US CRP Assembly Site Cold Box: Technical Overview

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Overview

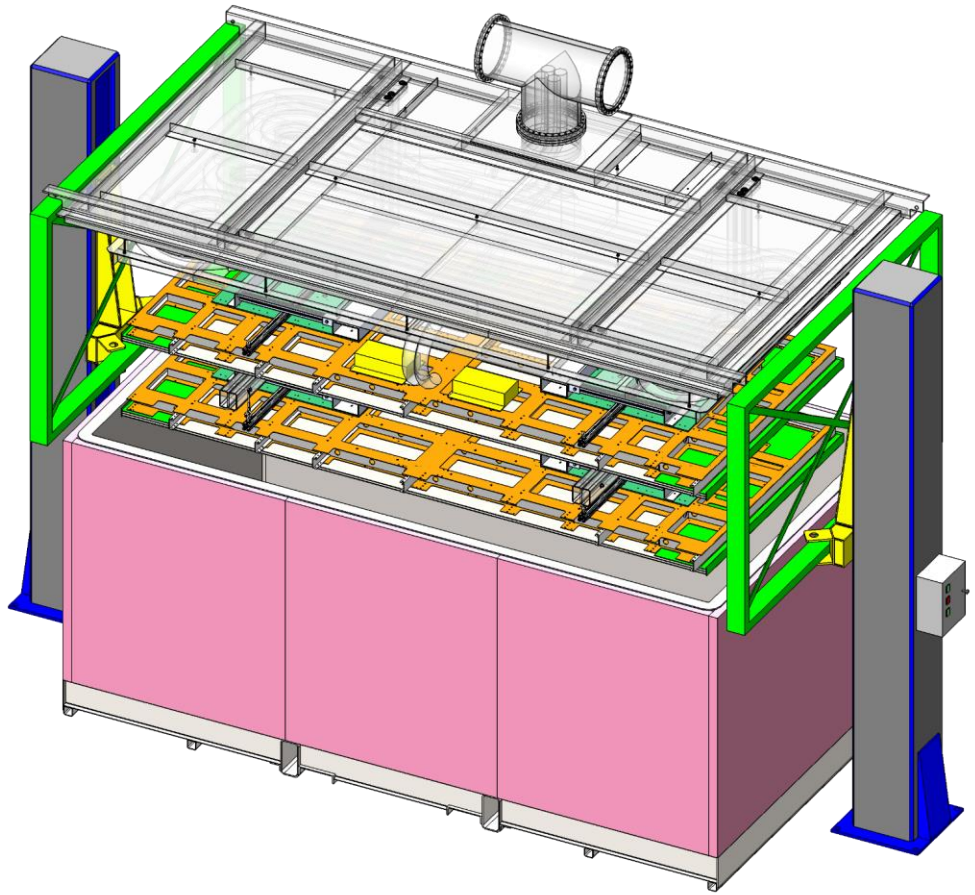
- **Cold Box Requirements:** Assembly Site Needs
- **Cold Box Design Motivation:** Why we need a Dual CRU Cold Box
  - Lessons learned from pre-production (ProtoDUNE-VD)
  - Required design changes for full production
- **Dual CRU Cold Box Design**
  - Current design
  - Design items in progress

Assembly Site: Core Functions and Requirements

- Receive bottom CRU deliverables
- Assemble and perform QA/QC on **two CRUs per week**
  - **Target throughput drives infrastructure needs**
- Electrical QA/QC of CRUs
  - Test of BDE at Warm and Cold
  - Test of HV at Cold in Faraday Cage
- Record QA/QC in HWDB
- Package and ship completed CRUs to SURF

Operational Requirements

- Production Requirements:
  - Must cryo-cycle 2 CRU per week
- CRP Requirements:
  - Anode, AB/EC/CE interconnection QC
  - Test at warm and cold
- BDE Requirements:
  - BDE WIB crate* on top of cold box (handles 24 FEMBs)
  - Full length (27m) signal and power cables inside of cold box
  - Cold box must act as Faraday cage
  - QC test of CRU channels at warm
  - QC test of channels at cold
  - HV test to check for leakage currents at cold (SHV cables)
  - QC test of CRU channels at warm again

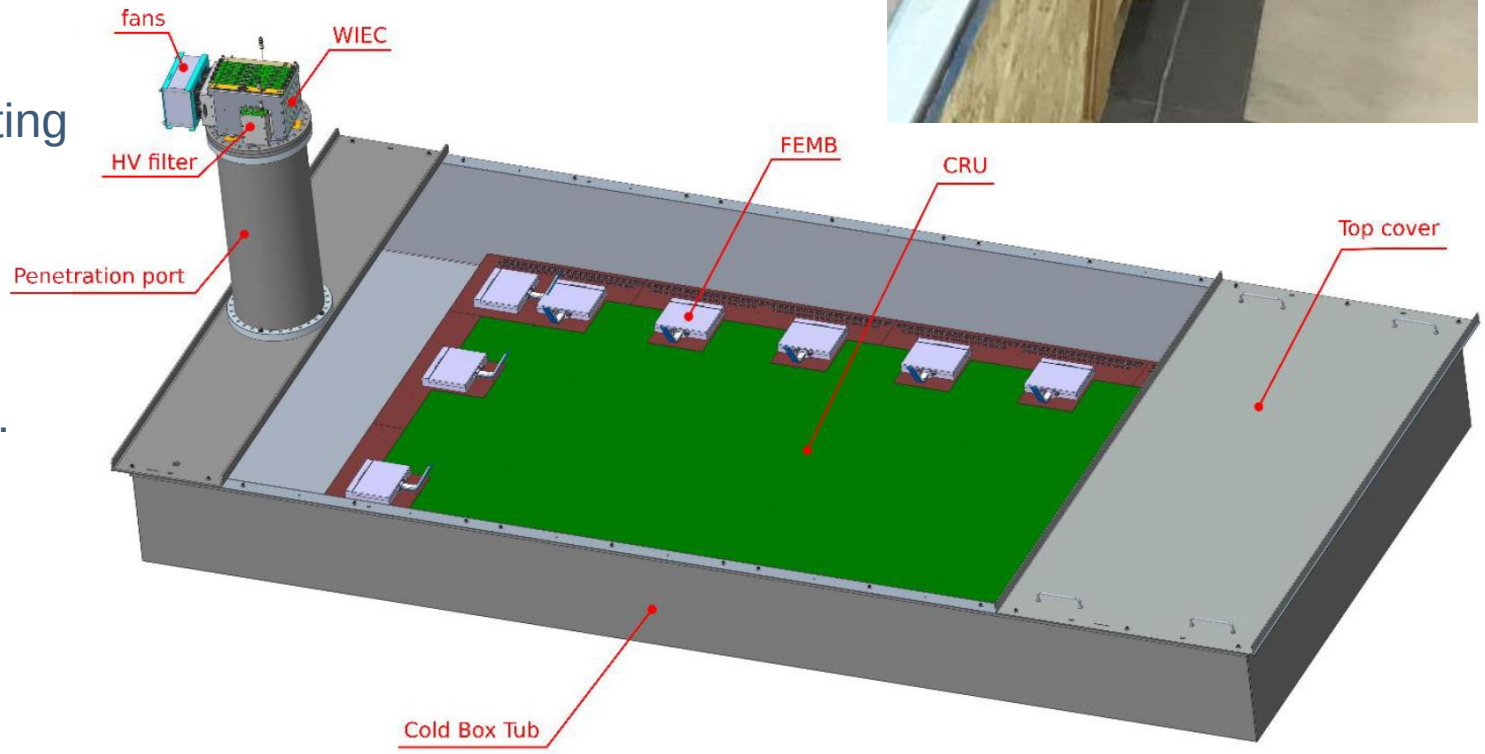


*The BDE group has promised to supply 1 WIB crate to each assembly site

Pre-production Cold Bath: Construction

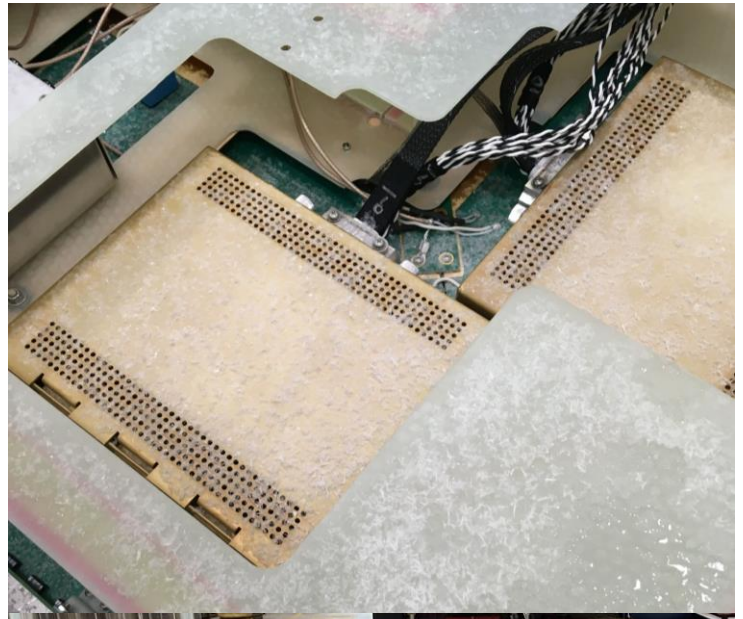
*this was not a cold box

- Containment volume:
  - Tub:
    - Welded ⅛” SS pan with 2” flange
    - Dimensions: 160” x 74” x 16” [4.1m x 1.9m x 0.4m]
  - Cover:
    - four ⅛” Al sections: 78” x 37”
    - One ¼” SS section: 78” x 16”
    - Includes chimney penetration and mounting
- Chimney:
  - SS pipe w/ 14” CF flanges.
- Insulation:
  - Sides and bottom: 4” residential foam board.
  - Top: 2” foam board.
- Crating:
  - Sides: ½” Plywood.
  - Skid: 2x6’s with 2” steel pipe for lift points.



Pre-production Cold Bath: Issues

- Shallow depth & top loading → only 1 CRU per test
  - Limits throughput of assembly site
- Tub bowed outward → hard to secure lid segments
- Lack of seal (by design) → exhaust difficult to control
  - Ideal: Maintain slight positive pressure from LN boil while passively capturing exhaust
  - Problems: When approaching end of boil off, exhaust began to draw air through cold bath.
- Operational Bottlenecks:
  - Boil off and warm up were slow and inefficient
- Ergonomics:
  - Awkward patch panel access



Pre-production Cold Bath: Issues (continued)

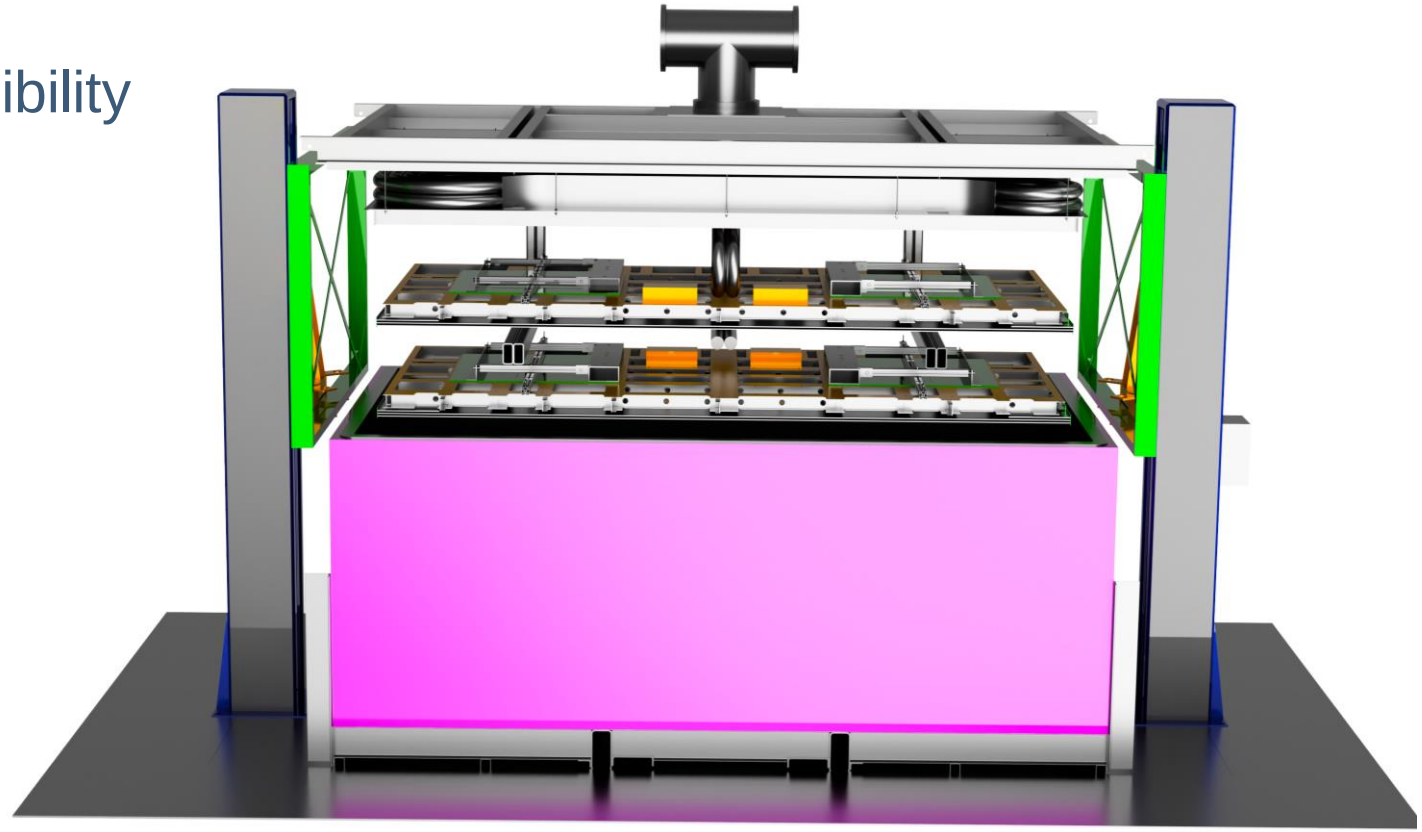
- Required ~4 times the footprint to operate
  - Removed lid segments, lifting frame exchange area, and box itself
  - 5 times if counting >17 LN Dewars required for filling
- Lifting frame utilized for testing interfered with assembly process. Had to be swapped in for assembly lifting hardware.
- Filling with many Dewars was labor intensive, as technician constantly monitoring/swapping Dewars
  - Additionally, Airgas required advanced notice to deliver this volume in the 180L format.
  - Method has little contingency capacity
  - **Not viable for sustained production**

Design Goals: Full Production

- **Enable 2 CRU throughput per week**
- **Reduce Assembly Site Footprint**: Side loading, external LN dewar
- **Minimize operational bottlenecks**: Filling time, boil off time, simultaneous testing
- **Improve Ergonomics**: patch panel access, cable management
- **Ensure cold box safety**: stable exhaust, thicker and more reinforced SS pan
- **Contingency**: Include weekly buffer to absorb unexpected delays and maintain throughput

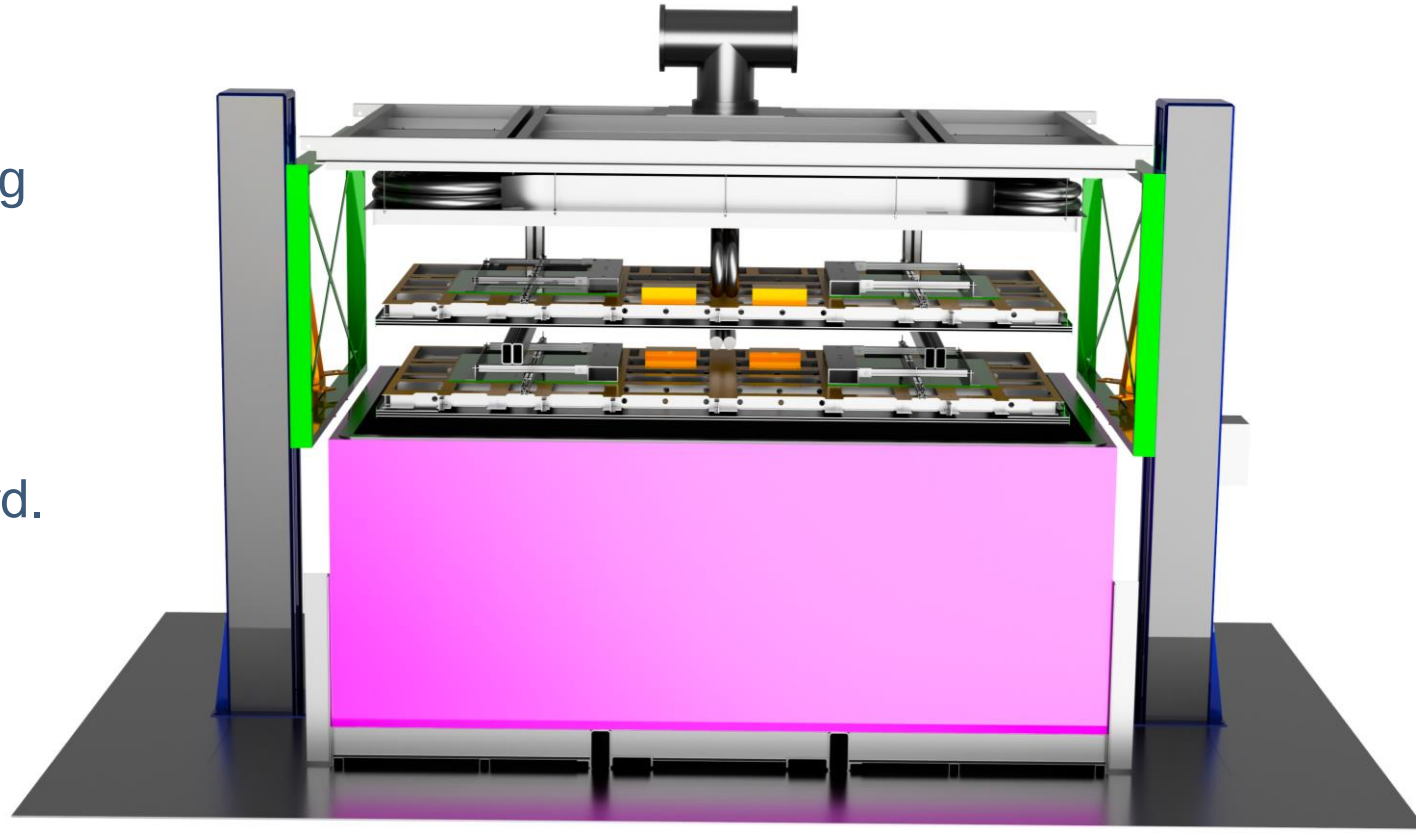
Dual CRU Cold Box Concept

- Enables simultaneous testing of two CRU
- Side Loading Design: Reduces footprint, eliminates overhead crane, and enables ergonomic access for installation
- Functions as Faraday cage for HV testing
- Patch panel location optimized for accessibility
- Exhaust improvements: sealing lid



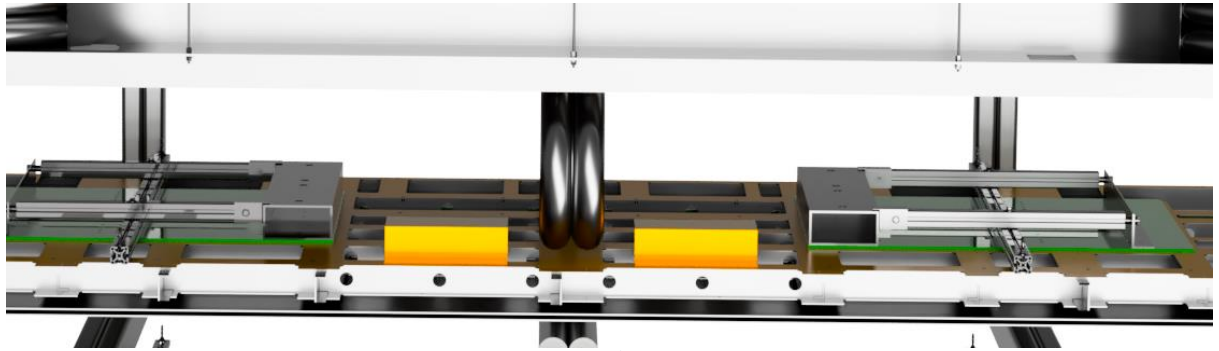
Dual CRU Cold Box: Construction

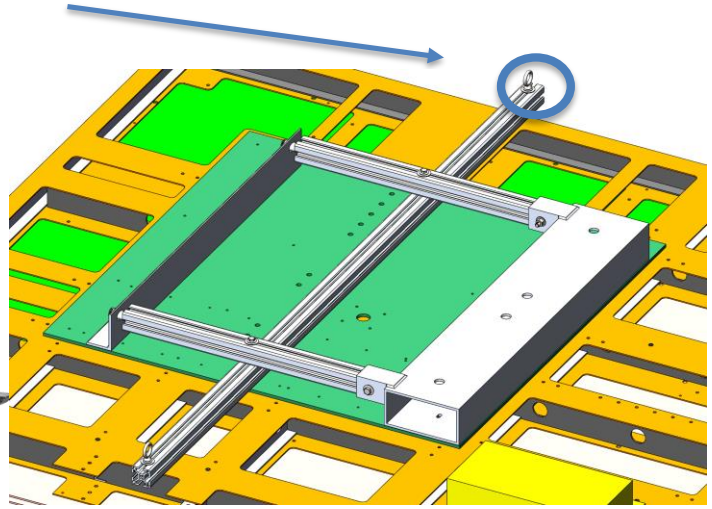
- Containment volume:
  - Welded 3/16” SS pan with 2.5” flange & reinforcing ribs
  - Dimensions: 140” x 74” x 52” [3.56m x 1.88m x 1.32m]
- Cover:
  - Aluminum framing with SS sheet skin
  - Lift mechanism: Hydraulic (TBD)
  - Includes chimney penetration and mounting
- Chimney:
  - SS pipe w/ 14” CF flanges.
- Insulation:
  - Sides and bottom: 4” residential foam board.
  - Top: 6” foam, expanding/board.
- Base:
  - 6” steel beams
  - Structural steel base with welded framing

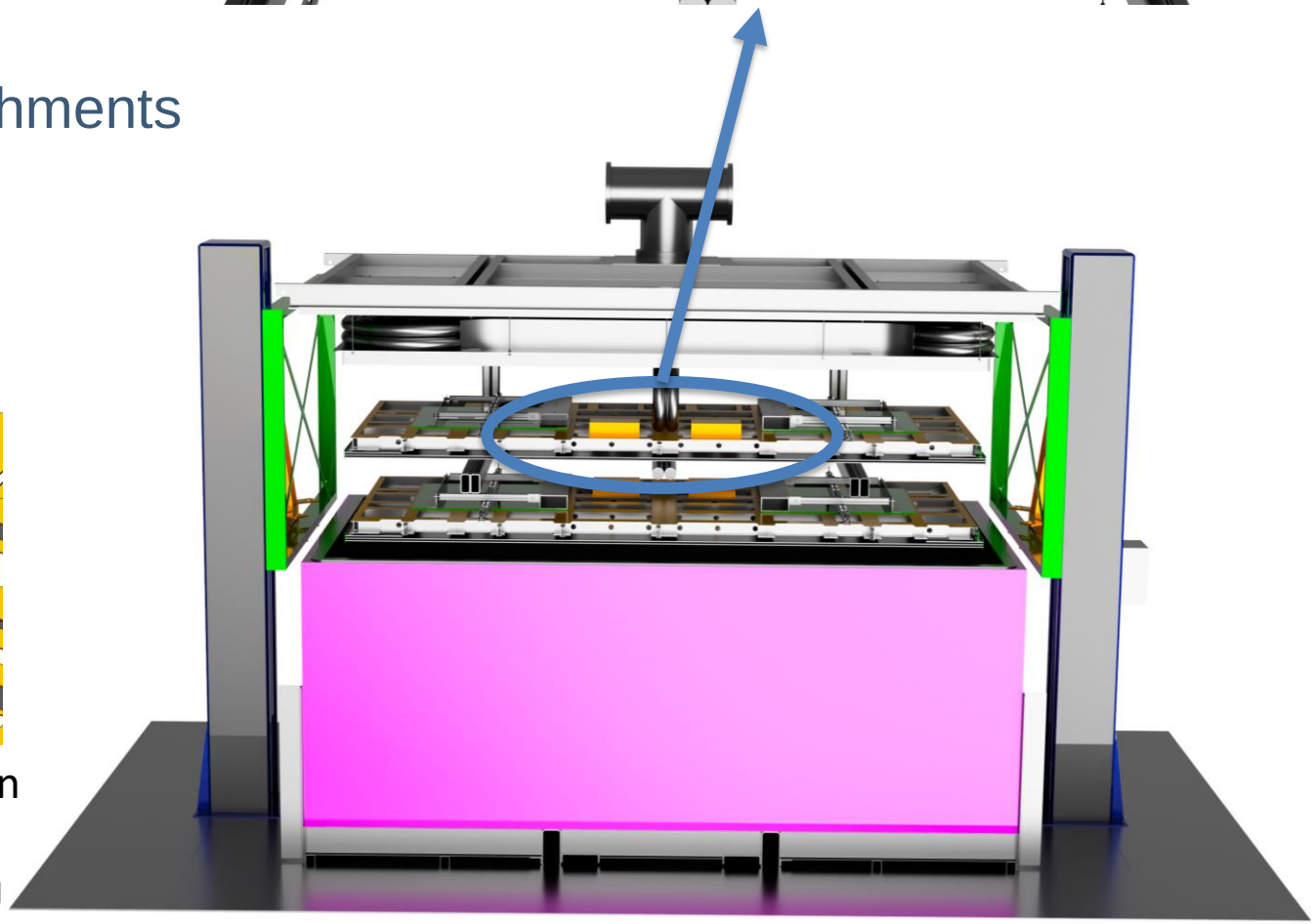


Sideloading Design

- Pallet stacker loads both CRUs from one side
- Fork receiving frames allow CRU to be transported by pallet stacker
- These frames also have suspension attachments for CRU in cold box

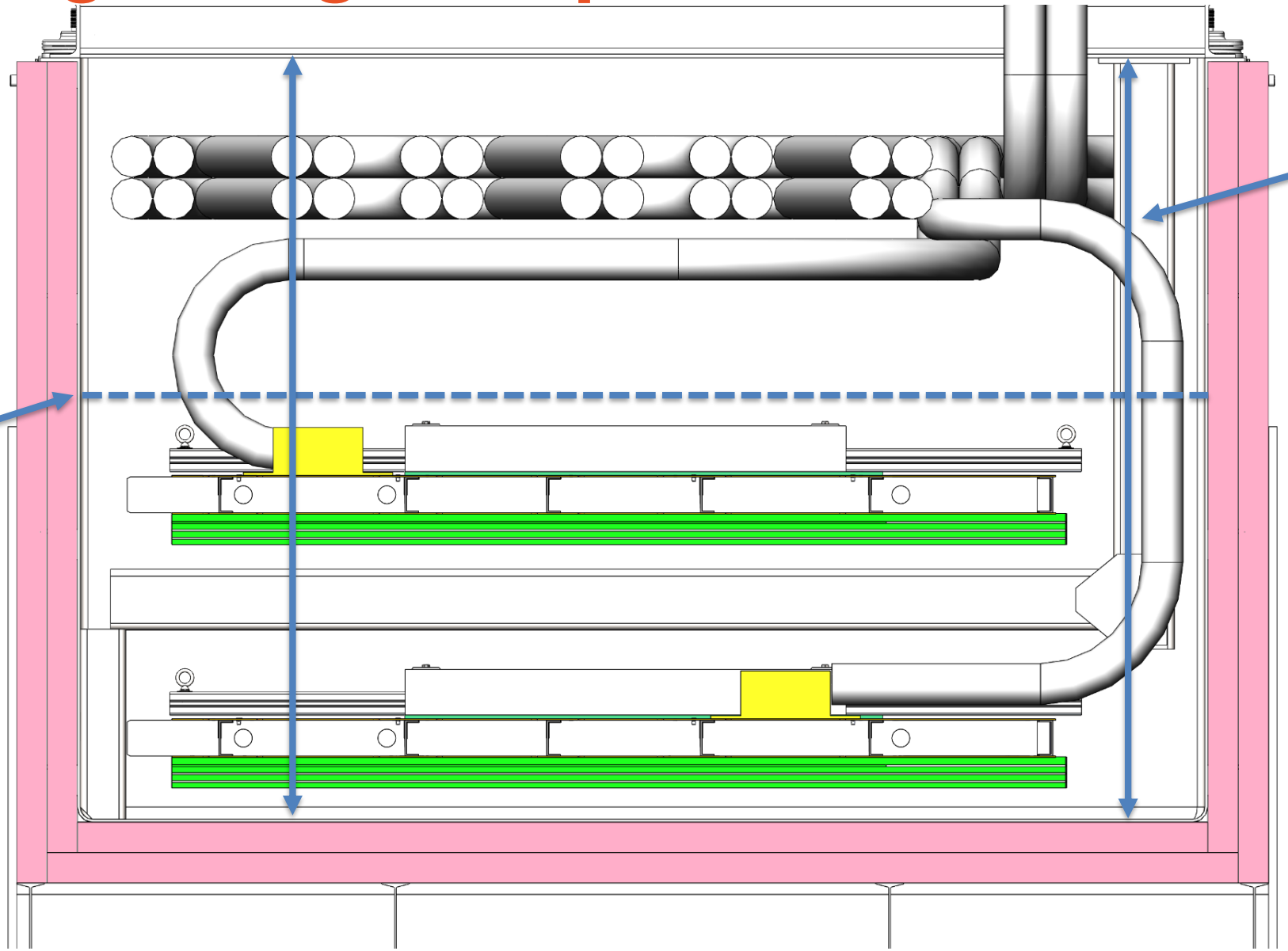






Design use mostly stock Al extrusion
Provisions for thermal contraction included to eliminate strain on CRU

Sideloading Design: Depth and LN



Overall depth increased to 132cm to include cables.

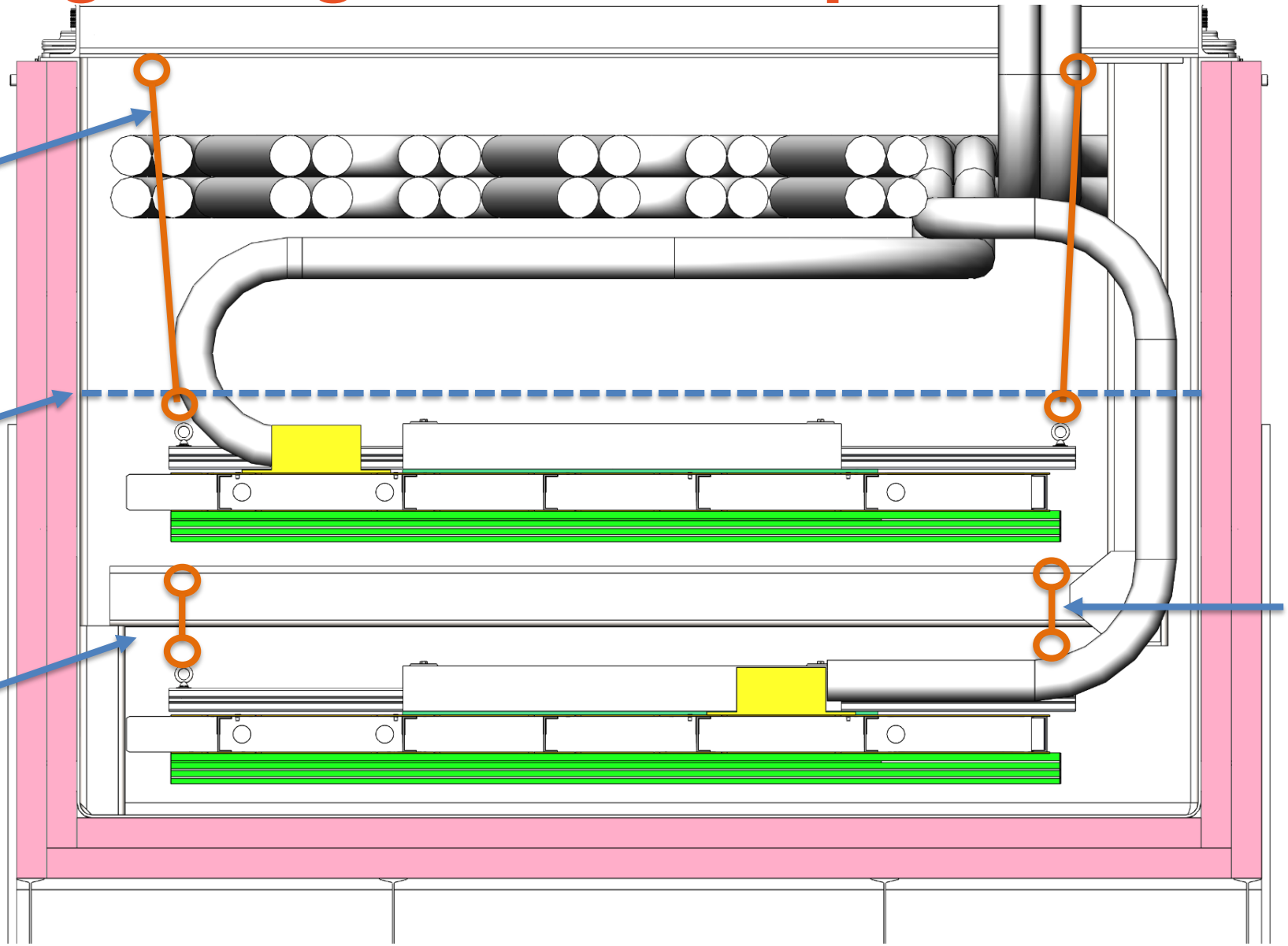
LN fill height ~70cm to 75cm

Sideloading Design: CRU Suspension

CRU suspended from cantilever support via wire

LN fill height ~70cm to 75cm

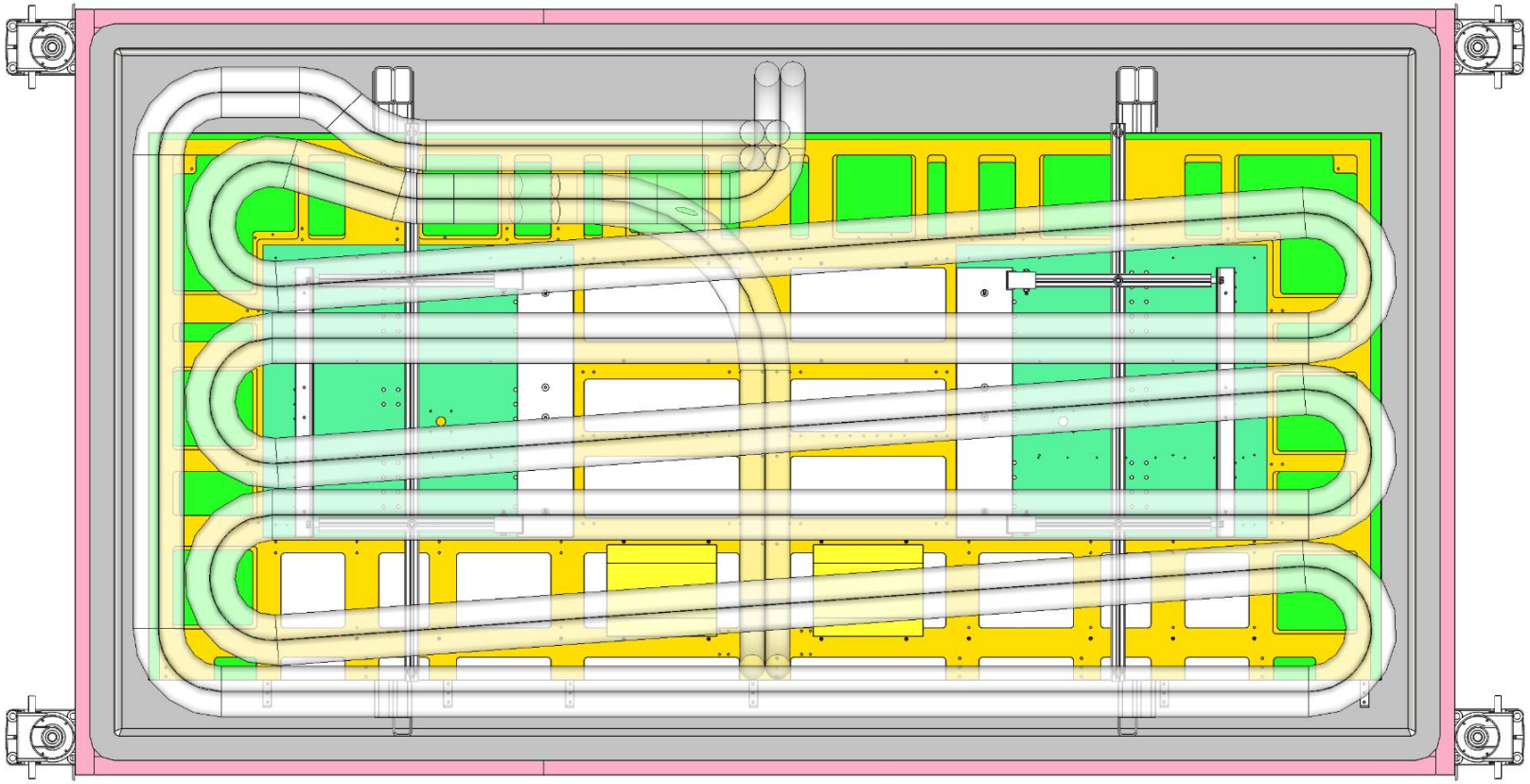
In lowered position, cantilever support arm rests on prop



CRU suspended from cantilever support via wire

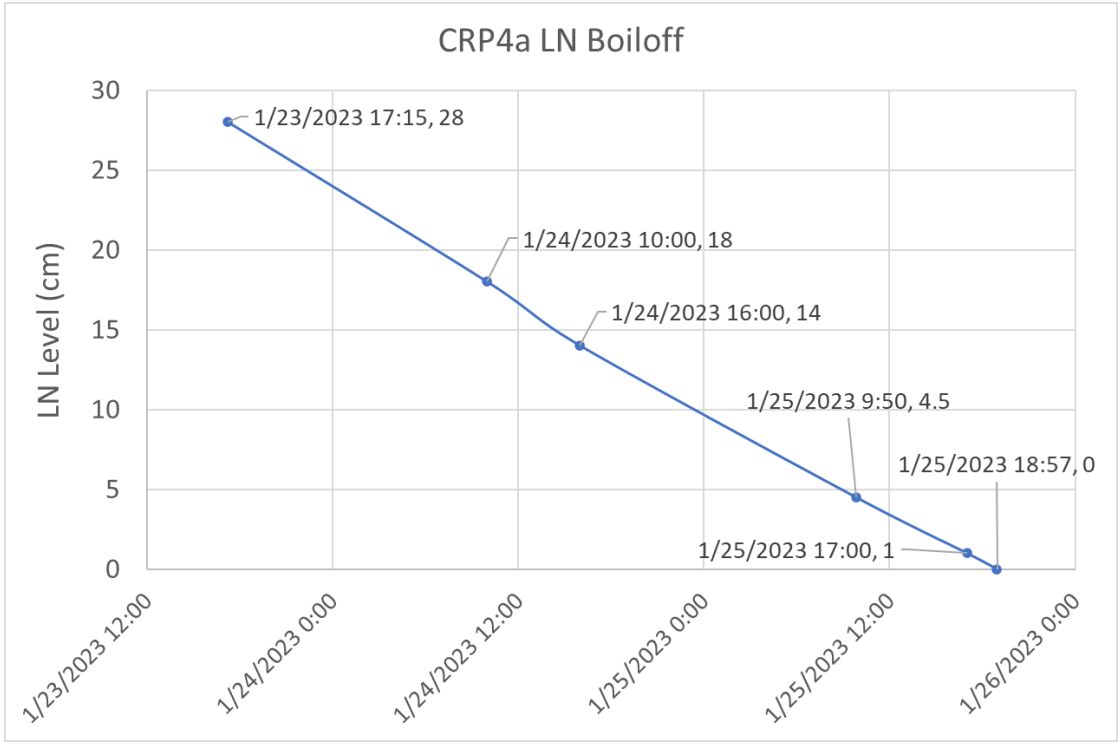
Cable Routing and Tray Layout

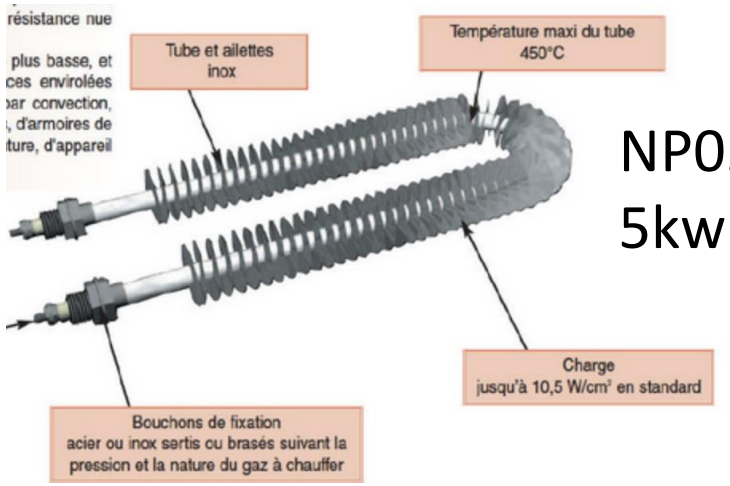
- Cold Box must house the full 27m BDE cables for each CRU
- Cable trays for housing the BDE cables are placed below the Cold Box lid
- Example cable routing is shown



Boil Off and Warm Up

- Boil off and warm up were major bottlenecks in pre-production
  - Took 5 days for 1 CRU!
- We **must** produce 2 CRU per week
- To increase the boil off rate heaters will be used
  - 1 5 kW heater = 59 hours
  - 2 5 kW heaters = 29.5 hours
  - 3 5 kW heaters = 19.5 hours
- Final heater layout still in progress





NP02 cold box
5kw heater

Design Items in Progress

- Assess vertical spacing between CRUs
  - Can this be reduced while preserving accessibility for installation?
- Finalize lifting columns for cold box lid
  - Identifying columns that can reach necessary height
- Final heater location and layout quantities
- Finalize cold box pan dimensions based on necessary clearances
  - Between LN/GN delivery lines and CRUs
  - Adjust base, lid dimensions accordingly

Dual CRU Cold Box Price Estimate

Cost estimates based on materials and labor to fabricate elements of the system. LN plumbing not included.
Points of comparison;
Dec. 2022 Quote to reproduce BNL cold box SS Pan: $13,850 without freight
"160"L x 74"W x 16"H stainless steel tank made from 11ga 304 stainless steel with 2x2x1/4" angle flange per drawing DUNE-CETT-AUGI" plus additional lid segments.

	Est. Materials	Est. Fabrication	Est. Welding	Est. Total	Total + 25%*
304SS Pan	$16,500	$1,500	$9,000	$27,000	$33,750
Steel Base	$5,000	$2,000	$2,000	$9,000	$11,250
Mobile Lid	$8,000	$7,500	$500	$16,000	$20,000
CRP Support	$4,500	$2,000	$1,000	$7,500	$9,375
Cable Tray	$3,500	$1,000	$1,500	$6,000	$7,500
Lift Mechanism	$12,000	$1,500	$1,500	$15,000	$18,750
Insulation	$1,500	$500	-	$2,000	$2,500
Slow Control	$14,000	-	-	$14,000	$17,500
Totals	$65,000	$16,000	$15,500	$96,500	$120,625

*Contingency, Profit margin, etc.

Summary

- Dual CRU Cold Box meets production requirements
  - 2 CRU throughput per week
- Design Improvements informed from pre-production:
  - Reduced assembly site footprint
  - Operation bottlenecks mitigated
- Mechanical and structural design in place
  - Welded SS pan, foam insulation, steel base, and hydraulic lifting lid
- Open Questions:
  - Lifting column height
  - Vertical spacing between CRUs

After This Point: Past slides exist.. In progress slide deck

Bottom CRP Weekly Production Schedule

- ~72 hours available for warmup in schedule for dual CRU cold box scenario!

		Assembly Table 1			Assembly Table 2		CF-Prep Table	Cold box	Crating	HWDB Entry
Monday	8:00-12:00	First		AB + Jumper prep				Warm-up		CRPa Entry
		Second + Third		CF prep						
		Fourth								
	13:00-17:00	Fifth	BDE Prep	Sixth			CF-Prep Table prep			
		CE Installation						Warm Testing		CRPa Entry
Tuesday	8:00-12:00	CE warm Test CRPa			Clean & Prep for next assembly			Remove CRPa' + CRPb'' to rack		
							CF-Prep#1			CRP Entry
	13:00-17:00						CF-Prep#2+#3			
		Prep CRPa for insertion			AB + Jumper prep + CF prep			Clean coldbox		CRP Entry
Wednesday	8:00-12:00				First	AB + Jumper prep		Insert CRPa		
					Second + Third	CF prep				
					Fourth	BDE prep				
	13:00-17:00				Fifth	Sixth		Insert CRPb'		
					CE Installation					
Thursday	8:00-12:00				CE warm Test CRPb			Close Cold box	Crate prep	CRP Entry
								Warm Testing	Crate CRPa	
					Prep CRPb for insertion					
	13:00-17:00							Purge (overnight)	Crate CRPb	
Friday	8:00-12:00	Clean & Prep for next assembly						Fill CRP		CRP Entry
							CF-Prep#1			
	13:00-17:00						CF-Prep#2+3	Cold testing		
								Warm-up		Extra/Make-up Entry

Yale University Wright Laboratory DUNE

Draft Schedule For Dual CRU Cold Box Setup

- For detailed breakdown of Dual CRU cold box setup production:
  - (May CM: Slides 9 to 14)
- Fiducial volume of ~5,000L (75 cm fill height (59% not 70%)

	Wednesday	Thursday	Friday	Weekend	Monday	Tuesday
Early AM	Load CRUs into cold box	Contingency for loading	Fill cold box	Boil Off	Contingency for warm up	Remove CRUs from cold box
Late AM						
Early PM		Warm Test CRUs	BDE Cold Test HV Cold Test		Warm Test CRUs	
Late PM		Purge cold box	Boil Off			
Overnight						

- Boil off can extend until end of day Monday (72 hours)
  - No cold box activities on Monday
  - Built in contingency time if needed

Draft Schedule For Tiered 2x Cold Box Setup

*boil off after 2nd box (no pump included)

	Tuesday	Wednesday	Thursday	Friday	Weekend	Monday
Early AM	Load CRU into Cold box A and B	Fill A Warm Test B	Transfer LN from A to B Purge A	BDE Cold Test B HV Cold Test B	Boil off B	Warm Test B
Late AM						
Early PM		BDE Cold Test A HV Cold Test A Purge B	Top off LN in B Warm up/Purge A	Warm test A		Remove CRU from Cold box A and B
Late PM	Warm Test A		Warm up A	Boil off B		
Overnight	Purge A					

- Eats into CRU assembly time
- Requires more personnel
- Removes contingency from cold box testing

Rough Estimate of Boil Off Time

Dual CRU testing Cold box

- LN2 Volume = 356cm x 188cm x 75cm = 5014 L
- LN2 Mass = 4046 kg
- Energy to Vaporize LN2 = 8.05 E 8 J
- With three 5kW heaters this would take ~16.5 hours
- Given the mass of the other components, it would take an additional ~3 hours to bring to room temp
- Total turn around:
  - 3 5kW heaters: ~19.5 hours
  - 2 5kW heaters: ~29.5 hours
  - 1 5kW heater: ~59 hours

Summary

- **Operations:** Dual CRU cold box
  - Simplifies operations and testing at assembly sites
  - Increases overall contingency time
    - With multiple heaters additional contingency time is available
      - Allows for retesting if needed
  - Has flexibility to test 1 or 2 CRU at a time
    - Only need to adjust fill level of LN

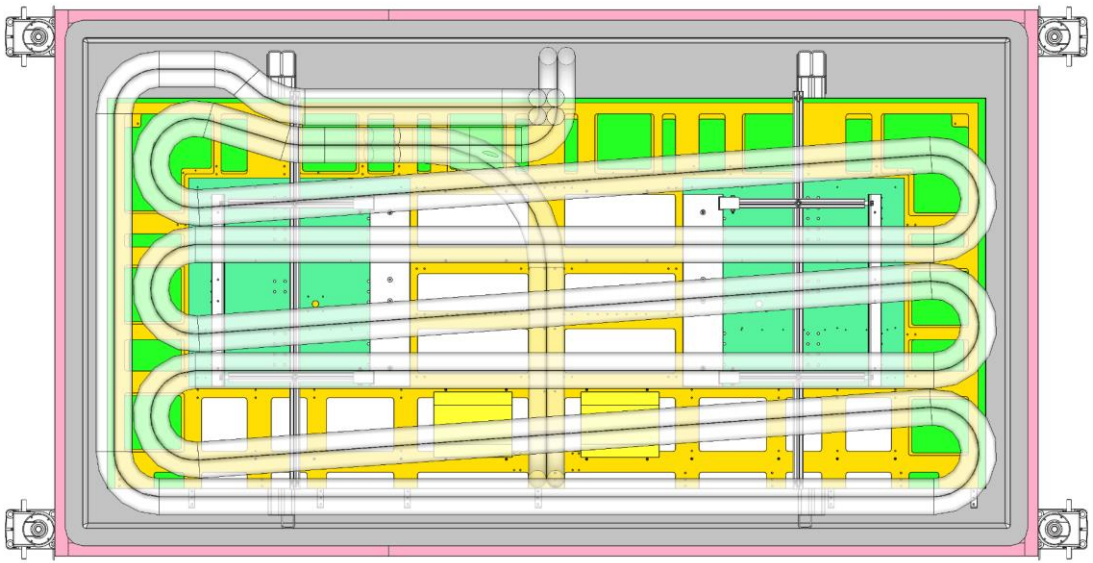
- **LN Usage & Cost**: For 100 CRUs: ($0.43/gallon)
  - Dual cold box: 92,500 gallons
    - $40,000
  - Tiered 2x cold box: 71,500 gallons
    - $30,000
  - Dual cold box requires at max: ~25% more LN than 2 single boxes

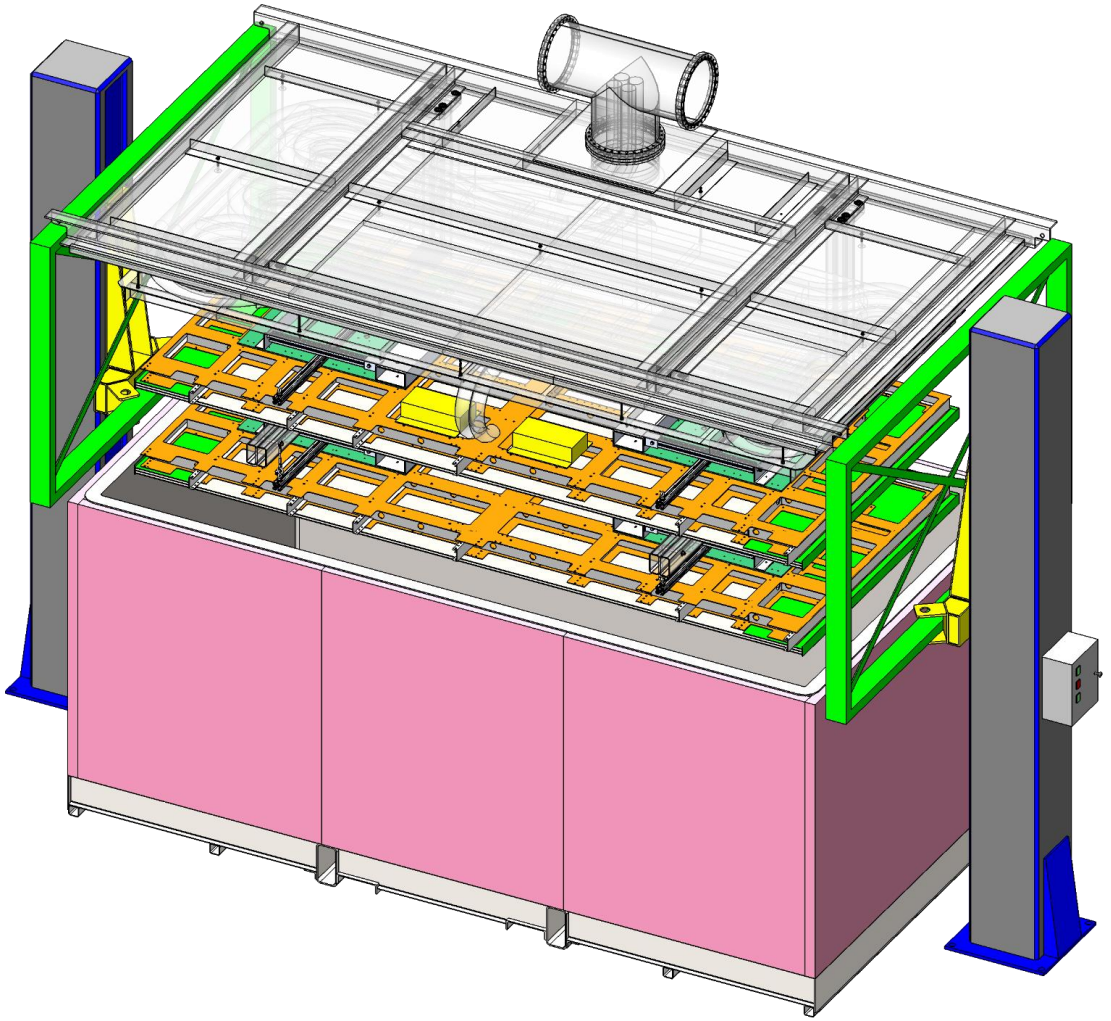
~$10,000 saved at most
Dual cold box → Tiered 2x cold box (LN)

- **Cold Box Construction Cost:**
  - Dual cold box: ~$100K

Extra Slides

BDE Cables and Cold Box Images





Overview: Tiered 2x Cold Box Design

- **Assumption: 2 boxes with CRU tests on consecutive days & Liquid Nitrogen transfer**
- Quantity to be produced: 100 CRUs → 71,500 gallons of LN in total
- Quantity of LN per 2 CRU for cold testing: ~1,430 gallons
  - Gas Purge: ~100 gallons
  - Cooldown of ~425 gallons
  - Fill volume of 665 gallons
  - Maintenance/top-off of 10 gallons/hr → ~24 hours → ~240 gallons
- Assumptions:
  - Length of cooldown/filling: 3 to 4 hours
  - Length of Testing: 2 hours at warm & 2 hours at cold
- Testing Scenario/Order

Overview: Dual Cold box

- **Assumption: 2 CRU stacked cold box**
- Quantity to be produced: 100 CRUs → 92,500 gallons of LN in total
- Quantity of LN per 2 CRU for cold testing: 1,850 gallons
  - Gas Purge and backfill: ~100 gallons
  - Cooldown of 425 gallons
  - Fill volume of 1,325 gallons (75 cm fill height (59% not 70%)
- Length of cooldown/fill: 3 to 4 hours
- Length of Testing: 2 hours at warm & 2 hours at cold
- Testing Scenario/Order

Cold Box Price Estimates

04/08/2025

Tiered 2x Cold Box Price Estimate

Cost estimate for both cold boxes.
Assumes tiered cold boxes are built and function similarly to dual CRU cold box.

	Est. Materials	Est. Fabrication	Est. Welding	Est. Total	Total + 25%*
304SS Pan	$26,000	$3,000	$15,000	$44,000	$55,000
Steel Base	$10,000	$4,000	$4,000	$18,000	$22,500
Mobile Lid	$16,000	$15,000	$1,000	$32,000	$40,000
CRP Support	$1,000	-	-	$1,000	$1,250
Cable Tray	$7,000	$2,000	$3,000	$12,000	$15,000
Lift Mechanism	$12,000	$1,500	$1,500	$15,000	$18,750
Insulation	$3,000	$1,000	-	$4,000	$5,000
Heaters?	$14,000	-	-	$14,000	$17,500
Totals	$89,000	$26,500	$24,500	$140,000	$175,000

*Contingency, Profit margin, etc.

Grenoble Cold Box

Another point of reference, below is Jean-Francois' round up of costs for the Grenoble cold box.
A single CRU cold box without the extensive BDE cabling, flange, etc.

	Item	Company	k€	total
Grenoble coldbox cost	Cold box cover mechanical structure	Ateliers du Fontanil	5,46 €	20,81 €
	Screws	PointP	0,20 €	
	Screws	SMG	0,21 €	
	CRU support composite rods	Rochling	1,59 €	
	Cover mechanical components	MAPE-RGA	4,48 €	
	Lift mechanism	LINAK	3,53 €	
	Lift mechanism remote control	LINAK	0,10 €	
	LN2 vent	Tubage Center	0,50 €	
	SS Pan insulation	Isol Concept isere	1,40 €	
	Spare lift mechanism	LINAK	3,36 €	
	Stereo SS Pan		30,00 €	
			50,81 €	