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Advancements and Challenges in Large-Scale Cryogenics for Accelerator Facilities

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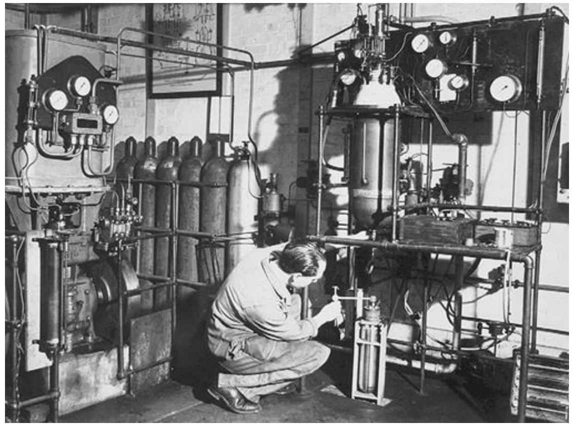
Outline

- Background: Helium Cryogenics for Particle Accelerator Facilities
- Motivation toward Designing an Efficient System
- Cryogenic System Design for Efficient Wide-Range Operation
  - Ganni Floating Pressure Process Cycle
  - Development of Warm Compressor Skids
  - Development of Cold Box System
- Sub-atmospheric (2.0 K) Refrigeration System
- Quench Handling and Inventory Management
- Present Challenges
  - Small-scale 2.0 K Systems
  - Helium Recovery and Purification
- Summary and Path Forward

Background: Helium Cryogenics for Particle Accelerator Facilities

- Large-scale 4.5 K / 2.0 K cryogenic systems are a foundational support system for modern superconducting accelerator systems
  - Helium was first liquefied by Heike Kamerlingh Onnes in 1908
  - S.C. Collins and his colleagues at MIT developed (1946) the first practical liquefier with expansion engines
  - In the late 1960s, the first Collins helium refrigerator located at Brookhaven National Laboratory (BNL) (~200W at 4.5K) and the refrigerator at Stanford University (300W at 1.8K), designed by Sam Collins, were considered as large cryogenic plants
- These are highly energy intensive systems. Present day large-scale helium systems (kW-class) can require approx. 800-1100 Watts of input power for every 1 Watt of cooling at 2 Kelvin (30 mbar)



Photos in clock-wise order:
Stanford University 300W at 1.8 K Helium Liquefier (1969)
S.C Collins Helium Liquefier at MIT (1946)
Kapitza's liquefier at the Cavendish Laboratory (1934)

Motivation toward Designing an Efficient System

- By the end of 20th century, the plant sizes grew substantially to more than 25 kW at 4.5K (BNL) and 4.6 kW at 2.0 K (Jefferson Lab, or JLab)
  - Relatively rapid change to large systems that were *not consistently used at their maximum capacity and/or were used for modes different than those for which they were designed*
- Traditionally, cryogenic systems were designed based on a modified Claude-Brayton cycle (*i.e.*, constant-pressure process) and operated with the philosophy of the earlier systems (constant maximum load)
  - Actual load imposed on the cryogenic system are often lower than the design load and system exergetic efficiency falls off at part-load
  - In most cases, the equipment are not designed to operate at part-load maintaining system stability

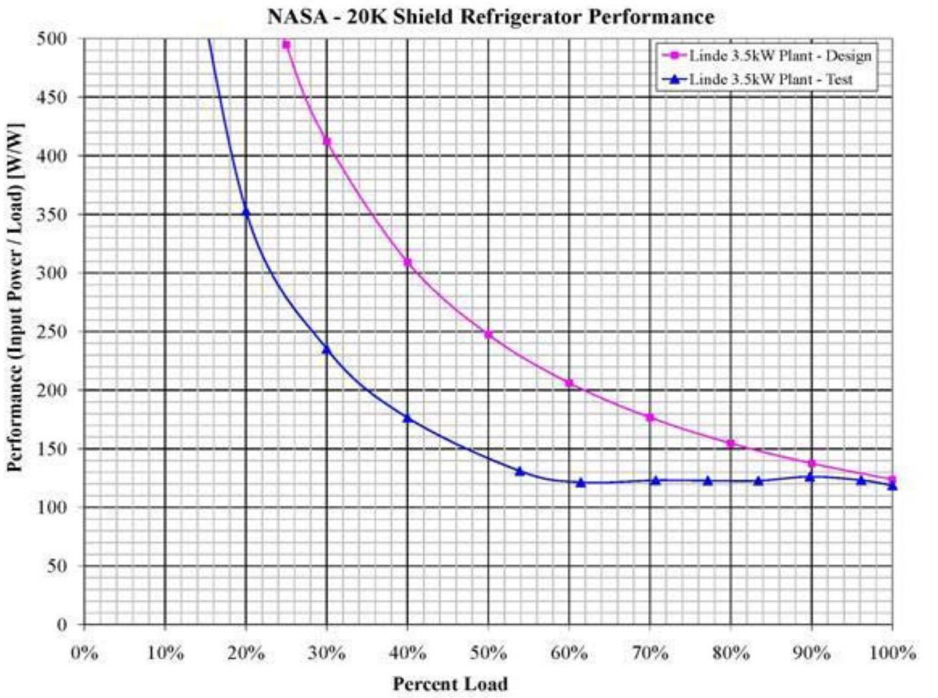
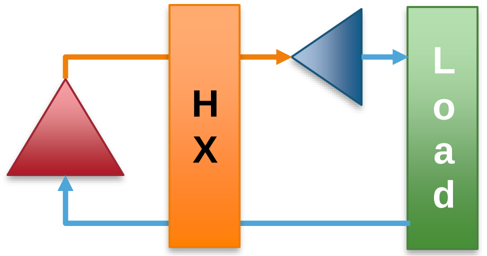
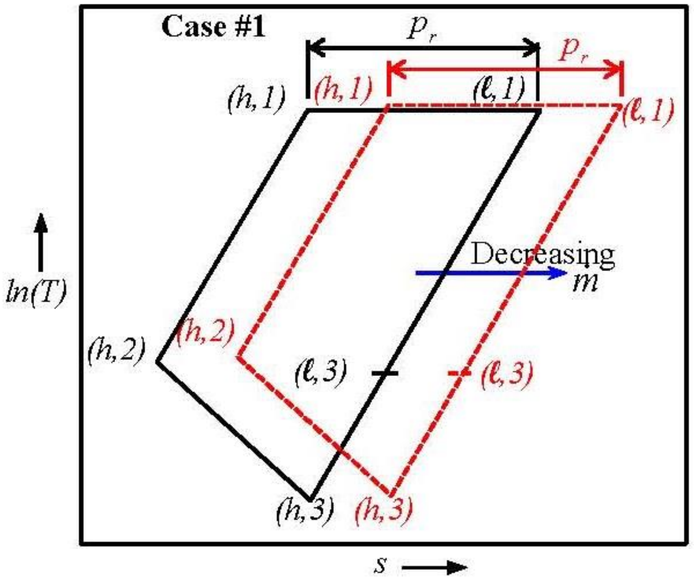


Figure:
Effect of Part-Load Operation on original NASA-JSC Cryogenic System (3.5 kW @ 20 K) Inverse COP
(Homan, 2013)

Cryogenic System Design for Efficient Wide-Range Operation
Ganni Floating Pressure Process Cycle

- Based on operational experience, it has been recognized that a system design based on a constant pressure ratio will lead to an optimal system design and improved efficiency of operating systems with the added benefits of stability
  - It is applicable to both new and existing systems with traditional processes and equipment (compressors, expanders, heat exchangers)
  - Requires a *balanced design* of the equipment / sub-systems to take full advantage of the process
- Both the expander and compressor are essentially constant volume flow devices, so for a given mass charge they set their own inlet pressures
  - Compressor establishes the system suction pressure and expander establishes the system discharge pressure
- With these, the gas charge establishes the system mass flow rate
- If left *unconstrained*, these two devices establish (for a given gas charge)
  - Essentially constant pressure ratio and, *constant Carnot efficiency*



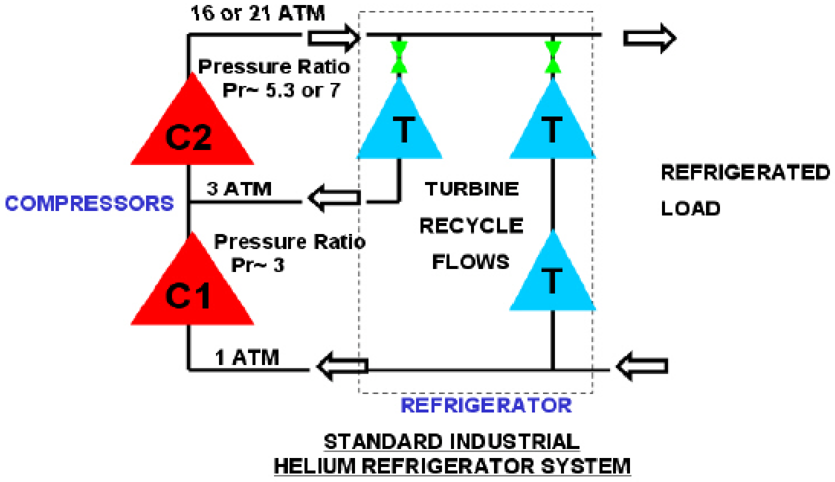


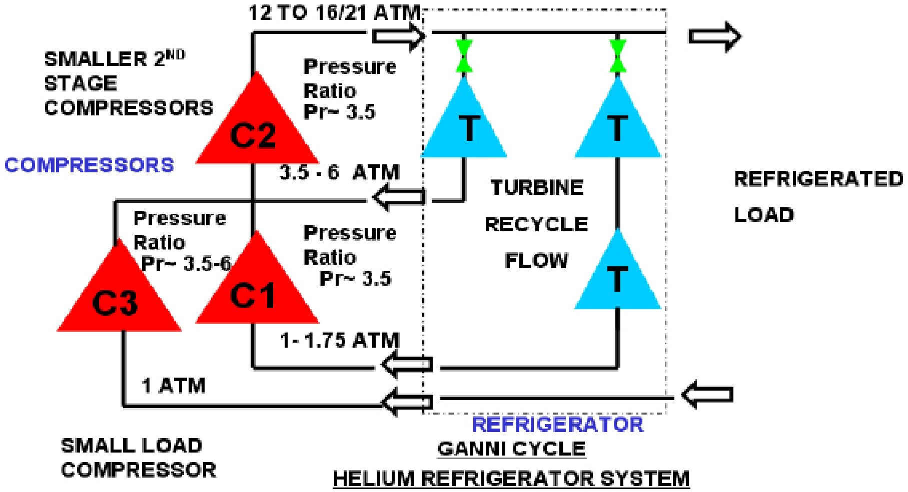
Cryogenic Cycle T-s diagram with load variation (decrease in mass flow rate) from maximum design point (Ganni, 2009)

Cryogenic System Design for Efficient Wide-Range Operation

Ganni Floating Pressure Process Cycle

- So, how does this apply to helium (4.5 K) liquefiers and refrigerators?
  - For liquefiers and mix-mode systems, 60-90% of the total system flow is through the turbines (providing the cooling)
  - ~2/3rd of the total system losses are in the compressor system; so we must consider what this means to properly match the compressor and cold box system
- Warm compressor (either 1st stage or 2nd stage) isothermal efficiencies are maximum around a *pressure ratio* of 3-4
- In traditional helium cycles poor pressure ratio matching results in greater losses in 2nd stage compressors (which require the largest fraction of the electrical input power).
- In Ganni Floating Pressure cycle, good (optimum) pressure ratio matching between *newly designed components*
  - Resulting in low losses for both stages.
  - Flow from load is separated from turbine flow (it is a smaller fraction of the total flow).



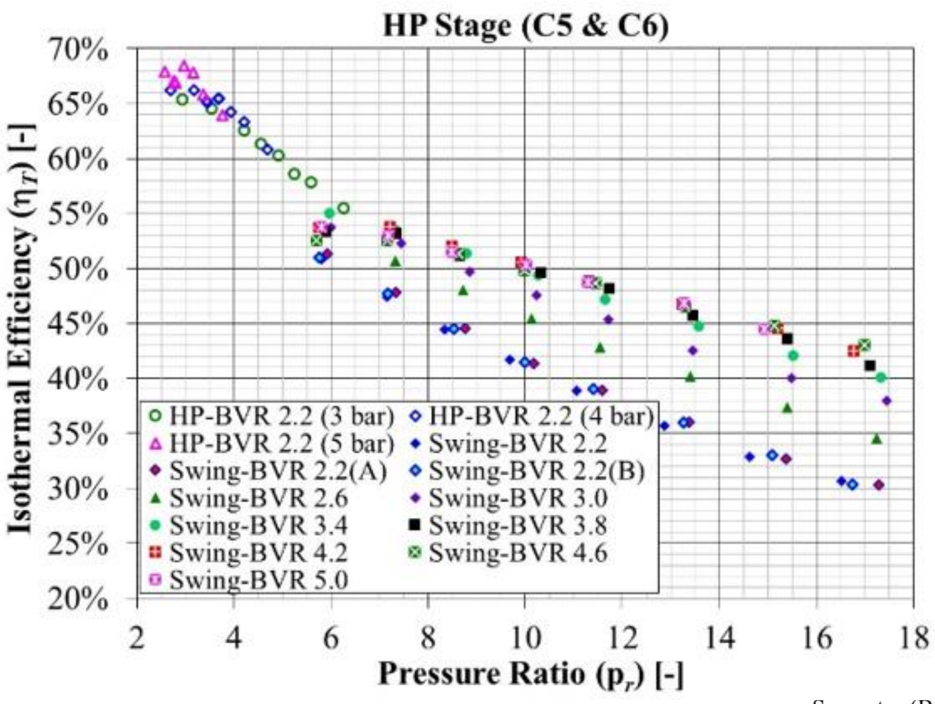


Cryogenic System Design for Efficient Wide-Range Operation
Development of Warm Compressor Skids

- The conventional oil injected rotary screw helium compressor systems are restricted in the suction and discharge pressure ranges that they can operate; especially regarding their bulk oil separation (BOS) process.
- The R&D opportunity emerged during the design and specification of a 12 kW, 20 K helium refrigeration system for NASA-JSC by US-DOE's Jefferson Lab (JLab).
- Several modifications to the oil injection and re-circulation system (compared to traditional designs) were made.
- This compressor skid design was further refined for JLab's 12 GeV upgrade project with the addition of a completely new type of bulk oil separator (BOS).
  - Horizontal vessel composed of a short cyclonic separation section followed by and inertial separation section.
  - There are no glass-fiber coalescing elements (unlike traditional designs)

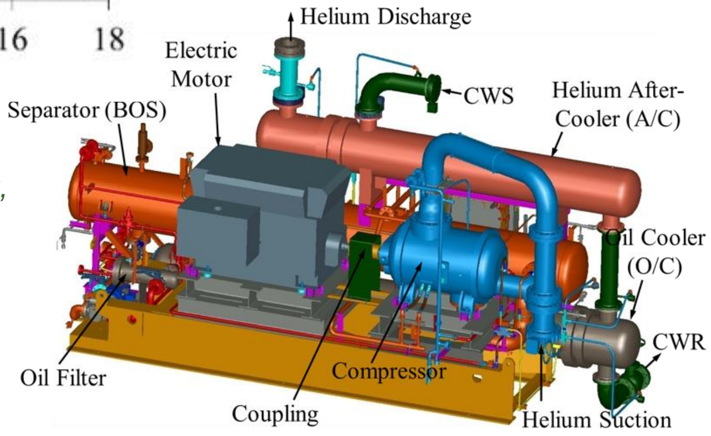
Cryogenic System Design for Efficient Wide-Range Operation

Development of Warm Compressor Skids



- At present, these compressor skids are being used 24/7/365 (50k – 100 k hrs of operation) at:
  - JLab (12 GeV) cryogenic system, since 2013
  - Facility for Rare Isotope Beams (FRIB) cryogenic system, since 2017
  - SLAC's LCLS-II cryogenic system, since 2020
- The FRIB swing stage compressor (C6) demonstrated operation from 6.0 bar to 18.0 bar of discharge pressure at approx. 1.05 bar suction pressure

Figure:
(top) FRIB HP stage helium compressor isothermal efficiency, Knudsen, 2019
(bottom, left) JLab 12GeV Compressor Skid
(bottom, middle), FRIB Helium Compressor Skids
(bottom, right) FRIB Final Oil Removal System



Cryogenic System Design for Efficient Wide-Range Operation
Development of Cold Box System

- In a cryogenic cold box, demand on equipment varies substantially between the types of loads
  - Deviations from this design load involve not only a deviation in overall capacity, but often this indirectly also results in a deterioration in the type of load (e.g., refrigeration, liquefaction).
  - Liquefaction dominated load governs the design / selection of expander flow coefficients and expander brake requirements, while refrigeration dominated load governs the heat exchanger performance requirements and the cold end component sizing.
  - The performance of the cryogenic system under other operating modes (e.g. minimum / stand-by capacity) are cross-checks for possible operational scenarios to verify that an unexpected condition does not occur.
  - A balanced plant design considering these factors at the start do not unnecessarily restrict the plant capacity under different modes and very little impact on in capital cost

Cryogenic System Design for Efficient Wide-Range Operation
NASA-JSC 12 kW @ 20 K Cold Box for SESL

- Following the methodology described, The NASA-JSC cryogenic system was designed to support a variable load from 100 kW at 100 K to 12.5 kW at 20 K, utilizing the Ganni Floating Pressure process cycle.
  - Design and requirements for turbo-expanders supporting such a wide range of load (approx. 2-25 kW at 20 K) was established Linde Process Systems and JLab
  - Automatically support loads at 20 K from 30% to 100% at practically constant efficiency within ±0.1 K.

NASA-JSC 12 kW @ 20 K Plant (2012)

JWST Testing at NASA-JSC Chamber A (2017)

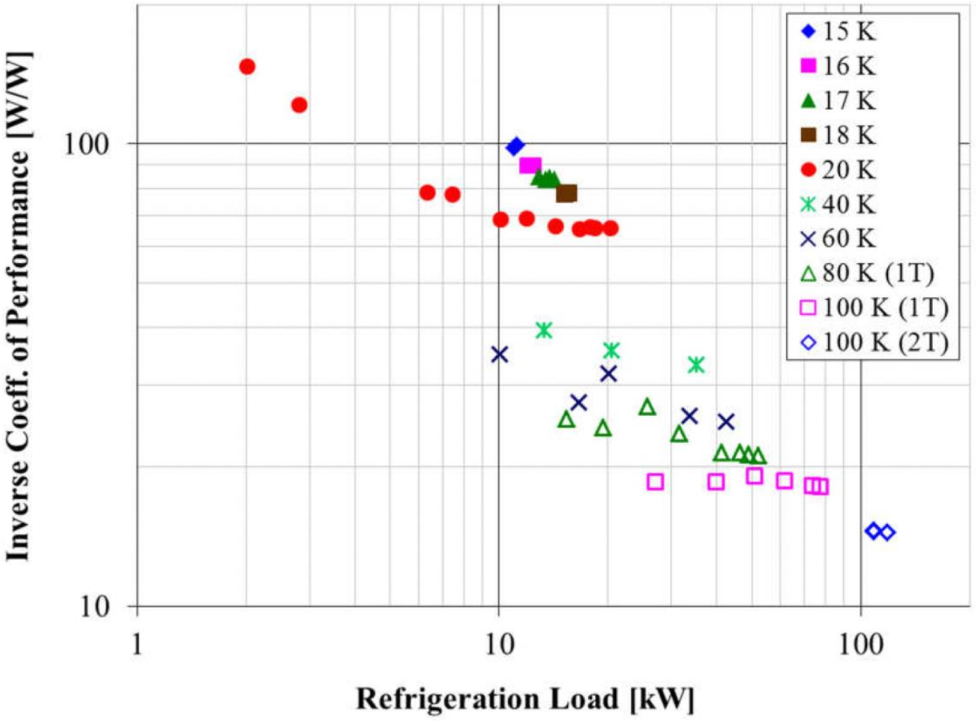


Figure:
Effect of Part-Load Operation on NASA-JSC Cryogenic System (3.5 kW @ 20 K and 12 kW @ 20 K) Inverse COP (Cerimele, 2018)

Cryogenic System Design for Efficient Wide-Range Operation
JLab 12 GeV 4.5 K Cold Box

- The cryogenic cold box for JLab's 12 GeV project (Central Helium Liquefier 2) was also designed as a balanced plant taking full advantage of the Ganni Floating Pressure process cycle
  - JLab performed the process design, sizing and selection of all major components, as well as the cold box internal component and piping design.
  - Testing showed excess LN use; corrected by the vendor
  - Realized performance parameter affecting long. conduction in 300-80 K HX for excess LN use


JLab 12 GeV Warm Compressor (2014)



JLab 12 GeV 4.5 K Cold Box (2014)

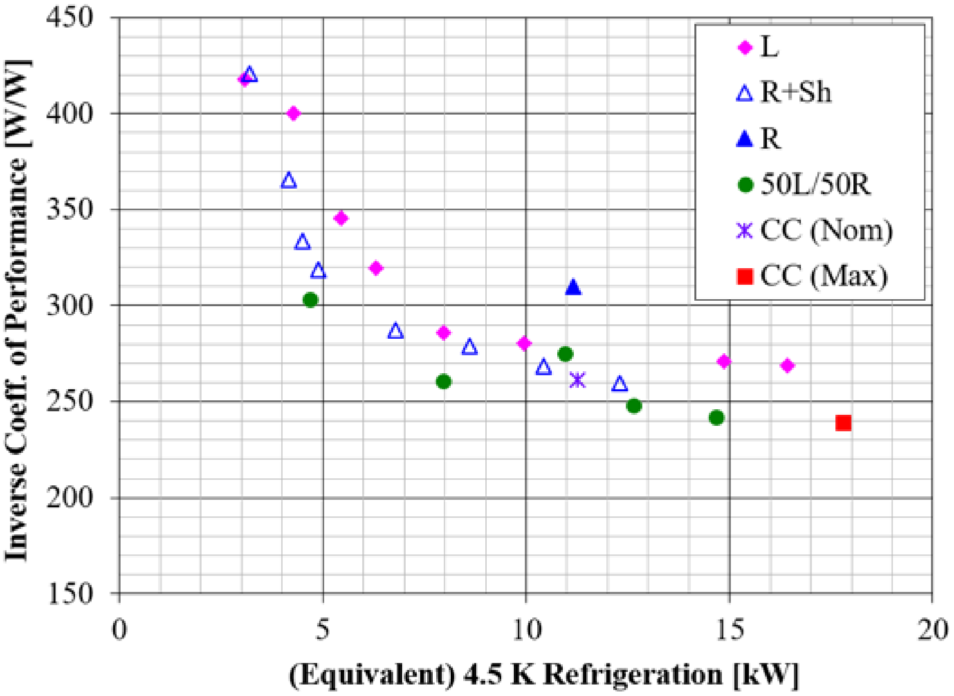


Figure:
Effect of Part-Load Operation on JLab 12 GeV 4.5 K Cold box Inverse COP (Knudsen, 2016)

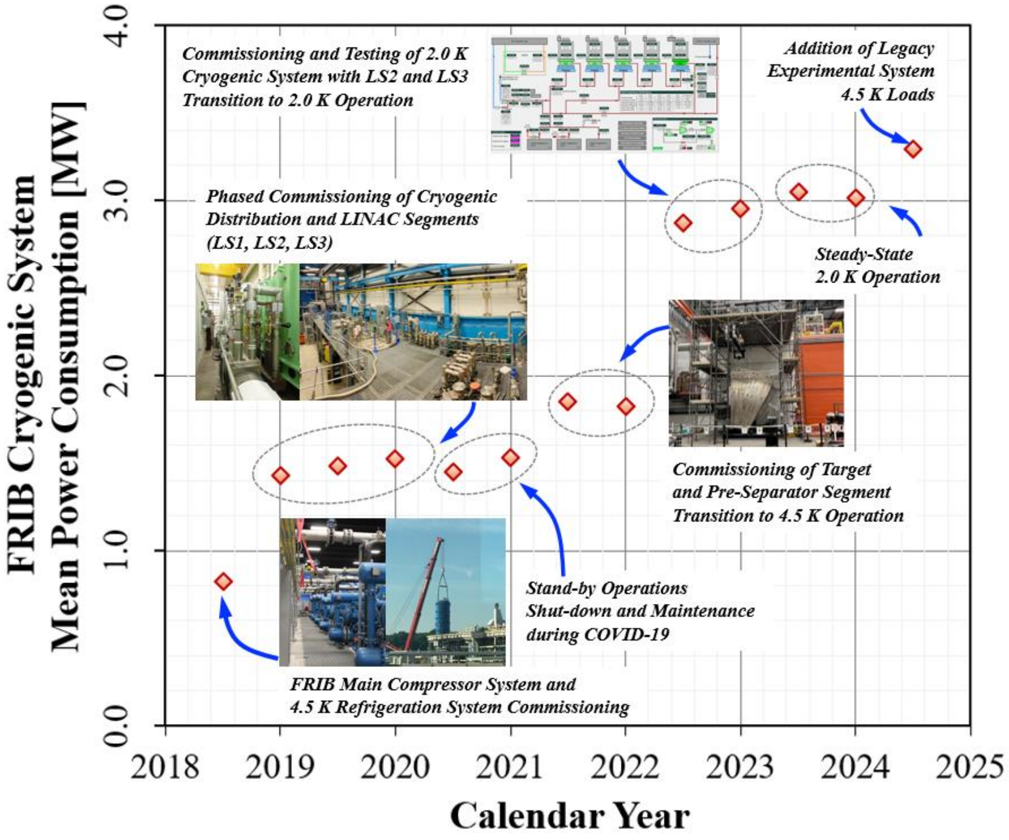
Cryogenic System Design for Efficient Wide-Range Operation

FRIB 4.5 K Cold Box

- FRIB cold box design was adapted from JLab 12 GeV with minor equipment modification to match different types of loads which have approximately the same total load exergy (equivalent to approx. 18.5 kW at 4.5 K).
  - Operates using Ganni Floating pressure process cycle; commissioned in 2017 (similar to JLab 12 GeV CBX performances)
  - The 300-80 K HX was redesigned, resulting in unprecedented reduction in LN use
  - The cryogenic system used very low energy during the 4 year accelerator incremental commissioning; resulting in substantial savings

FRIB Warm Compressor (2017)


FRIB 4.5 K Cold Box (2017)



Cryogenic System Design for Efficient Wide-Range Operation
Application of Ganni Floating Pressure Process Cycle over the years

- Fundamental aspects of the Ganni Floating Pressure process were originally conceptualized and subsequently applied to the cryogenic system for the Superconducting Super Collider Laboratory (SSCL) string test plant (known as ASST-A) in 1992
  - Partially implemented in traditionally designed cryogenic systems (JLab Central Helium Liquefier 1, ORNL-SNS cryogenic system).
  - Turn-down capacity and efficiencies are limited due to the unbalanced design
  - Appropriate design / modifications to such systems are technically feasible
  - Demonstrated by the BNL-RHIC cryogenic system (2002-2007). Phased modifications performed on this system caused an input power reduction from 9.4 MW to 5.0 MW for the same cryogenic load
  - Fully implemented for NASA-JSC (2012), JLab 12 GeV (2016), FRIB (2017)
  - Presently designing FRIB Exp. System Cold Box

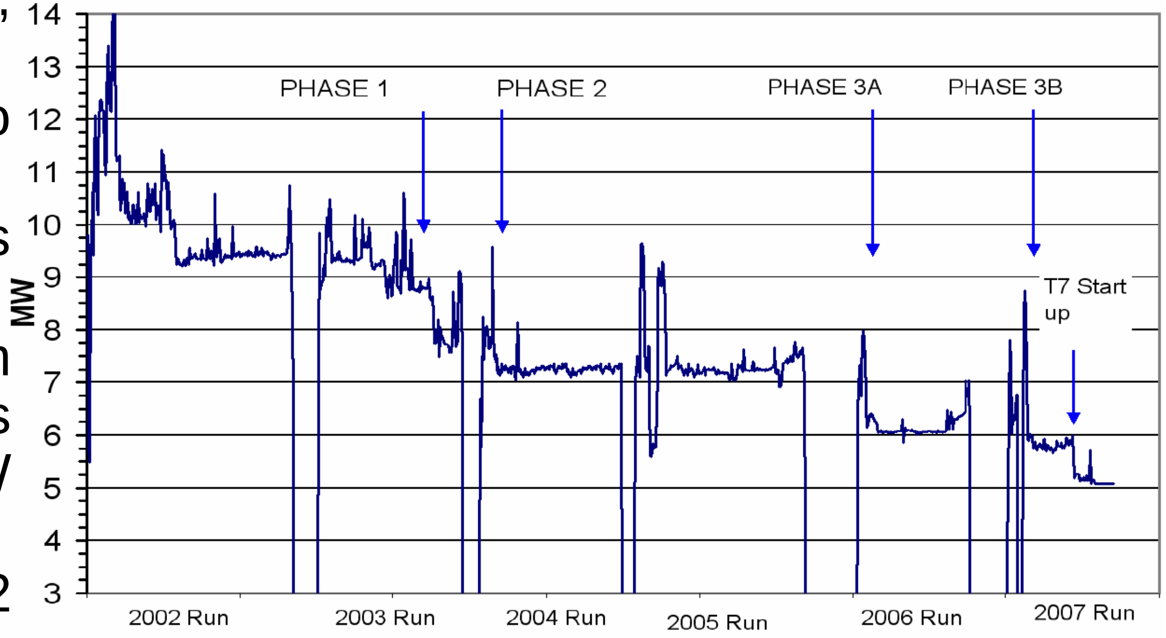


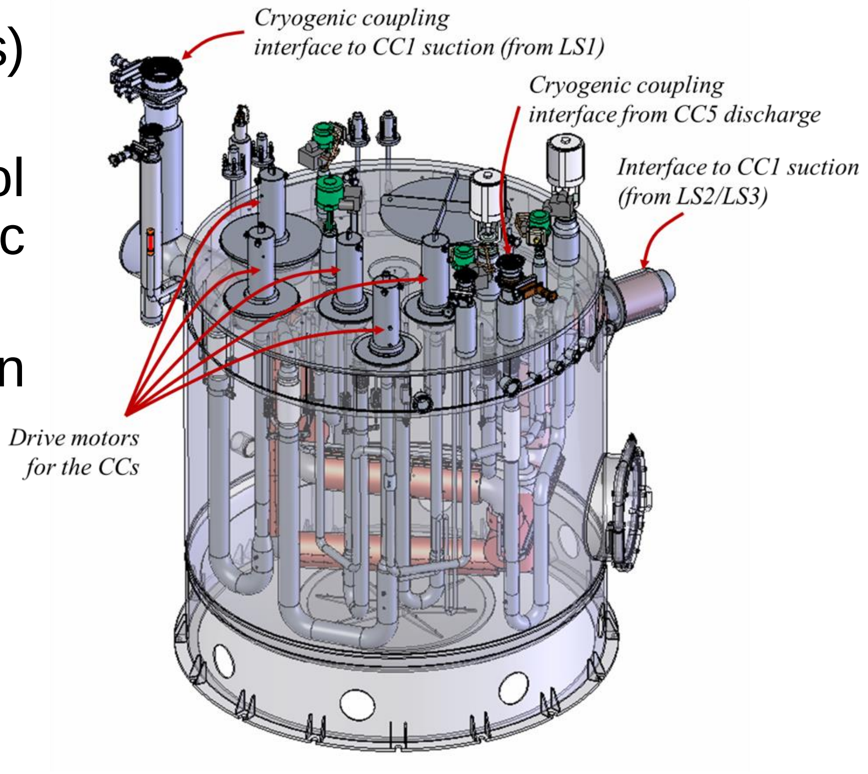
Figure:
BNL Cryogenic System Overall Power Consumption, Than, 2008

Sub-atmospheric (2.0 K) Refrigeration System
System Efficiency, Operational Stability and Turn-down Capacity

- Advancement in the sub-atmospheric cryogenic compression technology over the last several decades has been driven by the increased interest in SRF technology (requiring 2.0 K)
  - For large-scale systems, the most practical approach is to use multi-stage cryogenic centrifugal compressors (CCs) to fully recompress the sub-atmospheric helium returning from the load
  - Over the year, the isentropic efficiency of re-compression using CCs have increased from 55% at Tore Supra (1988) to nearly 75% at FRIB (2018)
  - Recent developments (2010 onwards) in high-speed VFD with AMBs has significantly improved the operational stability and the turn-down capacity
  - Turn-down capacity / stability of the CC mass flow rate is a major factor in terms of cost savings. A g/s reduction in CC mass flow can result in a 15 – 20 kW reduction of input power at the main compressor
  - The overall cryogenic system operational cost savings from turning down the CC flow (liquefaction load) can significantly outweigh the energy cost savings of lower compression efficiency
  - Energy savings for this kind of turn-down can only be realized if the 4.5 K refrigeration system can also turn-down efficiently over this range

Sub-atmospheric (2.0 K) Refrigeration System
FRIB Sub-atmospheric System Wide-Range Operation

- The FRIB CC train was designed for a wide range of operating loads (based on program requirement) by the vendor (Air Liquide Advanced Technologies) in collaboration with the FRIB cryogenics department
  - The overall design and fabrication of this cold box (except the CCs) was performed completely in-house at FRIB.
  - Further R&D of the pump-down, steady-state operation and control philosophy was carried out recently through MSU Cryogenic Initiative
  - Theoretical models were developed to eliminate reliance on empirical and statistical methods employed traditionally.



Sub-atmospheric (2.0 K) Refrigeration System
FRIB Sub-atmospheric System Wide-Range Operation

- In collaboration with Air Liquide Advanced Technologies, appreciable progress was made in understanding the physical characteristics of the multi-stage centrifugal cold-compressor sub-atmospheric system at FRIB during transient and steady-state operation
  - System has a considerable operating range, and a turn-down of nearly 2 to 1 at the operating condition (approx. 30 mbar)
  - Methodology developed for the FRIB sub-atmospheric system can be applied to other large-scale sub-atmospheric cryogenic facilities utilizing cold-compression

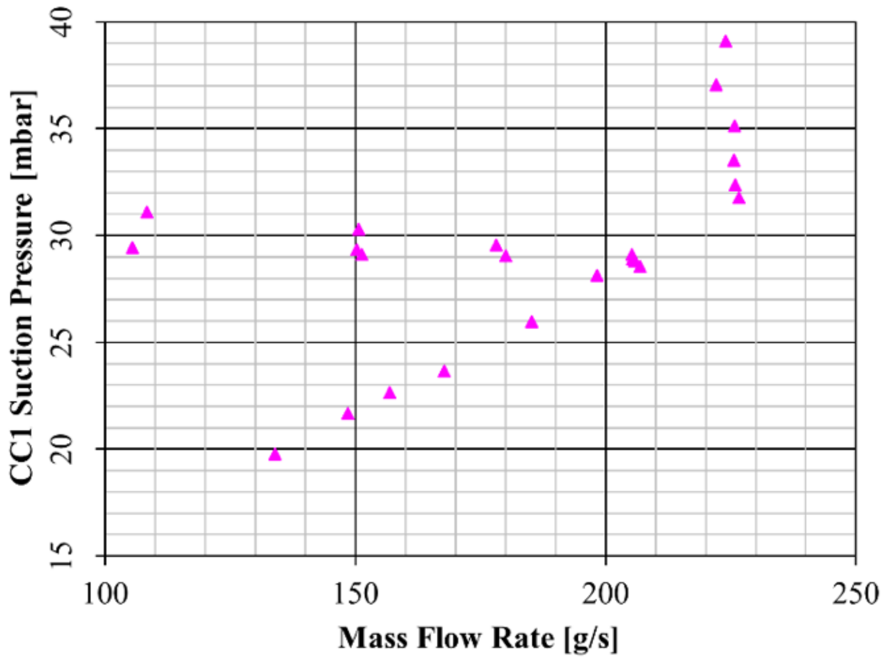
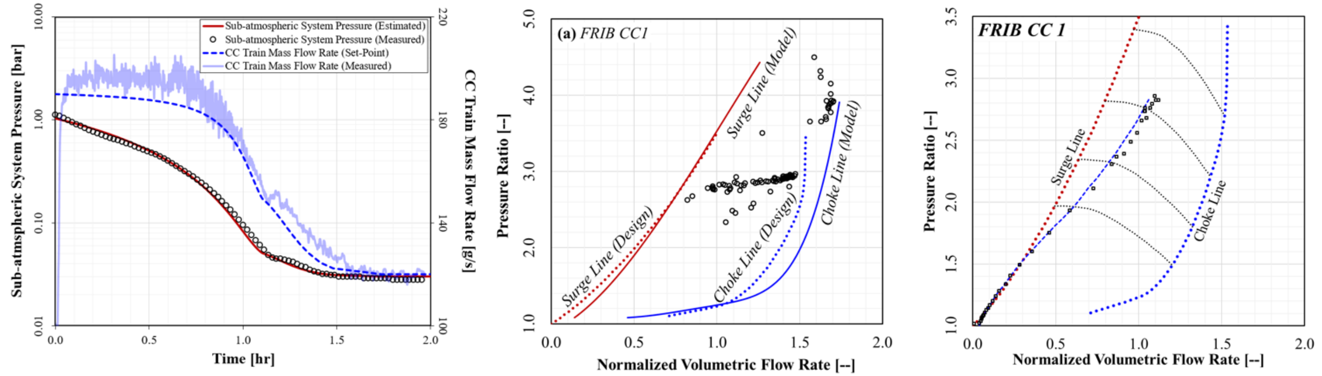


Figure:
(top) Measured performace characteristics of FRIB CC Train, Kundsen (2019)
(bottom) Predictive model development for pump-down of CC train to operating point, Howard (2024)

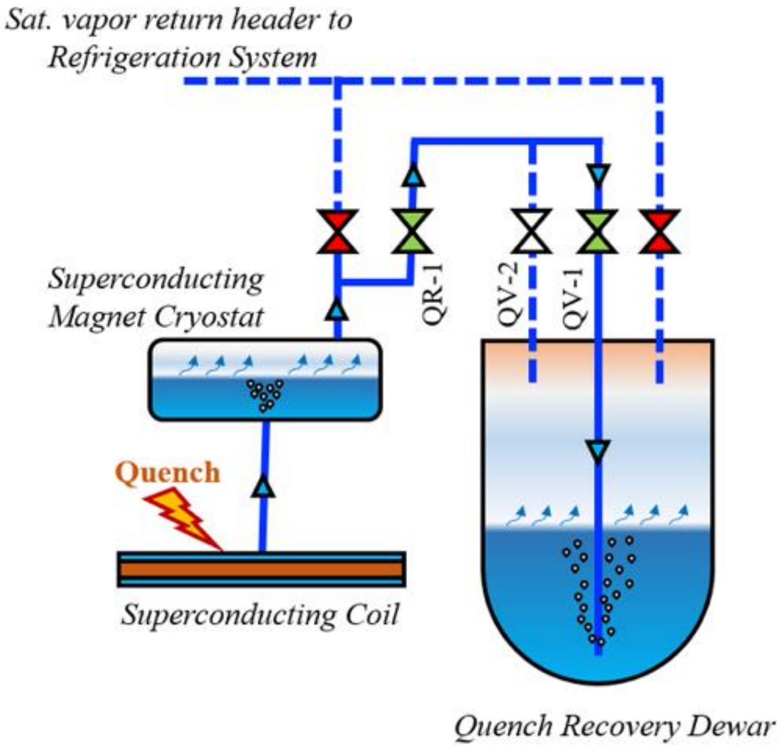


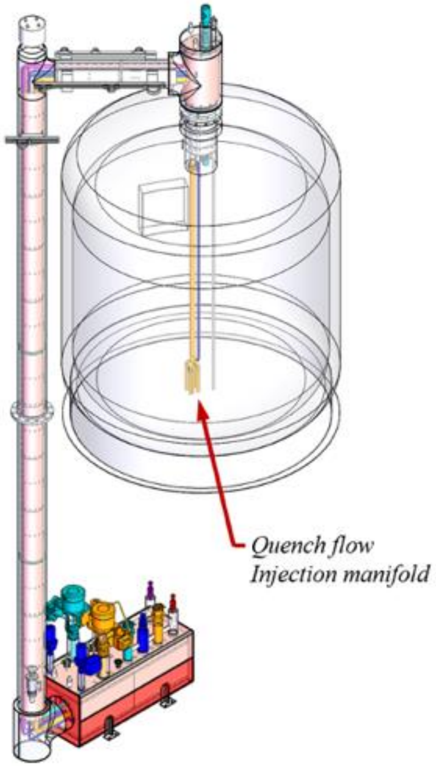
Magnet Quench Handling and Inventory Management
Operational Stability and Helium Preservation

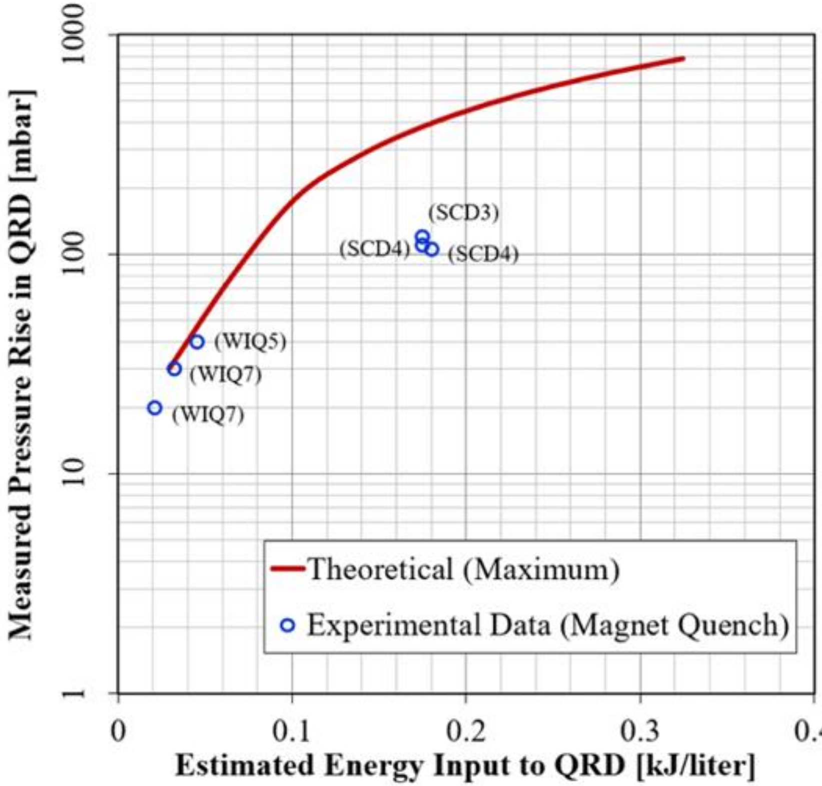
- Traditionally, a quenched low temperature superconducting (LTS) magnet is isolated from the rest of the cryogenic system and the cryogen (helium) is expelled from the LTS magnet cryostat via a pressure relief valve (PRV) to prevent over-pressurization.
  - Results in a loss of both the cryogenic coolant, which is release to atmosphere, and the associated stored refrigeration in the fluid.
  - Causes unnecessary operational cost to both replenish the helium and to recover the quenched LTS magnet.
- A novel method of using a cryogenic buffer volume to absorb both the mass and energy release during the quench of a LTS magnet was first conceptualized at SSCL for magnet string testing
  - This process has been designed and implemented for the FRIB experimental system superconducting magnets by incorporating a 10,000 liter (nominal) cryogenic dewar vessel (Hasan, 2021)
  - Following a quench, the stored refrigeration is recovered by the FRIB cryogenic refrigerator by depressurizing the buffer volume.
  - This doesn't pose a risk to the refrigerator stability or operation of the rest of the loads, due to the implementation of the Ganni Floating Pressure process cycle

Magnet Quench Handling and Inventory Management
Operational Stability and Helium Preservation

- The quench handling system at FRIB was commissioned in April 2021.
  - To date, there have been 20+ recorded events of a quench with the quench handling system absorbing each of these without affecting the cryogenic refrigerator or other operating magnets and without venting helium.





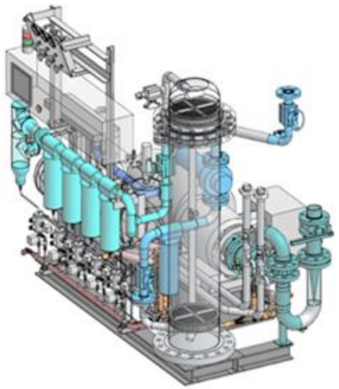


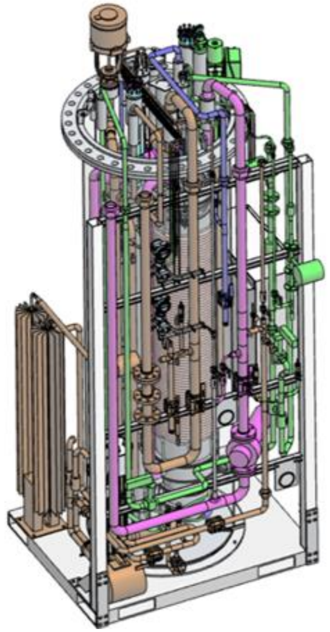
Present Challenges: Small-scale 2.0 K Systems

- The optimal design of 2.0 K refrigeration system using full cold-compression (i.e. higher efficiency, smaller footprint, and lower capital cost) becomes challenging at lower capacities due to reduced volumetric flow rates.
  - Either custom design-engineered systems or what is known as direct vacuum pumping systems are used
  - Direct VPS have the advantage of being relatively inexpensive to purchase and easy to implement, but are quite power intensive
  - Many require more than 3200 Watts of input power per 1 Watt of cooling (at 2 K, or around 30 mbar), but can easily require twice this input power
  - Many are plagued with contamination problems
  - A preliminary process study (Knudsen, 2009) indicates it is very reasonable to achieve a small-scale system efficiency of better than 1500 Watts of input per 1 Watt of cooling at 2.0 K
  - Goal is to develop a build-to-print design for a small 2.0 K refrigeration system combined with existing *off-the shelf* 4.5 K refrigerator

Present Challenges: Helium Recovery and Purification

- Helium recovery and purification systems are necessary to support commissioning and operation of the cryogenic refrigerators, and associated sub-systems used in particle accelerators.
  - Traditional designs are not effective, has high utility consumption
  - R&D effort is underway at MSU Cryogenic Initiative (Freeze-out Purification, Variable speed warm compressor – helium recovery, small-scale cryogenic system application)





Summary and Path Forward

- Progressive and synergistic development activities have been carried out over the last couple of decades that lead to the complete understanding and deployment of the Ganni Floating Pressure process cycle
  - It can be implemented for most refrigeration and/or liquefaction cycles (new or existing systems) - improved efficiency with turn-down
  - Stable and efficient long-term operation has been demonstrated at multiple US-DOE particle accelerator facilities.
  - Some practical challenges relating to cryogenic sub-systems (helium recovery, purification) and scalability (small-scale 2.0 K) remains to date

- MSU-FRIB Cryogenic initiative was established in 2017, to train the future generation work force (through undergraduate and graduate research)
  - Actively involved in advancing the understanding and application of various critical cryogenic system / processes important to FRIB and the other existing and future superconducting accelerators