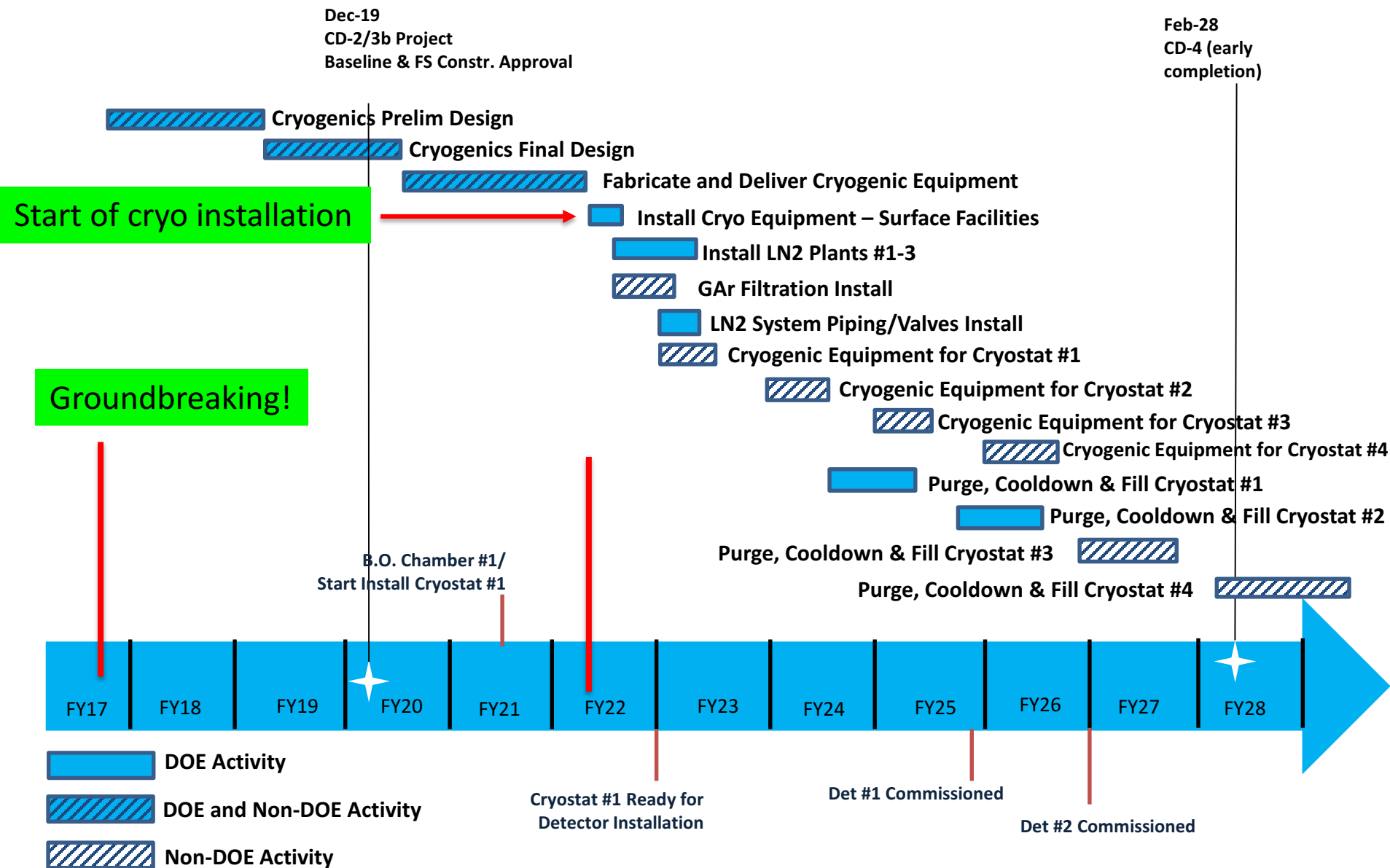


# LAr Procurement

- Contracted with a consultant to develop LAr procurement strategy and refine cost and schedule estimates.
- Required Purity: less than 10 ppm Water, 5 ppm Oxygen, 10 ppm Nitrogen (1 ppm would be desirable for N<sub>2</sub>, but not needed as a requirement).
- Assuming can max out the LN<sub>2</sub> refrigeration capacity.
- In Dec 2016 we have visited the five major US LAr suppliers.
- Key takeaway:
  - Supply is feasible, even likely coming from several hundreds miles away.
  - New plants capable of producing LAr put in service since previous analysis when it was likely coming from 1,000 miles away (reduced travel distance).
- Currently no single supplier, probably 2-3 suppliers either contracted separately or as subs of a LAr procurement coordinator.
- Gathered very useful information for the development of the LAr receiving facility, especially the amount of storage.
- Reviewing replies to a Request For Information (RFI) issued to collect more information about how to structure this procurement, current costs and how to project them in the future.



# Cryogenics Schedule Summary Overview



# Summary and Next Steps

- Advancing the **design** of all parts focusing on **requirements** and **interfaces**, in particular between Cryostat, Cryogenics and Conventional Facilities. Expected sign-off on cryostat feedthroughs early Nov 2017 to being preliminary study with GTT early 2018.
- Identified the **equipment layout** and the spaces needed in each zone (above ground, shaft, detector cavern, central utility cavern, drifts).
- Studied the **logistics** from above ground to underground and we can deliver all the components to their location.
- Working on a design/fabricate/install strategy for the **LN2 system**. Iterating with DOE and writing Functional Requirements Specifications. Goal is to award a phase funded contract by Jun 2018.
- Contracted with a consultant to develop a strategy for **LAr procurement**. Reviewing replies from the industry to RFI. Process also informing the development of the receiving facilities on the surface.
- Developing the **Proximity Cryogenics** on the mezzanine to inform the cryostat design.
- In parallel, continuing the prototyping effort to inform the LBNF/DUNE design, fabrication, installation.
- Ground breaking in Jul 2017! Planning to start cryo installation at SURF in **2022**.

# Thanks



# Backup Slides









# Cooling Power Requirements under different scenarios

4 x 97 kW units → Only 3 needed in purity maintenance mode, one full spare unit.

		Unit Loads (kW)	Scenarios														
			1	2	3	4	5	6	7	A	B	C	D	E	F	G	
Recondenser Load, 1st Cryostat																	
Cryostat Heat Ingress	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	
With 2 Recirculation Pumps	6.7			6.7	6.7	6.7	6.7		6.7	6.7	6.7	6.7	6.7	6.7	6.7		
With 4 Recirculation Pumps	13.4	13.4	13.4														
Piping and Purification vessel Heat ingress	3.7	3.7	3.7	3.7	3.7	3.7	3.7		3.7	3.7	3.7	3.7	3.7	3.7	3.7		
Detector Electronics in cryostat	23.7			23.7	23.7	23.7	23.7		23.7	23.7	23.7	23.7	23.7	23.7	23.7		
Cryostat Fill - GAr transfer / recondense		227.20															
Number of condensers in operation	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Condenser Load		273.0	45.8	62.8	62.8	62.8	62.8	28.7	62.8	62.8	62.8	62.8	62.8	62.8	62.8	28.7	
Recondenser Load, 2nd Cryostat																	
Cryostat Heat Ingress	28.7				28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7	
With 2 Recirculation Pumps	6.7						6.7		6.7	6.7	6.7	6.7	6.7	6.7	6.7		
With 4 Recirculation Pumps	13.4				13.4	13.4			6.7	6.7	6.7	6.7	6.7	6.7	6.7		
Piping and Purification vessel Heat ingress	3.7				3.7	3.7	3.7		3.7	3.7	3.7	3.7	3.7	3.7	3.7		
Detector Electronics in cryostat	23.7						23.7		23.7	23.7	23.7	23.7	23.7	23.7	23.7		
Cryostat Fill - GAr transfer / recondense					164.40												
Number of condensers in operation	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Condenser Load					210.2	45.8	62.8	28.7	62.8	62.8	62.8	62.8	62.8	62.8	62.8	28.7	
Recondenser Load, 3rd Cryostat																	
Cryostat Heat Ingress	28.8								28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	
With 2 Recirculation Pumps	6.7										6.7	6.7	6.7	6.7	6.7		
With 4 Recirculation Pumps	13.4								13.4	13.4							
Piping and Purification vessel Heat ingress	3.7								3.7	3.7	3.7	3.7	3.7	3.7	3.7		
Detector Electronics in cryostat	23.7										23.7	23.7	23.7	23.7	23.7		
Cryostat Fill - GAr transfer / recondense									192.50								
Number of condensers in operation									3	1	1	1	1	1	1	1	
Condenser Load									238.4	45.9	62.9	62.9	62.9	62.9	62.9	28.8	
Recondenser Load, 4th Cryostat																	
Cryostat Heat Ingress	28.8											28.8	28.8		28.8		
With 2 Recirculation Pumps	6.7													6.7			
With 4 Recirculation Pumps	13.4											13.4	13.4				
Piping and Purification vessel Heat ingress	3.7											3.7	3.7		3.7		
Detector Electronics in cryostat	23.7														23.7		
Cryostat Fill - GAr transfer / recondense												129.60					
Number of condensers in operation												3	1	1	1	1	
Condenser Load												175.5	45.9	62.9	62.9	28.8	
Caern DM desorb heat ingress (1 kW/each)	1	18	18	18	18	18	18		24	24	24	24	24	24	24		
Refrigeration Needed		291.0	63.8	80.8	291.0	126.6	143.6	57.4	388.0	195.5	212.5	388.0	258.4	275.4	115.0		
Refrigeration Plants in Operation		3	1	1	3	2	2	0	4	3	3	4	3	3	0		
Total Refrigeration Capacity Available		291	97	97	291	194	194		388	291	291	388	291	291			
Required Duty per plant	97	97	78	81	97	78	78		97	78	78	97	86	92			
Electric trim heater load		0.0	14.2	0.0	0.0	29.4	12.4		0.0	38.5	21.5	0.0	0.0	0.0			
Total Refrigeration Load		291	78	80.8	291	156	156	0	388	234	234	388	258.4	275.4	0		
UAr mass in cryostat		1710000			1710000				1710000			1710000				kg	
Fill Time using available cooling above		5712			7895				6742			10014				hr	
(units listed on right side of table)		238.0			329.0				281.0			417.0				days	
		7.8			10.8				9.2			13.7				weeks	
																months	

1st

2nd

3rd

4th

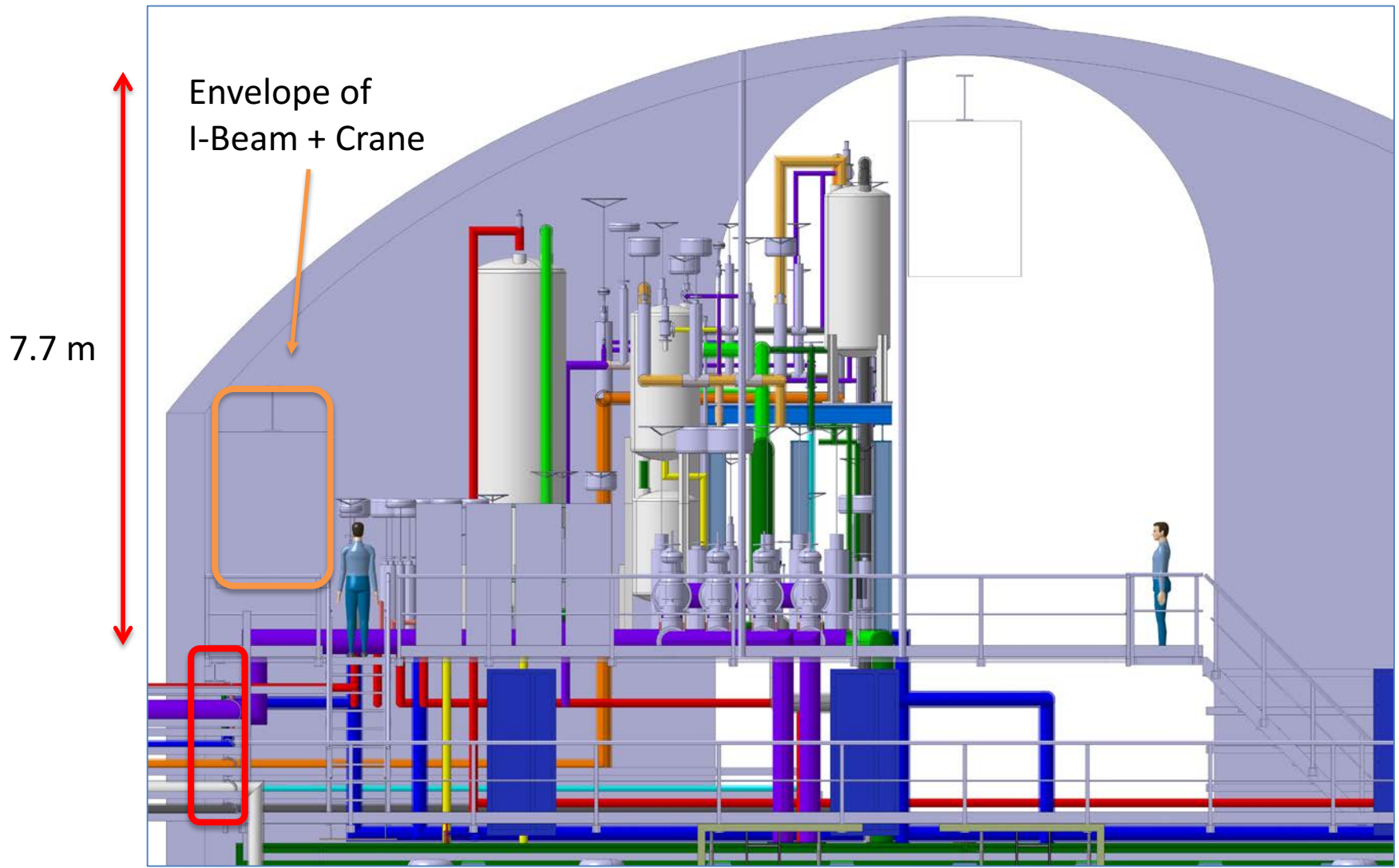
Scenario 1	Cryostat 1 Cool&Fill	Scenario 2	Cryostat 1 Purification	Scenario 3	Cryostat 1 Maintain pur.
	Cryostat 2 NA		Cryostat 2 NA		Cryostat 2 NA
	Cryostat 3 NA		Cryostat 3 NA		Cryostat 3 NA
	Cryostat 4 NA		Cryostat 4 NA		Cryostat 4 NA
Scenario 4	Cryostat 1 Maintain pur.	Scenario 5	Cryostat 1 Maintain pur.	Scenario 6	Cryostat 1 Maintain pur.
	Cryostat 2 Cool&Fill		Cryostat 2 Purification		Cryostat 2 Maintain pur.
	Cryostat 3 NA		Cryostat 3 NA		Cryostat 3 NA
	Cryostat 4 NA		Cryostat 4 NA		Cryostat 4 NA
Scenario 7	Cryostat 1 invent. protection	Scenario A	Cryostat 1 Maintain pur.	Scenario B	Cryostat 1 Maintain pur.
	Cryostat 2 invent. protection		Cryostat 2 Maintain pur.		Cryostat 2 Maintain pur.
	Cryostat 3 NA		Cryostat 3 Cool&Fill		Cryostat 3 Purification
	Cryostat 4 NA		Cryostat 4 NA		Cryostat 4 NA
Scenario C	Cryostat 1 Maintain pur.	Scenario D	Cryostat 1 Maintain pur.	Scenario E	Cryostat 1 Maintain pur.
	Cryostat 2 Maintain pur.		Cryostat 2 Maintain pur.		Cryostat 2 Maintain pur.
	Cryostat 3 Maintain pur.		Cryostat 3 Maintain pur.		Cryostat 3 Maintain pur.
	Cryostat 4 NA		Cryostat 4 Cool&Fill		Cryostat 4 Purification
Scenario F	Cryostat 1 Maintain pur.	Scenario G	Cryostat 1 invent. protection		
	Cryostat 2 Maintain pur.		Cryostat 2 invent. protection		
	Cryostat 3 Maintain pur.		Cryostat 3 invent. protection		
	Cryostat 4 Maintain pur.		Cryostat 4 invent. protection		

- Purification = Achieve purity.
- Maintenance = Maintain purity.

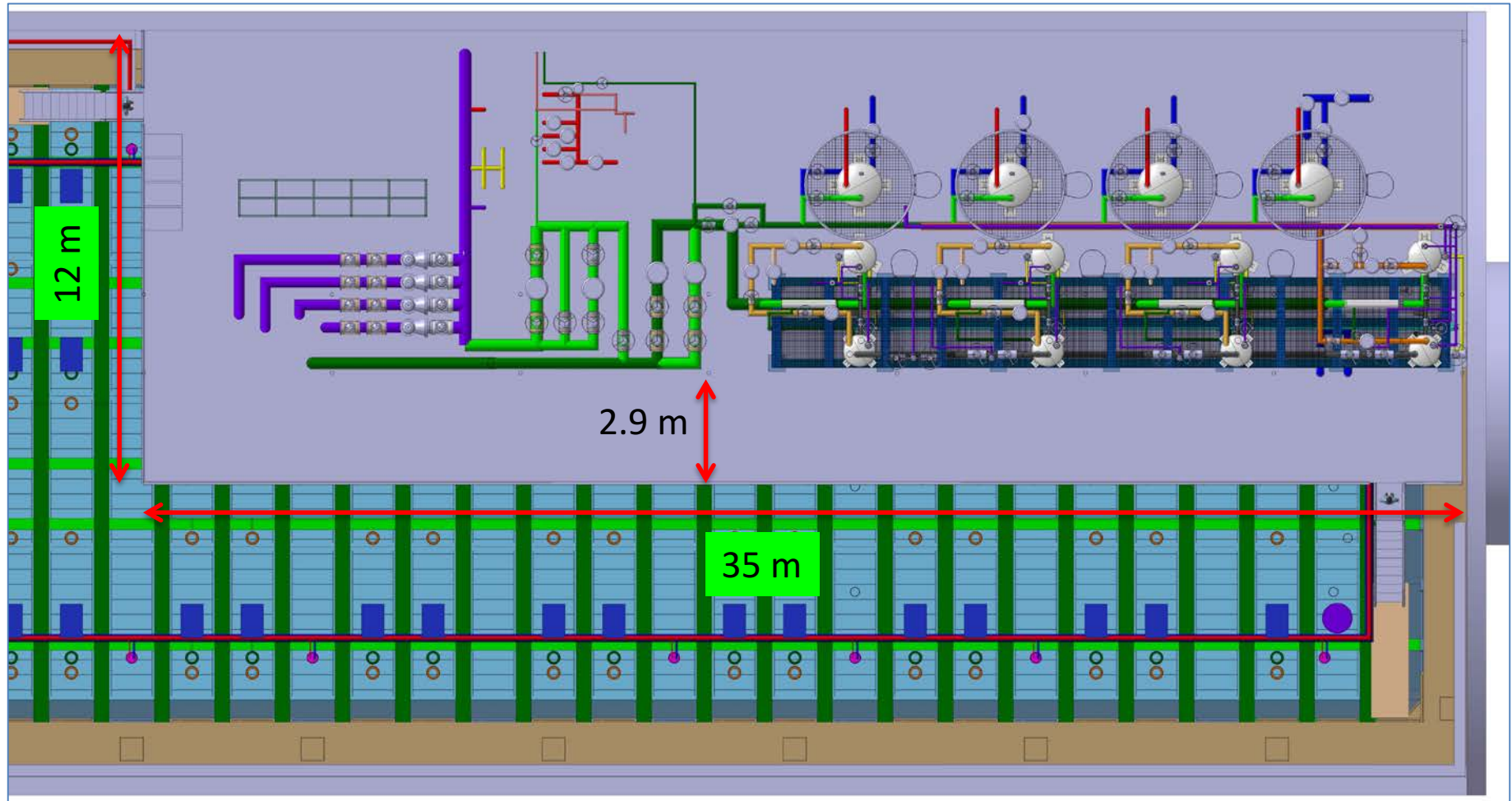
# Internal Piping

- We have modeled the feedthroughs through the roof of the cryostat and are now modeling the internal piping.
- At the bottom of the cryostat there will be:
  - LAr return lines (across the length of the cryostat).
  - GAr purge lines (across the length or the width of the cryostat).
- At the top of the cryostat there will be:
  - Cool down penetrations (currently 10 each side, but it could change). Each one contains:
    - LAr/GAr pipes with nozzles at the end.
    - GAr momentum pipes with nozzles at the end.
  - GAr boil-off.
  - GAr line to PSVs.
  - GAr Make-up.
  - LAr emergency return.

## Side View

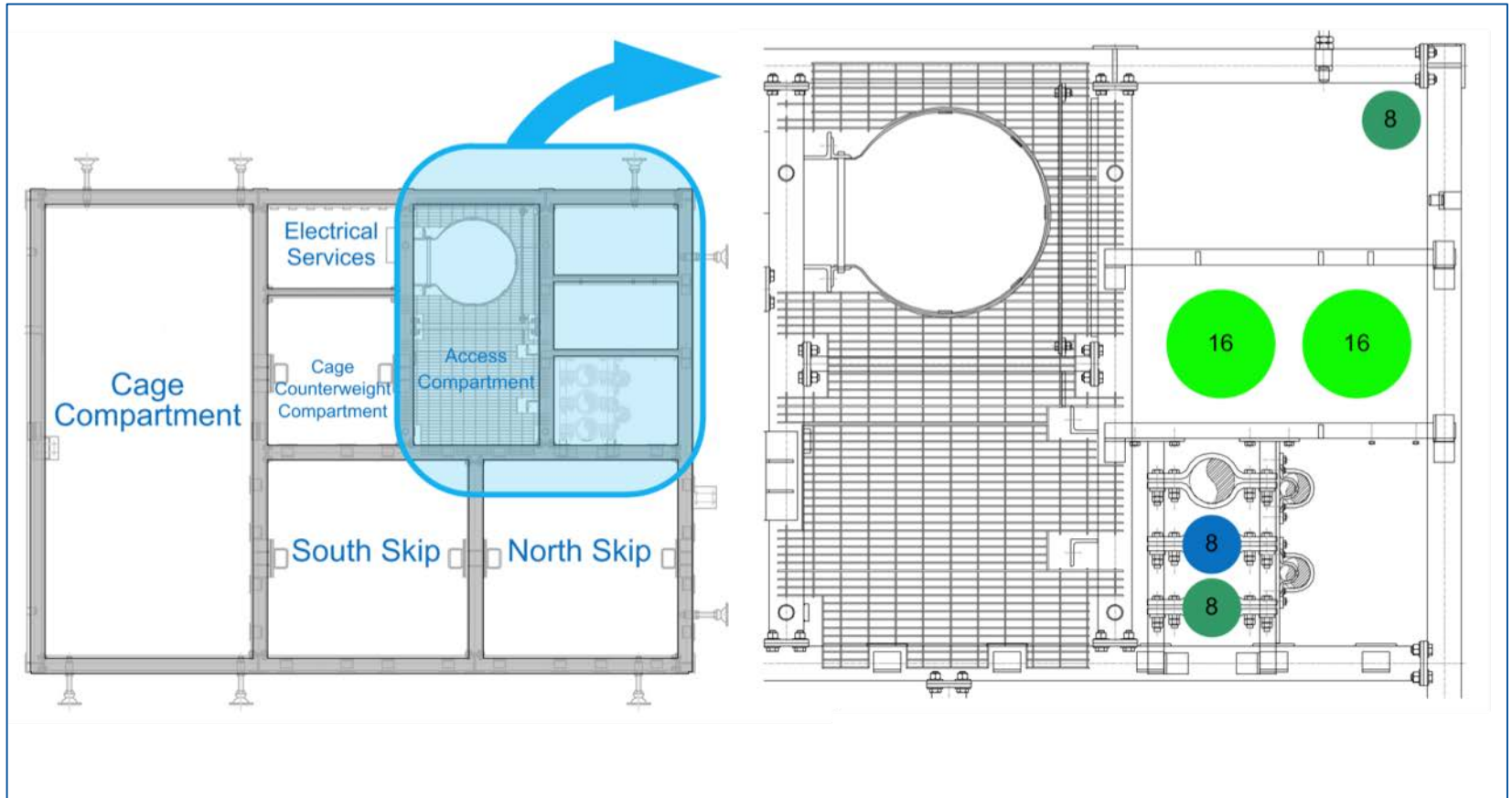


# Top View

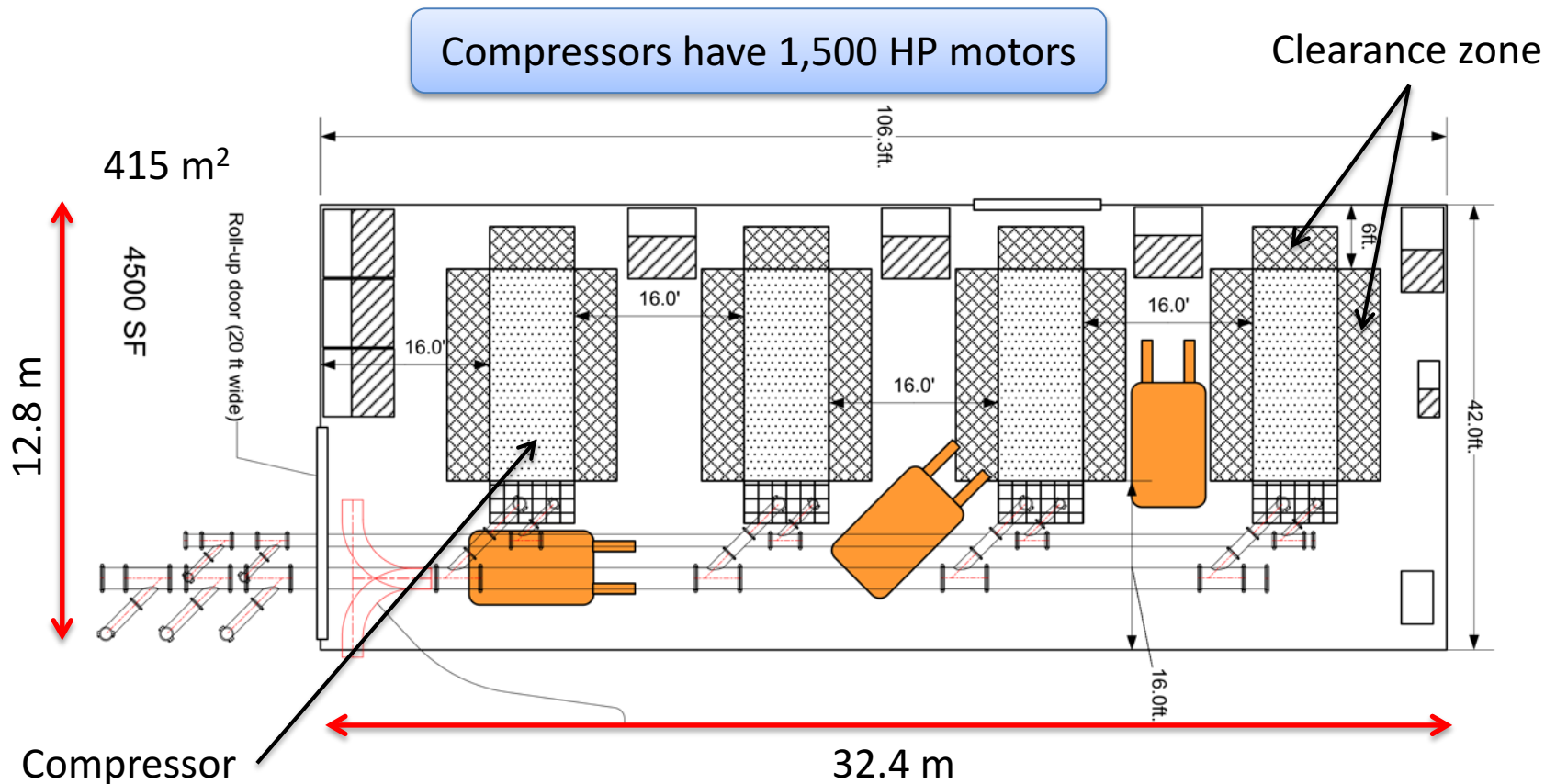




# Infrastructure Cryogenics – Piping in the Shaft



# Infrastructure Cryogenics on Surface – Nitrogen Compressors

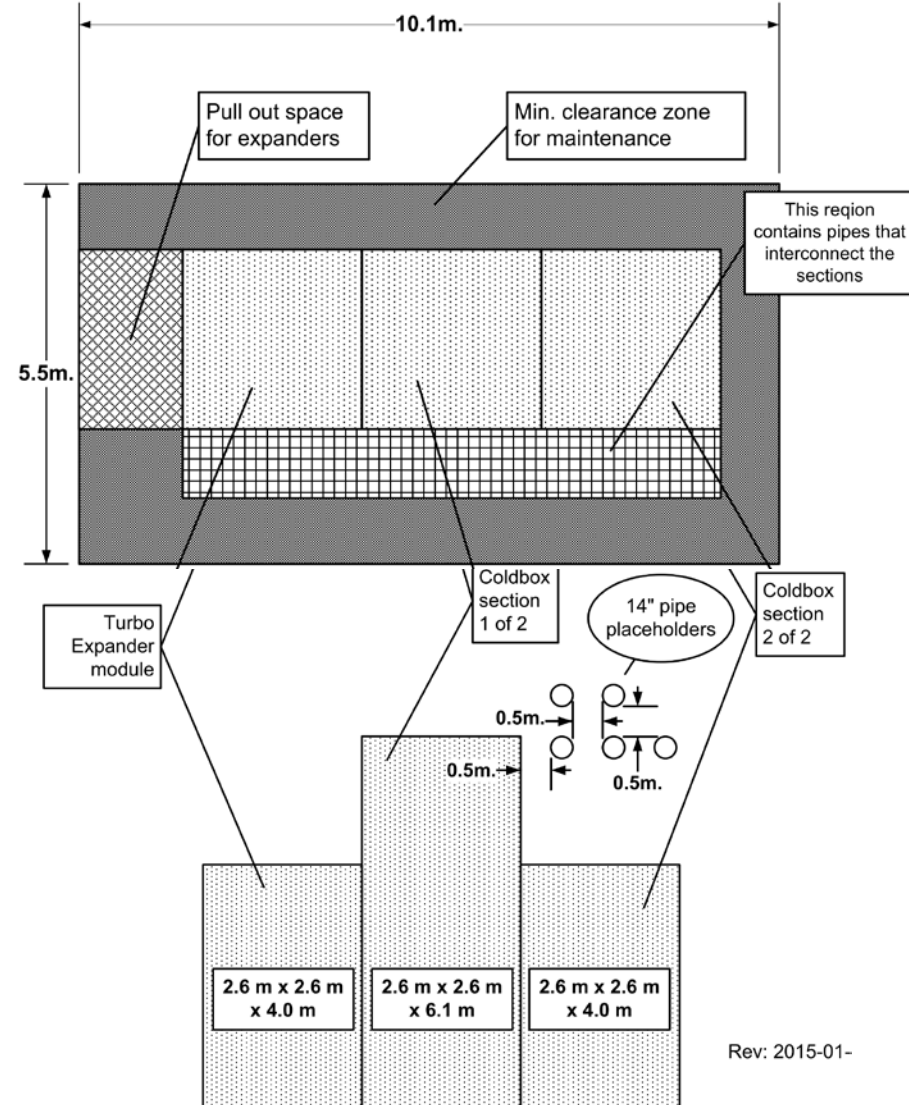
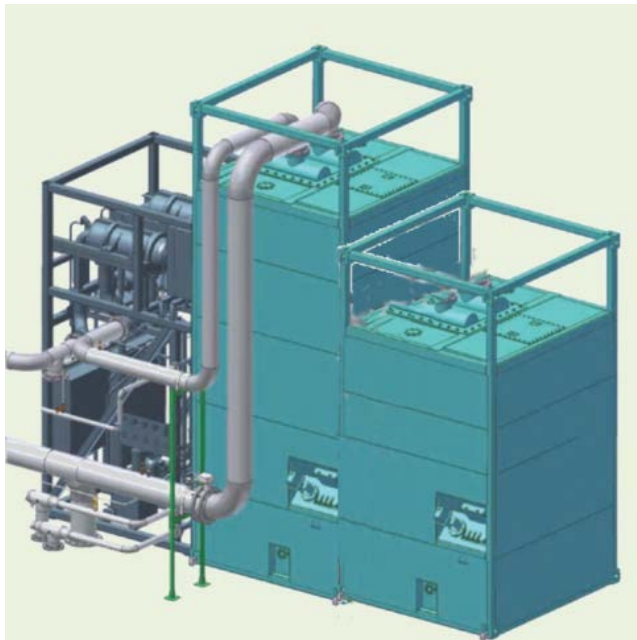


## Heat rejection (4 units):

- 3,600 kW to cooling water.
- 764 kW to room.

# Infrastructure Cryogenics in Central Utility Cavern – Cold boxes

- **Commercial** cold boxes.
- Assembled in cavern.
- **Assembly sections based on transport limits.**
- 3 units for cryostat 1, 2 and 4<sup>th</sup> unit added for cryostat 3, 4.



# Infrastructure Cryogenics

- **Main items:**

- Cryogenics receiving station (surface).
- GN2/GAr piping in the shaft.
- LN2 refrigeration system.
- LN2 storage dewars (underground).
- Interconnecting piping, buffer tanks, valves, instrumentation, etc.

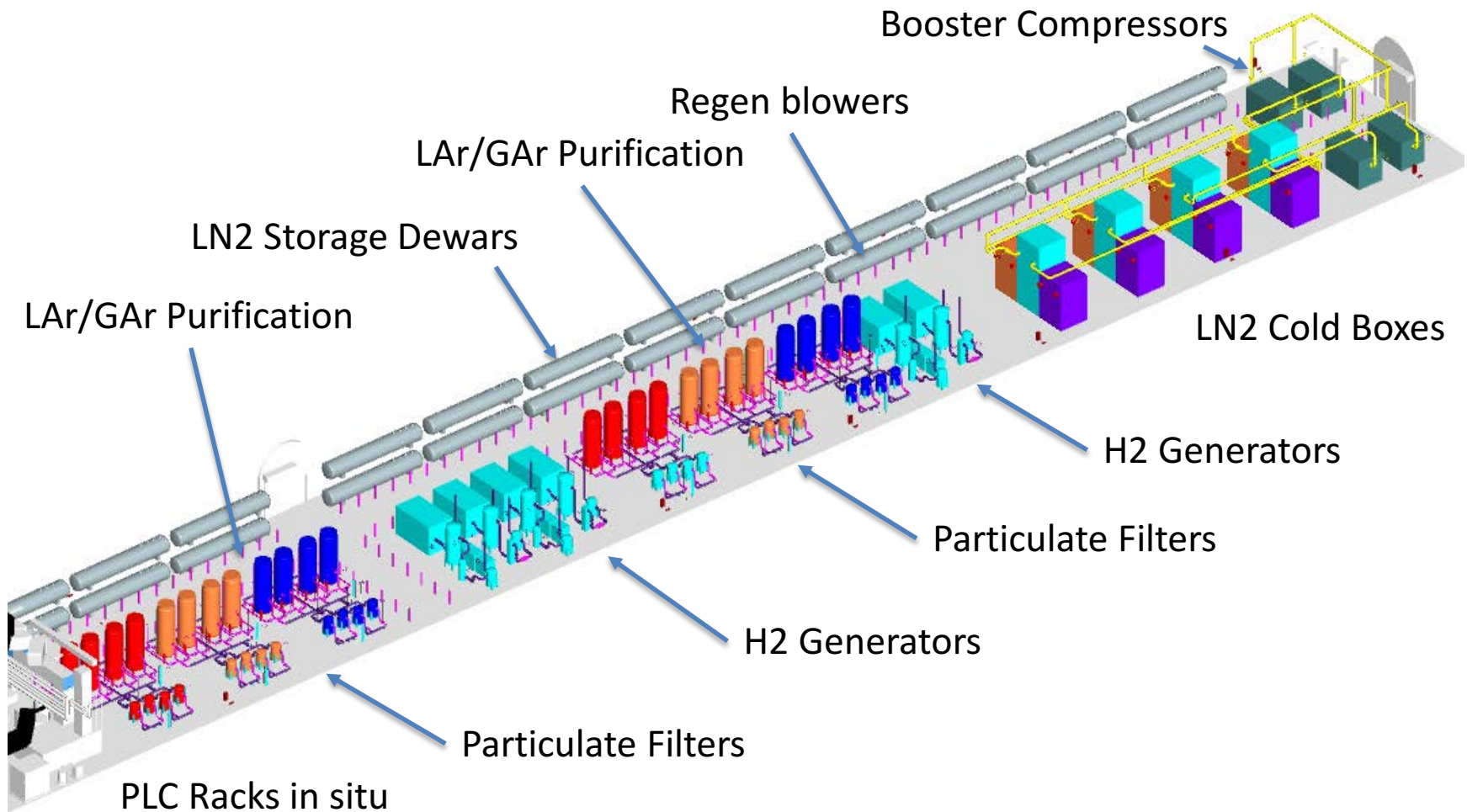
# Proximity Cryogenics

- **Main items:**

- LAr circulation pumps (Detector cavern).
- Condensers for boil-off GAr (Detector cavern).
- LN2/LAr Phase Separators (Detector Cavern).
- GAr/LAr Purification System with regeneration (CUC).
- Interconnecting piping, buffer tanks, valves, instrumentation, etc.

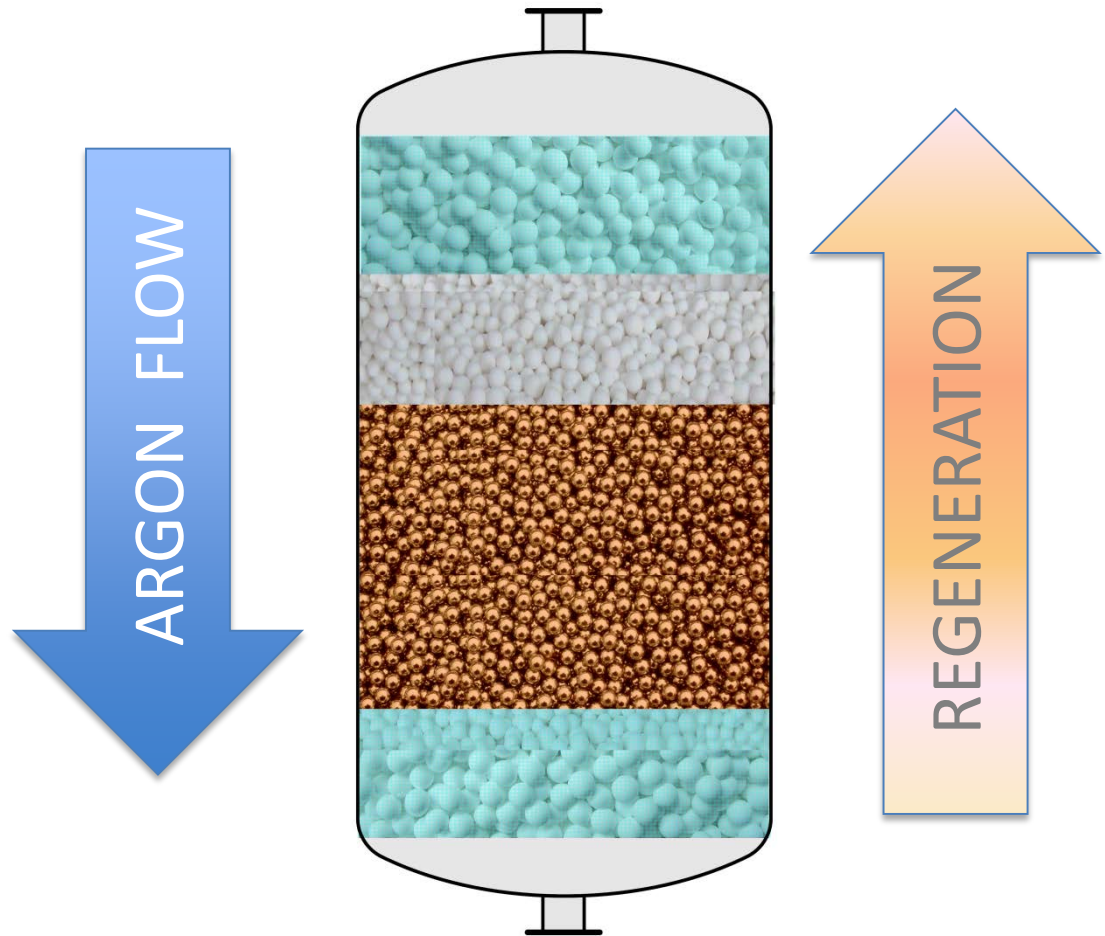


# Central Utility Cavern



# Liquid filtration

- Mole Sieve
  - Water capture
- Copper
  - Oxygen capture



# Strategy

- We exploit the **large expertise** existing at CERN and Fermilab (PAB, LAPD, 35 ton, MicroBooNE, ATLAS, WA105 1x1x3), but also in the LN2/LNG industry.
- We use **commercial items** to the extent possible (e.g. LN2 refrigeration, LAr circulation pumps).
- We have built our **own** process simulation **models** using COCO-COFE, for mass and energy balance.