21st International Conference on Radio-Frequency Superconductivity (SRF 2023)

Tutorial Lecture on

Cryogenics

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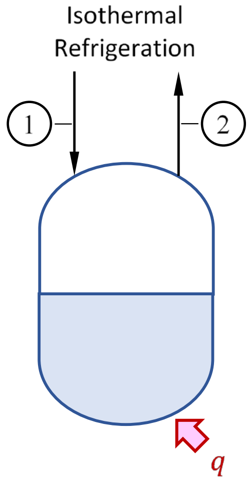
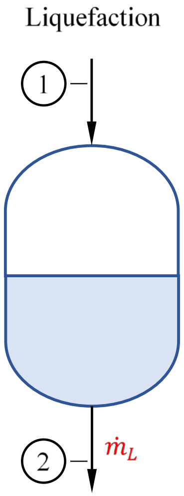
Cryogenic Engineering

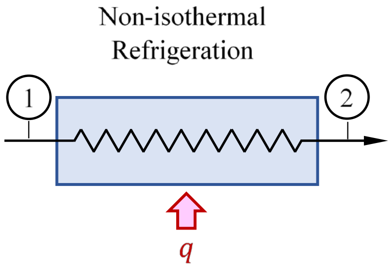
- Cryogenic Engineering
  - What is it?
    - It is…the *research of the governing physics and the design of thermal process equipment and systems that operate at cryogenic temperature*
      - i.e., at or below the temperature necessary to liquefy natural gas (NBP -260 F, or 112 Kelvin)
  - What is unique about it?
    - Very energy intensive processes; ~1 kilo-Watt of input power for every one Watt of cooling at 2 Kelvin
      - 2 Kelvin corresponds to saturated Helium at 30 milli-bar (3/100 of an atm)
    - Requires an understanding and proper application of non-constant and non-ideal fluid and material properties
    - Superconductivity and superfluidity (helium cryogenics) – both researched (fundamentally) and exploited for applications

Cryogenic Refrigeration / Liquefaction

- Cryogenic loads:
  - Isothermal (constant temperature) refrigeration;
    - heat into a saturated liquid bath, maintained at constant pressure
    - Involves phase change (at constant pressure) of refrigerant fluid
  - Liquefaction; liquid supplied and withdrawn from a saturated liquid bath, maintained at a constant pressure
  - Non-isothermal refrigeration; e.g., fluid sensibly heated



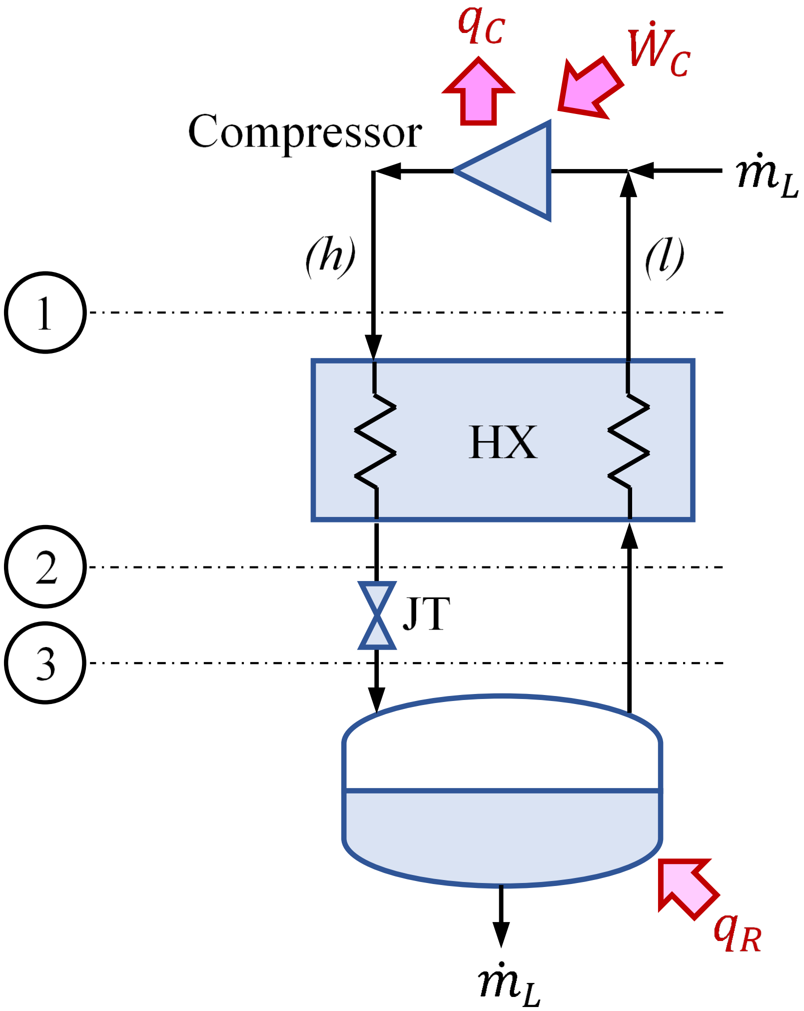




Cryogenic Refrigeration / Liquefaction [2]

- Generally, the overall capacity rate in a cycle for an isothermal refrigeration load is “balanced” (in the heat exchanger sense)
  - Although, with the actual process cycle, this may not be ‘locally’ true

- Generally, the overall capacity rate in a cycle for a liquefaction load is *not* “balanced” (in the heat exchanger sense)
  - This may be true over the entire temperature range (saturated fluid to ambient), or only for a portion of the temperature range



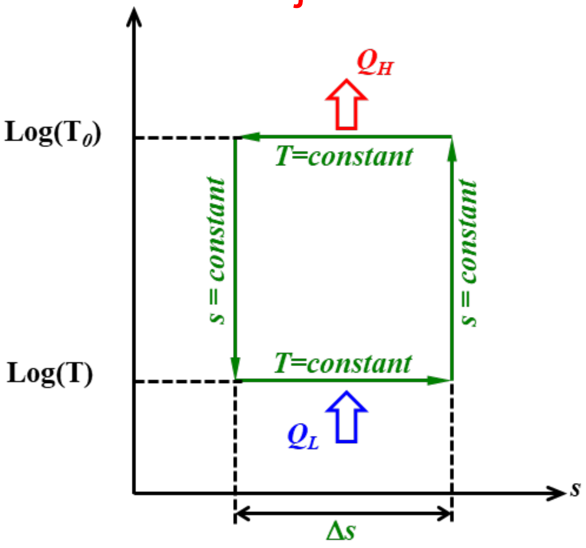
Cryogenic Refrigeration / Liquefaction [3]

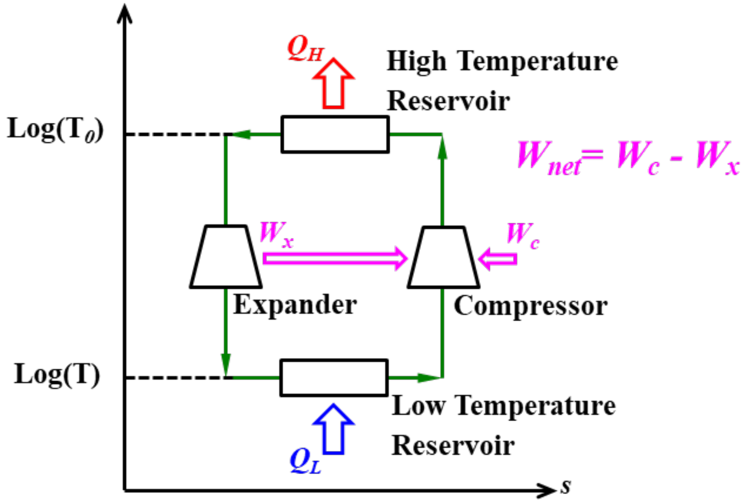
- Sometimes the wording used for an actual refrigeration cycle is ambiguous…
- A “refrigeration system”, “refrigerator”, and “liquefier” can have all of these loads.
  - However, usually a “refrigerator” refers to a system dominated by a refrigeration load
  - And, a “liquefier” refers to a system dominated by a liquefaction load
- Note: for refrigeration systems that have isothermal refrigeration and a liquefaction load, it does not take much of liquefaction load for the overall capacity rate to be non-balanced

Thermodynamic Basis
The Traditional Carnot Cycle

- Carnot cycle can be a heat engine, *transferring* heat from a high temperature reservoir to a lower temperature reservoir with a net work output
  - It can also be a refrigerator, operating in reverse and requiring a net work input
  - Carnot cycle does *not convert* heat energy!

- Carnot cycle demonstrates a result of the 2nd Law
  - » "It is impossible to construct an engine which will work in a complete cycle, and produce no effect except the raising of a weight and the cooling of a heat reservoir" (Max Planck, Treatise on Thermodynamics, 1897)
  - There must be heat rejection to the environment!





Thermodynamic Basis
The Traditional Carnot Cycle [2]

- 2^{nd} law tells us that for reversible heat transfer from a constant temperature (thermal) reservoir for this Carnot cycle,

$$\Delta S = Q_H / T_0 = Q_L / T$$

- And, from the 1^{st} Law, since we start and end at the same state point for a cycle,

$$\Delta E = 0 = \oint \delta W + \oint \delta Q = W_{net,rev} - Q_H + Q_L$$

  - Where, $W_{net,rev}$ is the net work input; i.e., total input work (W_c) minus total output work (W_x)

$$W_{net,rev} = W_c - W_x = \Delta S (T_0 - T)$$

- For an (isothermal) refrigerator, the coefficient of performance is defined as,

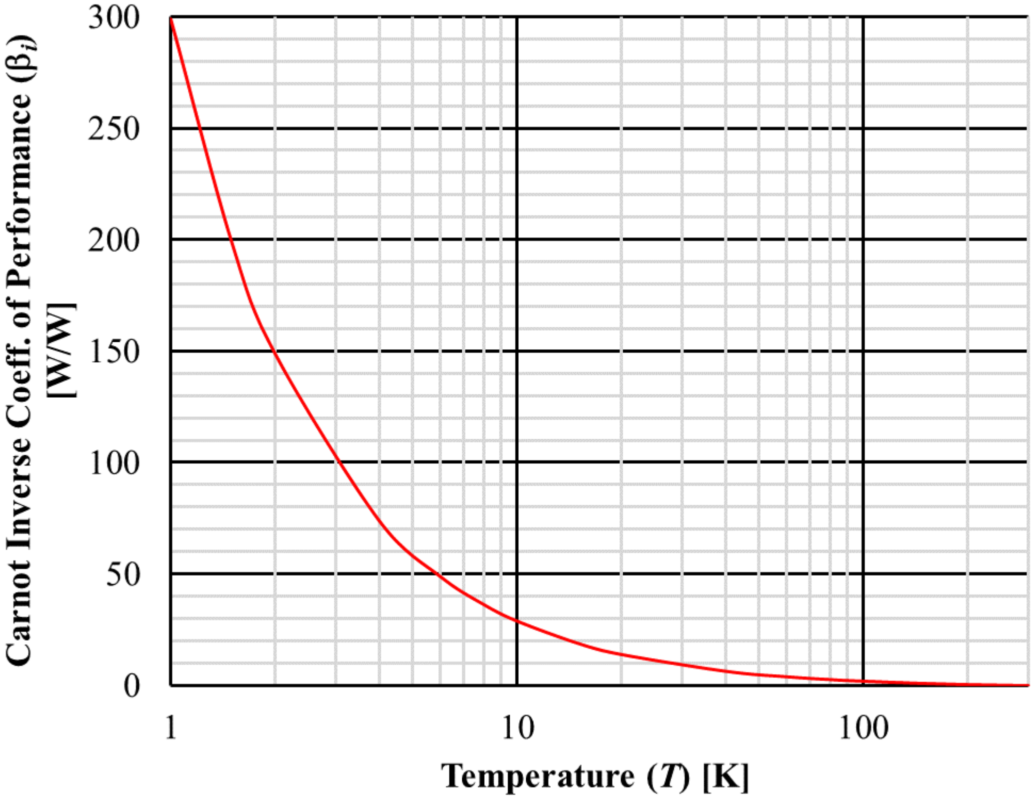
$$\beta \equiv \frac{Q_L}{W_{net,rev}} = \left(\frac{T_0}{T} - 1 \right)^{-1}$$

Thermodynamic Basis
The Traditional Carnot Cycle [3]

- More commonly in cryogenics, we refer to the inverse of the coefficient of performance, as it is more representative of the energy intensiveness of such processes; i.e., ratio of net input power to cooling provided to the load

$$\beta_i = COP_{inv} = \frac{T_0}{T} - 1$$

- Note that to arrive at this result, we did not have to assume anything about the process between the reversible isothermal heat transfer steps, except that the entropy difference was constant at a given temperature



Thermodynamic Basis
The Traditional Carnot Cycle [4]

- Below are some results for a number of refrigerants:

Name	Symbol	R #	MW [g/mol]	T_{sat} at p_0 [K]	λ [J/g]	σ [J/g-K]	w_{rev} [J/g]	β_i [W/W]
Refrigerant-11	CCl_3F	R-11	137.4	296.8	181.3	0.611	2.0	0.01
Refrigerant-134A	$C_2H_2F_4$	R-134a	102.0	246.9	217.0	0.879	46.7	0.22
Refrigerant-12	CCl_2F_2	R-124	120.9	243.4	166.0	0.682	38.6	0.23
Ammonia	NH_3	R-717	66.05	239.8	1369	5.708	343.5	0.25
Refrigerant-22	$CHClF_2$	R-22	86.48	234.3	230.4	0.992	67.1	0.29
Xenon	Xe		131.3	165.0	96.4	0.584	78.8	0.82
Krypton	Kr	R-784	83.80	119.8	107.9	0.901	162.4	1.50
Methane	CH_4	R-50	16.04	111.7	510.3	4.571	860.8	1.69
Oxygen	O_2	R-732	32.00	90.19	213.1	2.362	495.7	2.33
Argon	Ar	R-740	39.95	87.28	161.3	1.848	393.0	2.44
Nitrogen	N_2	R-728	28.01	77.31	198.9	2.571	572.4	2.88
Neon	Ne	R-720	20.18	27.09	85.7	3.164	863.4	10.1
Deuterium	D		4.028	23.66	320.9	13.77	3810	11.9
Para Hydrogen	p-H_2		2.016	20.28	445.4	21.97	6145	13.8
Helium-4	He	R-704	4.003	4.22	20.7	4.898	1449	69.9

- Note that we reference to 1.0 atm for the saturated condition, and λ is the latent heat at 1.0 atm.

- w_{rev} is the reversible (specific) input work required for isothermal refrigeration at T_{sat}

Concept of Exergy (Availability)

- Not all forms of energy (electric, chemical or thermal) are created equal.
- Quality of energy varies depending on form of energy, mode of storage, environment. Quality of a given form of energy depends on modes of storage (ordered or disordered).
- The quality (capacity to cause change) of disordered energy forms, characterized by entropy, is variable and depends both on the form of energy (chemical, thermal, etc) and on the parameters of the energy carrier and of the environment.
- Ordered forms of energy, which are not characterized by entropy, have invariant quality and are fully convertible, through work interaction, to other forms of energy.
- A universal standard of quality is needed. The most natural and convenient standard is the maximum work which can be obtained from a given form of energy using the environmental parameters as the reference state.

- This standard of energy quality is called *exergy*.

Liquefaction to Refrigeration Equivalence [1]

- Equivalence is established based on equal ‘Carnot Work’, *i.e.* reversible input work (exergy or availability)

  - If a Carnot Liquefier is able to produce 1 [g/s] of liquefaction at the expense of x [kW] of reversible input work, then how much isothermal heat load will a Carnot Refrigerator support using the same amount of reversible input work.

Liquefaction to Refrigeration Equivalence [2]

- Consider a general steady process; the First Law is,

$$\dot{Q} + \dot{W} + \sum_{in} \dot{m}_i h_i - \sum_{out} \dot{m}_e h_e = 0$$

- If the heat transfer is reversible, then it occurs at dT (higher or lower) than the environment temperature, T_0

$$\dot{Q} = \dot{Q}_{rev} = T_0(S_e - S_i) = T_0 \sum_{out} \dot{m}_e s_e - T_0 \sum_{in} \dot{m}_i s_i$$

- Further, if the input power is equal to the reversible input power then,

$$\dot{W} = \dot{W}_{rev}$$

- So, we have, for a steady reversible process,

$$\dot{W}_{rev} = \sum_{out} \dot{m}_e (h_e - T_0\, s_e) - \sum_{in} \dot{m}_i (h_i - T_0\, s_i)$$

- We define the quantity of 'physical exergy' as,

$$\varepsilon \equiv h - T_0\, s$$

  - Note that physical exergy has units of [J/kg]
- Reversible input power, $\dot{W}_{rev} = \dot{m}_e\, \varepsilon_e - \dot{m}_i\, \varepsilon_i$

Liquefaction to Refrigeration Equivalence [2]

- For the Carnot refrigerator:

Name	Symbol	R #	MW [g/mol]	T_{sat} at p_0 [K]	λ [J/g]	σ [J/g-K]	w_{rev} [J/g]	β_i [W/W]
Helium-4	He	R-704	4.003	4.22	20.7	4.898	1449	69.9

- For the Carnot liquefier:

Name	Symbol	R #	*MW* [g/mol]	T_{sat} at p_0 [K]	Δh [J/g]	Δs [J/g-K]	$(T_0 \cdot \Delta s)$ [J/g]	w_{rev} [J/g]
Helium-4	He	R-704	4.003	4.22	1564	28.01	8403	6839

- Refrigeration specific load exergy (reversible input work)

$$\dot{w}_{rev,R} = \Delta\varepsilon_R = 1449 \text{ J/g}$$

- Latent heat (mass specific cooling provided)

$$\lambda = 20.7 \text{ J/g}$$

- Liquefaction specific load exergy

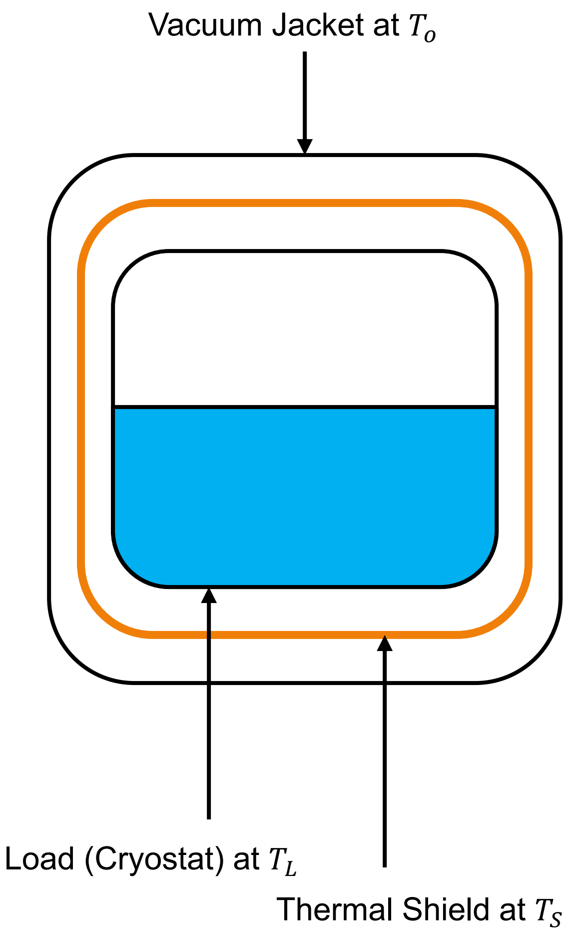
$$\dot{w}_{rev,L} = \Delta\varepsilon_L = 6838 \text{ J/g}$$

- Equivalence:

$$\lambda_{eq} = \frac{q_{R,eq}}{\dot{m}_{L,eq}} = \lambda \frac{\Delta\varepsilon_L}{\Delta\varepsilon_R} = 97.7 \text{ W/(g/s)}$$

Concept of Thermal (Radiation) Shield [1]

- Cryogenic equipment (heat exchangers, transfer lines, storage vessels) are often thermally shielded with insulation (MLI) and ‘intercepted’ using a lower than ambient temperature.
- In that case, part of the thermal radiation heat in-leak is ‘intercepted’ by the thermal shield (i.e. part of the thermal radiation heat in-leak is absorbed by the thermal shield maintained at a lower than environment temperature), and the rest of the heat in-leak is absorbed by the load maintained at load temperature (say, 4.5 K for a LHe cryostat).
- There exists an optimum thermal intercept temperature at which exergy (loss) associated with this heat in-leak is minimum.



Concept of Thermal (Radiation) Shield [2]

- Heat in-leak from environment to thermal shield

$$q_s = eA_s\sigma_b(T_o^4 - T_s^4)$$

- Reversible input work (exergy) associated with this heat transfer

$$E_s = \left(\frac{T_o - T_s}{T_s}\right) q_s$$

- Heat in-leak from thermal shield to load

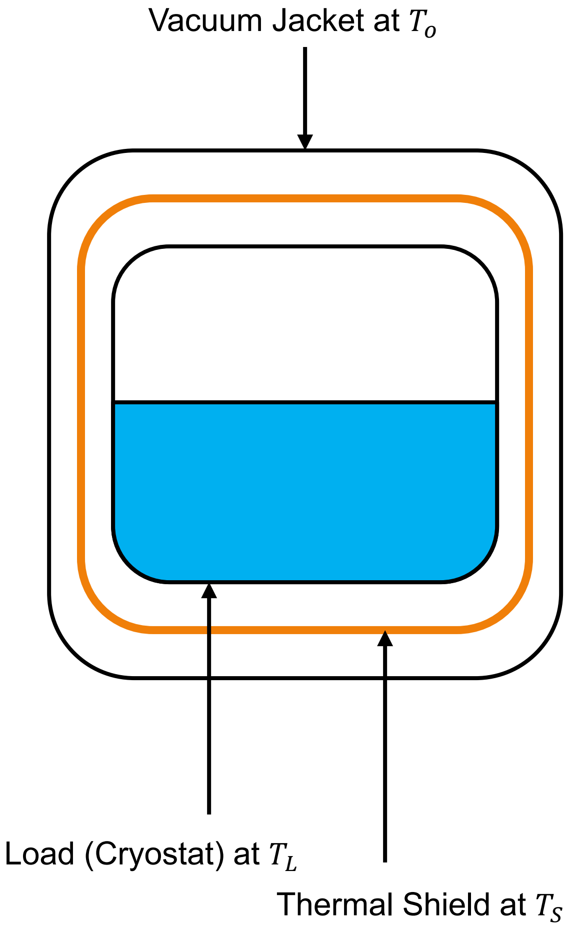
$$q_L = eA_L\sigma_b(T_s^4 - T_L^4)$$

- Reversible input work (exergy) associated with this heat transfer

$$E_L = \left(\frac{T_s - T_L}{T_L}\right) q_L$$

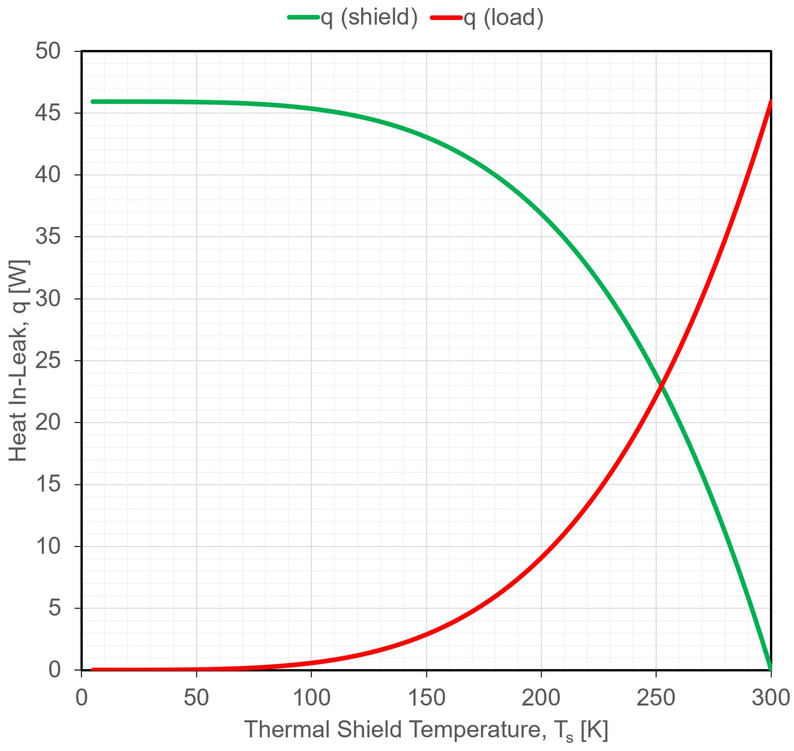
- Total exergy (loss) for heat in-leak due to radiation

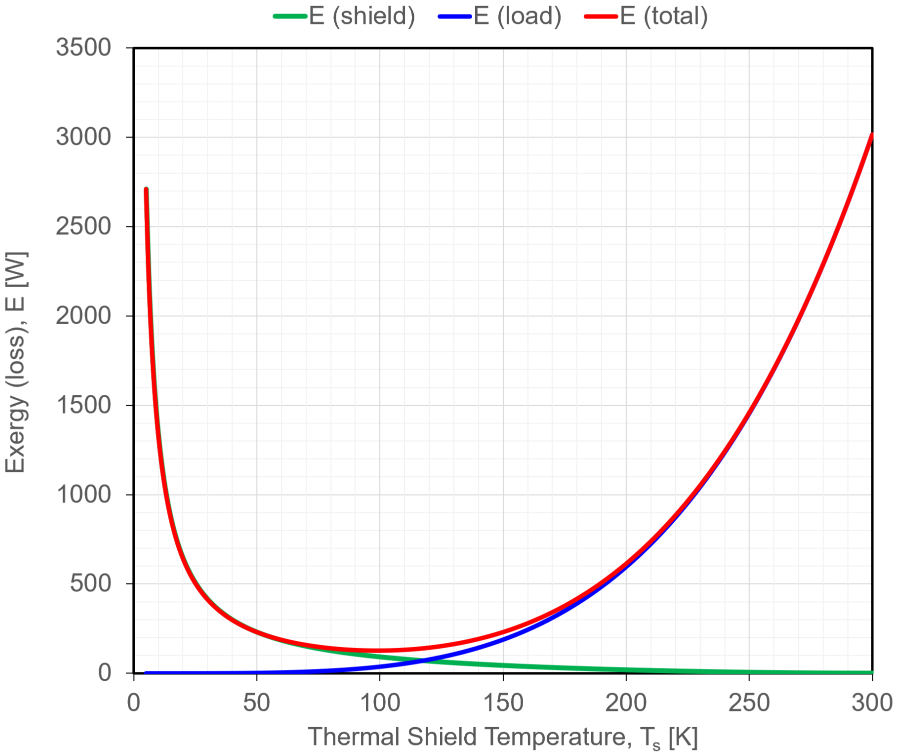
$$E = E_s + E_L$$



Concept of Thermal (Radiation) Shield [3]

- Considering a LHe cryostat (T_L = 4.5, A_s = 1.0 m^2, A_L = 1.0 m^2, $e = 0.1$), the optimum temperature at which exergy (loss) due to radiation heat in-leak will be minimum is approx. 99 K.





Practical Cryogenic Cycles [1]

- There are many different types of refrigeration cycles, with many variants

- In addition, these may be distinguished as recuperative and regenerative – according to the heat exchanger type used
  - e.g., for above 2 K: Philips (Sterling), Vuilleumier, Solvay, Gifford-McMahon, pulse tube, etc.

- Regenerative refrigeration cycles involve cyclic process, where the flow through the heat exchanger is not continuous, but periodic, with alternating flow direction, storing and removing heat
  - Commonly used in ‘*Cryo-coolers*’

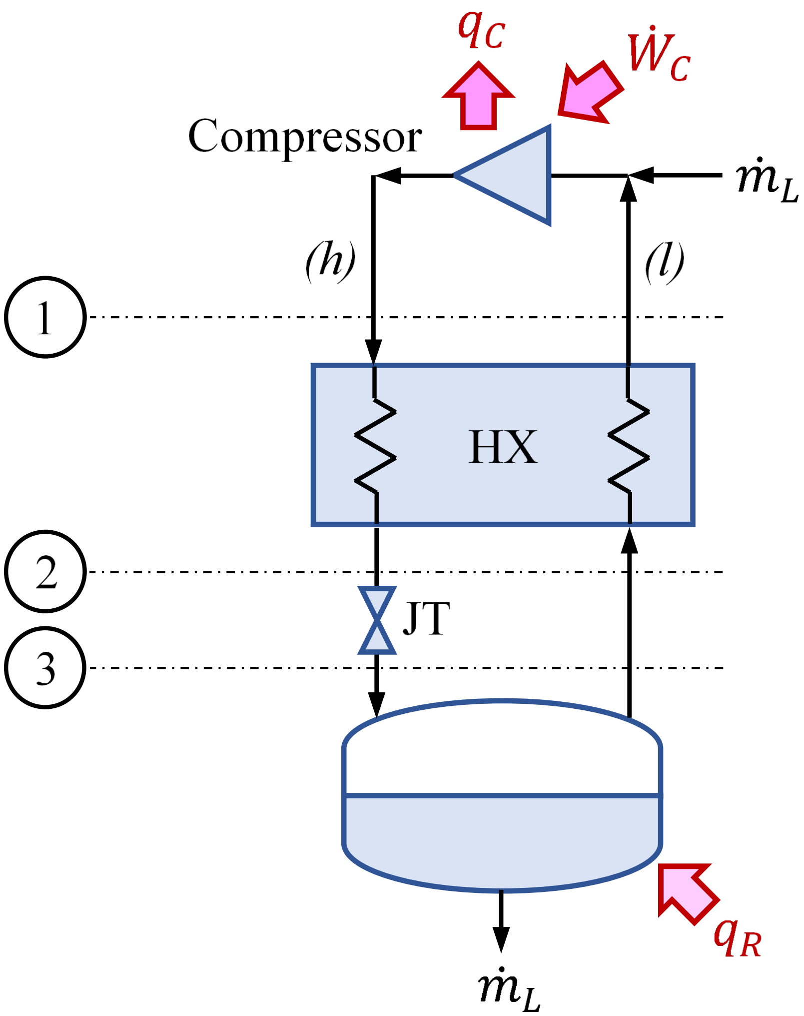
Practical Cryogenic Cycles [2]

- We will concern ourselves with ones involving recuperative heat exchange, and to the following:
  - Linde-Hampson or JT process
  - Modified Brayton process
  - Claude process
  - Collins (helium liquefaction) process

- Many of these basic types are ‘super-imposed’ or ‘cascaded’ in actual cryogenic systems

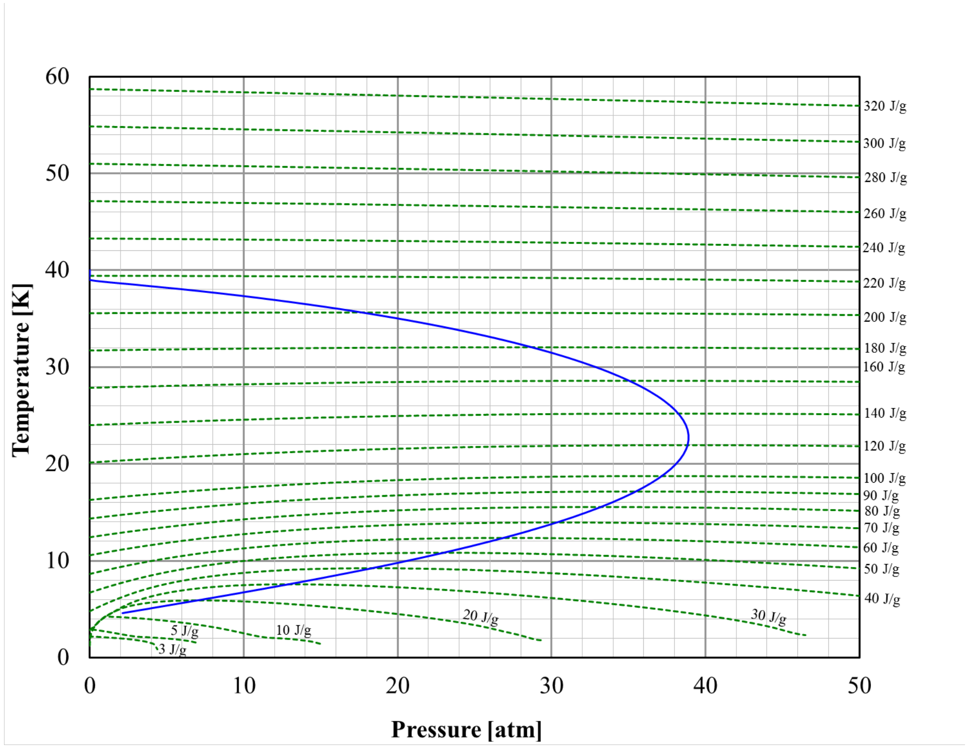
JT Process [1]

- JT (Joule-Thompson) process
- Also called a Linde-Hampson process
- The is no work extraction, only isenthalpic expansion across the JT valve
- From the start-up (cool-down) phase, the refrigerant gas must produce cooling due to the isenthalpic expansion across the valve



JT Process [2]

- JT coefficient is defined as the partial derivative, $\mu_j = \left(\frac{\partial T}{\partial p}\right)_h$
- Below is a plot of constant enthalpy lines (dashed green lines) on a pressure-temperature diagram for helium
- So, the ‘slope’ of these constant enthalpy lines is the JT coefficient
- Observe that above approx. 40 K, the JT coefficient (for helium) is always negative; i.e., no cooling will occur when the pressure is reduced at constant enthalpy
- This is called the maximum inversion temperature and varies with the fluid



JT Process [3]

- Table below shows the inversion temperature for selected fluids

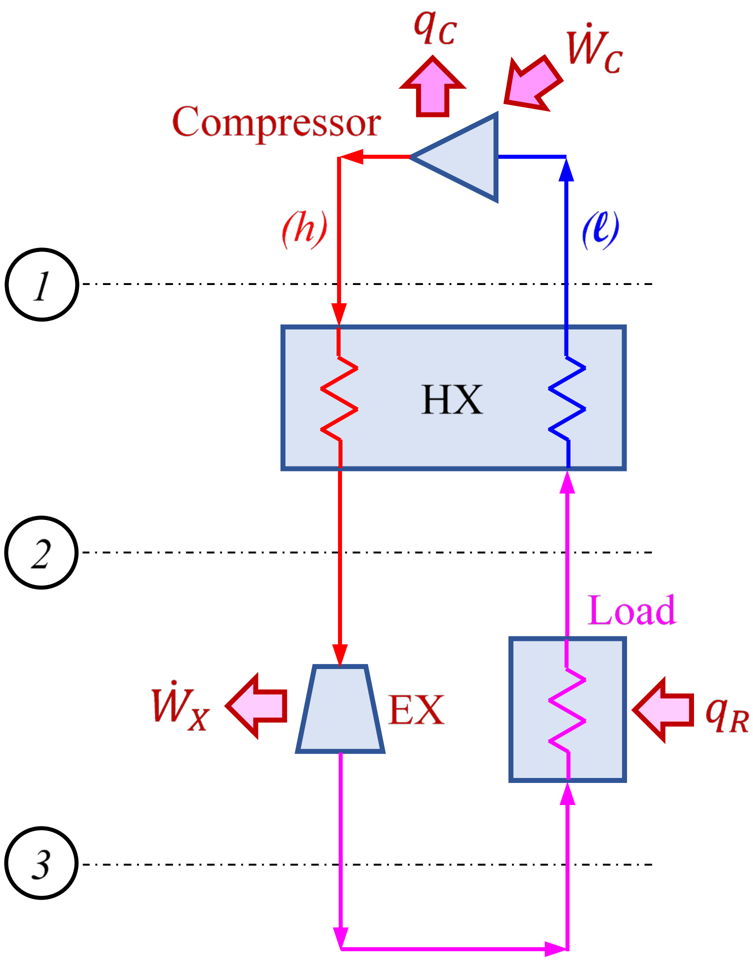
Name	Symbol	R #	NBP	R	a	b	$T_{i,max}^{\circ}$	$T_{i,max}$
			[K]	[J/kg-K]	[Pa-m^6/kg^2)]	[m^3/kg]	[K]	[K]
Oxygen	O_2	R-732	90.19	259.8	135.0	0.0009956	1043	757
Argon	Ar	R-740	87.30	208.1	85.33	0.0008062	1017	763
Nitrogen	N_2	R-728	77.35	296.8	174.3	0.001379	852	607
Neon	Ne	R-720	27.10	412.0	52.90	0.0008550	300	220
Deuterium	D		23.66	2064	1573	0.005890	259	211
Hydrogen	H_2	R-702	20.37	4124	6082	0.01318	224	201
Helium-4	He	R-704	4.22	2077	218.9	0.006009	35.1	45.2

  - Where, $T_{i,max}^{\circ}$, is computed using van der Waals equation, and, $T_{i,max}$, is computed using CoolProps

- We can see from this table that Neon, (Deuterium), Hydrogen, and Helium must be pre-cooled below ambient temperature for the JT process

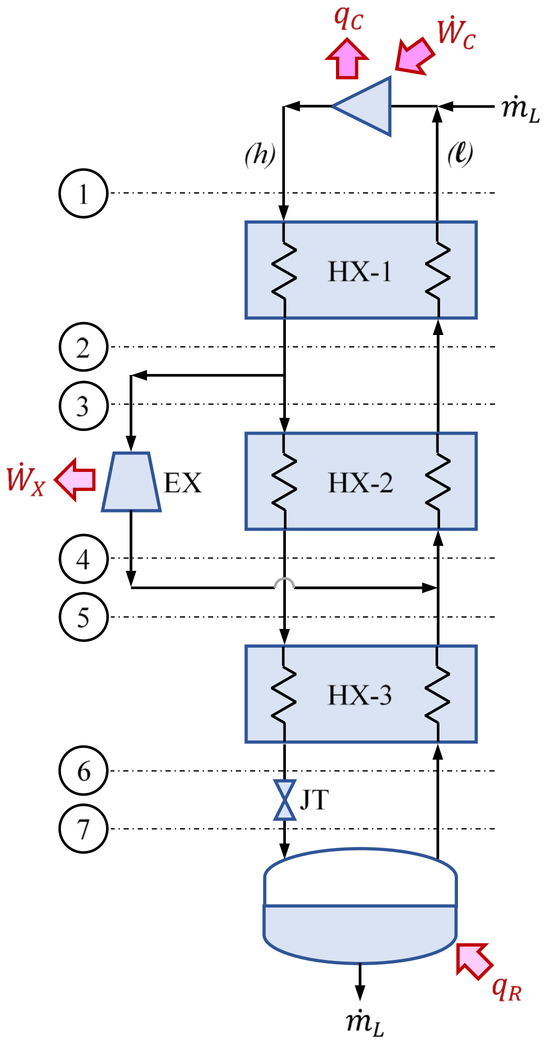
Reversed-Modified Brayton Process

- Reversed – because it is used for refrigeration rather than power generation
- Modified – because it has isothermal compression and isentropic expansion
- Recall a Brayton cycle has isentropic compression and expansion
- Note that this process provides non-isothermal cooling



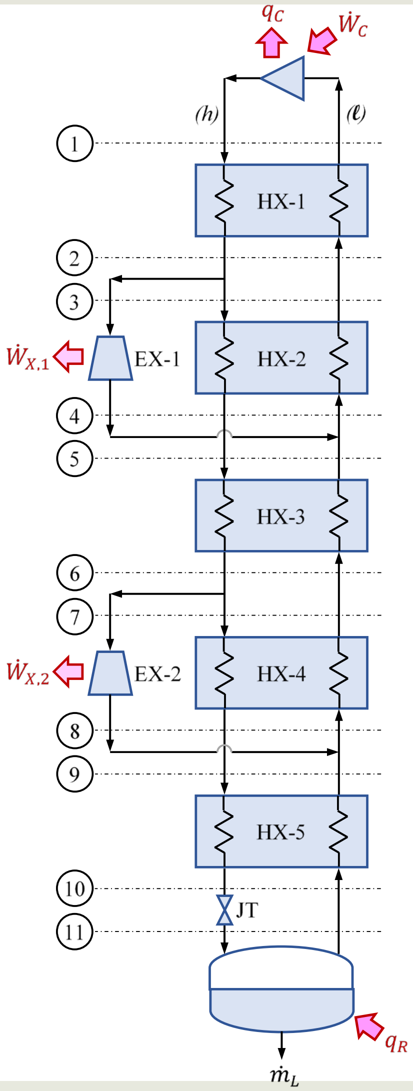
Claude Process

- Think of this as a super-position of a Brayton process-stage and a JT process-stage
- With the Brayton stage providing sensible cooling of the liquefaction mass flow ($\dot{m}_L$) from, $T_{l,3}$, to, $T_{l,4}$
- Since this additional cooling is provided, less input exergy is required from the compressor, than would otherwise be needed for a pure JT process supporting the same liquefaction load



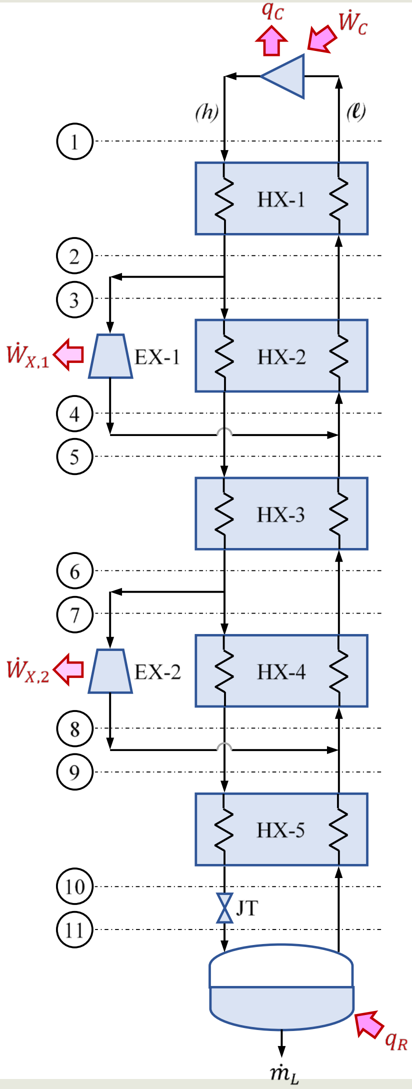
Collins Process [1]

- This cycle consists of two Brayton process-stages and a JT process-stage at the cold end
- Cycle is named after Sam Collins (MIT) who pioneered practical helium liquefiers, developing the equipment-technology that has made them available in laboratories doing low temperature research world-wide
- He recognized that two expansion stages were necessary (~16:1 pressure ratio) for a practical helium liquefier

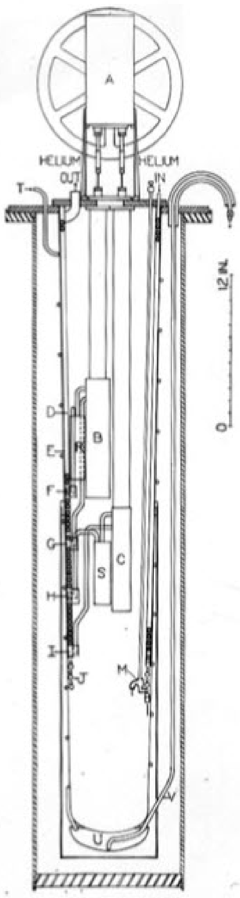


Collins Process [2]

- Peter (Pyot) Kapitza (1934) was the first to use an expansion engine (of his design) to produce liquid helium
- However, it was the development of S.C. Collin's 1946 liquefier with its flexible rod piston expanders at MIT, which was subsequently commercialized by Arthur D. Little (ADL), Inc. that made helium liquefier's common place
- Later Collins designed and built the Model 2000 and the highly successful and well known Model 1400 helium liquefiers
- These used a piston-displacer expander consisting of a 3 inch diameter solid phenolic-plastic bar with the seal, a Buna rubber O-ring, at the warm end

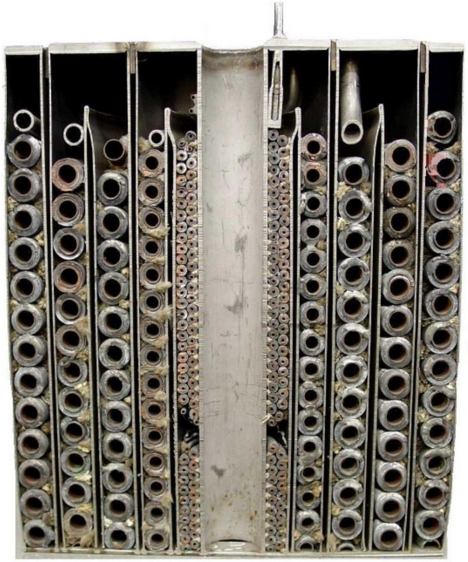


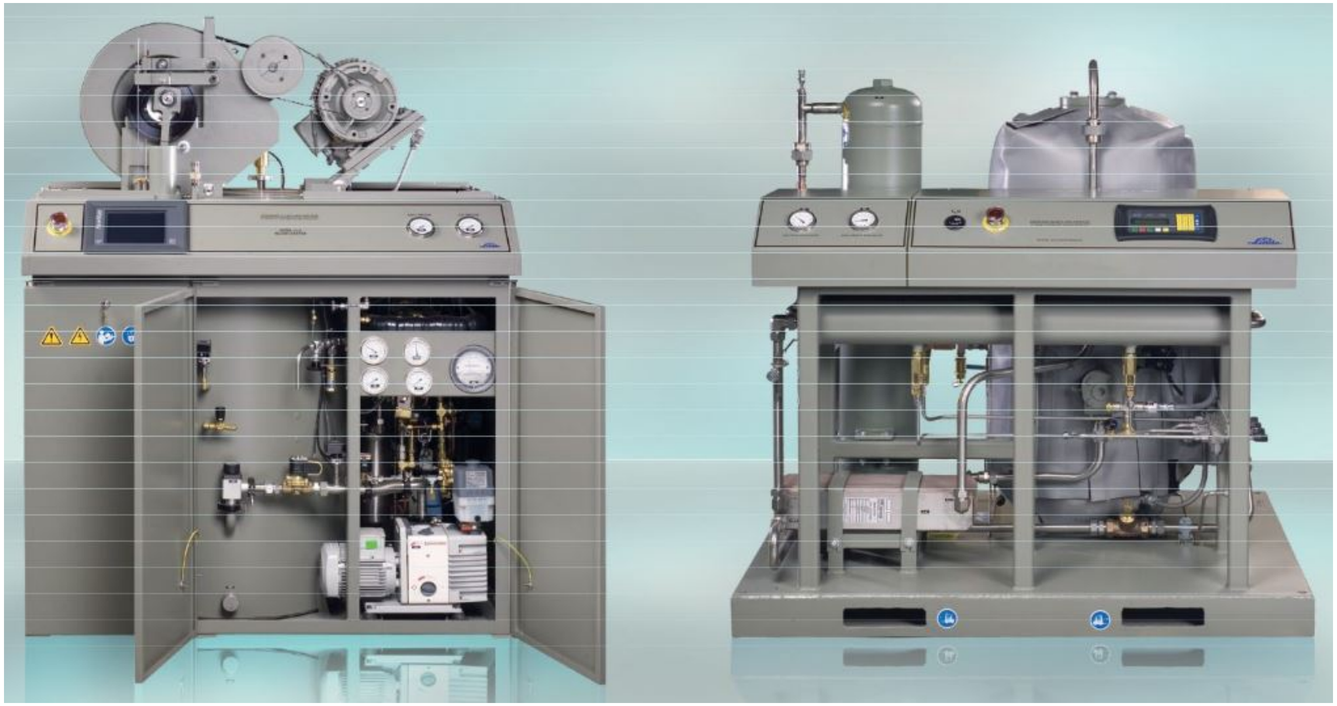
Collins Process [3]



Collins Process [4]

- (Now) Linde model 1410





Overview - Large Helium Cryogenic Systems

Major Helium Refrigerator Sub systems:

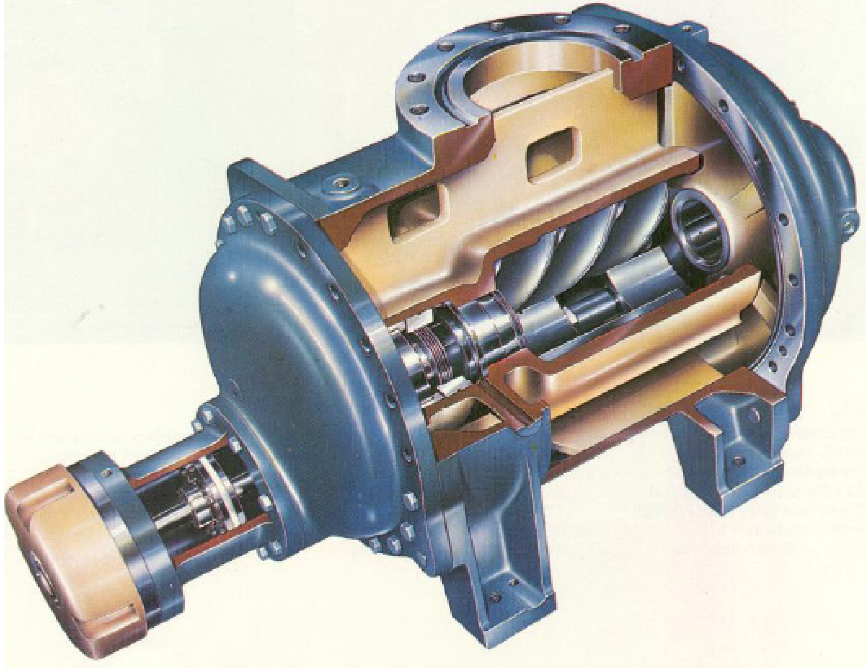
- Warm (Helium) Gas Storage
- Warm compressors
  - *Compressor skids*
  - *Gas management*
  - *Bulk oil removal*
- Oil Removal System
  - Ads. Beds
  - Coalescing Filters
- Gas Purification System
- Cryogenic Storage (Dewar)
- 4.5 K Helium Refrigerator (Cold Box)
  - LN Pre-cooling
  - Expansion Stages
  - Heat Exchangers
- 2.0 K (Sub-Atm) Refrigerator
  - Vacuum Pump
  - Cryogenic Centrifugal Compressors
  - Heat Exchangers
- Cryogenic Distribution System
- Cryostats
  - Cryo-modules
  - Superconducting Magnets

Cryogenics at FRIB

- What does cryogenics at FRIB look like?
  - FRIB is large scale facility – similar to an air separation or to liquid natural gas (LNG) process plant

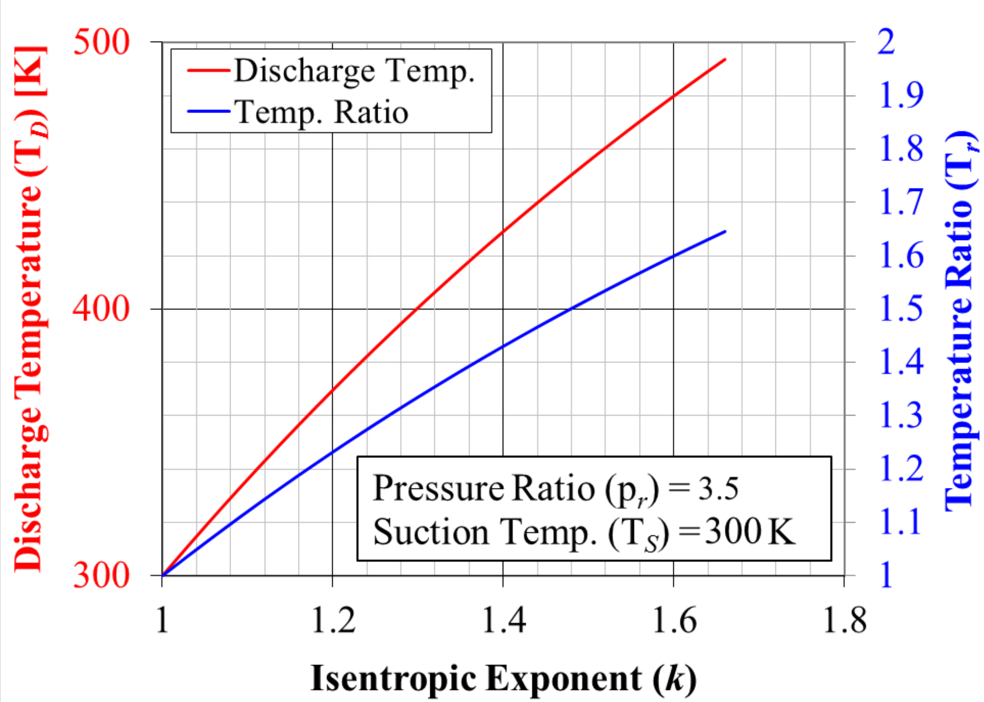
Warm Gas (Helium) Compressors

- Compressors (isothermal):
  - Used as the ‘prime movers’ for modern helium systems
  - Most helium refrigeration systems use rotary screw compressors (also known as twin screw compressor)
  - These are their own sub-system
  - Provide the availability, or exergy, to the refrigeration system



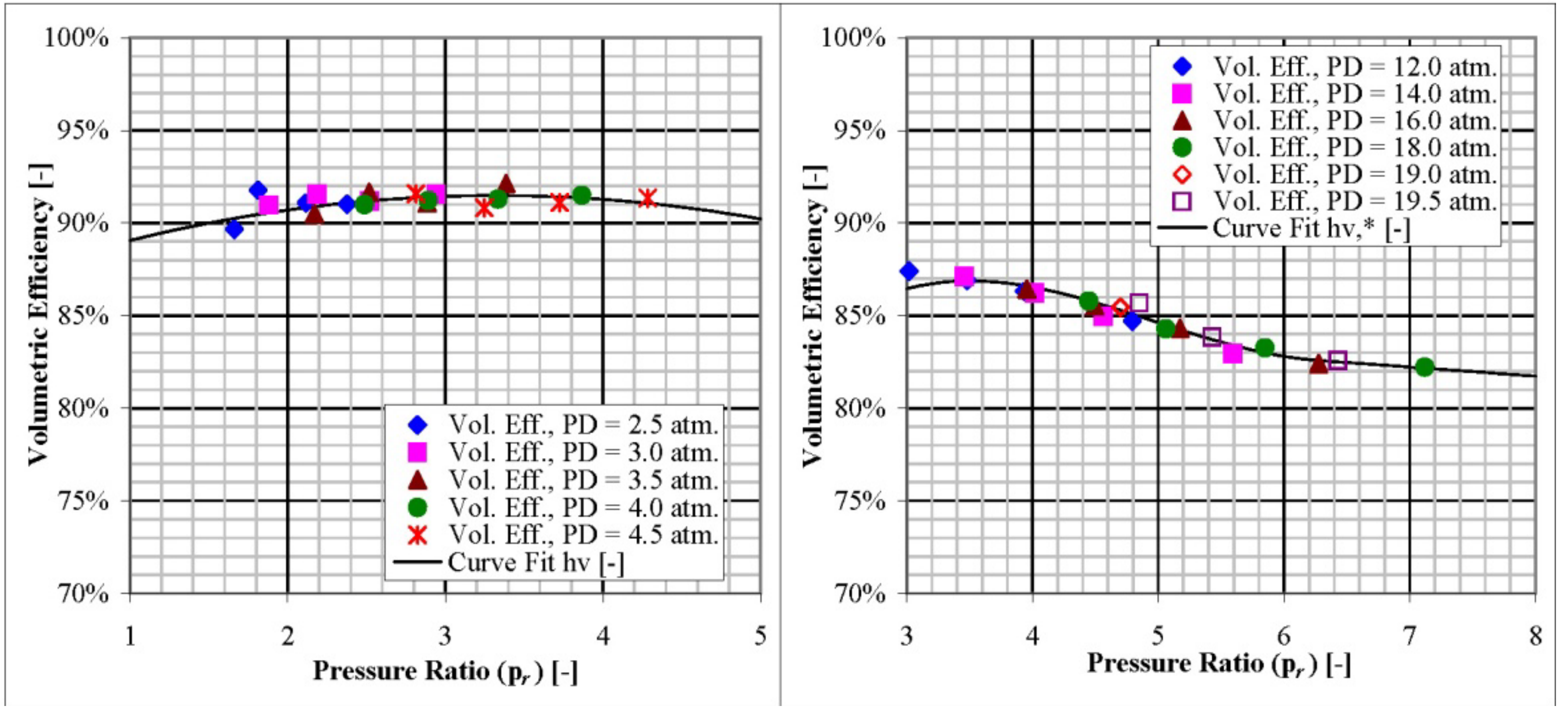
Rotary Screw Compressor [1]

- Influence of the polytropic exponent (k) on the compression process and the temperature ratio for a pressure ratio of 3.5
- Since the isentropic exponent for helium is high (5/3), oil is injected into the helium gas to reduce the compression temperature so that normal materials and seals can be used in the construction of the compressors



Rotary Screw Compressor [2]

- Typical volumetric efficiency (η_v) for a given BVR
  - Left: SSCL Sullair LP stage 2.2 BVR
  - Right: SSCL Sullair HP stage 2.6 BVR
- For a given BVR, and compressor stage (i.e., LP, MP, HP), the efficiency is primarily dependent on the pressure ratio (p_r)



Rotary Screw Compressor [3]

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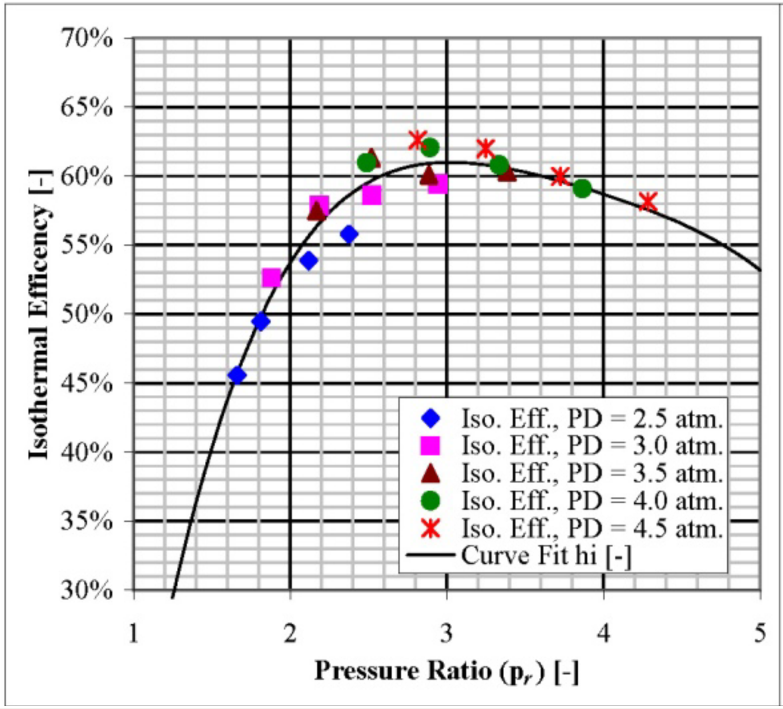
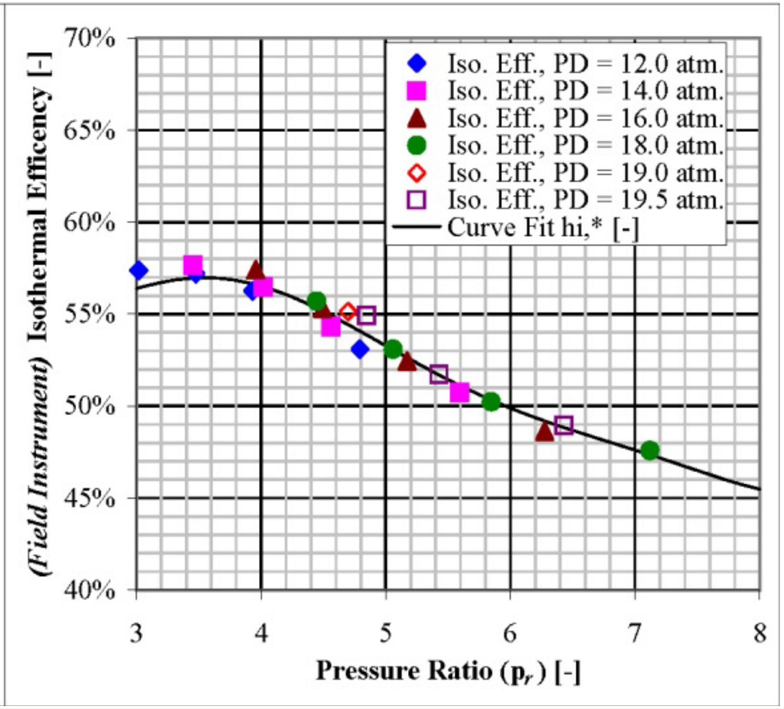
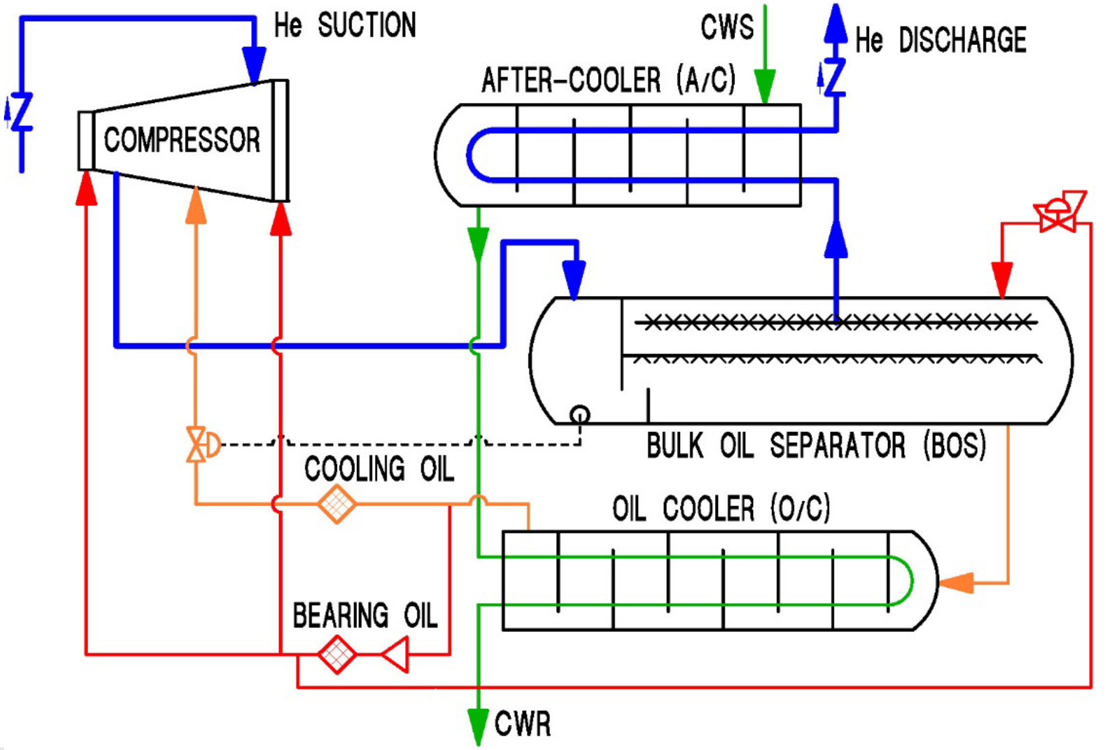
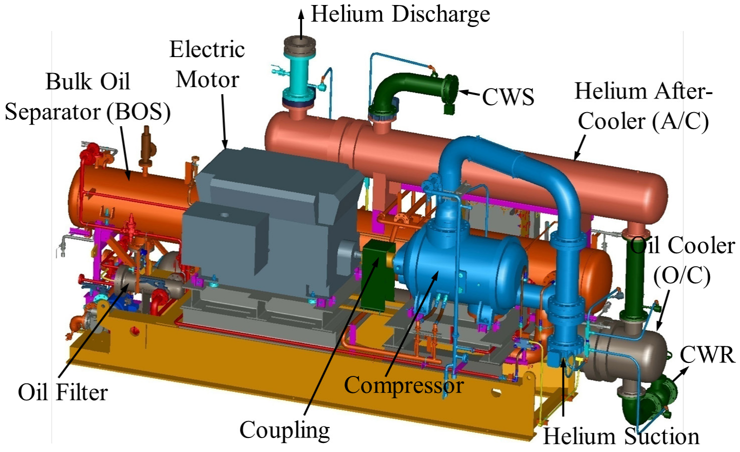


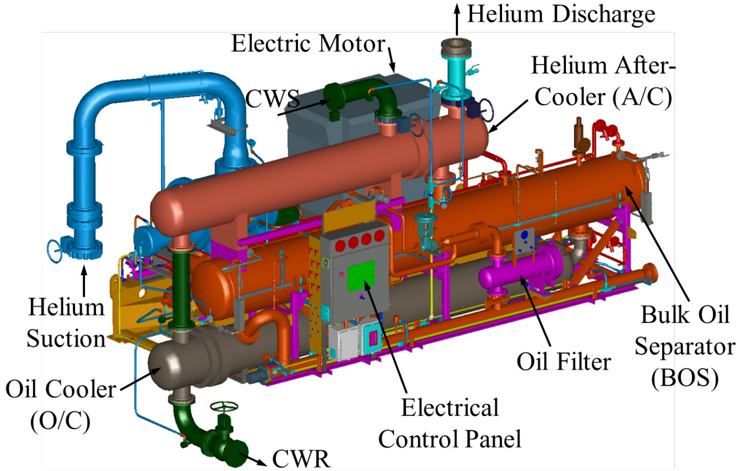


Rotary Screw Compressor [4]

- Helium compressors

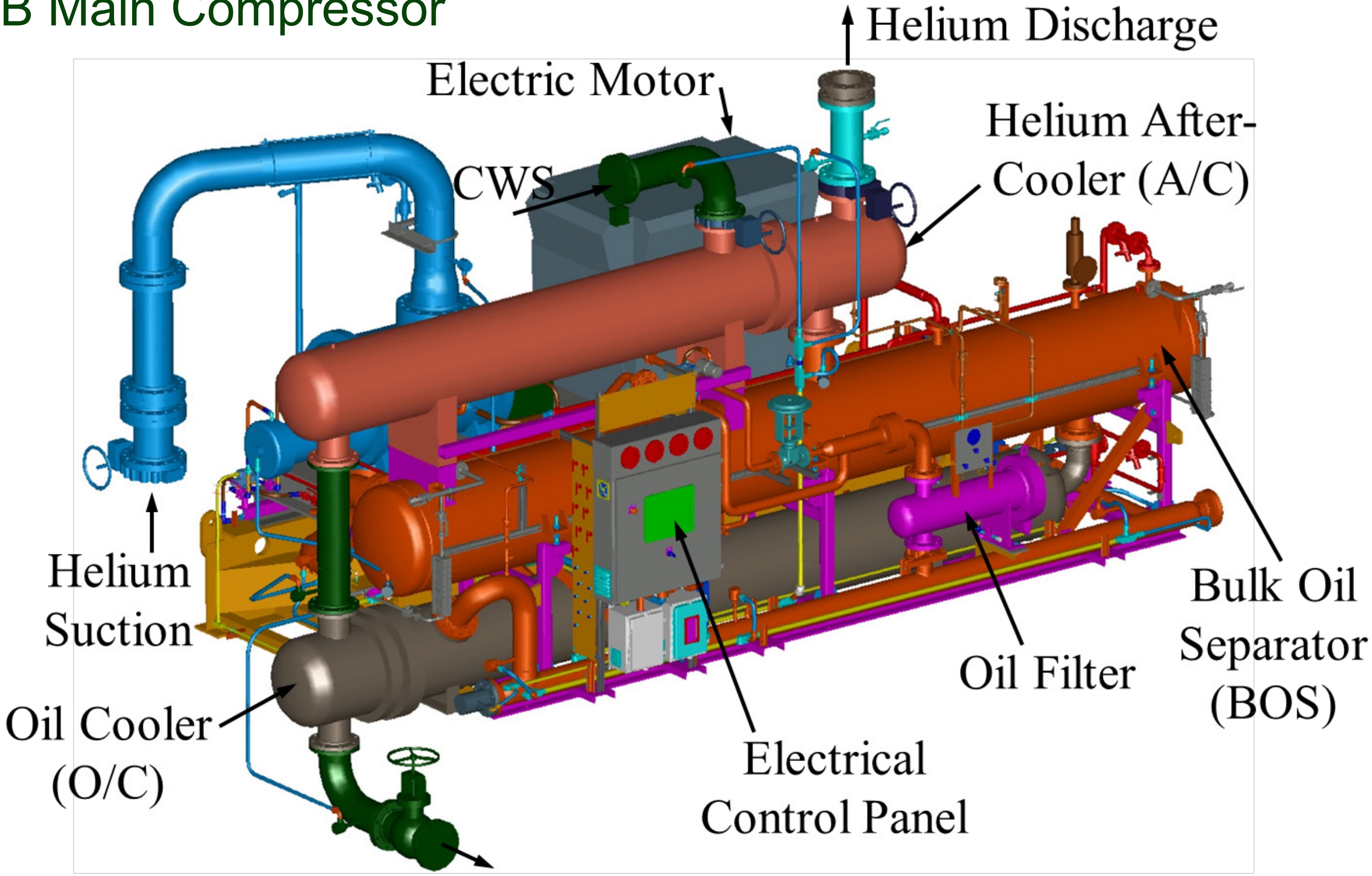






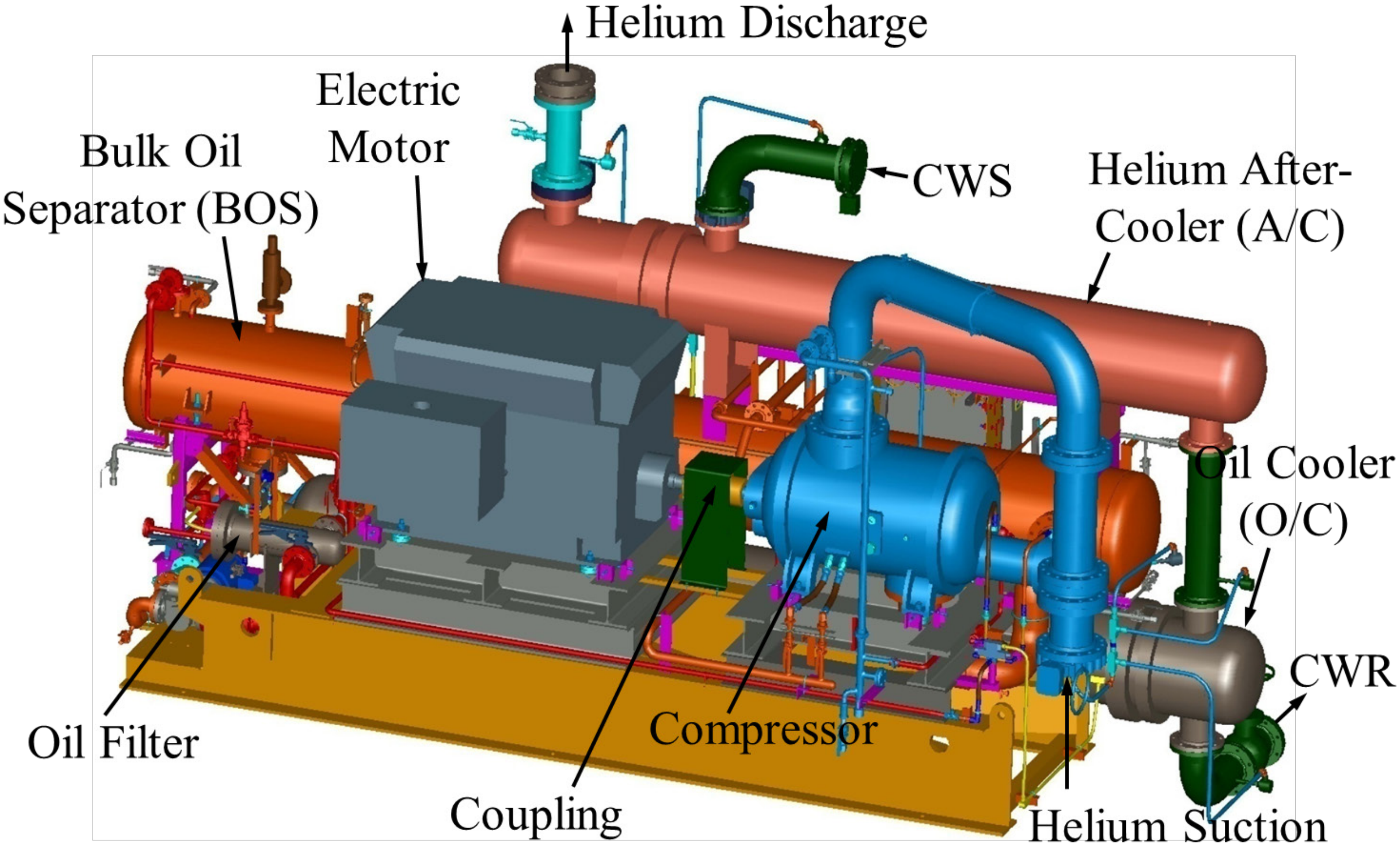
FRIB Warm Compressor Skids [1]

- FRIB Main Compressor



FRIB Warm Compressor Skids [2]

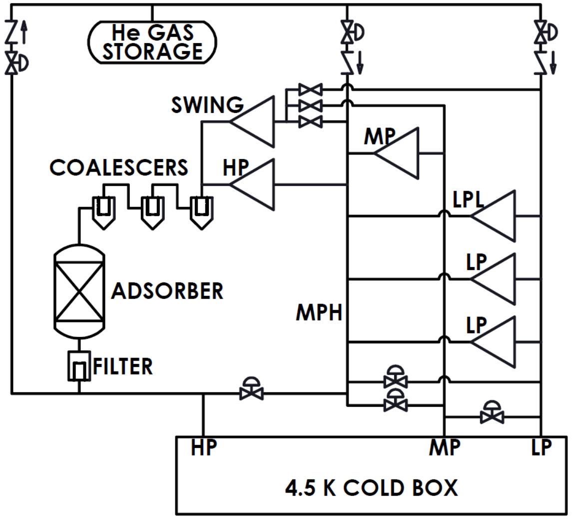
- FRIB Main Compressor



FRIB Warm Compressor System [1]

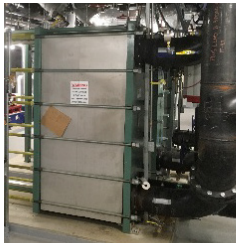
- Used *to increase the thermodynamic availability* of the helium gas by effectively isothermally pressurizing the gas

	LPL Stage	LP Stage	MP Stage	HP Stage
No. of Units	1	2	1	2
Compressor Model No.	WLVi 321/220	WLVi 321/193	WLVi 321/165	WLViH 321/193
Suction Swept Volume	35.526 l/rev	29.979 l/rev	26.649 l/rev	29.979 l/rev
Motor Frame	4009	3508	3508	4512
Full-load amperage (FLA)	124	99	99	305
Motor Rating	746 kW	597 kW	597 kW	1864 kW

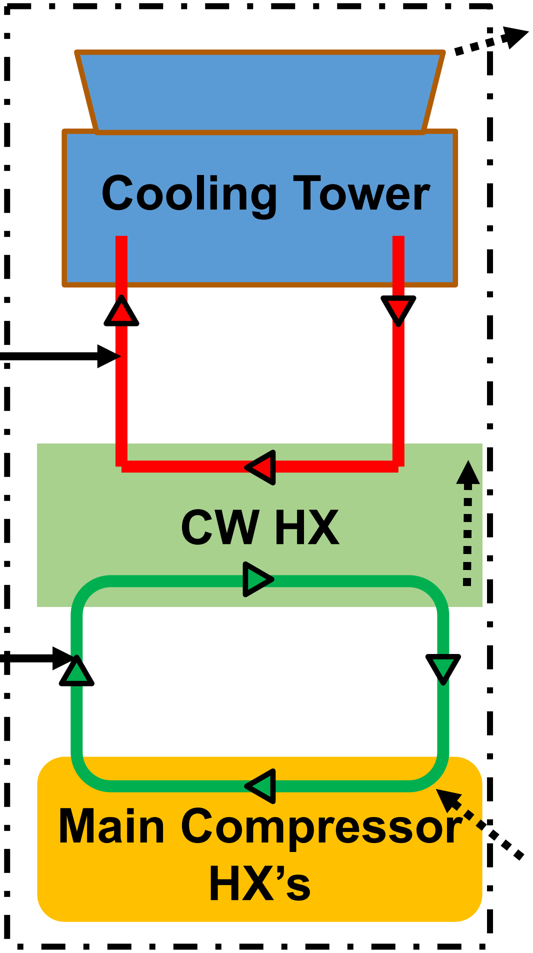


FRIB Warm Compressor System [2]

Cooling Tower Loop



Process CW Loop



Cooling Tower

CW HX

Main Compressor HX's

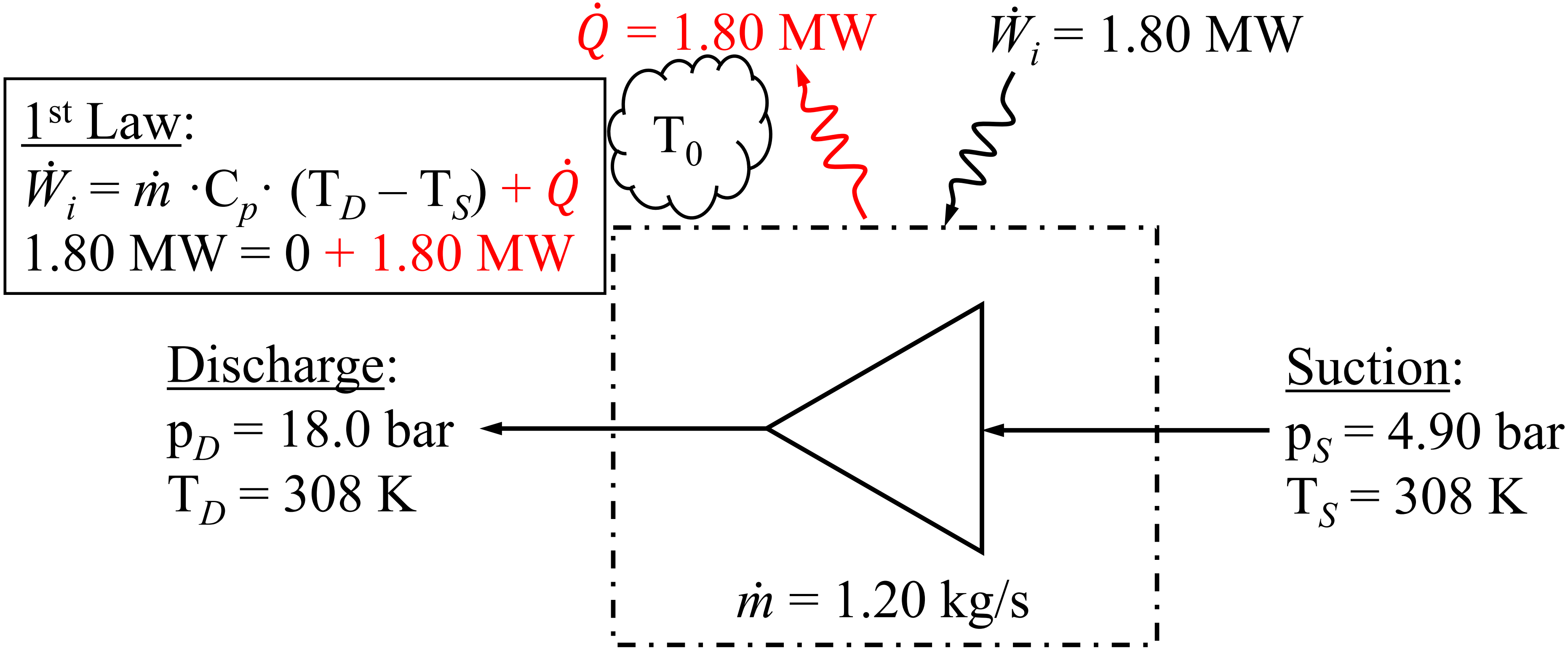
q *Heat rejected to atmosphere*

q *Heat rejected from process CW to Cooling Tower CW*

q *Heat rejected from compressors to process CW*

FRIB Warm Compressor System [3]

- Electrical input power = heat rejected out cooling towers
- Enthalpy into compressors = enthalpy out of compressors



$\dot{Q} = 1.80\ \mathrm{MW}$

$\dot{W}_i = 1.80\ \mathrm{MW}$

1st Law:

$\dot{W}_i = \dot{m} \cdot C_p \cdot (T_D - T_S) + \dot{Q}$

$1.80\ \mathrm{MW} = 0 + 1.80\ \mathrm{MW}$

Discharge:

$p_D = 18.0\ \mathrm{bar}$

$T_D = 308\ \mathrm{K}$

Suction:

$p_S = 4.90\ \mathrm{bar}$

$T_S = 308\ \mathrm{K}$

$\dot{m} = 1.20\ \mathrm{kg/s}$

Isothermal Compression: $T_D = T_S = T_0$ ► $W_i = \dot{Q}$

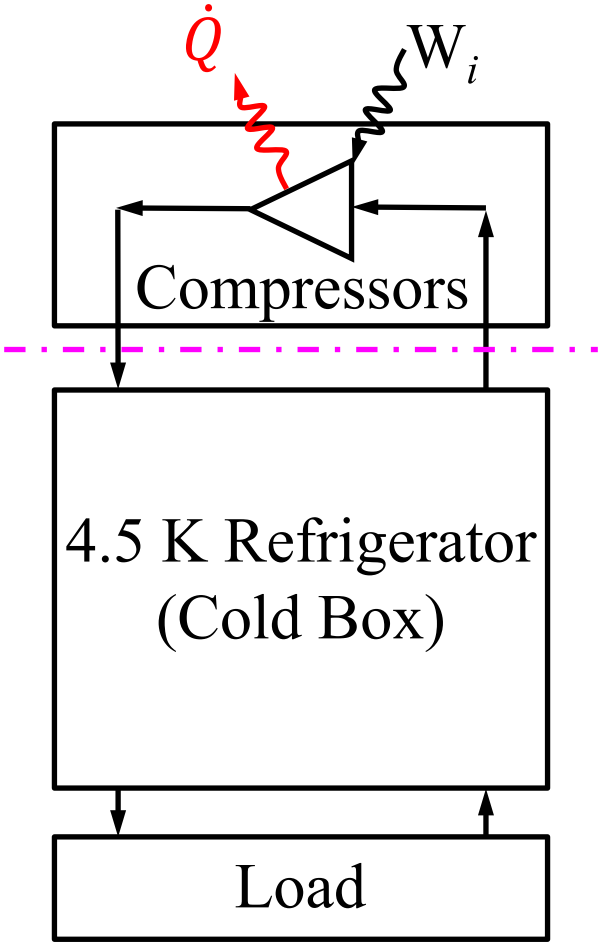
FRIB Warm Compressor System [4]

- Net enthalpy flux:
  - Essentially zero to the cold box + load

- The power put into the compressors did *not increase the energy of the helium*

$$\sum_i \dot{m}_i \cdot h_i = \Delta H = 0$$

- **So, what is really being supplied to the refrigerator to support the load?**

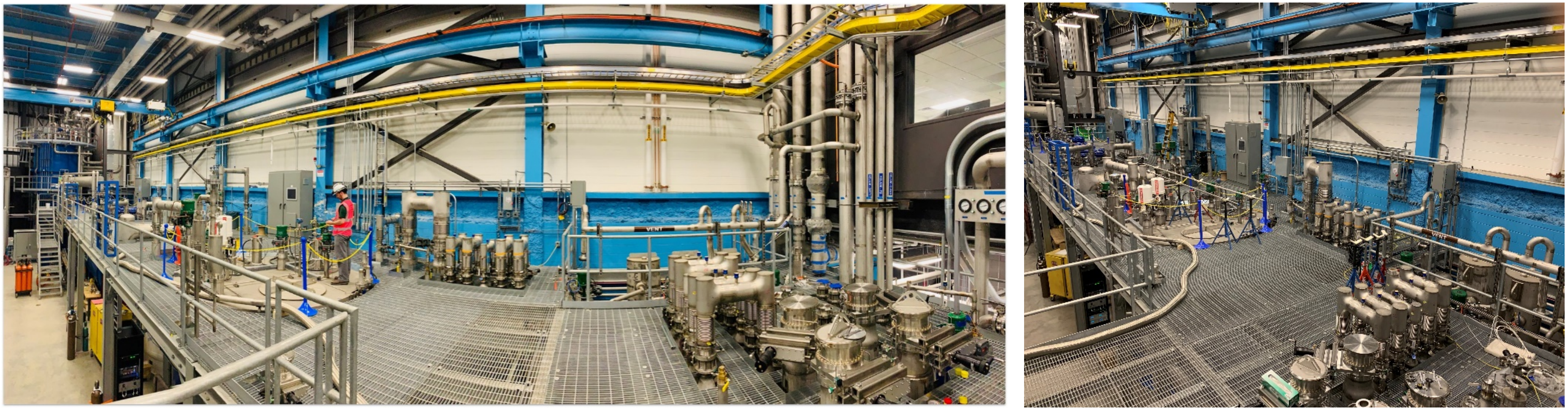


Oil Removal (Main Compressor Sub-System)

- Use to remove oil (liquid and vapor) from helium gas prior to being supplied to the 4.5 K cold box
- Oil (coating) on cold box heat exchangers would significantly degrade heat exchanger performance, and oil could permanently damage cold box turbines
- Usually comprised of three stages of glass-fiber coalescing elements, followed by an activated carbon adsorber and filter (5 μm abs.)

Final oil removal
(outside, south side)

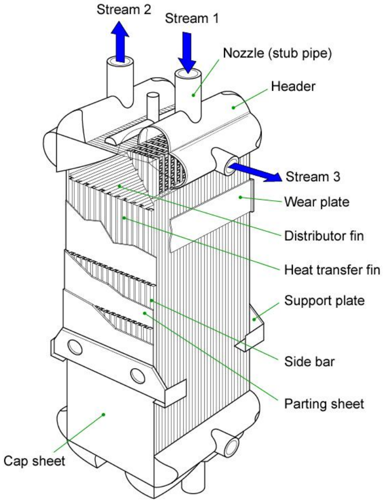
FRIB 4.5 K Refrigeration System [1]

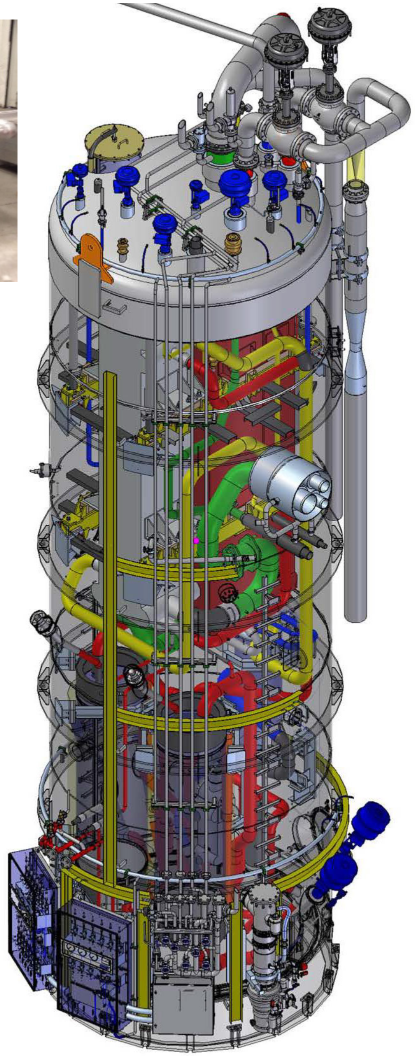


- Maximum capacity approx. 18.5 kW at 4.5 K (equivalent refrigeration); i.e.,
  - 180 g/s of Cold Compressor (CC) return flow (1.16 bar, 30 K)
  - 4.0 kW of 4.5 K Refrigeration
  - 14.0 g/s of 4.5 K Liquefaction
  - 20.0 kW of Shield Refrigeration (35-55 K)

FRIB 4.5 K Refrigeration System [2]

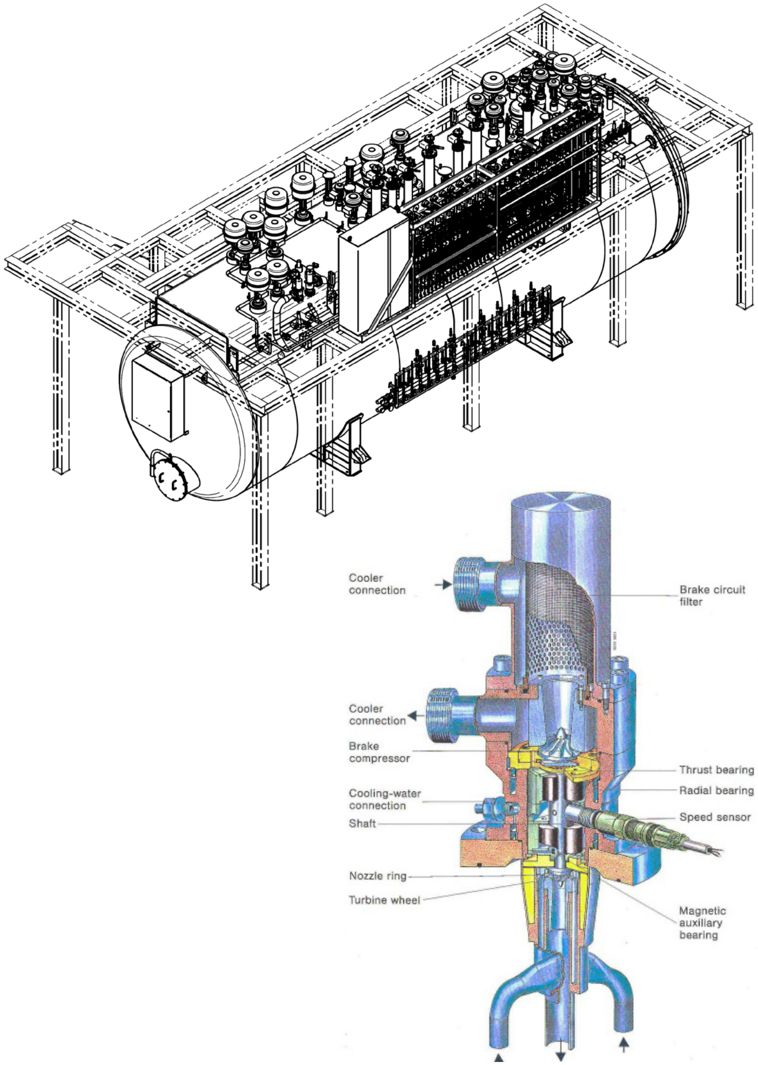
- Upper cold box (300 K to 60 K):
  - Liquid nitrogen used to cool helium from 300 to 80 K
    - » Uses thermo-siphon with proper LN/VN phase separation
  - Dual carbon adsorber beds at 80 K to remove any remaining air contaminates
    - » Beds can be regenerated using electric heater bands
    - » Equipped with bed bypass
  - 4 aluminum-brazed plate-fin heat exchanger's in 4 cores





FRIB 4.5 K Refrigeration System [3]

- Lower cold box (60 K to 4.5 K):
  - 7 centrifugal turbines arranged in four expansion stages
    - i.e., 3 Brayton stages, each with 2 turbines in series, plus a “JT-expander” stage
    - 22 to 45 mm (turbine) wheel dia., up to 3000 Hz
  - 12 aluminum-brazed plate-fin HX’s in 5 cores
  - Carbon adsorber at 20 K for neon and hydrogen
  - 2000 ℓ helium phase-separator and sub-cooler

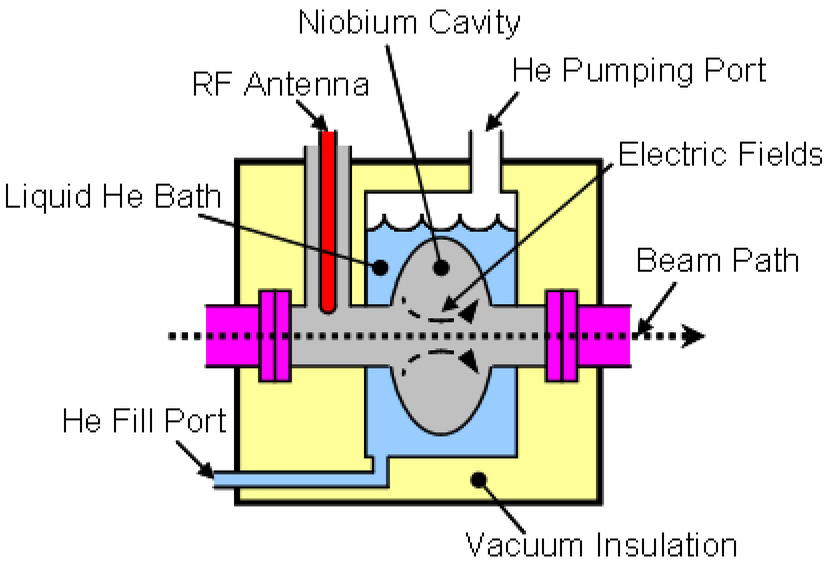


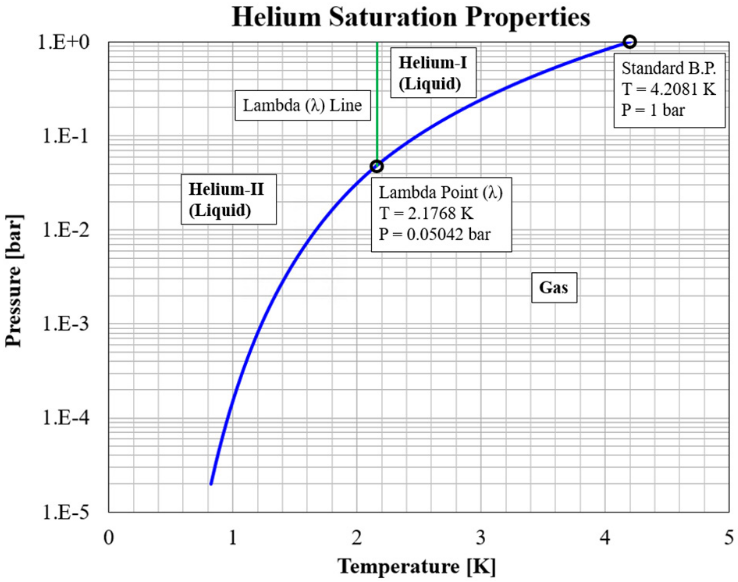
FRIB 4.5 K Refrigeration System [4]

4.5 K helium cold box
(upper and lower sections; cold box room)

2.0 K Refrigeration System [1]

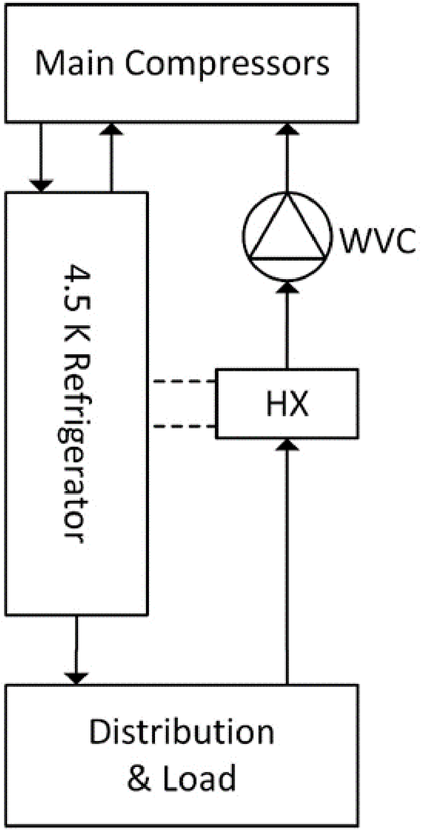
- Heavy ions are accelerated in the linear segments of the beam line by employing superconducting radio-frequency (SRF) cavities
- SRF cavities operate at temperatures below the standard boiling point of helium (4.2 K @1 bar), at FRIB this temperature is ~ 2 K
- A reduction in pressure is required to reach saturation conditions which match the temperature requirements (FRIB ~ 30 mbar)



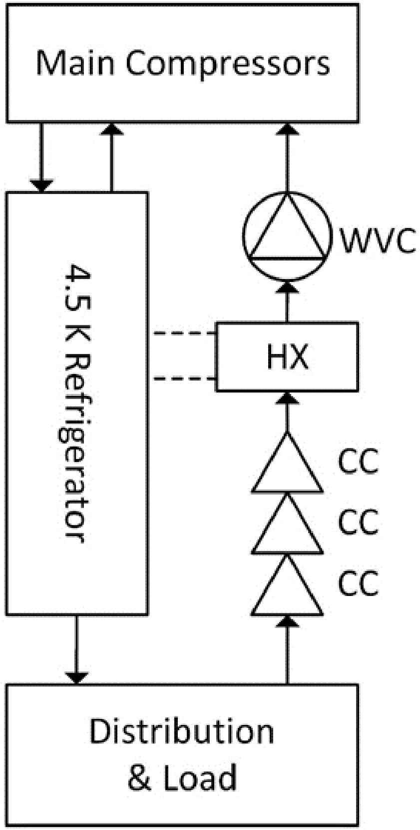


2.0 K Refrigeration System [2]

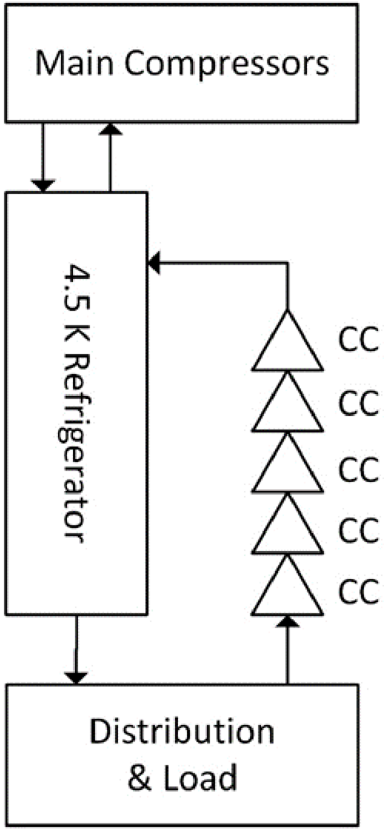
- There are several common methods that reduce the helium bath pressure; each having unique advantages and disadvantages



Warm-Compression

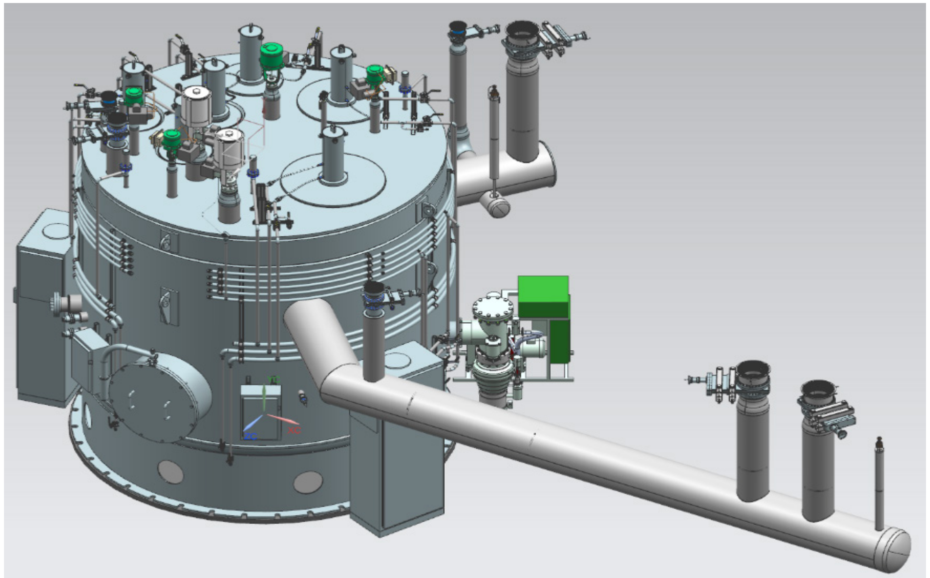


Mixed-Compression



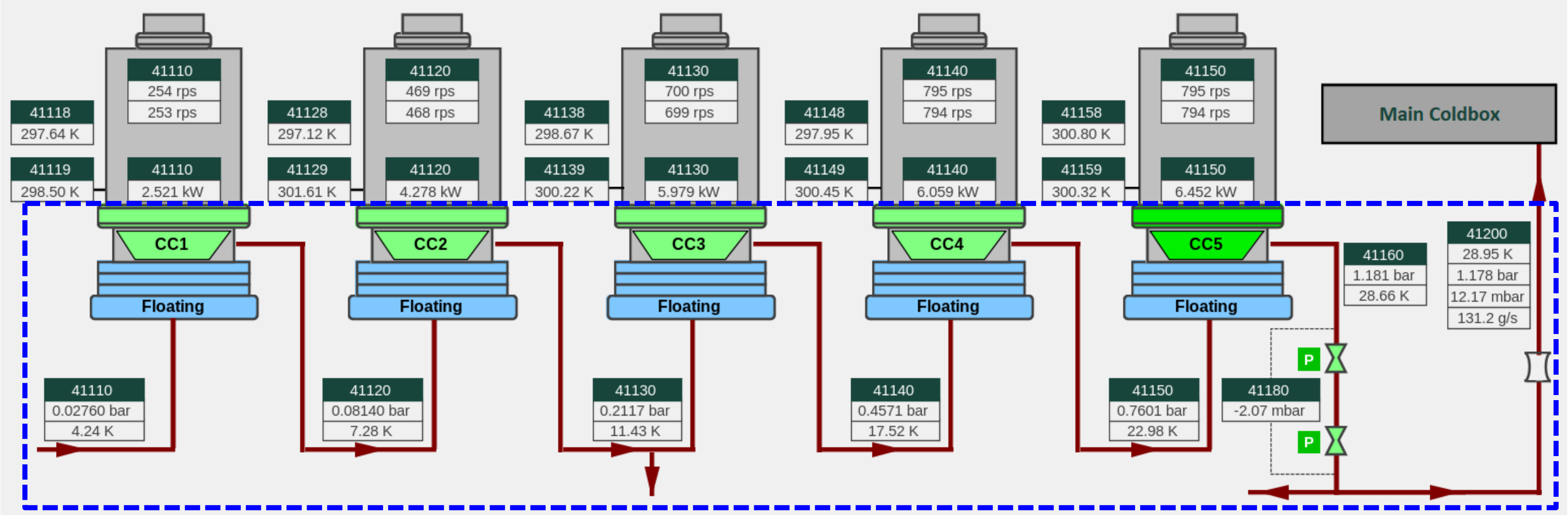
Cold-Compression

FRIB 2.0 Refrigeration System Sub-Atmospheric Cold Box (SCB) [1]



- Sub-atm cold box (SCB) allows FRIB Linac to operate at 2 Kelvin (30 mbar)
- FRIB utilizes a full cold-compression system
- Cold-compression typically involves multiple centrifugal-type compressors in series
  - Used to re-compress the sub-atmospheric 30 mbar 4.5 K helium returning from cryo-module Niobium cavities back up to ~1.2 bar
  - Vapor is 4 K since a 4.5 K to 2 K Collins heat exchanger is used within the cryo-module to cool the primary supply to the cavities

FRIB 2.0 Refrigeration System
Sub-Atmospheric Cold Box (SCB) [2]



- Re-compression accomplished using 5 centrifugal cryogenic (cold) compressors in series
  - Compressors are directly coupled to an externally mounted (ambient temperature) permanent magnet synchronous motors and controlled using a variable frequency drive (VFD)
  - Impeller diameters range from around 7-5/8 to 3-3/8 inches, and operate at speeds up to around 300 to 800 Hz (depending on ‘gear ratio’ and impeller diameter)

FRIB 2.0 Refrigeration System
Sub-Atmospheric Cold Box (SCB) [3]

- Top plate installation into vacuum shell (left) and typical cold compressor (right)

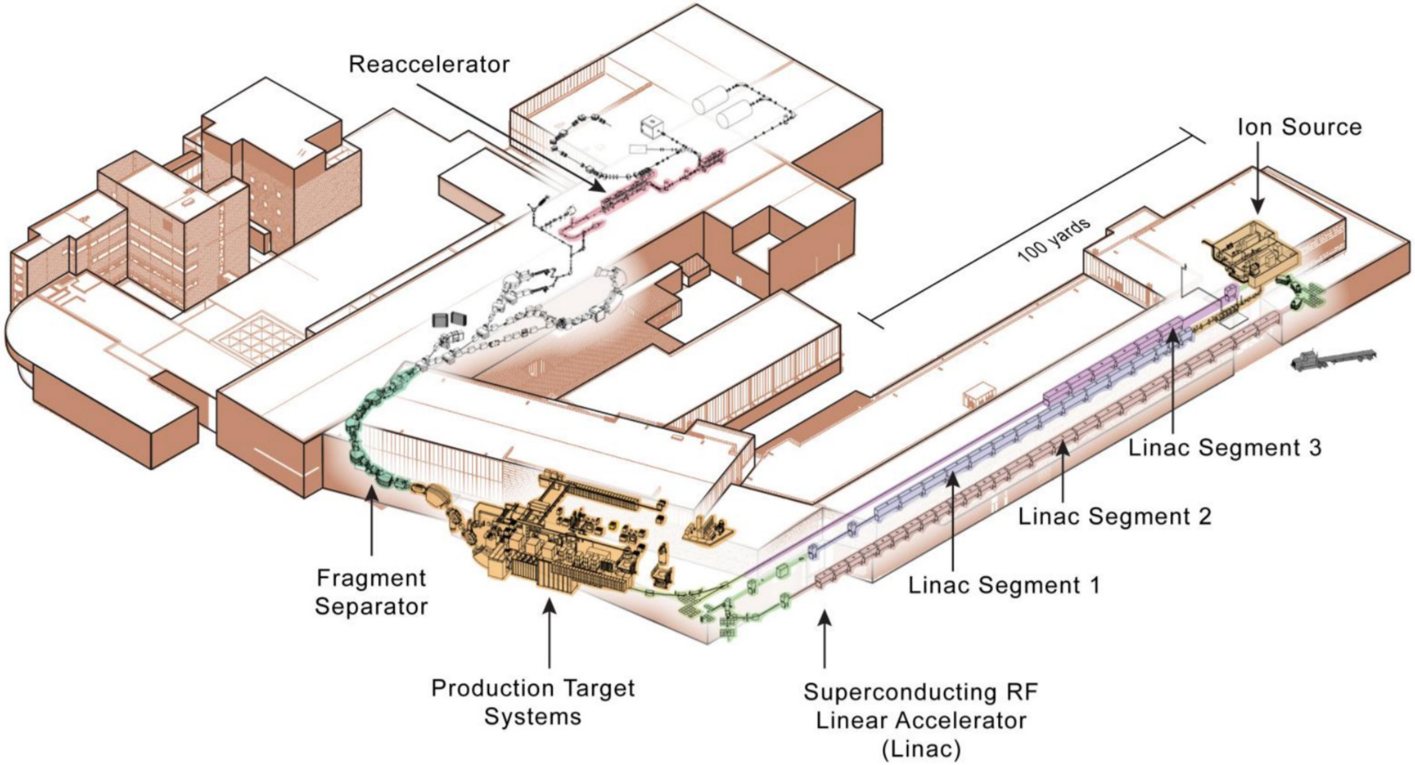
FRIB Helium Purification System

Helium purifiers (left) and compressor (right)
(Located in FRIB compressor room)

- Used for low level impurity removal (~100 ppm to below 1 ppm)
- Purifier cold box
  - Freeze-out HX for moisture
  - Carbon bed for air
  - Uses liquid nitrogen
- Purifier compressor
  - ~112 kW, 480 V, 3-ph
  - 109 ℓ/s swept volume
  - Hermetic housing
  - Oil used for lubrication of bearings and rotors

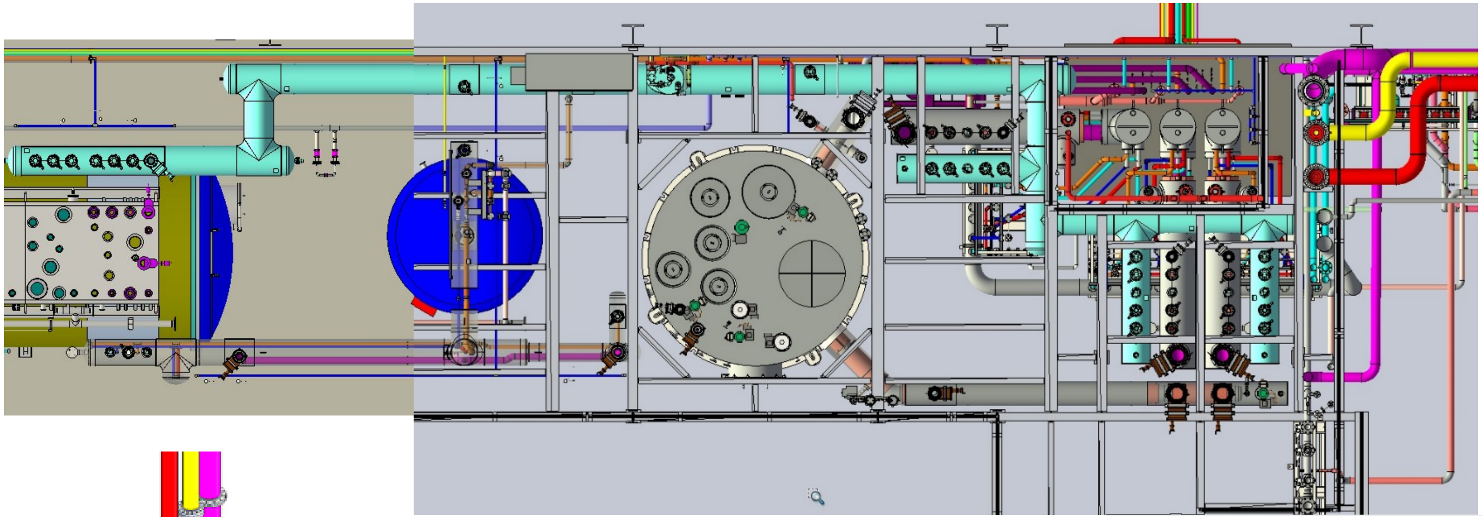
FRIB Cryogenic Distribution [1]

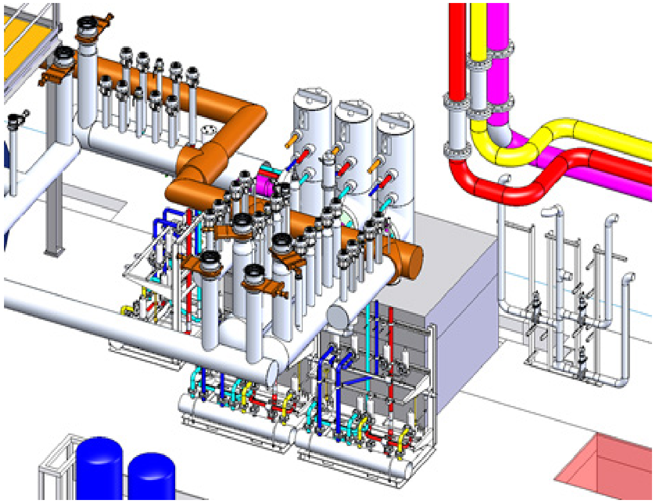
- Cryogenic distribution connects the FRIB main refrigeration system with the loads; which for FRIB are the,
  - Linear accelerator (Linac) and,
  - Experimental system superconducting magnets



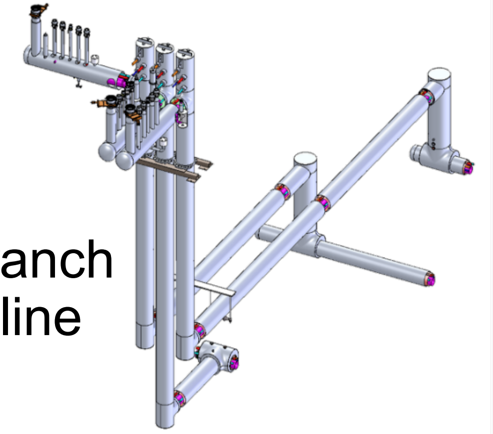
FRIB Cryogenic Distribution [2]

- Cold box room (Linac) distribution plan view



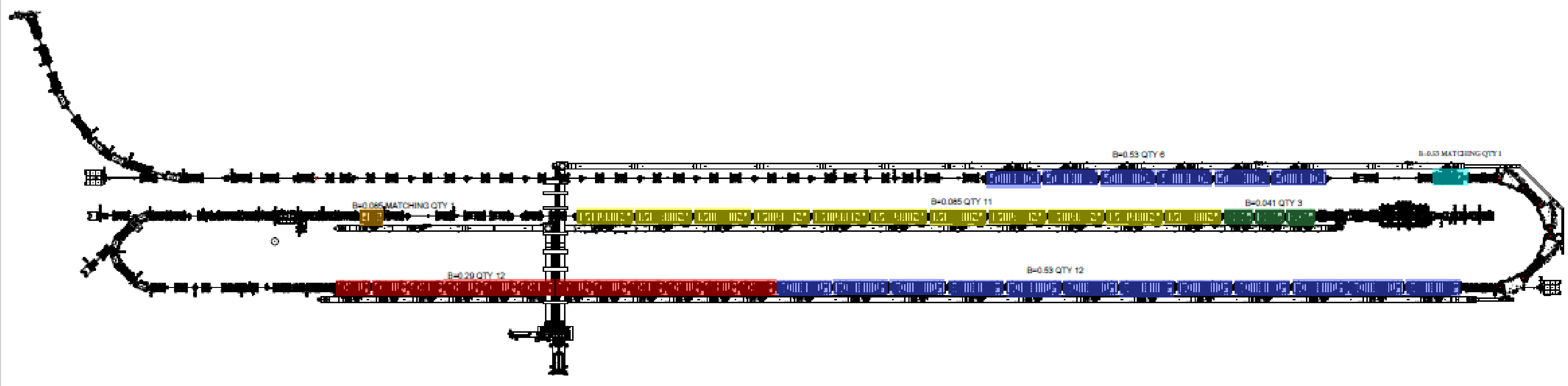


Right: Vertical shaft and branch sections for Linac transfer-line segments



FRIB Cryogenic Distribution [3]

- Linac is ‘folded’ into the shape of a ‘paper clip’: three straight sections, LS1, LS2, and, LS3

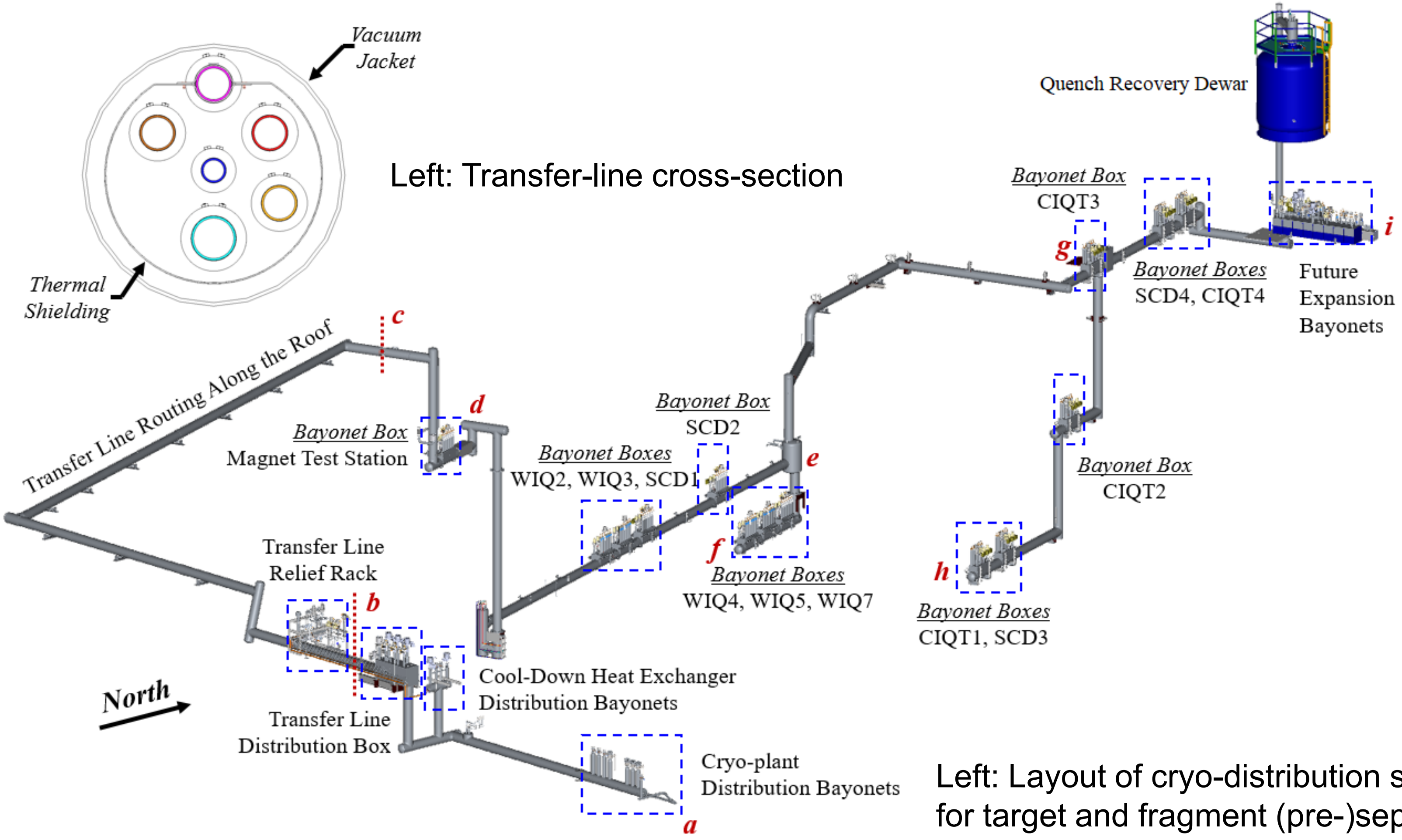


- Type and number of CM’s in each Linac segment: 6 types

Beta ratio (β)	0.041	0.085	0.085M [a]	0.29	0.53	0.53M [a]	Total
LS1	3	11	1	0	0	0	15
LS2	0	0	0	12	12	0	24
LS3	0	0	0	0	6	1	7
Total CM's	3	11	1	12	18	1	46

- [a] M = ‘Matching’

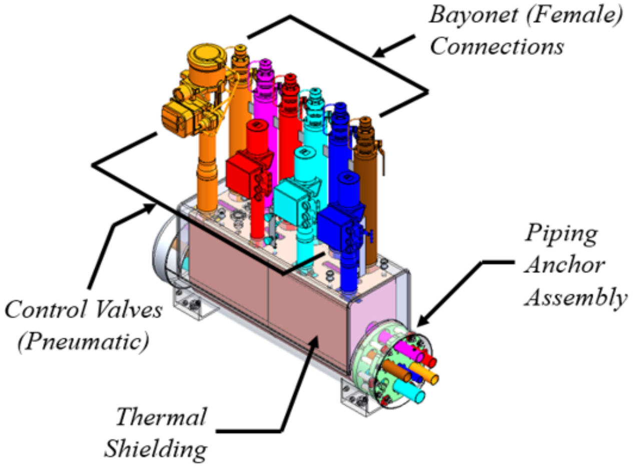
FRIB Cryogenic Distribution [4]

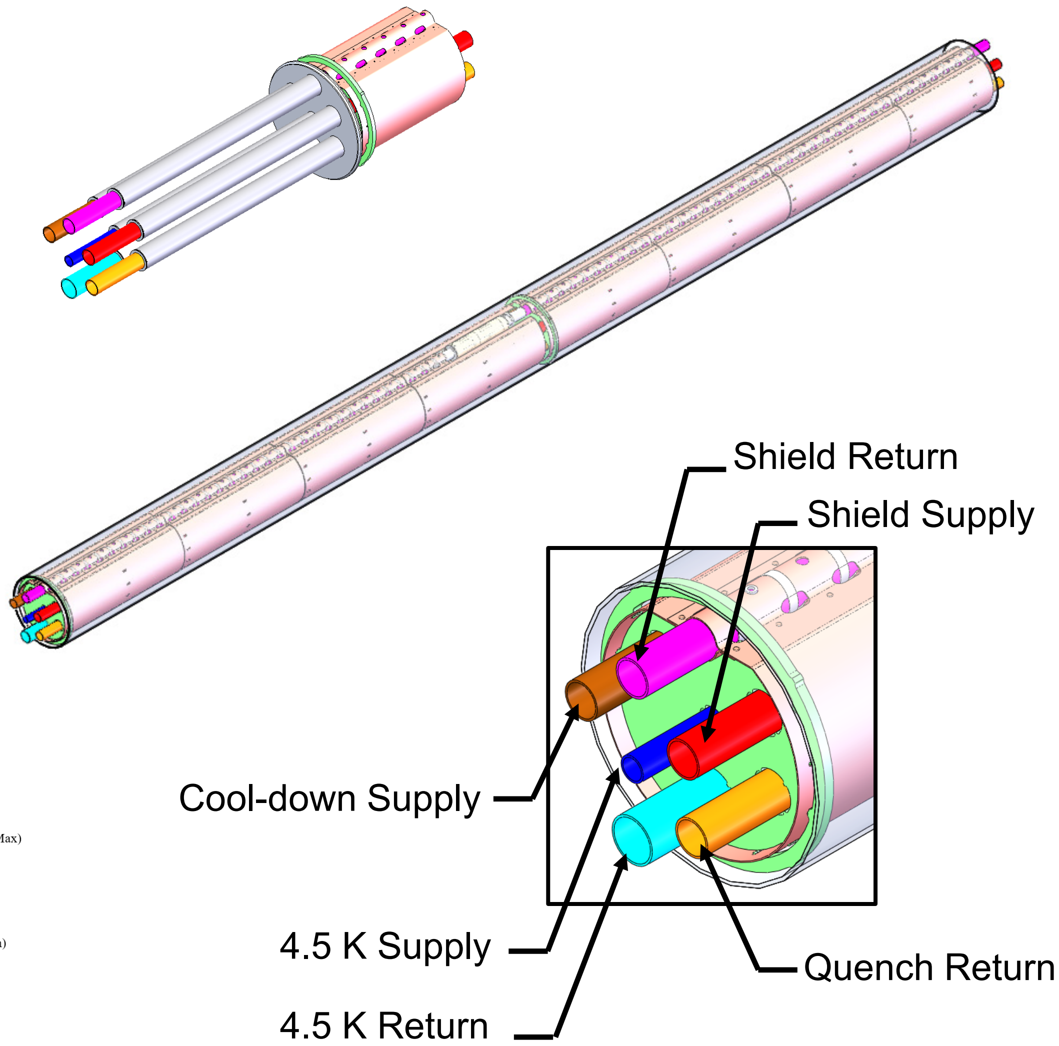


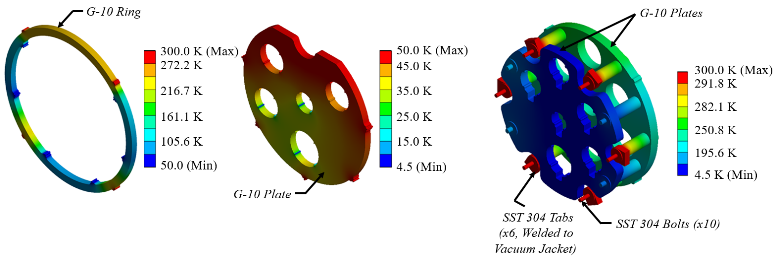
Left: Transfer-line cross-section

Left: Layout of cryo-distribution system for target and fragment (pre-)separator segment

FRIB Cryogenic Distribution [5]







FRIB Cryogenic Distribution [6]

Figure: (left) Magnet Test Station Distribution / Bayonet Box and,
(right) SCD1 magnet field mapping ongoing at Magnet Test Station

Magnet Test Station:

- One of the magnet distribution boxes are used as a magnet testing station

- Consists all other required utility connection for magnet field mapping, quench handling and protection and steady-state operation

FRIB Cryogenic Distribution [7]

Magnet Quench Recovery Dewar:

- It is a 10,000-liter (nominal) vessel designed to –
  - *Absorb the pressure pulse and energy from the quench in a magnet and contain the helium with out venting*
  - *Aid in helium inventory management during maintenance*

- The dewar vessel is connected to the distribution system via bayonet style cryogenic couplings
- The cool-down / quench return header is routed to both the top (vapor space) and bottom (liquid space) of this dewar vessel.
- This design concept is based on the successful quench testing of magnet strings (ASST-A) at Super Conducting Super Collider without venting helium (Ganni, V., SSCL 5, 1993)

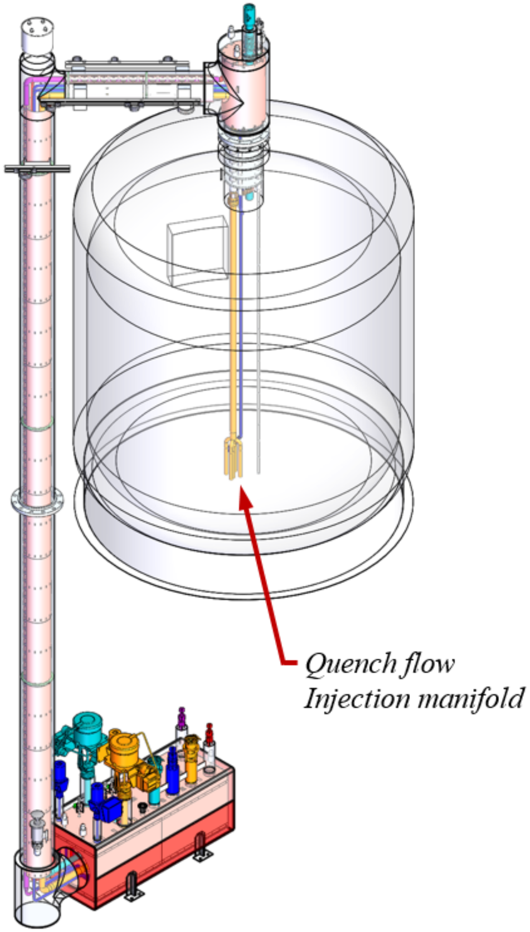


Figure: 3D Model of quench management dewar and associated distribution box.

FRIB Cryogenic Distribution [8]

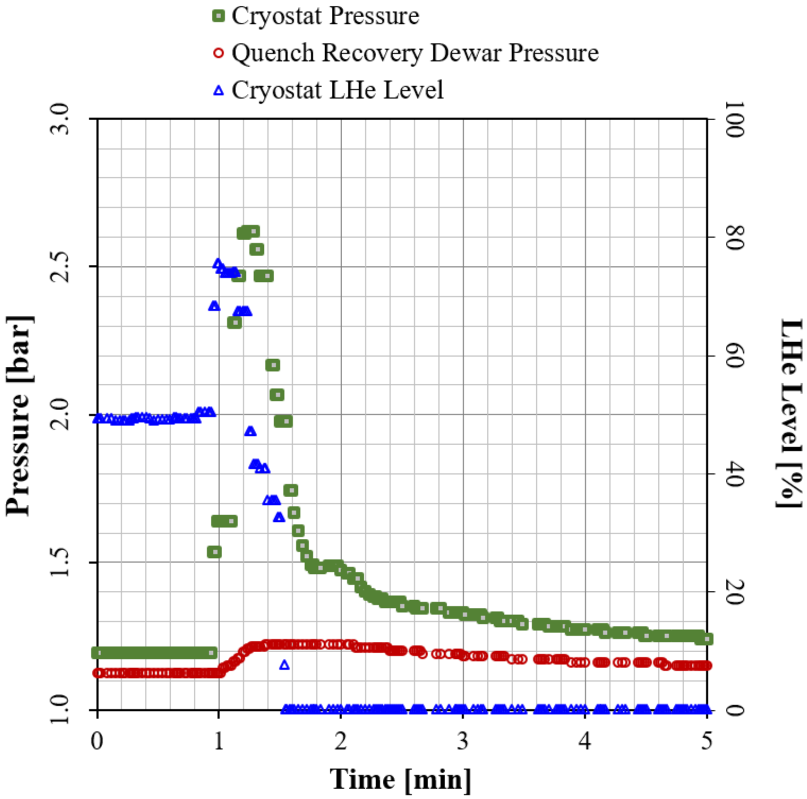


Fig.: Transient response of the FRIB Experimental System LTS Di-pole magnet (SCD3), and the quench recovery dewar following a quench

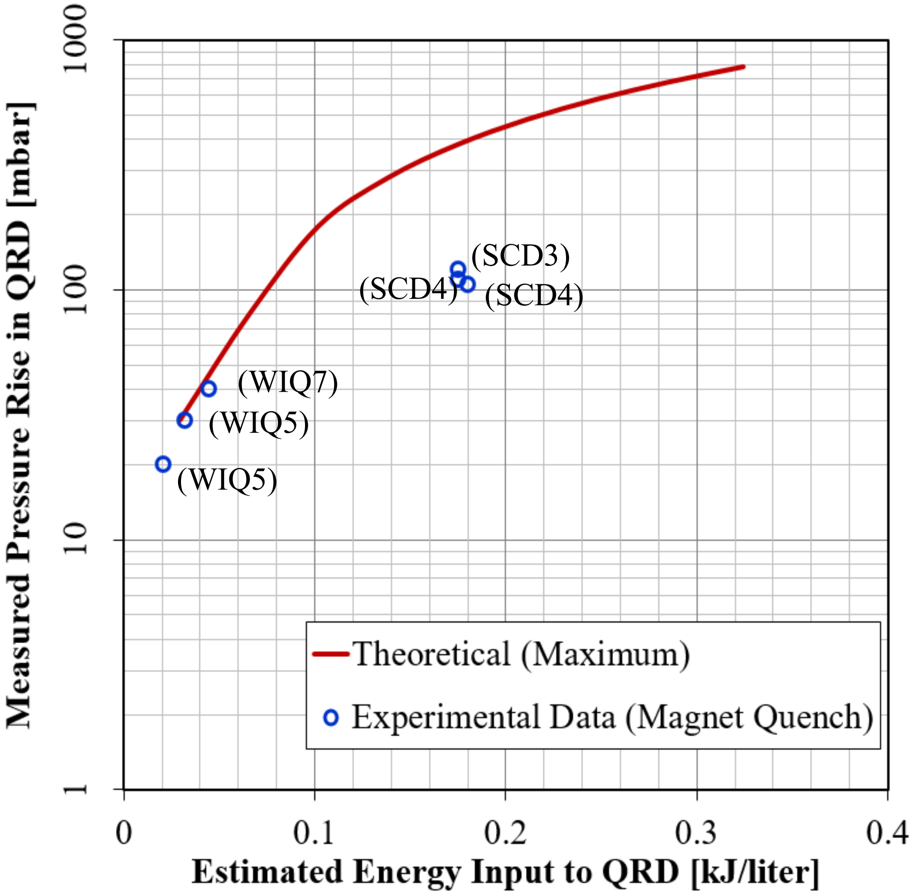


Fig.: Calculated and measured pressure rise in QRD due to (quench) energy addition

MSU Cryogenic Initiative [1]

- MSU Cryogenic Initiative is a collaboration between FRIB and the College of Engineering
- Goals
  - Educate and train future cryogenic engineers and system innovators
  - Investigate, propose, and foster efficient cryogenic process designs, and perform research to advance cryogenic technologies
  - Sustain a knowledge base of cryogenic technology and skills

Cryogenic Engineering: Research and Development

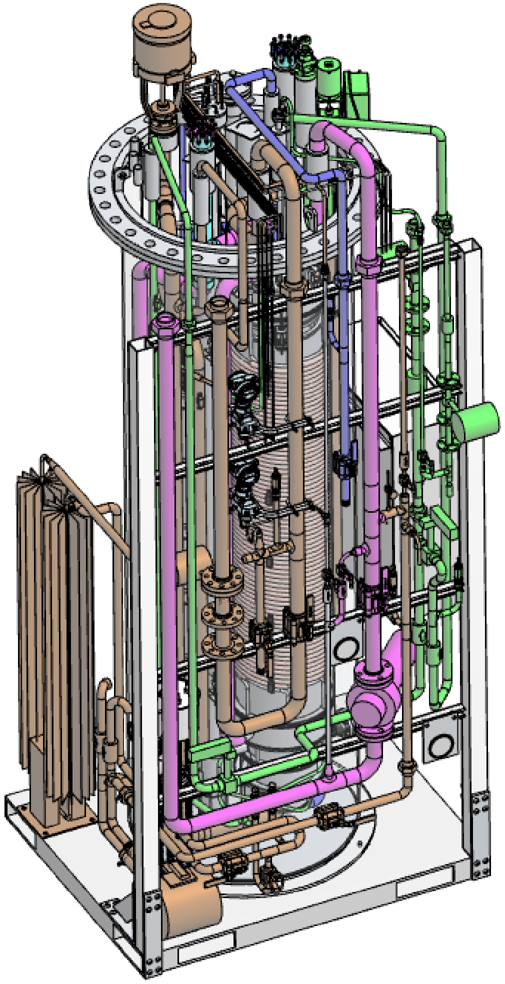
- Are helium cryogenic systems an ‘established’ technology like ‘conventional’ facilities?
  - Cryogenic engineering is a specialized engineering discipline
  - These systems are largely one-of-a-kind due to the experimental nature of the science they support, and the long project timespans (e.g., 14 years for FRIB; 2008 to 2022)
  - *The low volume production, one-of-a-kind design/application, and long project time-span aspects are limiting industry from sustaining any R&D effort for equipment, systems, and technology needed*

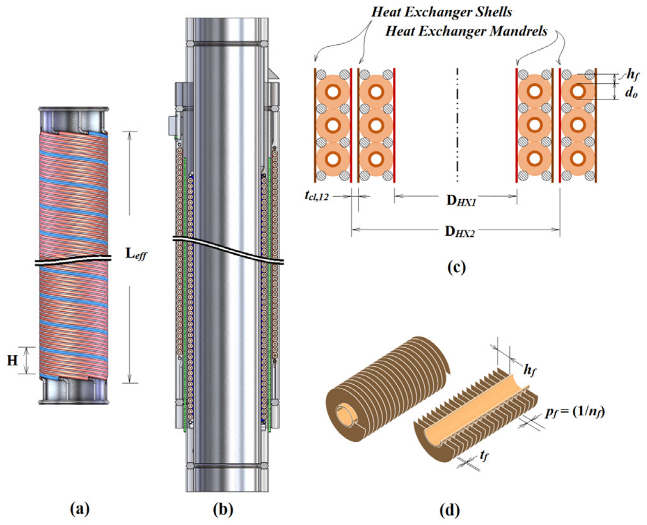
  - Consequently, much of the equipment is adapted from other industries, such as oil and gas and commercial refrigeration
    - » But the adaptation is usually inefficient and lacking reliability and robustness
    - » Often manufacturers will not even want to supply their equipment for others to adapt it for cryogenic system application!

Cryogenic Engineering: Research Focus [1]

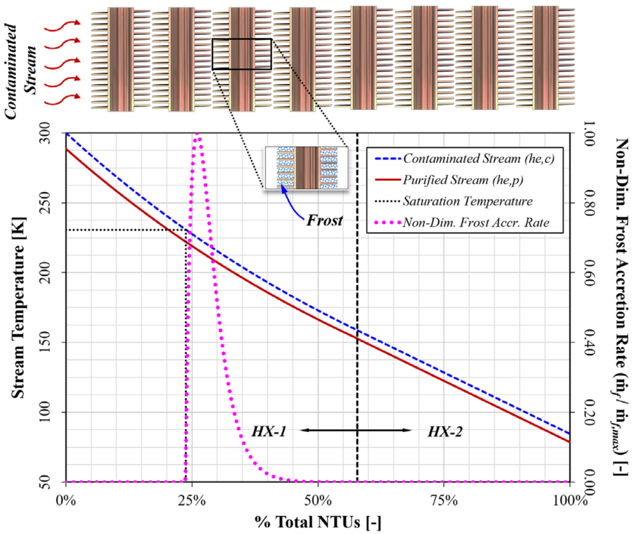
- Research Focus
  - Cryogenic System Operational Optimization
    - Operating the system under optimal process conditions for a given experimental system requirement
    - Failure Mode Analysis – Operating the system under various sub-component failure
    - Overall modes of operation for FRIB cryogenic system
  - Cryogenic System Hardware
    - Helium Purification and Preservation
    - Quench Recovery and Inventory Management
    - Warm Compressor Efficiency Improvement
    - Small-scale 2K System Capacity Improvement
  - Cryogenic Component Development
    - Heat exchangers for small / medium scale cryogenic systems, and sub-systems
    - Cryogenic control valve studies

Cryogenic Engineering: Research Focus [2]





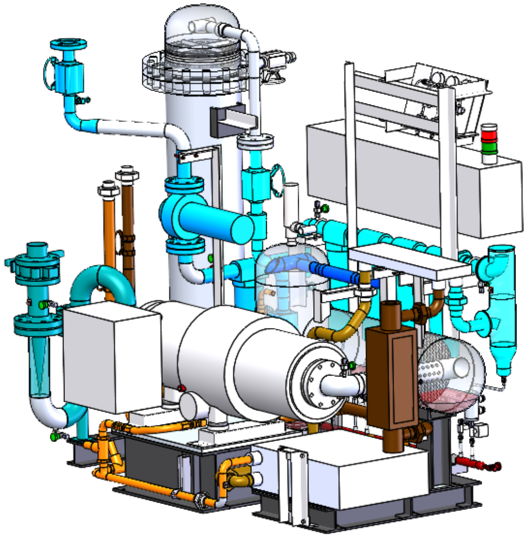
(a) (b) (c) (d)

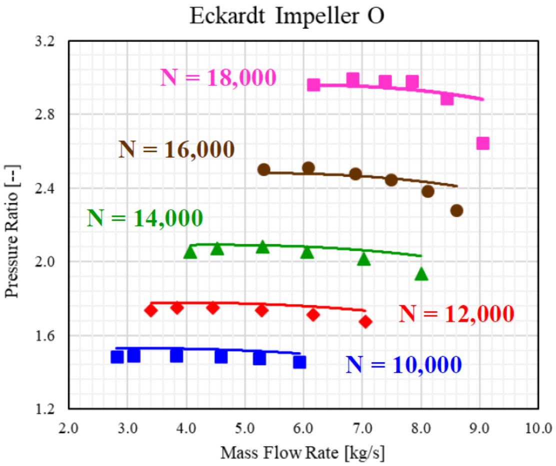


Graduate Research Work: Study of frost formation in cryogenic heat exchangers

Cryogenic Engineering: Research Focus [3]

- Warm Helium Compressor
  - Highly resource intensive, majority of the system losses
  - Development of compressor skid for small-scale systems with wide-range operation
- Cryogenic centrifugal compressors (‘cold compressors’)
  - Operating envelop of these equipment under cryogenic condition is not well-defined; often determined via extensive testing
  - Lack of interest from Industry due to niche market, unavailability of associated cryogenic system (distribution) for equipment development





THANK YOU

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