C4Or1B-07: Process Design for FRIB's Experimental System Cold Box

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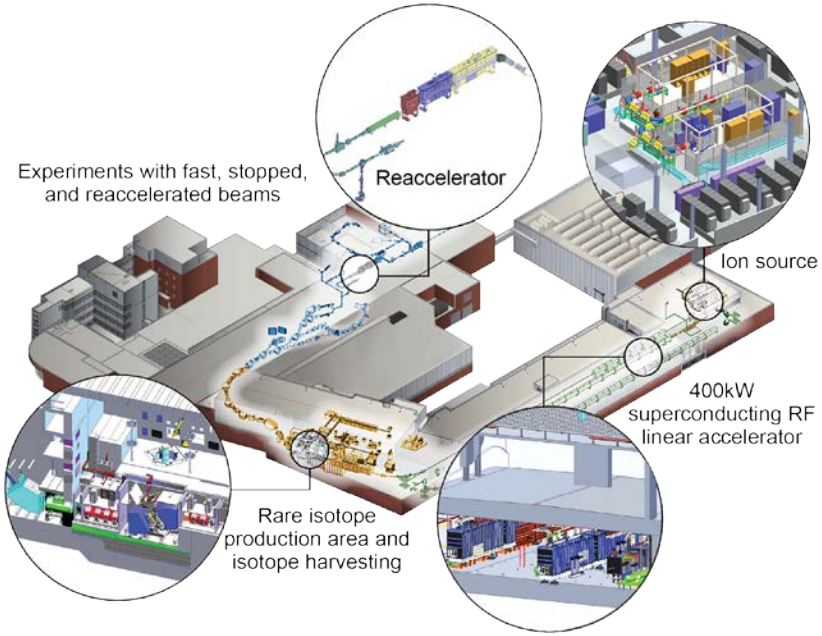
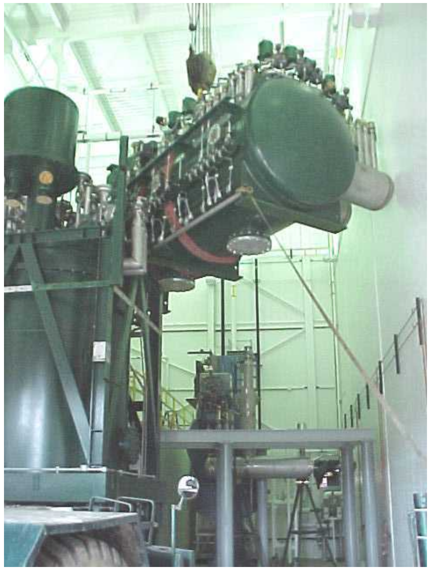
Background [1]

- The FRIB central helium refrigeration system was commissioned in late 2017
  - Designed based on the Ganni Floating Pressure cycle and offers a wide range of operational flexibility.
  - Presently supports operation of the LINAC cryo-modules, superconducting magnets in the target and pre-separator segment of the experimental system.
- A1900 fragment separator and S800 spectrograph (transfer hall beam line) segments of the FRIB experimental system is supported by the legacy NSCL cryogenic helium refrigerator (‘*Green Cold Box*’).
  - Originally designed as a helium liquefier in the mid 70’s for the Bureau of Mines Excell Helium Plant (Amarillo, TX)
  - Refurbished and re-commissioned as a helium refrigerator for the Coupled Cyclotron Facility (CCF) at the then National Superconducting Cyclotron Laboratory (NSCL) in CY2000



Background [2]

- In its present configuration, this refrigerator can support only up to 1250 W of 4.5 K refrigeration (approximately), which is not sufficient for future experimental system expansion.
  - From cryogenic operational stability and reliability stand-point, it is logical to segregate the experimental system loads from the accelerator system loads (*i.e.* cryo-modules supported at 2.0 K).



- Also not feasible to either obtain replacement parts or expect reliable operational support in the future.
- Based on the cryogenic loads (present and future), an upgrade plan for the experimental system cryogenic refrigerator has been proposed
  - Focusing towards the efficiency, reliability, backup options and to minimize the LINAC thermal cycle impact if and when refrigerator maintenance is required.

Estimated Present and Future Cryogenic Loads (Relevant) [1]

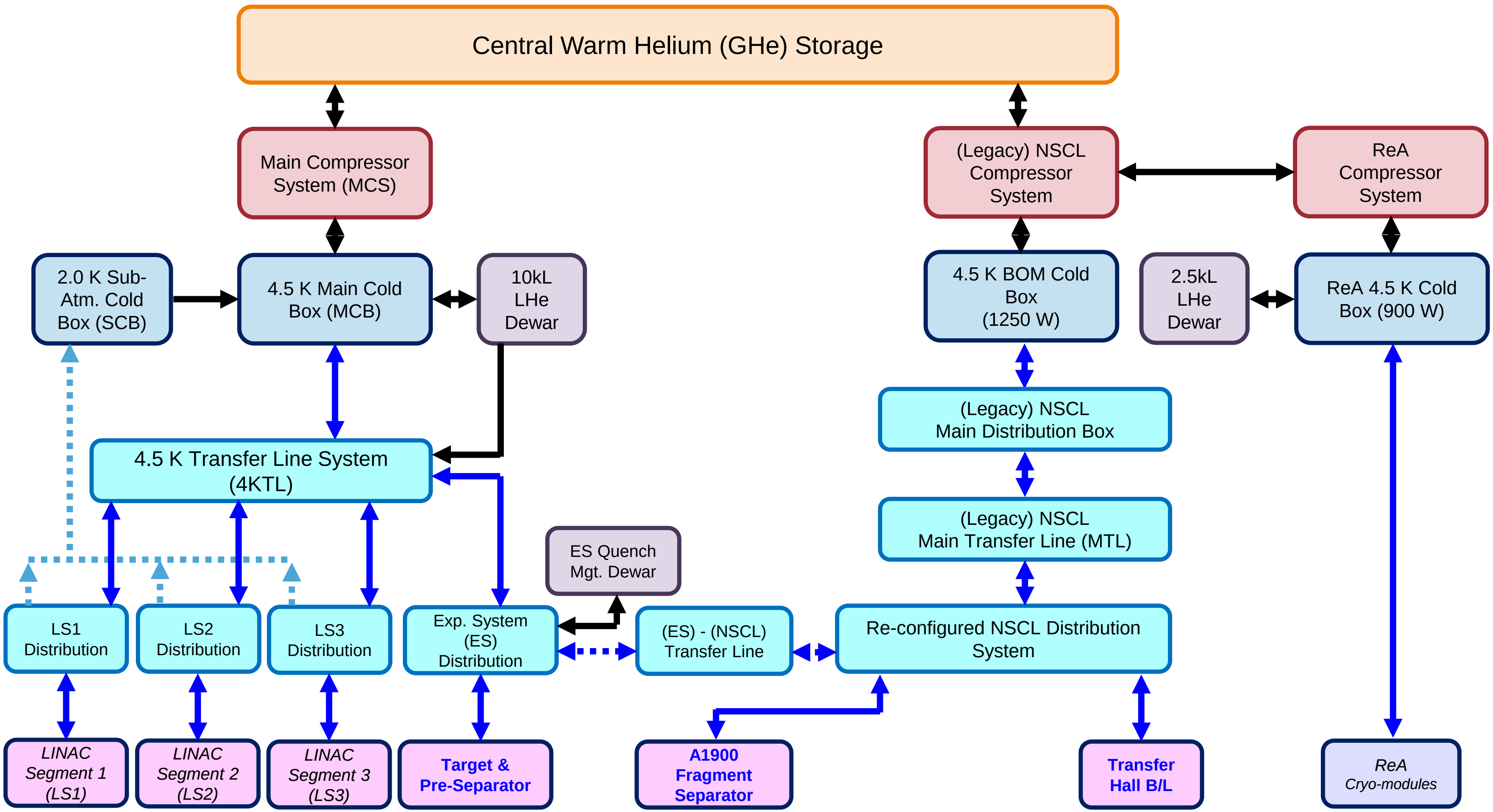
Loads	4.5 K (Static) [W]	Thermal Shield (@ 55K) [W]	Lead Flow [g/s]
LINAC Segments (with future upgrade)	4000	14000	3.5
ReA (Cryo-modules)	400	(LN Cooled)	N/A
Target and Pre-Separator	850	3500	5.0
A1900 Fragment Separator	800	(LN Cooled)	
Transfer Hall Beam Line			
S1/S2/S3 Spectrographs			
K500 Single Event Effects (SEE) Facility			
High Rigidity Spectrometer (HRS)	850	4500	

Loads in Red are future experimental system loads
Loads in Blue are not part of the experimental system

Estimated Present and Future Cryogenic Loads (Relevant) [2]

- Only 4.5 K (static), thermal shield and lead flow loads are shown.
- Some of these loads (4.5 K static heat in-leak and thermal shield) are measured (*e.g.* LINAC Segments, target and pre-separator segment) during commissioning.
- Others (A1900 fragment separator, Transfer Hall Beam Line, K500, S1/S2/S3 spectrographs) are based on engineering estimates and operational experience.
- The HRS loads are based on the present design basis and may evolve with the design.
- In general, all values presented in table 1 include adequate safety margin and should be considered solely for planning and design of future cryogenic infrastructure (cryogenic refrigeration system and distribution) serving the FRIB long range plan.

Present Cryogenic Configuration

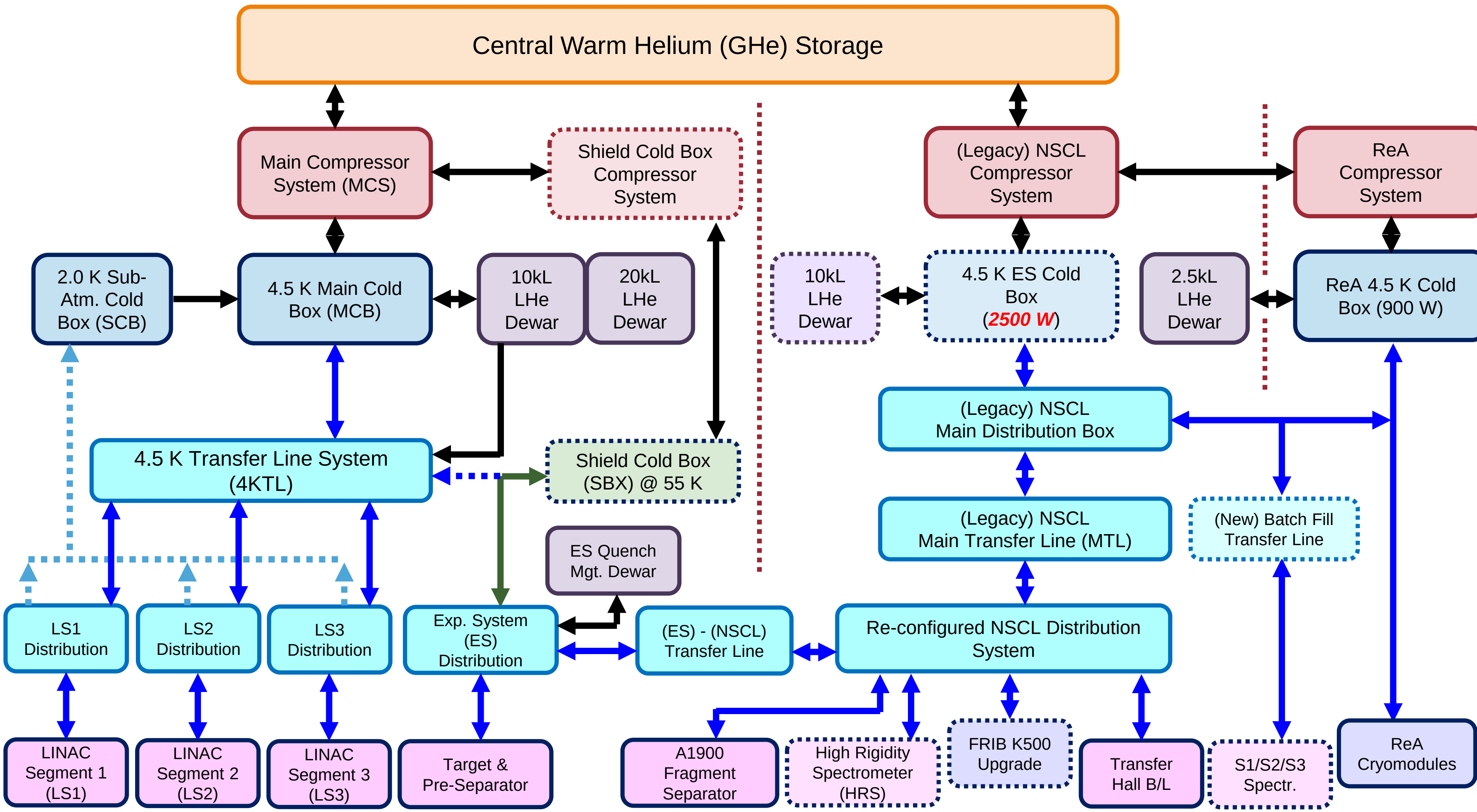


Proposed Cryogenic Configuration [1]

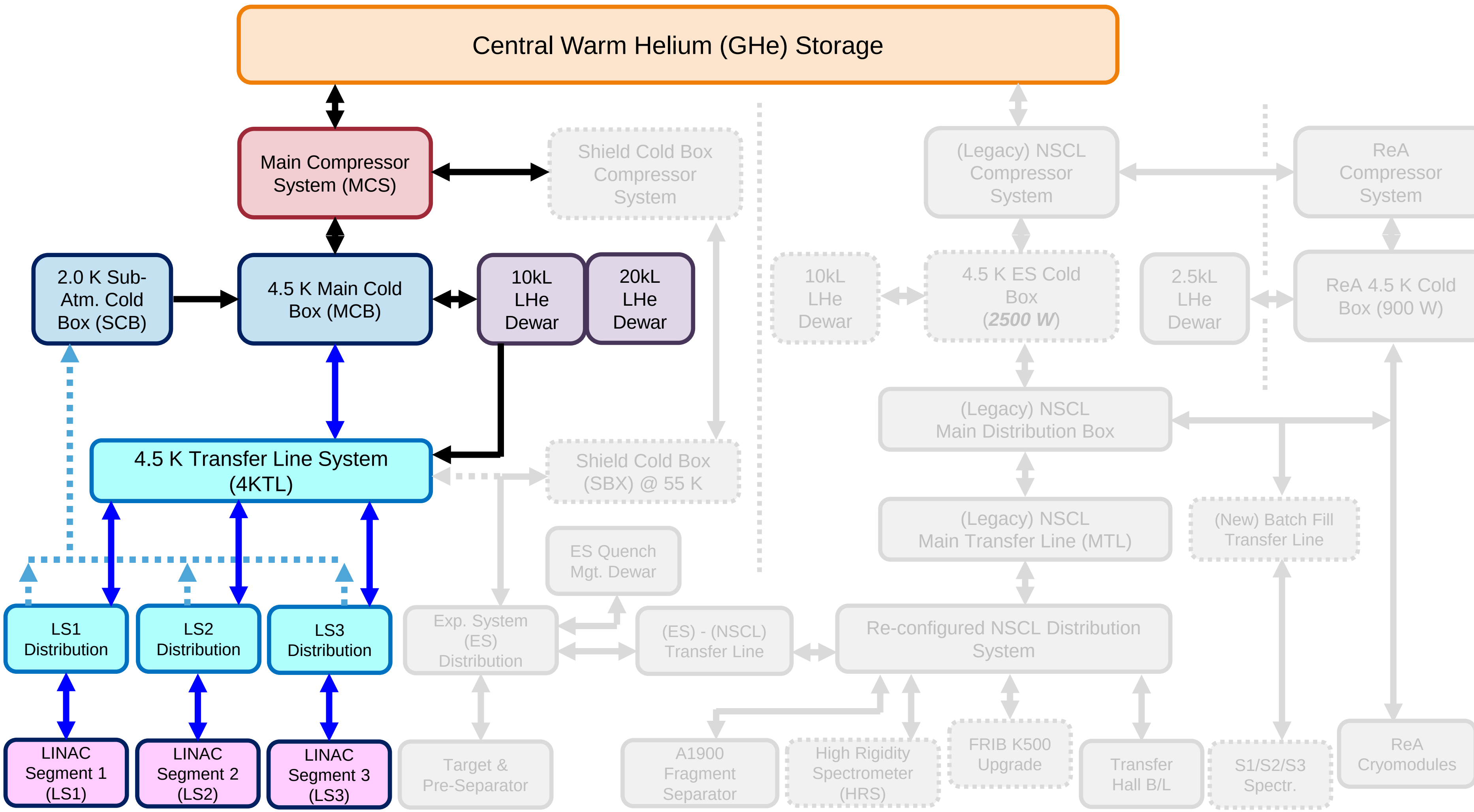
- The upgradation philosophy of the experimental system cryogenics infrastructure will follow the FRIB LINAC cryogenic system design basis with the following priorities:

  - Efficient operation to minimize the utilities (electric power and liquid nitrogen usage) with floating pressure process, adjust the cryo-plant cycle to the loads and maintain high efficiency.
  - Maximum availability with adequate redundancies.
  - Incremental system commissioning for continuously evolving experimental configurations to fit the user needs and minimizing down-time for reconfigurations.
  - Segregation to multiple sub-systems for maintainability with low impact on the availability, and expandability for future upgrade.
  - Completely automated system operation with minimal workforce

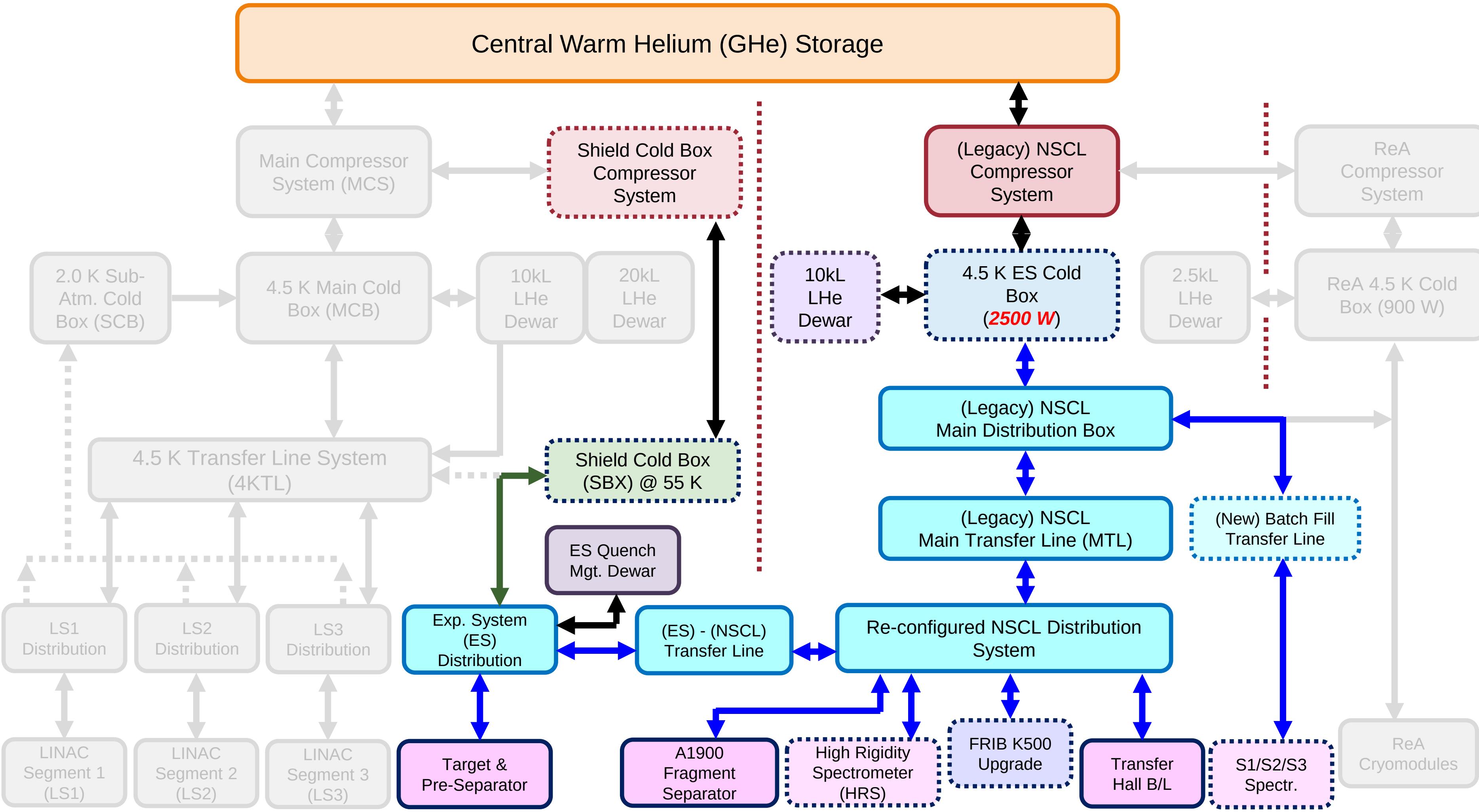
Proposed Cryogenic Configuration [2]



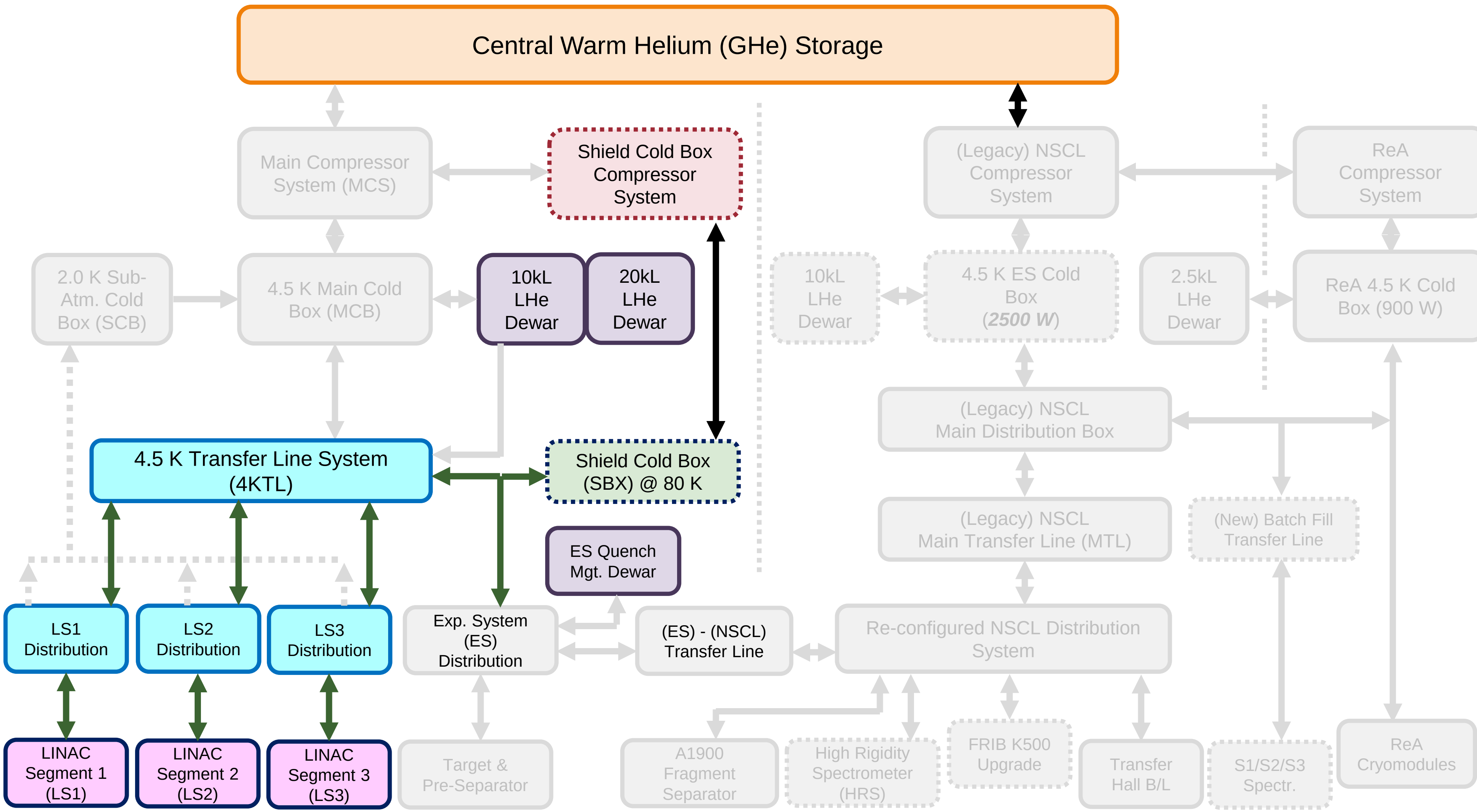
Proposed Cryogenic Configuration [3]
LINAC Operation



Proposed Cryogenic Configuration [4]
ES Operation

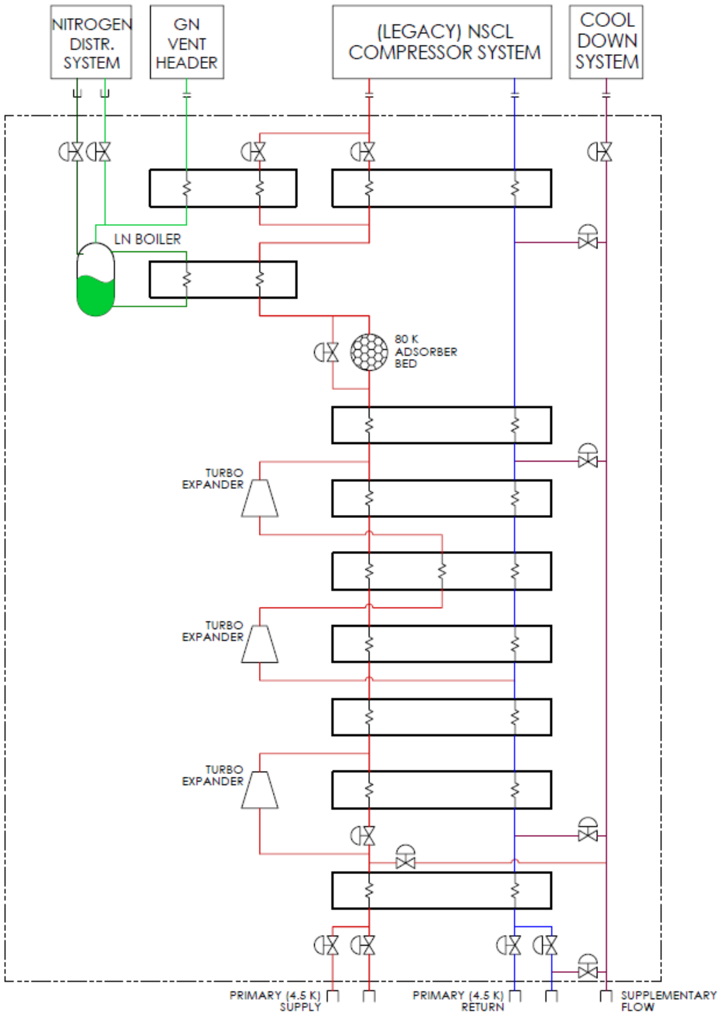


Proposed Cryogenic Configuration [5]
FRIB Refrigeration System Maintenance



Experimental System (ES) 4.5 K Cold Box [1]

- Nominal 2.5 kW (equivalent capacity at 4.5 K) cryogenic helium refrigerator with multiple turbo-expander stages and LN pre-cooling.
  - Provide 4.5 K refrigeration (and lead cooling) to all the experimental system loads during nominal operation.
- Operate with one of the two existing 200 g/s two-stage Mycom warm compressor skids, oil removal and gas management system. The other warm helium compressor skid will serve as redundancy.
- It will also have the capability to utilize the saturated vapor nitrogen return from the magnet thermal shields.
- Will be connected to the existing main distribution box in place of the green cold box and independently support the experimental system loads.
  - This distribution box also has spare bayonet inter faces to add additional 4.5K refrigeration capacity if and when needed.



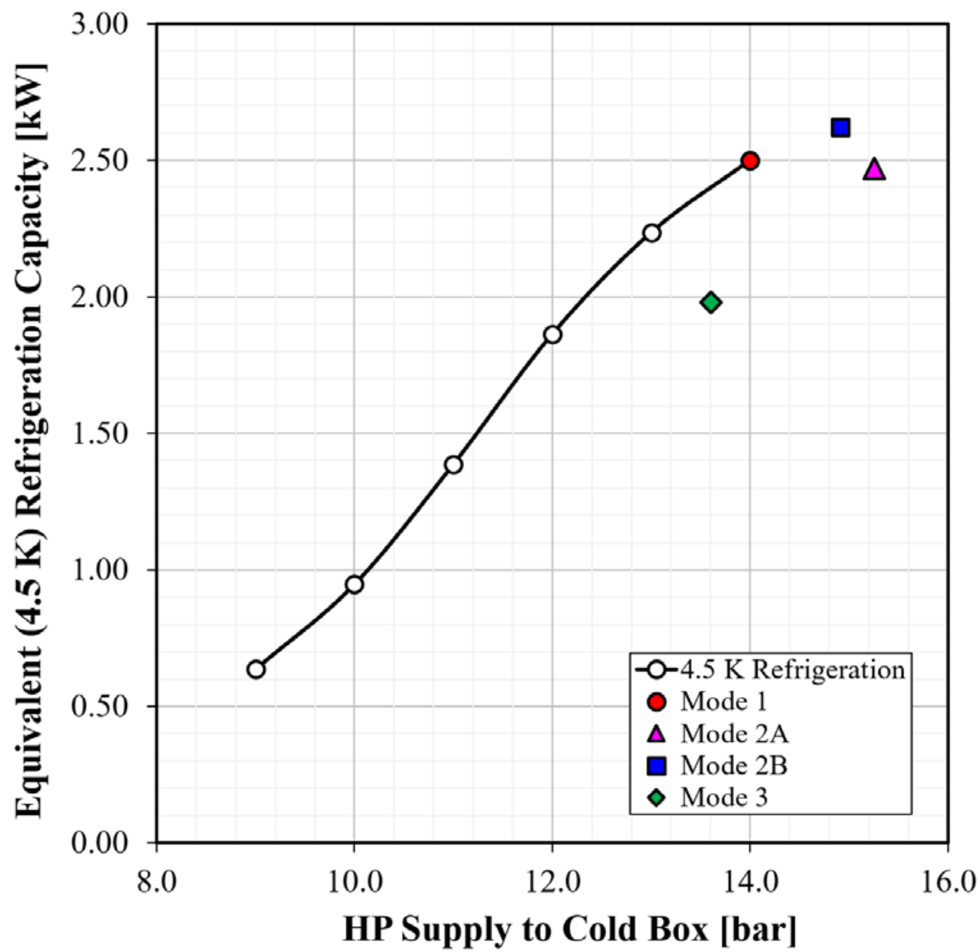
Experimental System (ES) 4.5 K Cold Box [2]

Mode #	Description	4.5 K Refrigeration [kW]	4.5 K Liquefaction [g/s]	SBX Suppl. Flow (at approx. 40 K) [g/s]
Mode 1	Max. Refrigeration	2.50	0.0	0.0
Mode 2A	Nominal Operation A	2.00	5.0	0.0
Mode 2B	Nominal Operation B	2.20	5.0	5.0
Mode 3	Min. Operation	1.65	3.5	0.0

- The main design constraint for the refrigeration process optimization for all these modes is the (flow) capacity of the existing warm compressor system (approx. 200 g/s).
- Maintaining this design constraint, combinations of 4.5 K refrigeration / liquefaction capacities of the cold box were simulated using a process cycle model.
- The list of operating modes and the corresponding 4.5 K refrigeration and liquefaction capacities (estimated from process cycle model) are provided in the table above.

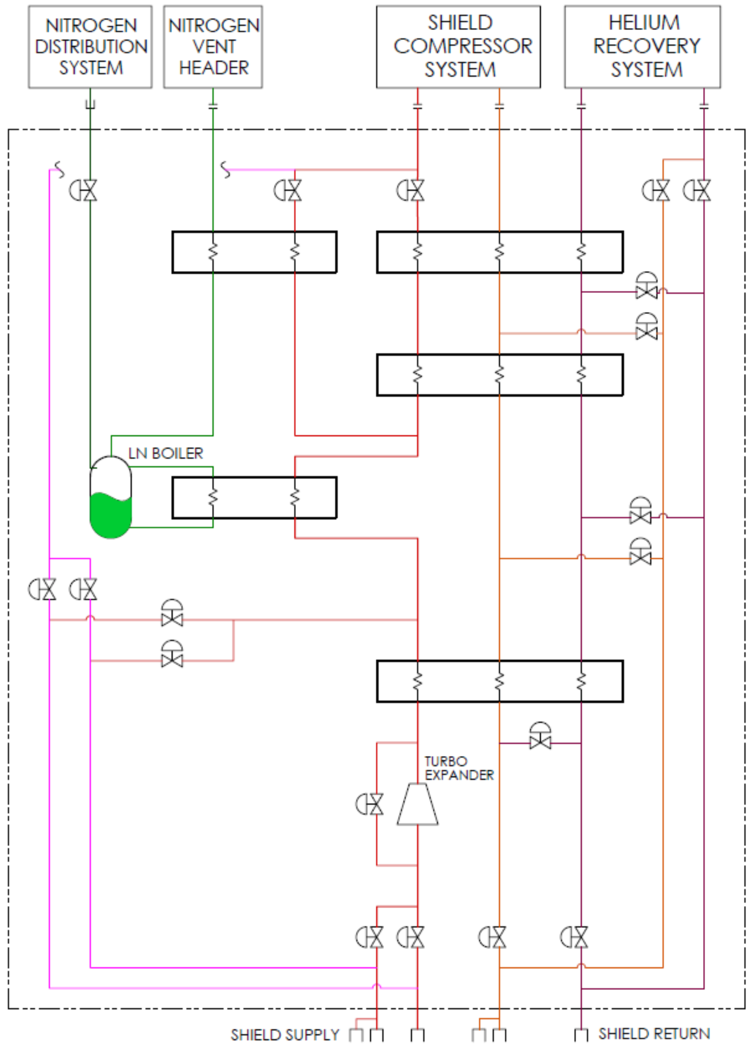
Experimental System (ES) 4.5 K Cold Box [3]

- The simulated equivalent (4.5 K) refrigeration capacity variation of this cold box with different HP header supply (pressure) ranging from 9.0 – 16.0 bar is shown.
- The existing warm compressor system has an operating pressure range of 12.0 – 18.0 bar.
- The turn-down (estimated) capacity of the cold box within the compressor operating pressure range was found to be acceptable and satisfying all the modes described before.



Experimental System Shield Refrigerator [1]

- It will be a 10.0 kW (at 55 K) cryogenic helium refrigerator with a turbo-expander stage and LN pre-cooling.
  - It will operate on Ganni floating pressure process.
- It will provide thermal shield cooling (at 55 K) to the target, pre-separator and HRS (and HTBL) experimental system segments.
- Moreover, it will be designed to support the LINAC cryo-modules at or below 100 K (along with the experimental system thermal shields, with a total capacity of 26.0 kW at ~100 K return temperature)
  - During planned maintenance of CHL minimizing the need for complete ambient temperature warm-up of the LINAC cryogenic system components.



Experimental System Shield Refrigerator [2]

Mode #	Description	Thermal Shield		LINAC Cryo-module (Non-Isothermal)		Suppl. Flow to ES 4.5 K Refrigerator [g/s]
		q [kW]	T_R [K]	q [kW]	T_R [K]	
Mode 1	Max. ES Shield Capacity	8.0	55	N/A	N/A	5.0
Mode 2	Nom. ES Shield Capacity	8.0	55	N/A	N/A	0.0
Mode 3	Min. ES Shield Capacity	3.5	55	N/A	N/A	0.0
Mode 4	FRIB MCB Maintenance	22.0	≤105	4.0	≤100	0.0

- The refrigerator will be designed to operate with two load return streams.
- The thermal shield circuit for the cryostats (*e.g.* LINAC cryo-module, ES superconducting magnets) are designed to withstand elevated pressures (up to 6.0 bar) and can take advantage of operating on the Ganni floating pressure process.
- In mode 4 the LINAC cryo-modules will be supported via the LP load return stream (at approx. 1.2-1.3 bar), where the return gas will be processed by the FRIB helium recovery system.

Other Additions

- *Shield Cold Box Compressor*:
  - It will be a 400 HP single-stage warm helium compressor skid (and associated gas management) capable of operating with the Ganni floating pressure process.
- *Batch Fill Transfer Line*:
  - It will be a cryogenic distribution and transfer line system from the existing main distribution box (in parallel to the main transfer line) serving the S1/S2/S3 spectrographs as well as a cryogenic interface to the ReA refrigerator and cryo-modules.
  - The spectrographs may require frequent configuration changes to accommodate various experiments, and hence it is logical to provide a separate cryogenic *artery* to serve these without affecting the other loads.
- *Miscellaneous*:
  - There will be a few minor additions such as – 10 kL dewar at the ES 4.5 K cold box for managing operational transients, a transfer line system connecting the shield cold box to the major transfer lines, several transfer line systems to connect the major cryogenic arteries to the future loads.

Summary

- Over the last couple of decades, the particle accelerator facility at MSU's campus has gone through an organic evolution (from NSCL era CCF, to addition of the re-accelerator, and now the newly commissioned FRIB).
- For such a facility, it is essential to provide a long-range pathway for upgradation of the cryogenic infrastructure as the loads grow over time.
- The overall goal of the proposed upgrades is to increase the long-term stability, reliability, and operability of the FRIB cryogenic system, while minimizing the capital investment on new cryogenic infrastructure by keeping existing reliable hardware.
- A long-range plan for FRIB cryogenic system upgrades is detailed, with special attention to the experimental system and cryogenic support during maintenance periods.

Acknowledgement

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Thank You

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