FRIB Helium Refrigeration System Commissioning and Performance Test Results

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Presentation Outline

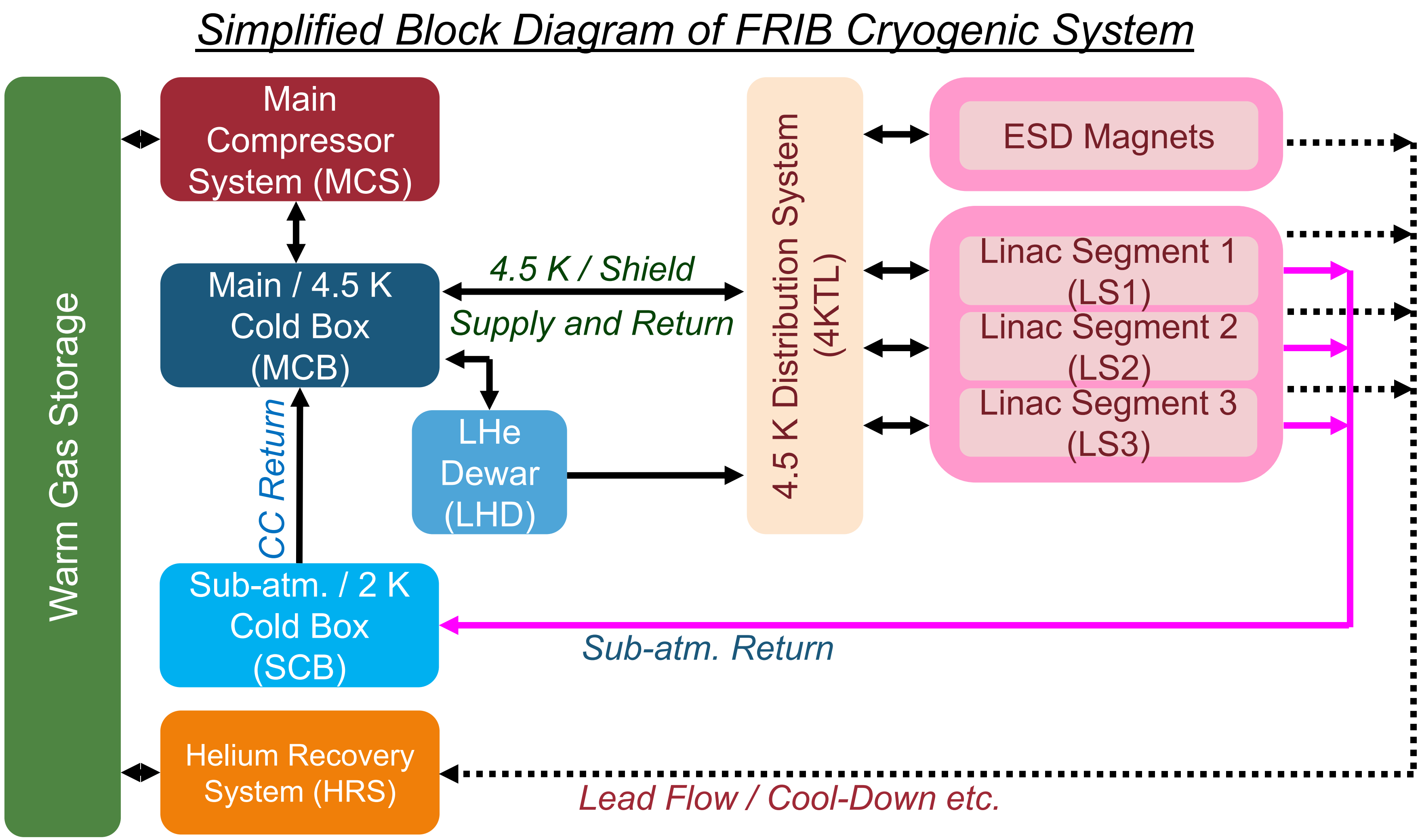
- FRIB Cryogenic System and Loads

- FRIB 4.5 K Refrigeration System
  - *Brief Description of System*
  - *4.5 K Cold Box LN Pre-Cooler*

- Commissioning and Performance Testing
  - *4.5 K Cold Box Commissioning*
  - *Performance Testing Configuration*
  - *Measuring LN Usage*
  - *Efficiency Calculation*
  - *Performance Test Results*

- Overall Summary

FRIB Cryogenic System and Loads



FRIB Cryogenic System and Loads (Cont.)

- Main Compressor System (MCS)
  - 6 Warm Compressors:
    - » 3 each – LP Stage (LP to MPH)
    - » 1 each – MP Stage (MP to MPH)
    - » 1 each – HP Stage (MPH to HP)
    - » 1 each – Swing Stage (either LP, MP or MPH to HP)
- Sub. Atmospheric Cold Box System (SCB)
  - Five '*Cold Compressors*' (CC's) operating in series
  - Sub – atm. return flow from the loads varies between ~120 – 180 g/s (max.)
  - CC return flow to Main / 4.5 K Cold Box System at ~1.16 bar & 30 K
- Cryogenic Loads
  - Linac Segments 1, 2 and 3 plan to have,
    - » 46 cryo-modules (supported nominally at 2.0 K and 4.5 K) and,
    - » 4 superconducting dipole magnets (supported at nominal 4.5 K)
  - Experimental Systems (ES) plan to have,
    - » 14 magnet systems (nominally at 4.5 K)

FRIB 4.5 K Refrigeration System

FRIB 300-60 K Cold Box

FRIB 60-4.5 K Cold Box

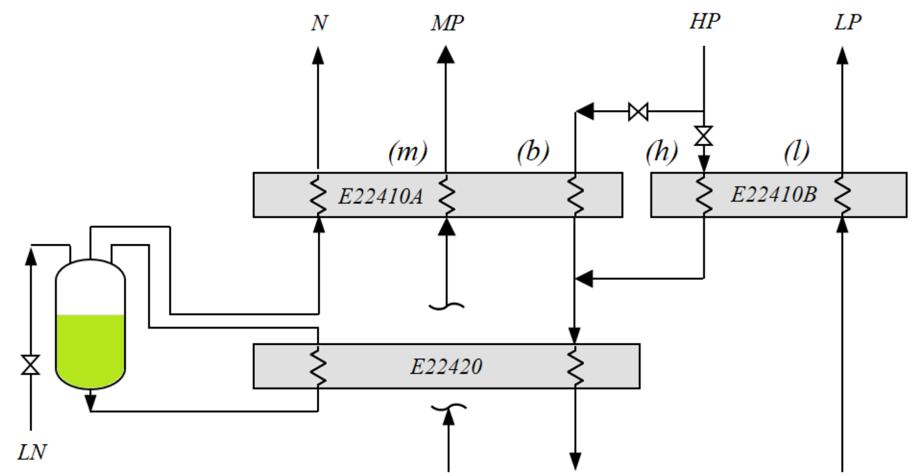
- Main/4.5 K Cold Box System (MCB) comprised of –
  - 3 Process streams (HP, MP & LP) and LN pre-cooler.
    - » *Construction is split into – 300-60 K vertical ('upper') cold box and 60-4.5 K horizontal ('lower') cold box*
    - » *Cold boxes interconnected by a relatively short vacuum insulated line*
  - 7 Turbo-expanders (T1 through T7) configured in 4 expansion stages
  - 2000 liter (nominal, 4.5 K) sub-cooler
  - 10,000 liter (nominal) liquid helium dewar

FRIB 4.5 K Refrigeration System (Cont.)

- Maximum capacity approx. 18.5 kW at 4.5 K (equivalent refrigeration)
  - 180 g/s of Cold Compressor (CC) return flow (1.16 bar, 30 K)
  - 4.0 kW of 4.5 K Refrigeration
  - 14.0 g/s of 4.5 K Liquefaction
  - 20.0 kW of Shield Refrigeration (35-55 K)
- Very similar to the Jefferson Lab (JLab) 12 GeV design.
  - Exergy of the maximum capacity for these cold boxes is nearly identical; however, the actual loads are somewhat different
  - Significant 4.5 K refrigeration load, higher 35-55 K shield load, but relatively lower CC load

FRIB 4.5 K Refrigeration System (Cont.)

- Liquid Nitrogen Pre-Cooler:
  - Designed based upon the experience from the 12 GeV cold box
  - Similar to the *configuration proposed in the 12 GeV request for proposal (to industry)*
  - Two HX used for the sensible cooling
    - » Three stream heat exchanger - HP, MP, and nitrogen (N) streams
    - » Two stream heat exchanger - HP and LP streams
    - » There is a re-mixing header for the HP stream
    - » Two control valves are used to regulate the split of the HP stream between the two HXs



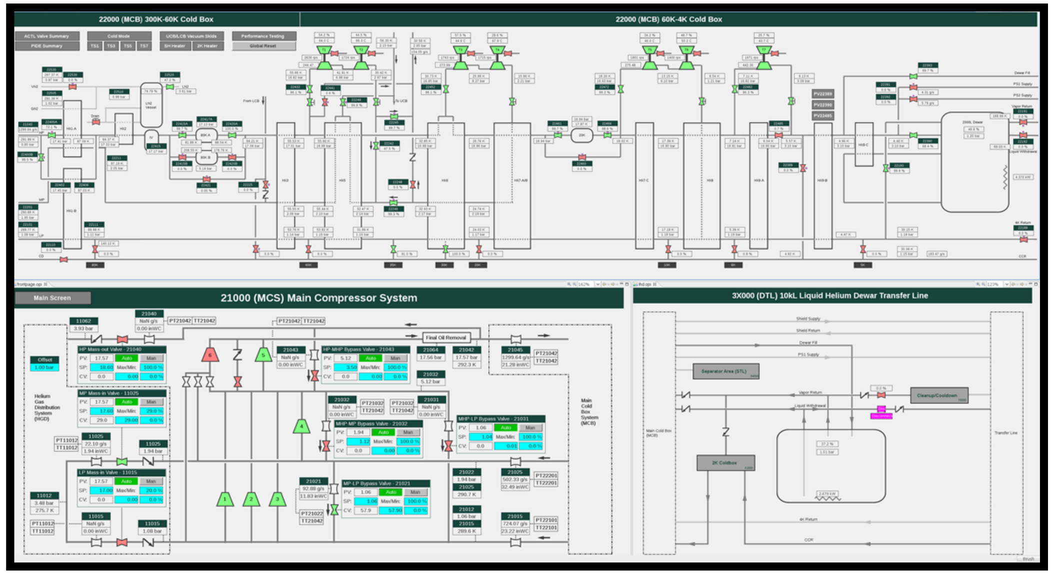
Simplified Schematic of FRIB 4.5 K Cold Box 300-80 K heat exchangers

FRIB 4.5 K Refrigeration System (Cont.)

- Liquid Nitrogen Pre-Cooler (Cont.):
  - (UA) margin (ratio of UA provided to required for specified process conditions) is approx. 250% or greater
    - » *FRIB/12 GeV specification: ≥ 15% including long. conduction*
  - Ratio of NTU to core length of the three stream and two stream heat exchanger is 8.4 m^{-1} and 8.1 m^{-1} respectively
    - » *FRIB/12 GeV specification: ≤ 10 NTU/m*
  - The empirical parameter termed the 'aspect ratio' (ratio of effective length to square root of total free flow area), is > 6 for both FRIB HXs
    - » *FRIB LN consumption was well below manufacturer's 'T-s' design*
    - » *12 GeV HX modifications <u>just met</u> the manufacturer's 'T-s' design for the LN consumption with an aspect ratio of 4.9*

4.5 K Cold Box Commissioning and Performance Testing

- 4.5 K Cold Box Commissioning:
  - First start-up and LHe production in mid-November 2017 with all turbo-expanders operating
  - Commissioned in Dec. 2017
  - Successfully operated at all guaranteed design modes

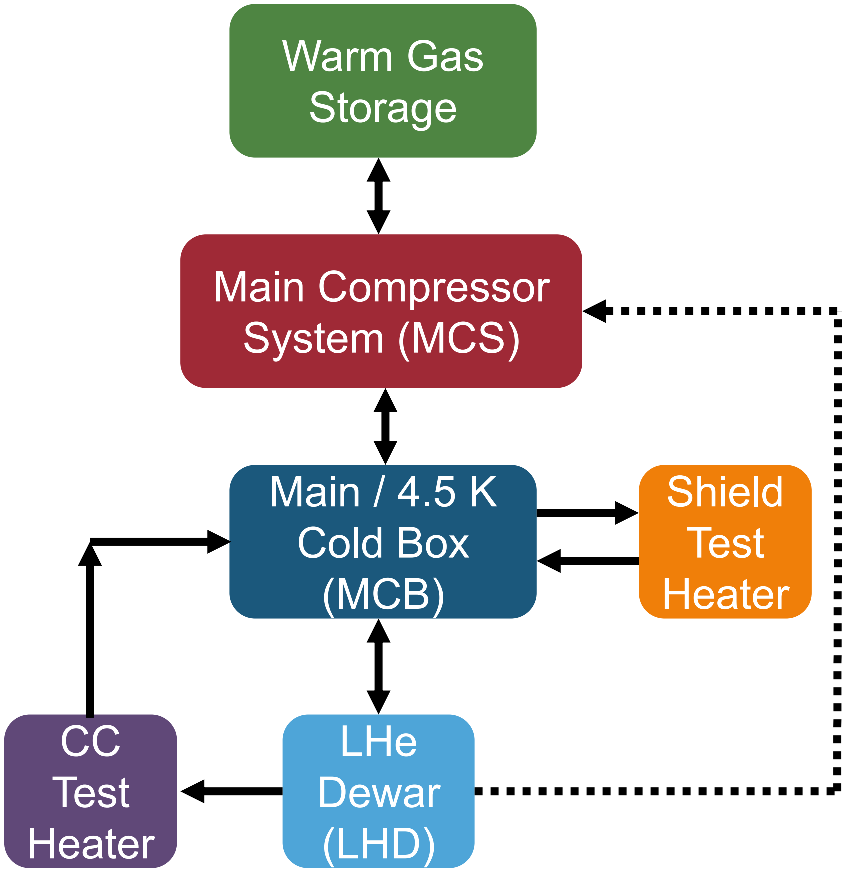


FRIB 4.5 K Cryogenic System HMI screens (top)

4.5 K Cold Box LHe Sub-Cooler liquid level read-out during first LHe produced (bottom)

4.5 K Cold Box Commissioning and Performance Testing (Cont.)

- Performance Testing Configuration
  - Tests performed in Spring (April) 2018
  - Testing was performed with system disconnected from the Linac
  - Loads are simulated using compact test heaters for each load type
    - 30 kW shield test heater
    - 45 kW CC test heater (and 4.5 K sat. vapor helium from LHD) for CC flow to MCB
    - Combination of 6.0 kW heater in 10,000 liter LHD and 7.5 kW heater in 2000 liter helium sub-cooler to mimic 4.5 K refrigeration
  - JLab / SNS style cryogenic coupling (bayonets) are used to connect to the test equipment (heaters)



Simplified Block Diagram of FRIB 4.5 K Cold Box Testing Configuration

4.5 K Cold Box Commissioning and Performance Testing (Cont.)

- Summary of Tests Performed:

Mode	HP [bar]	R [kW]	L [g/s]	SH [kW]	CC [g/s]	E [kW]	q [kW]
CC	17.8	4.7	15.2	19.6	180	1352	18.7
	18.0	4.2	32.7	20.0	183	1431	19.9
L	18.0	1.4	189	13.4	0.0	1388	19.0
	7.0	1.0	32.9	12.6	0.0	359	4.8
R+Shield	11.7	11.8	0.0	20.0	0.0	955	13.6
	6.6	4.2	0.0	12.6	0.0	379	5.1
	6.7	4.3	0.0	18.9	0.0	404	5.4
50L/50R	13.6	7.2	75.8	13.4	0.0	1154	15.9
	7.3	2.0	20.8	13.4	0.0	284	3.8

4.5 K Cold Box Commissioning and Performance Testing (Cont.)

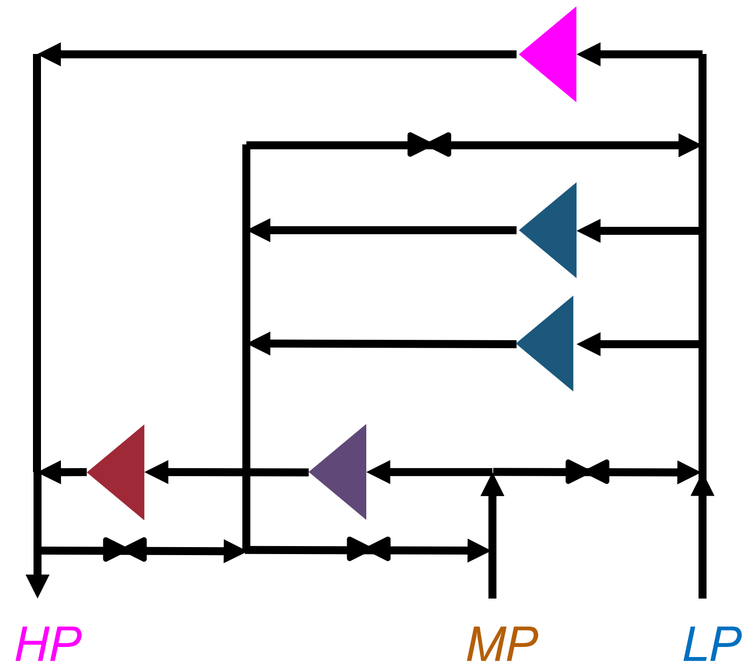
- Ganni Cycle – Floating Pressure Process:
  - FRIB 4.5 K refrigeration system (compressor and cold box systems) are designed to fully implement this process
  - Allows system to automatically adjust to capacity & load type in an efficient & stable manner anywhere between discharge pressures of 6 to 21 bar
    - » This a <u>constant pressure ratio process</u>, which is naturally inherent to a cycle using a fixed displacement warm compressor and a cold box using turbines with a fixed inlet nozzle
    - » Process is considerably more elegant than one in which, "…the high pressure level is monitored in order to control the bath level."
    - » Pressure levels (plural) 'float' in response to the actual load that is imposed
  - For a 'closed' inventory system, this response occurs naturally; i.e., system pressure levels inherently increase as the load increases, and visa-versa
    - » Term 'natural' is used, as this process follows Le Chatelier's principle; as opposed to a process which 'inherently' requires active process control (feed-back) to remain stable

4.5 K Cold Box Commissioning and Performance Testing (Cont.)

- Wide Range Cold Box Testing – LN Usage and Cold Box Efficiency
  - As evident from the table listed in the previous slide, tests at different cold box capacities ranging from minimum to maximum was performed
  - Any additional / artificial loads (other than the ones mimicking the cryo-module/magnet loads), such as throttling turbine inlet valves (or other exergy loss mechanisms) were not required for testing or stable operation of the cold box
  - LN usage was measured and cross-checked using 2 different methods
    - » Energy balance around LN pre-cooler and 300-80 K HX's using measured temperatures and helium mass flow rates
    - » Depletion rate of LN vessel (pot) with no LN supply to the cold box
  - Measured LN usage as compared to the (*T*-*s*) process design for the max. capacity, max. liquefaction, and max. refrigeration (i.e., a max. "CC", "L", and "R+Shield" type of load, respectively) was found to be approximately 35%, 90%, and 55% of the design, respectively

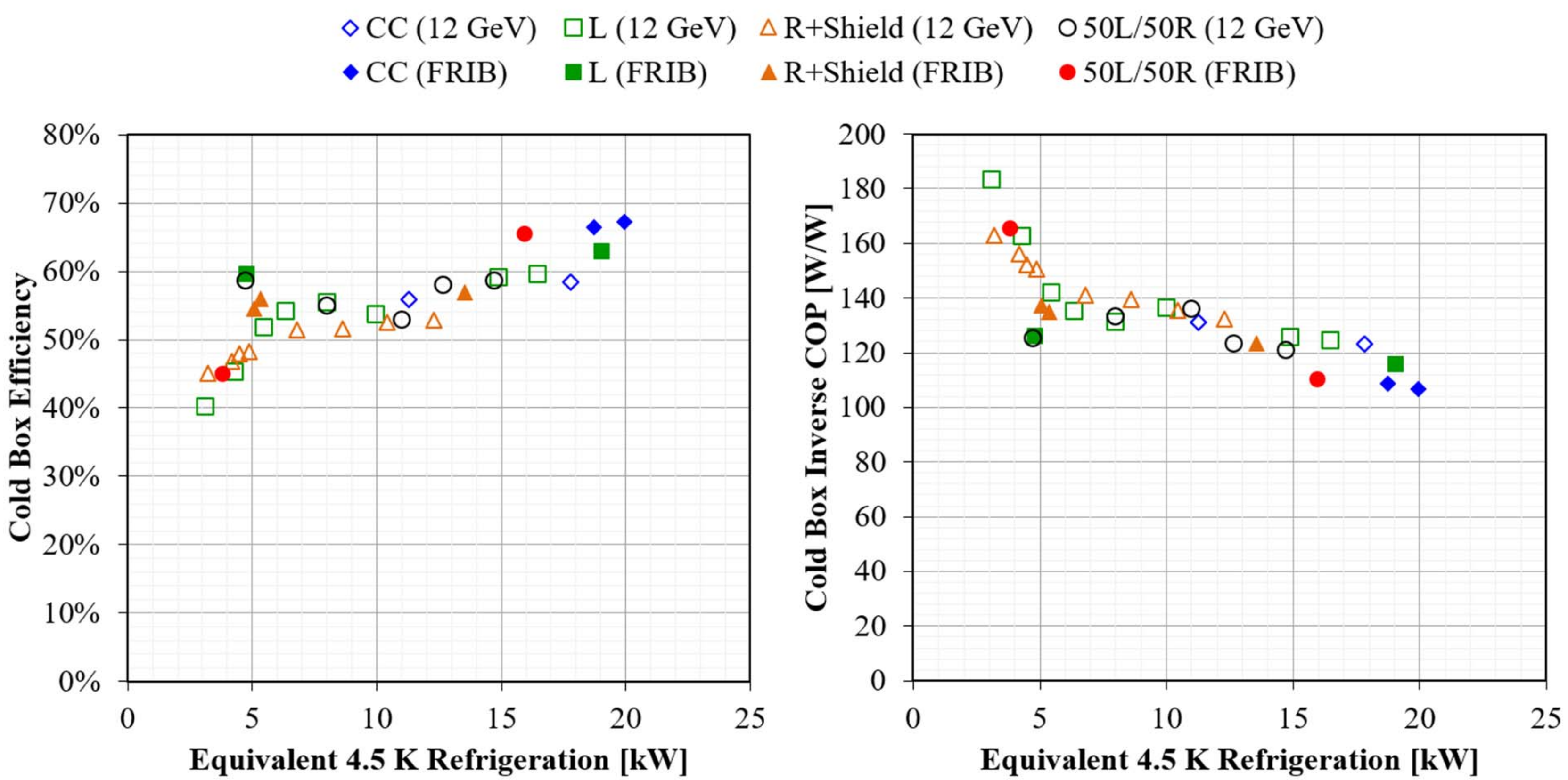
4.5 K Cold Box Commissioning and Performance Testing (Cont.)

- Wide Range Cold Box Testing – LN Usage and Cold Box Efficiency (Cont.)
  - One of the 1st stage (LP to MPH) compressors was unavailable during testing and the stand-by compressor (swing, LP to HP) was operated
  - MCS arrangement during testing is different from the 12 GeV performance testing compressor configuration
  - Data from JLab 12 GeV cold box performance testing and the data from the testing conducted in the spring of 2018 on the FRIB cold box is compared on the basis of the ideal (theoretical, reversible) isothermal input power; i.e., the 'cold box efficiency'



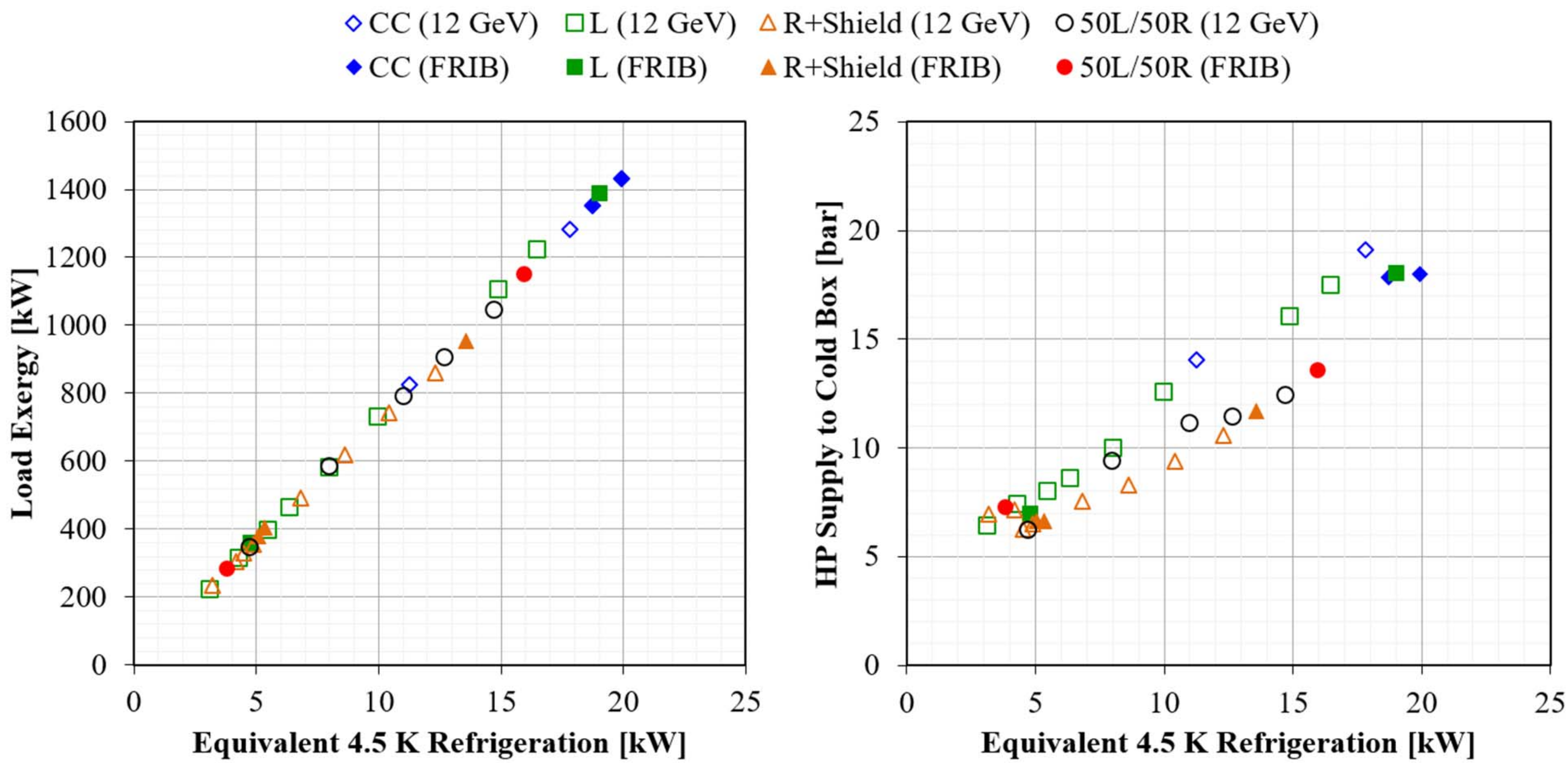
FRIB MCS Configuration during Spring 2019 Performance Testing

4.5 K Cold Box Commissioning and Performance Testing (Cont.)



Cold box inverse COP and efficiency vs. equivalent 4.5 K refrigeration load

4.5 K Cold Box Commissioning and Performance Testing (Cont.)



Total load exergy and HP supply pressure to the 4.5 K cold box vs. equivalent 4.5 K refrigeration load

4.5 K Cold Box Commissioning and Performance Testing (Cont.)

- Wide Range Cold Box Testing – LN Usage and Cold Box Efficiency (Cont.)
  - Analysis indicates reasonable corroboration of measured mass flow rates over test range
    - » Venturi flow meters at interface between compressor and cold box system and,
    - » 4.5 K cold box venturi meters at inlet to each turbine string had reasonable corroboration
  - Many mass flow and energy balance cross-checks were performed
  - Uncertainty analyses for the venturi flow meters and test heaters was performed
  - Over the entire range of conditions tested, the turbine strings (i.e., T1-T2, T3-T4, T5-T6, and T7) appear to be operating at an average adiabatic efficiency of 81.5 to 87.5% with a standard deviation of about 1.8%

Summary and Conclusions

- Testing has demonstrated that like the JLab 12 GeV refrigerator, the FRIB refrigerator has good efficiency or a wide capacity range and load type
- The natural load following process allowed for an efficient cryogenic system operation anywhere from a 6.0 to 21.0 bar supply pressure without any active control
  - This is while minimizing utility usage, and as the FRIB Linac has been progressively commissioned beginning in May 2018 with Linac segment one (LS1) and culminating this summer with Linac segment three (LS3)
- In addition to the helium cryogenic systems for the NASA-James Webb and JLab 12 GeV projects, this has proven to be another example of the efficiency and robustness of the implementation of the Ganni-Floating Pressure Process
- FRIB expresses it appreciation to Linde Engineering North America (Tulsa) and Linde Kryotechnik AG for their contribution to the success of this project