SRF 2013 Tutorials
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Cryogenics

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Outline of This Tutorial

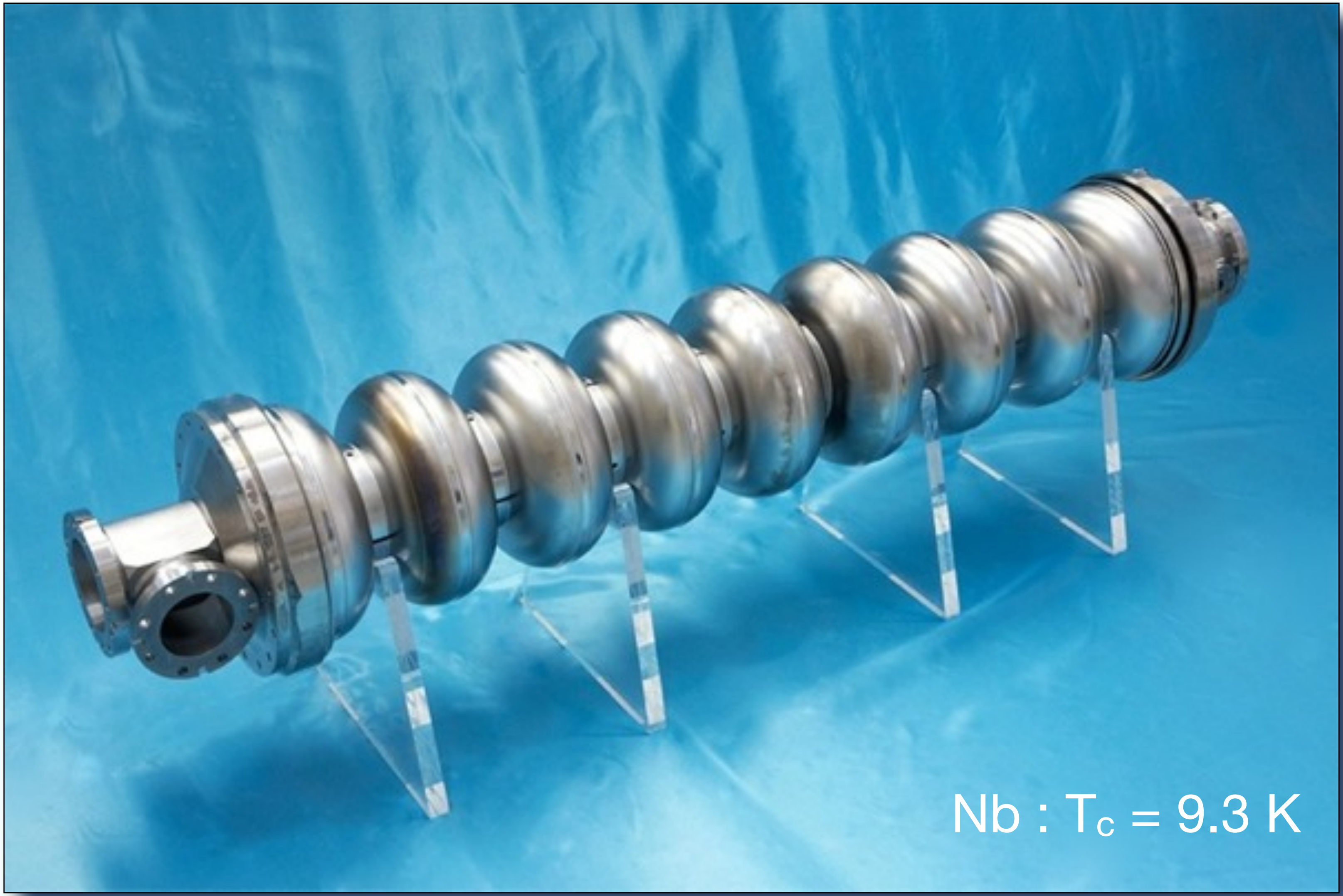
1. Introduction
   - Superconducting RF cavities and cryogenics
2. Helium refrigerators
   - Thermodynamics of helium liquefaction
   - Liquefiers and refrigerators
3. Superfluid helium and cryogenic systems
   - Superfluid helium (He II)
   - Superfluid helium cryogenic system
   - 2 K cryogenic systems at KEK
4. Cryogenic Engineering
   - Cryomodules
   - Transfer Lines
5. Summary

Introduction

What is Cryogenics?

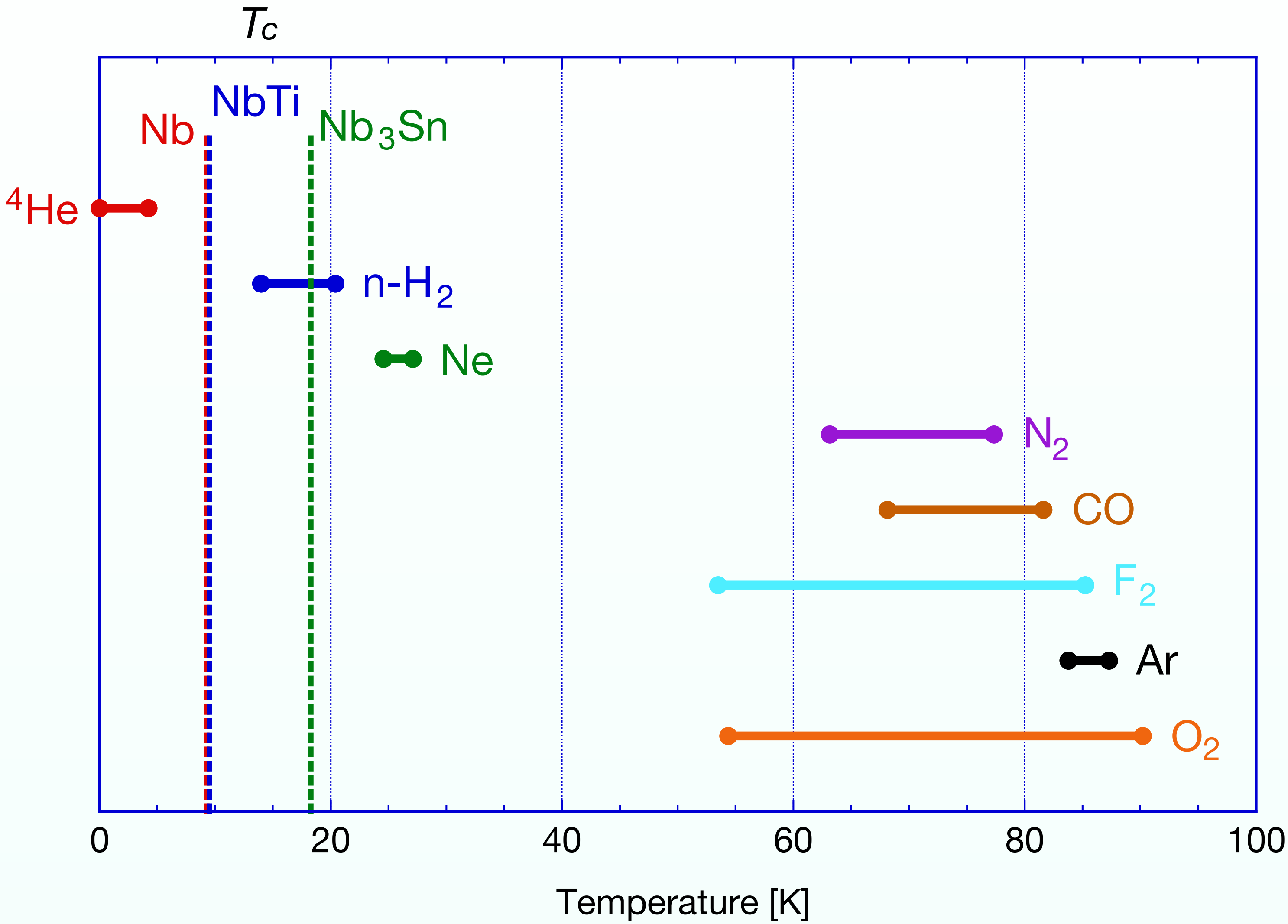
- Cryogenics - Science and engineering concerning with low temperature
- Low temperature - below normal boiling point temperature of oxygen (~ 90 K) or nitrogen (~ 77 K)

1.3 GHz Superconducting RF Cavity

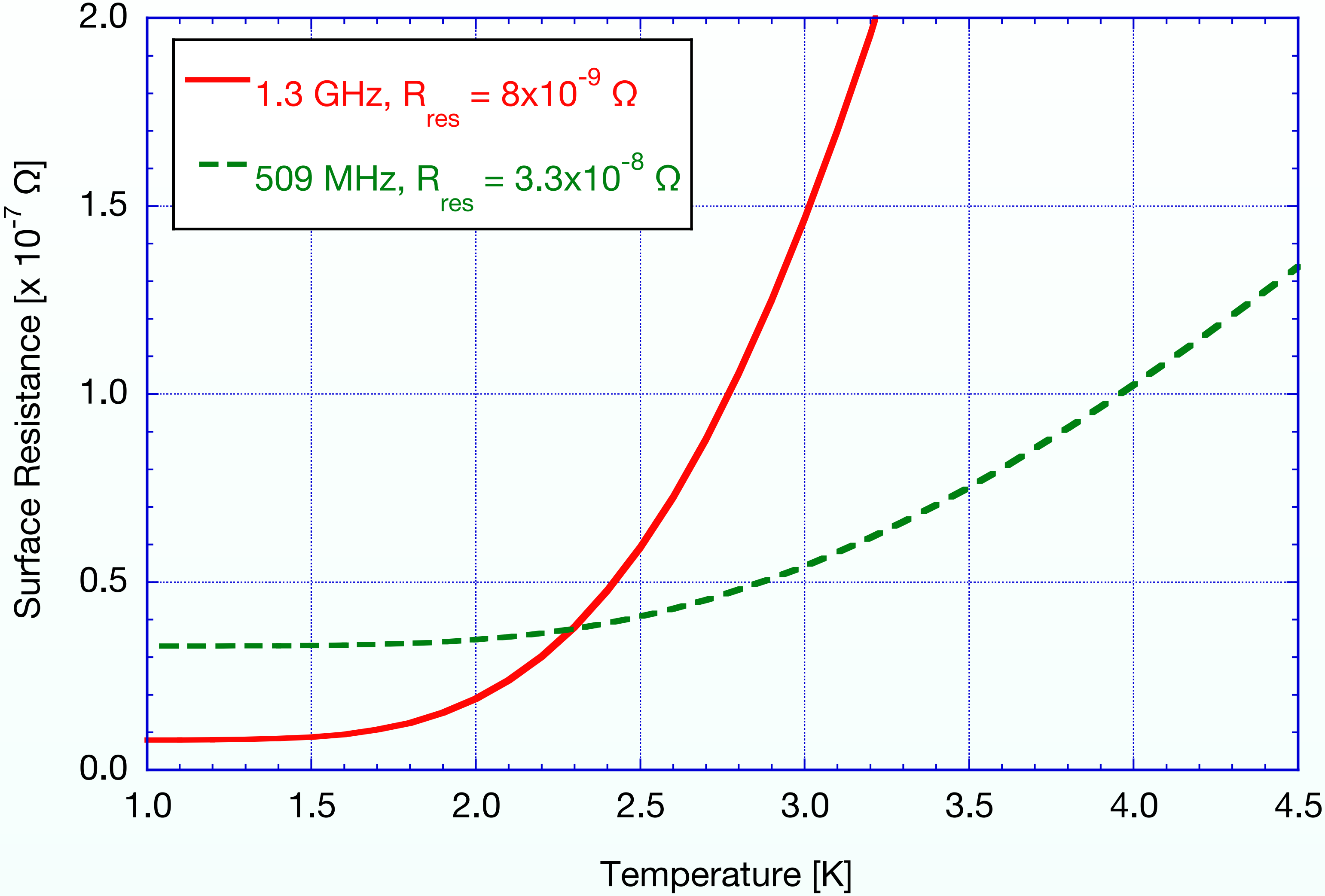


KEKB Superconducting RF Cavity (509 MHz)

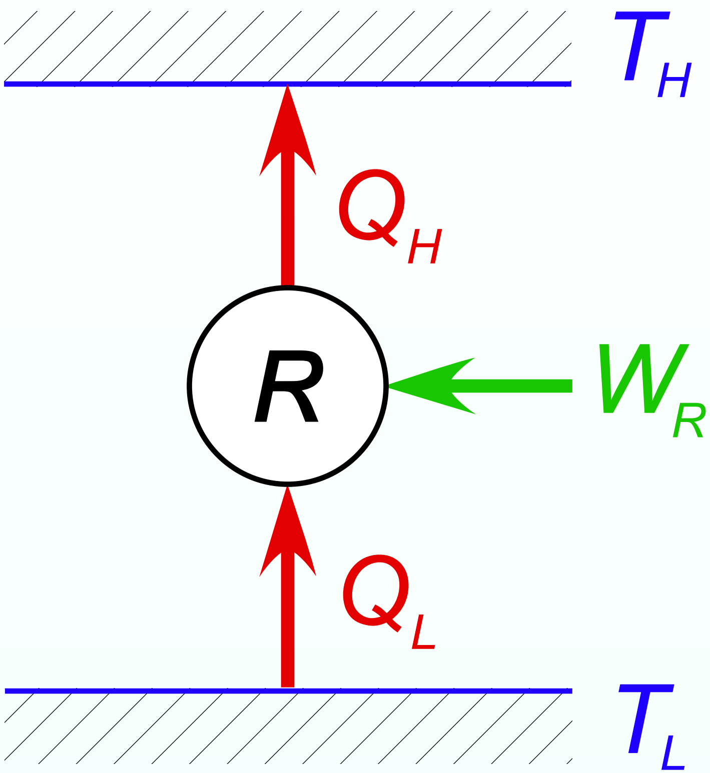
Normal Boiling Point & Triple Point Temperatures



Surface Resistance of Cavities



Refrigeration Cycle



Cited from Lebrun, Ph., “An Introduction to Cryogenics”, CERN/AT 2007-1 (2007)

$$Q_H = Q_L + W_R$$

$$\frac{Q_H}{T_H} \geq \frac{Q_L}{T_L}$$

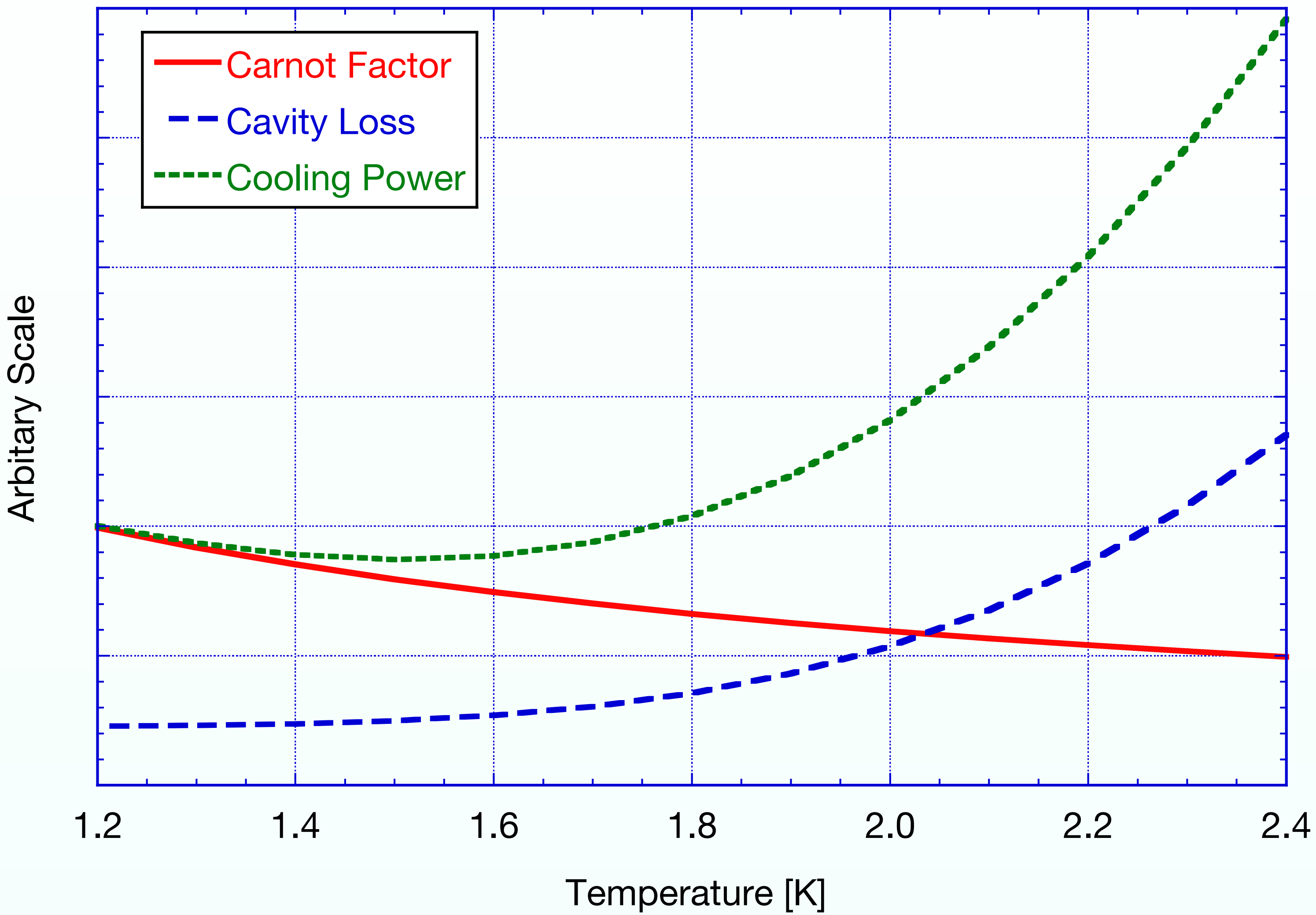
$$W_R \geq Q_L \left(\frac{T_H}{T_L} - 1 \right) = Q_L \cdot \beta$$

Carnot factor : $\beta = \frac{T_H}{T_L} - 1$

$T_H = 300$ K , $T_L = 4.5$ K

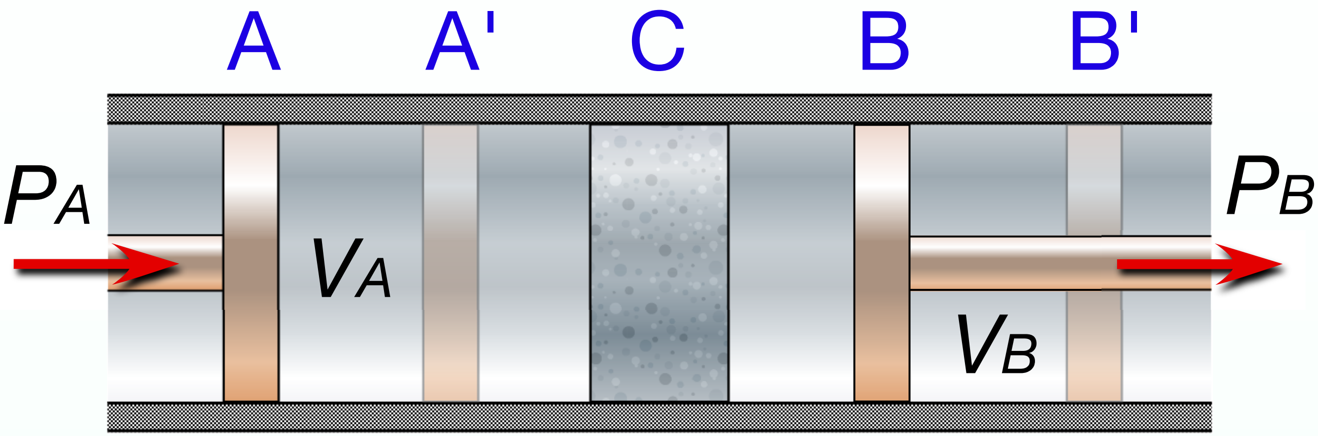
$Q_L = 1$ W $\longrightarrow W_R \geq 65.7$ W

Cavity Loss & Cooling Power (1.3 GHz)



Helium Refrigerators

Joule-Thomson Expansion (Isenthalpic Expansion)



Porous Plug

Cited from I. Oshida and T. Fujishiro, "Thermodynamics", Shokabo Publishing (1970) in Japanese

External work : $W = P_A V_A - P_B V_B$

First law of thermodynamics : $Q = \left(U_B - U_A\right) - W$

Adiabatic condition : $Q = 0$

Increased internal energy : $U_B - U_A = P_A V_A - P_B V_B$

Enthalpy (Gibbs' heat function) : $U + PV = const. = H$

Joule-Thomson Effect

Joule-Thomson Coefficient

Temperature Change

Volume

Coefficient of Cubical (Volume) Expansion

$$\mu = \left(\frac{\partial T}{\partial P}\right)_h = \frac{V}{c_p}\left(\alpha T - 1\right)$$

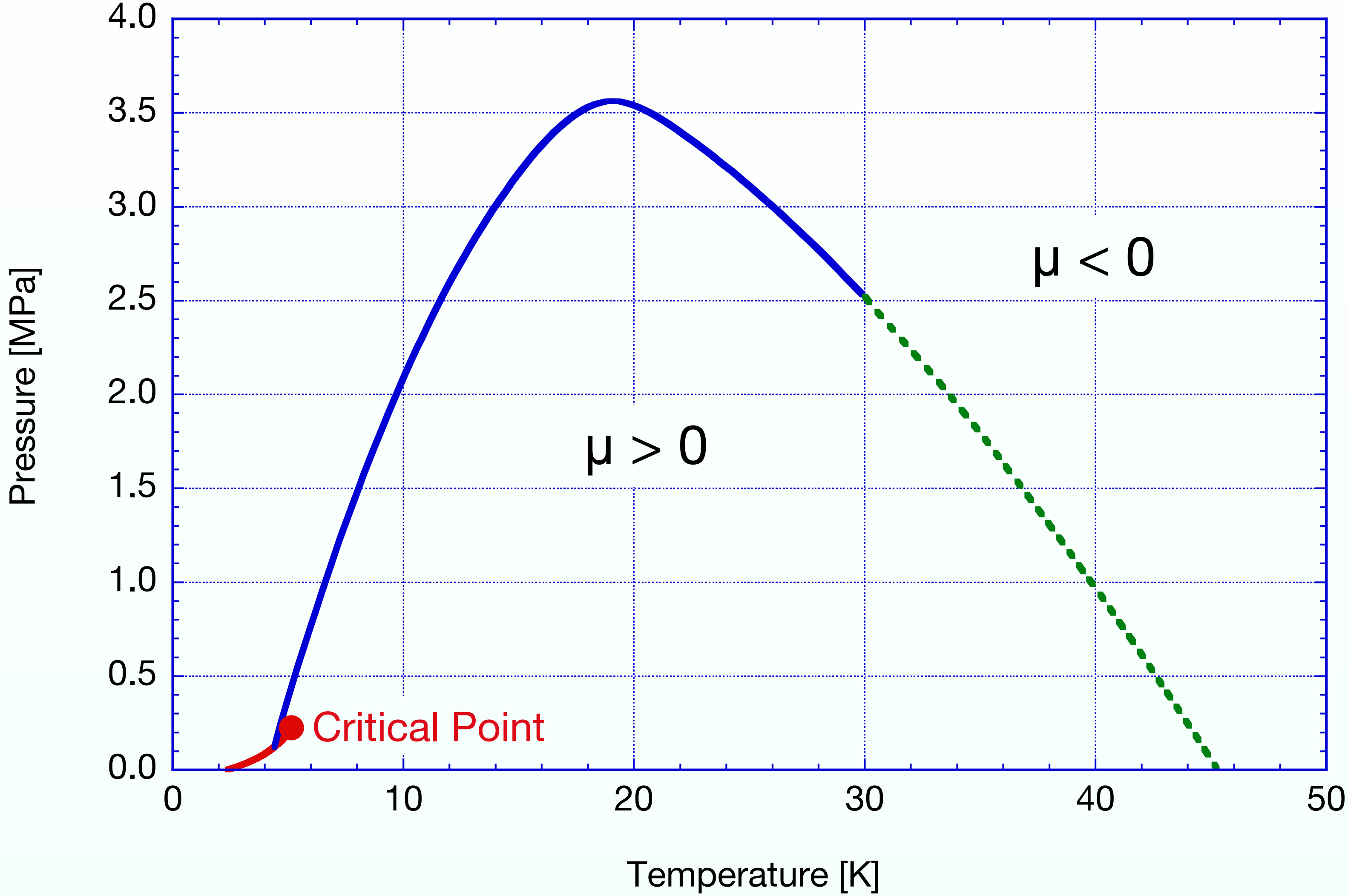
Pressure Change

Isenthalpic Change

Isobaric Specific Heat

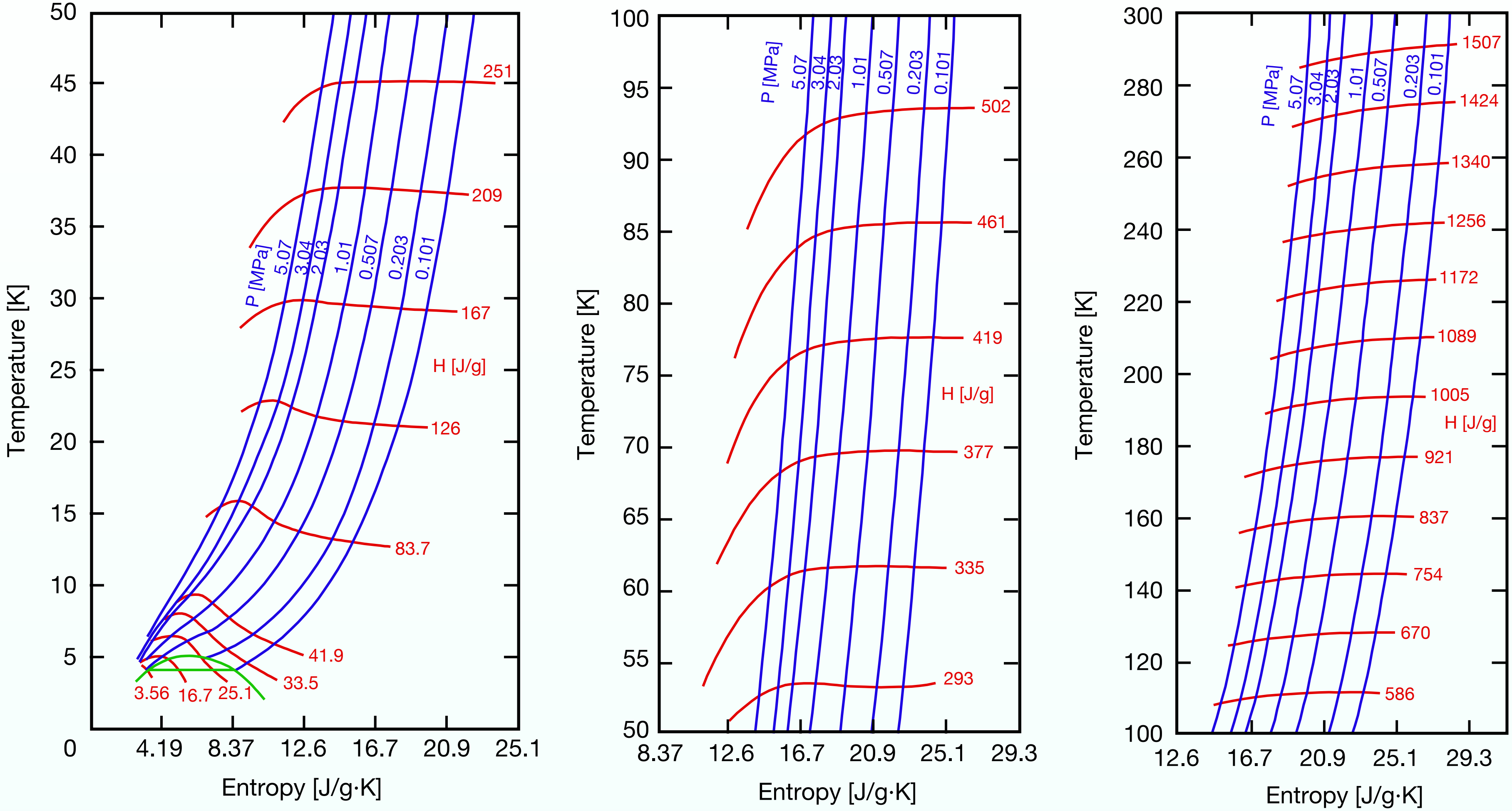
Temperature

Inversion Curve of Helium



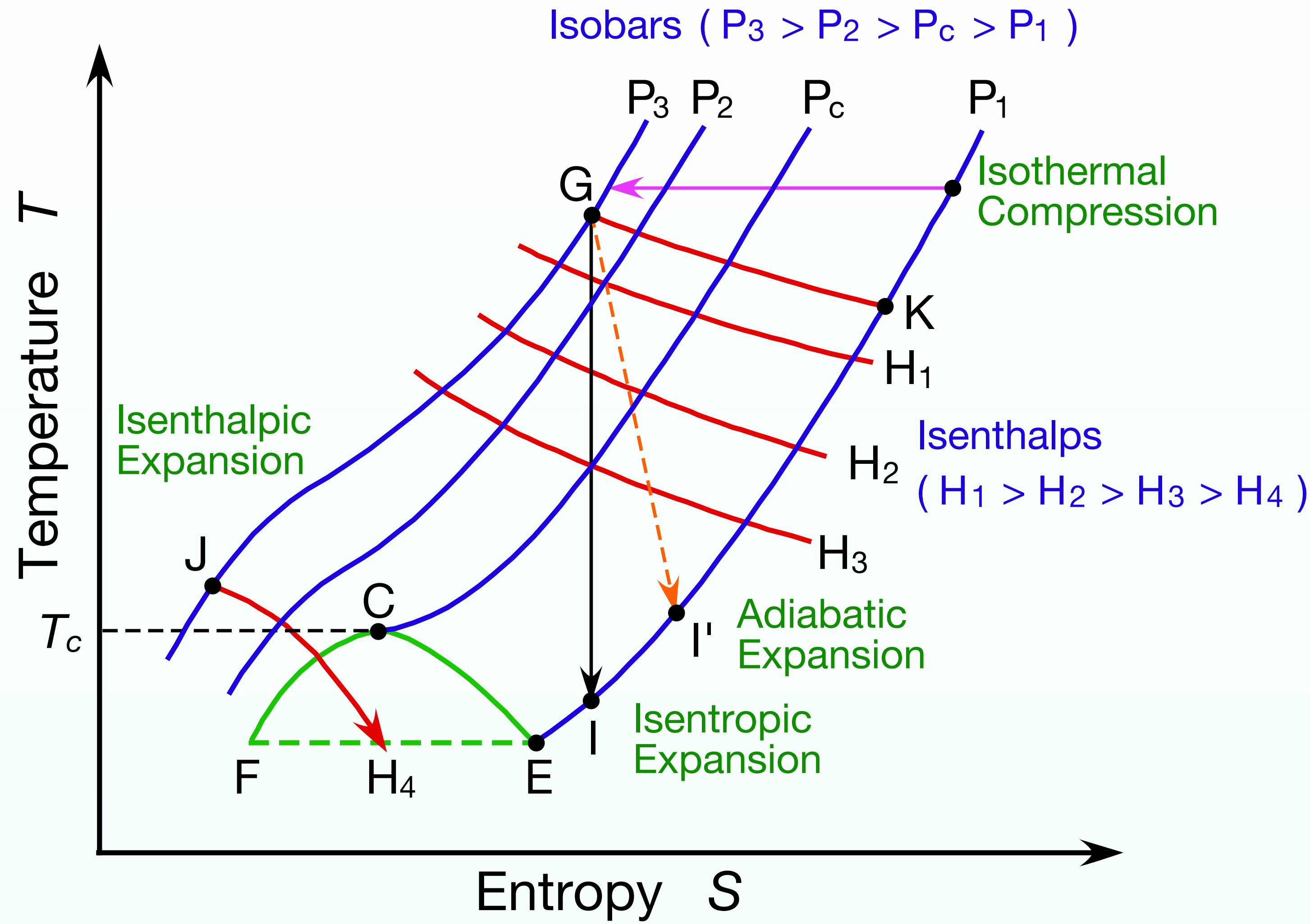
Cited from Verein Deutscher Ingenieure, Lehrgangshandbuch Kryotechnik (1977)

T-S Diagrams of Helium



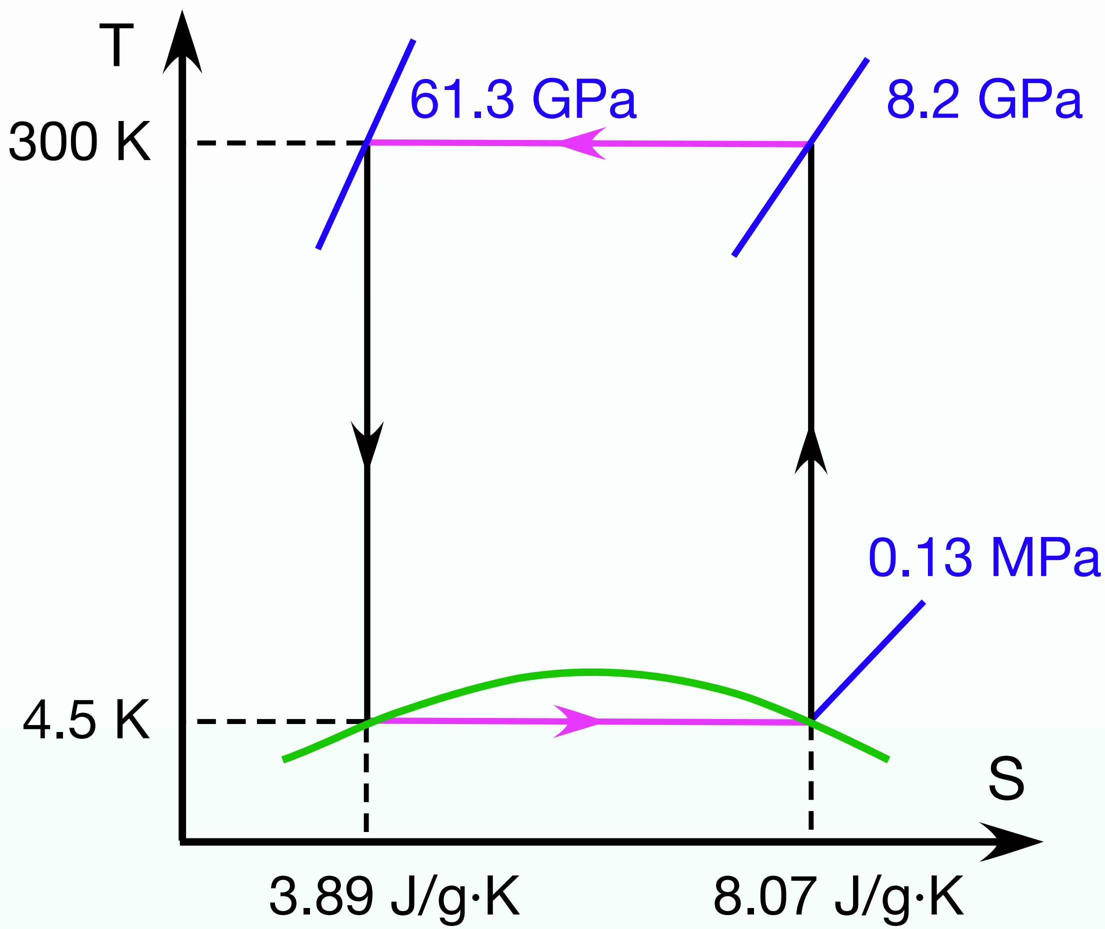
Cited from S. Tanuma ed., “Cryogenics”, Kyoritsu Shuppan (1974) in Japanese

Temperature-Entropy (T-S) Diagram



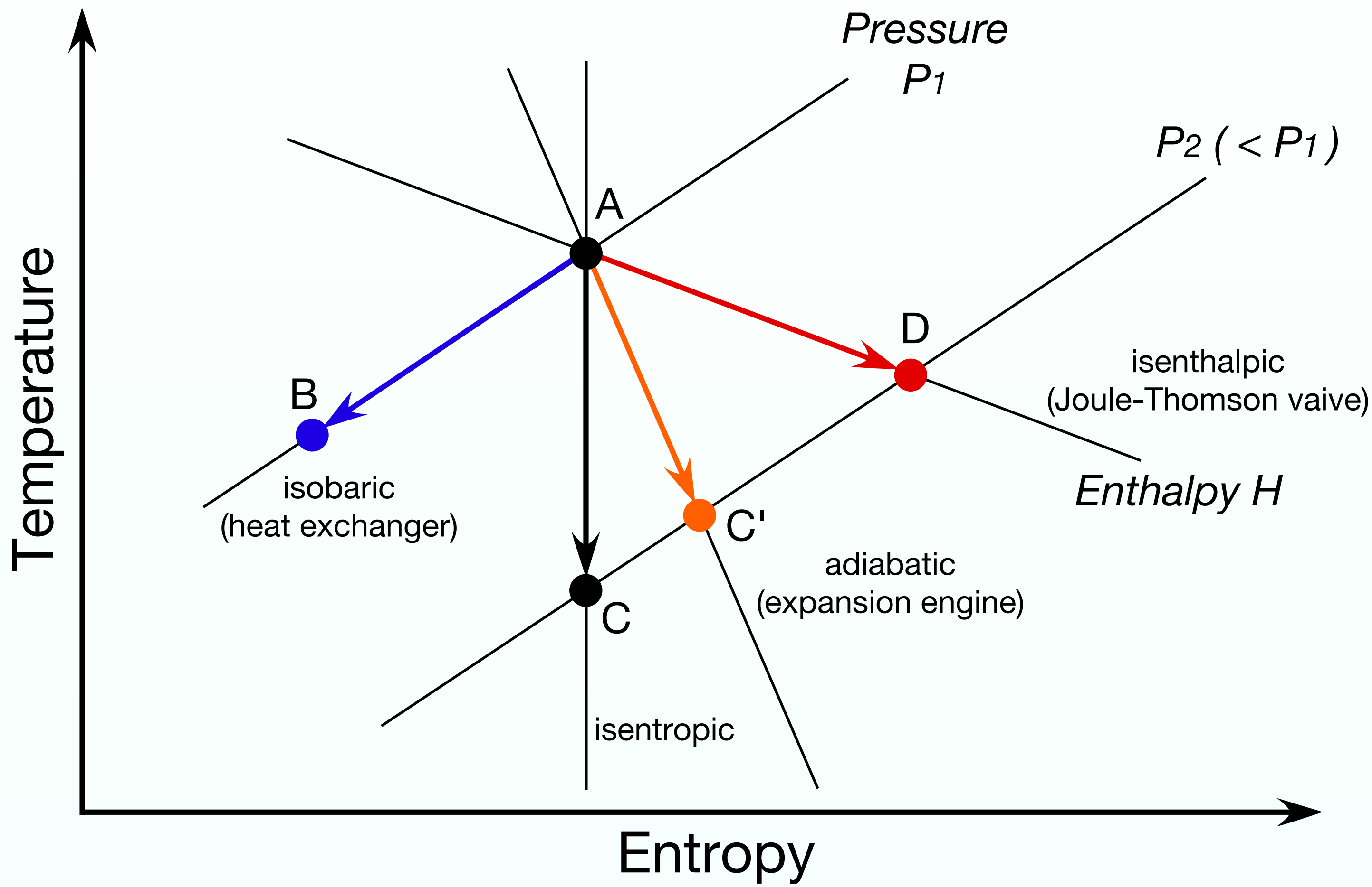
Cited from S. Tanuma ed., “Cryogenics”, Kyoritsu Shuppan (1974) in Japanese

Carnot Cycle and Helium Liquefaction



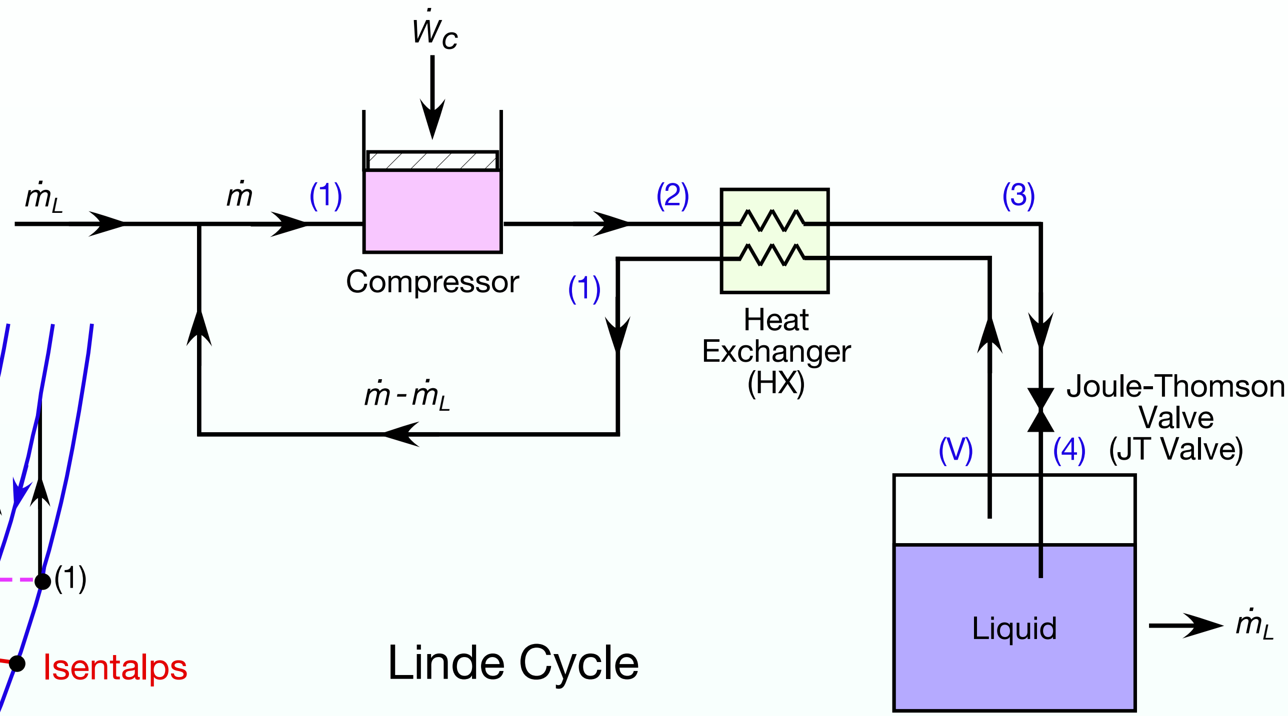
Cited from Lebrun, Ph., “An Introduction to Cryogenics”, CERN/AT 2007-1 (2007)

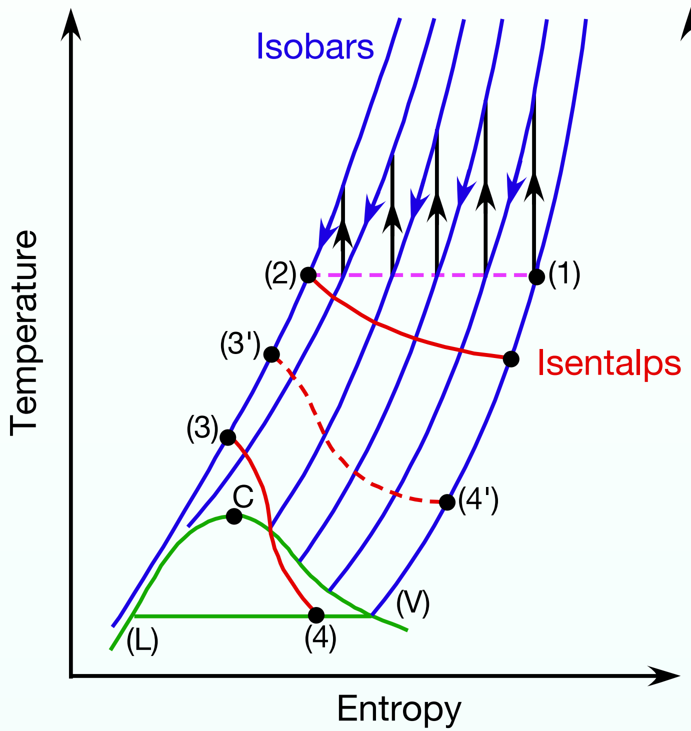
Various Thermodynamic Processes



Cited from Lebrun, Ph., “An Introduction to Cryogenics”, CERN/AT 2007-1 (2007)

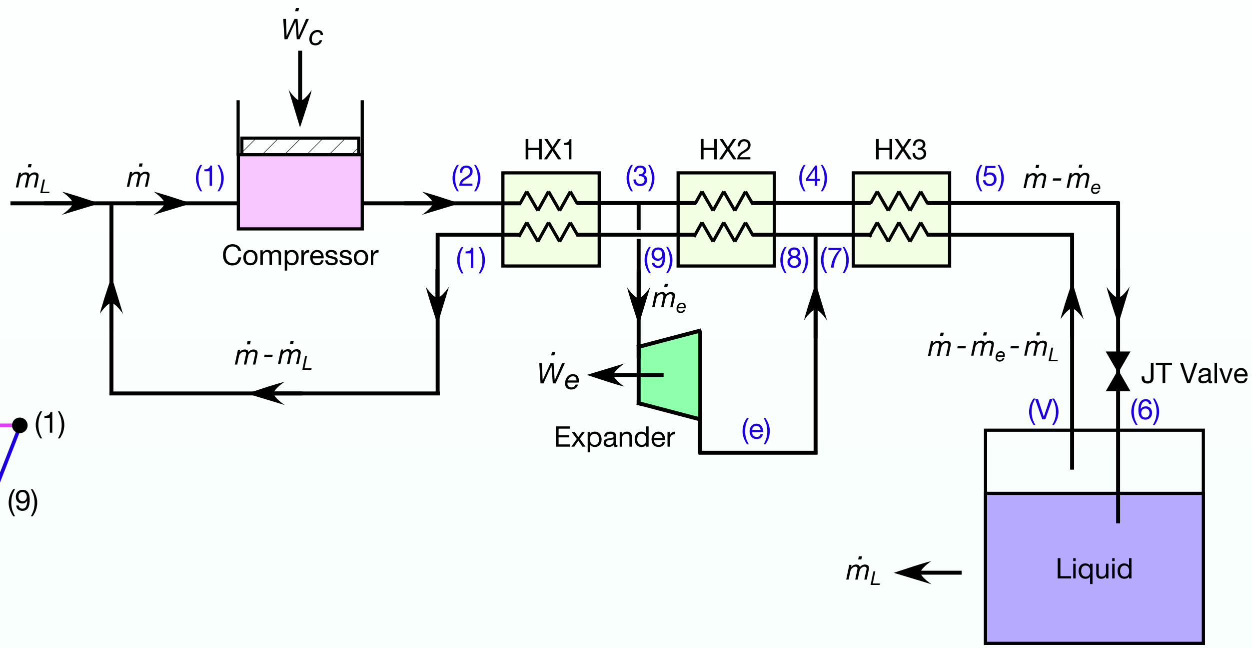
Joule-Thomson Liquefier

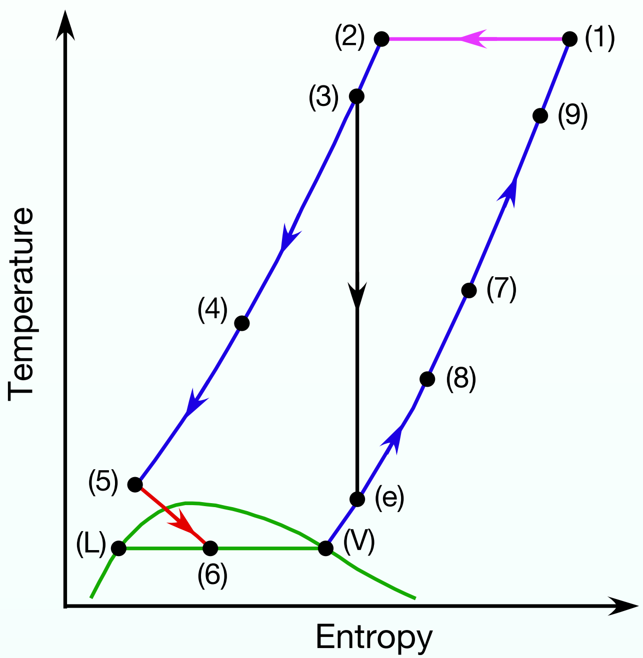




Cited from S. W. Van Sciver, "Helium Cryogenics," Plenum Press, 1986

Claude Liquefier

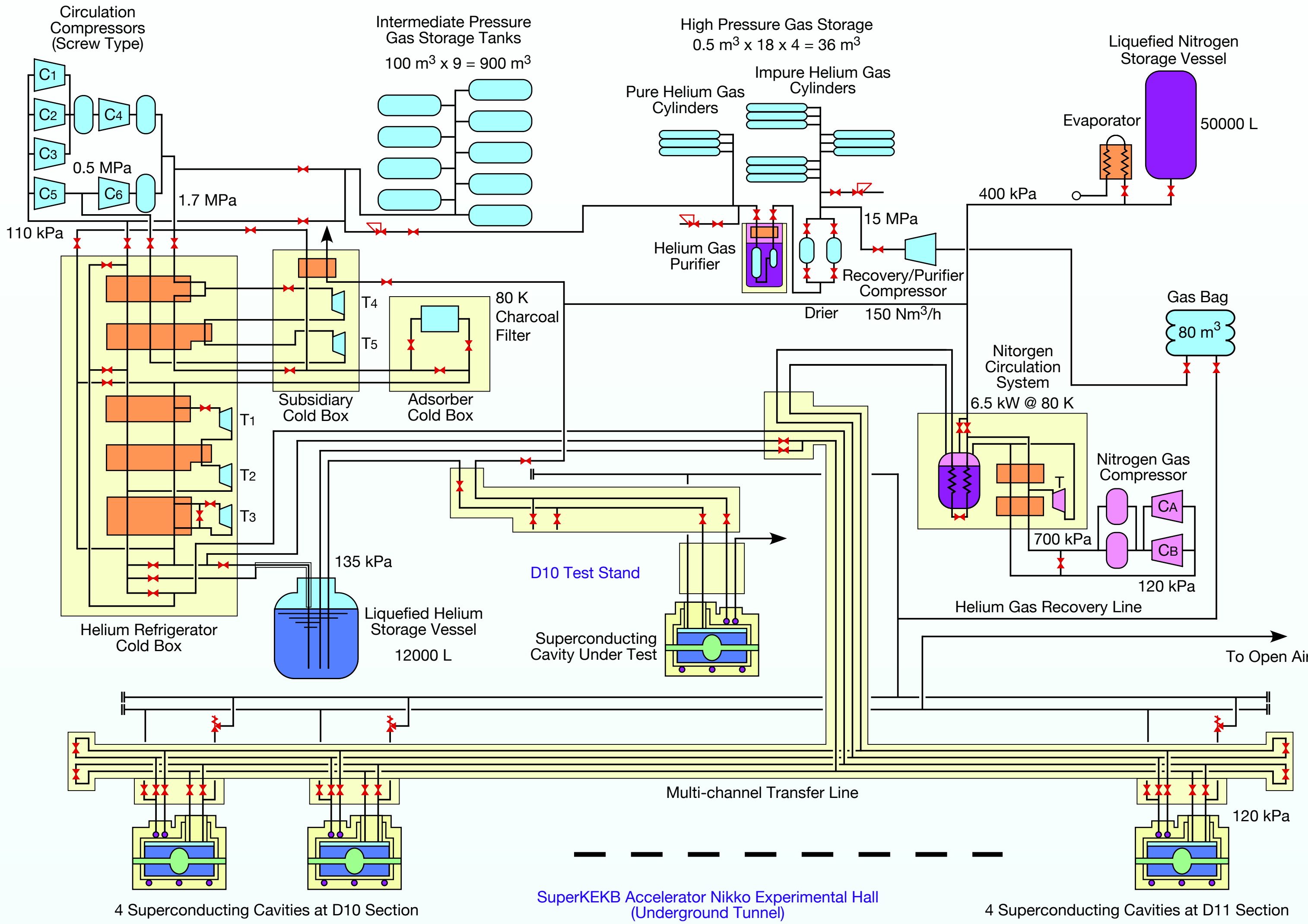




Claude Cycle

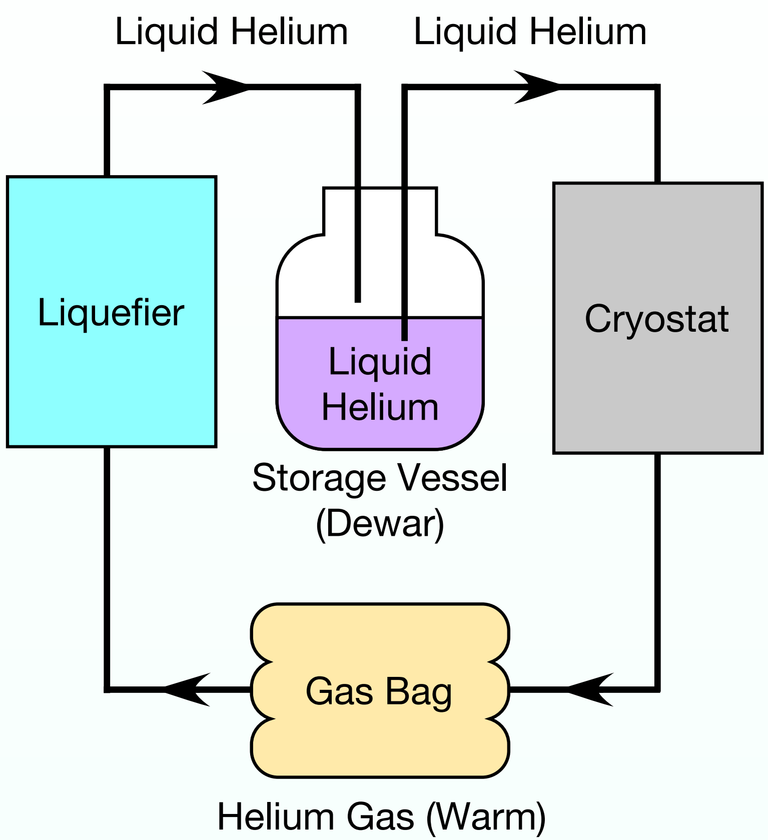
Cited from S. W. Van Sciver, "Helium Cryogenics," Plenum Press, 1986

SuperKEKB 6.5 kW Helium Cryogenic System

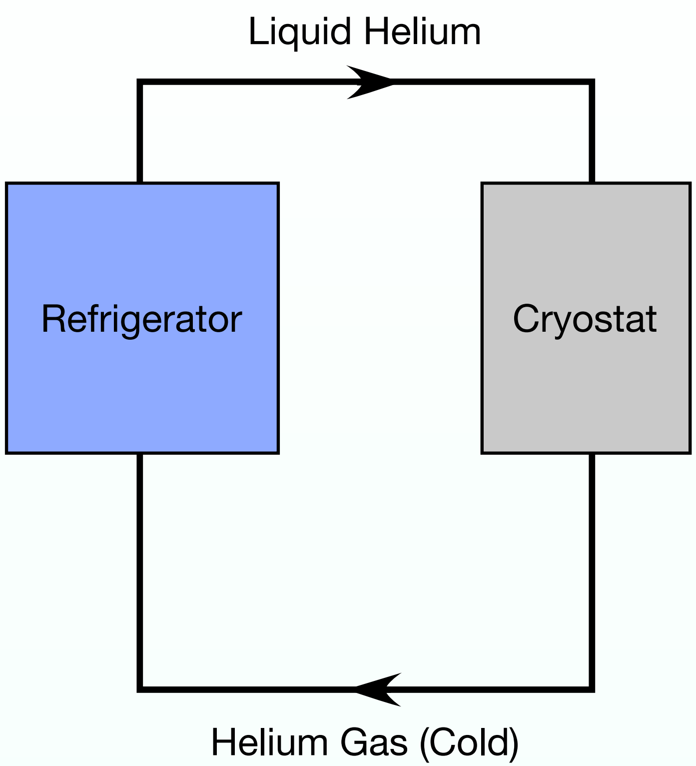


SuperKEKB 6.5 kW
Helium Cryogenic System

Liquefier and Refrigerator



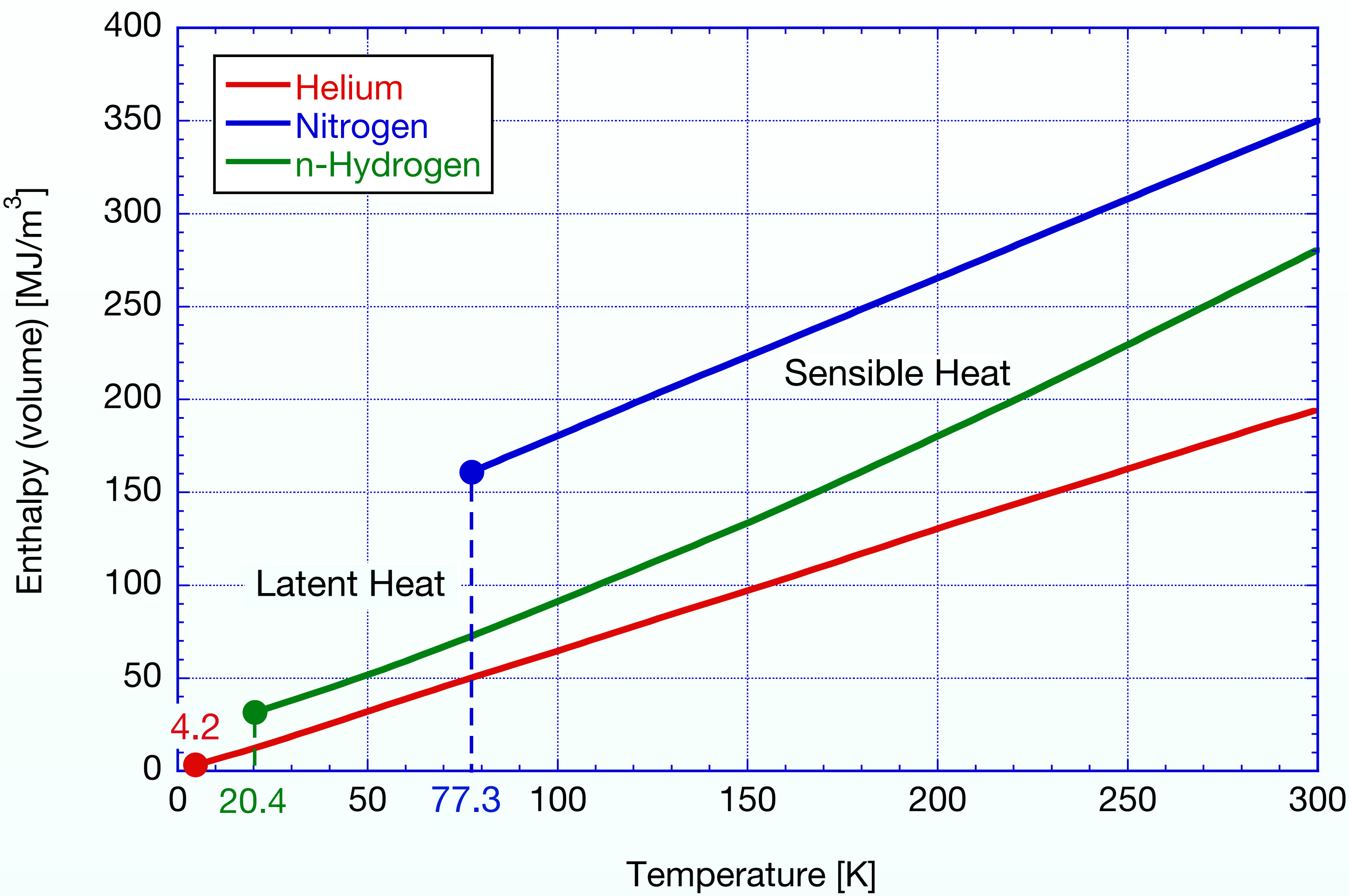
OPEN CYCLE REFRIGERATOR



CLOSED CYCLE REFRIGERATOR

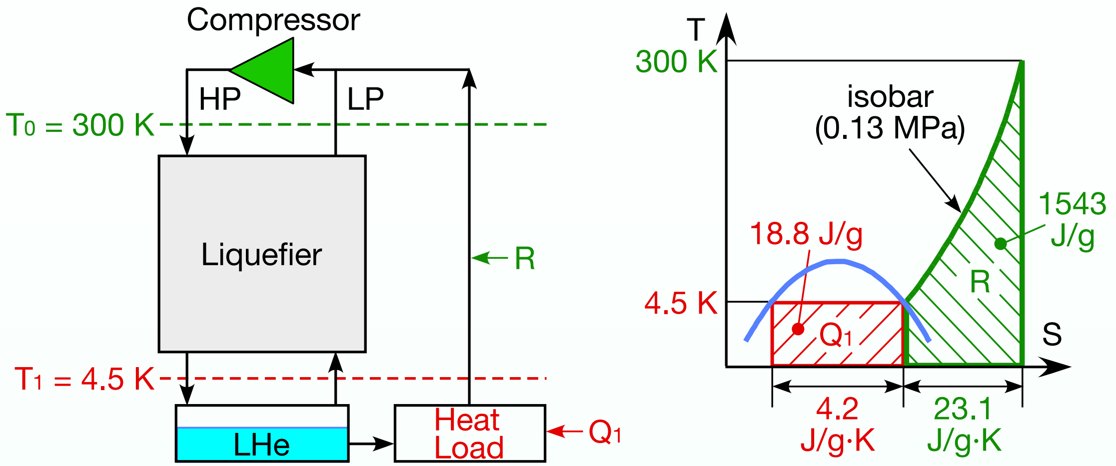
Cited from S. W. Van Sciver, "Helium Cryogenics," Plenum Press, 1986

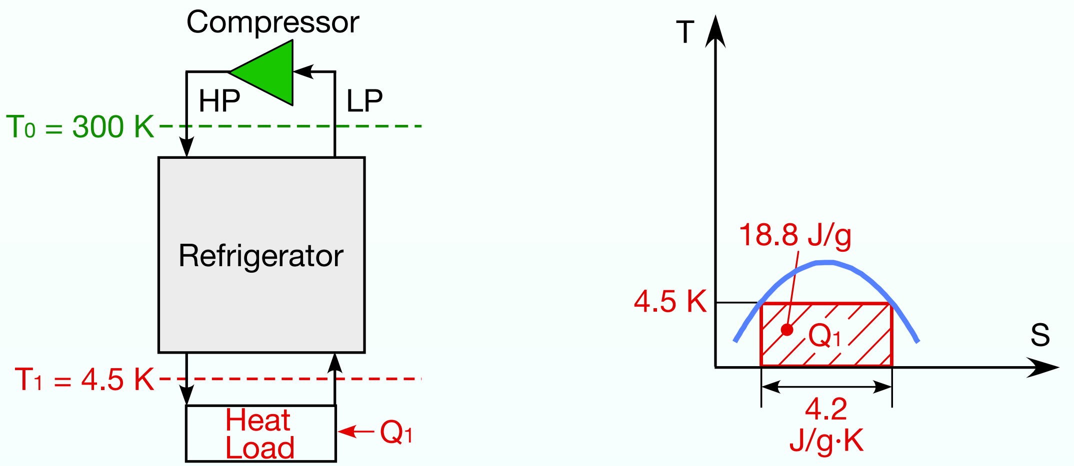
Latent and Sensible Heats



Cited from Verein Deutscher Ingenieure, Lehrgangshandbuch Kryotechnik (1977)

Heat Accounts of Liquefier and Refrigerator

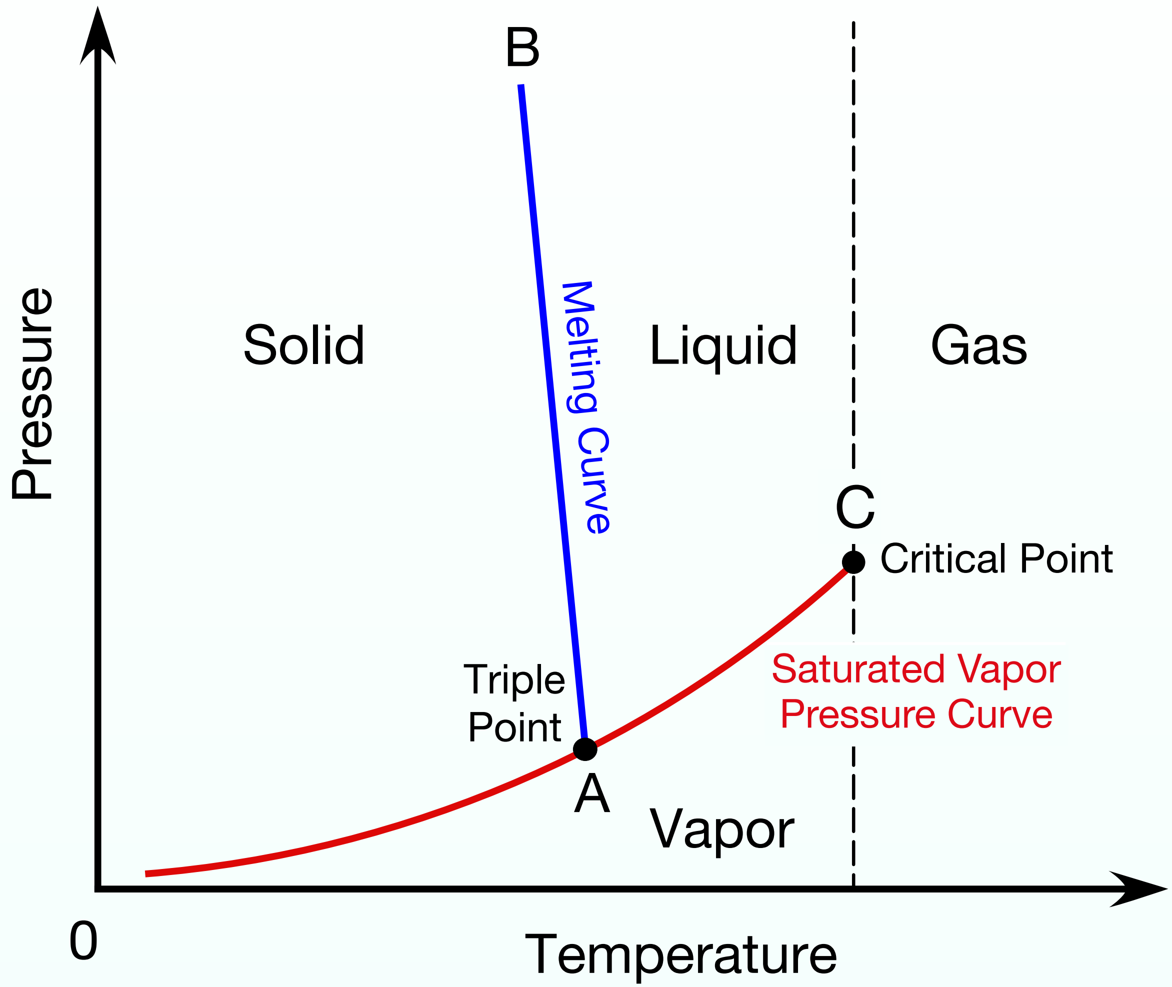




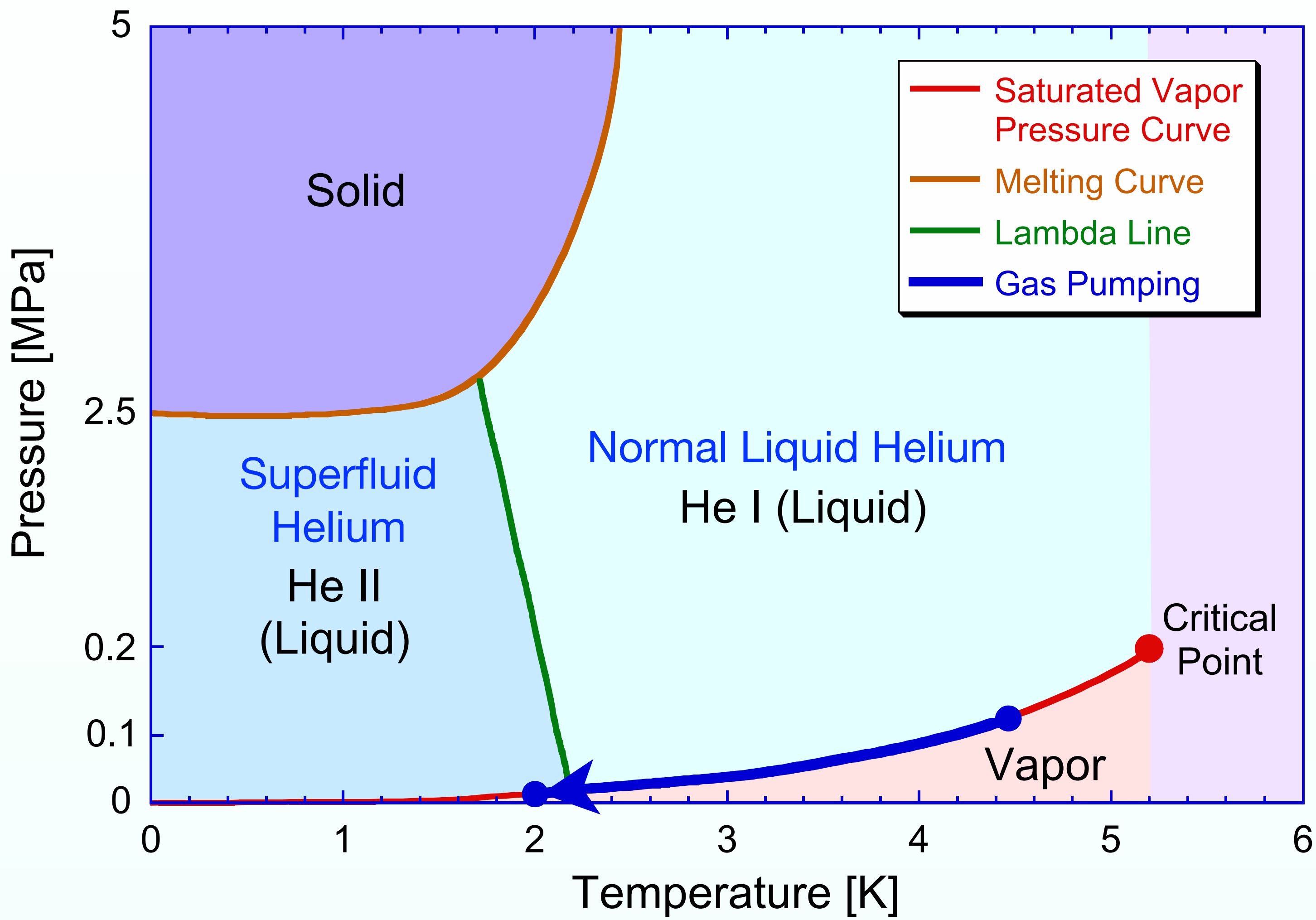
Cited from Lebrun, Ph., "An Introduction to Cryogenics", CERN/AT 2007-1 (2007)

Superfluid Helium and Cryogenic Systems

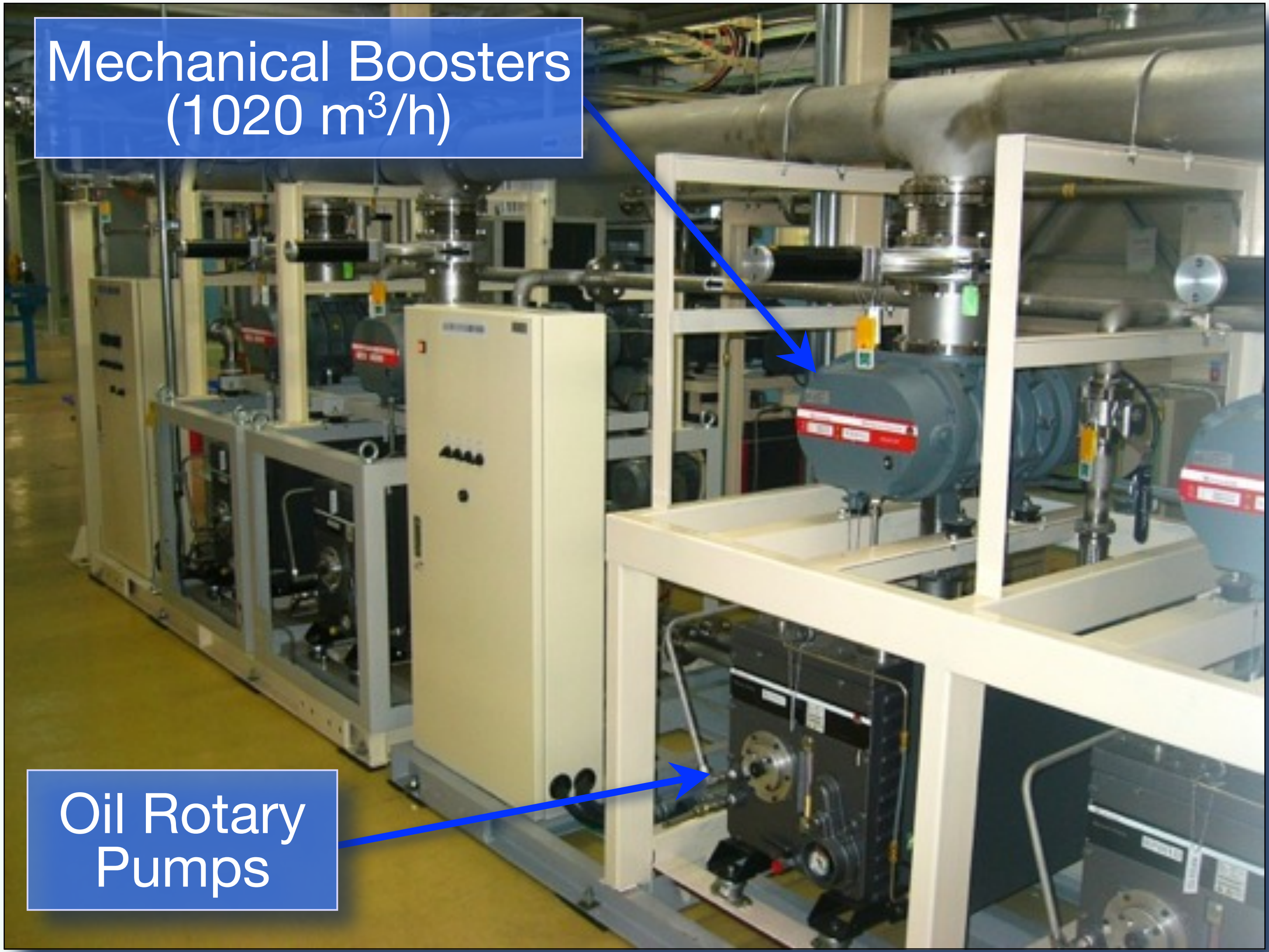
Phase Diagram of Ordinary Substance



Phase Diagram of Helium



Helium Gas Pumping System



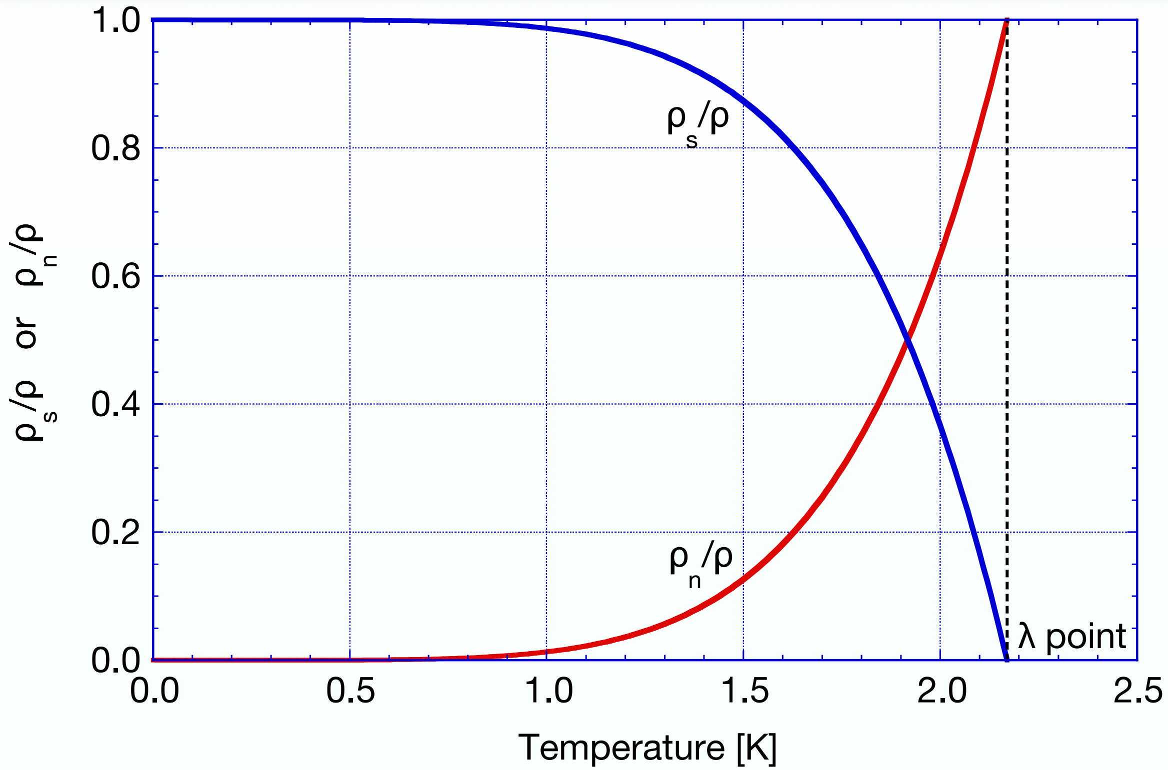
Superfluid Helium

- Superfluidity
  - Flowing through capillaries without any friction
- Super Thermal Conductivity
  - Apparent thermal conductivity about 100 times of that of high-purity copper
- Film Flow
  - Flowing in adsorbed layer of helium atoms

Two-fluid Model (1)

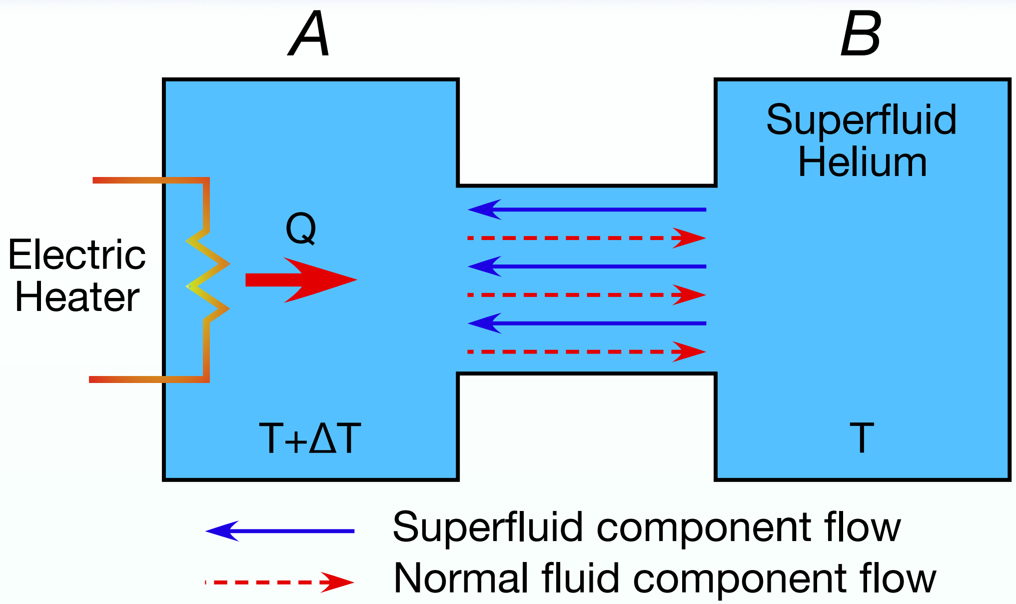
	Normal Fluid Component	Superfluid Component
Density	ρ_n	ρ_s
Viscosity	μ	0
Entropy Transport	Yes	No
Driven by	Pressure Difference	Temperature Difference

Two-fluid Model (2)



- Total density is sum of those of each component : $\rho = \rho_s + \rho_n$
- Density ratio depends on temperature
- Independent flow fields of each component

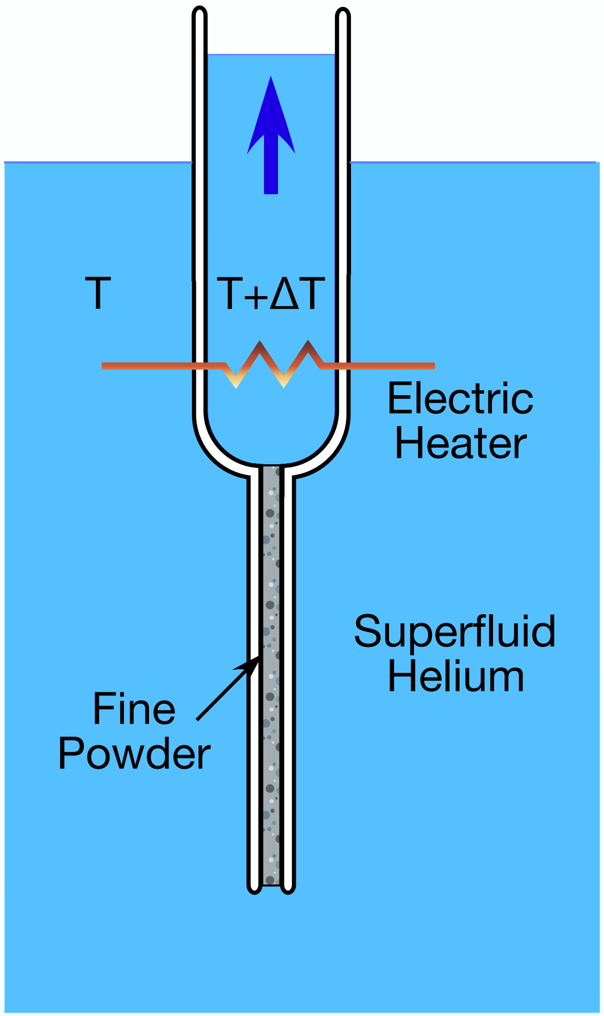
Heat Transport of Superfluid Helium

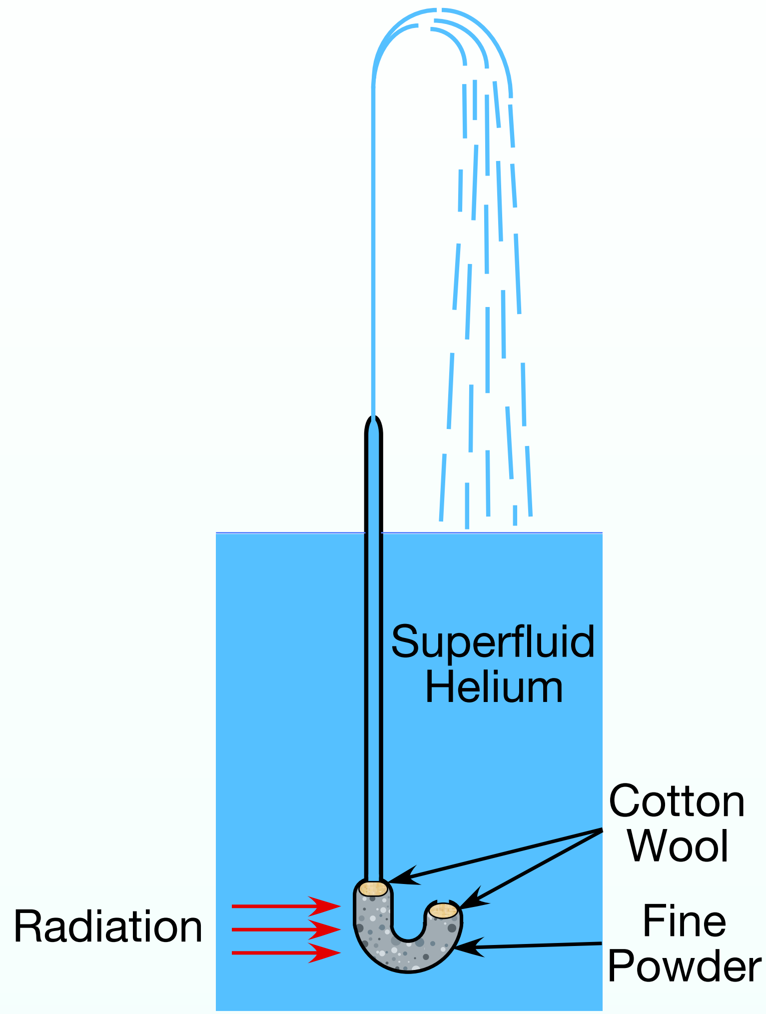


Cited from K. Yamada and T. Ohmi, "Superfluidity", Baifukan (1995) in Japanese

- Superfluid component flows toward higher temperature region
- Normal fluid component flows in opposite direction of superfluid component flow (thermal counterflow) ⟶ No net flow
- Entropy (heat) is transported only by normal fluid component
- Apparent large thermal conduction (internal convection)

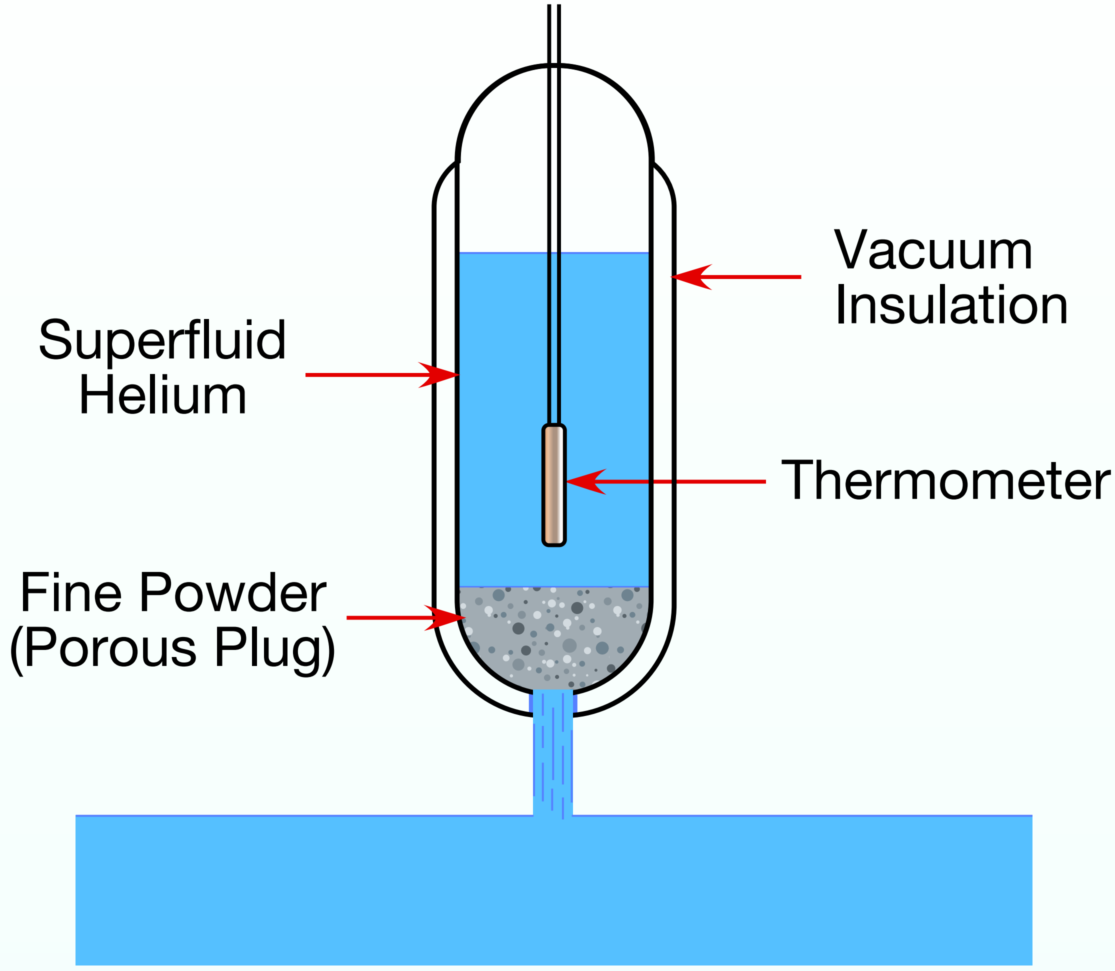
Thermomechanical Effect





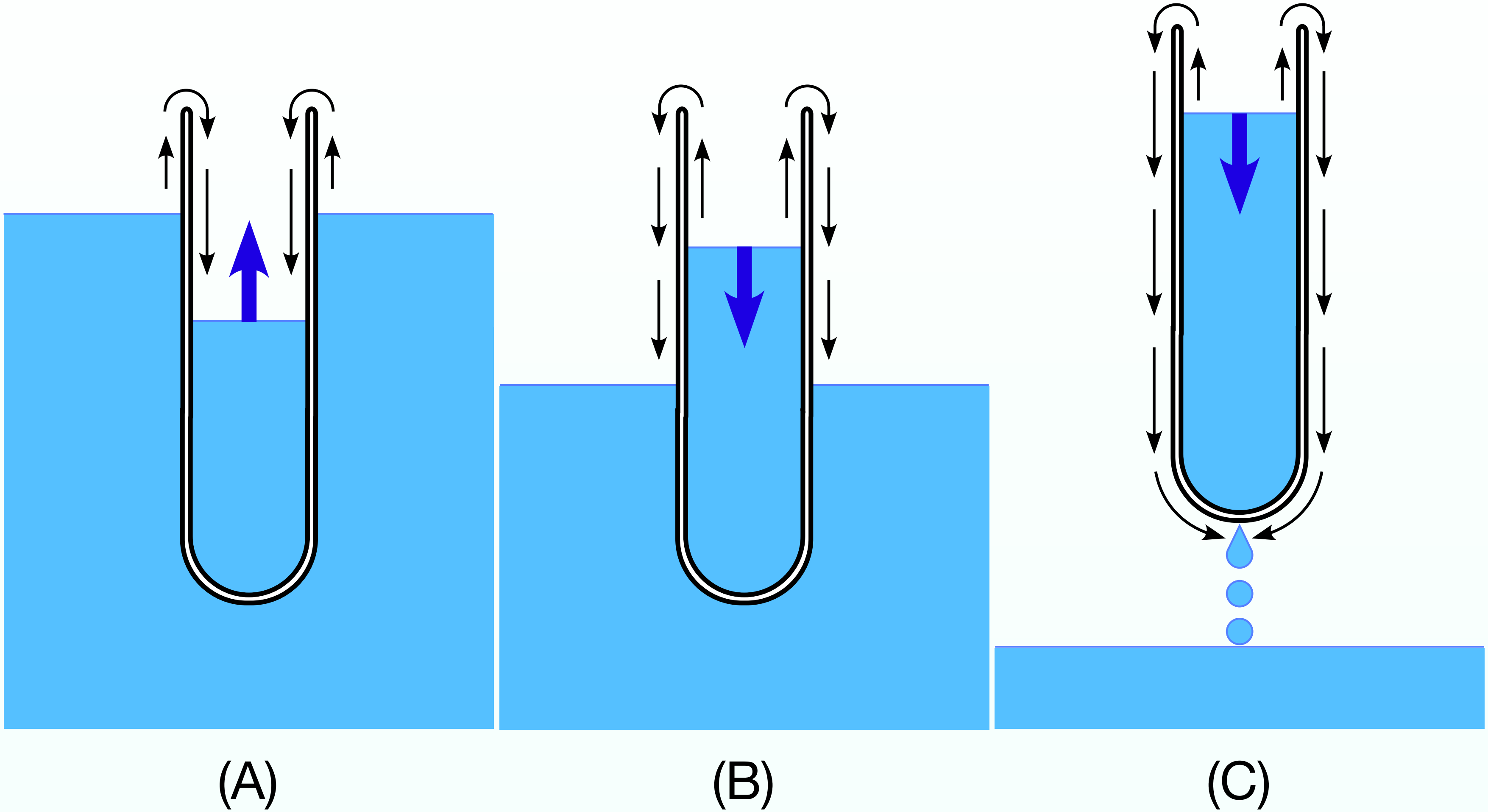
Cited from Donnelly, R. J., “Experimental Superfluidity”, University of Chicago Press (1967)

Mechanocaloric Effect



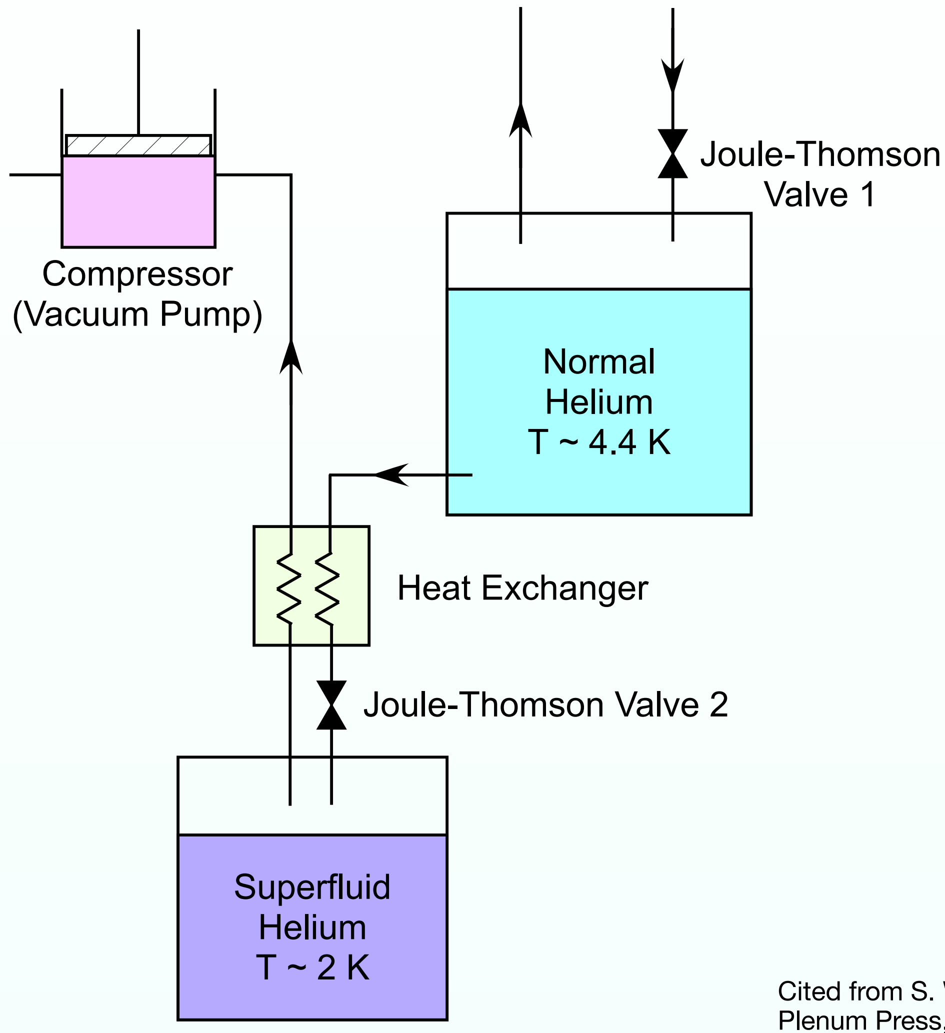
Cited from K. Yamada and T. Ohmi, “Superfluidity”, Baifukan (1995) in Japanese

Film Flow



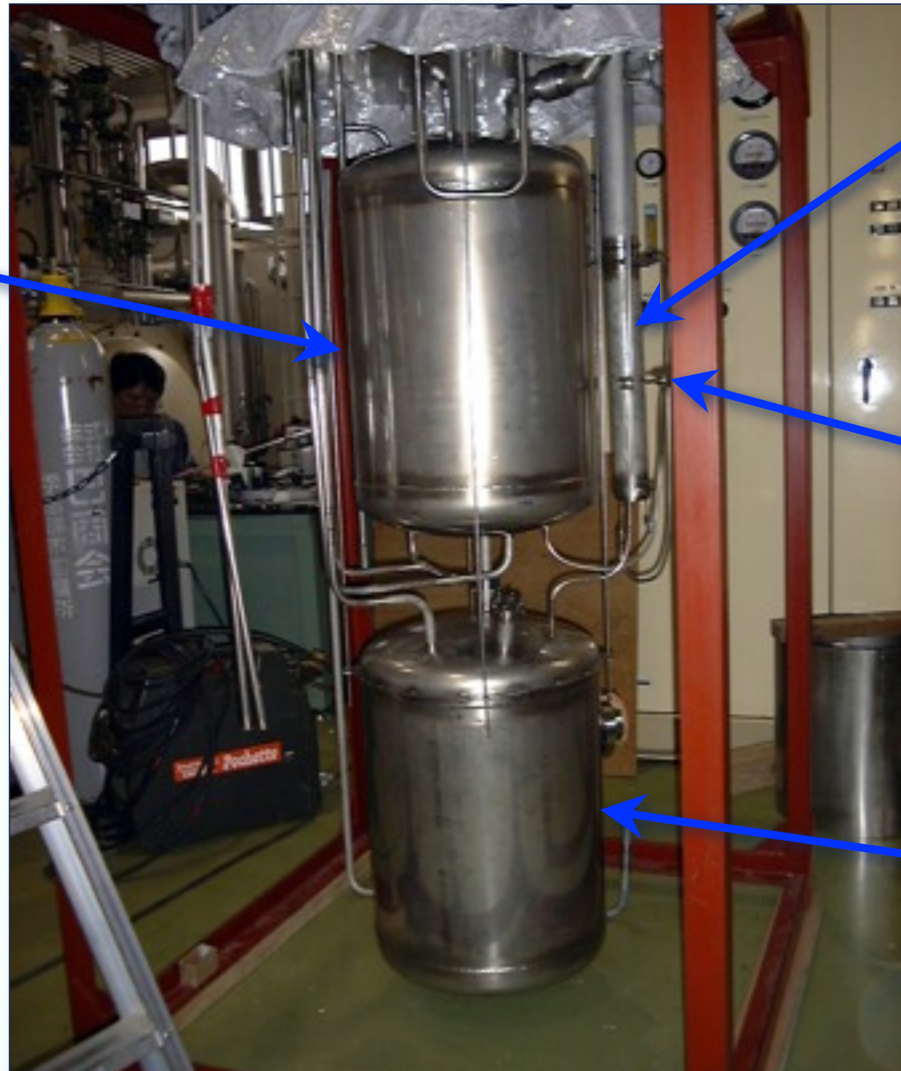
Cited from Donnelly, R. J., "Experimental Superfluidity", University of Chicago Press (1967)

Superfluid Helium Refrigerator



Cited from S. W. Van Sciver, “Helium Cryogenics,” Plenum Press, 1986

2 K Refrigerator Cold Box



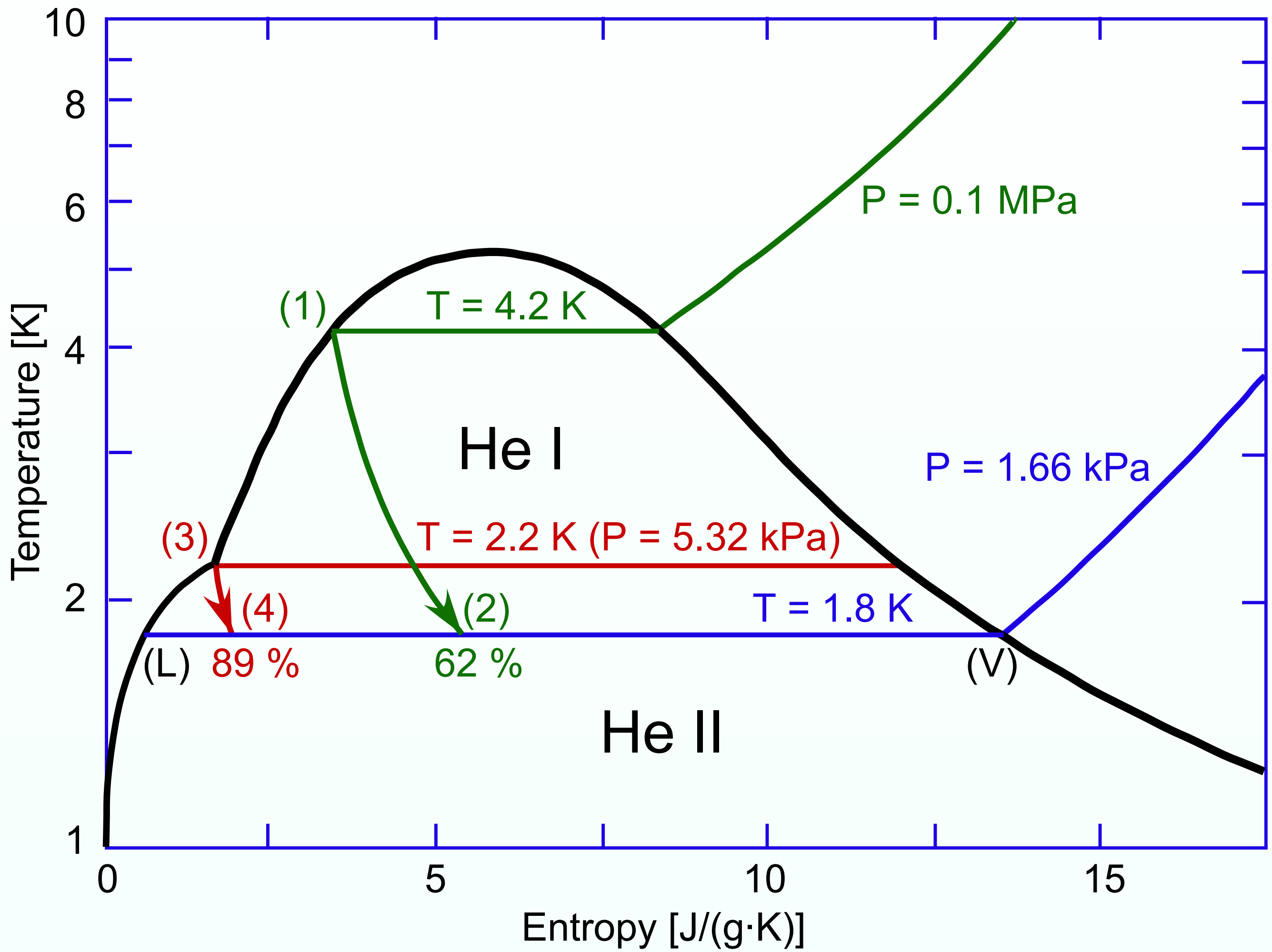
He I Pot

Heat Exchanger

J-T Valve

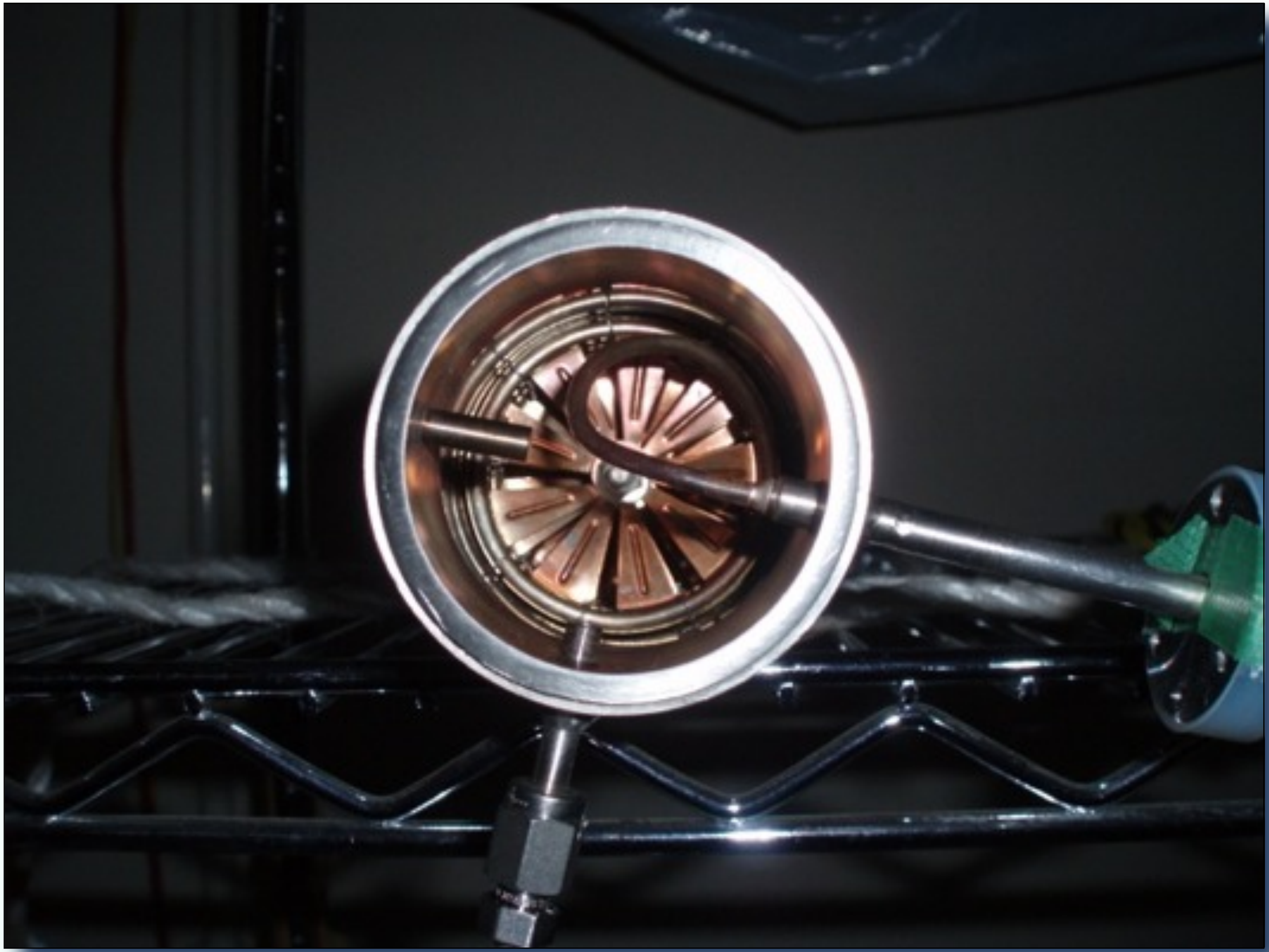
He II Pot

J-T Valve Inlet Temperature and Liquefaction Rate



Cited from S. W. Van Sciver, “Helium Cryogenics,” Plenum Press, 1986

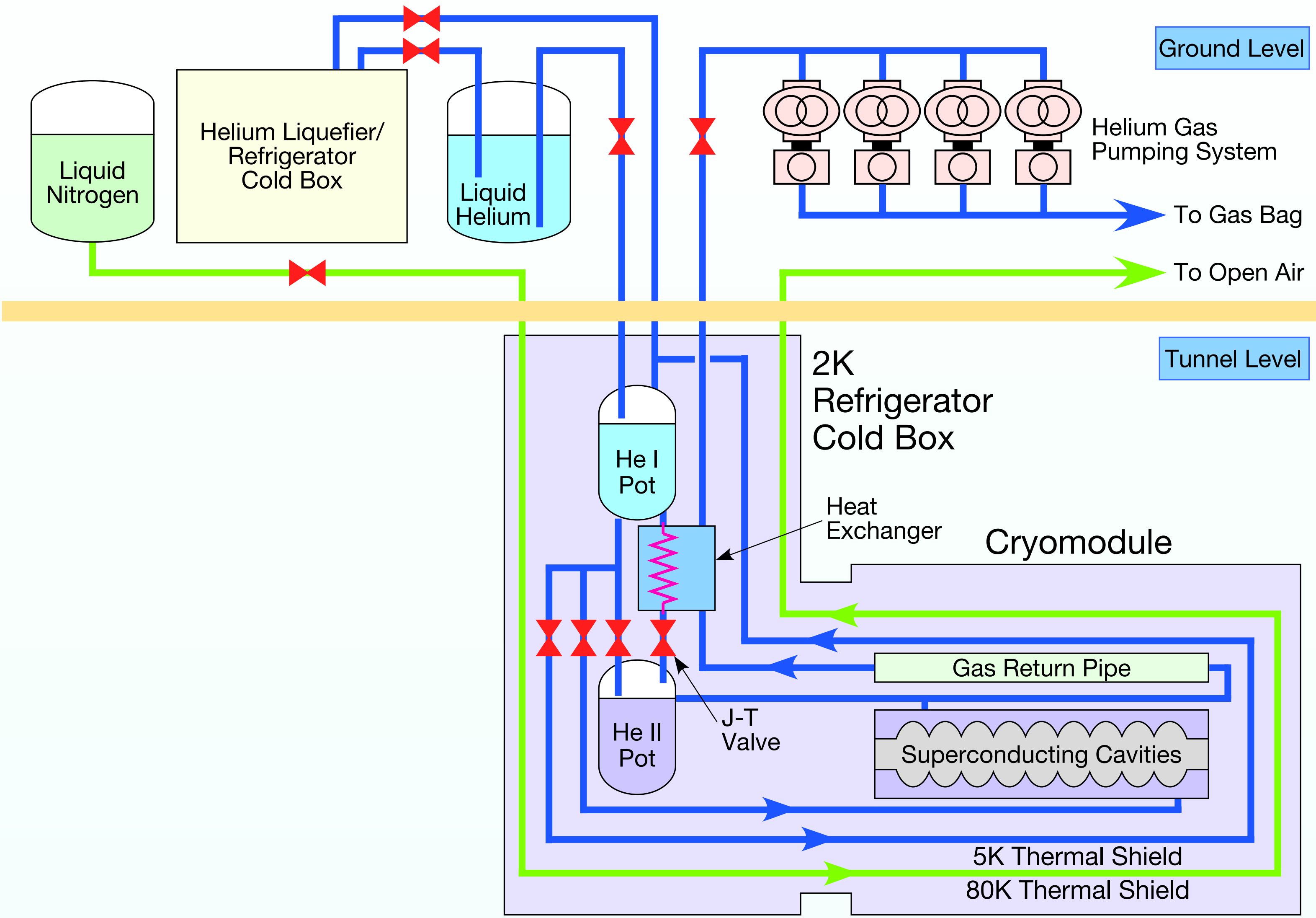
Heat Exchanger



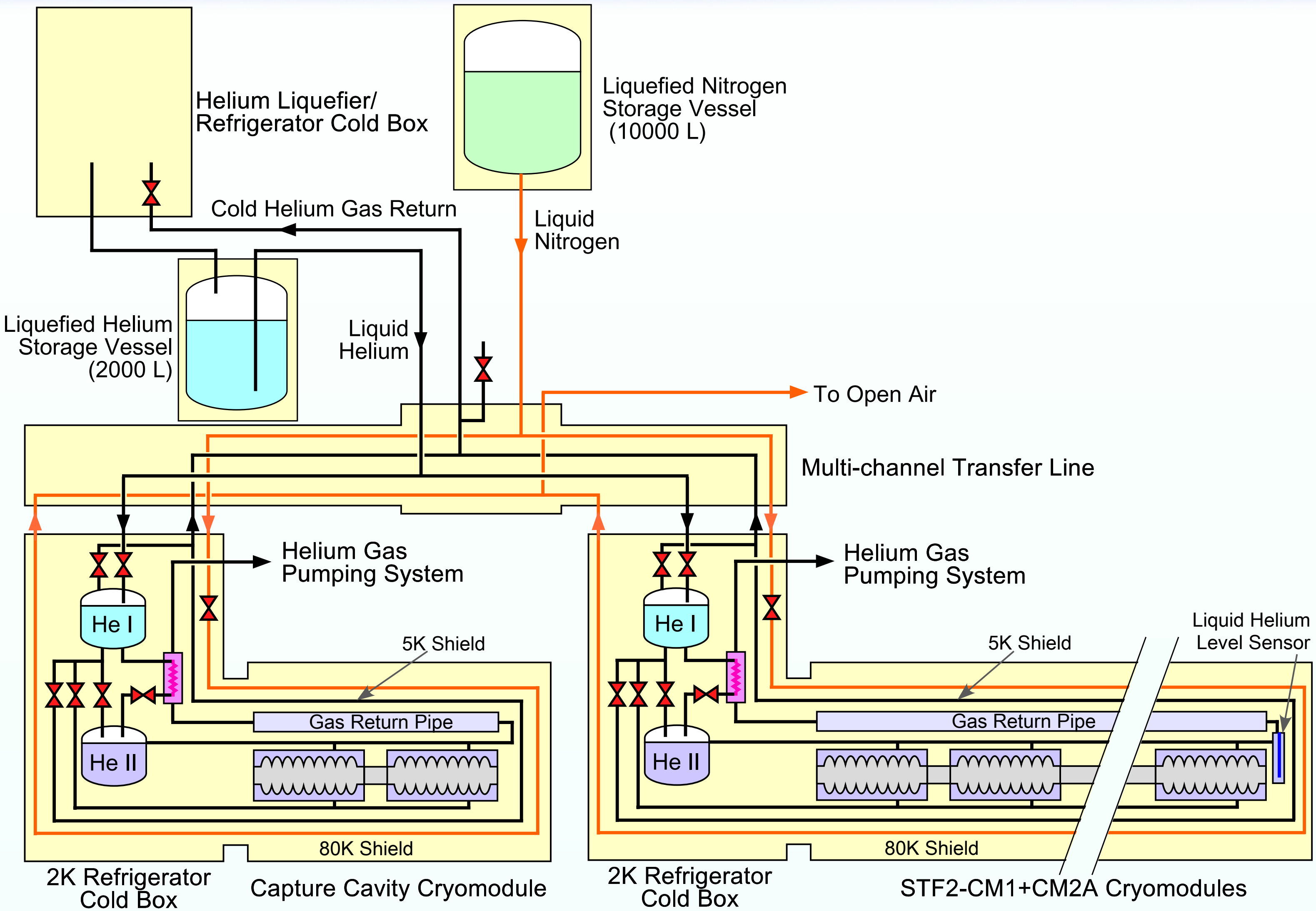
2 K Cryogenic Systems at KEK

- Superconducting RF Test Facility (STF)
  - Concerning with ILC project
  - Pulse mode operation
  - Capture cryomodule (2 x 9-cell cavities) + STF2-CM1 (8 x 9-cell cavities) + STF2-CM2A (4 x 9-cell cavities)
- Compact Energy Recovery Linac (cERL)
  - CW mode operation
  - Injector linac (3 x 2-cell cavities) + Main linac (2 x 9-cell cavities)

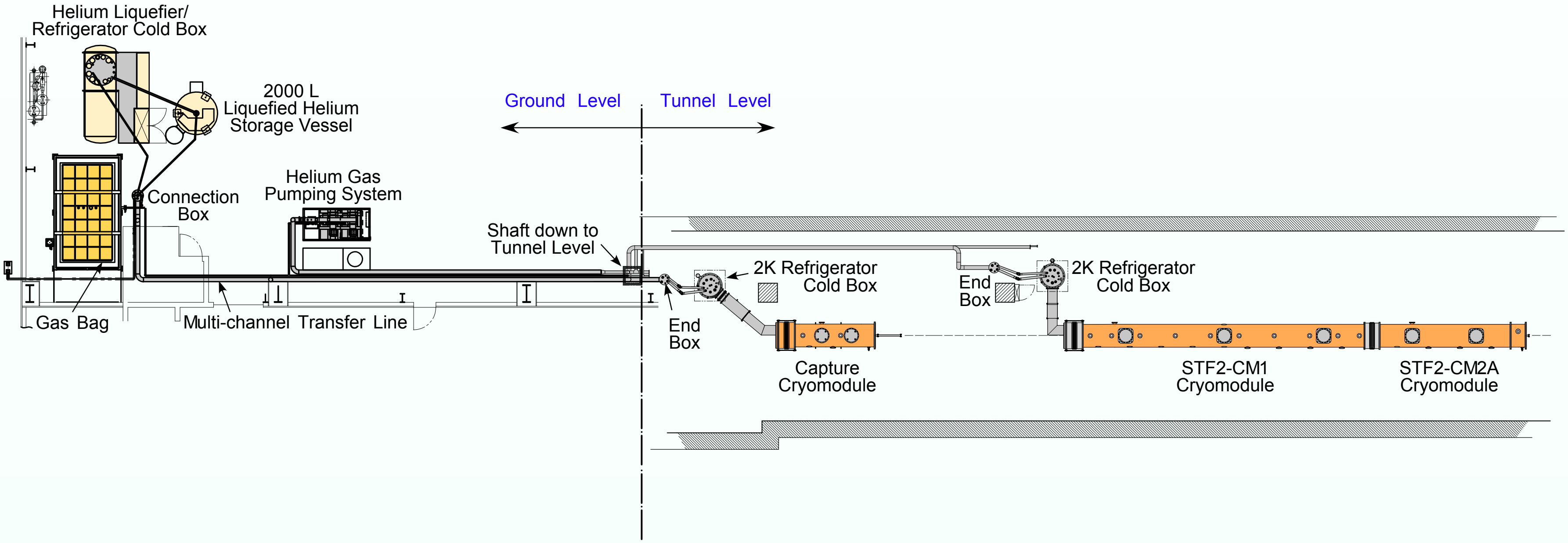
Superconducting RF Test Facility (STF)



STF Flow Diagram

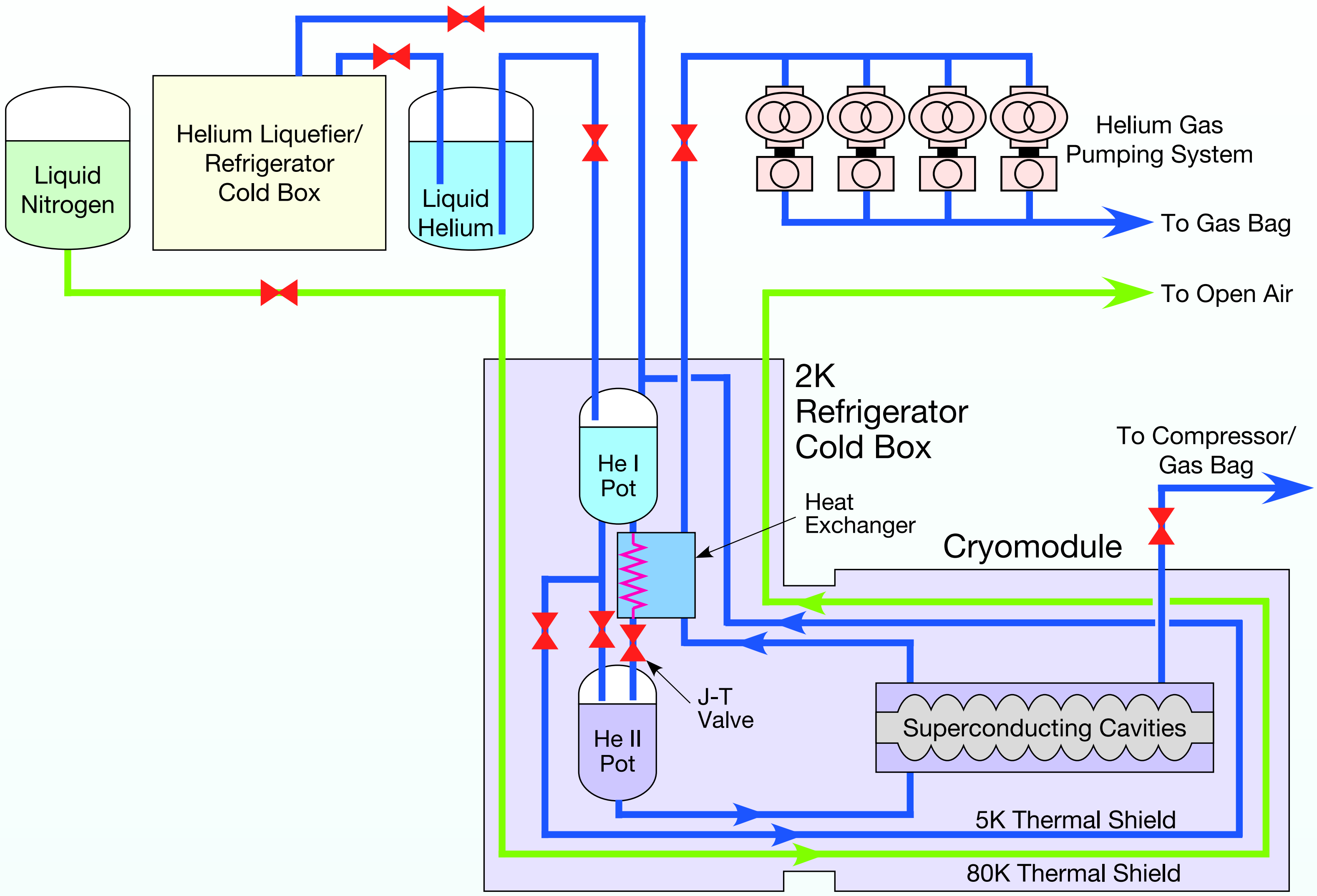


STF Layout

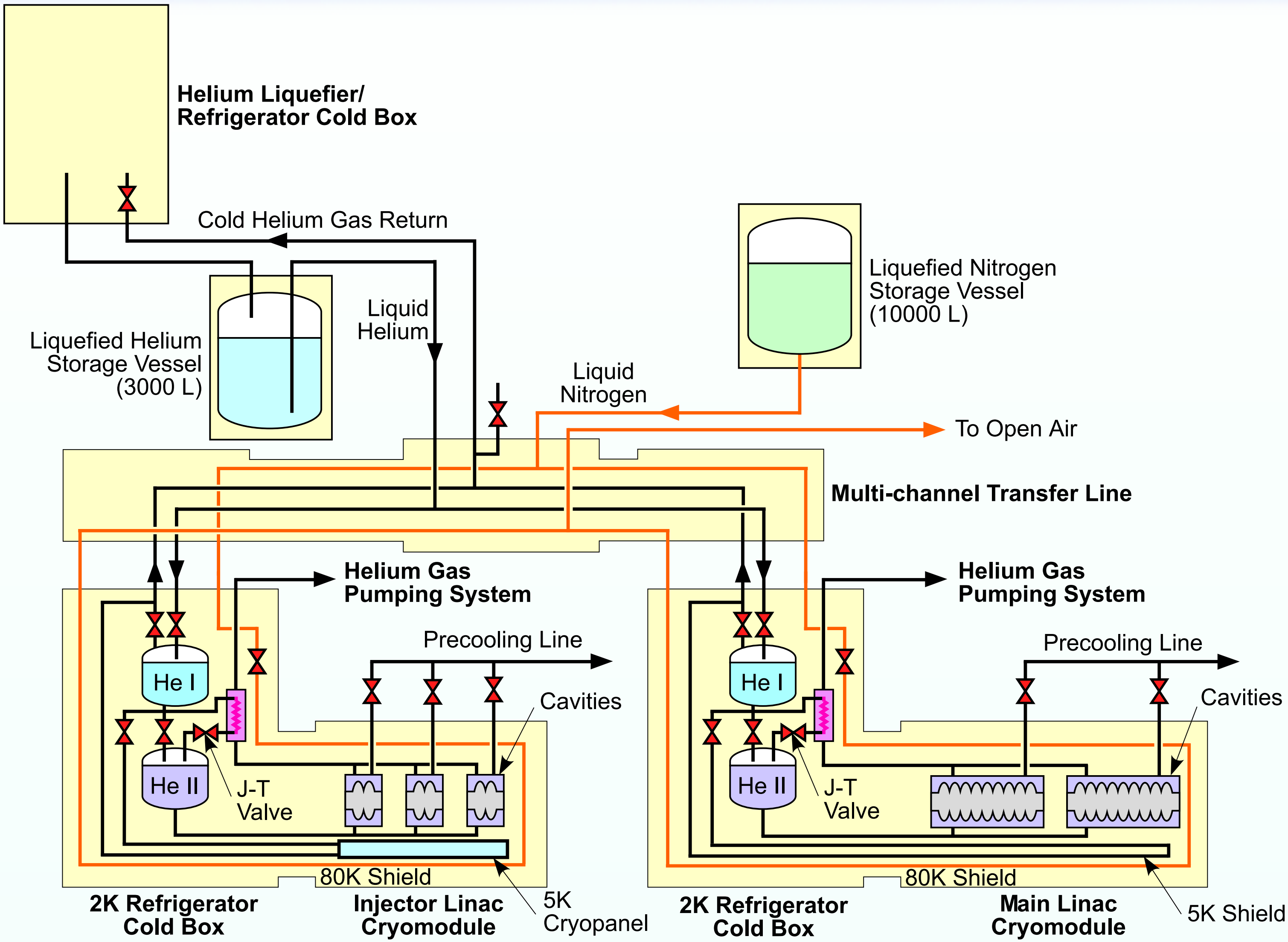


Helium Liquefier/
Refrigerator Cold Box
2000 L
Liquefied Helium
Storage Vessel
Ground Level
Tunnel Level
Helium Gas
Pumping System
Connection
Box
Shaft down to
Tunnel Level
2K Refrigerator
Cold Box
End
Box
2K Refrigerator
Cold Box
Gas Bag
Multi-channel Transfer Line
End
Box
Capture
Cryomodule
STF2-CM1
Cryomodule
STF2-CM2A
Cryomodule

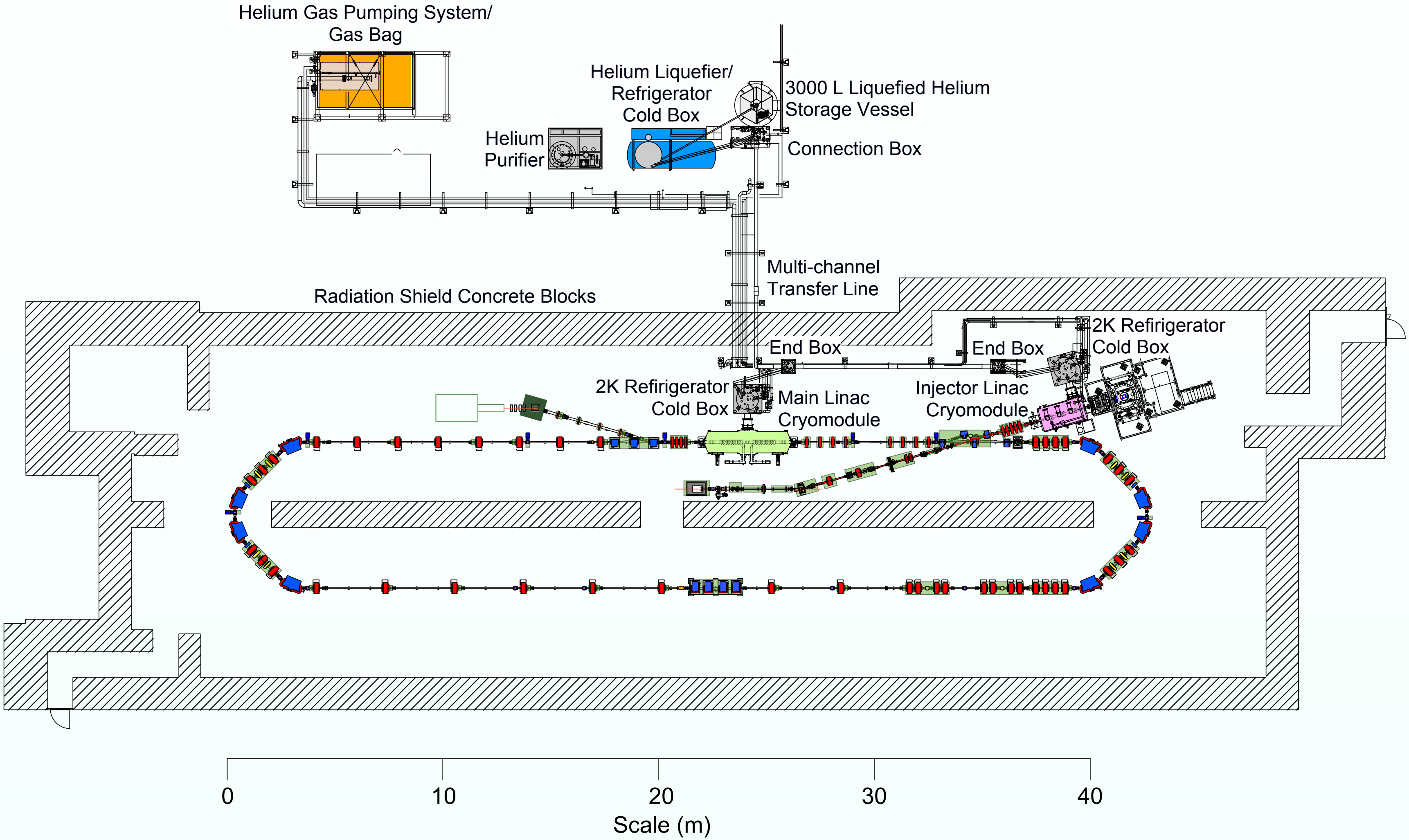
Compact Energy Recovery Linac (cERL)



cERL Flow Diagram



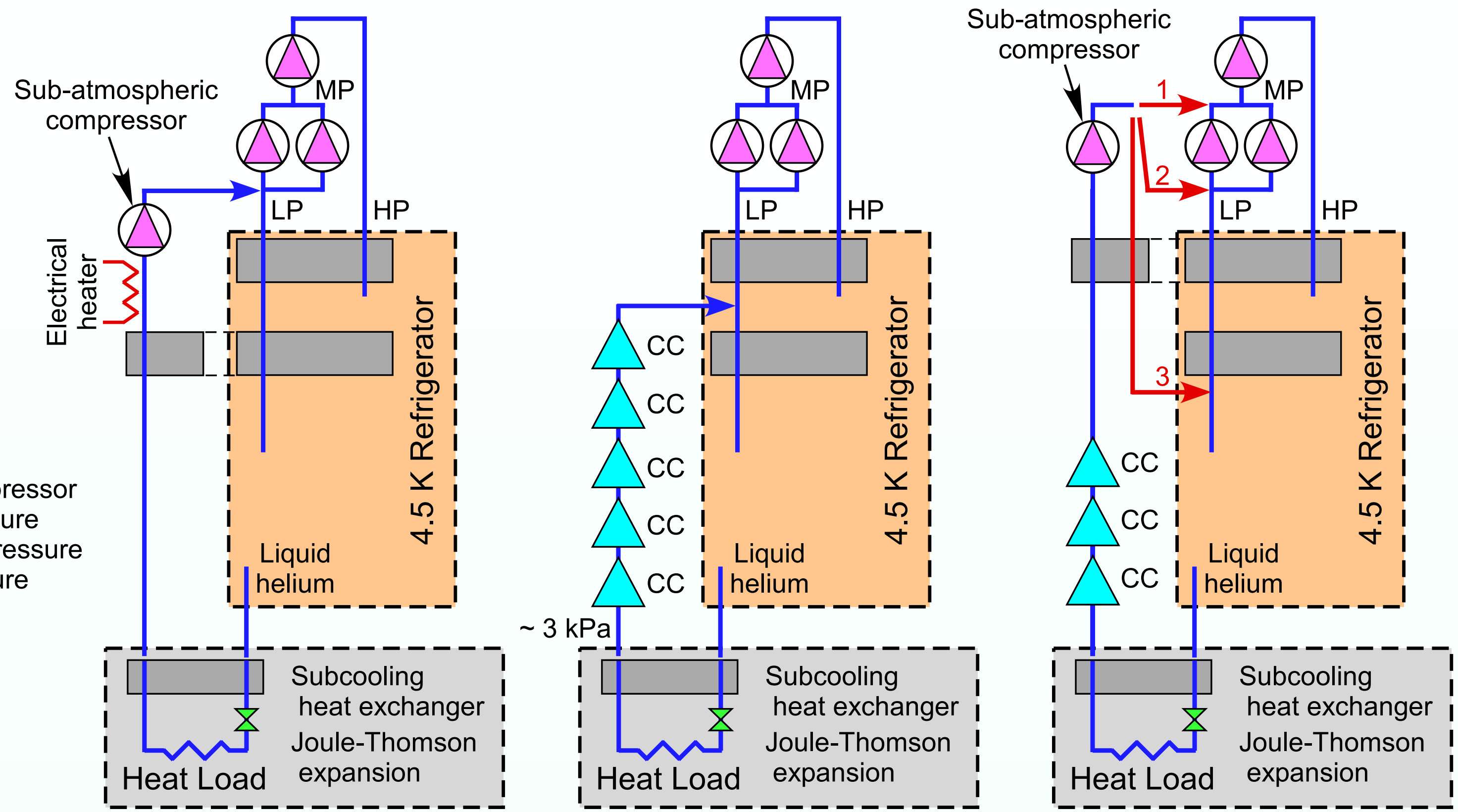
cERL Layout



Helium Gas Pumping System/
Gas Bag
Helium Liquefier/
Refrigerator
Cold Box
3000 L Liquefied Helium
Storage Vessel
Helium
Purifier
Connection Box
Multi-channel
Transfer Line
Radiation Shield Concrete Blocks
End Box
End Box
2K Refirigerator
Cold Box
2K Refirigerator
Cold Box
Main Linac
Cryomodule
Injector Linac
Cryomodule
0
10
20
30
40
Scale (m)

Helium Liquefier/Refrigerator (cERL)

Superfluid Helium Cryogenic Systems



CC: Cold compressor
HP: High pressure
MP: Medium pressure
LP: Low pressure

Warm Compression (a)

Cold Compression (b)

Mixed (Hybrid) Compression (c)

Cited from Ph. Lebrun and L. Tavian: "The technology of superfluid helium", European Graduate Course in Cryogenics Helium Week, WUT & CERN, August-September 2010

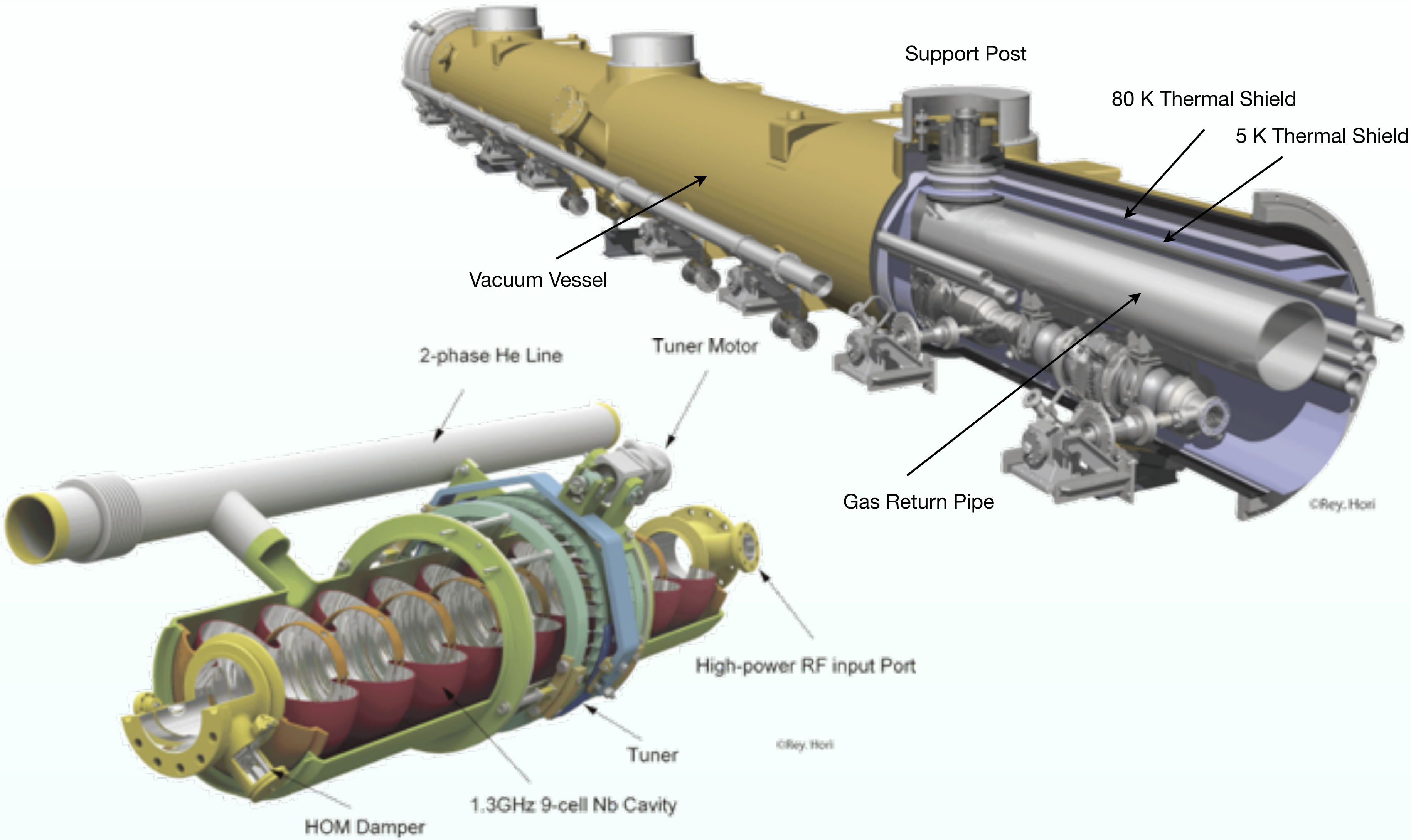
Cryogenic Engineering

Heat Transfer

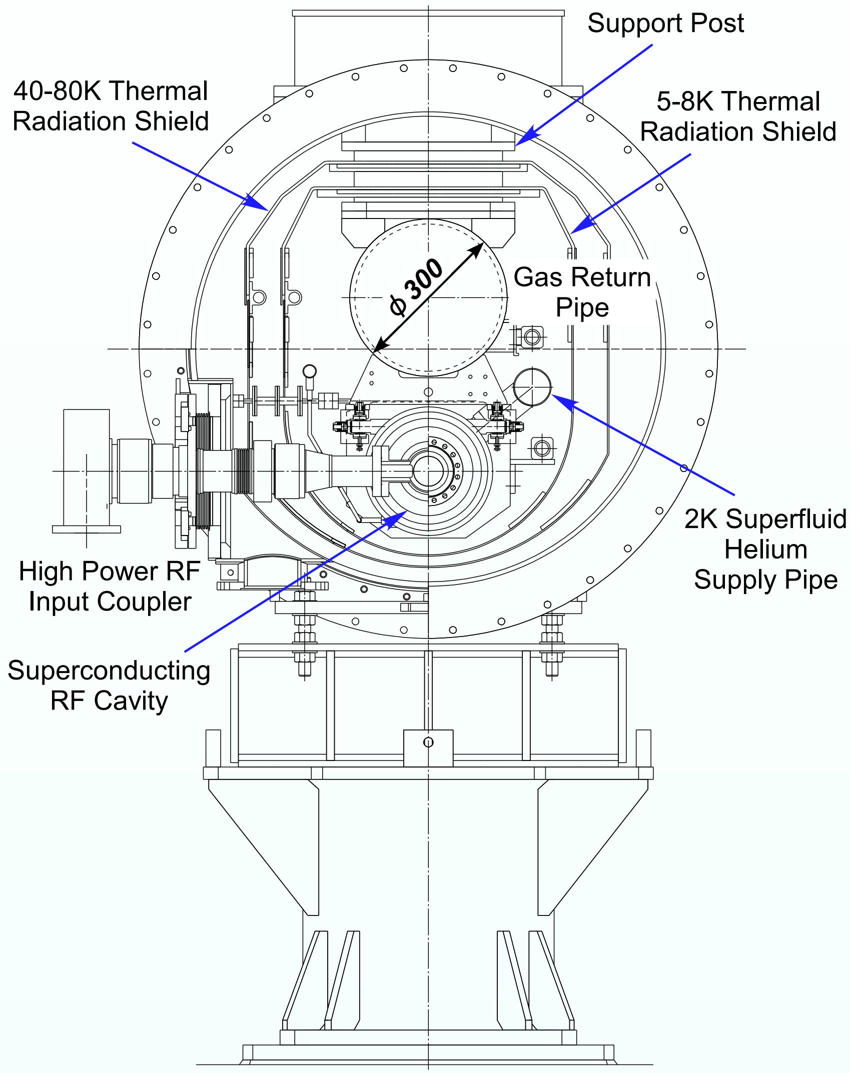
Three Modes of Heat Transfer

- Conduction
  - Thin-wall pipe
  - Low thermal conductivity material
- Convection
  - Vacuum insulation
- Radiation
  - Multi-layer insulation (MLI)

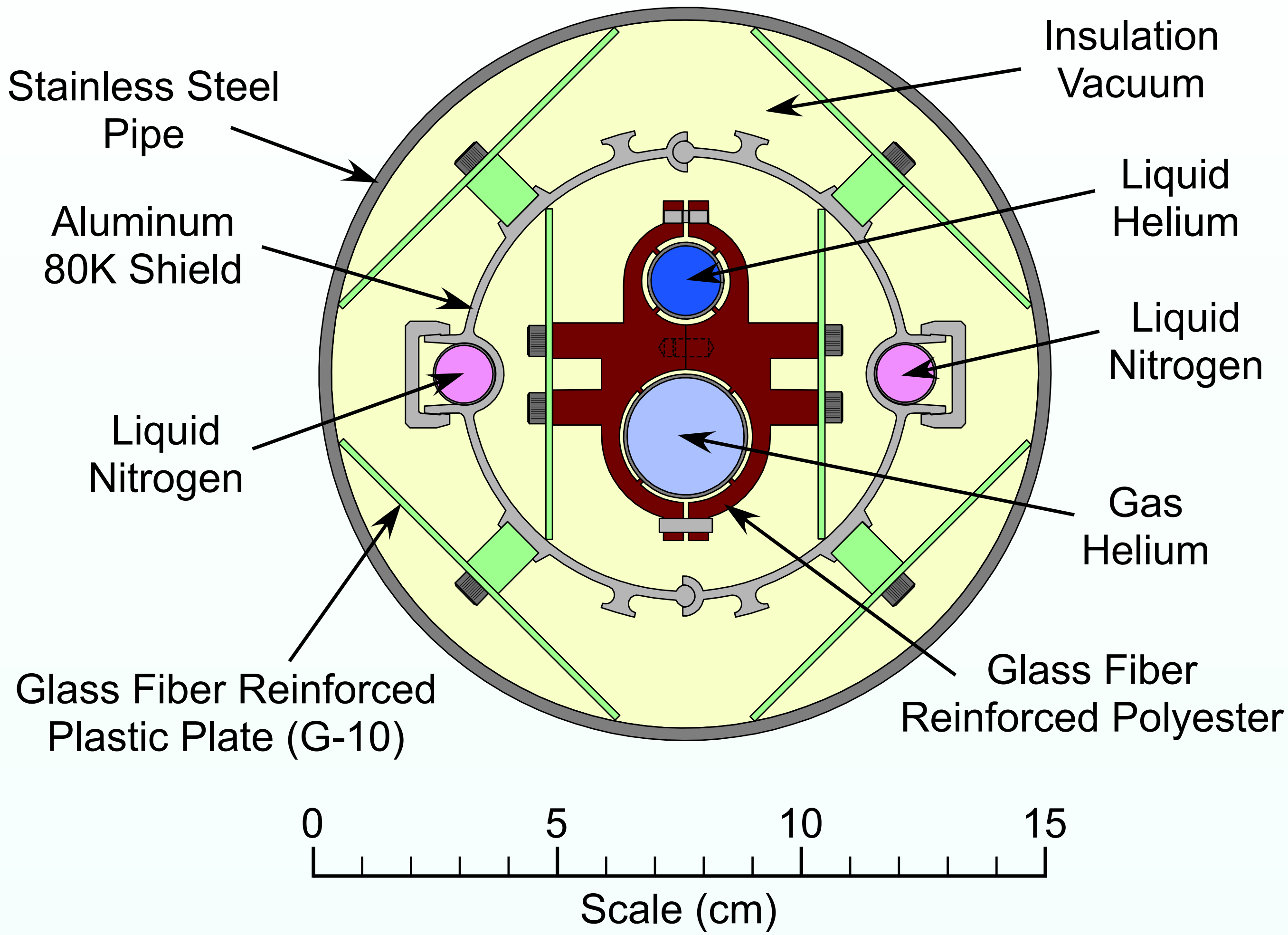
ILC Cavity & Cryomodule



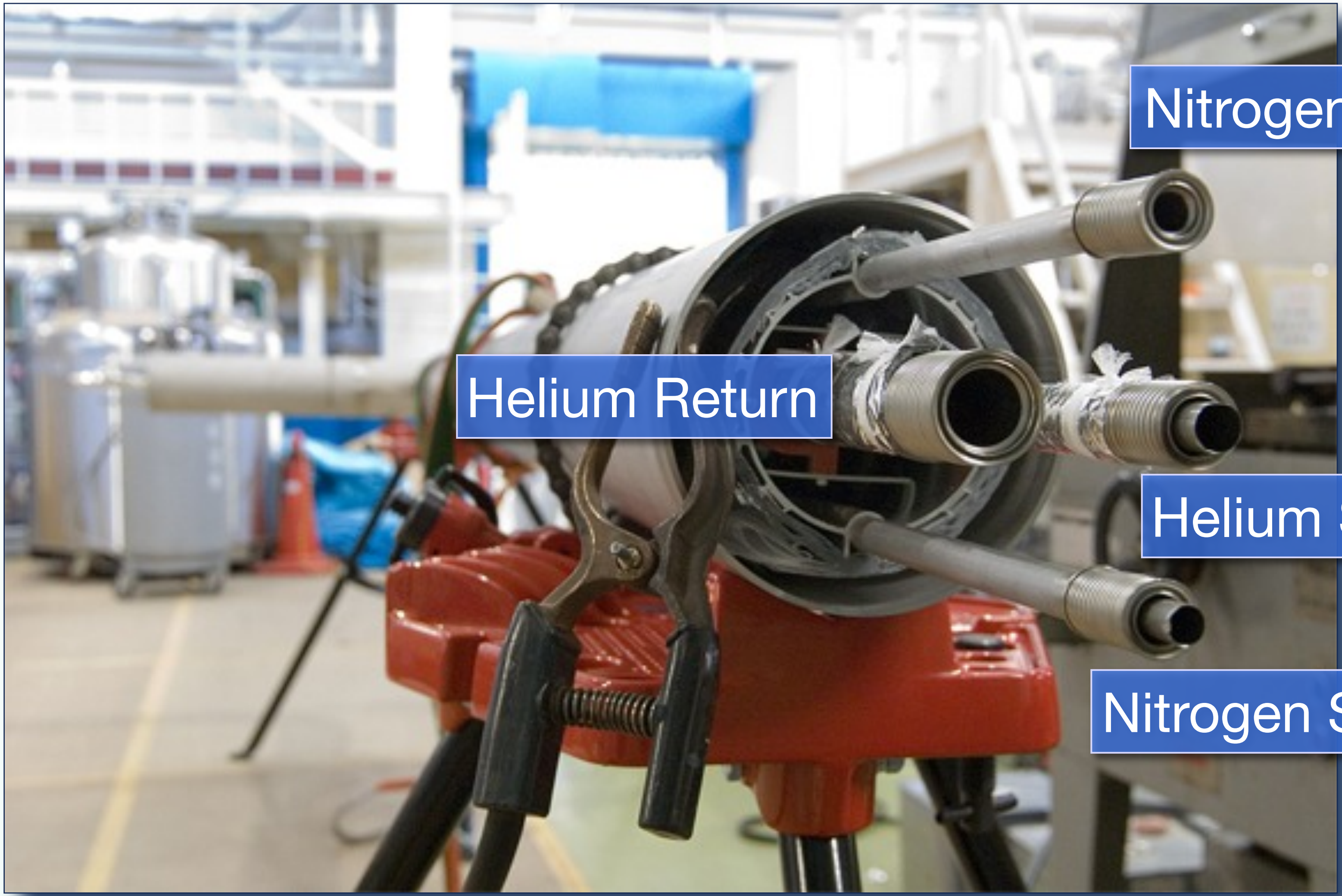
Cross Section of ILC Cryomodule



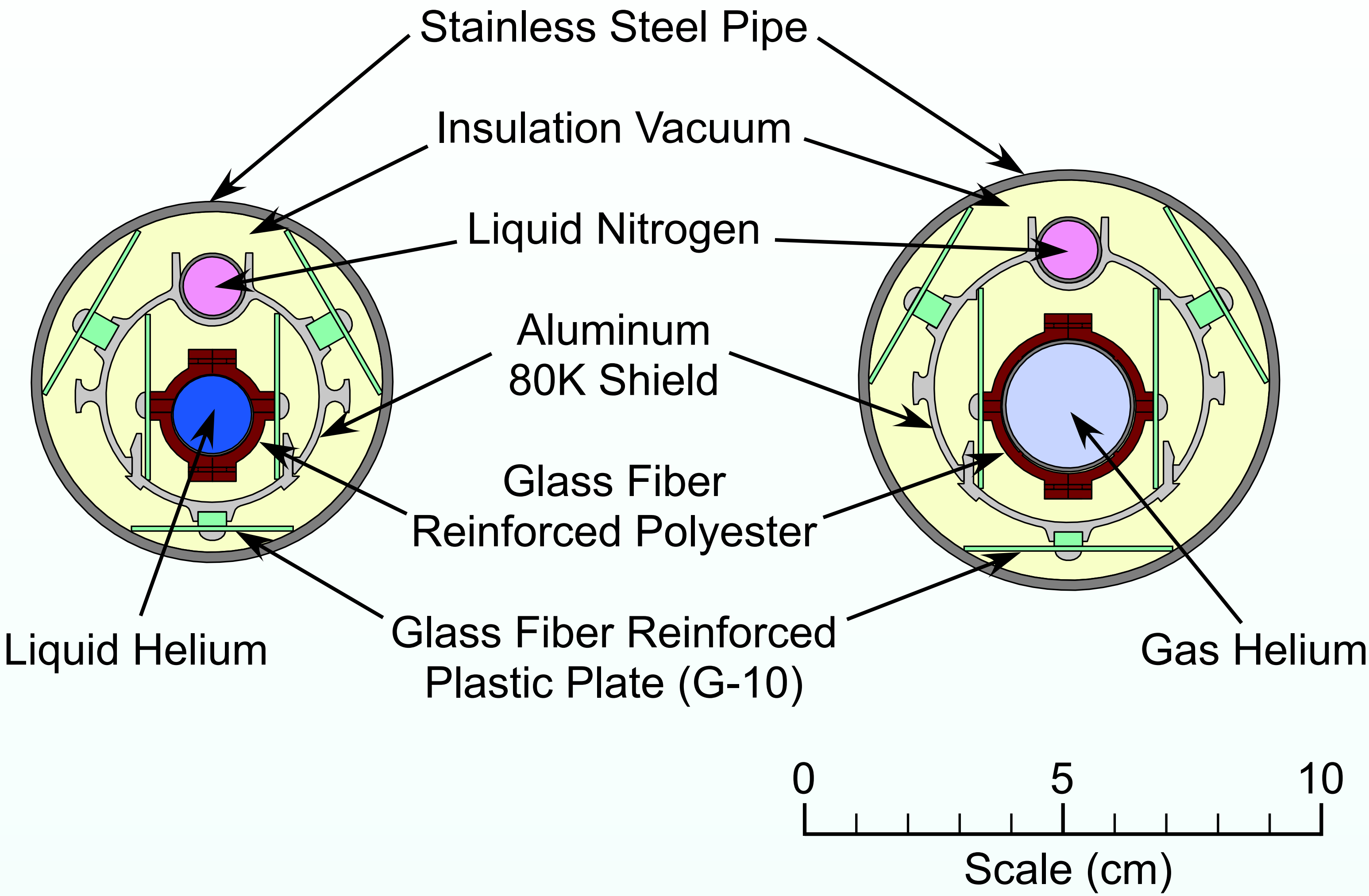
High-Performance Transfer Line (Multi-channel)



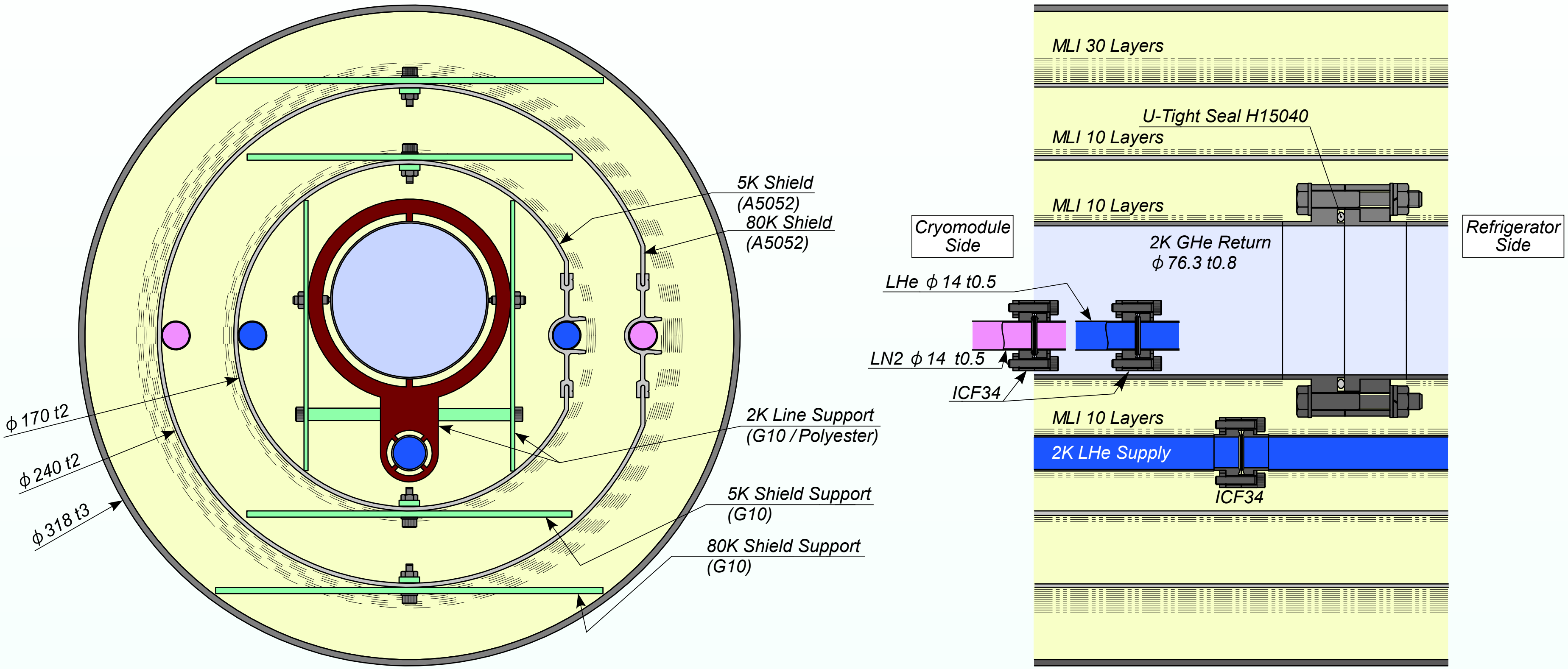
High-Performance Transfer Line



High-Performance Transfer Line (Single Channel)

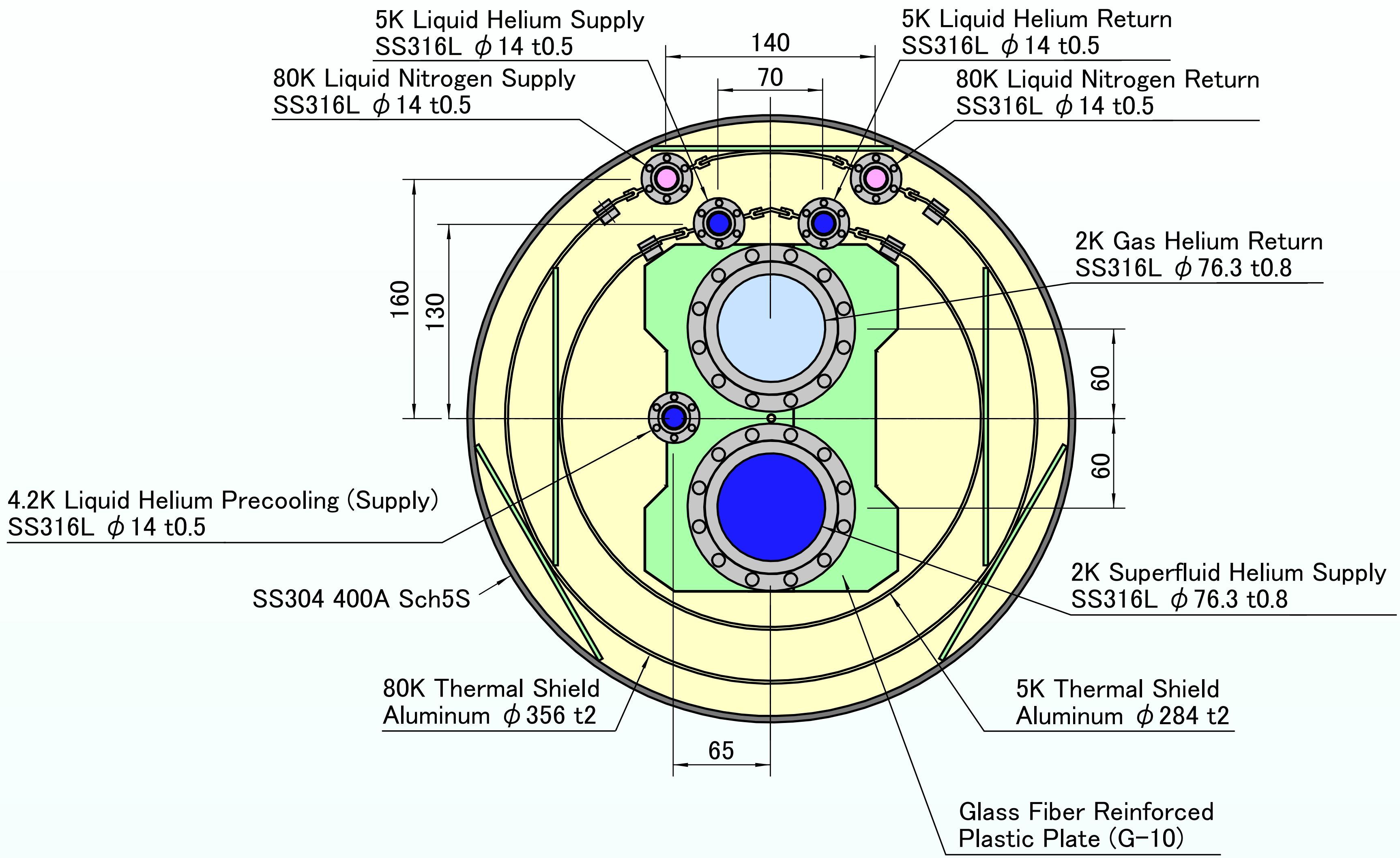


High-Performance Transfer Line (2 K Connection of cERL)



80K Shield Pipe	SS316L TP-SC	ϕ 14 t0.5
5K Shield Pipe	SS316L TP-SC	ϕ 14 t0.5
2K LHe Supply Pipe	SS316L TP-SC	ϕ 17.3 t0.8
2K GHe Return Pipe	SS316L TP-SC	ϕ 60.5 t0.8

High-Performance Transfer Line (2 K Connection of STF)



Cryogenic Hazards

- Asphyxiation (Anoxia)
  - Lack of oxygen
  - Cold and heavy nitrogen gas - lower level
  - Cold but light helium gas - higher level
- Frostbite
  - Low temperature liquid and gas on skin
  - Appropriate equipments for protection
- Explosion
  - Pressure rise of liquefied gas in closed space such as vessels and pipes
  - Evaporated oxygen

Summary

Summary (1)

1. Superconducting RF cavities and cryogenics
   - Liquid helium (He I) for 509 MHz RF cavities
   - Superfluid helium (He II) for 1.3 GHz RF cavities
2. Helium refrigerators
   - Joule-Thomson expansion (isenthalpic change)
   - Inversion curve
   - Difference of liquefiers and refrigerators

Summary (2)

3. Superfluid helium and cryogenic systems
   - Two-fluid model to understand unique properties of superfluid helium
   - Helium gas pumping system
   - J-T valves and heat exchangers
4. Cryogenic Engineering
   - Cryomodules and transfer lines
   - Cryogenic hazards

Thank you for your attention!