Status of the LBNF Cryogenic System

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Outline

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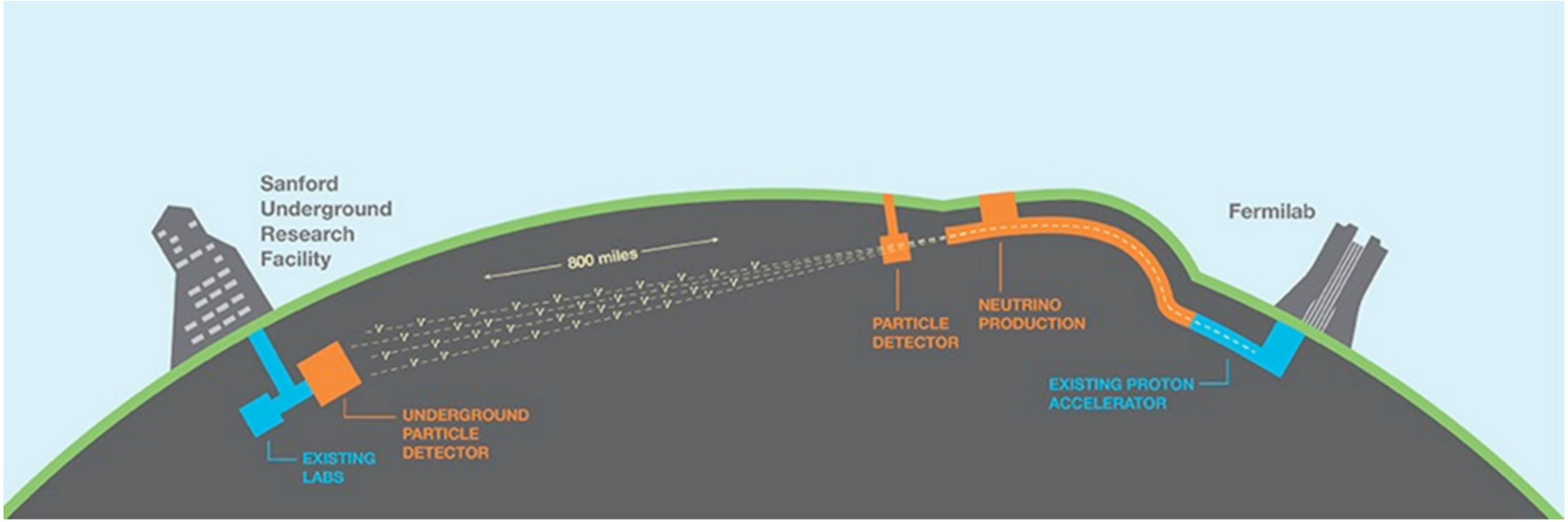
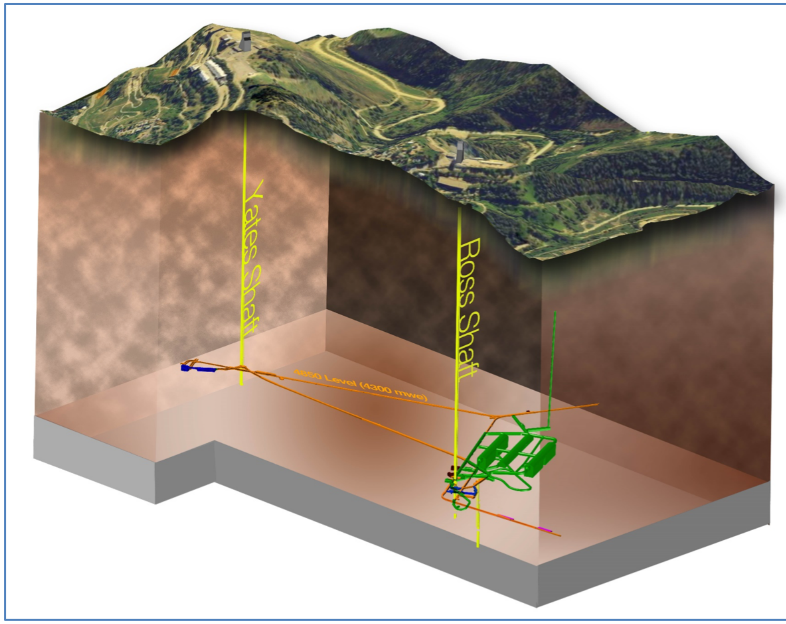
- Scope and Strategy.
- Modes of Operations.
- Requirements.
- Cryostat.
- Cryogenic Systems.
- LAr Procurement.
- Schedule.
- Summary.

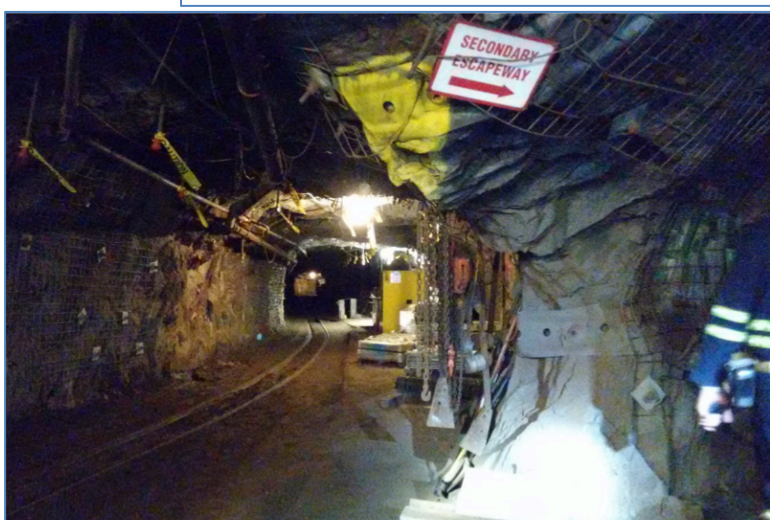
Intro: The LBNF/DUNE Project

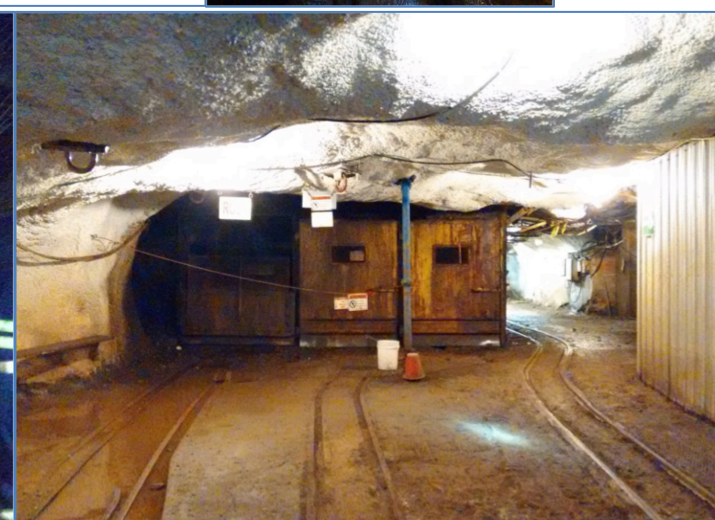
- The **L**ong-**B**aseline **N**eutrino **F**acility is the **infrastructure** necessary to send a powerful beam of neutrinos 800 miles through the earth, and measure them deep underground at South Dakota's Sanford Underground Research Facility (SURF). LBNF supports DUNE.
- The **D**eep **U**nderground **N**eutrino **E**xperiment 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.



Access Conditions at SURF







Cryogenics Infrastructure Scope and Strategy

- **Cryogenics Infrastructure** to support four 17-kton LAr mass detectors (~70 ktons 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 1st 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 are to be identified.
- **LAr procurement** of 70 ktons. 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 (O2, N2, H2O) to ppm level.
- **GAr Circulation:** GAr is circulated in a closed loop and purified through the GAr purification system. Reduces O2 and H2O 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.

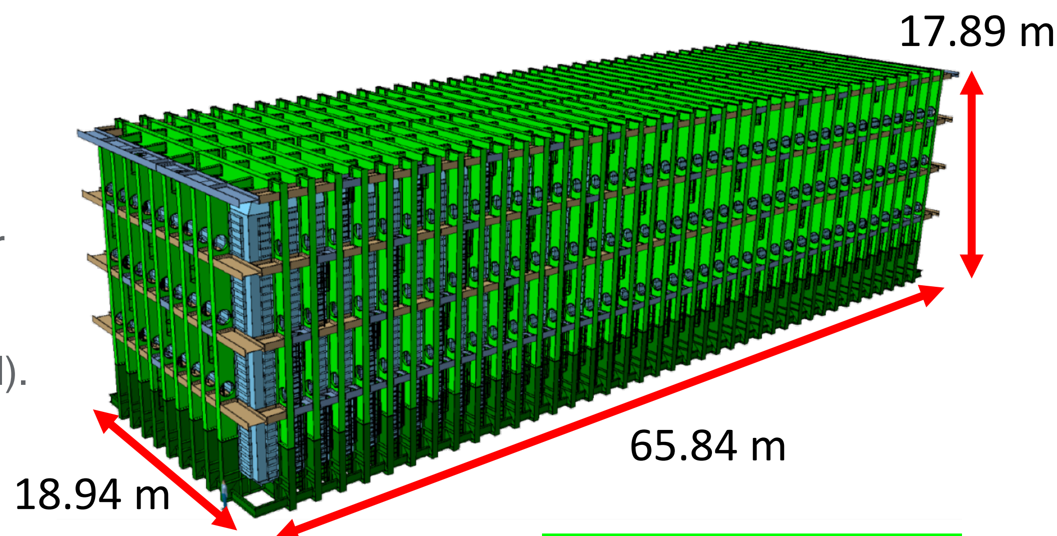
Selection of Design Parameters

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

Design Parameter	Value (per cryostat)
GAr Flow rate during piston purge	254 m^3/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.



4 x 17,100 tons LAr

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

Cryogenics Systems

- **Infrastructure/External Cryogenics (INF/EXT)**:
  - 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.

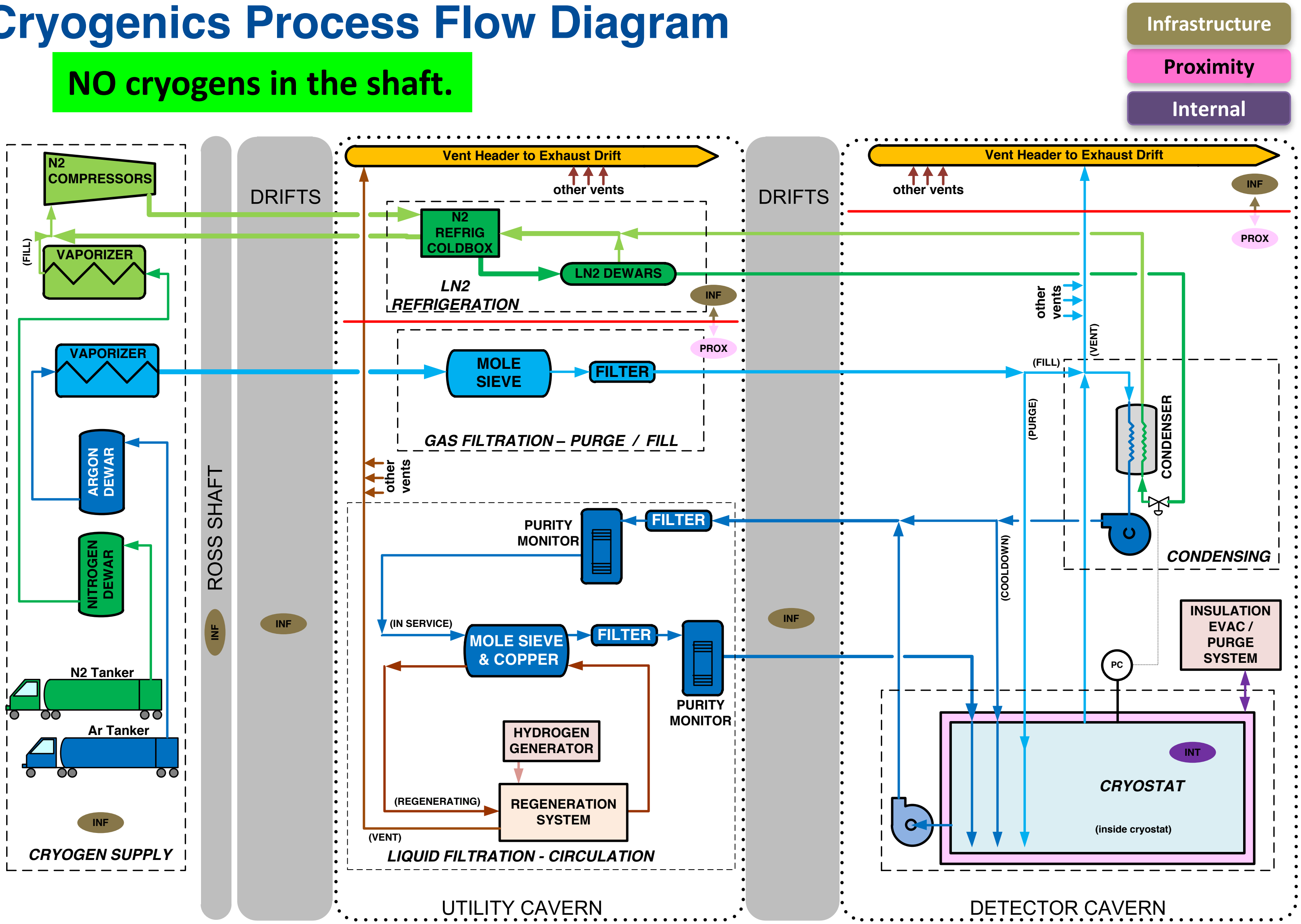
Non-DOE

- **Internal Cryogenics (INT):**
  - Inside the cryostat.
  - Cryostat purge, cool down, fill.
  - GAr/LAr distribution.

DUNE

Cryogenics Process Flow Diagram

NO cryogens in the shaft.

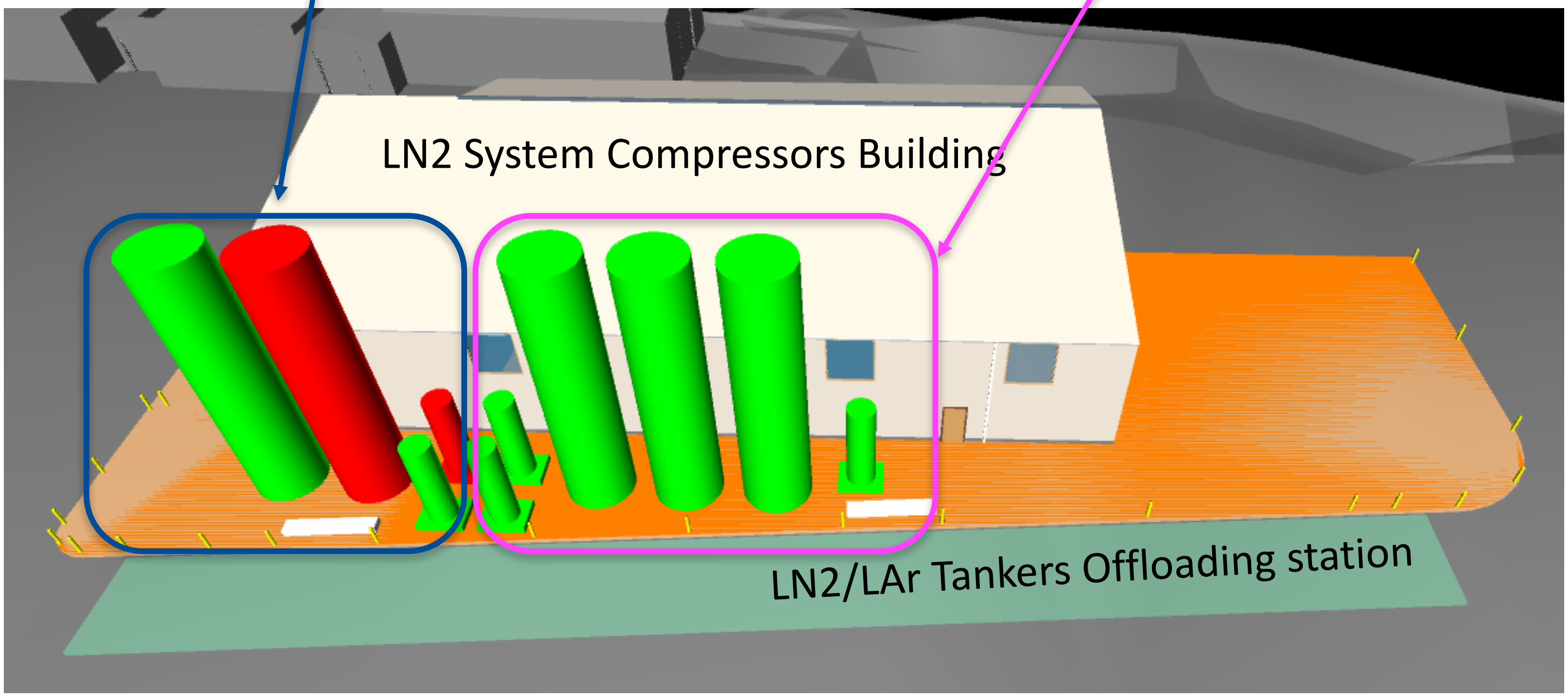


Infrastructure/External Cryogenics

External Cryogenics – Receiving Facilities

Current Cryogens Storage and vaporizers: 2x50 m^3

Proposed additional temporary LAr Storage and Vaporizers (LAr fill only): 3x50 m^3



LN2 Storage Tank and Vaporizer (1x50 m^3)

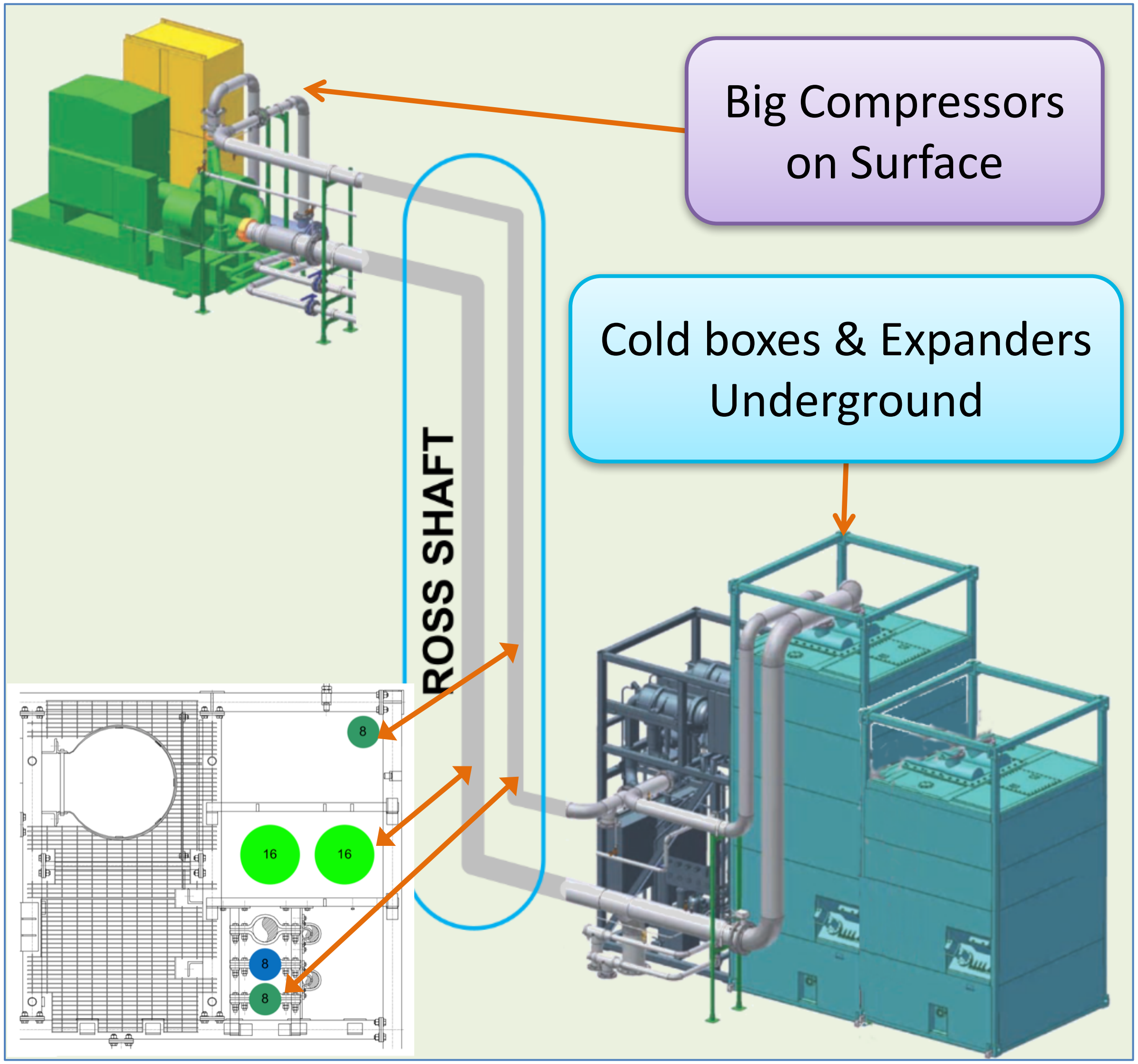
LAr Storage Tanks and Vaporizers (4x50m^3)

280 tons of LAr storage

External Cryogenics – LN2 Refrigeration System

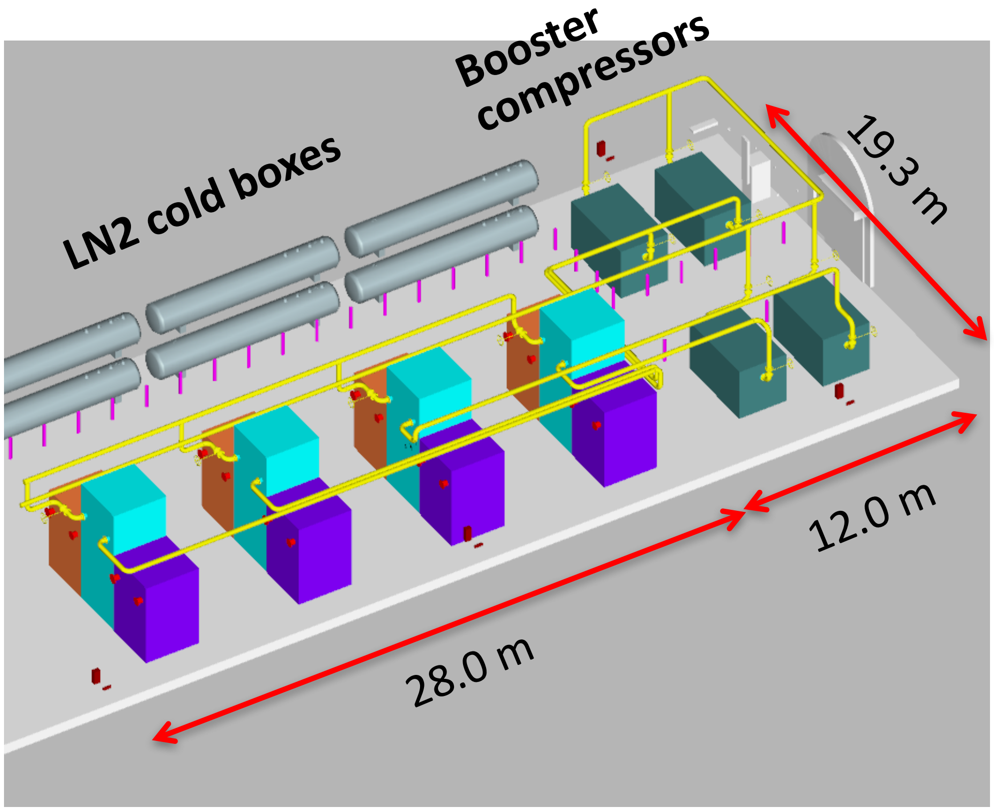
- 4 **Commercial** units:
  - Cold boxes and gas boosters in the cavern.
  - GN2 compressors above ground.
- Units assembled in cavern, based on transport limits.
- 3 units for cryostats 1, 2 and 4th unit added for cryostats 3, 4.
- 4x97 kW units.

- Refrigeration model validated with COCO-COFE simulator.



External 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.



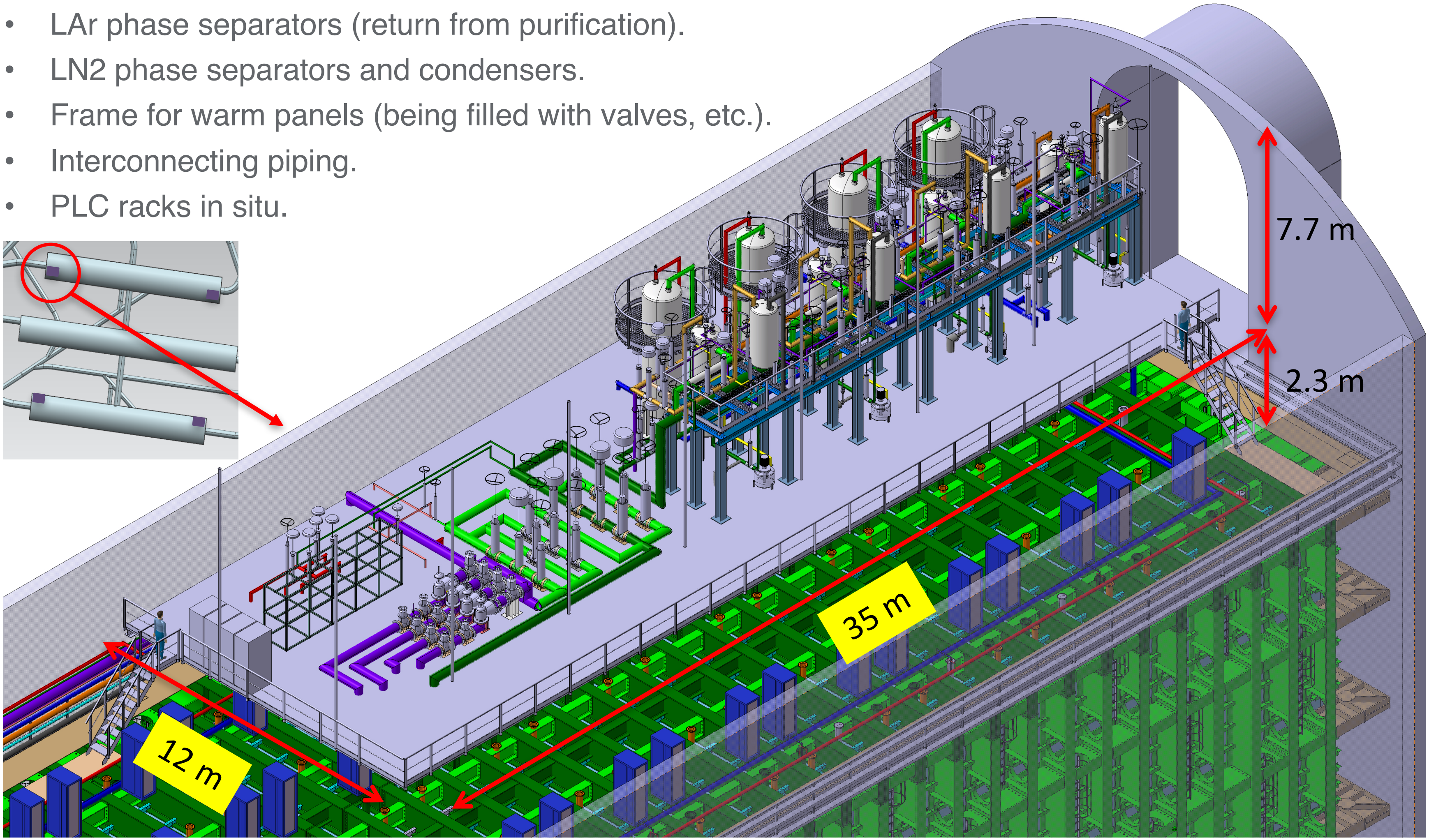
LN2 Refrigeration System – Procurement Strategy

- 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.
- Submitted Acquisition Plan (AP) for the whole LN2 system to DOE Fermi Site Office on Jan 30, 2017. ✓
- 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

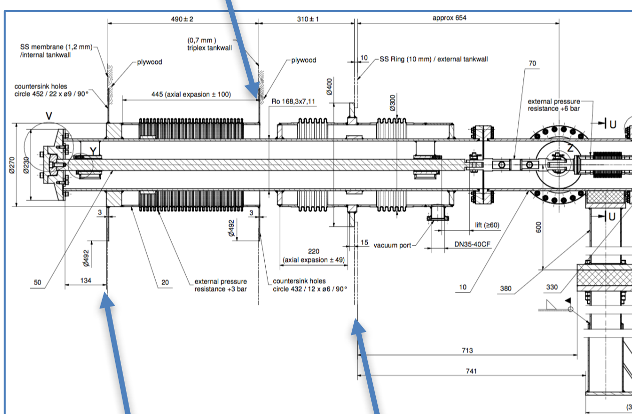
- Cryostat Pressure Safety Valves (PSVs), piping and lockout valves.
- Small LAr buffer tanks (for condenser pumps) and condenser LAr pumps.
- LAr phase separators (return from purification).
- LN2 phase separators and condensers.
- Frame for warm panels (being filled with valves, etc.).
- Interconnecting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



Proximity Cryogenics in Detector's Cavern – LAr Pumps

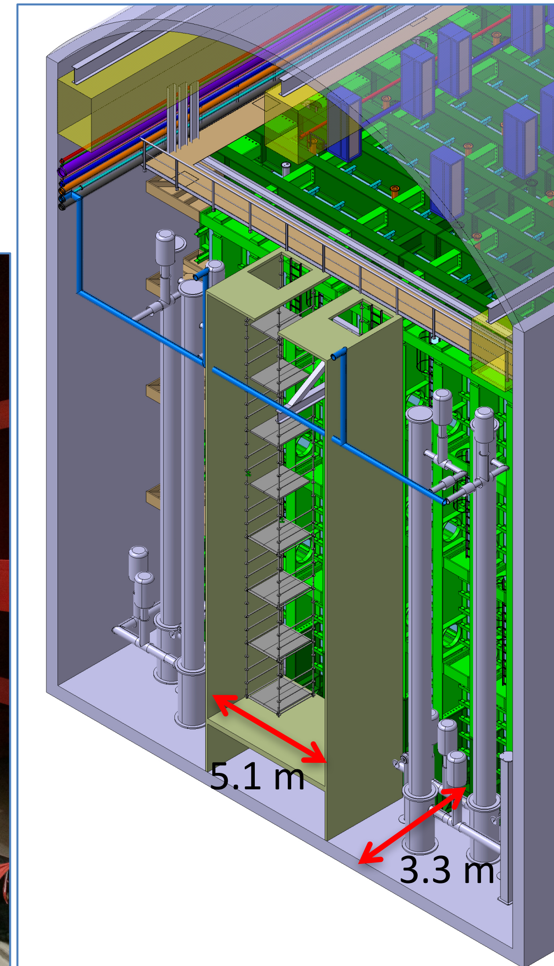
- LAr pumps.
- Concept of Clean Room (CR) for detector installation.
- Inline safety valves (one per penetration).

Secondary Barrier

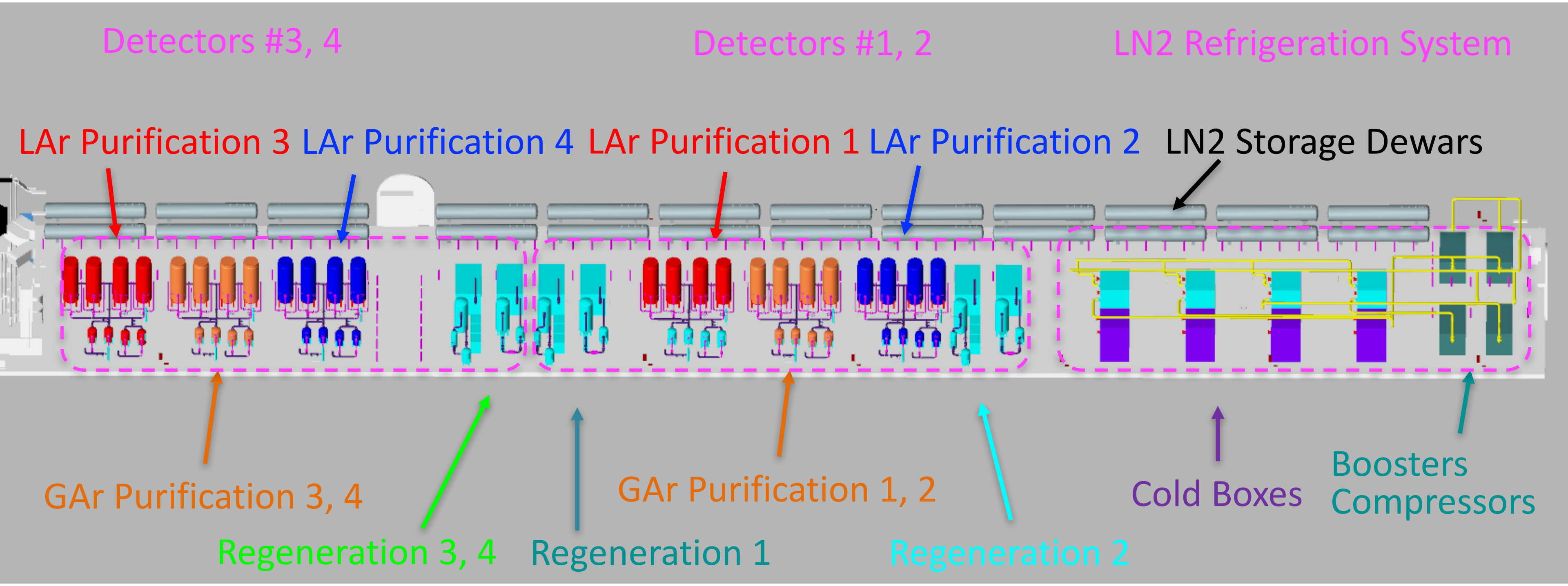


Cryostat Vapor Barrier

Cryostat Membrane



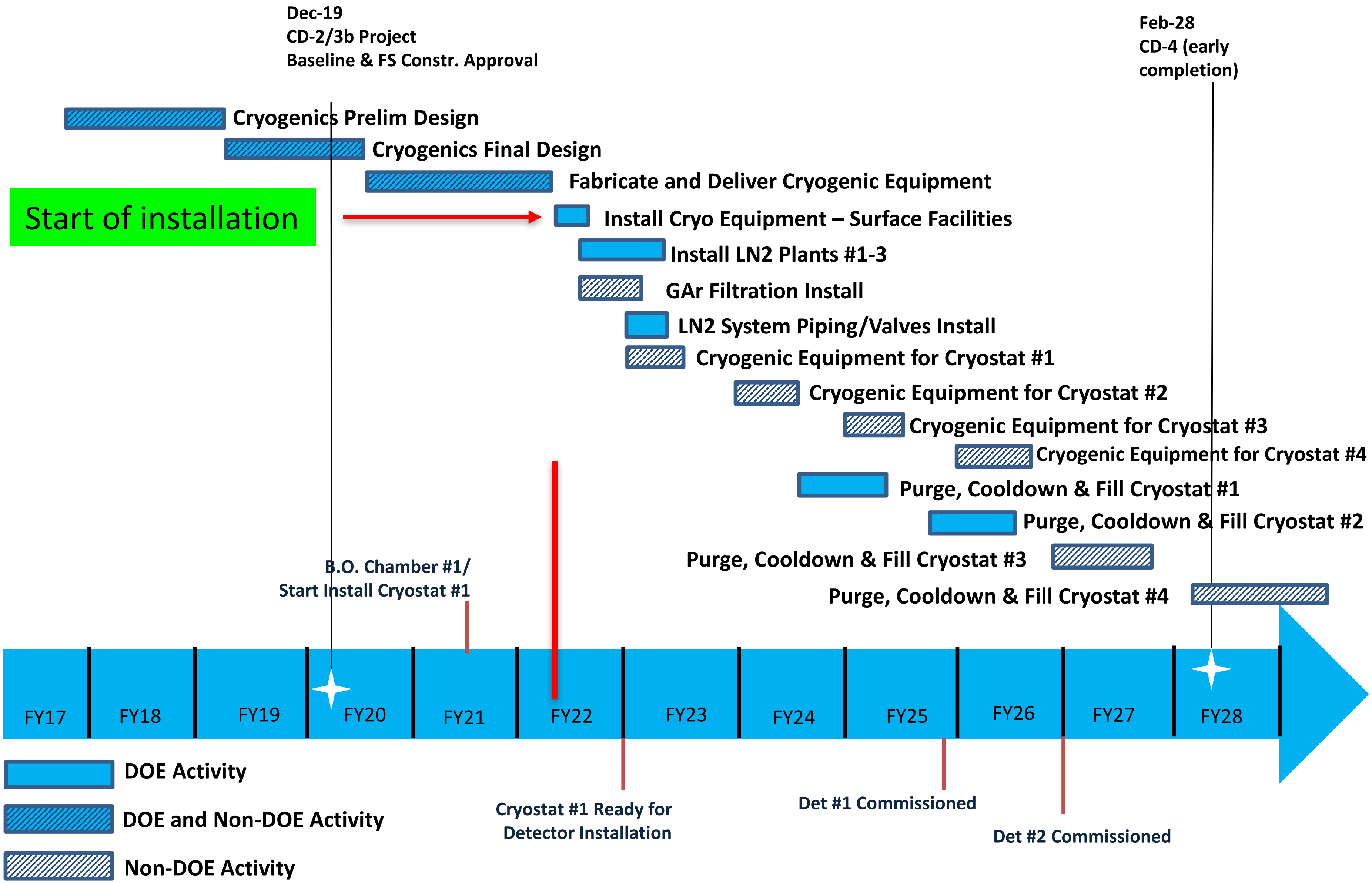
Proximity Cryogenics in the CUC – Layout



LAr Procurement

- Contracted with a consultant to develop LAr procurement strategy and refine cost and schedule estimates.
- 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.
  - Improvement with respect to a previous analysis when it was likely coming from almost a 1,000 miles.
  - New plants capable of producing LAr have been put in service since then reducing the average 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.

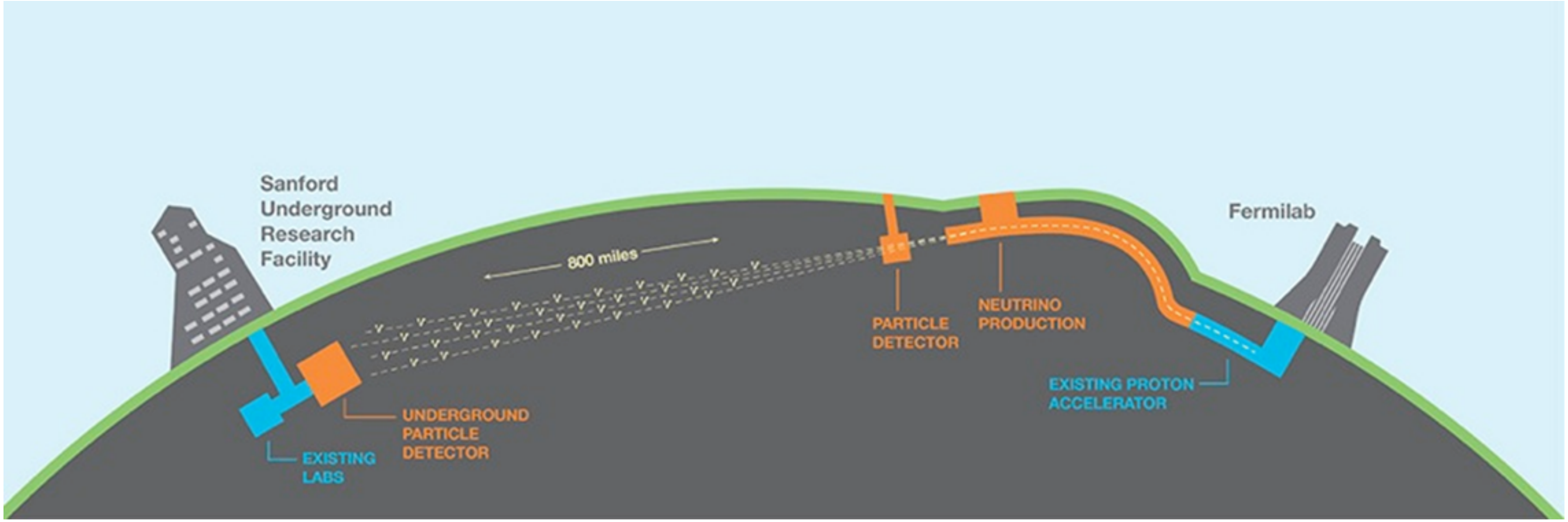
Cryogenics Schedule Summary Overview



Summary and Next Steps

- Advancing the **design** of all parts focusing on **requirements** and **interfaces**, in particular between Cryostat, Cryogenics and Conventional Facilities.
- 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**. Submitted documentation to 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.
- Planning to start installation at SURF in **2022**.

Thanks



Sanford
Underground
Research
Facility
800 miles
PARTICLE
DETECTOR
NEUTRINO
PRODUCTION
Fermilab
EXISTING PROTON
ACCELERATOR
UNDERGROUND
PARTICLE
DETECTOR
EXISTING
LABS

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	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4			10.4	10.4	10.4	10.4		10.4	10.4	10.4	10.4	10.4	10.4	
With 4 Recirculation Pumps	20.7	20.7	20.7												
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	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	
Cryostat Fill - GAr transfer / recondense		219.78													
Number of condensers in operation		4	1	1	1	1	1	1	1	1	1	1	1	1	1
Condenser Load		**273.0**	**53.2**	**66.6**	**66.6**	**66.6**	**66.6**	**28.8**	**66.6**	**66.6**	**66.6**	**66.6**	**66.6**	**66.6**	**28.8**
Recondenser Load, 2nd Cryostat															
Cryostat Heat Ingress	28.8				28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4						10.4		10.4	10.4	10.4	10.4	10.4	10.4	
With 4 Recirculation Pumps	20.7				20.7	20.7									
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	
Detector Electronics in cryostat	23.7						23.7		23.7	23.7	23.7	23.7	23.7	23.7	
Cryostat Fill - GAr transfer / recondense					153.22										
Number of condensers in operation					3	1	1	1	1	1	1	1	1	1	1
Condenser Load					**206.4**	**53.2**	**66.6**	**28.8**	**66.6**	**66.6**	**66.6**	**66.6**	**66.6**	**66.6**	**28.8**
Recondenser Load, 3rd Cryostat															
Cryostat Heat Ingress	28.8								28.8	28.8	28.8	28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4										10.4	10.4	10.4	10.4	
With 4 Recirculation Pumps	20.7								20.7	20.7					
Piping and Purification vessel Heat ingress	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	
Cryostat Fill - GAr transfer / recondense									177.66						
Number of condensers in operation									3	1	1	1	1	1	1
Condenser Load									**230.9**	**53.2**	**66.6**	**66.6**	**66.6**	**66.6**	**28.8**
Recondenser Load, 4th Cryostat															
Cryostat Heat Ingress	28.8											28.8	28.8	28.8	28.8
With 2 Recirculation Pumps	10.4													10.4	
With 4 Recirculation Pumps	20.7											20.7	20.7		
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												111.10			
Number of condensers in operation												2	1	1	1
Condenser Load												**164.3**	**53.2**	**66.6**	**28.8**
Cavern LN dewar heat ingress (1 kW/each)	1	18	18	18	18	18	18		24	24	24	24	24	24	
Refrigeration Needed		291.0	71.2	84.6	291.0	137.8	151.1	57.6	388.0	210.3	223.7	388.0	276.9	290.2	115.2
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	71	85	97	69	76		97	70	75	97	92	97	
Electric trim heater load		0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	
Total Refrigeration Load		**291**	**71.22**	**84.56**	**291**	**137.78**	**151.12**	**0**	**388**	**210.34**	**223.68**	**388**	**276.9**	**290.2**	**0**
LAr mass in cryostat		17165040			17165040				17165040			17165040			kg
Fill Time using available cooling above (units listed on right side of table)		3476			4986				4300			6876			hr
		145.0			208.0				179.0			287.0			days
		20.7			29.7				25.6			40.9			weeks
		4.8			**6.8**				**5.9**			**9.4**			months

Scenario 1: Cryostat 1 Cool&Fill; Cryostat 2 NA; Cryostat 3 NA; Cryostat 4 NA

Scenario 2: Cryostat 1 Purification; Cryostat 2 NA; Cryostat 3 NA; Cryostat 4 NA

Scenario 3: Cryostat 1 Maintain pur.; Cryostat 2 NA; Cryostat 3 NA; Cryostat 4 NA

Scenario 4: Cryostat 1 Maintain pur.; Cryostat 2 Cool&Fill; Cryostat 3 NA; Cryostat 4 NA

Scenario 5: Cryostat 1 Maintain pur.; Cryostat 2 Purification; Cryostat 3 NA; Cryostat 4 NA

Scenario 6: Cryostat 1 Maintain pur.; Cryostat 2 Maintain pur.; Cryostat 3 NA; Cryostat 4 NA

Scenario 7: Cryostat 1 invent. protection; Cryostat 2 invent. protection; Cryostat 3 NA; Cryostat 4 NA

Scenario A: Cryostat 1 Maintain pur.; Cryostat 2 Maintain pur.; Cryostat 3 Cool&Fill; Cryostat 4 NA

Scenario B: Cryostat 1 Maintain pur.; Cryostat 2 Maintain pur.; Cryostat 3 Purification; Cryostat 4 NA

Scenario C: Cryostat 1 Maintain pur.; Cryostat 2 Maintain pur.; Cryostat 3 Maintain pur.; Cryostat 4 NA

Scenario D: Cryostat 1 Maintain pur.; Cryostat 2 Maintain pur.; Cryostat 3 Maintain pur.; Cryostat 4 Cool&Fill

Scenario E: Cryostat 1 Maintain pur.; Cryostat 2 Maintain pur.; Cryostat 3 Maintain pur.; Cryostat 4 Purification

Scenario F: Cryostat 1 Maintain pur.; Cryostat 2 Maintain pur.; Cryostat 3 Maintain pur.; Cryostat 4 Maintain pur.

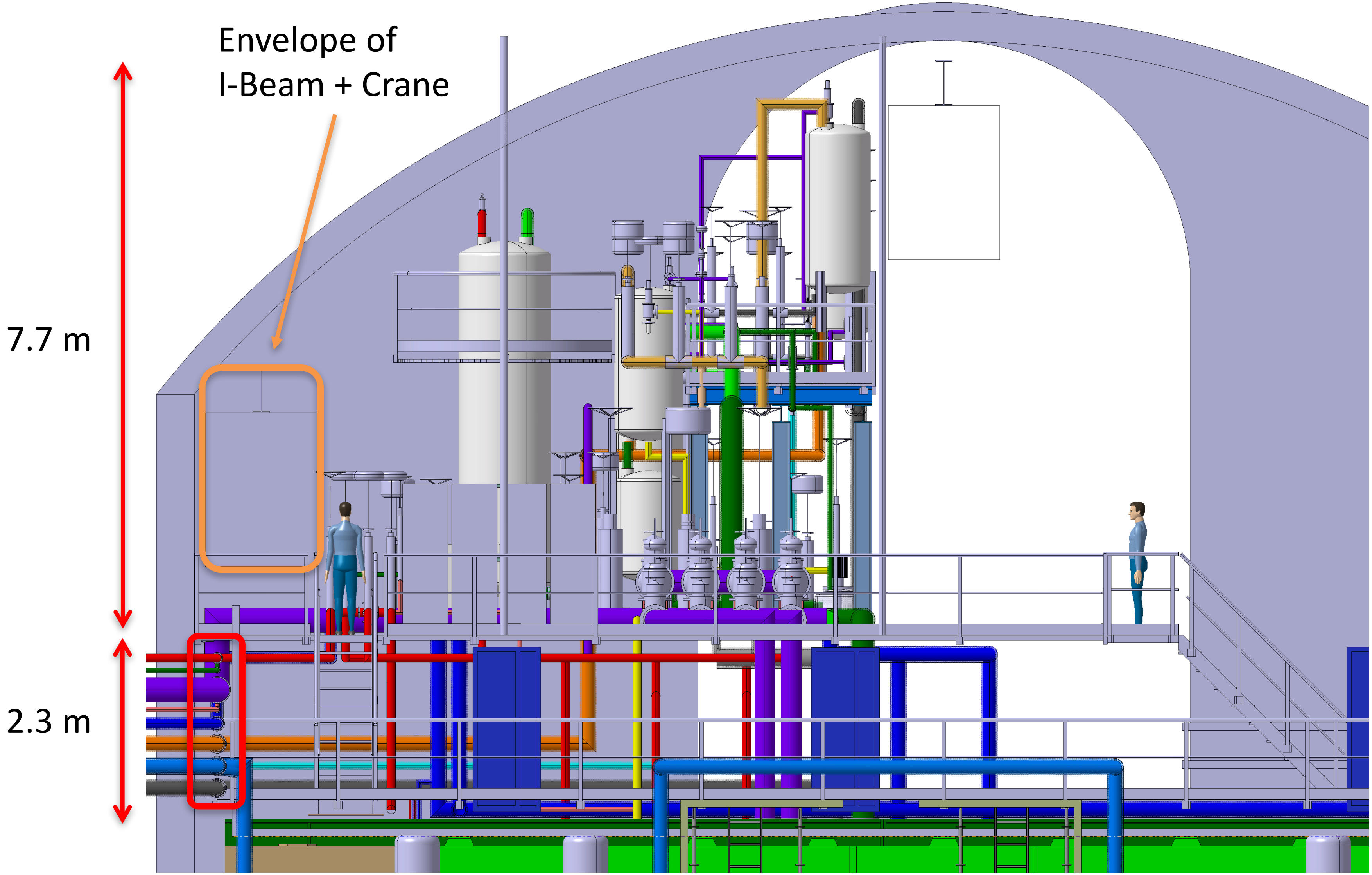
Scenario G: Cryostat 1 invent. protection; Cryostat 2 invent. protection; Cryostat 3 invent. protection; Cryostat 4 invent. protection

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

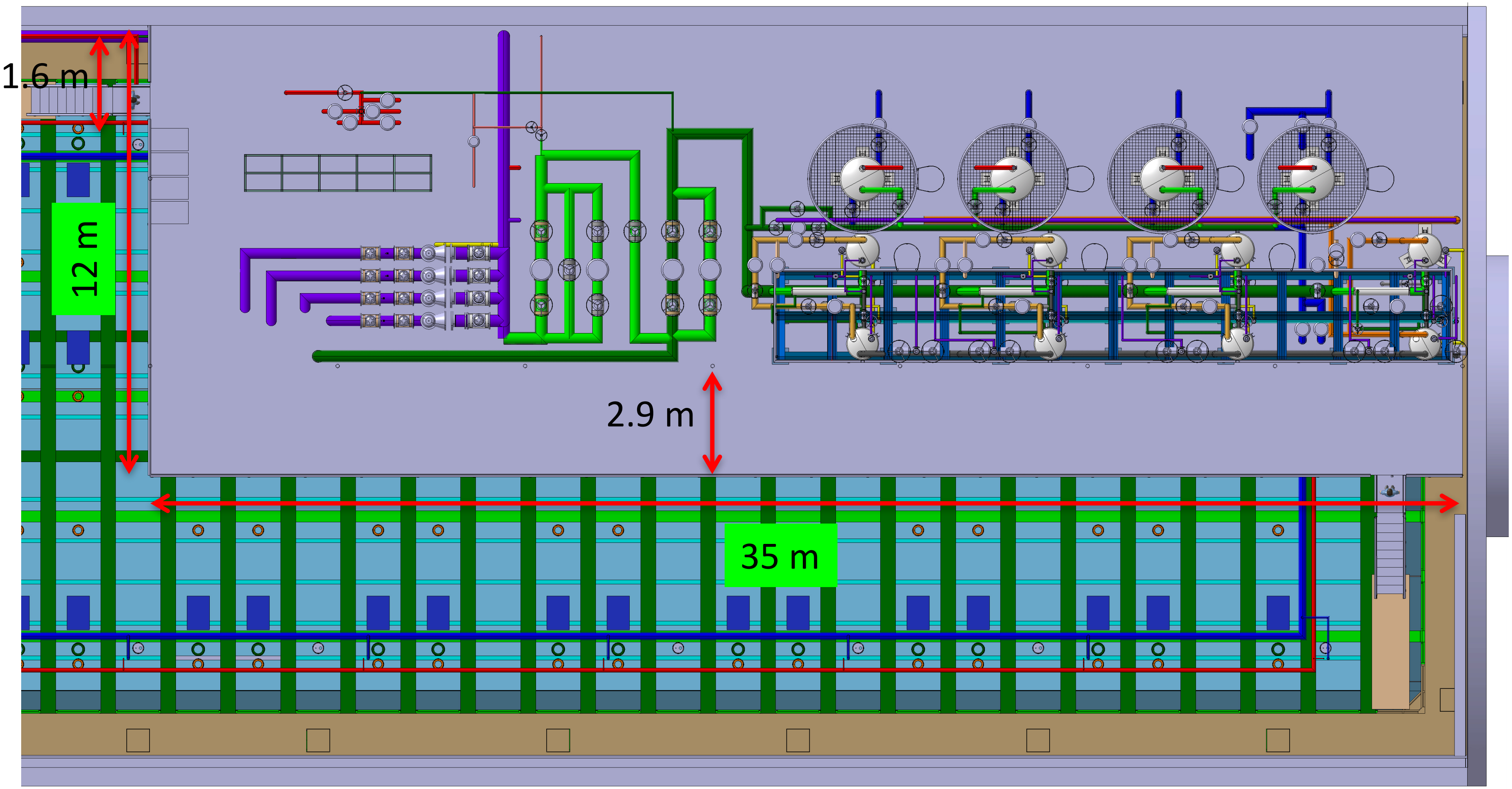
Internal Piping

- We have not modeled the internal piping yet, only the penetrations through the roof of the cryostat.
- 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).
- 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.

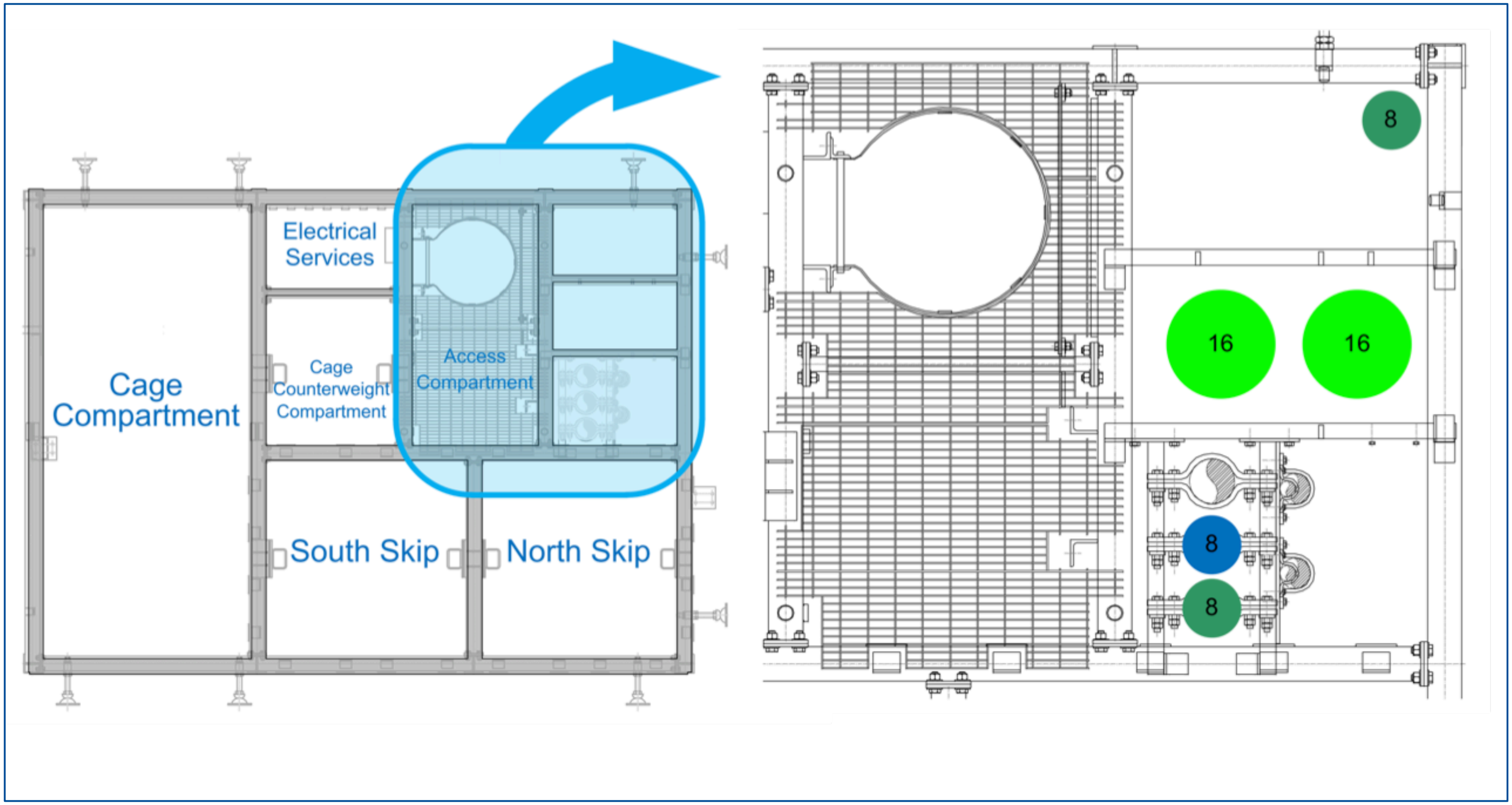
Side View



Top View

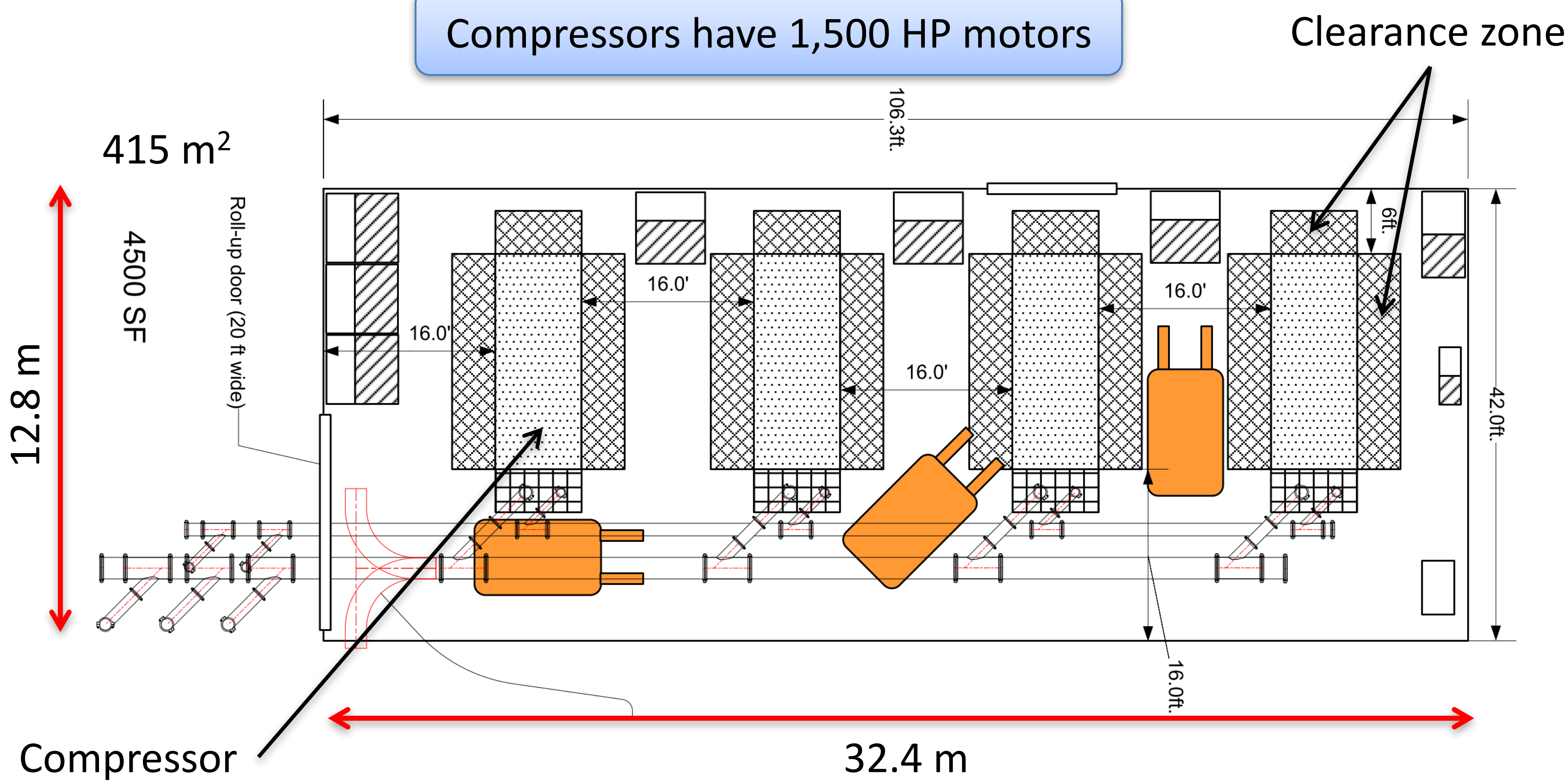


External Cryogenics – Piping in the Shaft



External Cryogenics on Surface – Nitrogen Compressors

Compressors have 1,500 HP motors

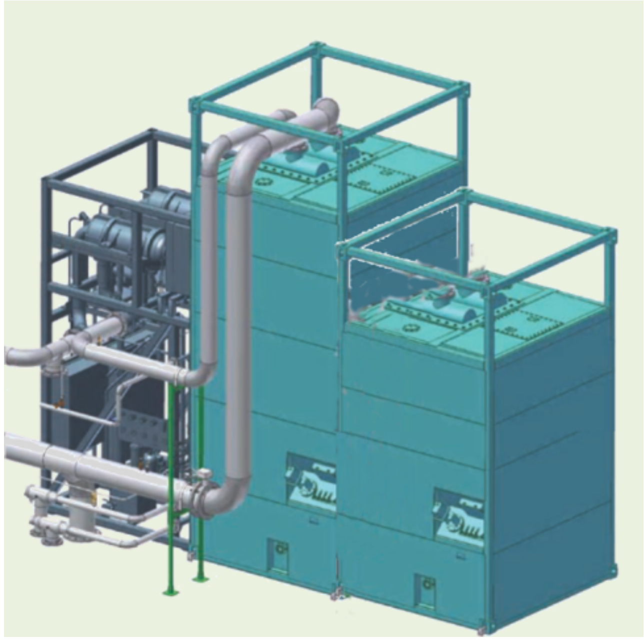


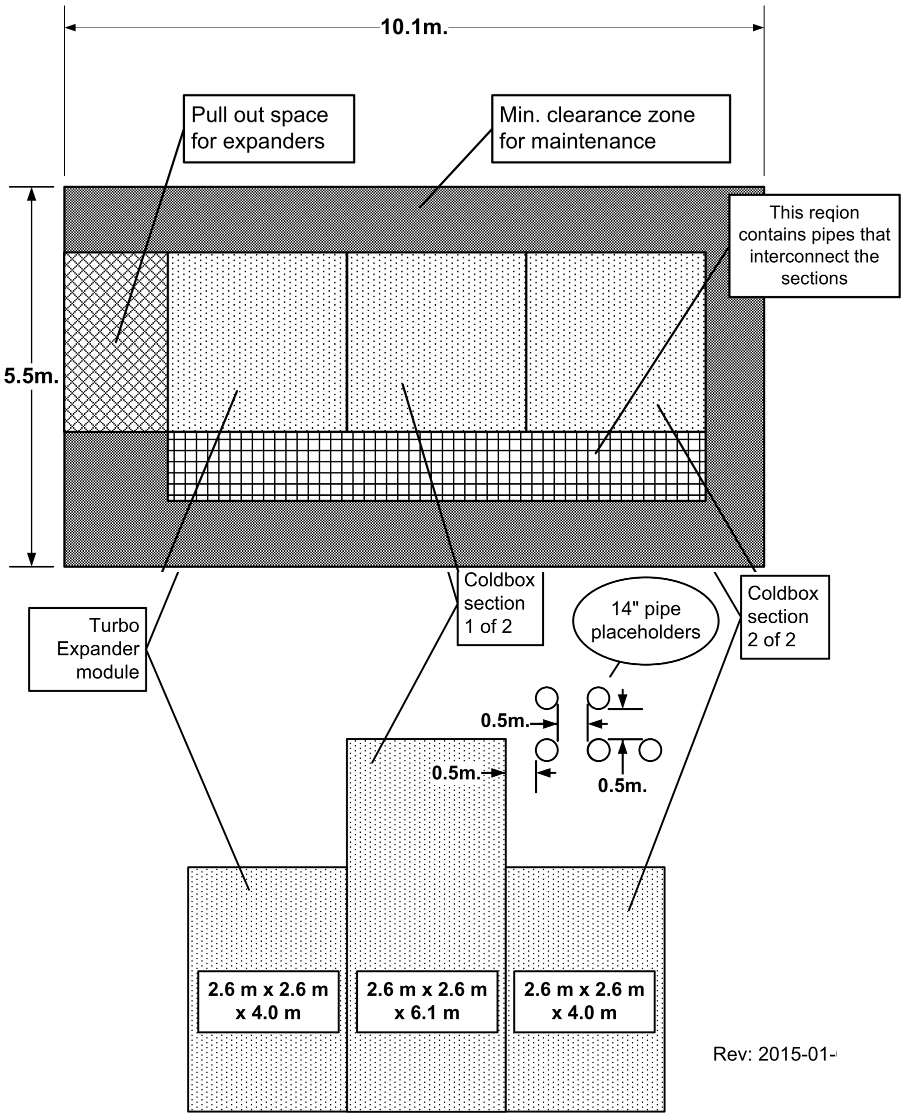
Heat rejection (4 units):

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

External 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 4th unit added for cryostat 3, 4.





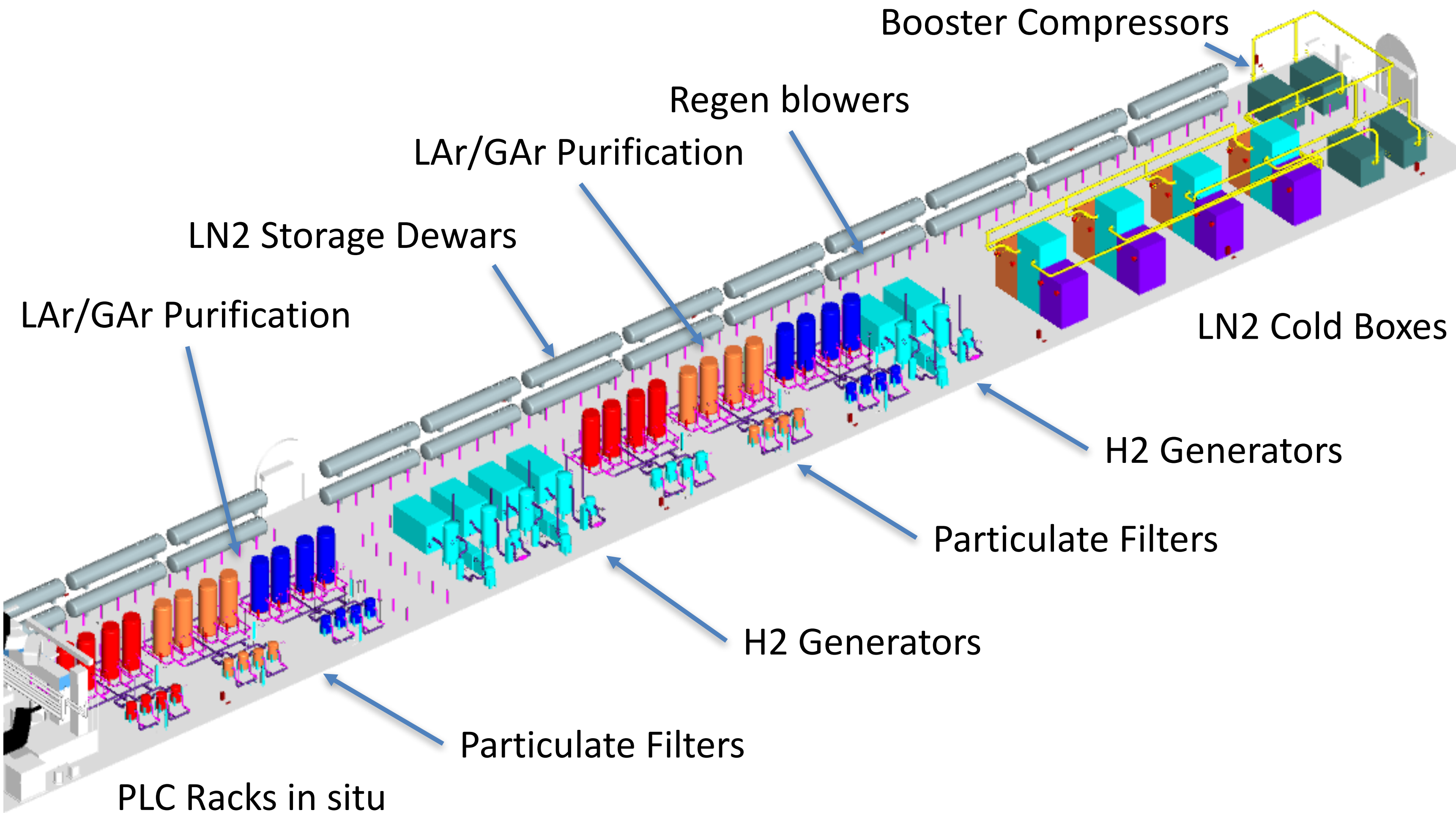
Infrastructure/External Cryogenics

- **Main items:**
  - Cryogens 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.

CUC


Booster Compressors
Regen blowers
LAr/GAr Purification
LN2 Storage Dewars
LAr/GAr Purification
LN2 Cold Boxes
H2 Generators
Particulate Filters
H2 Generators
Particulate Filters
PLC Racks in situ

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.