FRIB

PHY 862: Accelerator Systems

Lecture on Cryogenic Systems

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Introduction to Cryogenics [1]

- Processes that provide cooling to practical superconducting devices presently require cryogenic process conditions, namely temperatures generally below -150 ºC (~123 K)

- Typically this involves working fluids that have a normal boiling point less than this temperature

- Process cycles used to produce the required cooling are quite different from the more conventional vapor compression cycle

Introduction to Cryogenics [2]

- Key aspect to appreciate is the energy intensiveness
  - *e.g.*, a typical large 4.5 K helium refrigerator requires three orders of magnitude more energy input (for the same cooling) than a normal home cooling system; a 2 K helium refrigerator requires three and often closer to four times what is required for 4.5 K refrigeration

- In numbers: a typical large 4.5 K helium refrigerator requires ~250 W of input power per 1 W of cooling

- A typical 2 K (~30 mbar) helium refrigerator requires ~1000 W/W, although it should be possible to achieve ~750 W/W for a well matched and well-designed system

So Why Superconductors & Why Helium?

- Superconductor cables, implemented as electro-magnets, are commonly used in particle accelerators and colliders, MRI's, plasma confinement (fusion research), and more

- Practical type II superconductors (i.e., those made from alloys) used as electro-magnets, such as Nb-Ti and Nb_3Sn, have transition temperatures of 9.6 K and 18.1 K, respectively

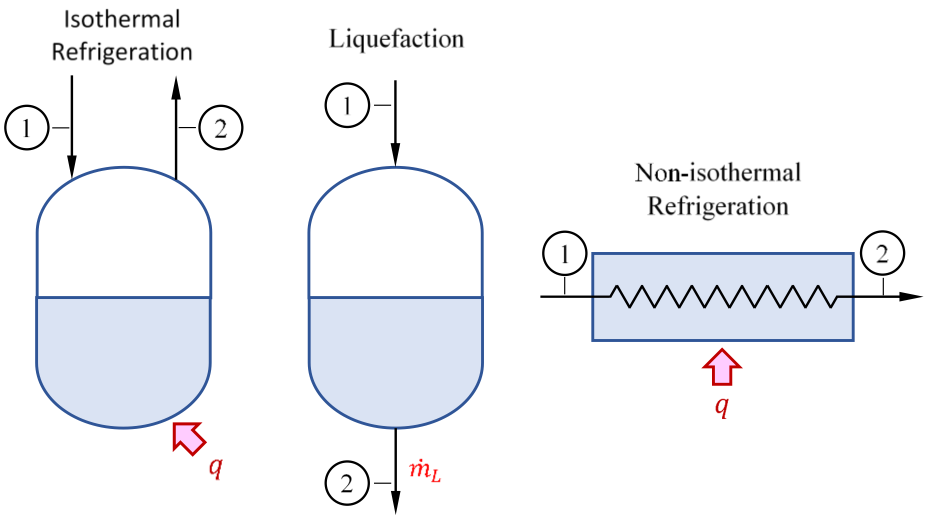
- Transition temperatures correspond to zero current density at zero magnetic field, but some margin is needed for actual operation
  - Note: The temperature, magnetic field and current (density) with which the superconductor transitions from normal to superconducting is a three-dimensional surface

So Why Superconductors & Why Helium? [2]

Name	Symbol	R #	MW [g/mol]	T_{sat} at p_0 [K]
Refrigerant-11	CCl_3F	R-11	137.4	296.8
Refrigerant-134A	$C_2H_2F_4$	R-134a	102.0	246.9
Refrigerant-12	CCl_2F_2	R-124	120.9	243.4
Ammonia	NH_3	R-717	66.05	239.8
Refrigerant-22	$CHClF_2$	R-22	86.48	234.3
Xenon	Xe		131.3	165.0
Krypton	Kr	R-784	83.80	119.8
Methane	CH_4	R-50	16.04	111.7
Oxygen	O_2	R-732	32.00	90.19
Argon	Ar	R-740	39.95	87.28
Nitrogen	N_2	R-728	28.01	77.31
Neon	Ne	R-720	20.18	27.09
Deuterium	D		4.028	23.66
Para Hydrogen	$p\text{-}H_2$		2.016	20.28
Helium-4	He	R-704	4.003	4.22

Cryogenic Refrigeration / Liquefaction [1]

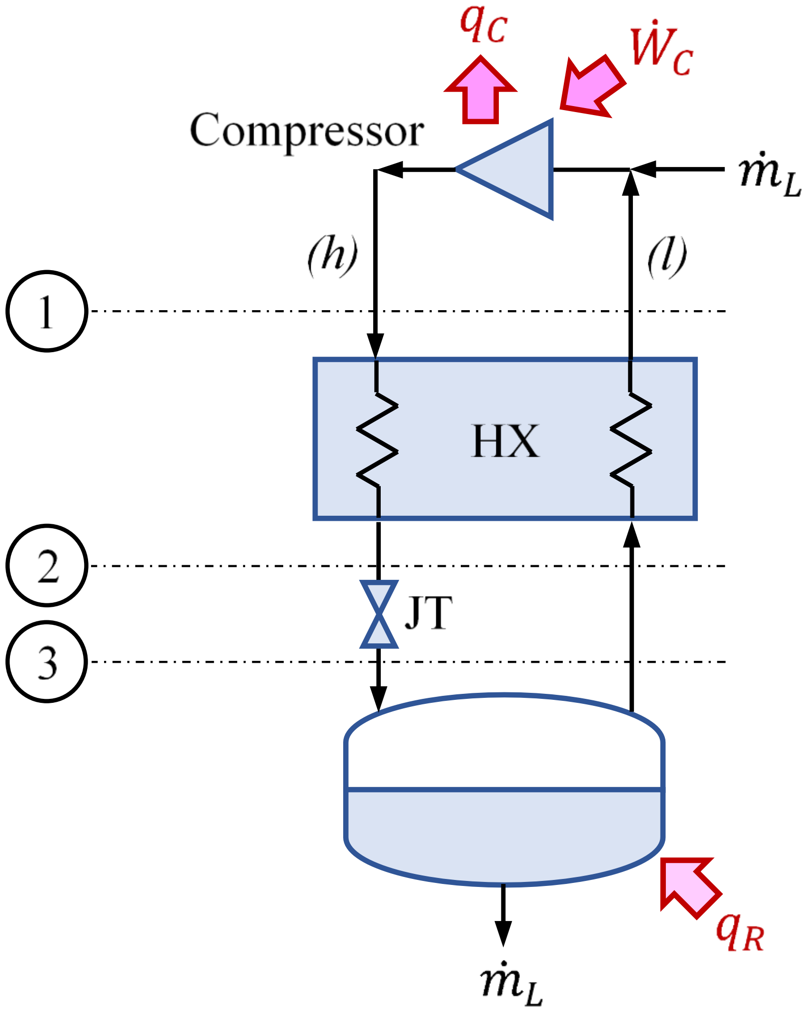
- Cryogenic loads:
  - Isothermal (constant temperature) refrigeration;
    - »heat into a saturated liquid bath, maintained at constant pressure
    - »Involves phase change (at constant pressure) of refrigerant fluid
  - Liquefaction; liquid supplied and withdrawn from a saturated liquid bath, maintained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

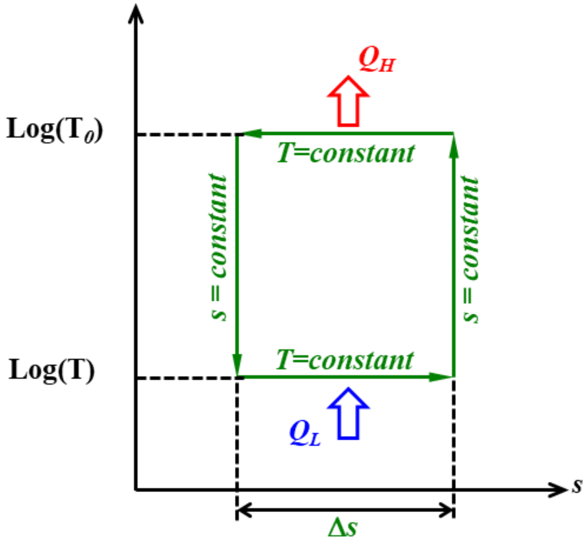


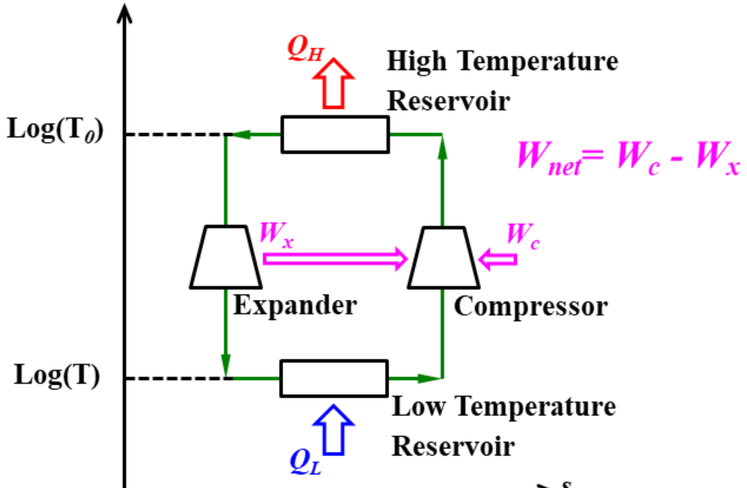
Cryogenic Refrigeration / Liquefaction [3]

- 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

The Traditional Carnot Cycle [1]

- 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!





The Carnot Cycle [1]

- So, from our previous discussion, we know that,

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

- And, from the First Law, we know that 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,

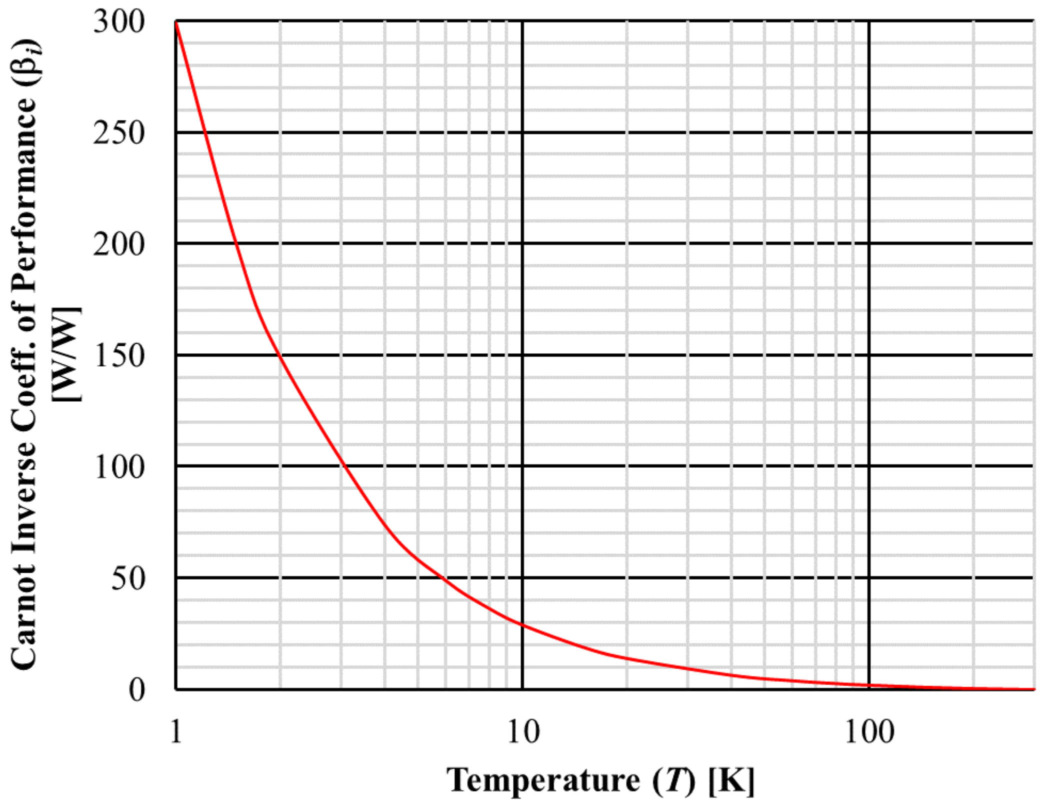
$$\beta \equiv \frac{Q_L}{W_{net,rev}} = \left(\frac{T_0}{T} - 1\right)^{-1}$$

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	T_{sat} at p_0	λ	b_i
			[g/mol]	[K]	[J/g]	[W/W]
Refrigerant-11	CCl_3F	R-11	137.4	296.8	181.3	0.01
Refrigerant-134A	**$C_2H_2F_4$**	**R-134a**	**102.0**	**246.9**	**217.0**	**0.22**
Refrigerant-12	CCl_2F_2	R-124	120.9	243.4	166.0	0.23
Ammonia	NH_3	R-717	66.05	239.8	1369	0.25
Refrigerant-22	$CHClF_2$	R-22	86.48	234.3	230.4	0.29
Xenon	Xe		131.3	165.0	96.4	0.82
Krypton	Kr	R-784	83.80	119.8	107.9	1.50
Methane	CH_4	R-50	16.04	111.7	510.3	1.69
Oxygen	O_2	R-732	32.00	90.19	213.1	2.33
Argon	Ar	R-740	39.95	87.28	161.3	2.44
Nitrogen	N_2	R-728	28.01	77.31	198.9	2.88
Neon	Ne	R-720	20.18	27.09	85.7	10.1
Deuterium	D		4.028	23.66	320.9	11.9
Para Hydrogen	$p\text{-}H_2$		2.016	20.28	445.4	13.8
Helium-4	**He**	**R-704**	**4.003**	**4.22**	**20.7**	**69.9**

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

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·Δs) [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)

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

- Latent heat (mass specific cooling provided)

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

- Liquefaction specific load exergy

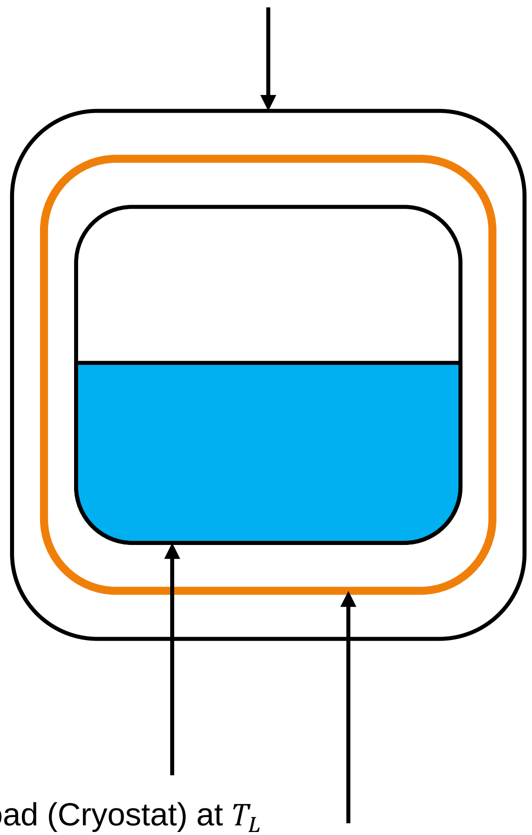
$$\dot{w}_{rev,L} = \Delta\varepsilon_L = 6838 \ \mathrm{J/g}$$

- Equivalence:

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

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

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

- Heat in-leak from thermal shield to load

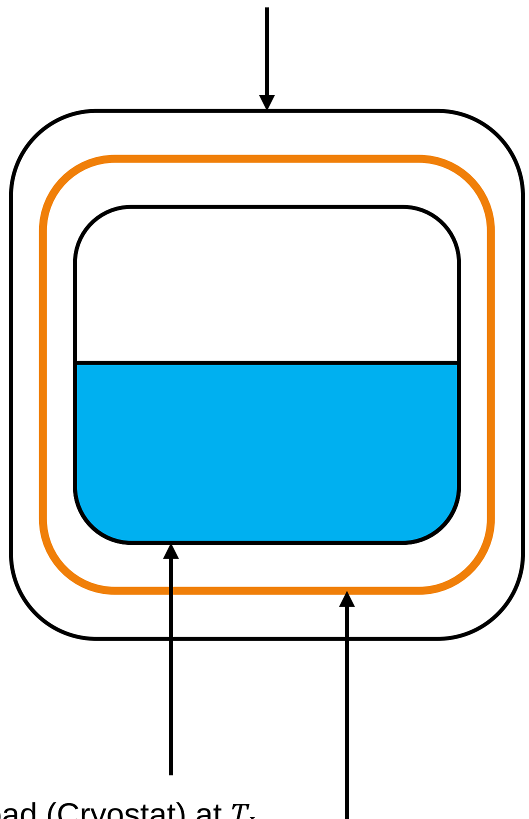
$$q_L = eA_L\sigma_b(T_s^4 - T_L^4)$$

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

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

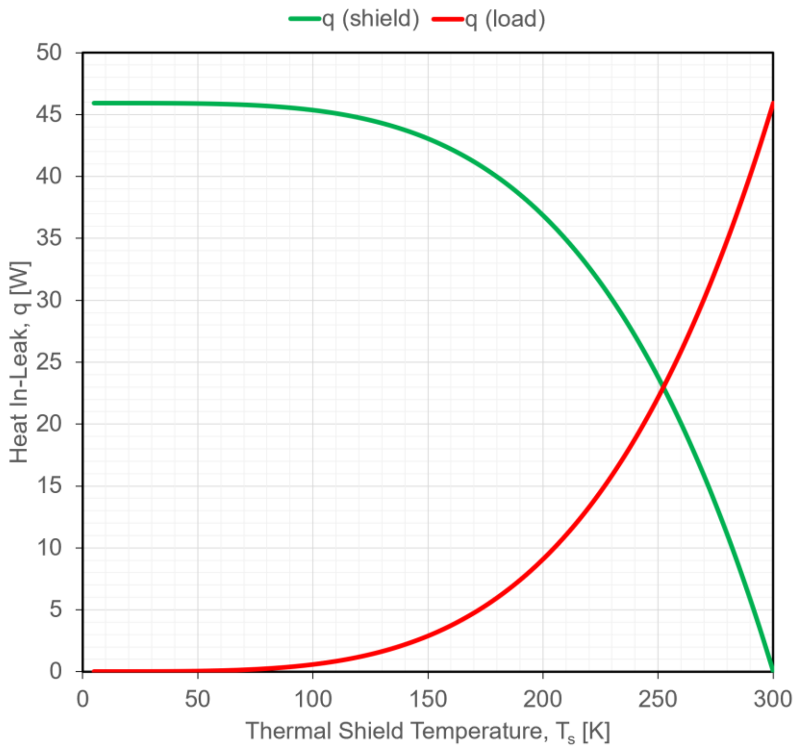
- Total exergy (loss) for heat in-leak due to radiation

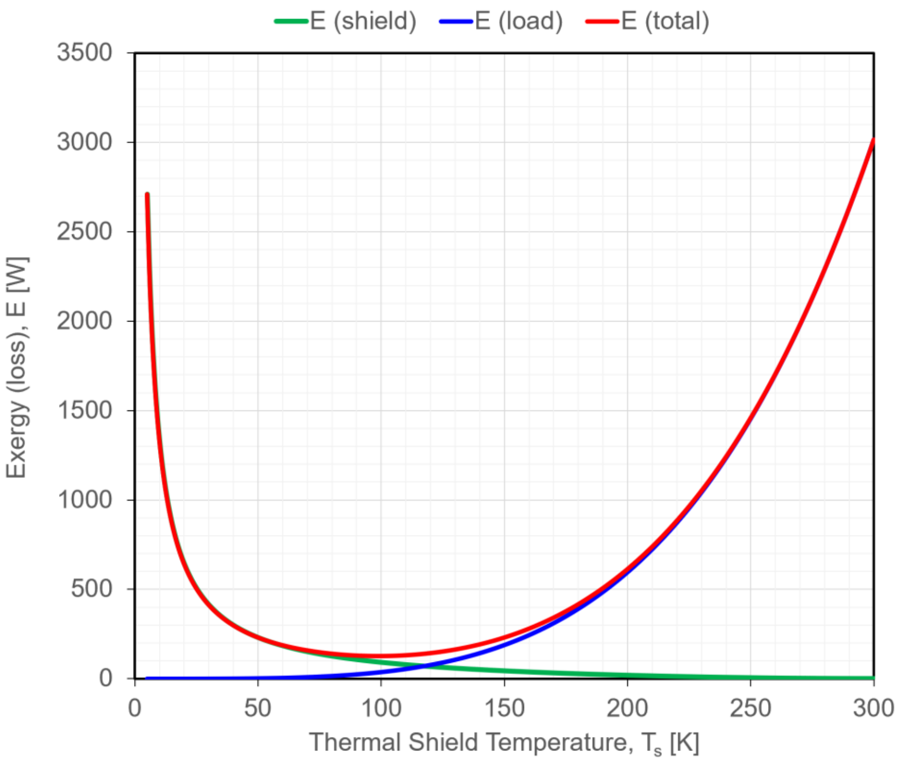
$$E = E_s + E_L$$



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*'

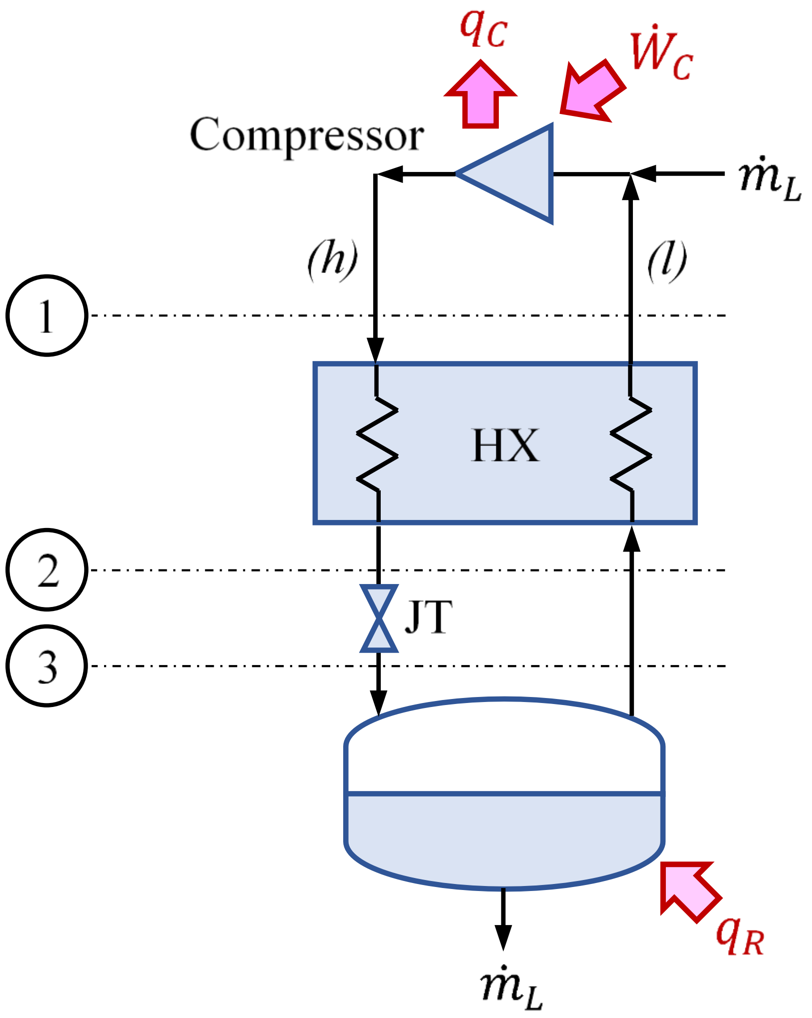
Practical Cryogenic Cycles [2]

- 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

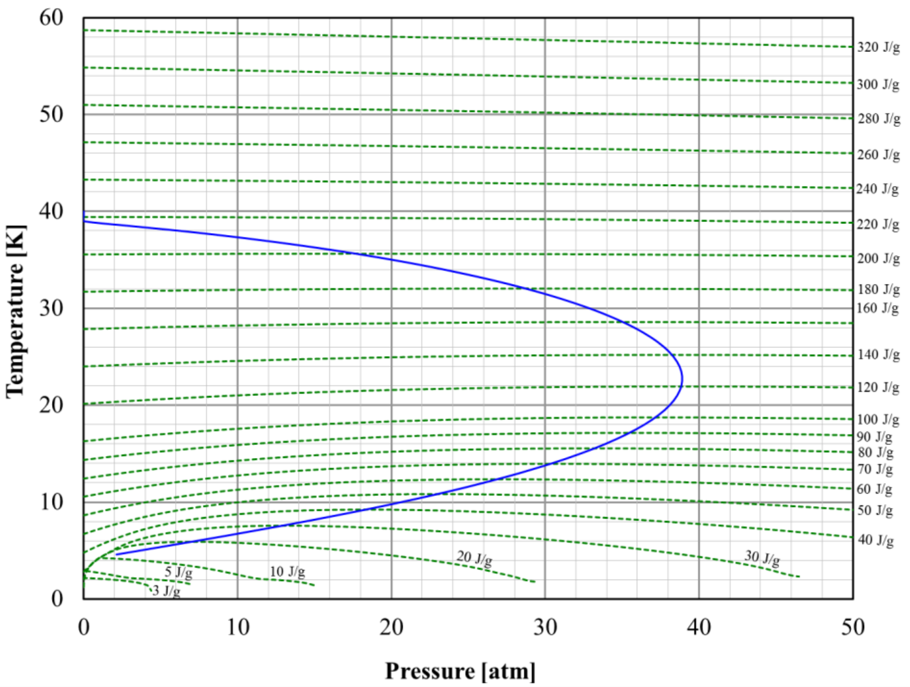
JT Process [1]

- 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*	$T_{i,max}$
			[K]	[J/kg-K]	[K]
Oxygen	O_2	R-732	90.19	259.8	757
Argon	Ar	R-740	87.30	208.1	763
Nitrogen	N_2	R-728	77.35	296.8	607
Neon	Ne	R-720	27.10	412.0	220
Deuterium	D		23.66	2064	211
Hydrogen	H_2	R-702	20.37	4124	201
Helium-4	He	R-704	4.22	2077	45.2

- Where, $T_{i,max}$, 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

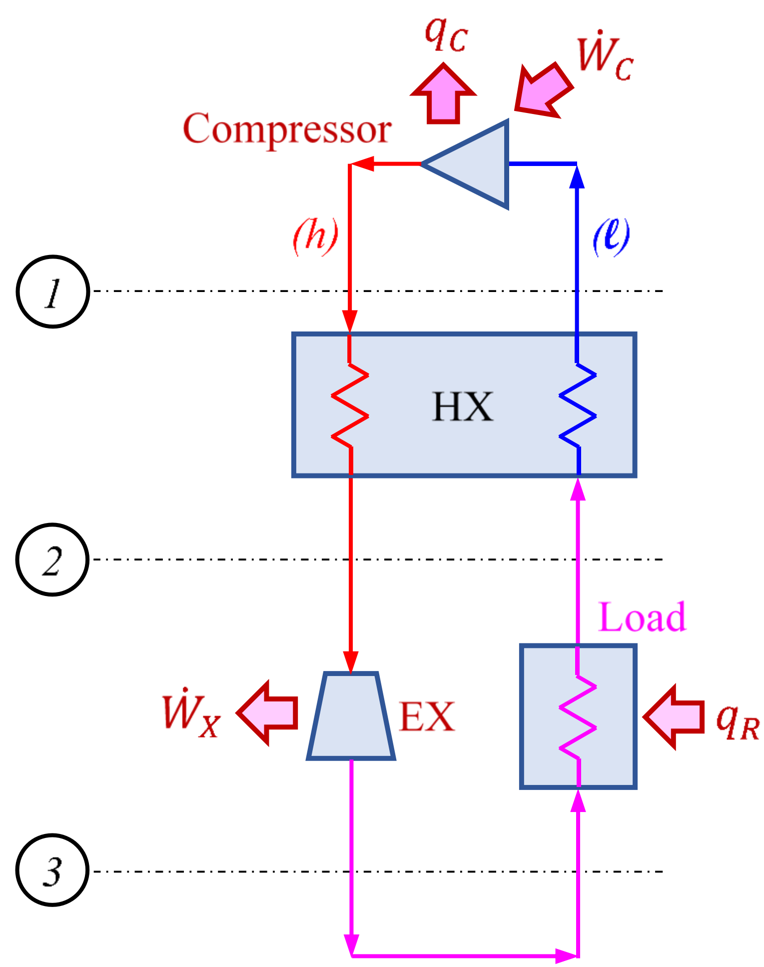
Reversed-Modified Brayton Process

- Reversed – because it is used for refrigeration rather than power generation

- Modified – because it has isothermal compression and isentropic expansion

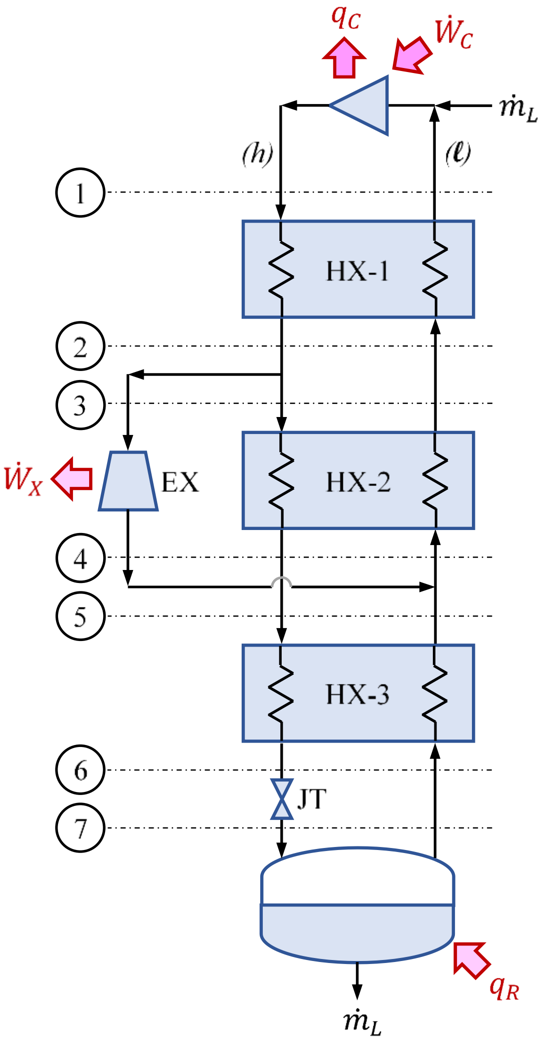
- Recall a Brayton cycle has isentropic compression and expansion

- Note that this process provides <u>non-isothermal</u> cooling



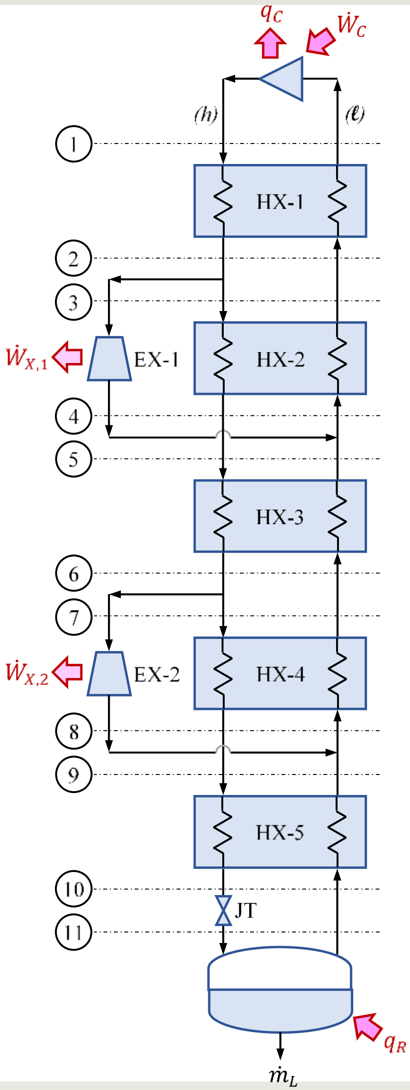
Claude Process

- 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



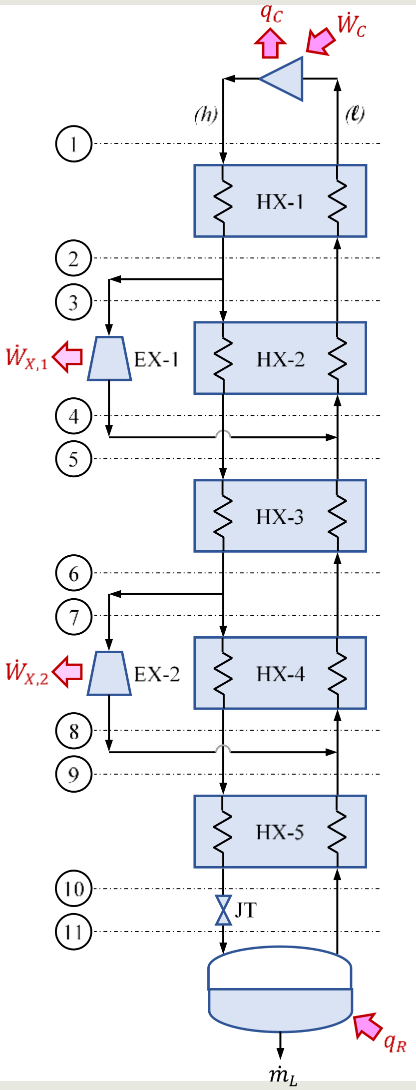
Collins Process [1]

- 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

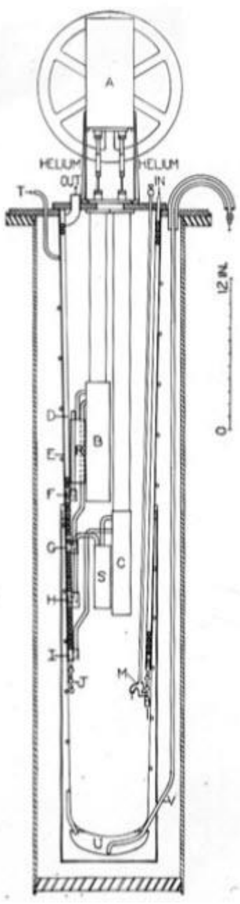


Collins Process [2]

- 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

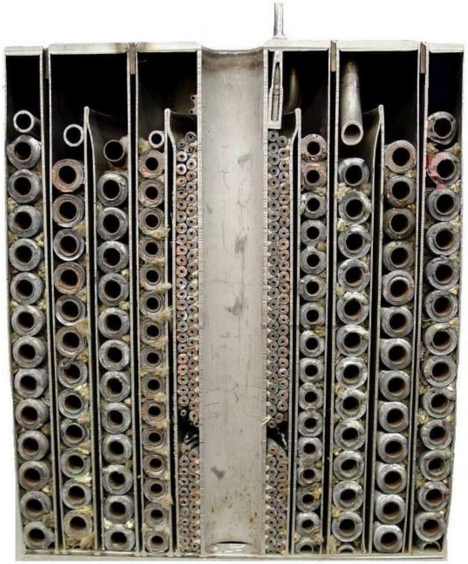


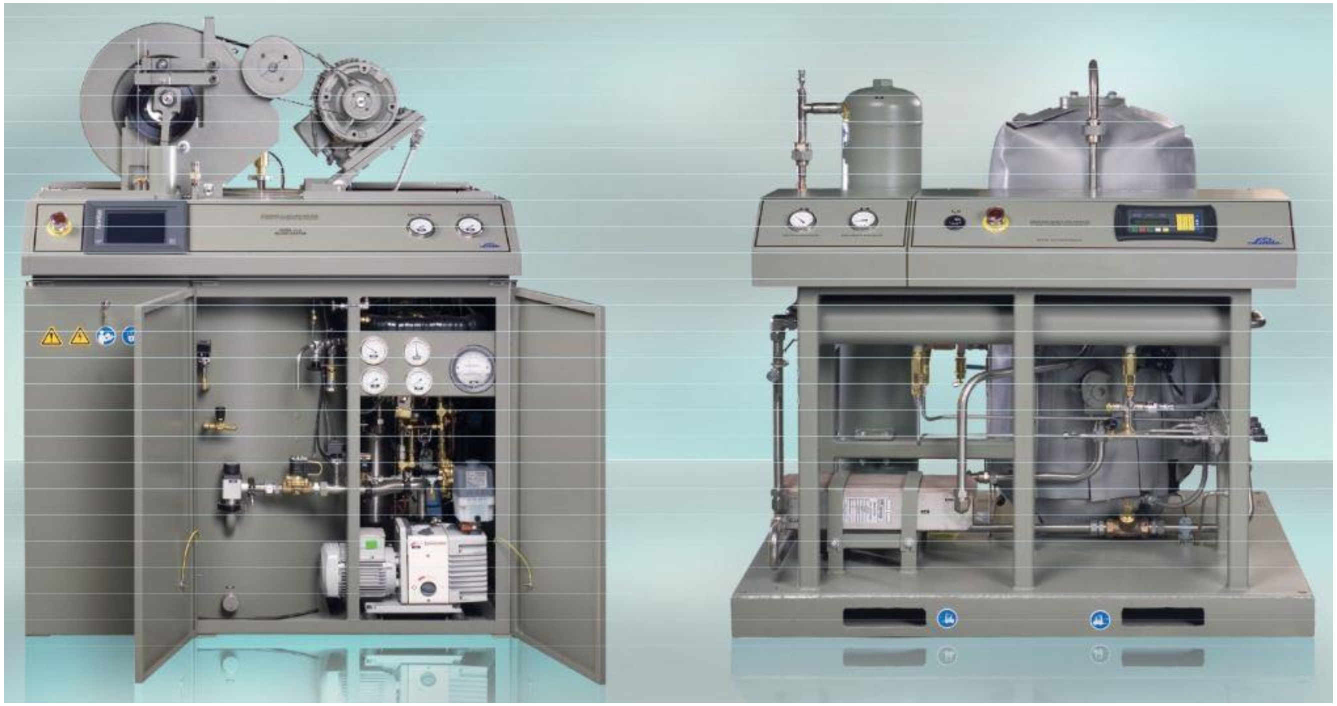
Collins Process [3]



Collins Process [4]

- (Now) Linde model 1410



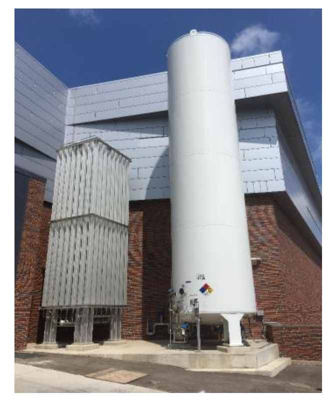


Overview - Large Helium Cryogenic Systems [1]

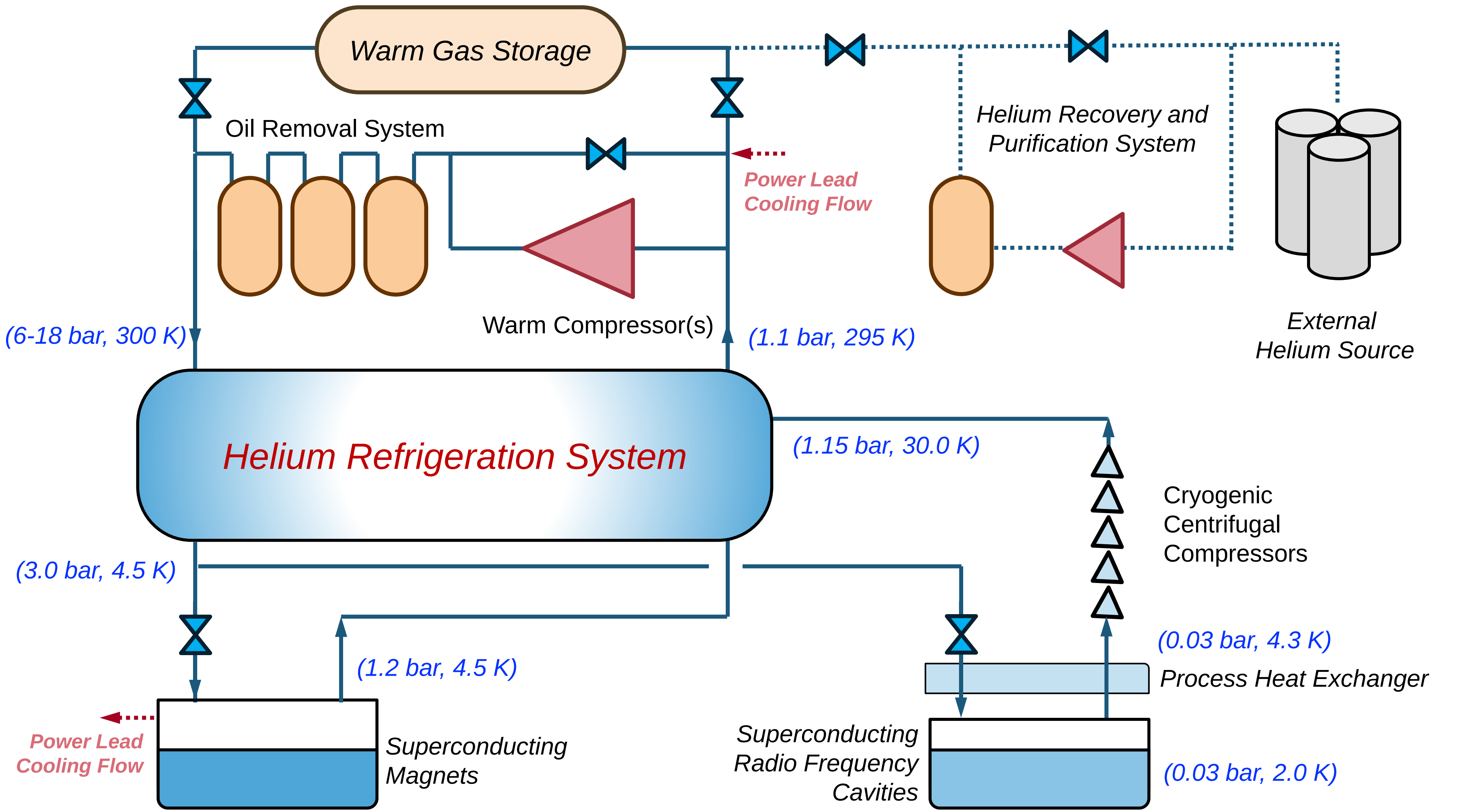
Major Helium Refrigerator Sub systems:

- 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

Overview - Large Helium Cryogenic Systems [2]

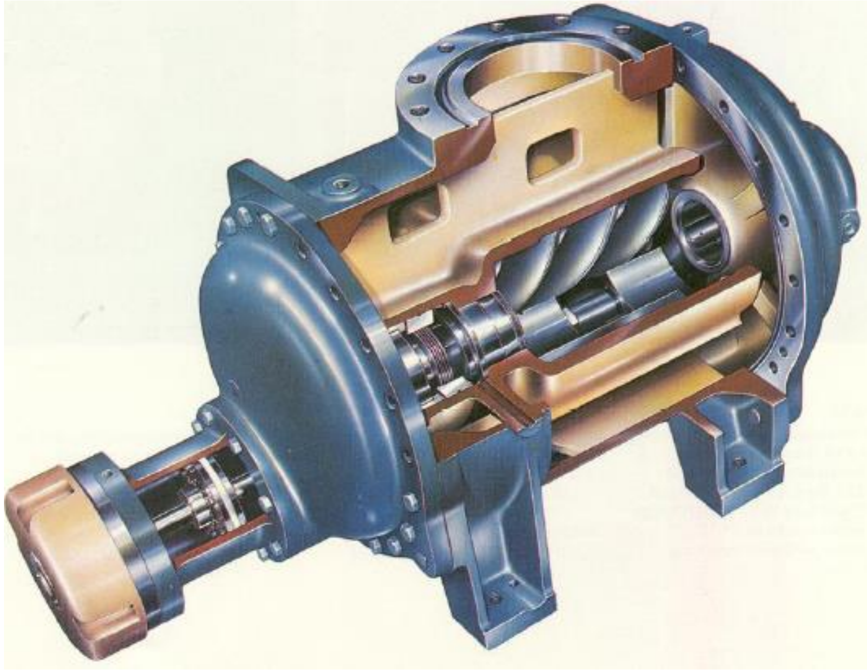


Overview - Large Helium Cryogenic Systems [3]



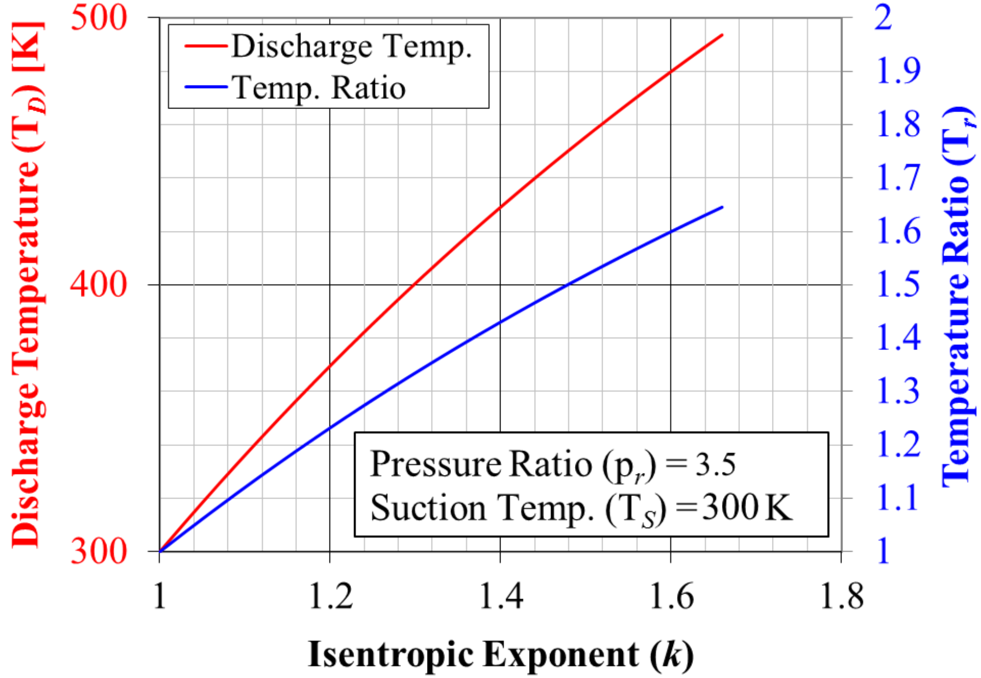
Warm Gas (Helium) Compressors

- 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



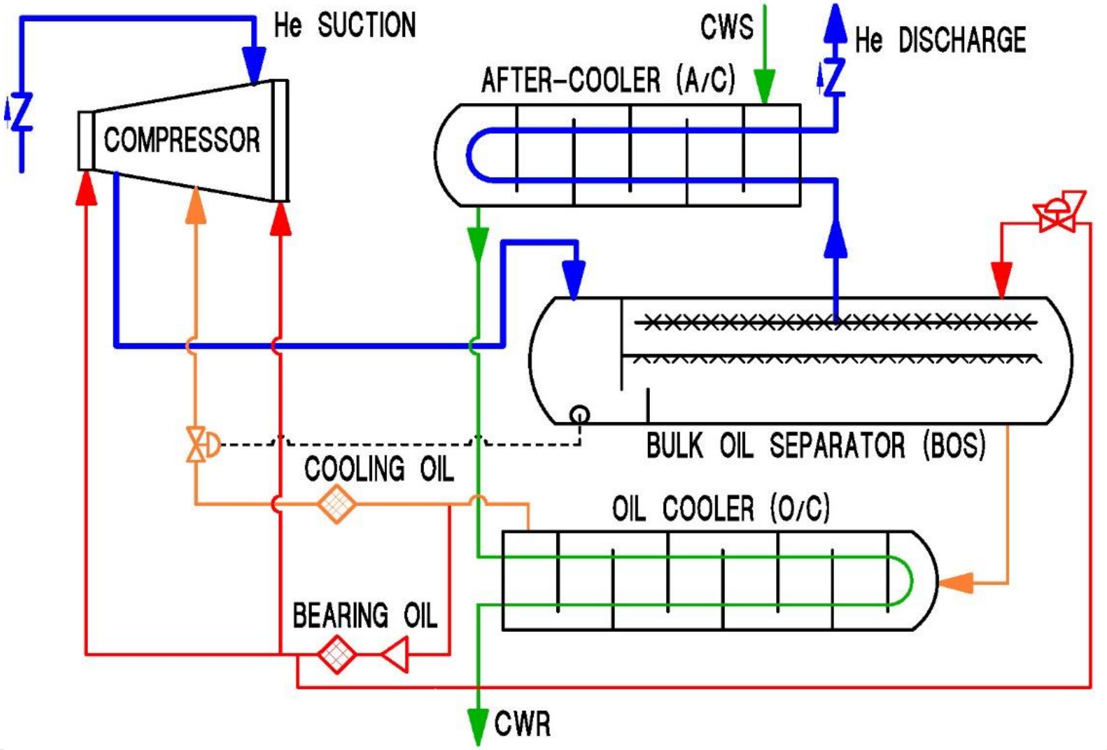
Rotary Screw Compressor [1]

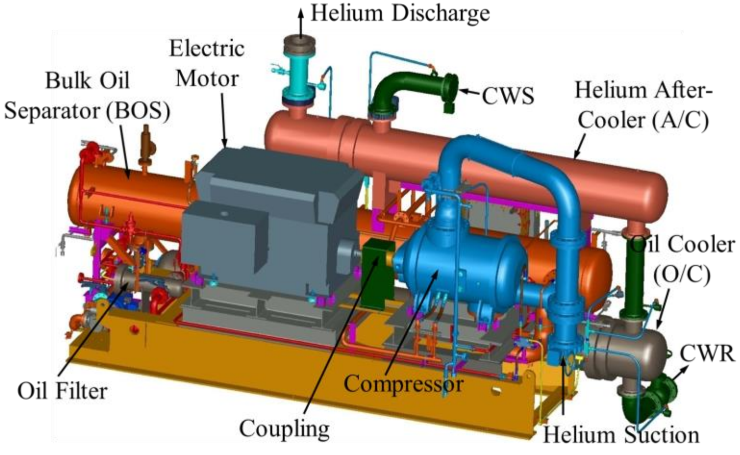
- Influence of the polytropic exponent (k) on the compression process and the temperature ratio for a pressure ratio of 3.5
- Since the isentropic exponent for helium is high (5/3), oil is injected into the helium gas to reduce the compression temperature so that normal materials and seals can be used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

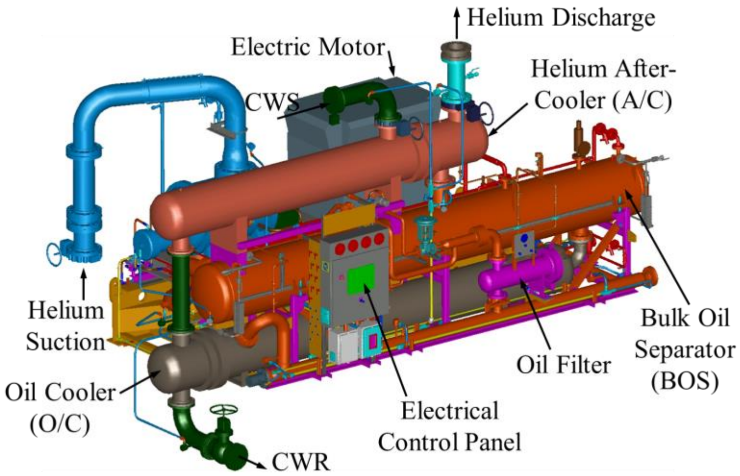


Rotary Screw Compressor [2]

- Helium compressors

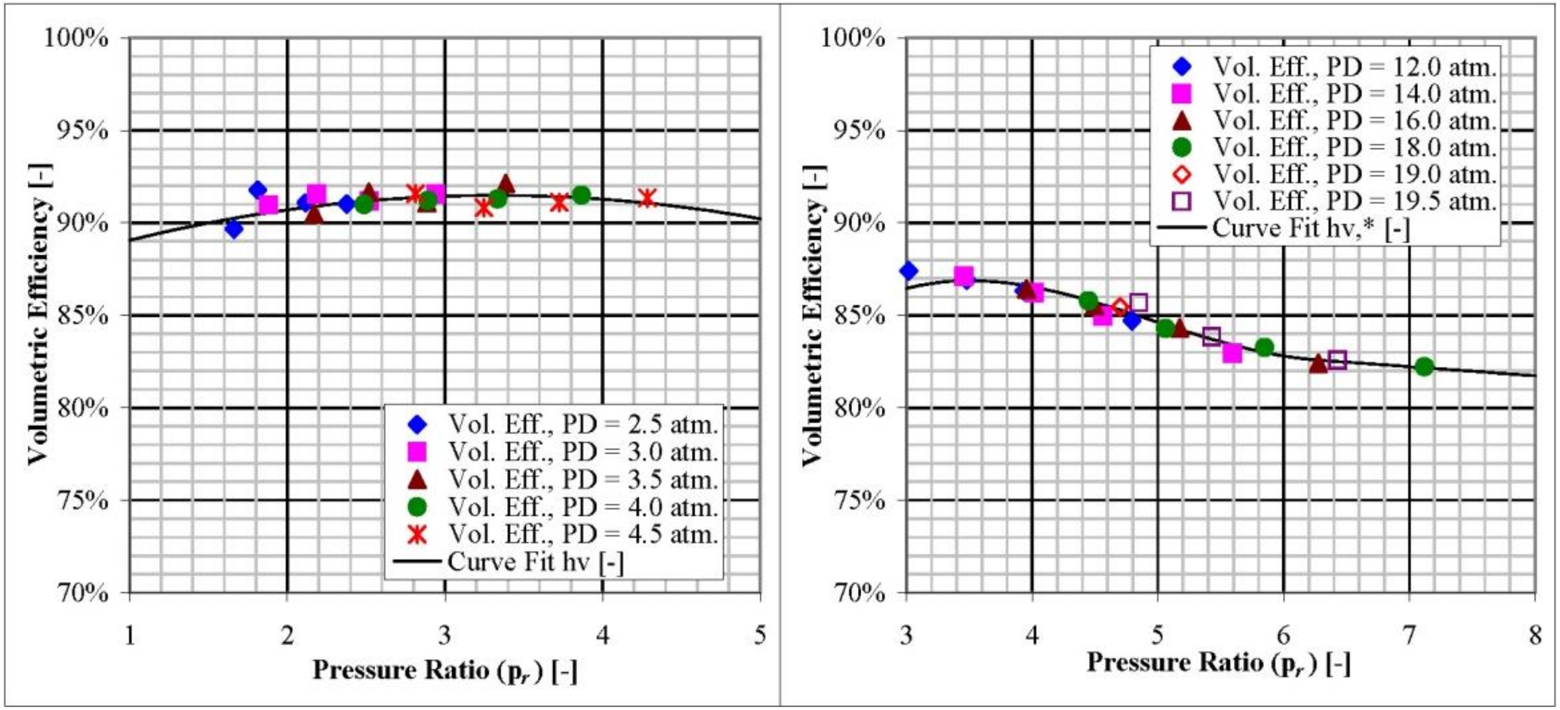






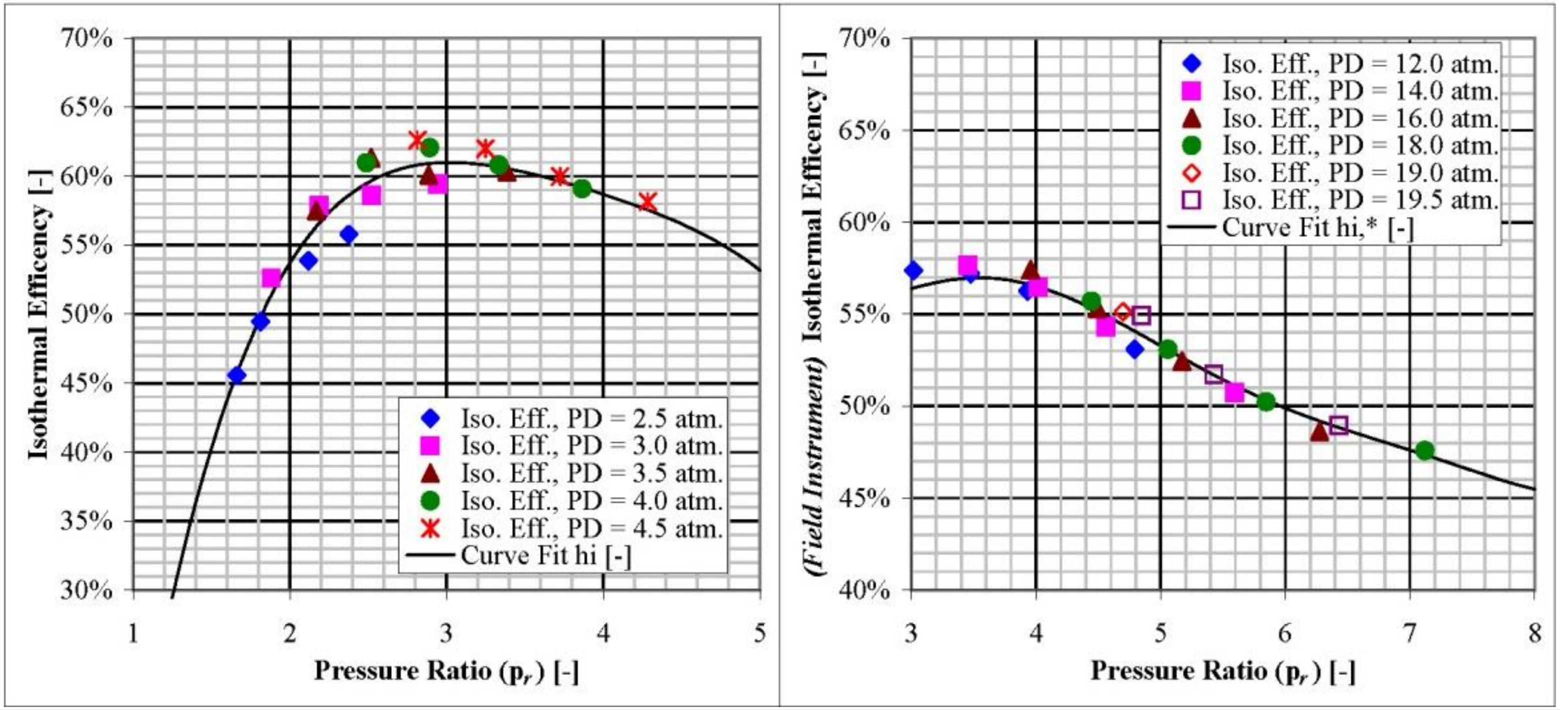
Rotary Screw Compressor [3]

- 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 [4]

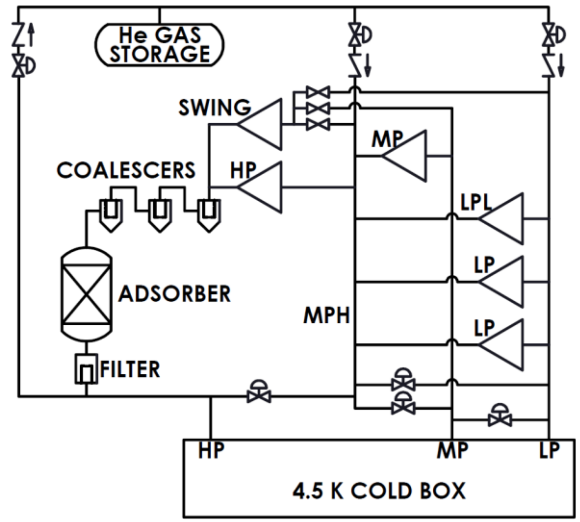
- Typical isothermal efficiency (η_i) for a given BVR
  - Left: SSCL Sullair LP stage 2.2 BVR
  - Right: SSCL Sullair HP stage 2.6 BVR
- For a given BVR, and compressor stage (i.e., LP, MP, HP), the efficiency is primarily dependent on the pressure ratio (p_r)



FRIB Warm Compressor System [1]

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

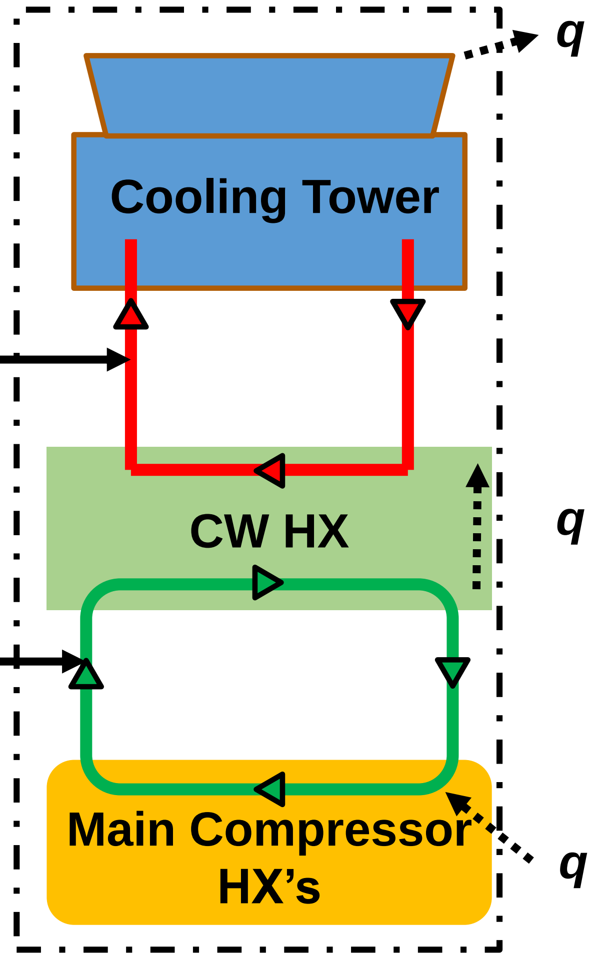
	LPL Stage	LP Stage	MP Stage	HP Stage
No. of Units	1	2	1	2
Compressor Model No.	WLVi 321/220	WLVi 321/193	WLVi 321/165	WLViH 321/193
Suction Swept Volume	35.526 l/rev	29.979 l/rev	26.649 l/rev	29.979 l/rev
Motor Frame	4009	3508	3508	4512
Full-load amperage (FLA)	124	99	99	305
Motor Rating	746 kW	597 kW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



FRIB Warm Compressor System [2]

Cooling Tower Loop

Process CW Loop



Heat rejected to atmosphere

Heat rejected from process CW to Cooling Tower CW

Heat rejected from compressors to process CW

FRIB Warm Compressor System [3]

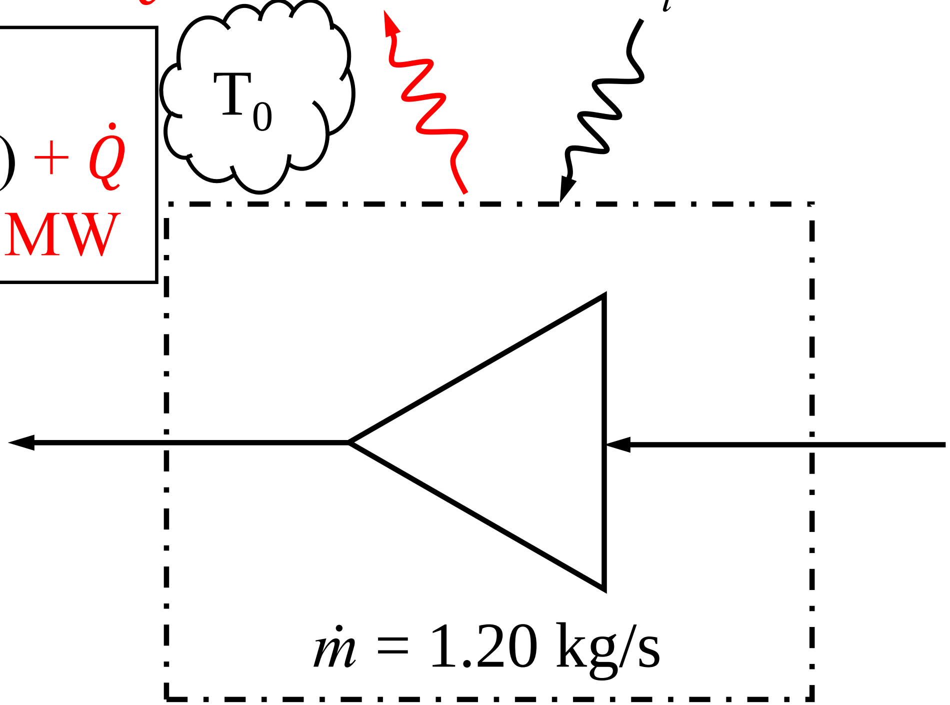
- Electrical input power = heat rejected out cooling towers
- Enthalpy into compressors = enthalpy out of compressors

$\dot{Q} = 1.80$ MW $\qquad \dot{W}_i = 1.80$ MW

1st Law:

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

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



Discharge:
$p_D = 18.0$ bar
$T_D = 308$ K

Suction:
$p_S = 4.90$ bar
$T_S = 308$ K

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

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

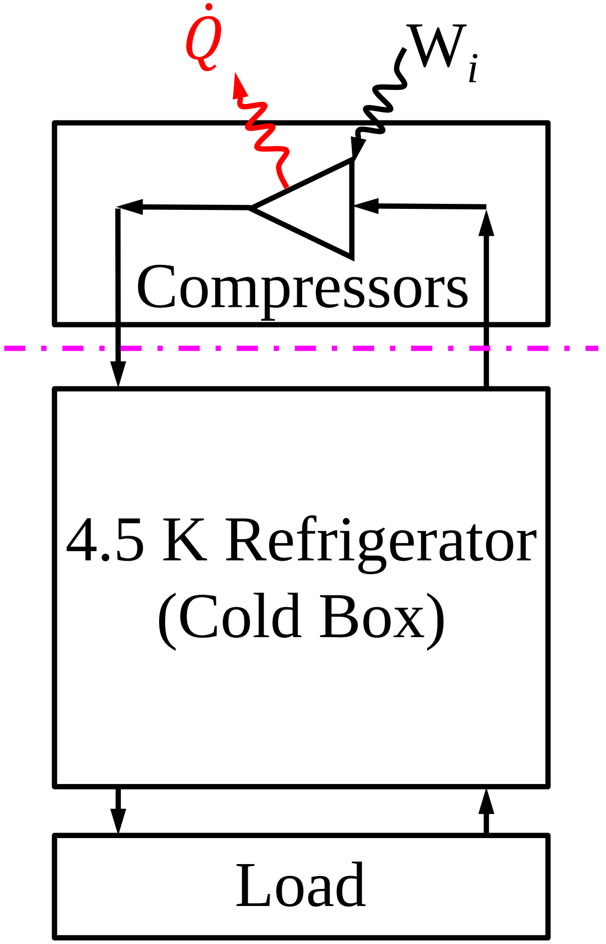
FRIB Warm Compressor System [4]

- 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.)

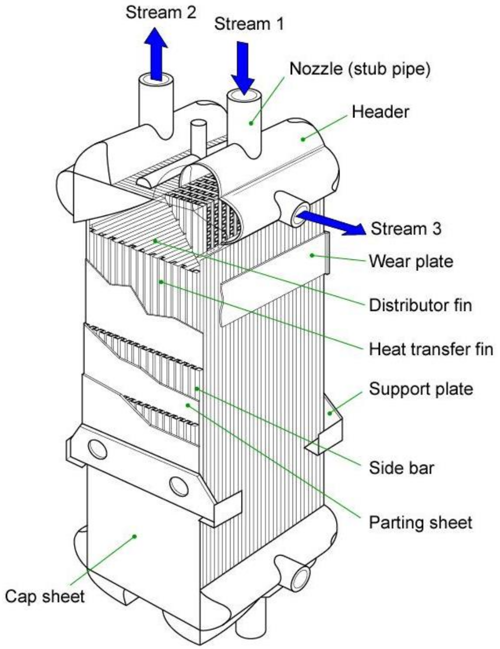
Final oil removal (outside, south side)

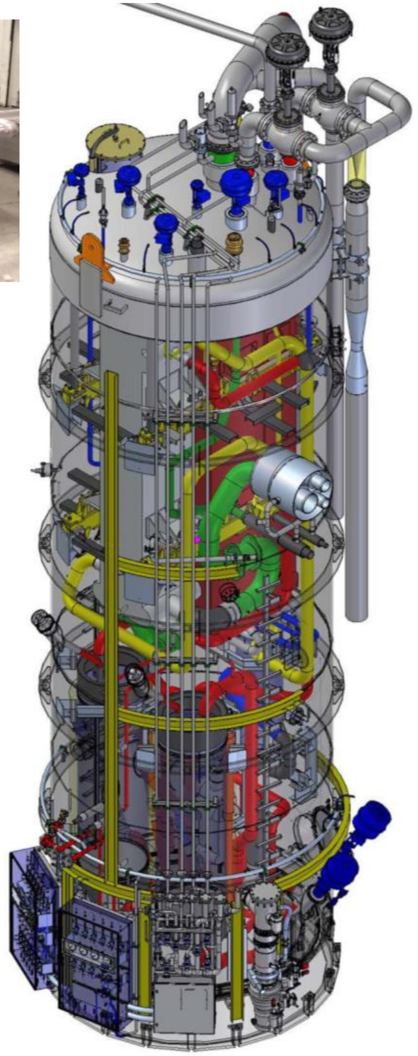
Helium Refrigeration/Liquefaction System [1]

- For FRIB, the refrigeration system maximum capacity is 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)

Helium Refrigeration/Liquefaction System [2]

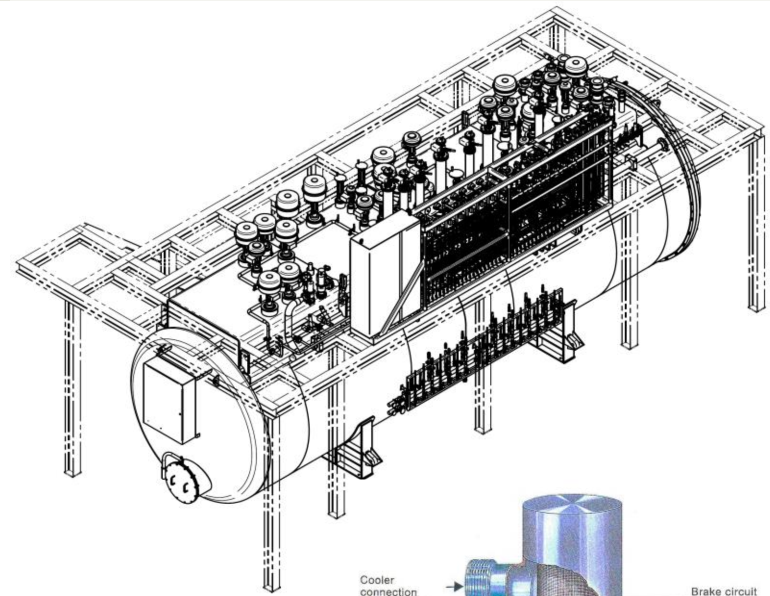
- LN Pre-Cooler (300 K to 60 K):
  - Liquid nitrogen used to cool helium from 300 to 80 K
    - »Uses thermo-siphon with proper LN/VN phase separation
  - Dual carbon adsorber beds at 80 K to remove any remaining air contaminants
    - »Beds can be regenerated using electric heater bands
  - Aluminum-brazed plate-fin heat exchanger's in multiple cores

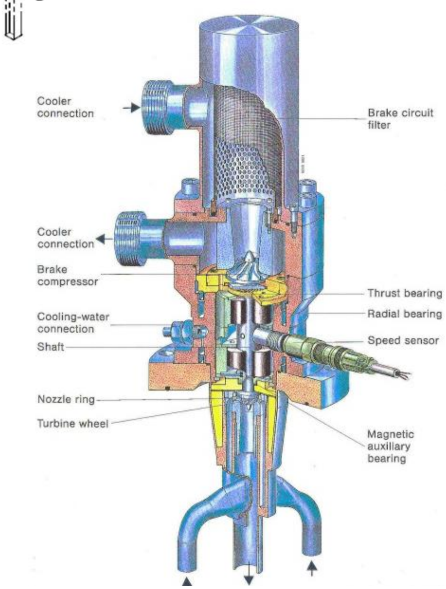




Helium Refrigeration/Liquefaction System [3]

- Expansion / JT Stages (60 – 4.5 K)
  - FRIB helium refrigerator has 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
  - Aluminum-brazed plate-fin HX's in multiple cores
  - Carbon adsorber at 20 K for neon and hydrogen
  - Helium phase-separator and sub-cooler



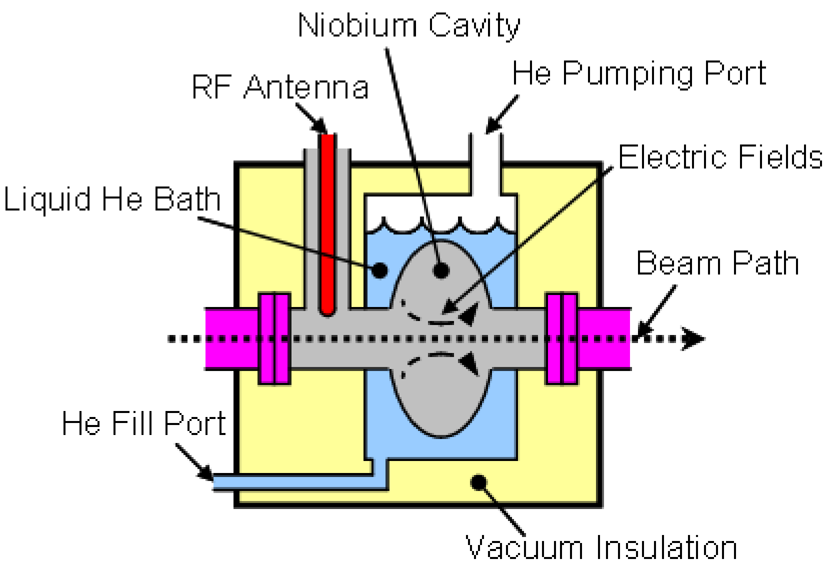


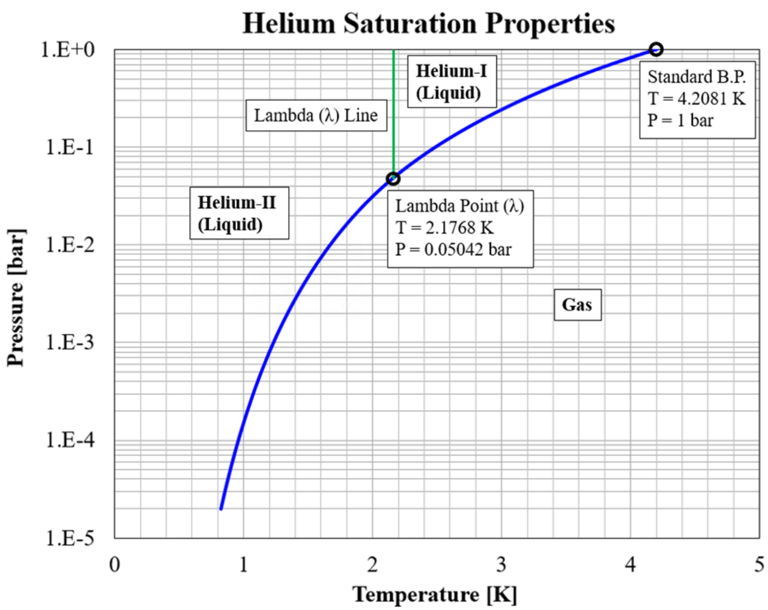
Helium Refrigeration/Liquefaction System [4]

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

2.0 K Refrigeration System [1]

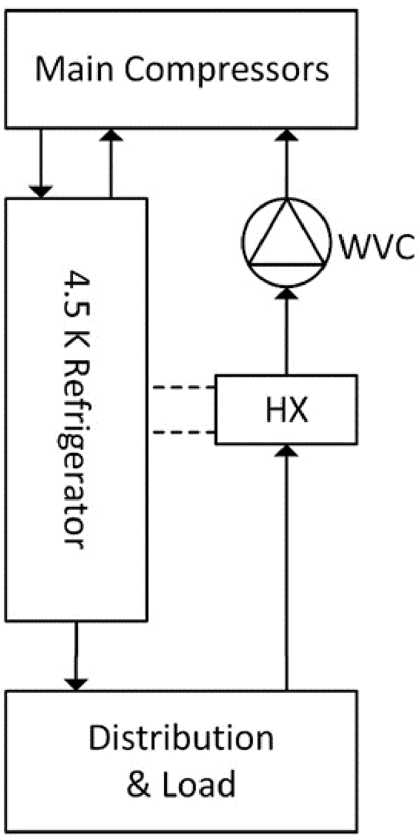
- Heavy ions are accelerated in the linear segments of the beam line by employing superconducting radio-frequency (SRF) cavities
- SRF cavities operate at temperatures below the standard boiling point of helium (4.2 K @1 bar), at FRIB this temperature is ~ 2 K
- A reduction in pressure is required to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



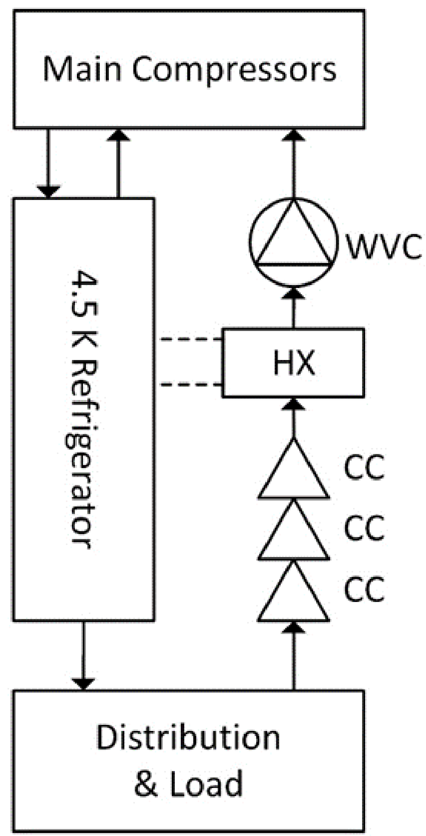


2.0 K Refrigeration System [2]

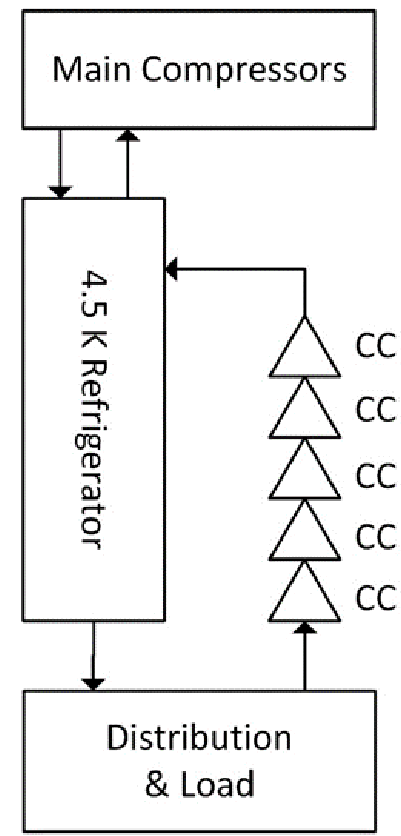
- There are several common methods that reduce the helium bath pressure; each having unique advantages and disadvantages



Warm-Compression

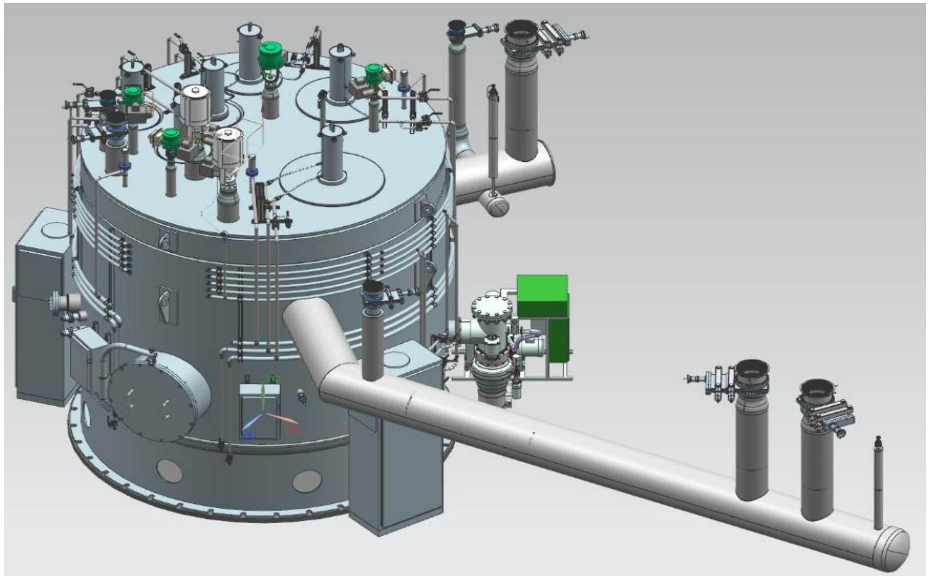


Mixed-Compression



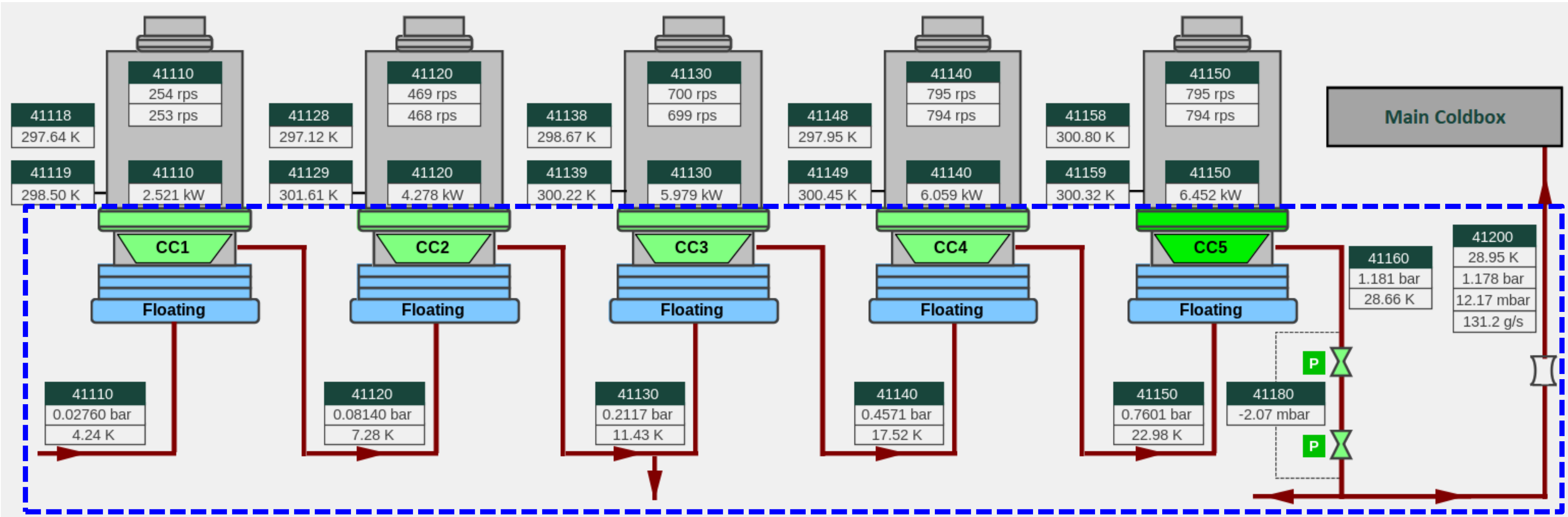
Cold-Compression

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

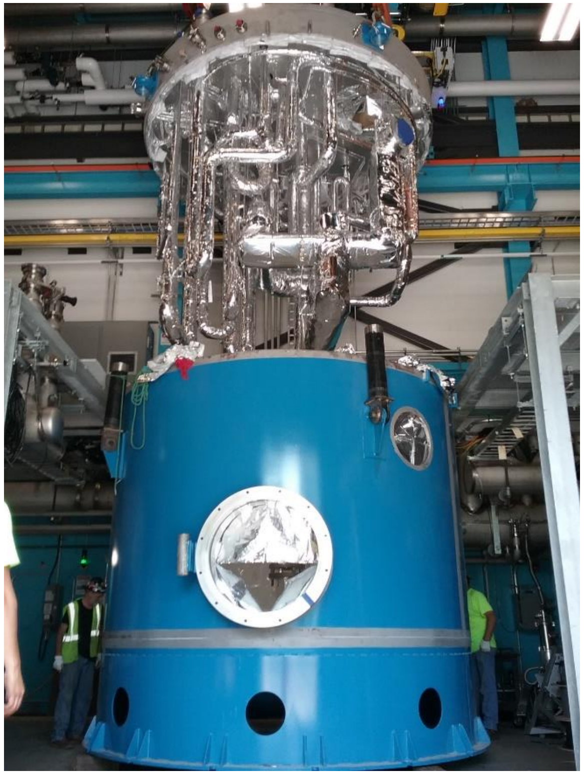
FRIB 2.0 Refrigeration System
Sub-Atmospheric Cold Box (SCB) [2]



- 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)



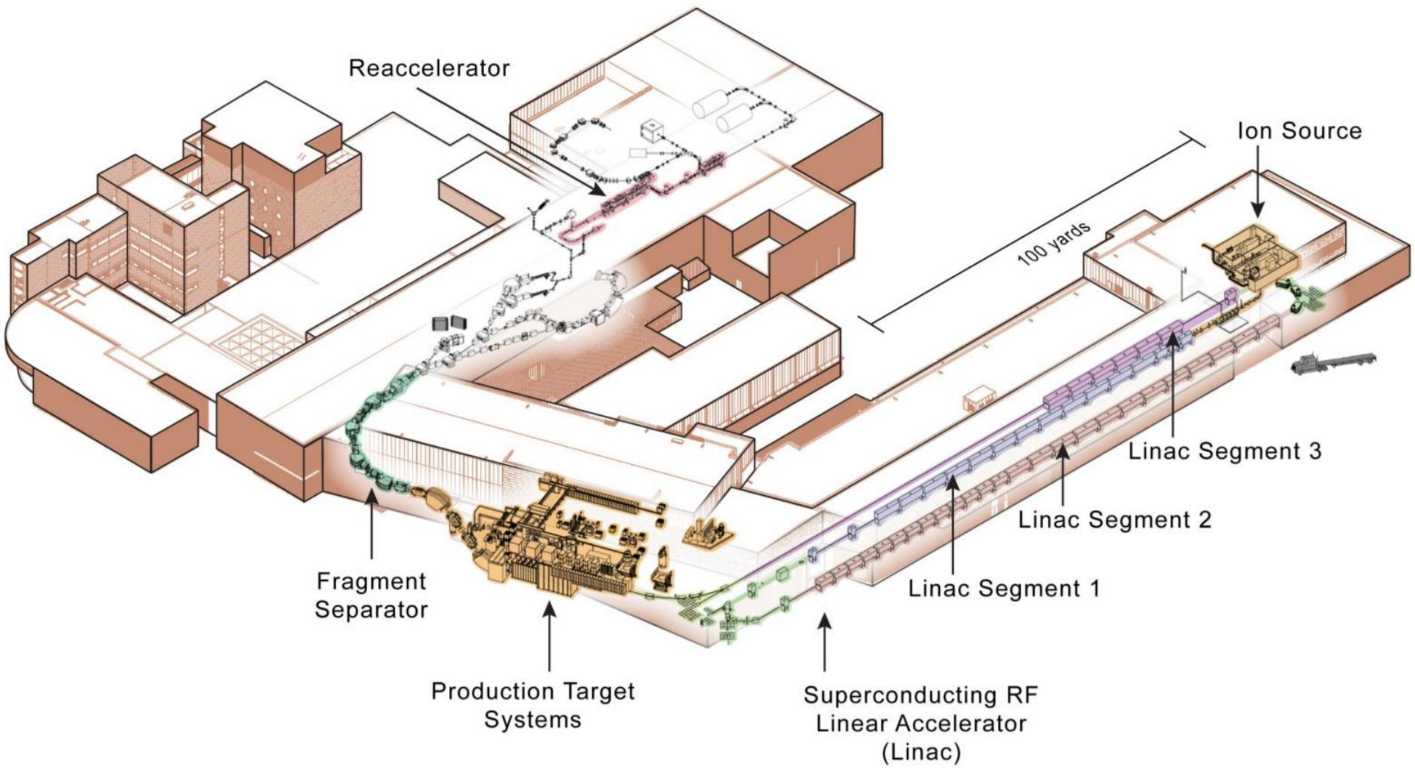
FRIB Helium Purification System

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

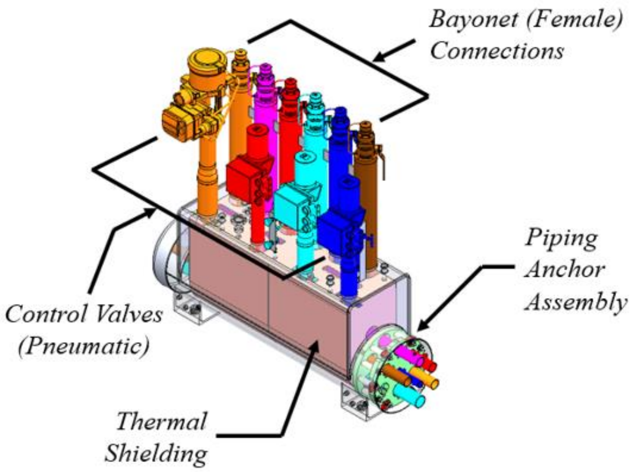
- Used for low level impurity removal (~100 ppm to below 1 ppm)
- Purifier cold box
  - Freeze-out HX for moisture
  - Carbon bed for air
  - Uses liquid nitrogen
- Purifier compressor
  - ~112 kW, 480 V, 3-ph
  - 109 ℓ/s swept volume
  - Hermetic housing
  - Oil used for lubrication of bearings and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

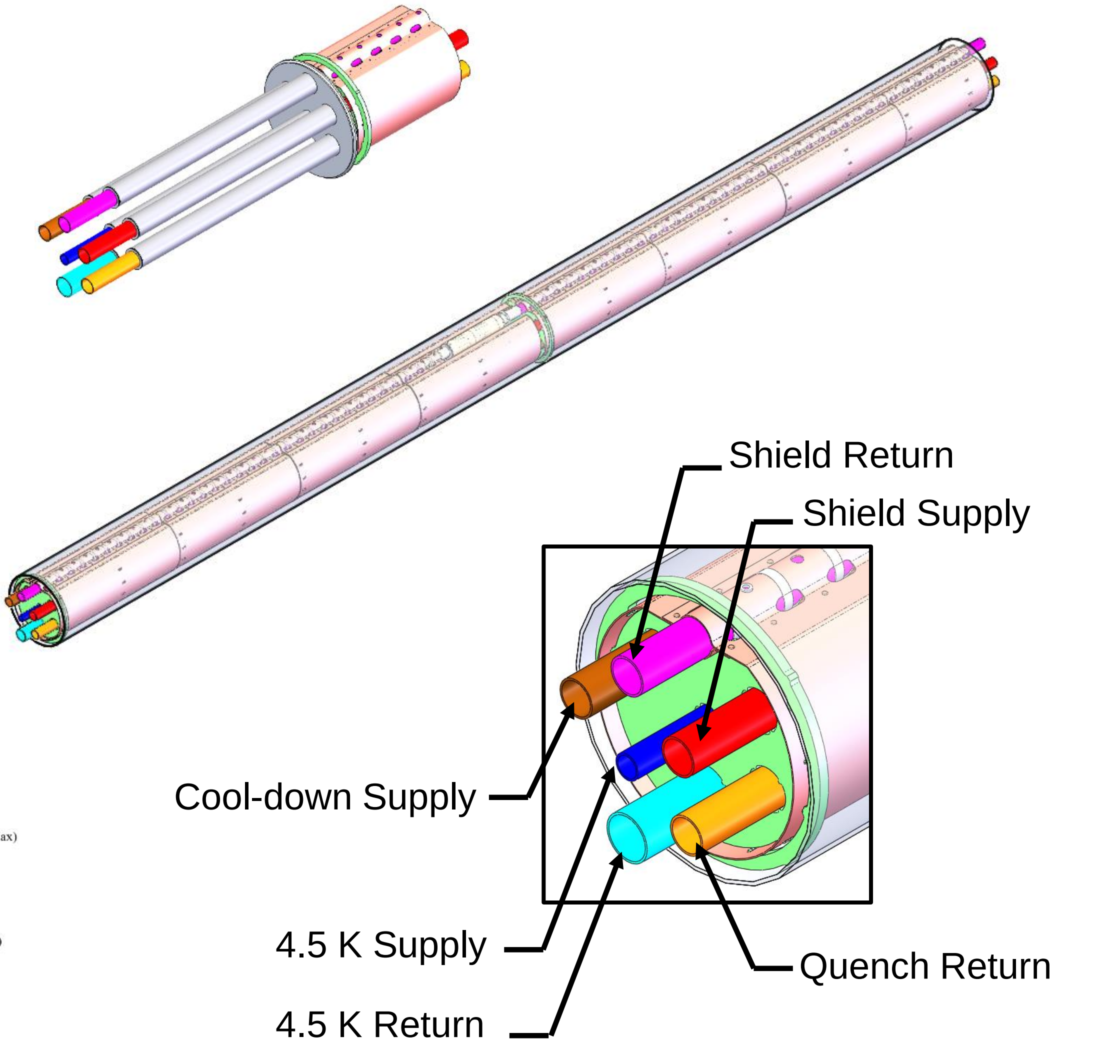
FRIB Cryogenic Distribution [1]

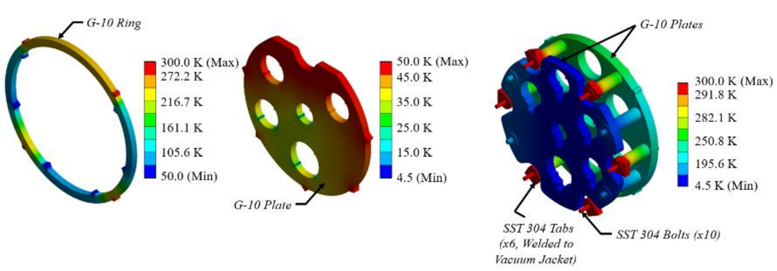
- Cryogenic distribution connects the FRIB main refrigeration system with the loads; which for FRIB are the,
  - Linear accelerator (Linac) and,
  - Experimental system superconducting magnets



FRIB Cryogenic Distribution [2]

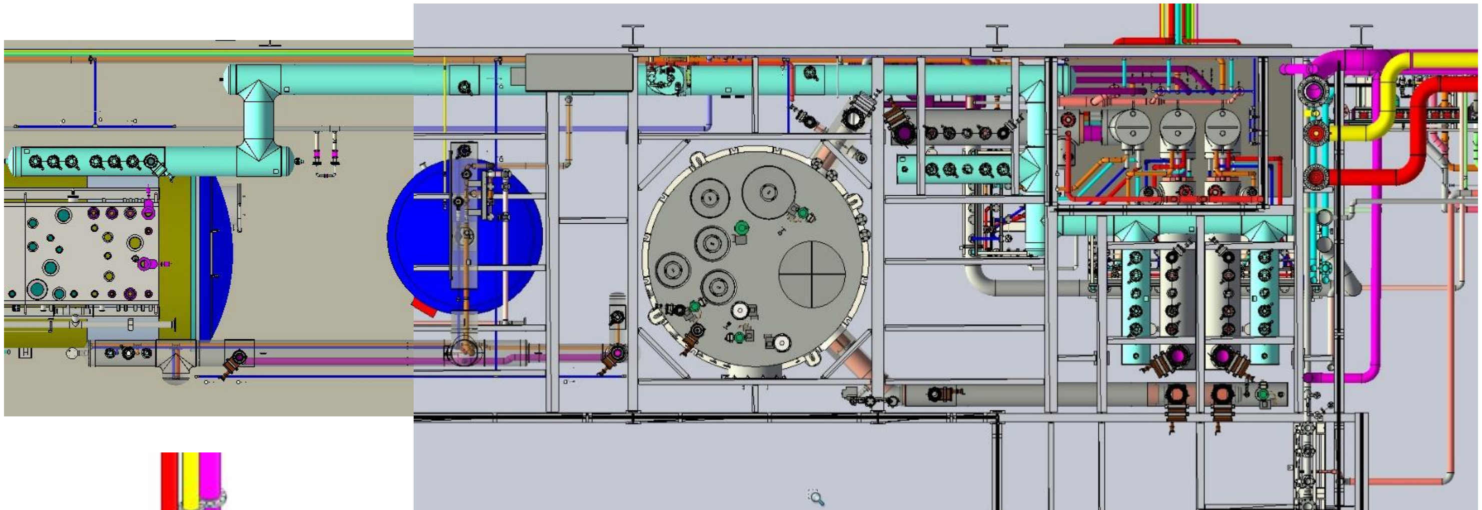


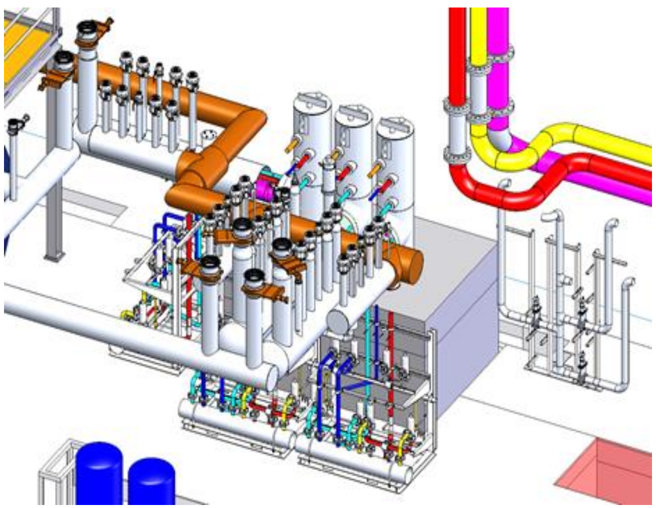




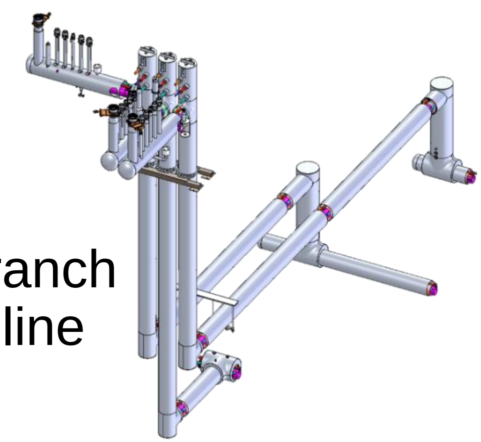
FRIB Cryogenic Distribution [3]

- Cold box room (Linac) distribution plan view

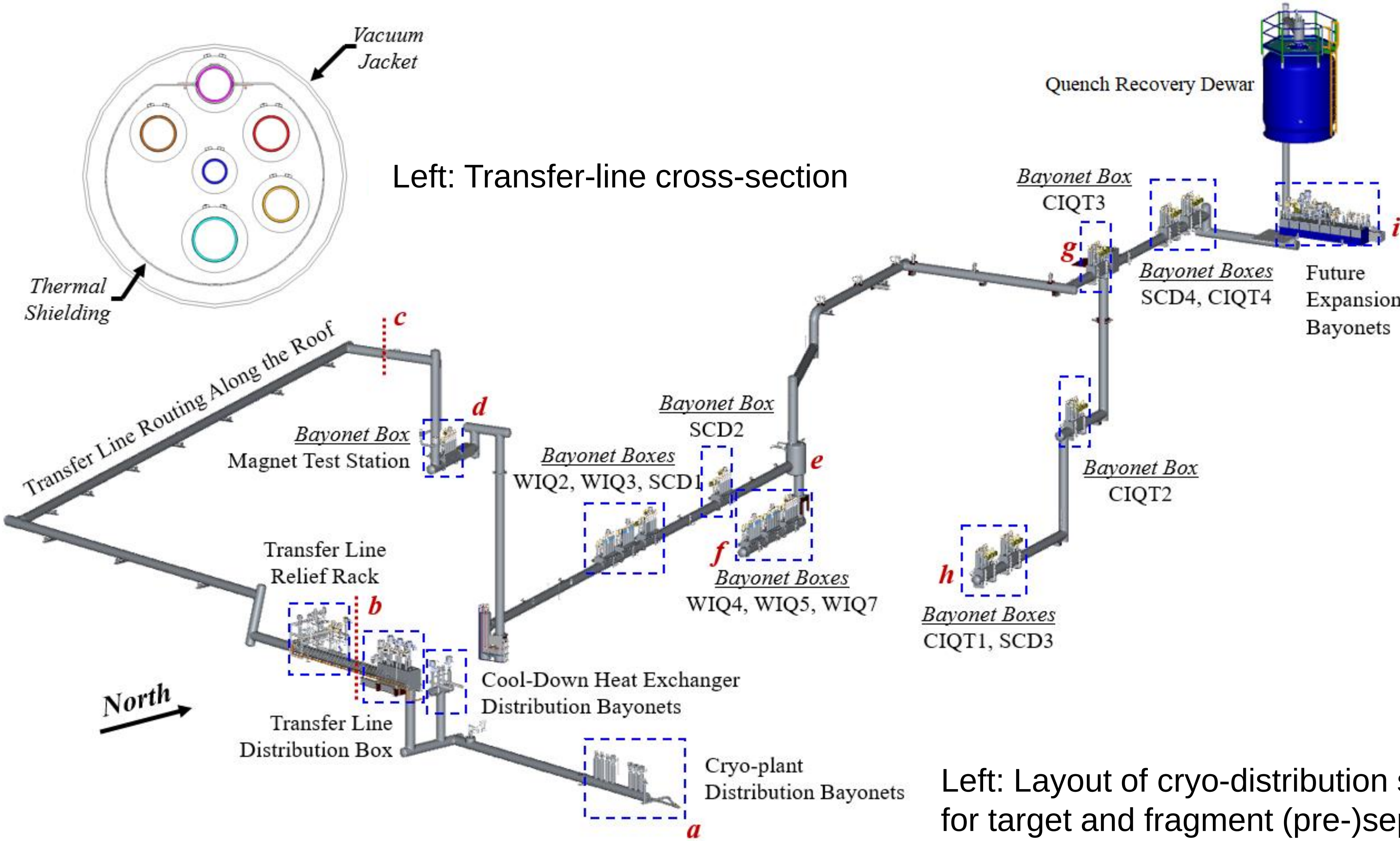




Right: Vertical shaft and branch sections for Linac transfer-line segments



FRIB Cryogenic Distribution [4]



Left: Transfer-line cross-section

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