

The 7th Asian School on Superconductivity and Cryogenics for Accelerators



Korea University Sejong Campus, Korea

Superfluid Helium Cryogenics and Superfluid Helium Cryogenic Systems



High Energy Accelerator Research Organization (KEK)
Accelerator Laboratory

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February 7, 2026



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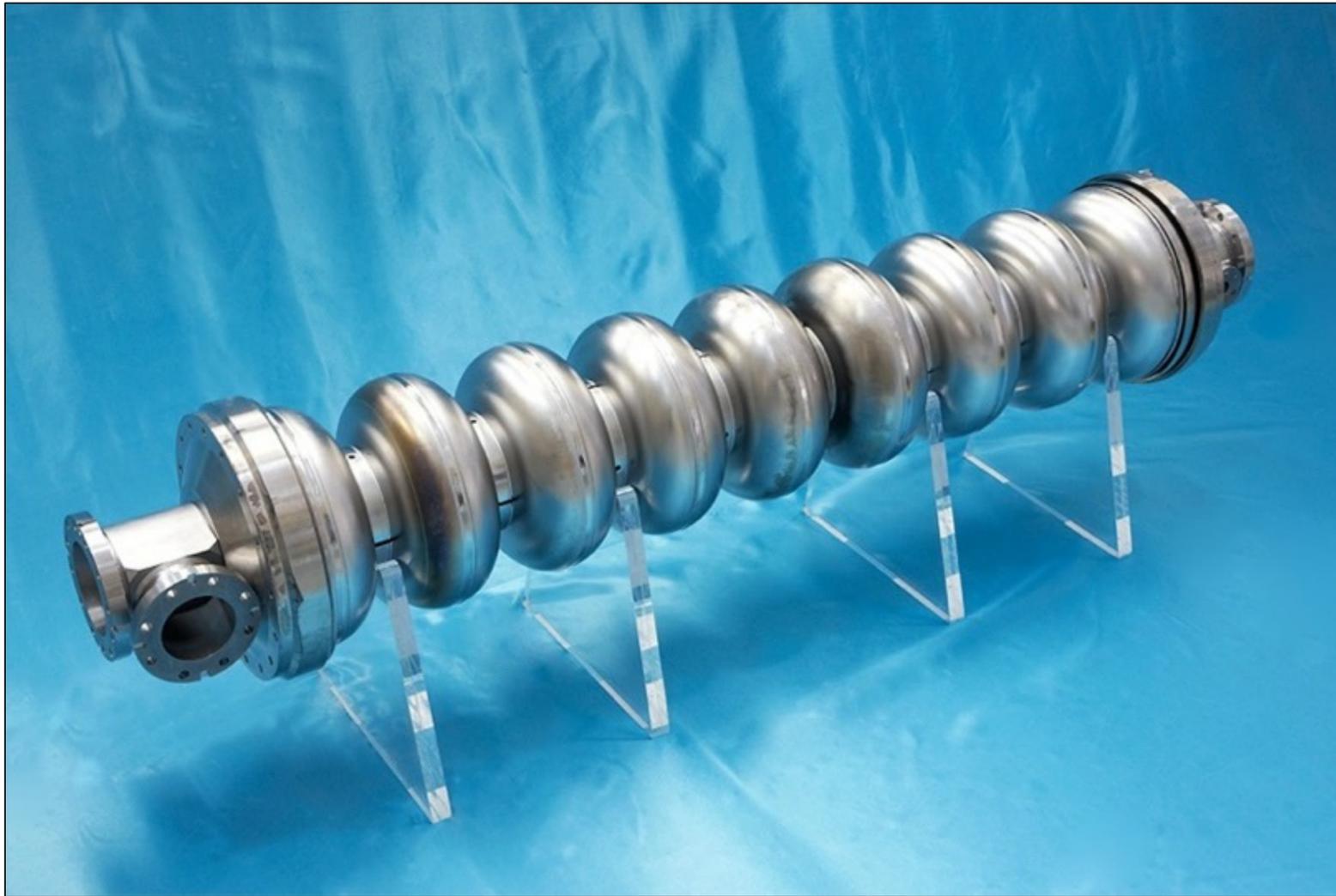
Introduction

- ◆ Higher energy accelerators
 - ◆ Limitations of copper devices (input power and heat generation)
- ◆ Superconducting magnets : NbTi, Nb₃Sn
 - ◆ Dipole (beam bending)
 - ◆ Quadrupole (beam focusing)
- ◆ Superconducting RF cavities : Nb
 - ◆ Accelerating cavities
 - ◆ Crab cavities

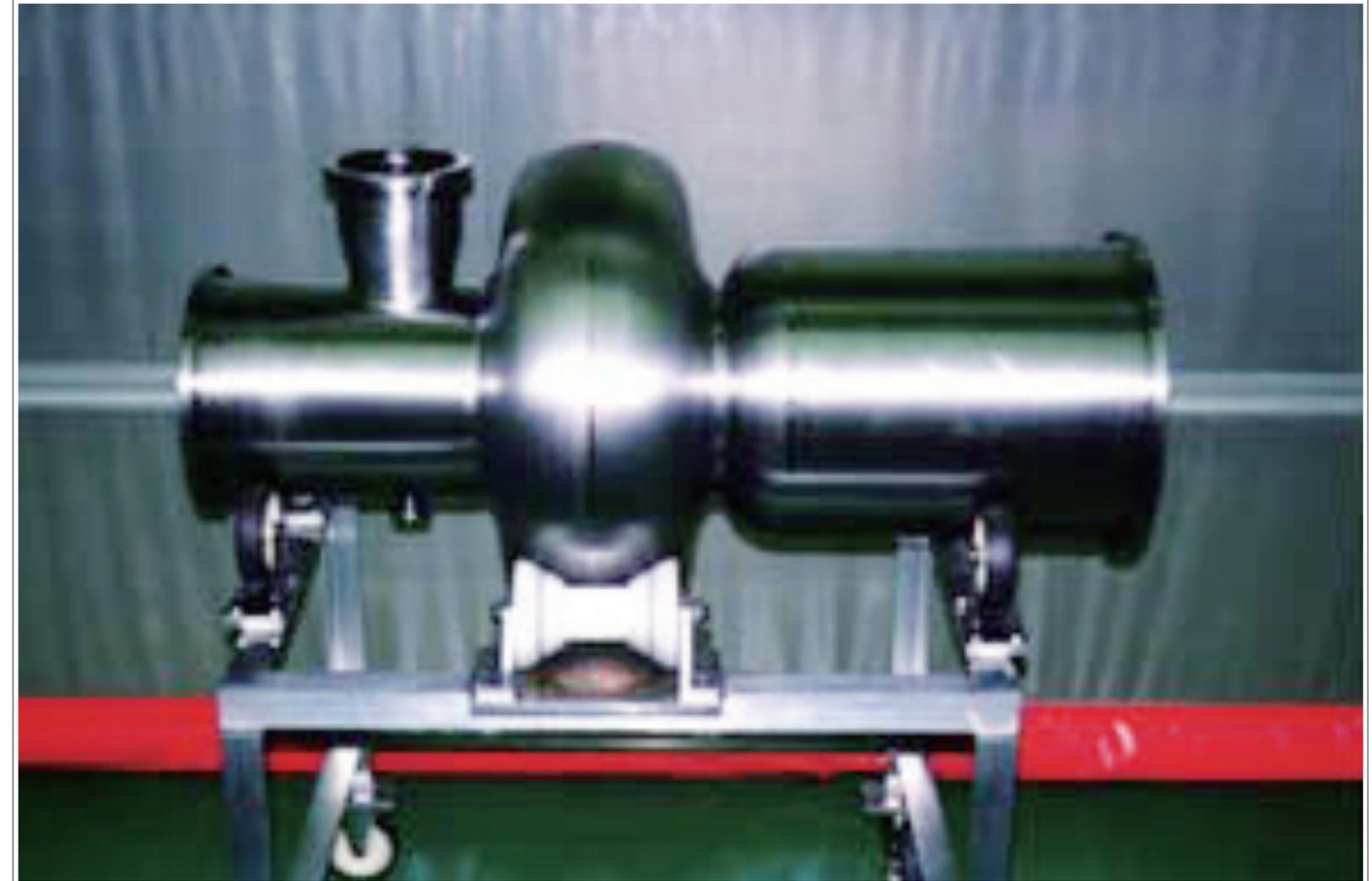
- ◆ SuperKEKB : 4.4 K (SC cavities, SC magnets)
 - ◆ J-PARC : 4.5 K (SC magnets)
 - ◆ ILC (International Linear Collider) : 2.0 K (SC cavities, SC magnets), 4.5 K (SC magnets)
 - ◆ LHC (Large Hadron Collider, CERN) : 1.9 K (SC magnets)
- etc ...

Cooling of Superconducting Cavities

Superconducting Cavity Resonators (Niobium)



1.3 GHz 9-cell cavity



509 Mz single-cell cavity

$$R_s = R_{BCS} + R_{res}$$

R_s : Surface resistance

R_{BCS} : BCS theoretical value

R_{res} : Residual surface resistance

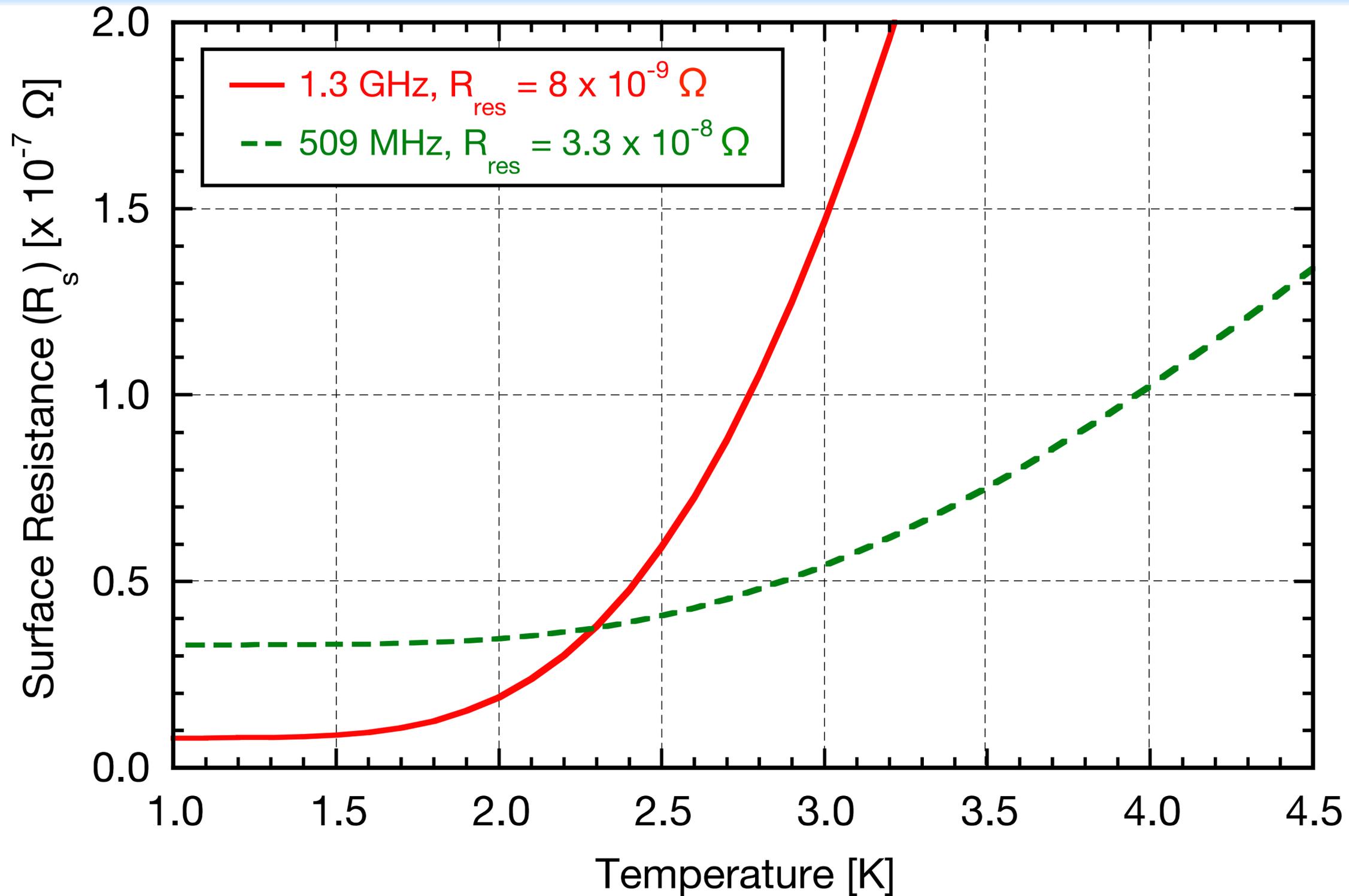
Semi-empirical equation for BCS theoretical value of niobium at temperature $T < T_c/2$

$$R_{BCS} = 2 \times 10^{-4} \frac{1}{T} \left(\frac{f}{1.5} \right)^2 \exp \left(-\frac{17.67}{T} \right)$$

T : Operation temp.

f : Frequency

Temperature Dependence of Surface Resistance



- ◆ Heat generated from cavity (cavity loss, RF loss) is proportional to surface resistance
- ◆ Surface resistance is sum of BCS resistance and residual resistance
- ◆ BCS resistance depends on operation temperature
- ◆ The higher resonant frequency the lower operation temperature
 - ◆ 509 MHz SC cavities → operated at 4.5 K
 - ◆ 1.3 GHz SC cavities → operated at 2 K or lower temperature

Superfluid Helium

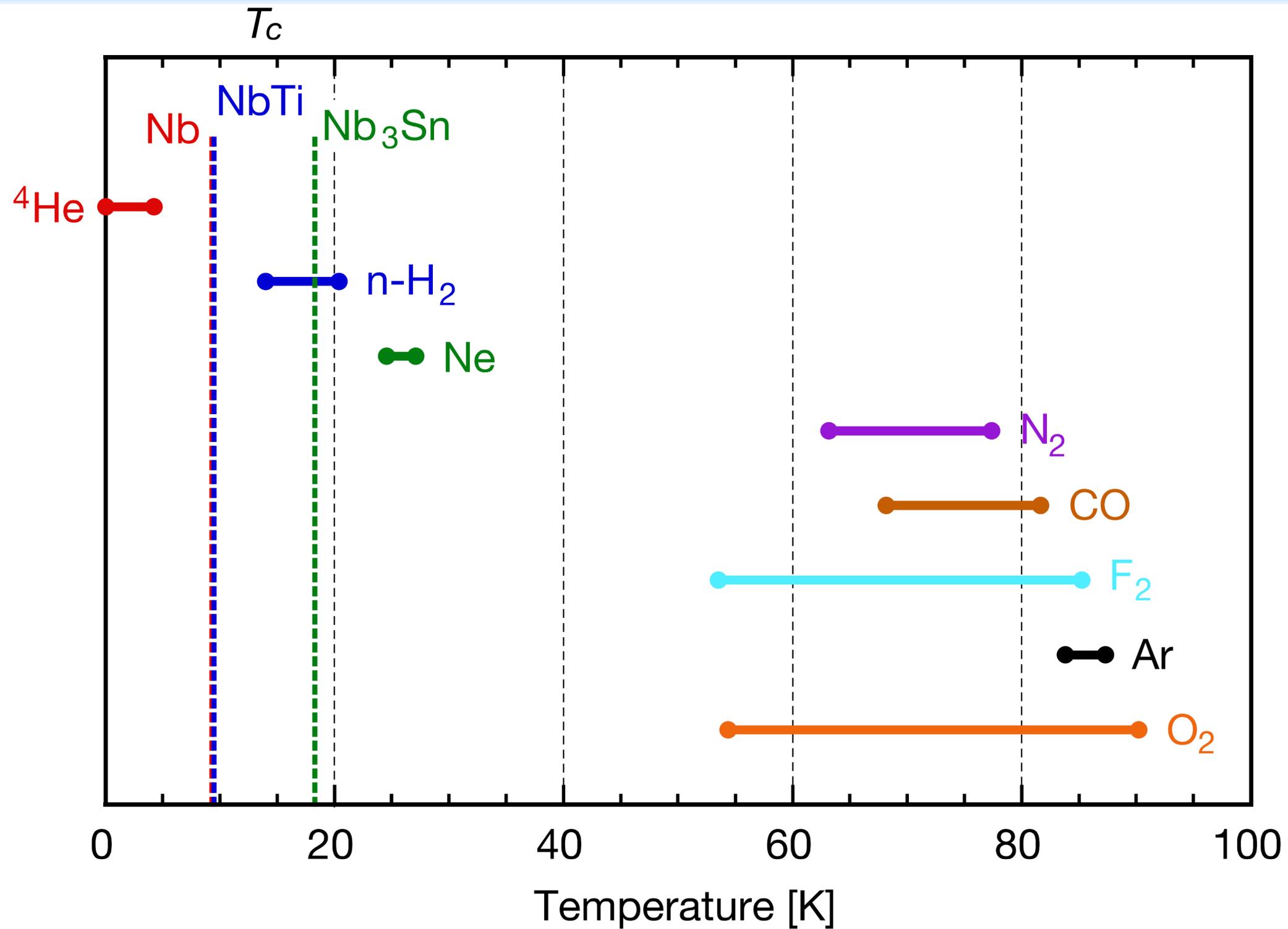
Liquid Phase Temperature Range

Substance	Triple Point [K]	Boiling Point# [K]
^4He	2.1773*	4.224
p- H_2	13.813	20.278
n- H_2	13.96	20.39
Ne	24.55	27.092
N_2	63.148	77.347
CO	68.14	81.62
F_2	53.48	85.24
Ar	83.78	87.290
O_2	54.361	90.185

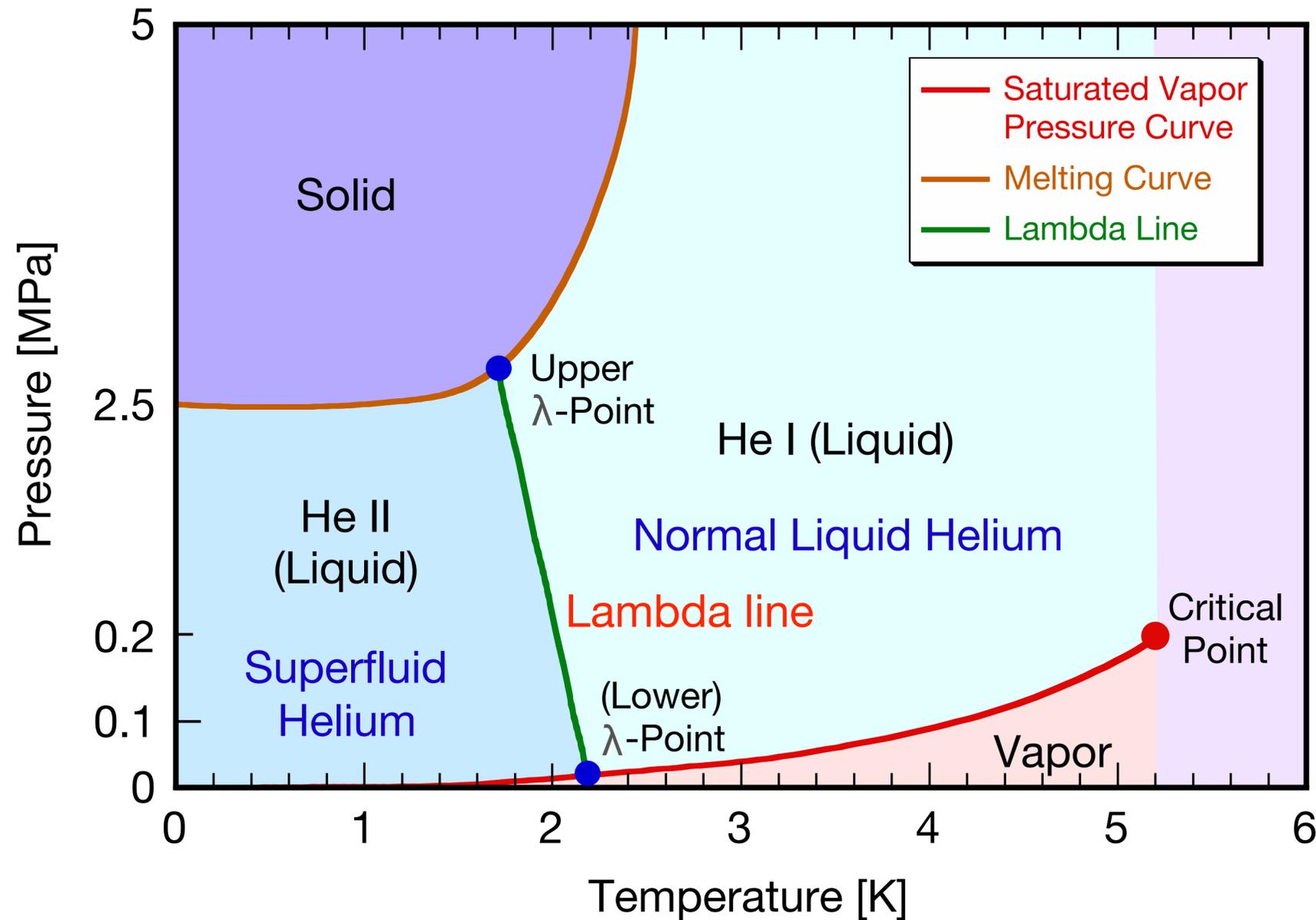
Under Atmospheric Pressure

* Lambda Point Temperature

Boiling and Triple Points, Transition Temperatures

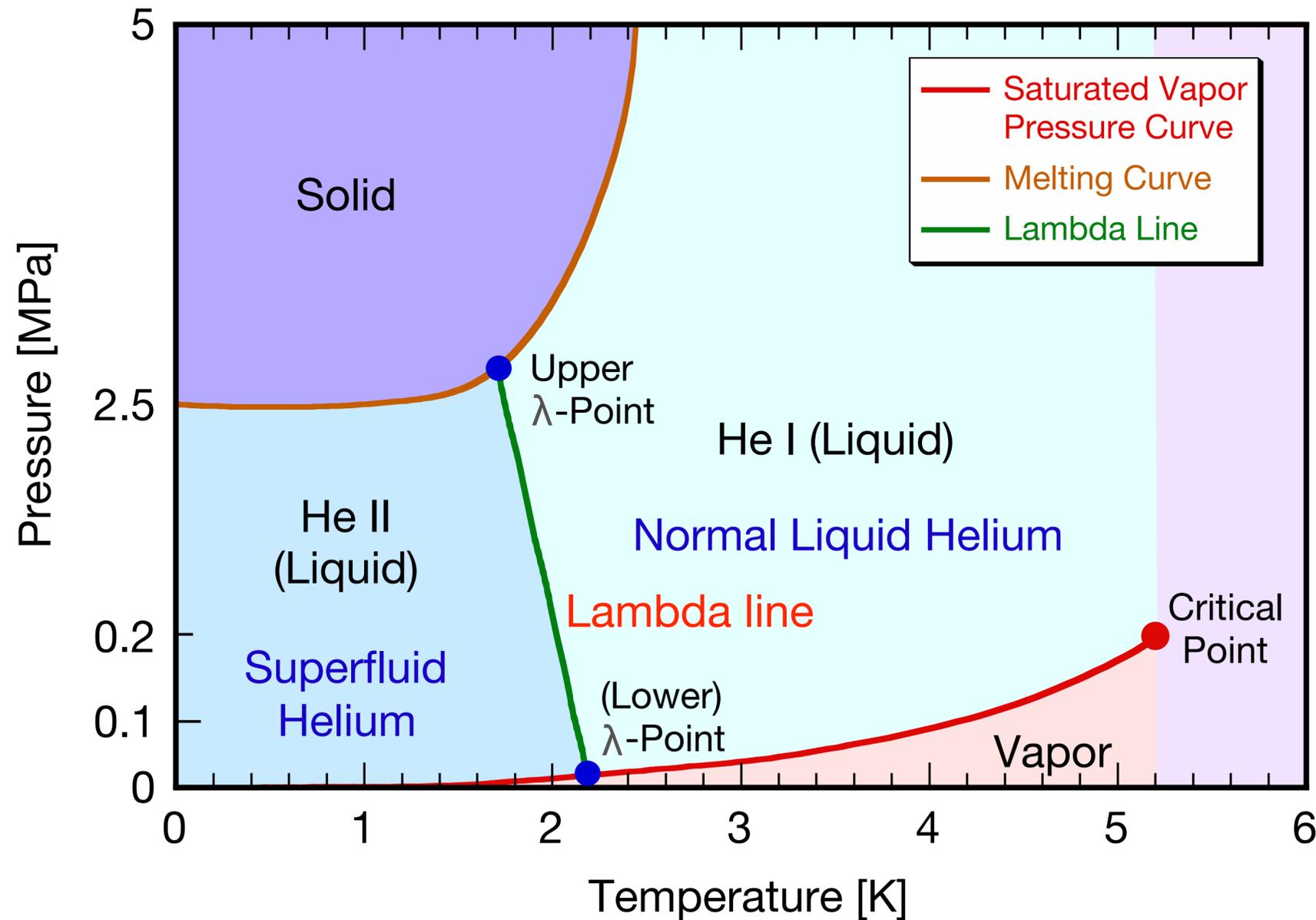


Phase (State) Diagram of Helium



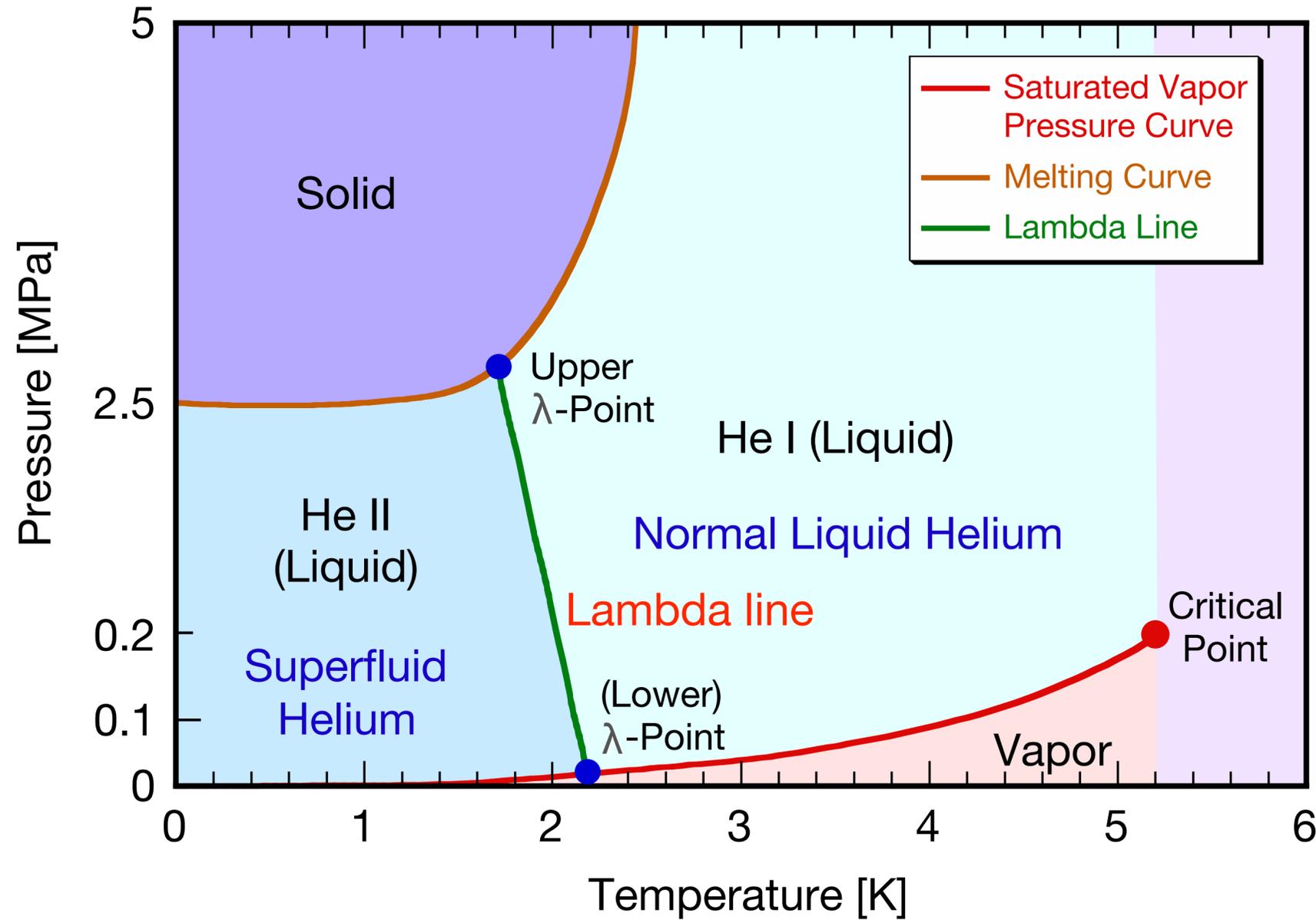
- ◆ Liquid phase remains even at 0 K
- ◆ Solid appears only under high pressure (**above 2.5 MPa**)
- ◆ Two different liquid phases
 - ◆ He I ('ordinary' liquid helium, normal fluid phase)
 - ◆ **He II (superfluid helium, superfluid phase)**
- ◆ Lambda line — border of these two liquid phases

Phase (State) Diagram of Helium (cont'd)



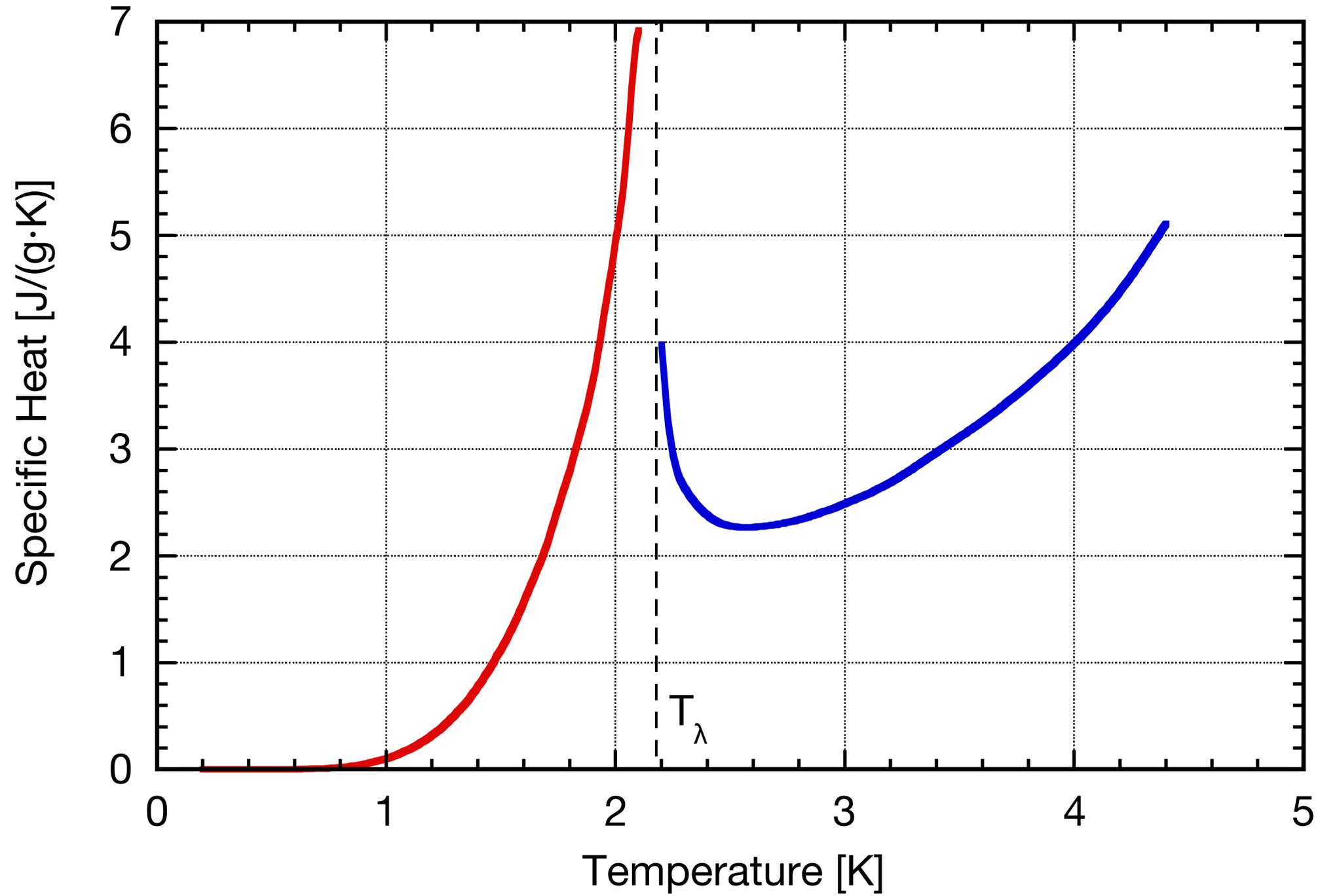
- ◆ No “triple point” in a **narrow sense** (coexistence of solid, liquid and vapor)
- ◆ Two “triple points” in a **broad sense** (three different phases)
 - ◆ Upper λ -point (two liquid phases and solid phase)
 - ◆ (Lower) **λ -point** (two liquid phases and vapor phase)

Phase (State) Diagram of Helium (cont'd)



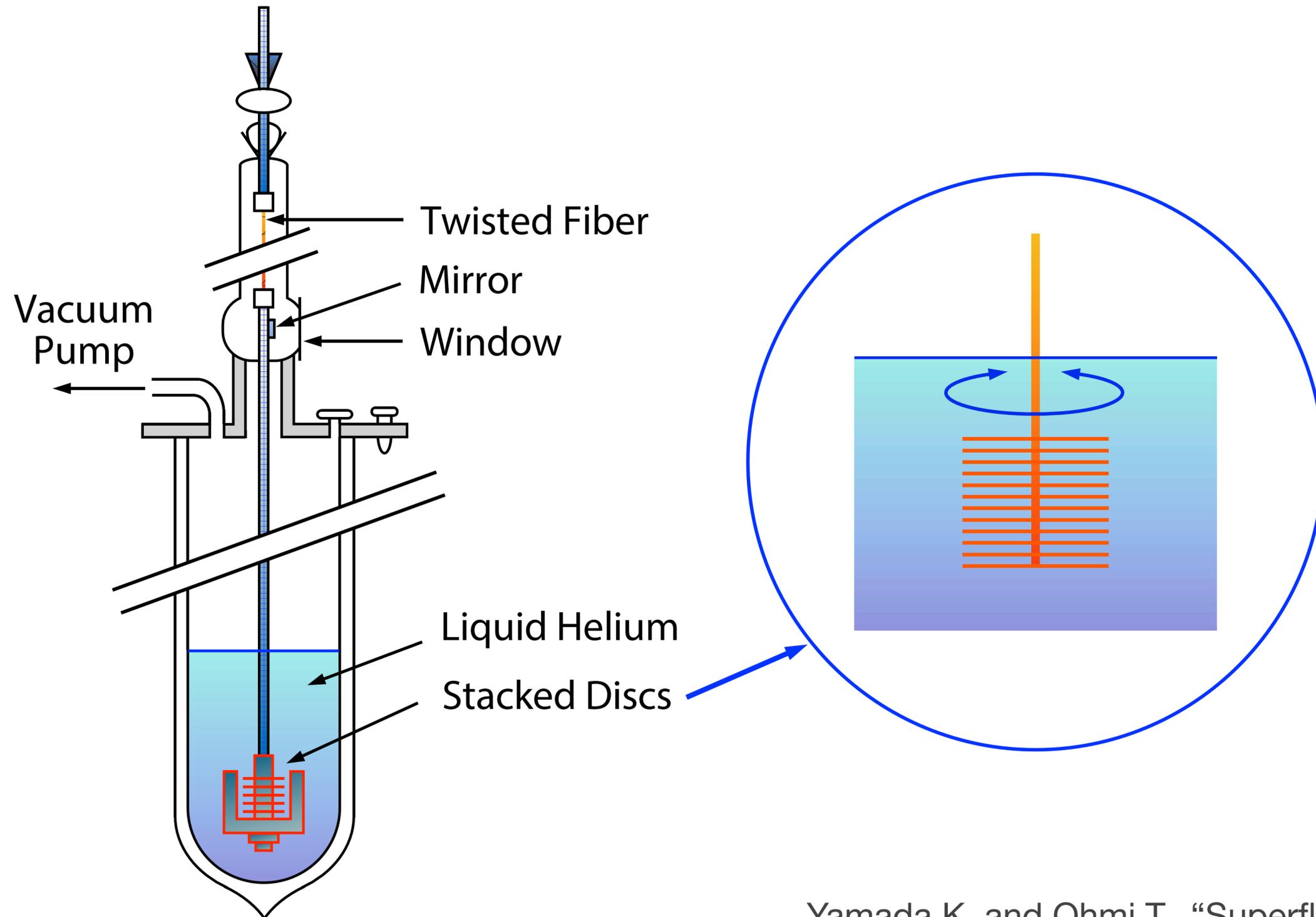
- ◆ Lambda point (λ -point)
 - ◆ Temperature : $T_{\lambda} = 2.1768$ K
 - ◆ Pressure : $P_{\lambda} = 5041.8$ Pa
 - ◆ Critical point
 - ◆ Temperature : $T_c = 5.1953$ K
 - ◆ Pressure : $P_c = 227.46$ kPa
 - ◆ Melting point at 0 K
 - ◆ Pressure : $P_{m0} = 2.5375$ MPa
- (Figures may vary among references)

Specific Heat of Liquid Helium



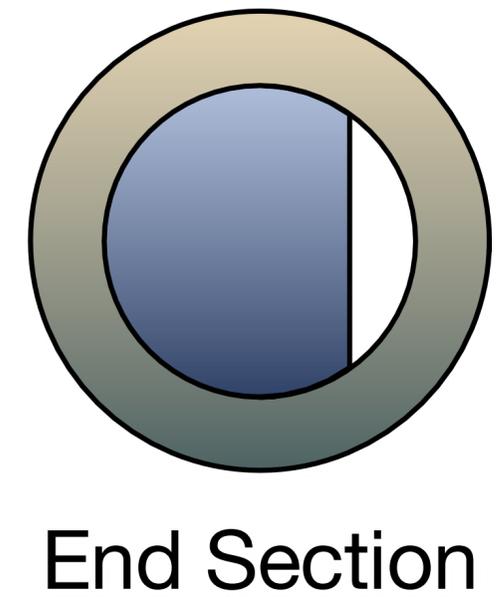
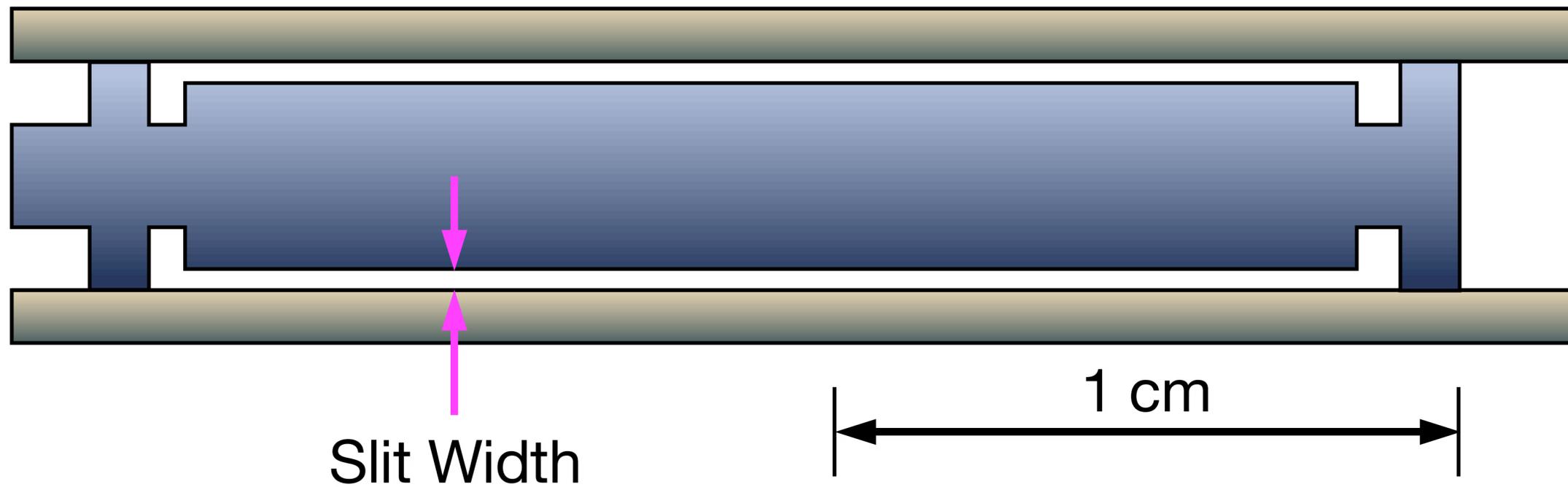
Schmidtchen, U., Private Communication (1984)

Rotational Viscometer



Yamada K. and Ohmi T., "Superfluidity", Baifukan (1995)

Flow Through Slit (1)



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

Radius of Flow Path

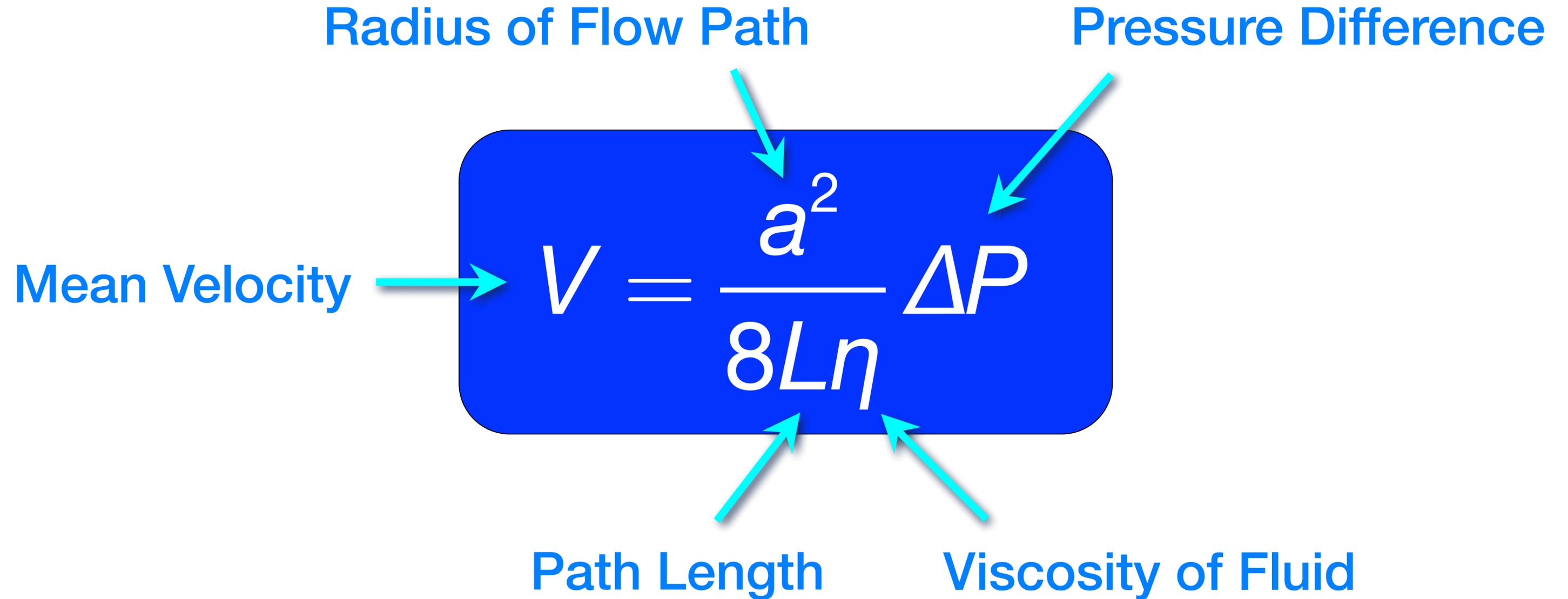
Pressure Difference

Mean Velocity

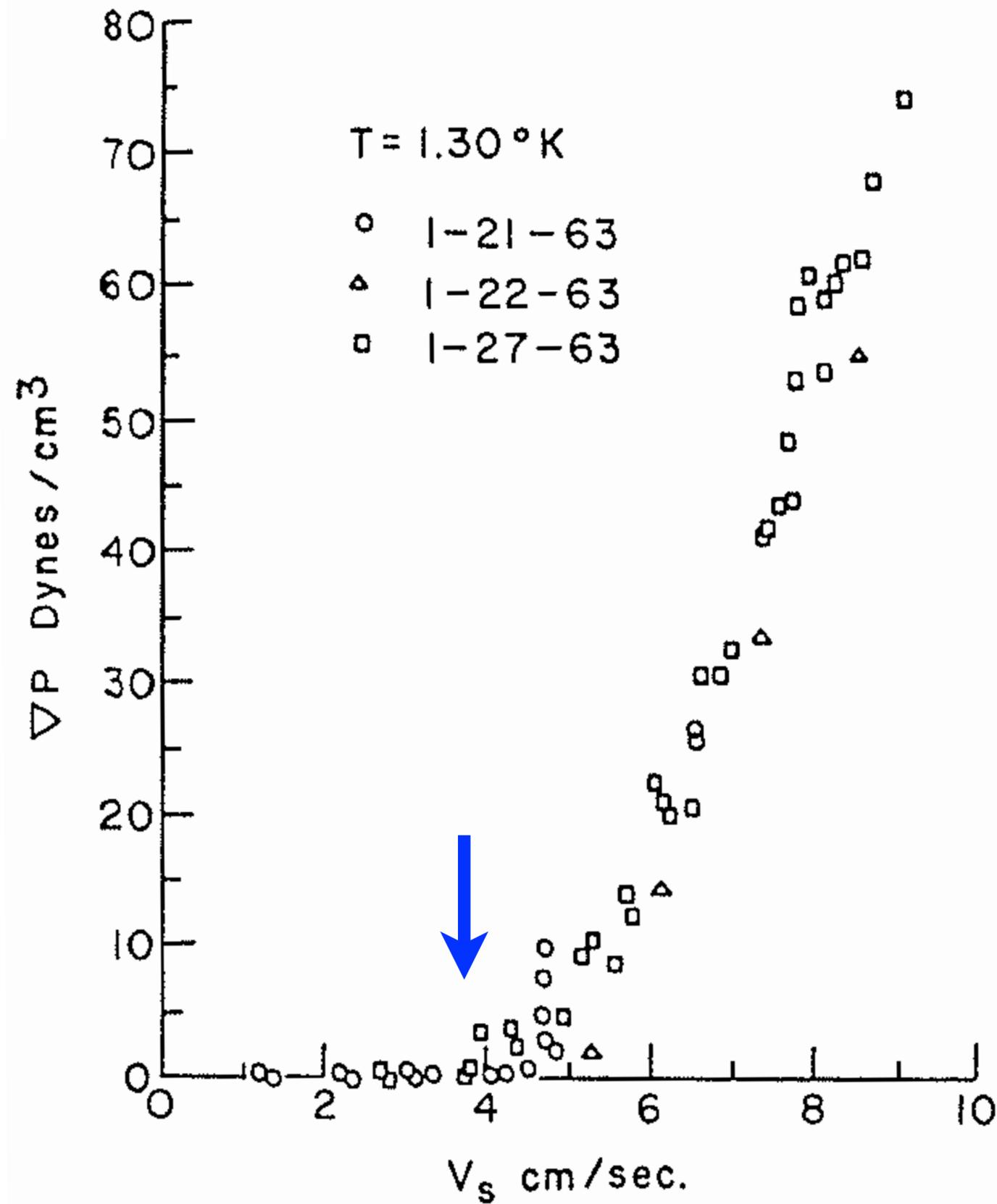
$$V = \frac{a^2}{8L\eta} \Delta P$$

Path Length

Viscosity of Fluid

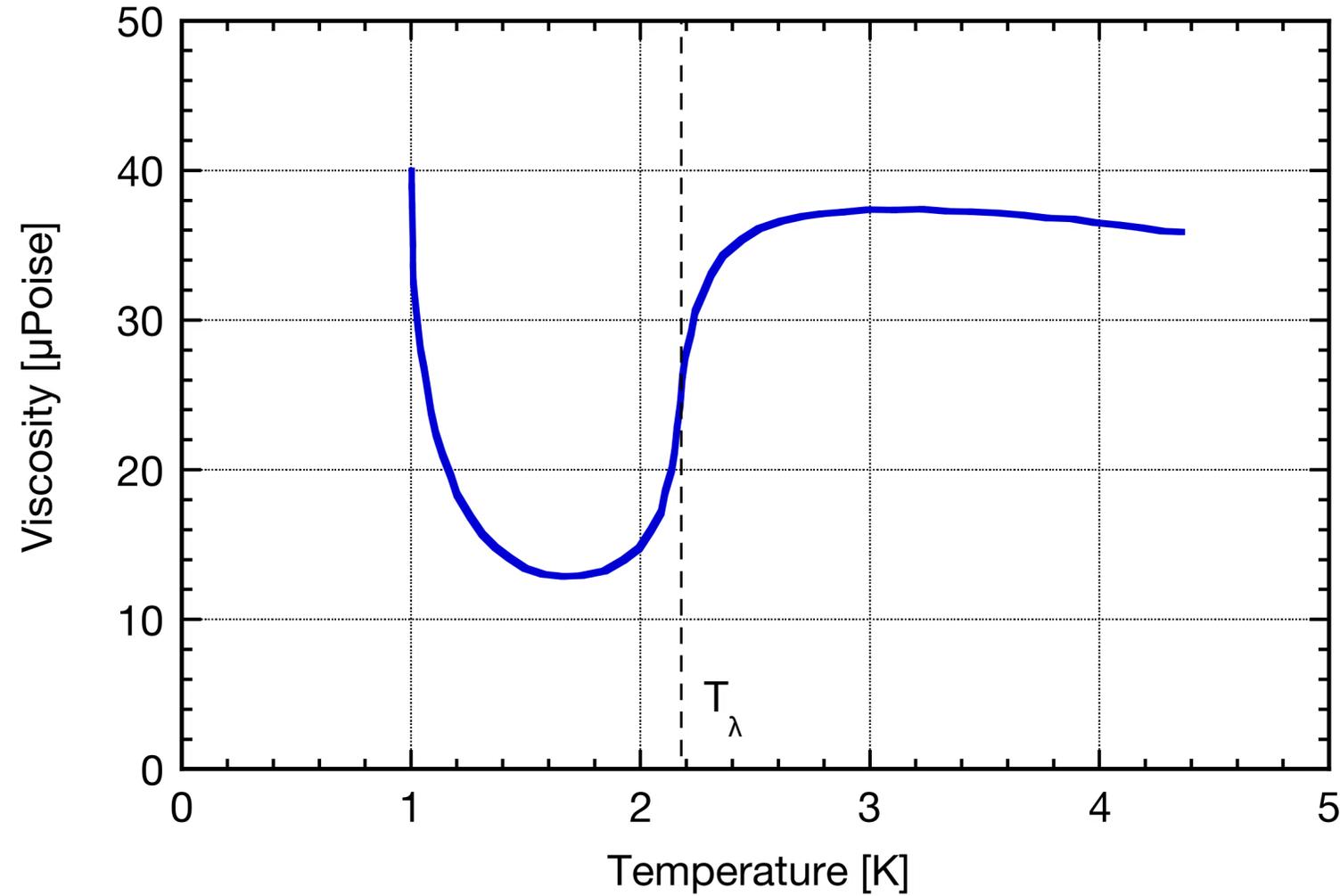
The diagram shows the Poiseuille flow equation $V = \frac{a^2}{8L\eta} \Delta P$ centered in a blue rounded rectangle. Four cyan arrows point from labels to variables in the equation: 'Radius of Flow Path' points to a^2 , 'Pressure Difference' points to ΔP , 'Path Length' points to L , and 'Viscosity of Fluid' points to η . A fifth cyan arrow points from 'Mean Velocity' to V .

Yamada K. and Ohmi T., "Superfluidity", Baifukan (1995)

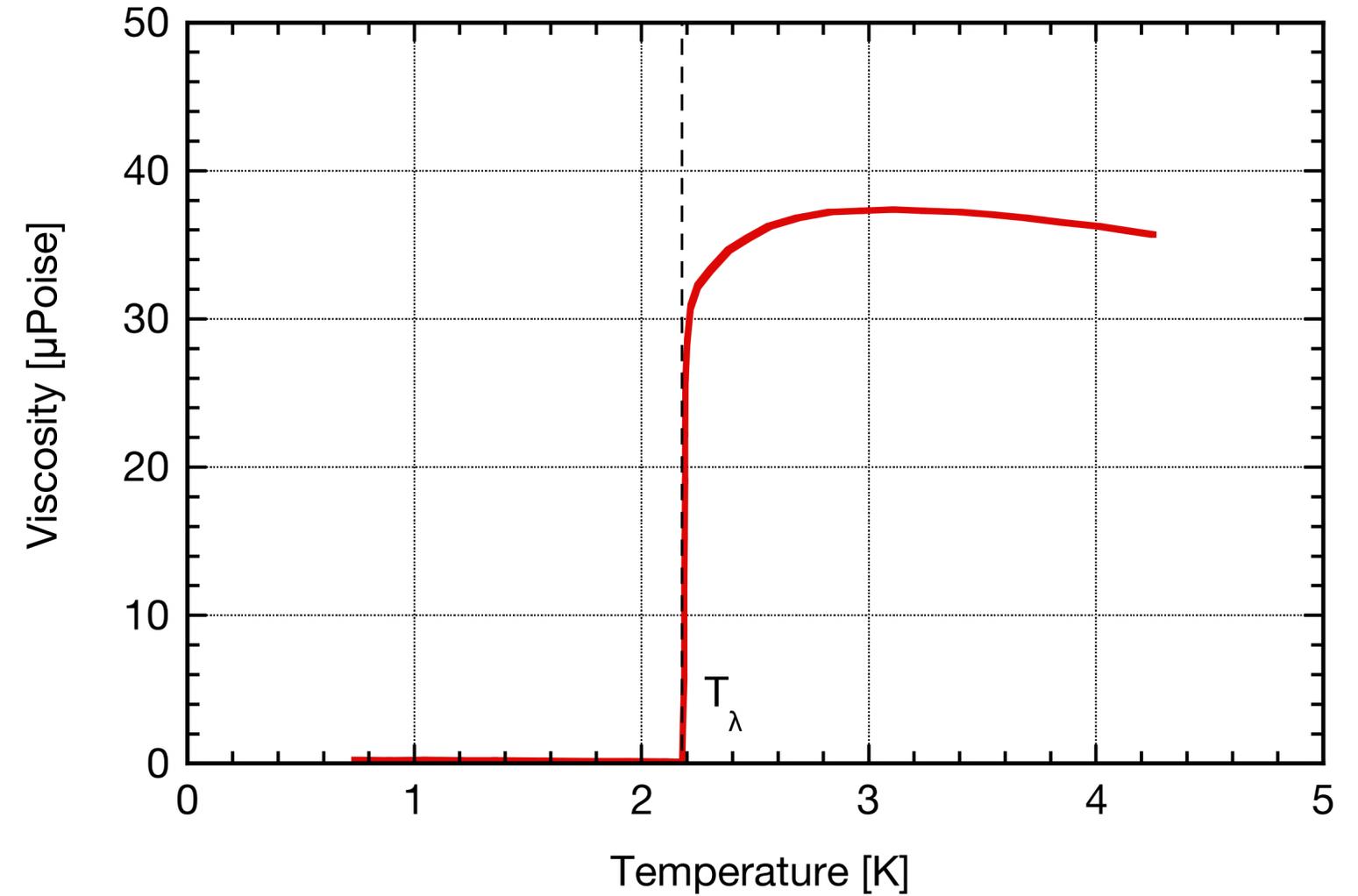


Donnelly, R. J., "Experimental Superfluidity", University of Chicago Press (1967)

Two Different Results of Viscosity Measurement



Rotational Viscometer

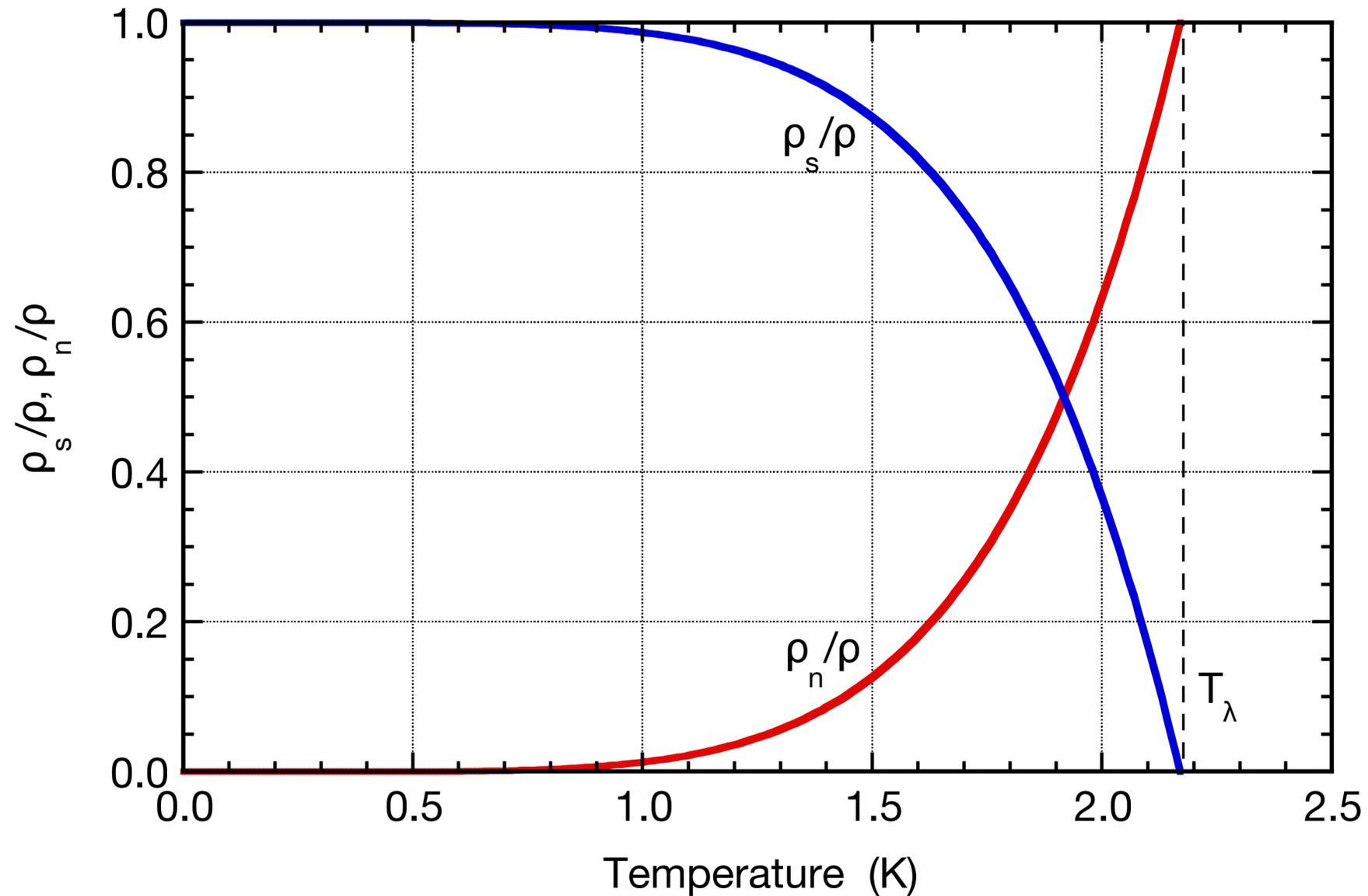


Poiseuille Flow in Capillary

Yamada K. and Ohmi T., "Superfluidity", Baifukan (1995)

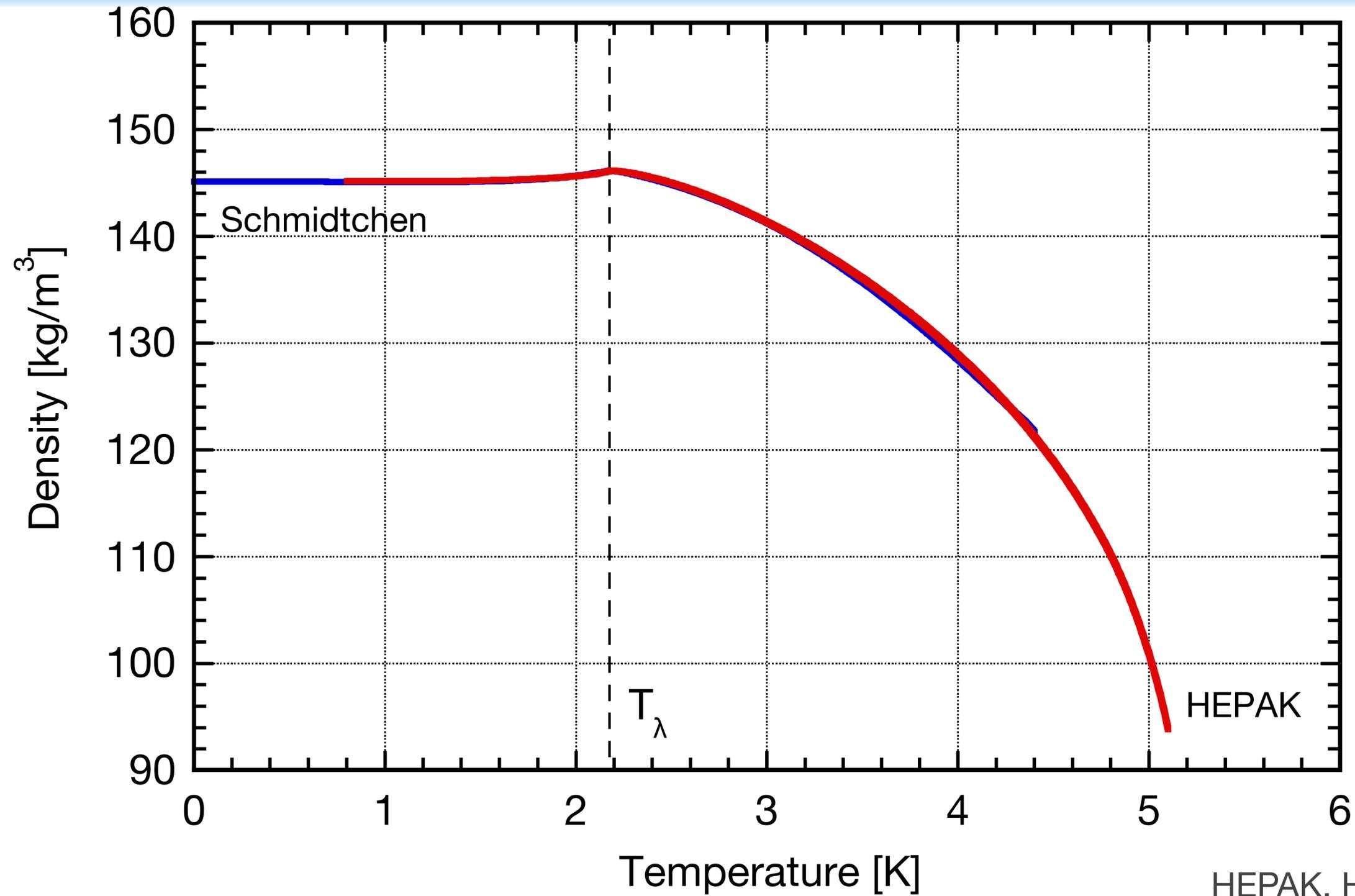
- ◆ A mixture of “superfluid component” and “normal fluid component”
 - ◆ Also referred as “superfluid” and “normal fluid”
- ◆ Superfluid component flows toward to higher temperature region
- ◆ Normal fluid component flows in opposite direction of superfluid component (“thermal counterflow”) → No net flow
- ◆ Entropy (heat) transported only by normal fluid component
- ◆ Large apparent thermal conductivity (“internal convection”)

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



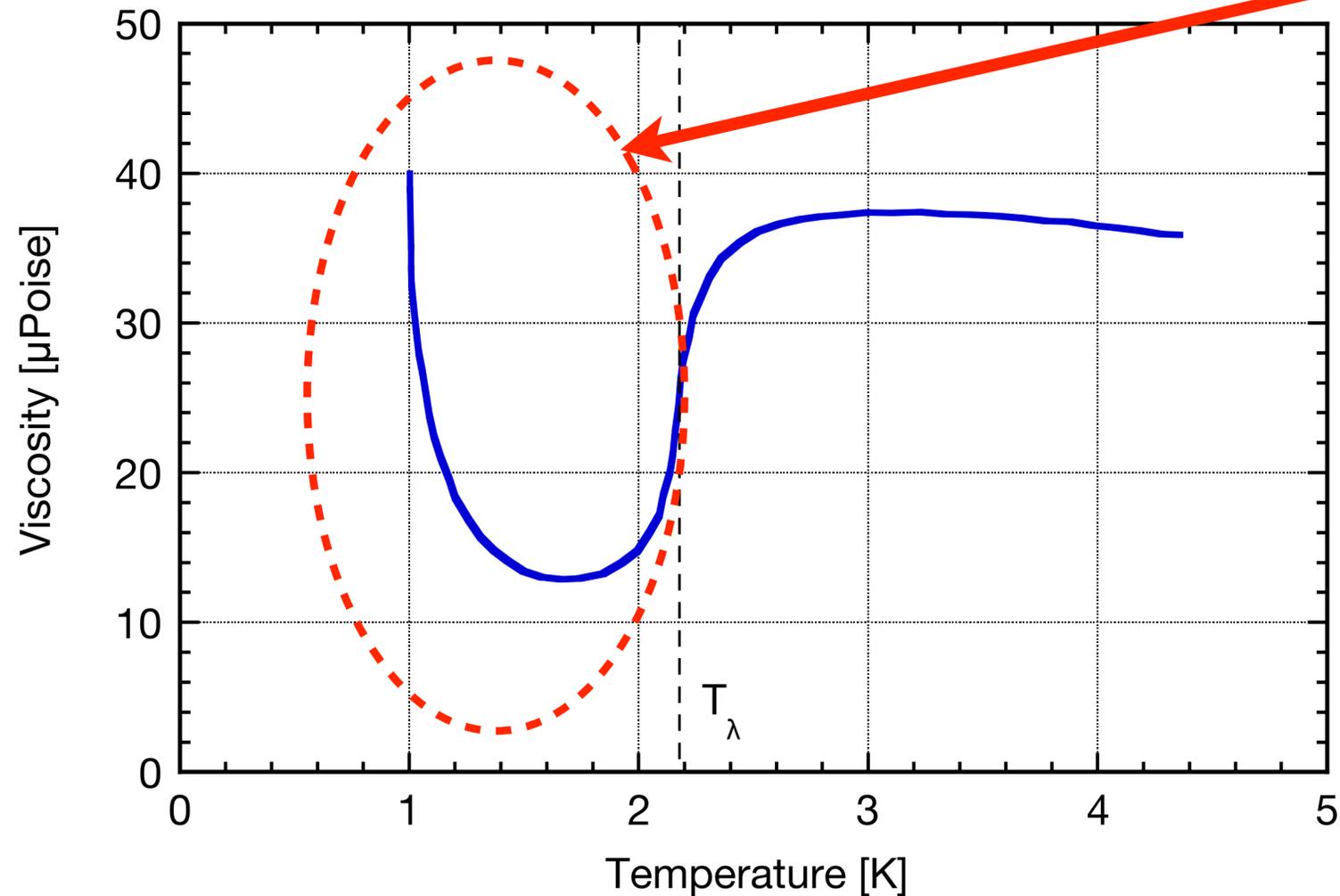
- ◆ Overall density is sum of densities of each components
- ◆ Density ratios (ρ_s/ρ , ρ_n/ρ) depend on temperature
- ◆ Each component makes independent flow field
- ◆ No interaction between each component flows

Density of Liquid Helium

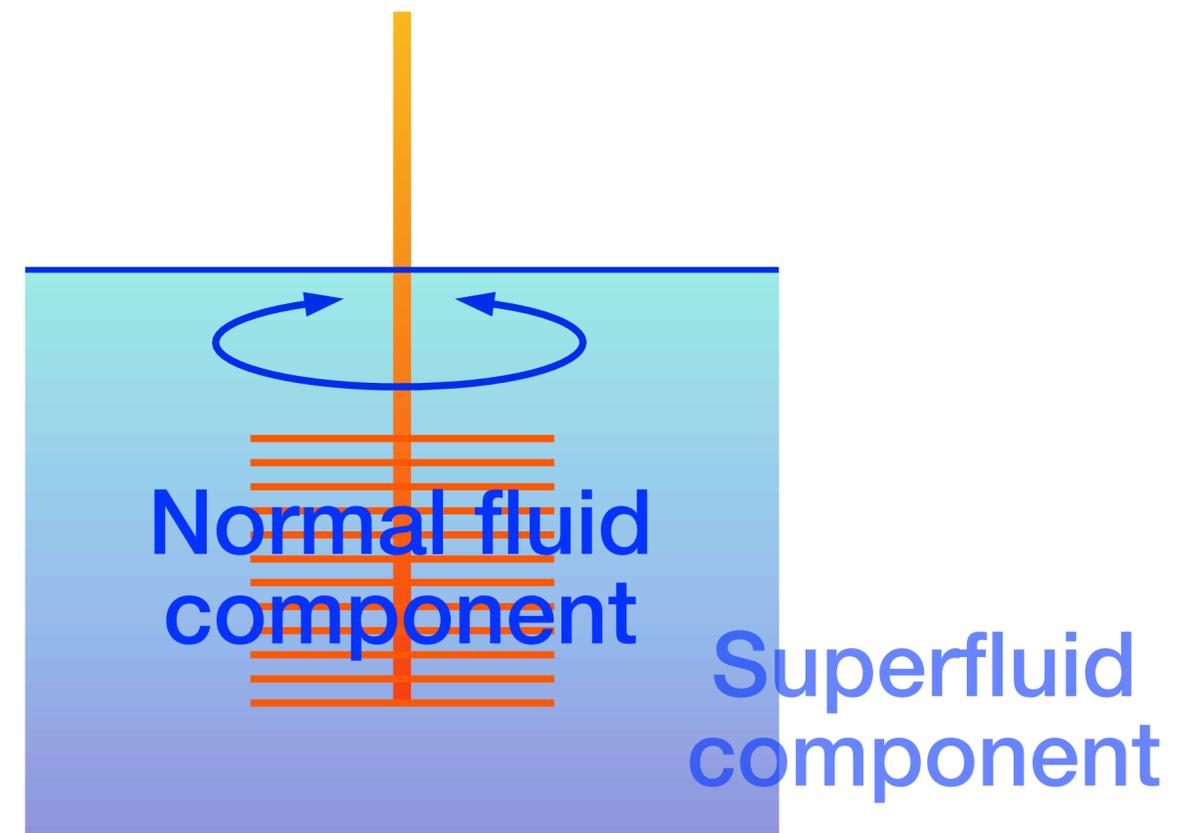


HEPAK, Horizon Technologies

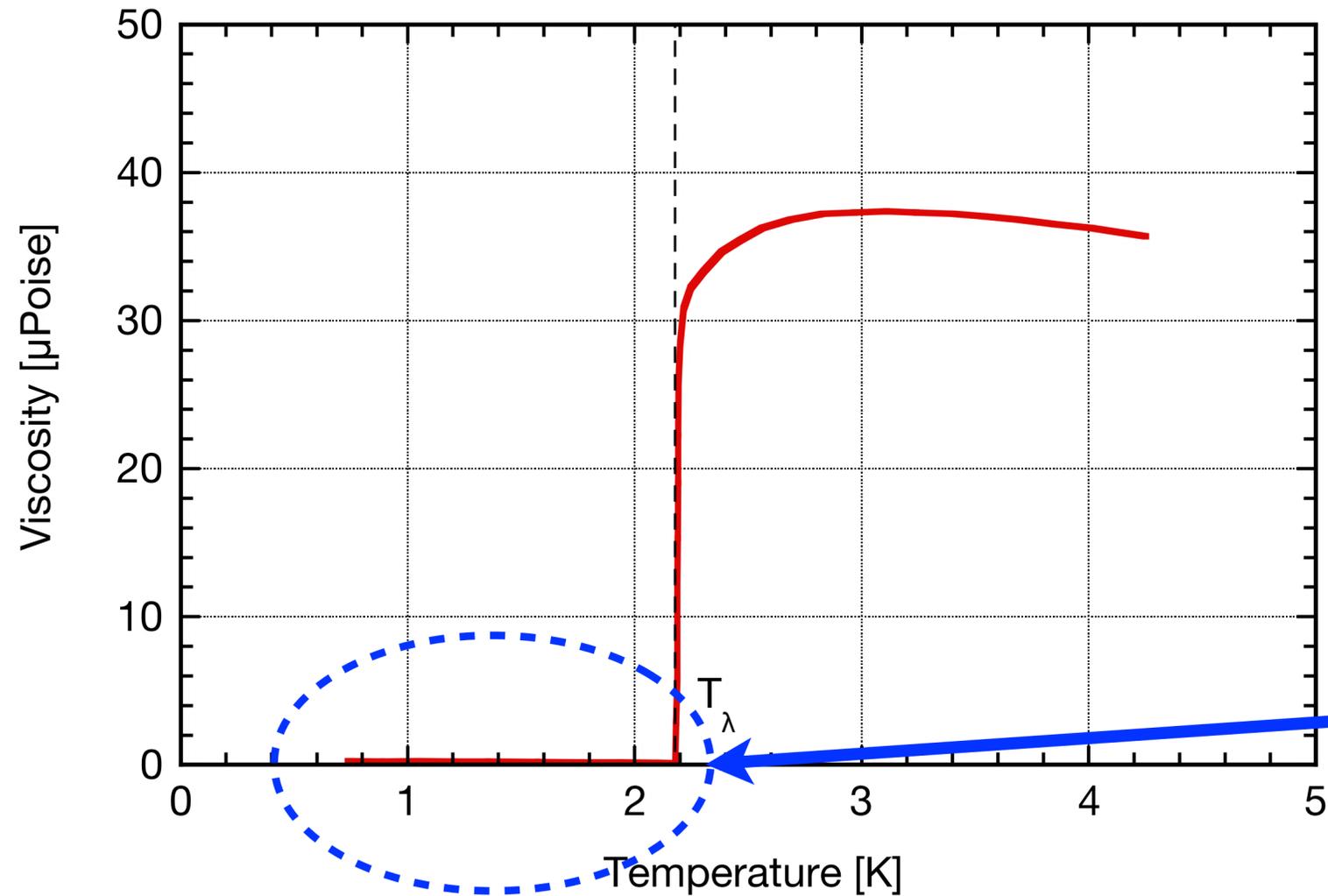
Schmidtchen, U., Private Communication (1984)



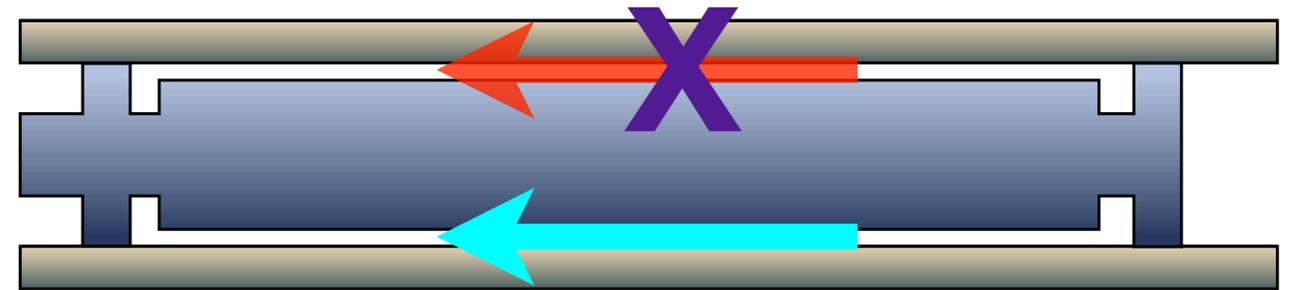
Normal fluid component motion with disks because of its viscosity



Superfluid component unrelated with disk motion



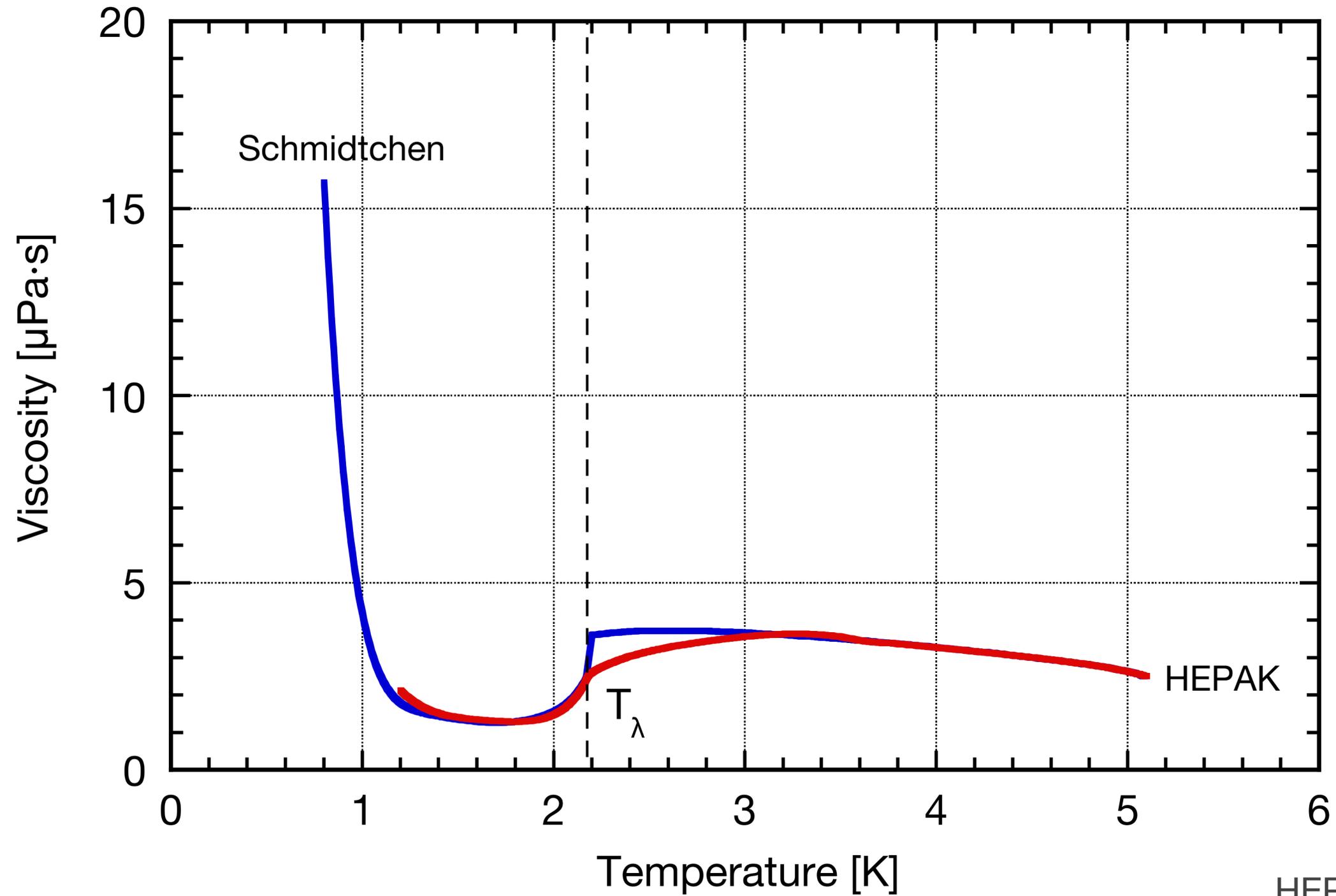
Stagnant normal fluid flow in the slit because of its viscosity



Superfluid flow through the slit without any pressure difference

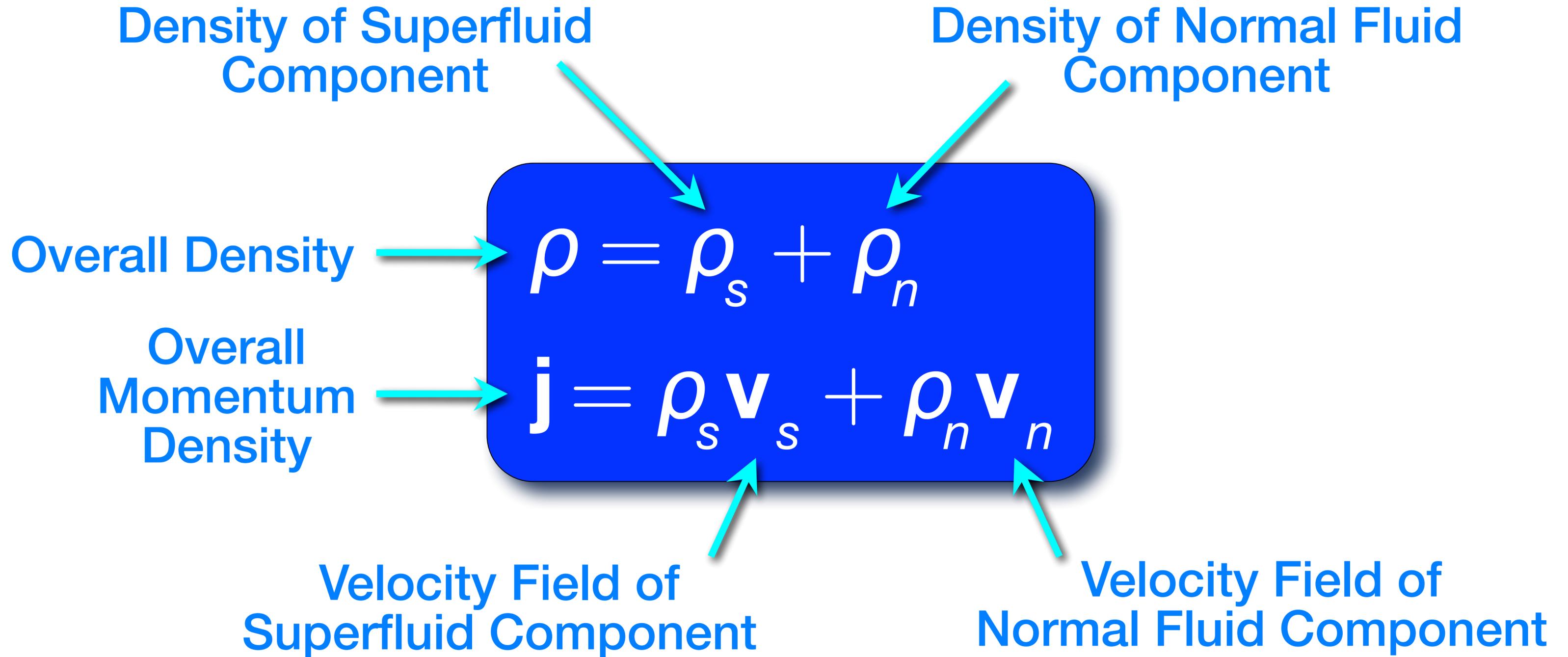
Donnelly, R. J., "Experimental Superfluidity", University of Chicago Press (1967)

Viscosity of Liquid Helium



HEPAK, Horizon Technologies

Schmidtchen, U., Private Communication (1984)



Yamada K. and Ohmi T., "Superfluidity", Baifukan (1995)

Total Fluid Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho_s \mathbf{v}_s + \rho_n \mathbf{v}_n) = 0$$

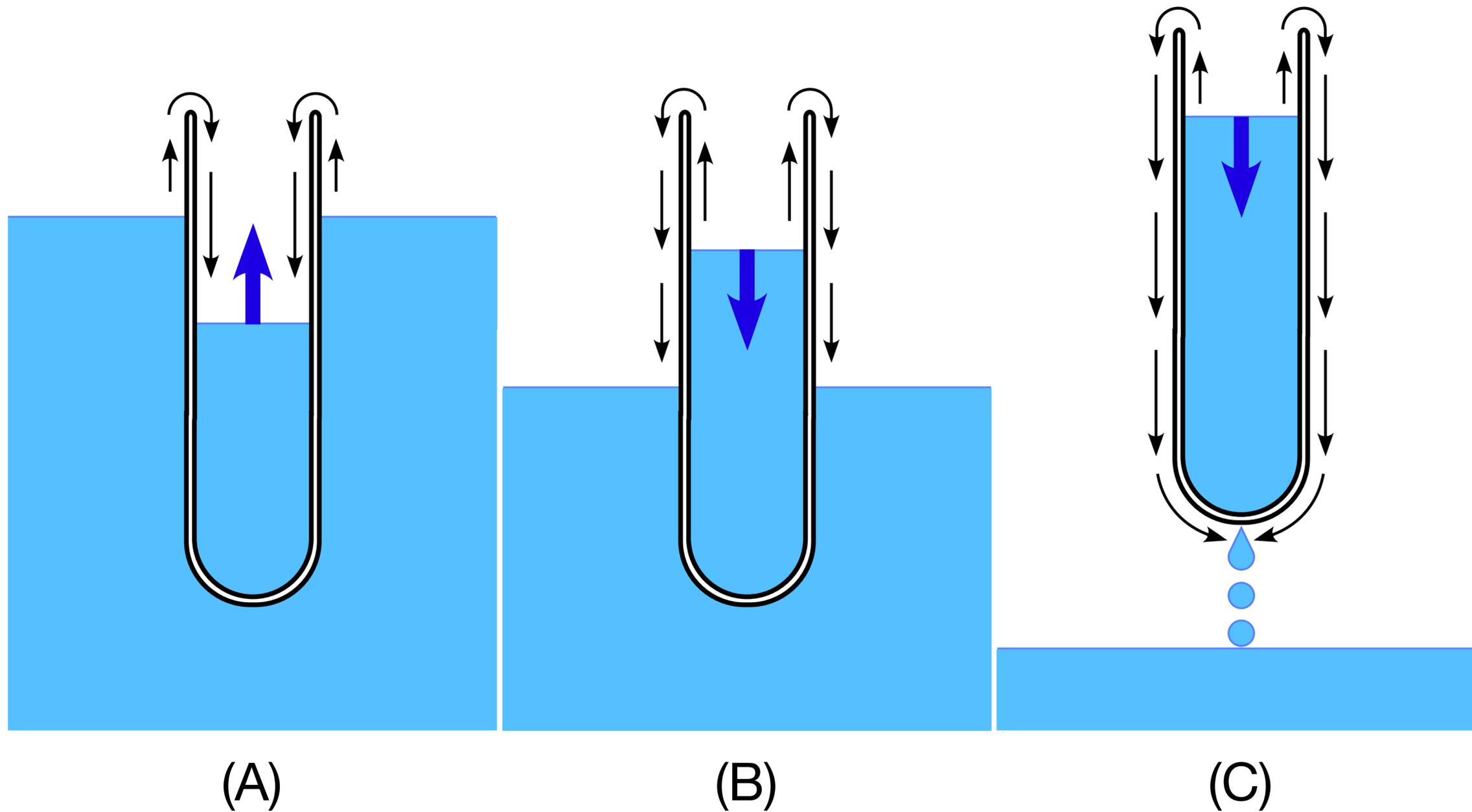
Total Fluid Momentum Equation

$$\frac{\partial (\rho_s \mathbf{v}_s)}{\partial t} + \frac{\partial (\rho_n \mathbf{v}_n)}{\partial t} + \nabla \cdot (\rho_s \mathbf{v}_s \mathbf{v}_s + \rho_n \mathbf{v}_n \mathbf{v}_n) = -\nabla P + \mu \nabla^2 \mathbf{v}_n$$

Momentum Equations for Each Component

$$\frac{\partial(\rho_s \mathbf{v}_s)}{\partial t} + \nabla(\rho_s \mathbf{v}_s \mathbf{v}_s) = -\frac{\rho_s}{\rho} \nabla P + \rho_s s \nabla T$$

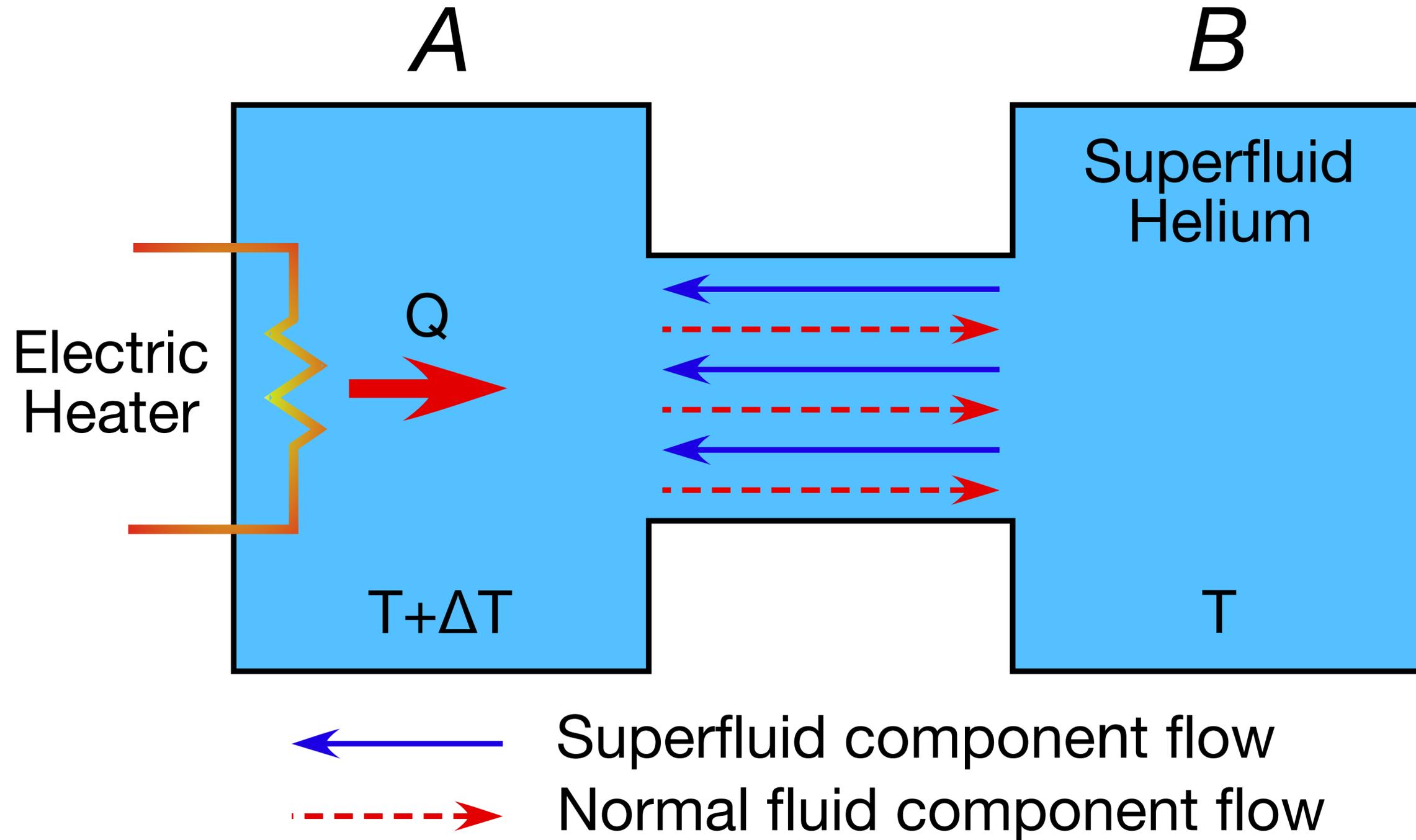
$$\frac{\partial(\rho_n \mathbf{v}_n)}{\partial t} + \nabla(\rho_n \mathbf{v}_n \mathbf{v}_n) = -\frac{\rho_n}{\rho} \nabla P - \rho_s s \nabla T + \mu \nabla^2 \mathbf{v}_n$$



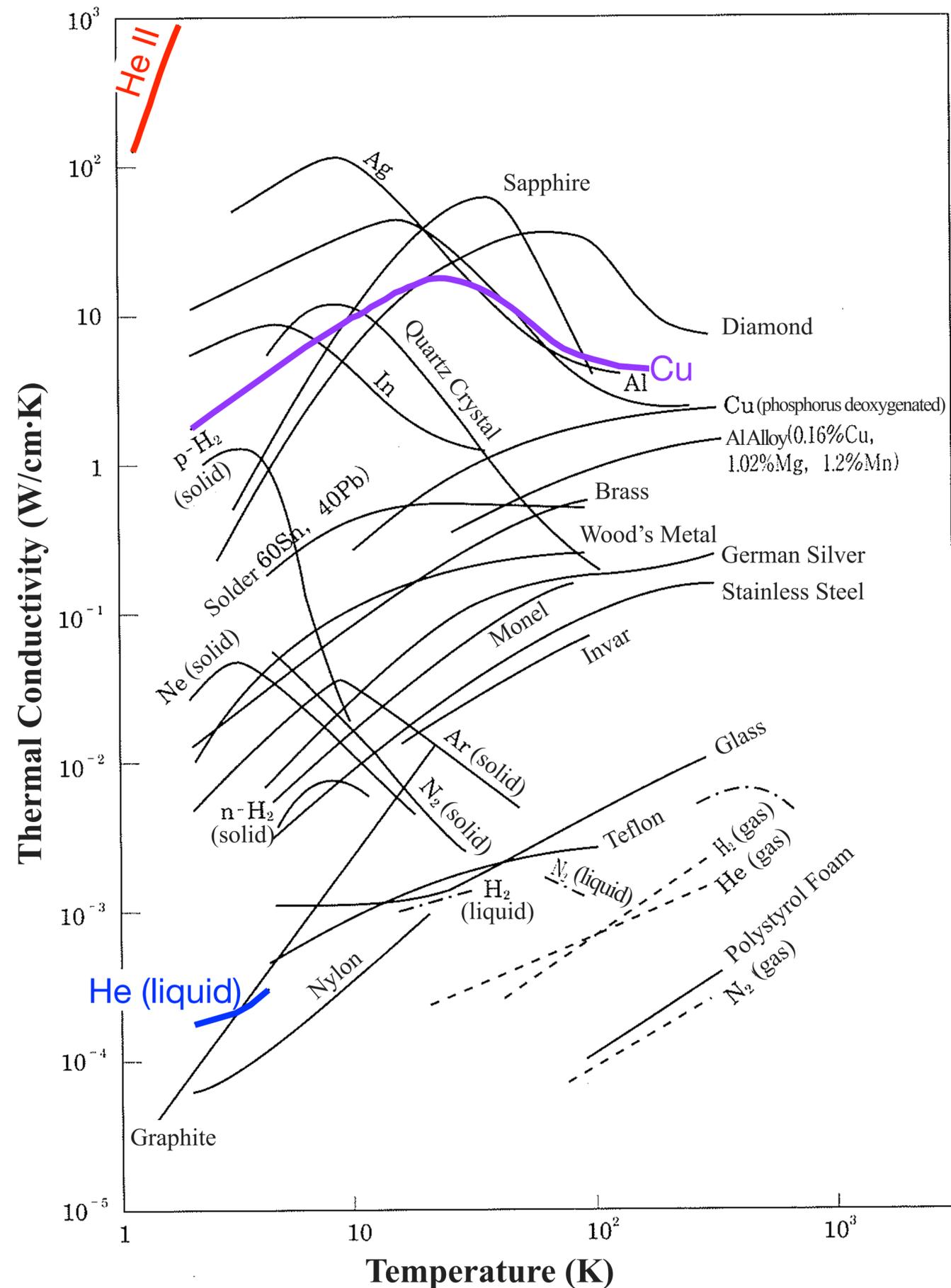
- ◆ Flow through an adsorbed film
- ◆ Thickness : a few atoms (20–30 nm)

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

Heat Transfer of Superfluid Helium

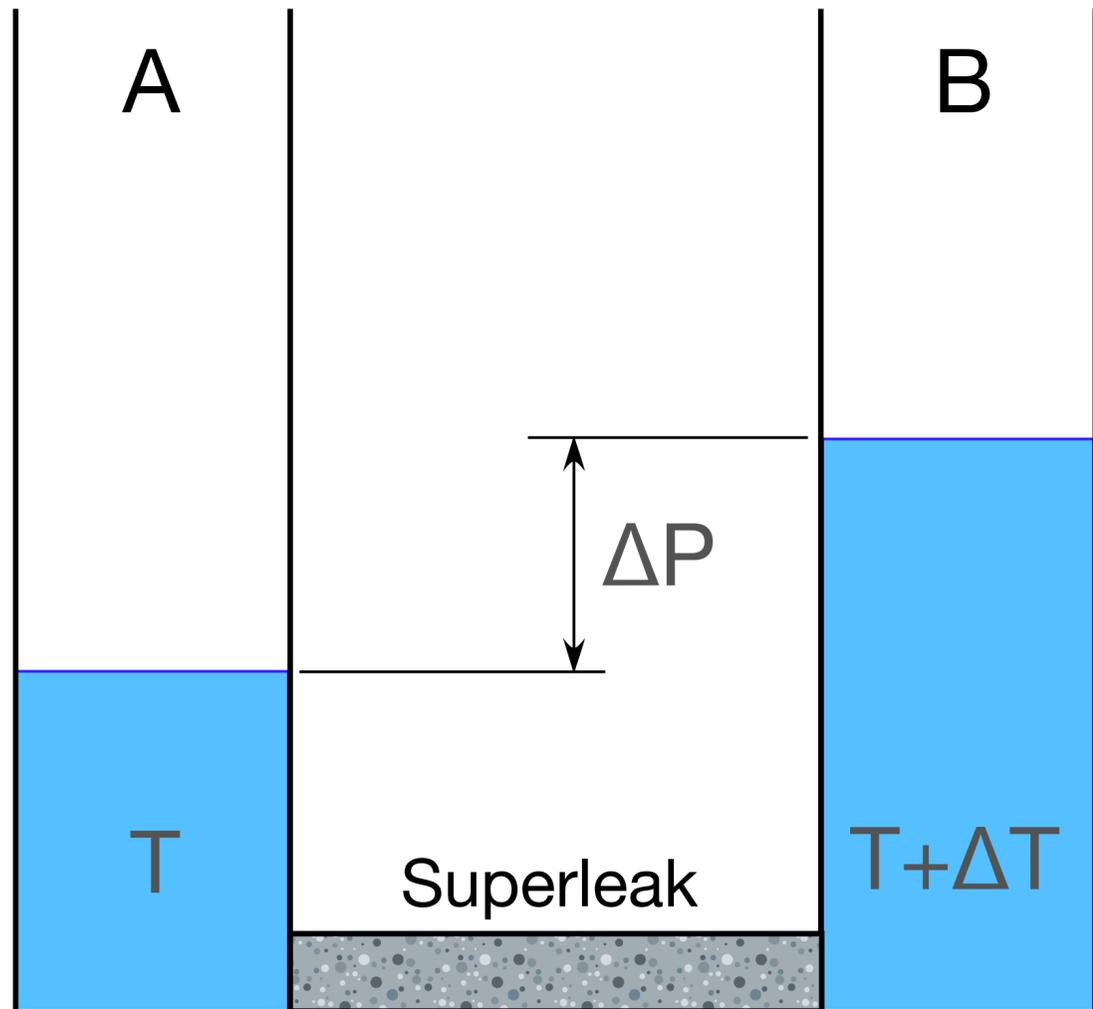


Donnelly, R. J., "Experimental Superfluidity", University of Chicago Press (1967)



- ◆ Apparent thermal conductivity (Super thermal conductivity)
- ◆ Larger than 100 times of that of pure copper
- ◆ Different mechanism of other substances and materials

Verein Deutscher Ingenieure,
“Lehrgangshandbuch Kryotechnik” (1977)



Density

Entropy

Pressure Difference

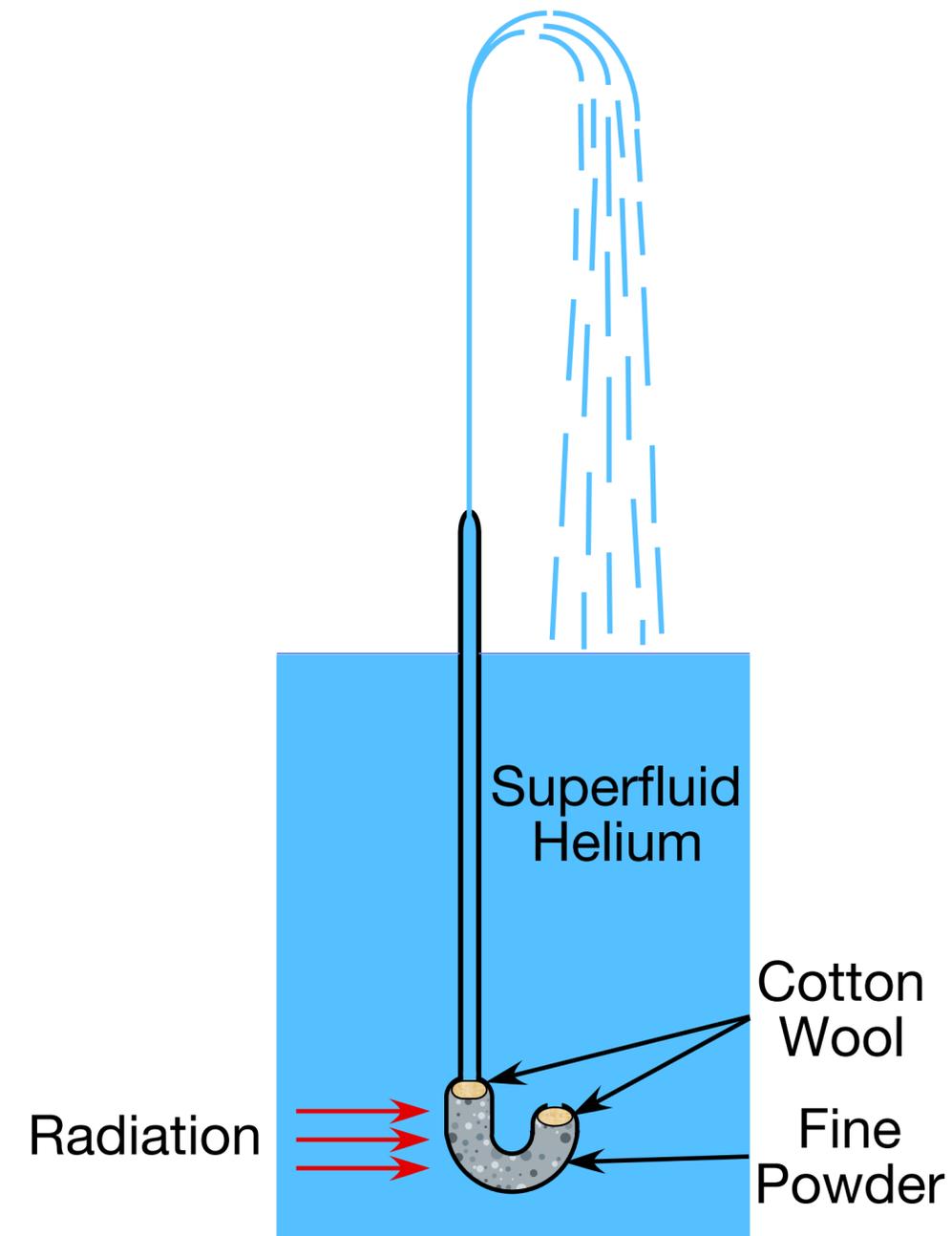
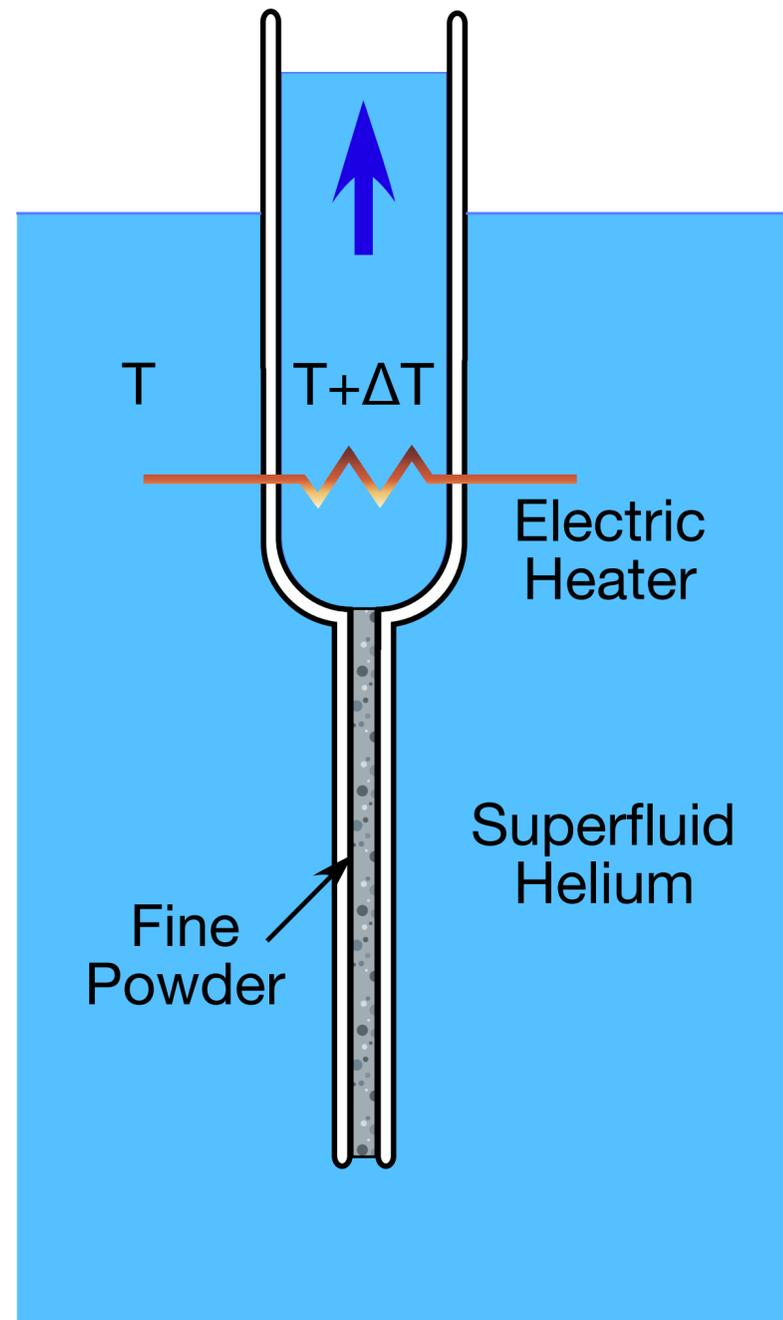
$$\Delta P = \rho s \Delta T$$

Temperature Difference

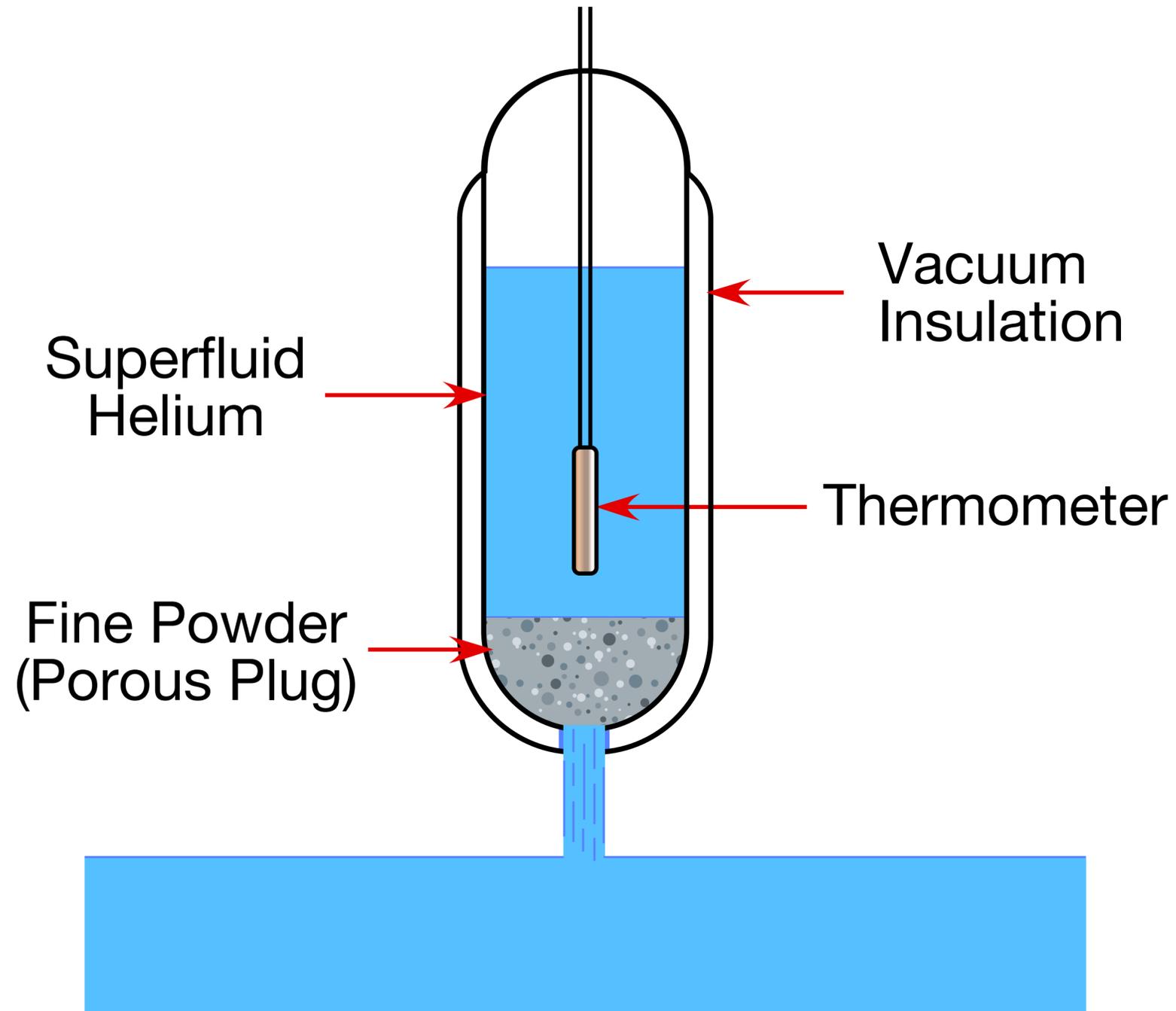
London's Relation (Fountain Effect)

Yamada K. and Ohmi T., "Superfluidity", Baifukan (1995)

Thermomechanical Effect (2)



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

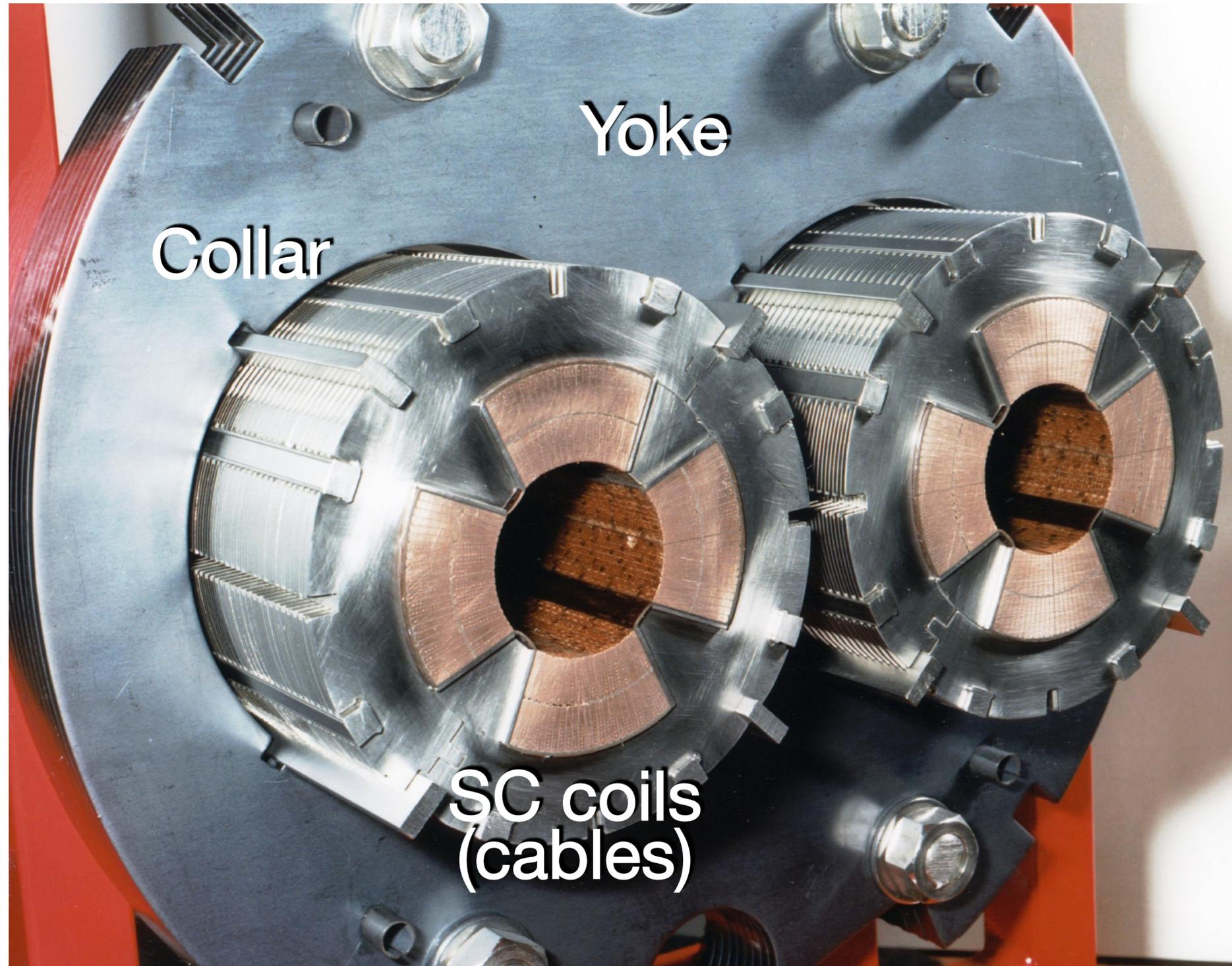


Entropy Filter

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

- ◆ High (apparent) thermal conductivity
 - ◆ No boiling → no gas on superconducting devices
- ◆ Superfluidity
 - ◆ Filling narrow gaps in superconducting magnet structure, cable strands, etc.
 - ◆ Good thermal contact with superconducting devices
 - ◆ Wet surface of superconducting devices

Superconducting Magnet



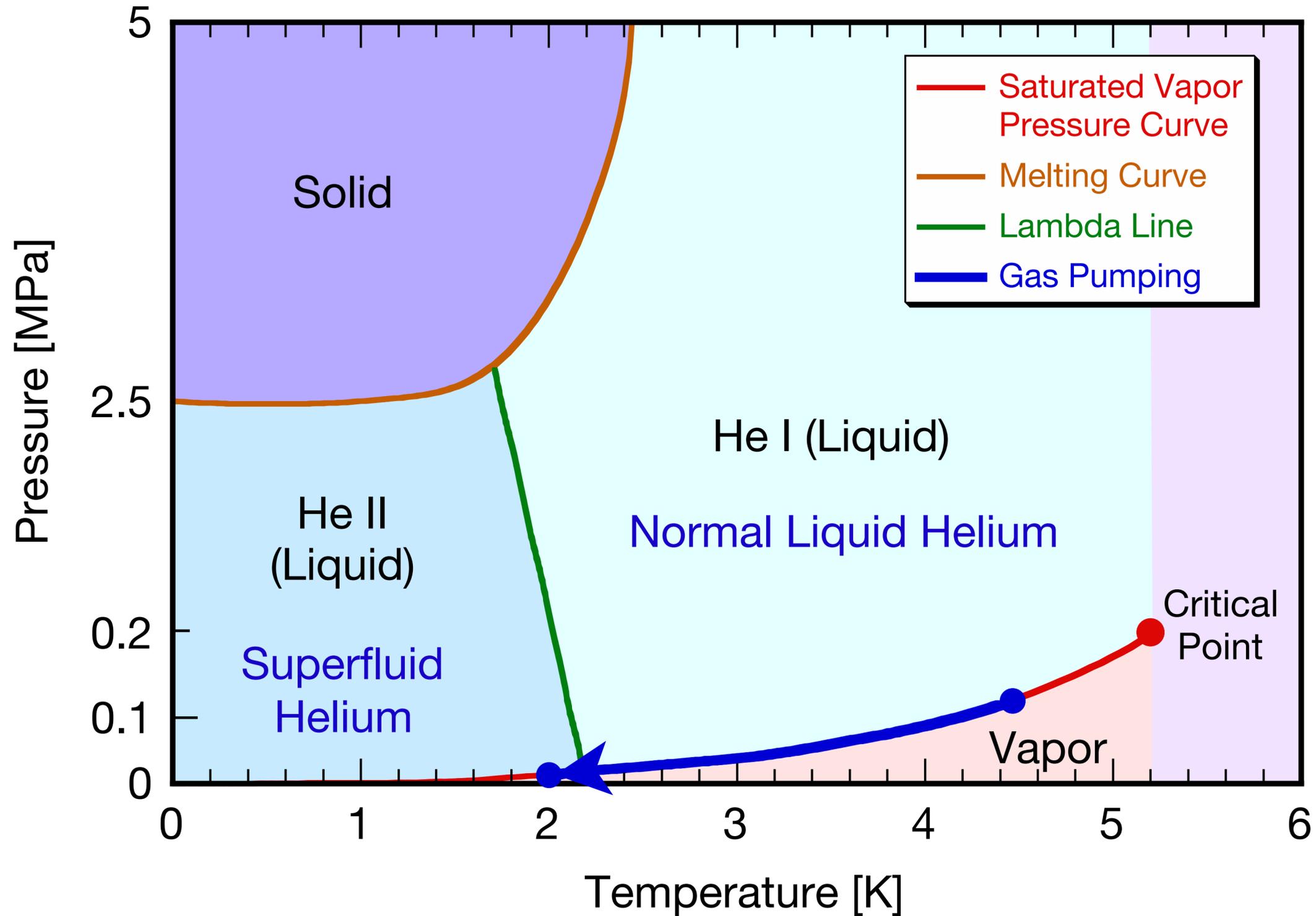
Superfluid Helium Cryogenic Systems

Classification of Cryogenic Refrigerators

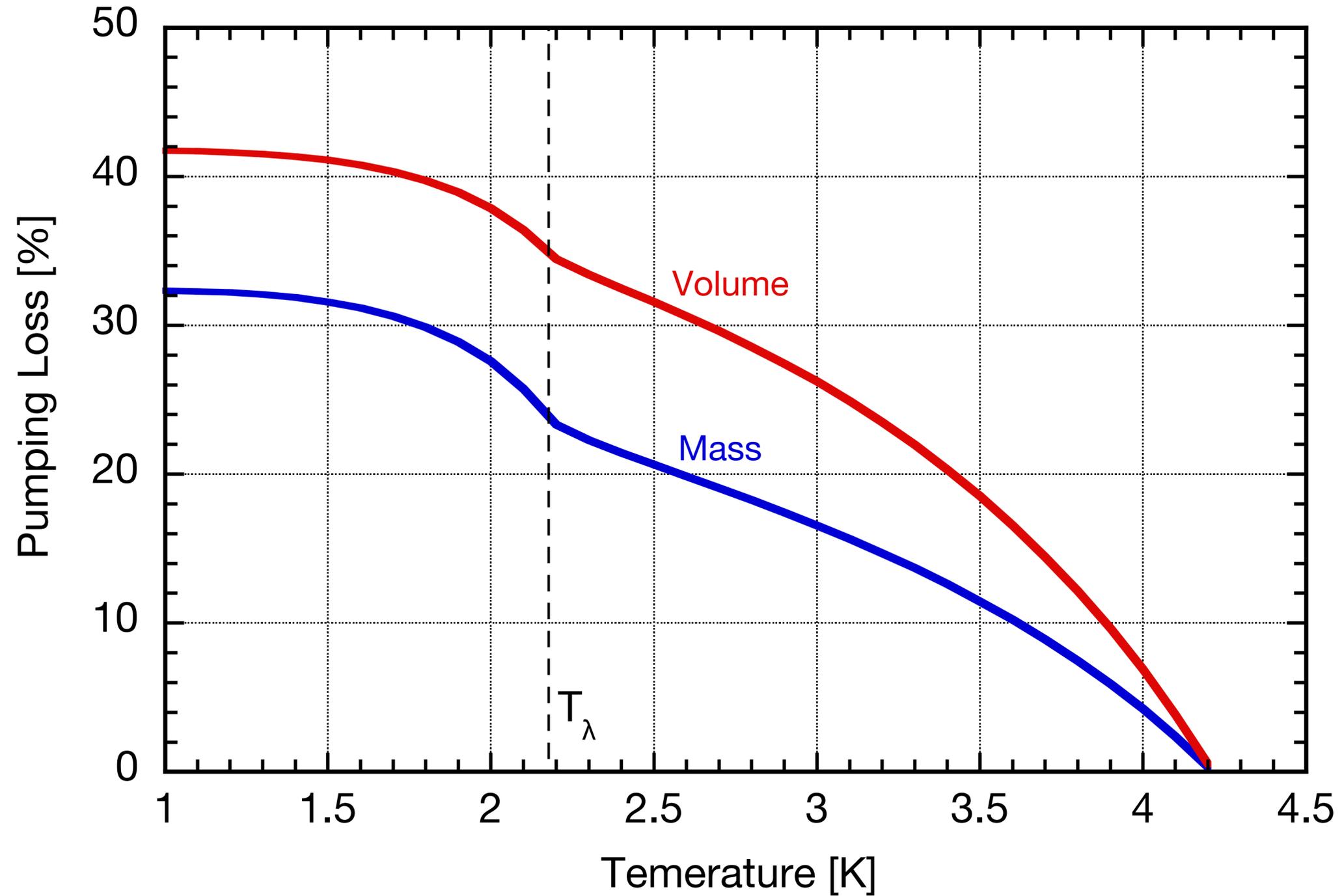
Scale	Heat Exchanger	Expansion	Refrigerator	Capacity
Small (Cryocooler)	Regenerative	Isothermal	Vuilleumier	0.1 - 1 W @ 4.2 K
			Stirling	
		Simon	Gifford-McMahon (GM)	
	Solvay			
	Pulse Tube			
	Medium - Large	Counterflow	Joule-Thomson (Isenthalpic)	Joule-Thomson (JT)
Isentropic			Claude	More than 10 W @ 4.2 K
		Brayton		

Ikushima, Y., "R&D on Ultra Low Vibration Cryocoolers", SOKENDAI Doctoral Thesis (2009)

Production of Superfluid Helium

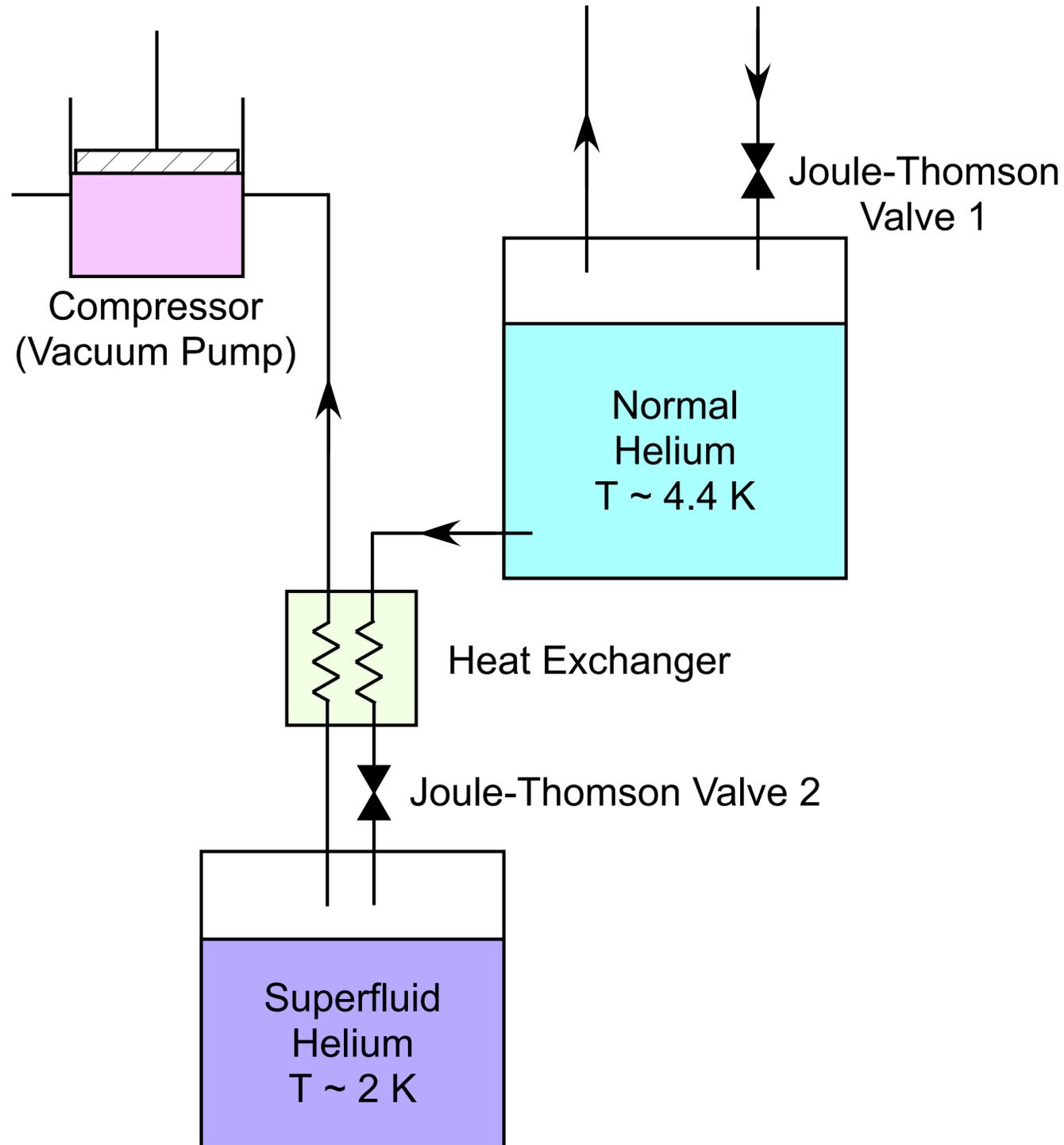


Liquid Helium Loss by Pressure Reduction



Schmidtchen, U., Private Communication (1984)

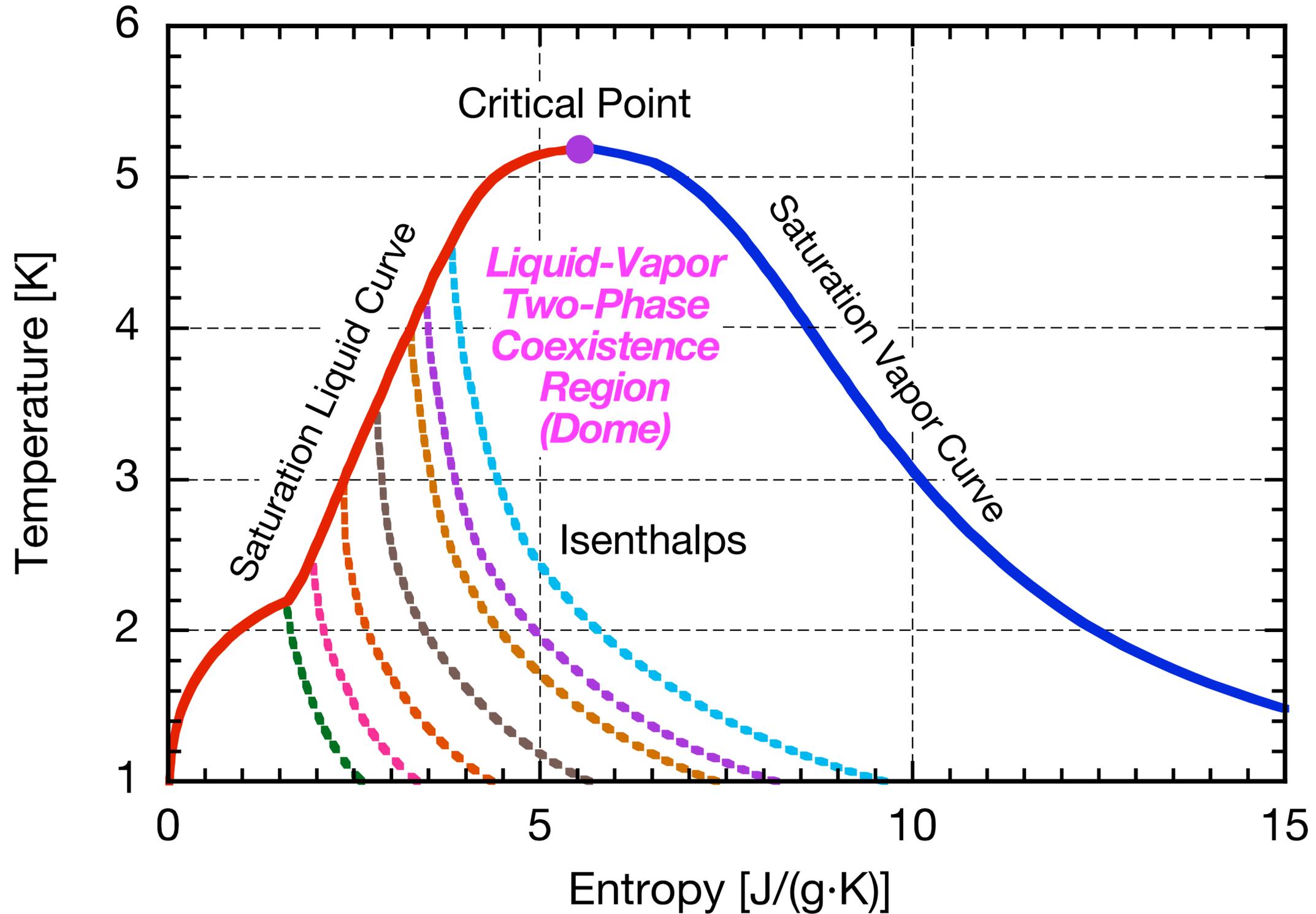
Continuous Production of Superfluid Helium



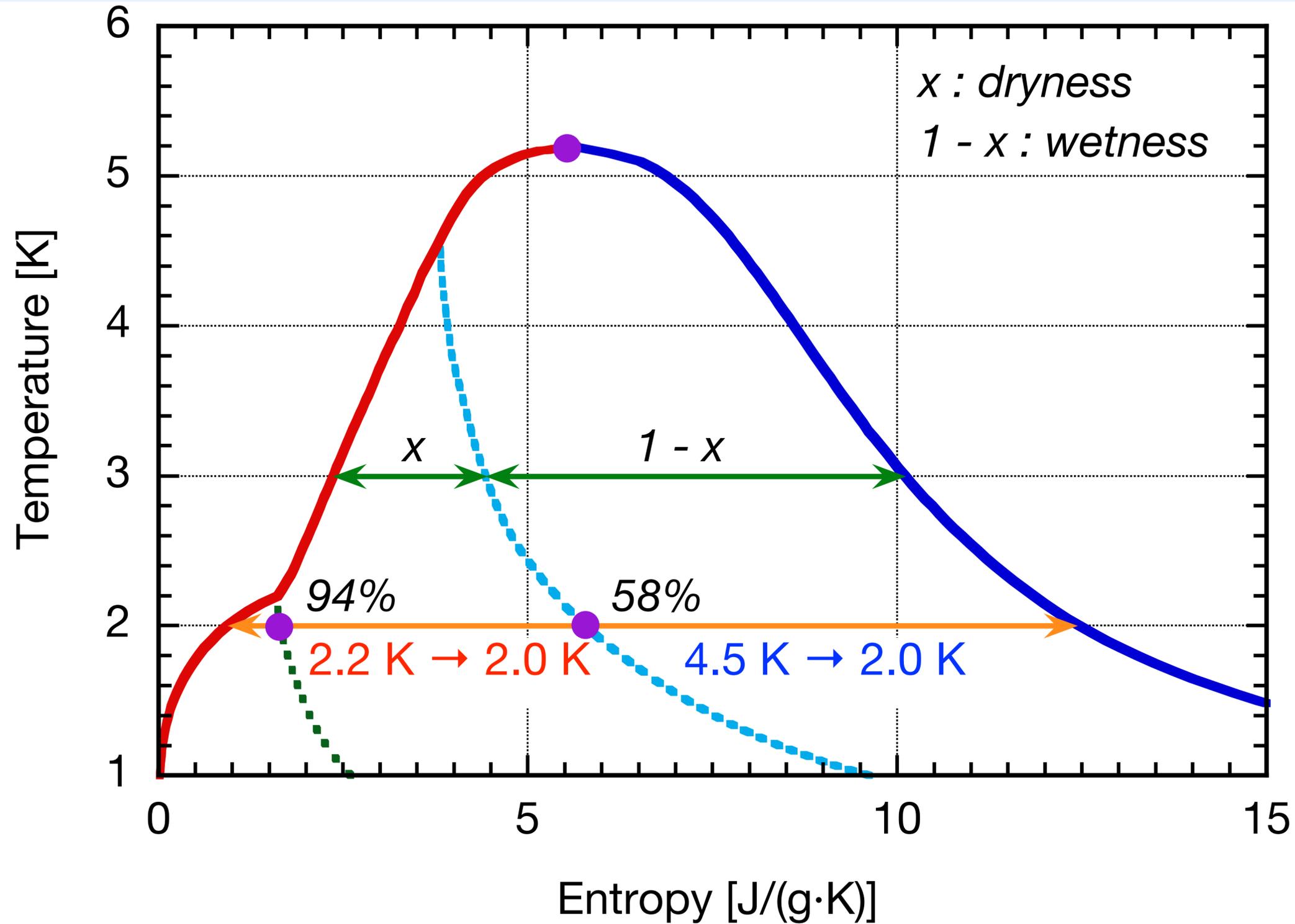
- ◆ Production of liquid helium
 - ◆ Joule-Thomson valve 1
- ◆ Cooling of liquid helium
 - ◆ Heat exchanger
- ◆ Isenthalpic expansion
 - ◆ Joule-Thomson valve 2
- ◆ Production of superfluid helium
- ◆ Compression of evaporated helium gas
 - ◆ Compressors
 - ◆ Vacuum pumps

Van Sciver, S. W., "Helium Cryogenics," Plenum Press (1986)

Temperature-Entropy (T-s) Diagram of Helium



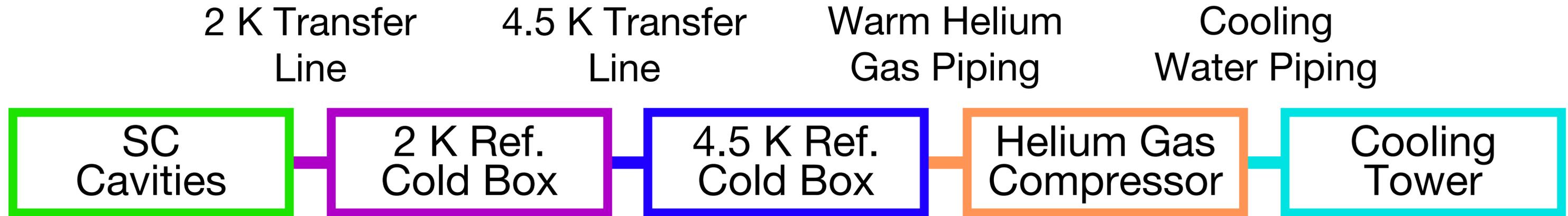
Dryness (vapor quality) & Wetness



2K Refrigerator (2K Cold Box)

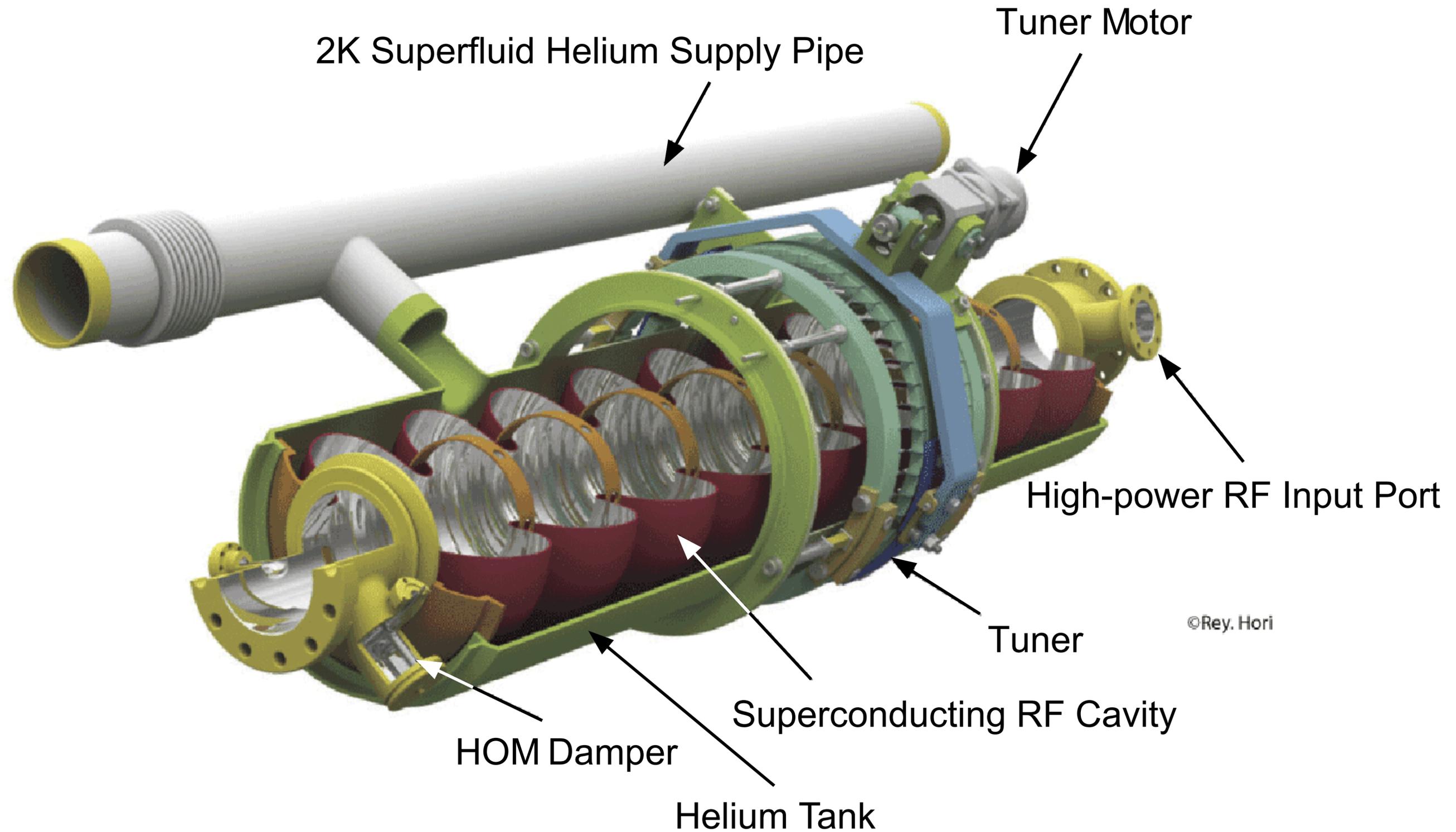
- ◆ Heat exchangers
 - ◆ To improve liquefaction rate (wetness) by reducing inlet liquid helium temperature
- ◆ Joule-Thomson valves
 - ◆ To control flow rate of liquid helium (throttle)
 - ◆ Less heat load from ambient required
- ◆ Compressors/Vacuum pumps
 - ◆ Cooling capacity at operation temperature determined by pumping capacity
 - ◆ Final discharge pressure depends on cryogenic system configuration

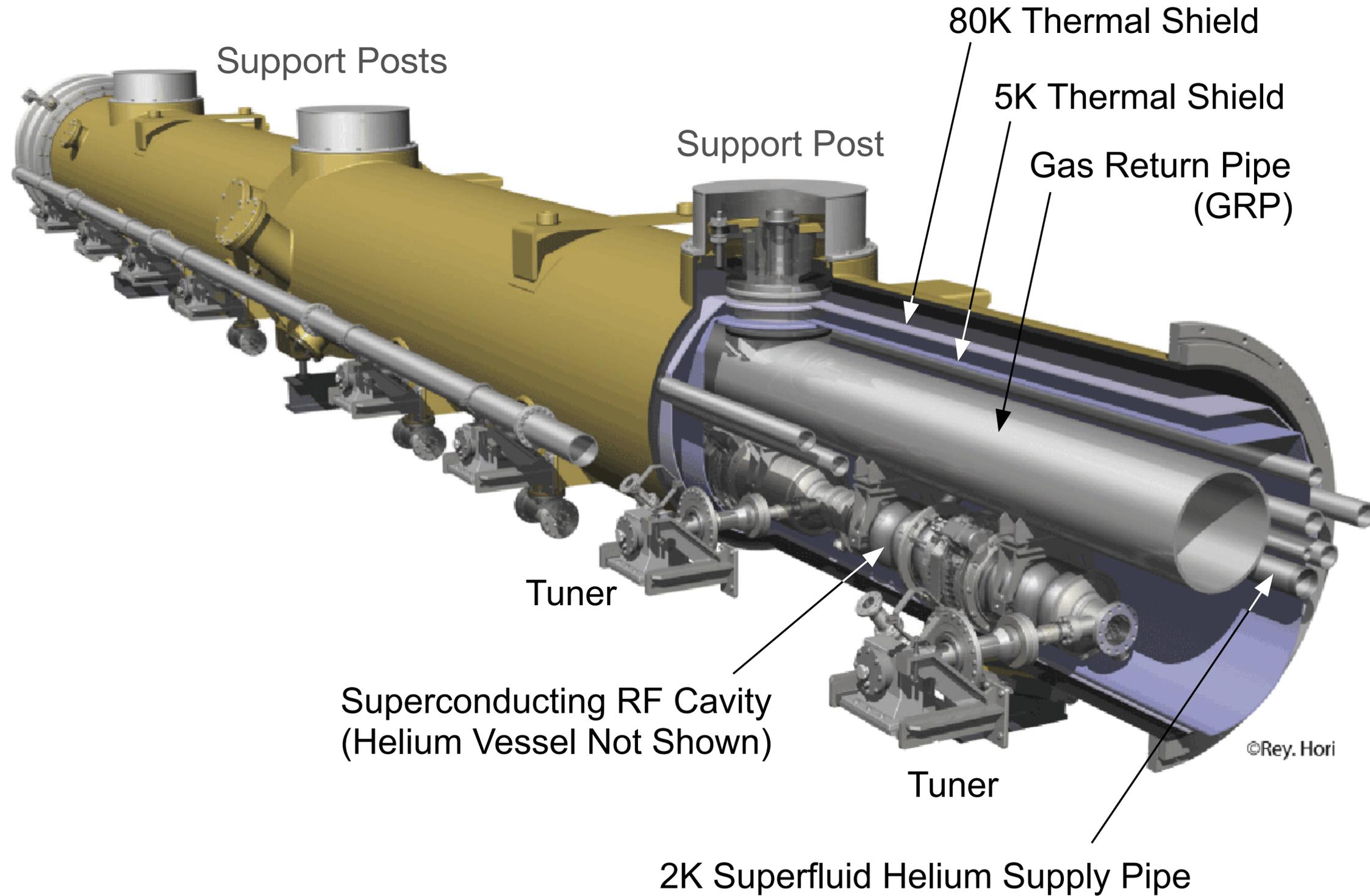
Concept of Superfluid Helium Cryogenic System



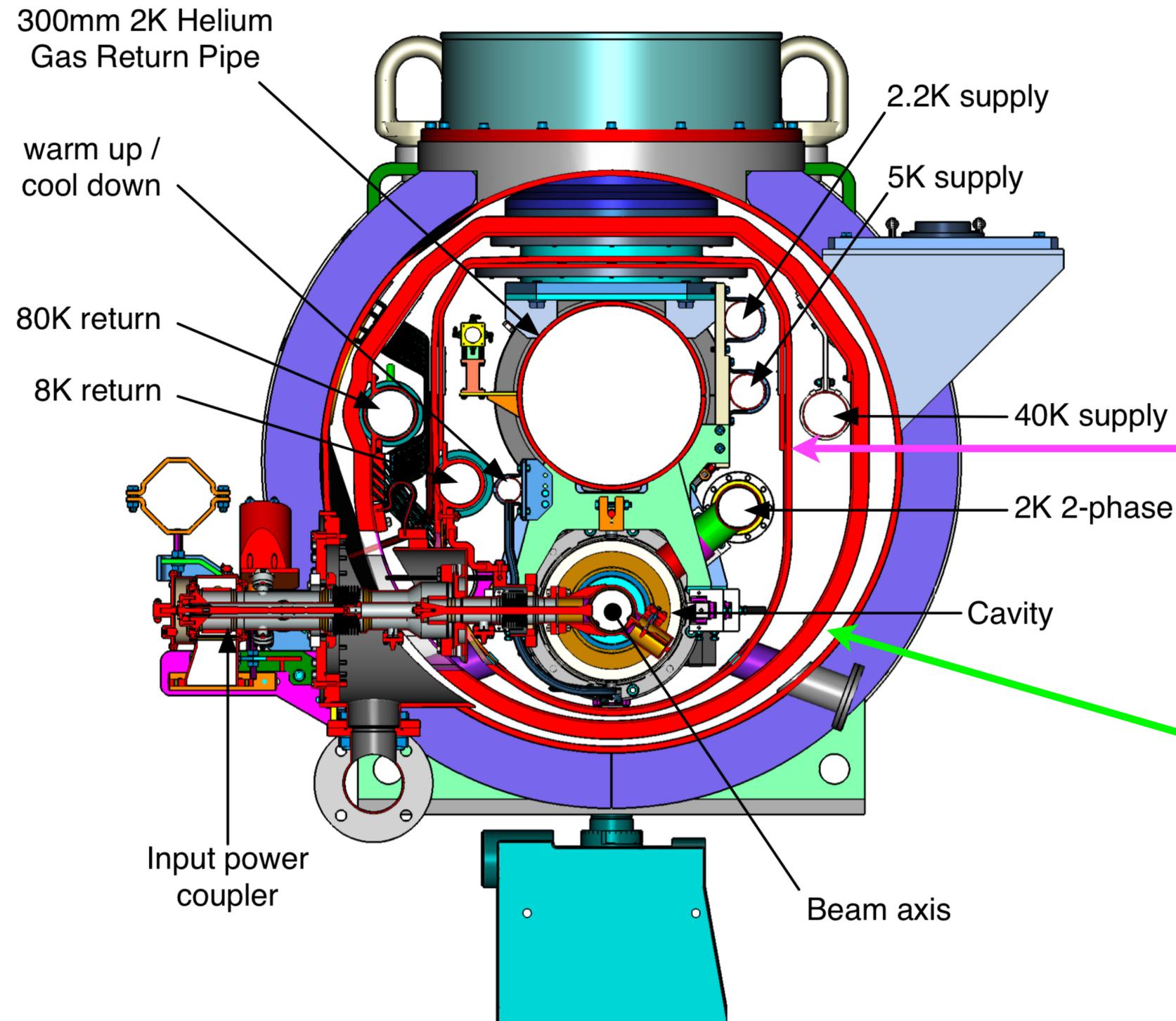
- ◆ Liquid helium production from helium gas at room temperature
 - ◆ Helium liquefier/refrigerator (4.5K cold box)
 - ◆ Helium compressors
- ◆ Superfluid helium production from liquid helium
 - ◆ 2K refrigerator (2K cold box)
 - ◆ Vacuum pumps/cold compressors

ILC Superconducting RF Cavity





Cross Section of Cryomodule



2K superfluid helium supply

- 2.2K supply line
- 2K 2-phase pipe
- 2K helium gas return pipe

5K thermal radiation shield

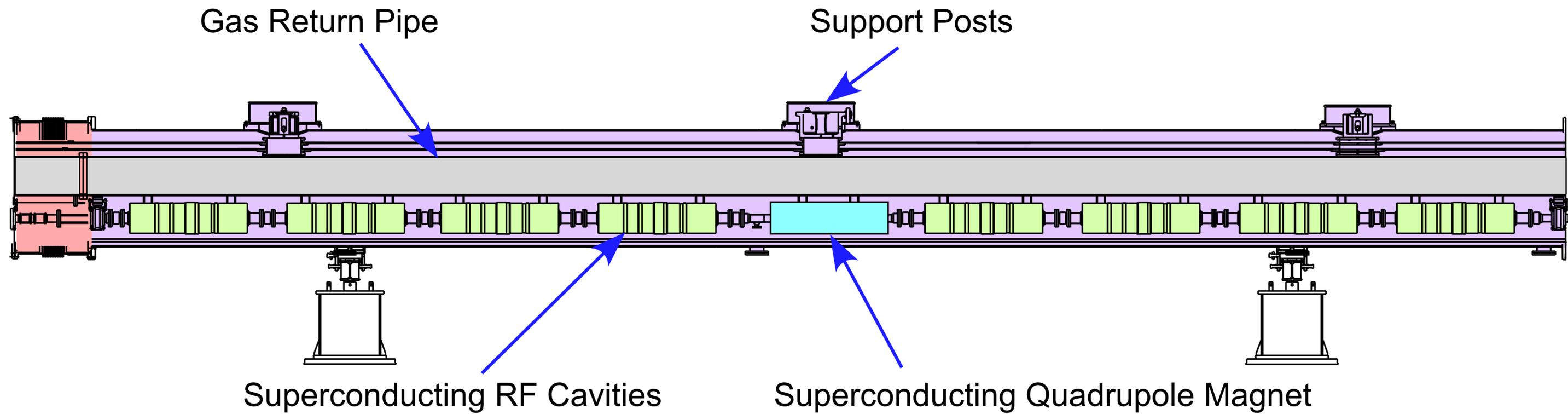
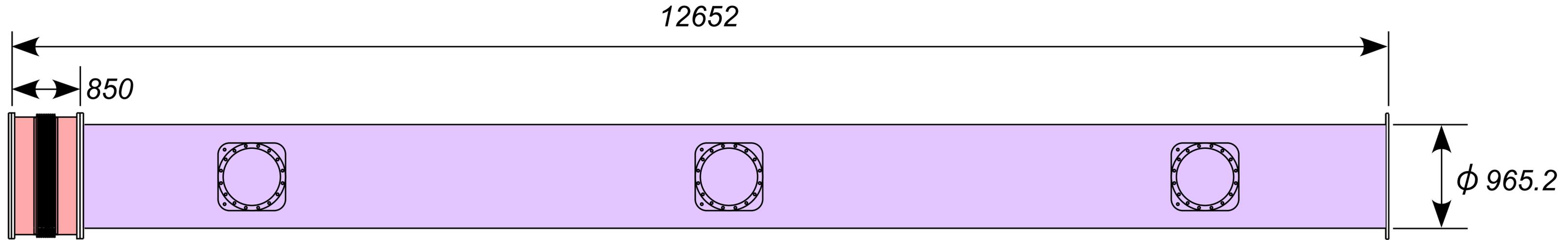
- 5K supply line
- 8K return line

40K thermal radiation shield

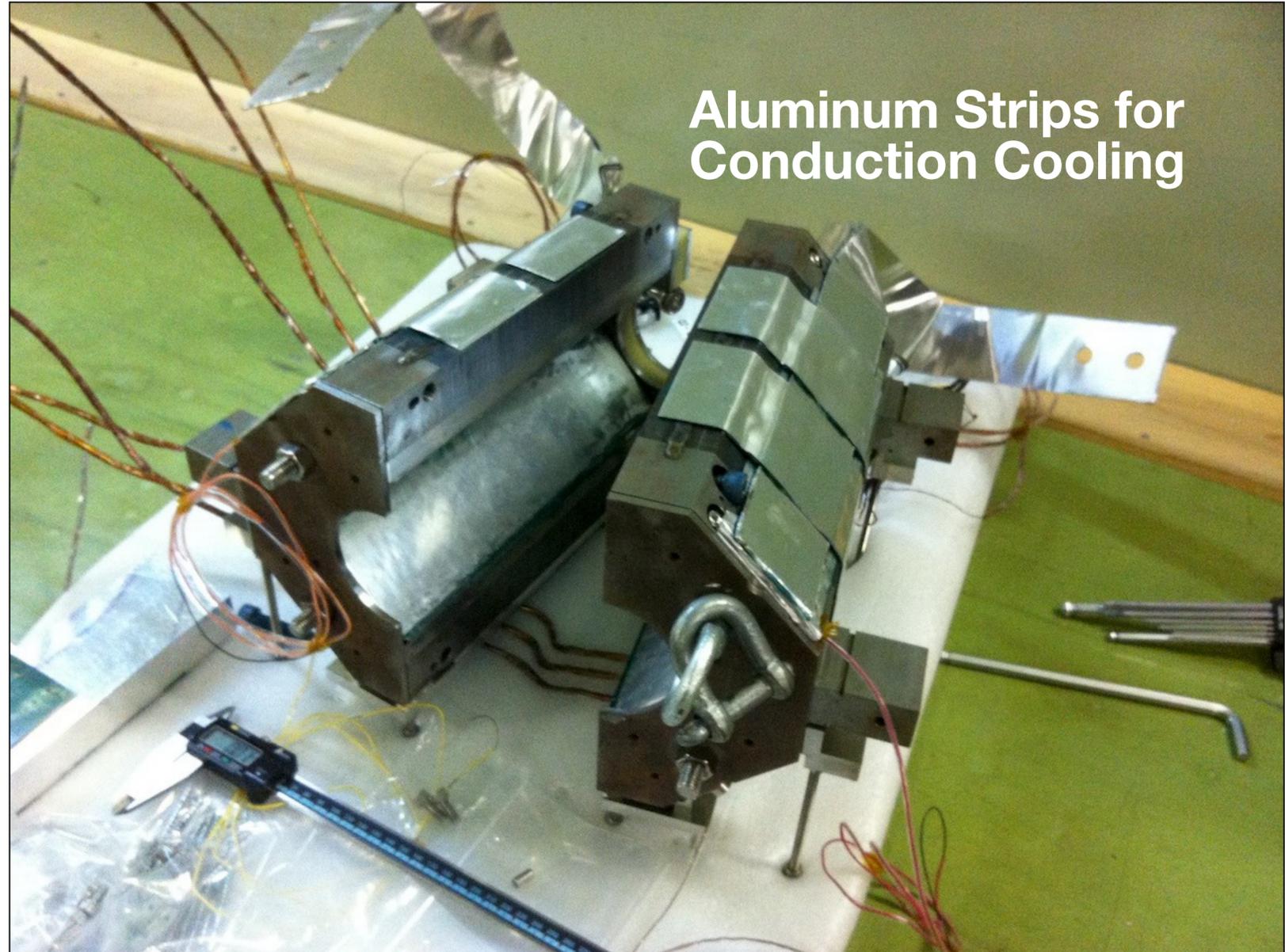
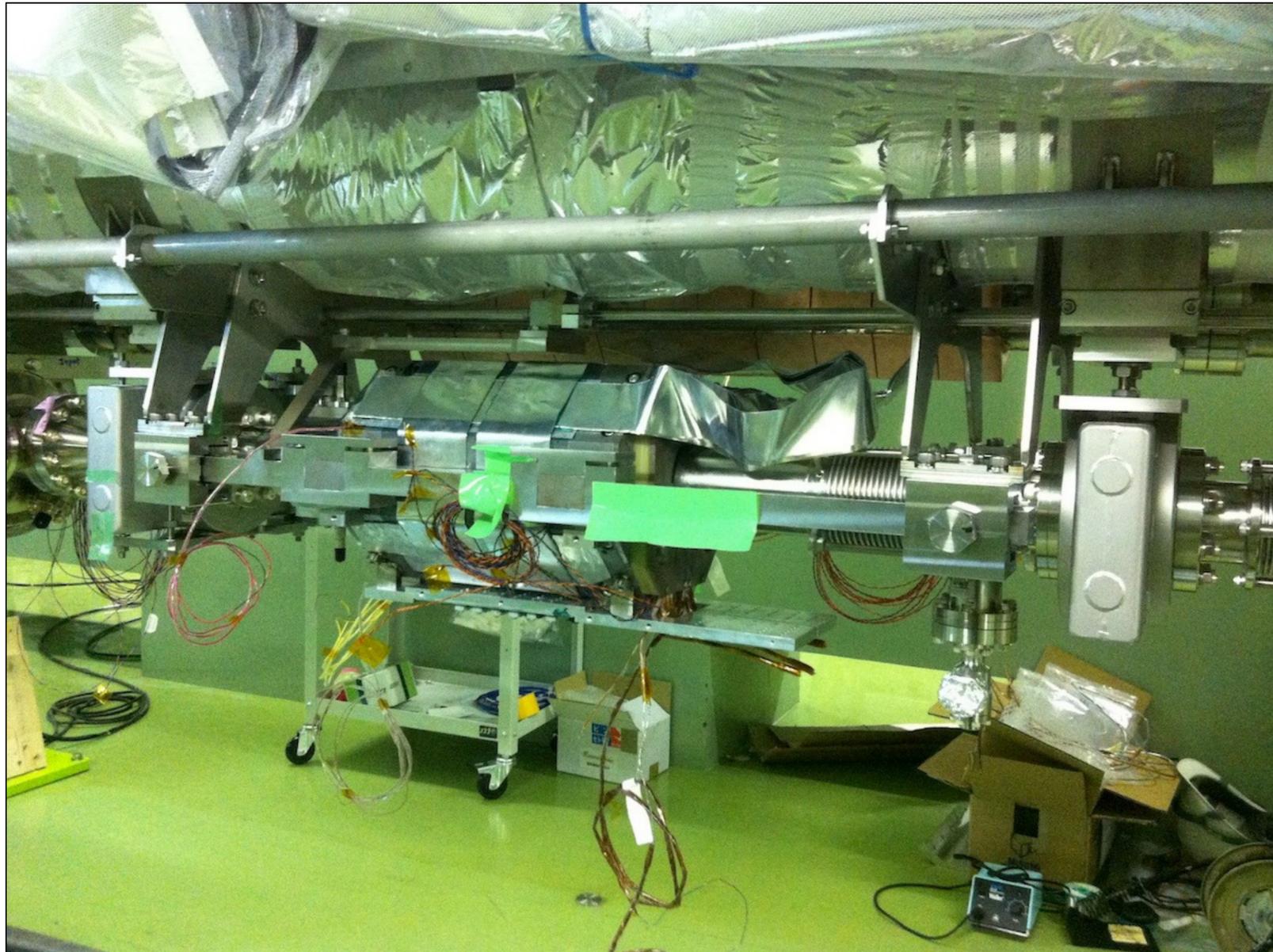
- 40K supply line
- 80K return line

Cited from ILC-TDR

Major Dimensions of ILC Cryomodule



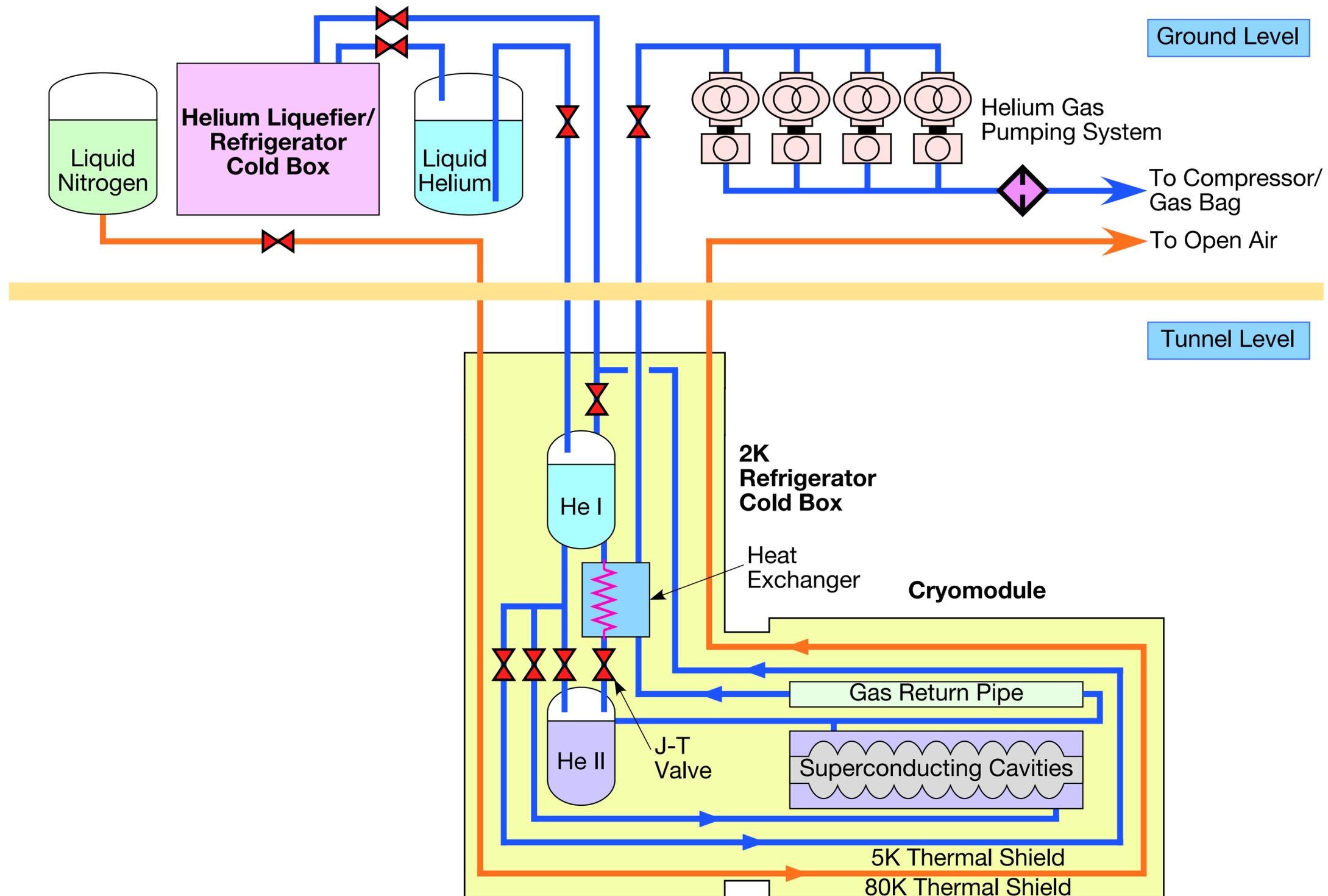
SC Quadrupole Magnet (Separated Vertically)



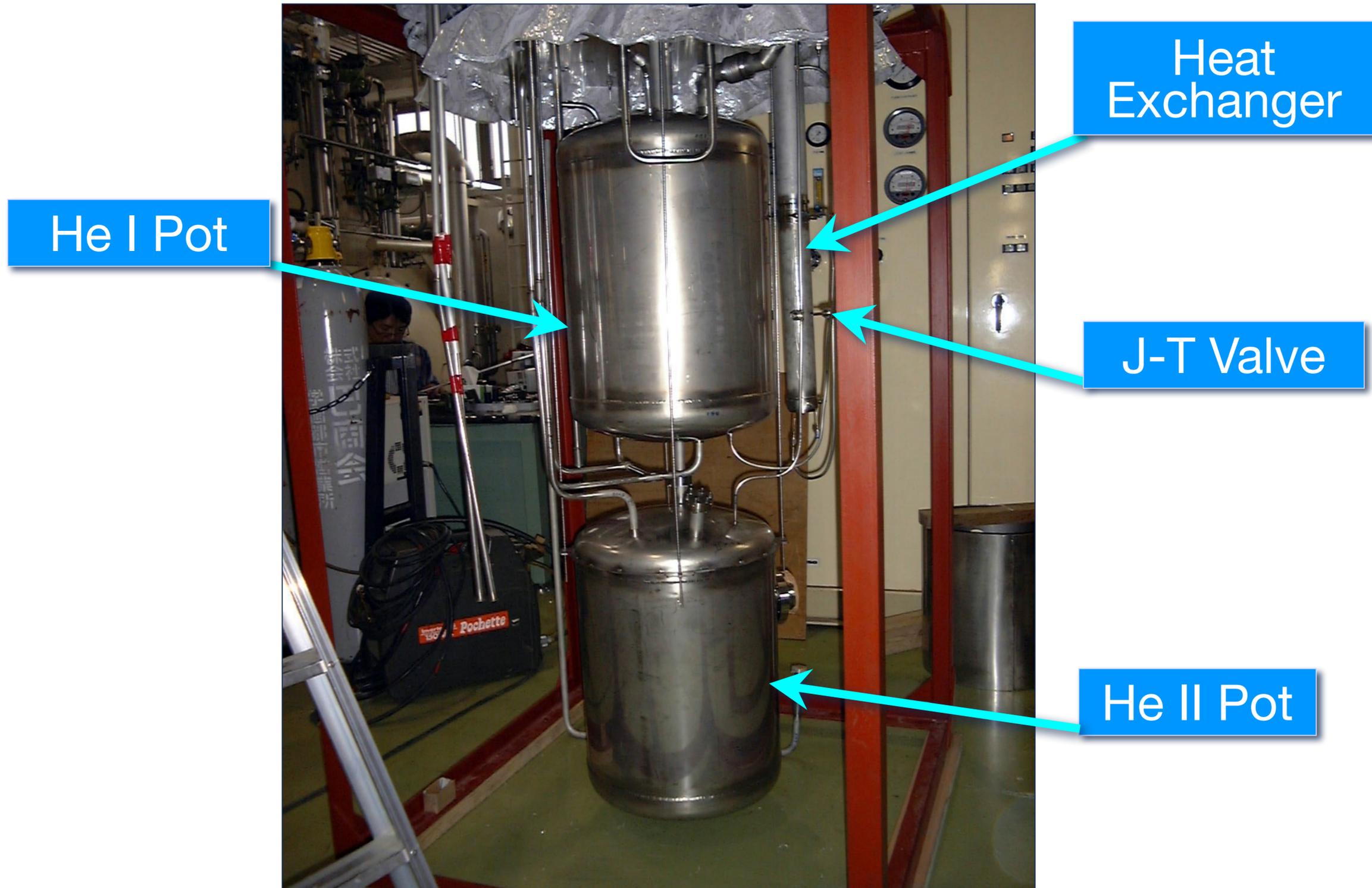
Assembly of STF CM-1



Cryogenic System at Superconducting RF Test Facility



2K Refrigerator Cold Box



He I Pot

Heat Exchanger

J-T Valve

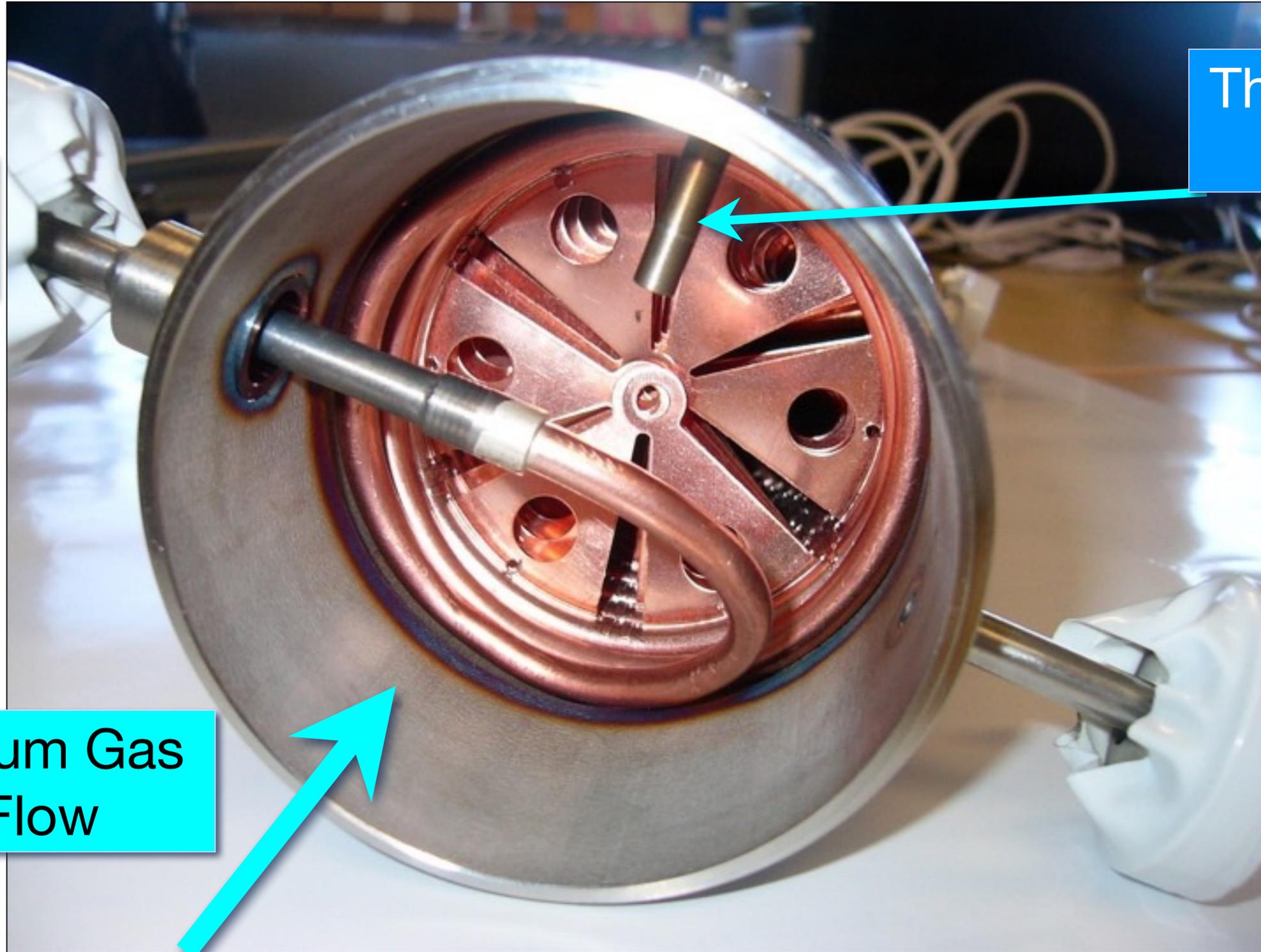
He II Pot

2K Heat Exchanger

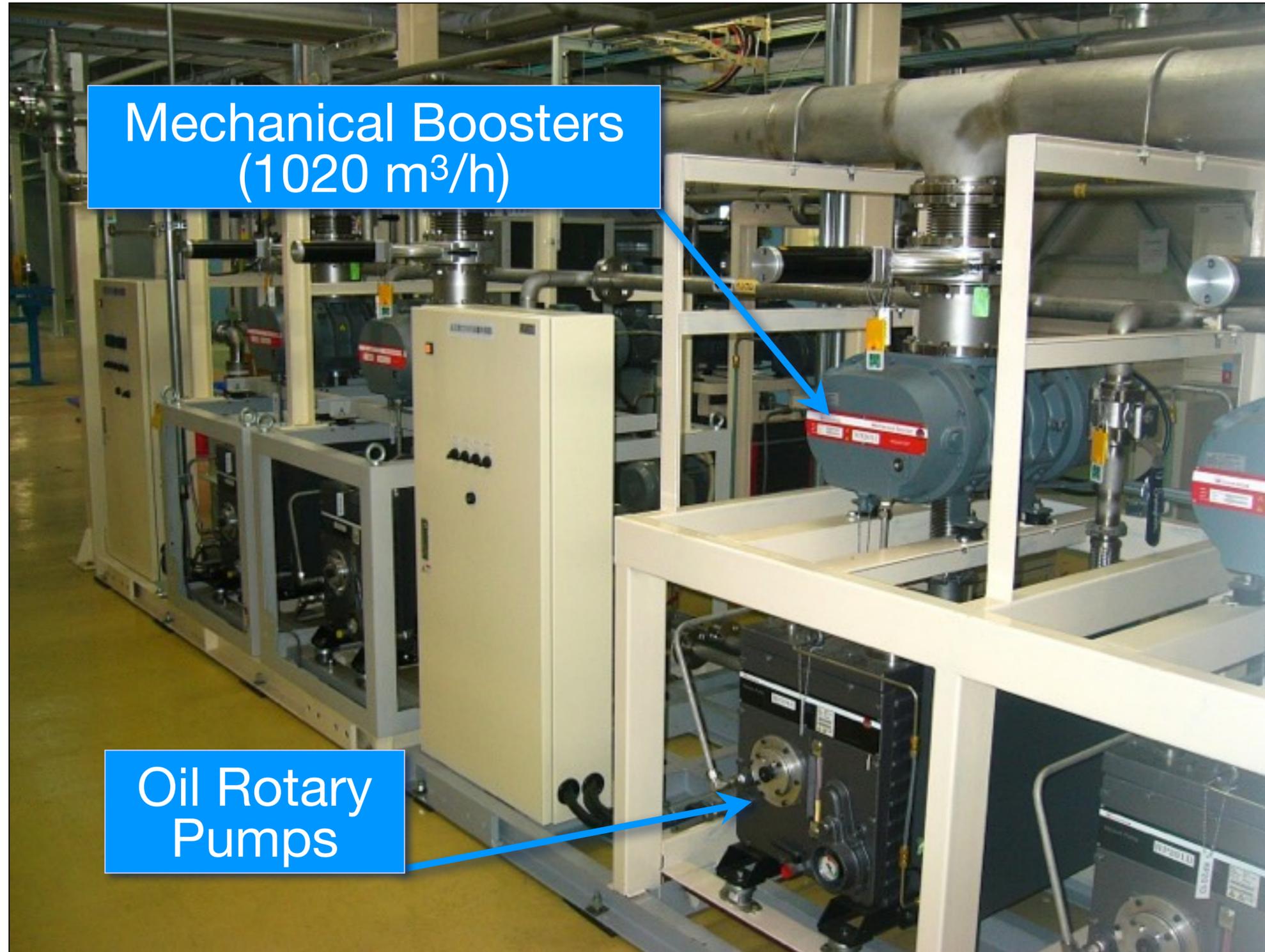
Liquid Helium Port

Thermometer Port

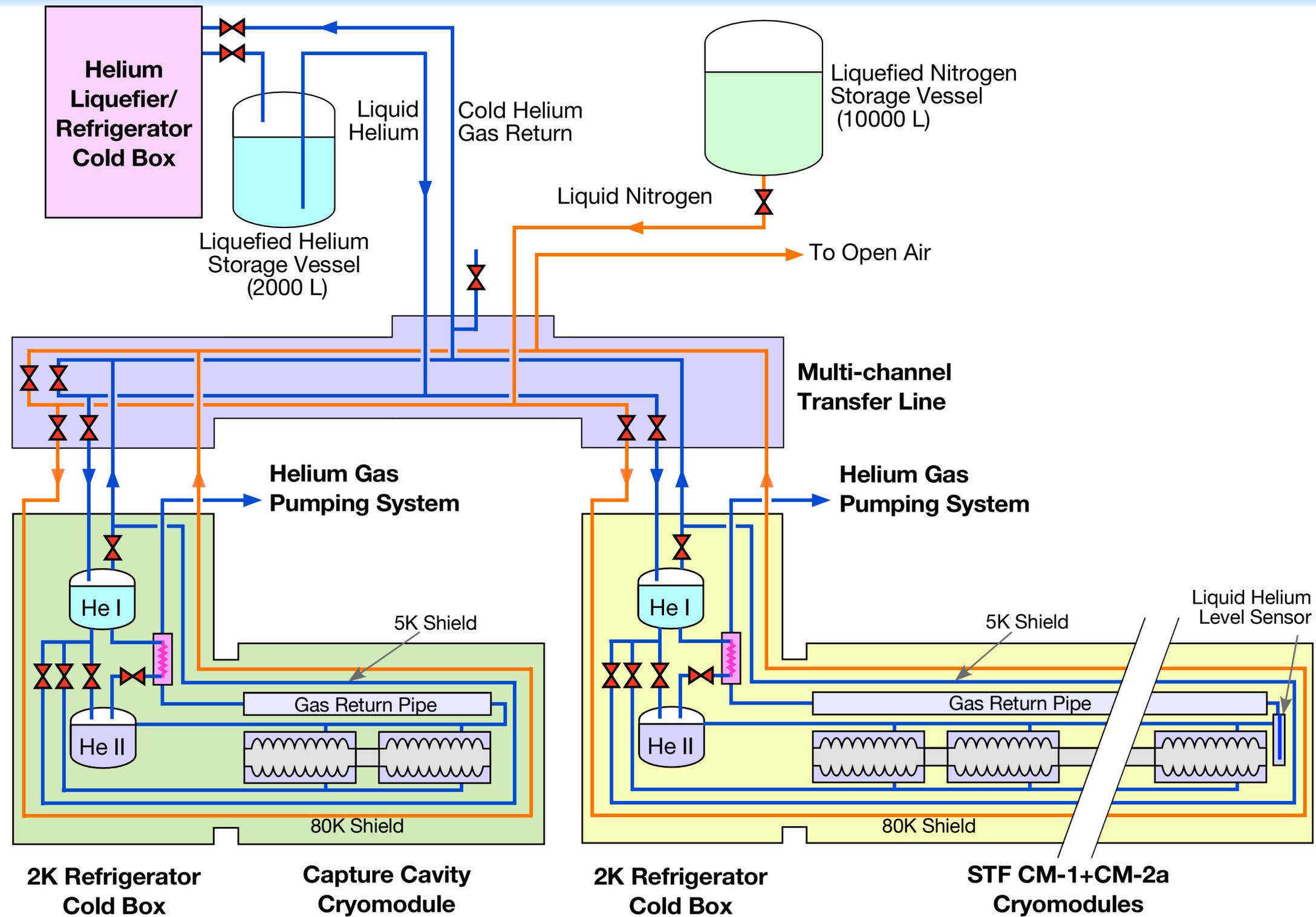
Helium Gas Flow



Helium Pumping System



STF 2K Superfluid Helium Cryogenic System



STF Beam Line and Cryomodules

- Capture : 9-cell cavities x 2
- STF CM-1: 9-cell cavities x 8 + sc quad. x 1
- STF CM-2a : 9-cell cavities x 4

STF CM-1 + CM-2a

2K Refrigerator
Cold Box

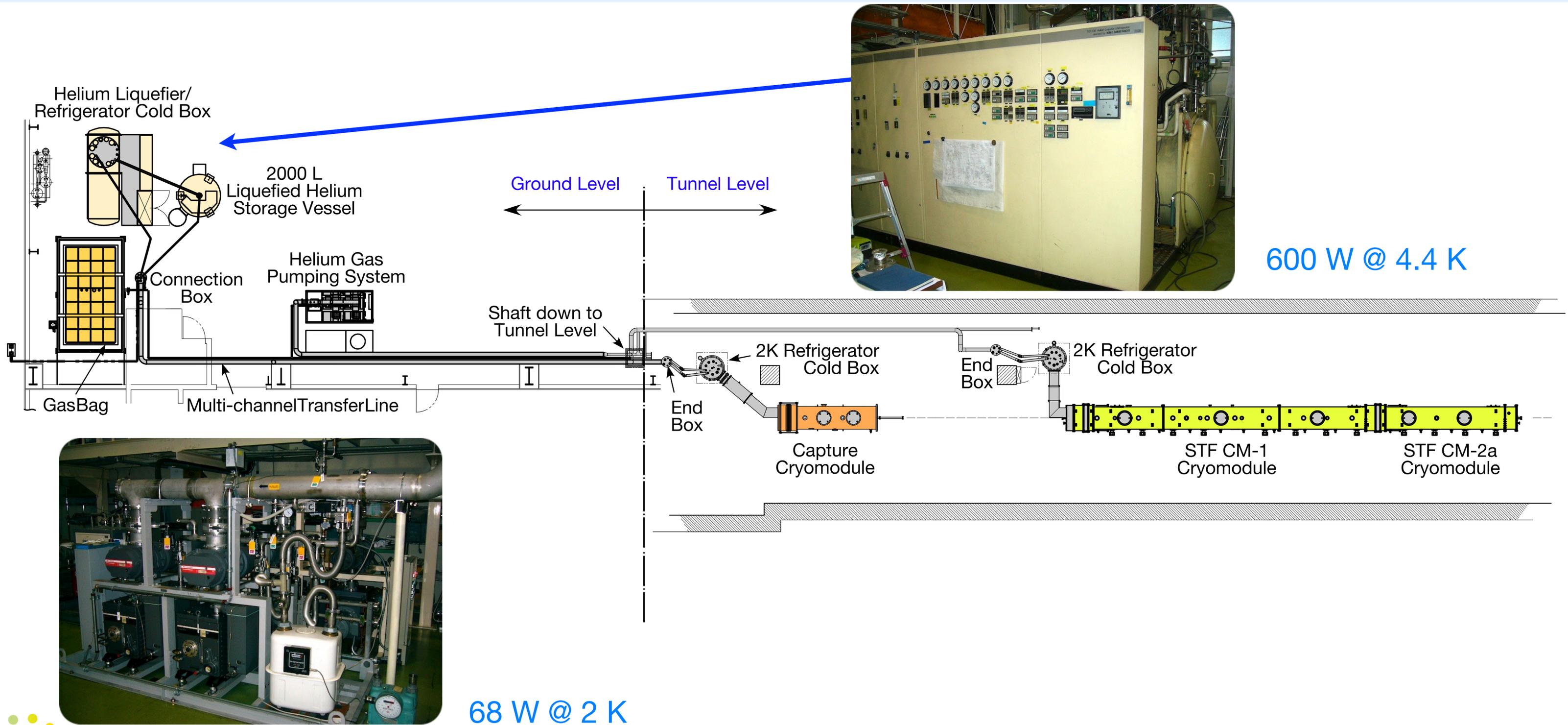
2K Refrigerator
Cold Box

Capture
Cryomodule

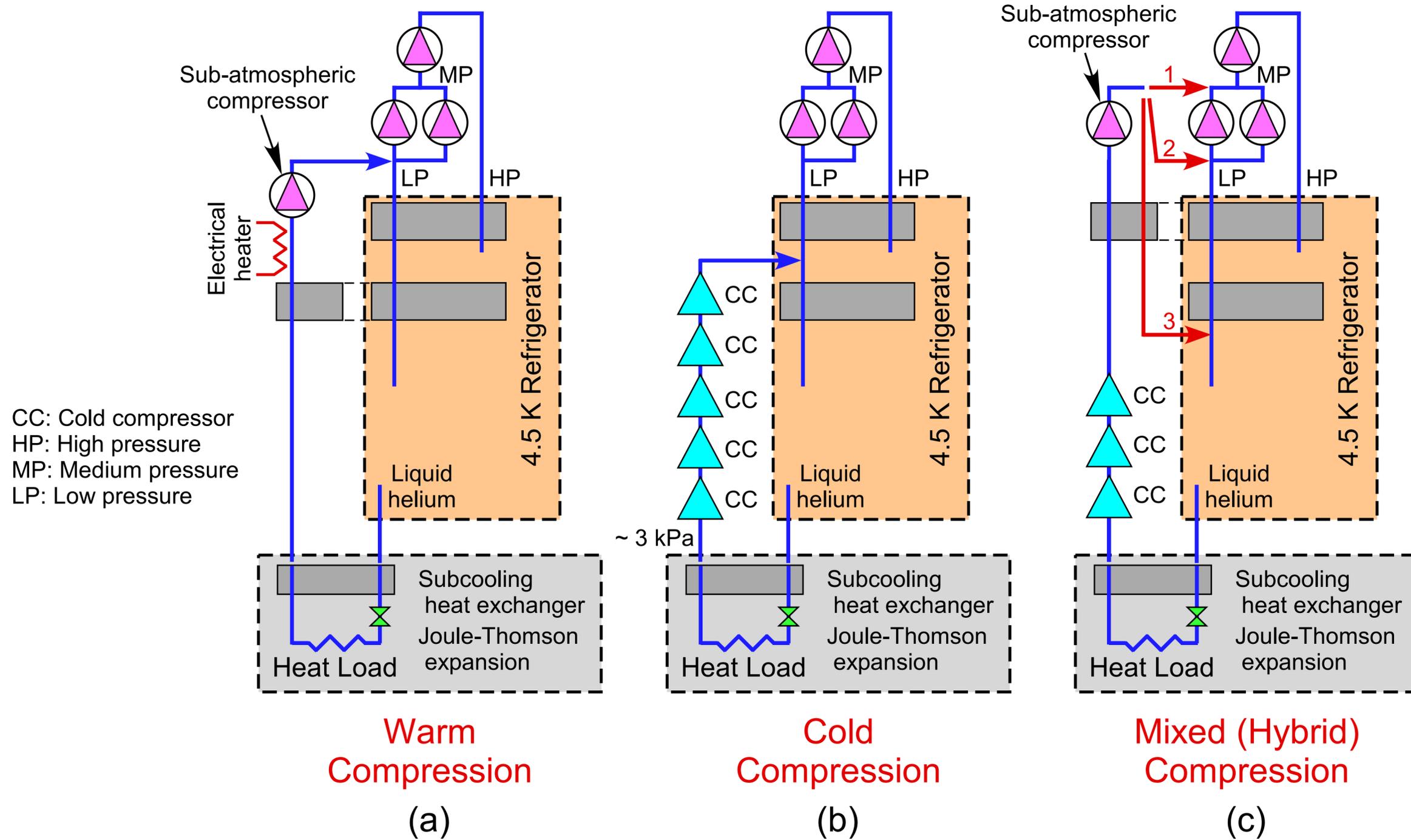
Photo-Cathode
RF Gun



STF Cryogenic System Configuration

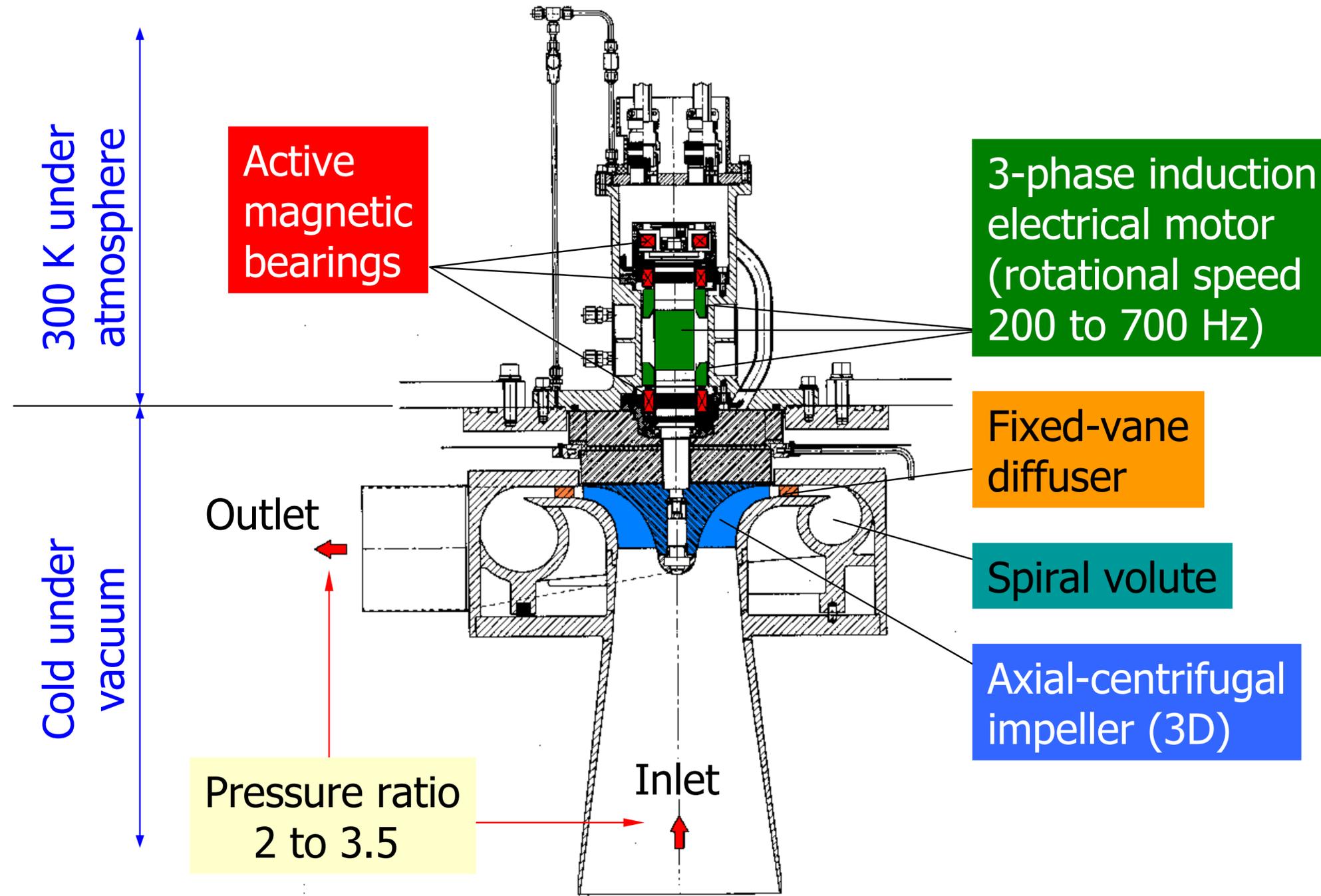


Pressure Reduction of Liquid Helium



Lebrun, Ph. and Tavian L., European Graduate Course in Cryogenics Helium Week (2010)

Structure of Cold Compressor



Lebrun, Ph., Magnet Technology for Fusion Training School (2009)

Cold Compressors for CERN-LHC

IHI-Linde

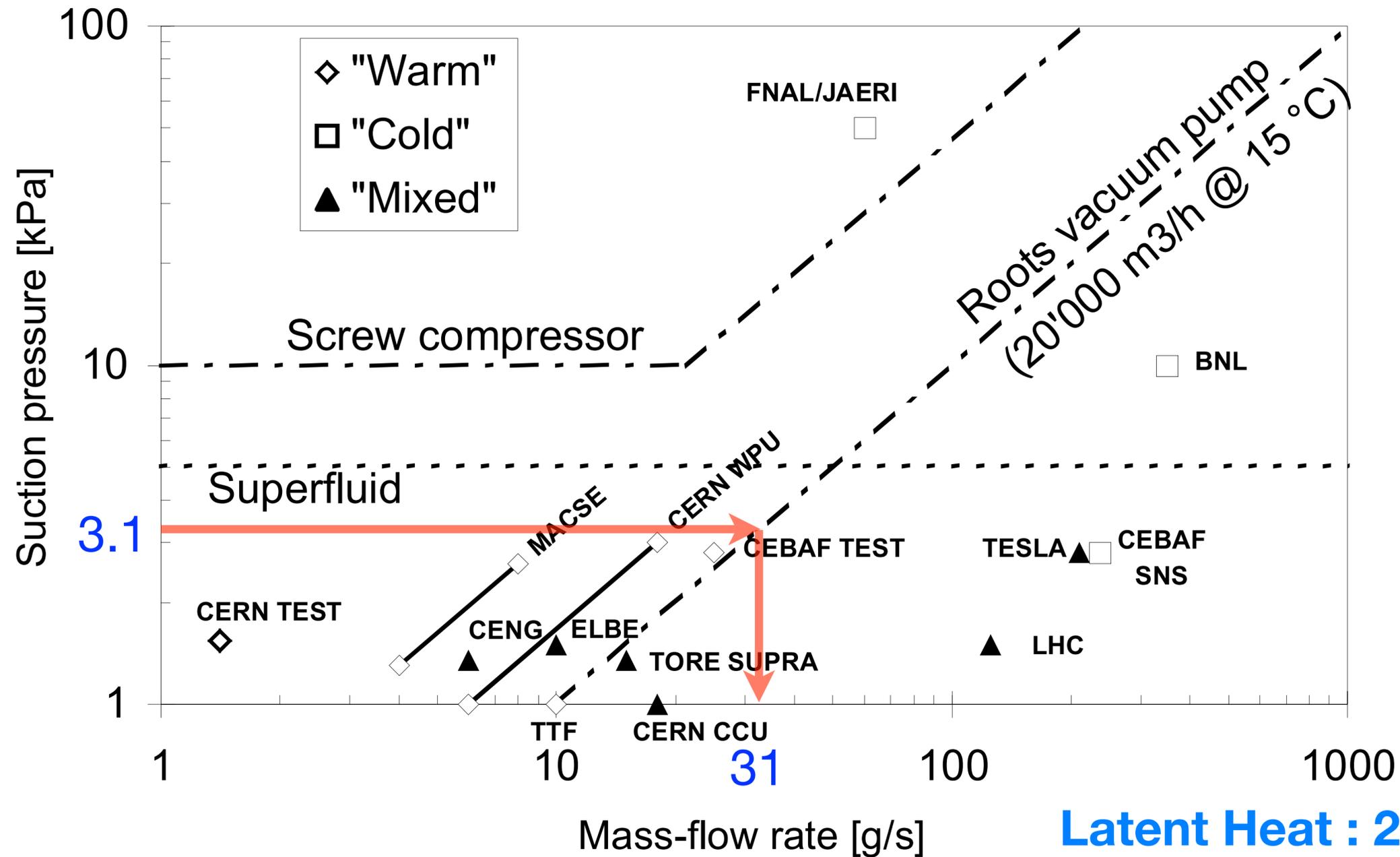


Air Liquide



Lebrun, Ph., Magnet Technology for Fusion Training School (2009)

Selection of Compressors



Latent Heat : 24 J/g at 2 K
24 J/g x 31 g/s ≈ 750 W

Lebrun, Ph. and Taviani L., European Graduate Course in Cryogenics Helium Week (2010)

Classification of Cryogenic Refrigerators

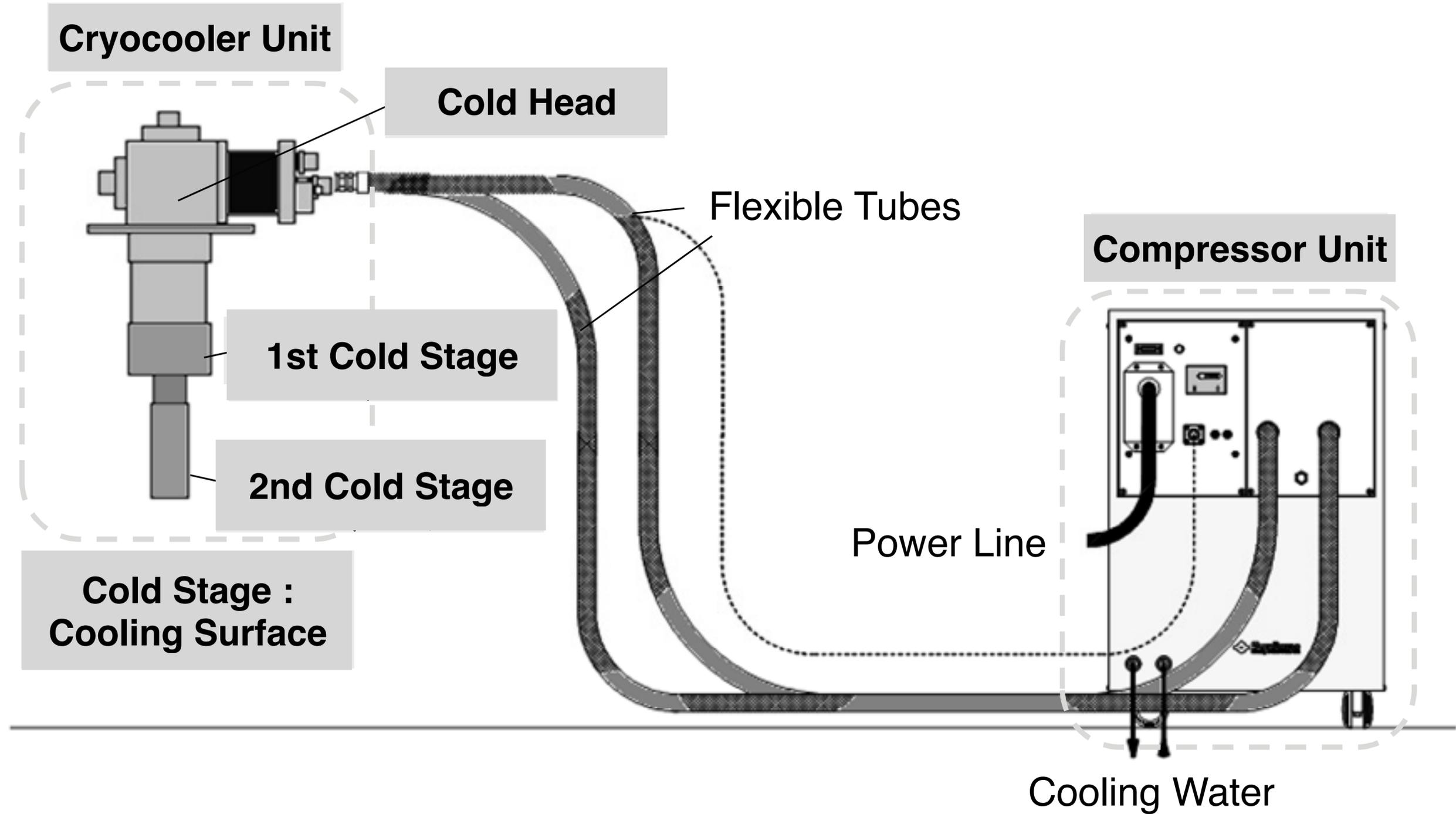
Scale	Heat Exchanger	Expansion	Refrigerator	Capacity
Small (Cryocooler)	Regenerative	Isothermal	Vuilleumier	0.1 - 1 W @ 4.2 K
			Stirling	
		Simon	Gifford-McMahon (GM)	
	Solvay			
	Pulse Tube			
	Medium - Large	Counterflow	Joule-Thomson (Isenthalpic)	Joule-Thomson (JT)
Isentropic			Claude	More than 10 W @ 4.2 K
		Brayton		

Ikushima, Y., "R&D on Ultra Low Vibration Cryocoolers", SOKENDAI Doctoral Thesis (2009)

- ◆ Gifford-McMahon (GM) Refrigerator
 - ◆ High performance and high reliability
 - ◆ Achieved temperature depends on specific heat of regenerator (large specific heat at low temperature)
- ◆ Pulse Tube (PT) refrigerator
 - ◆ No moving parts at low temperature area (small vibration)
 - ◆ Thermo-acoustic effect
- ◆ Gifford-McMahon/Joule-Thomson (GM-JT) Refrigerator
 - ◆ JT refrigerator added to GM refrigerator
 - ◆ Large cooling capacity

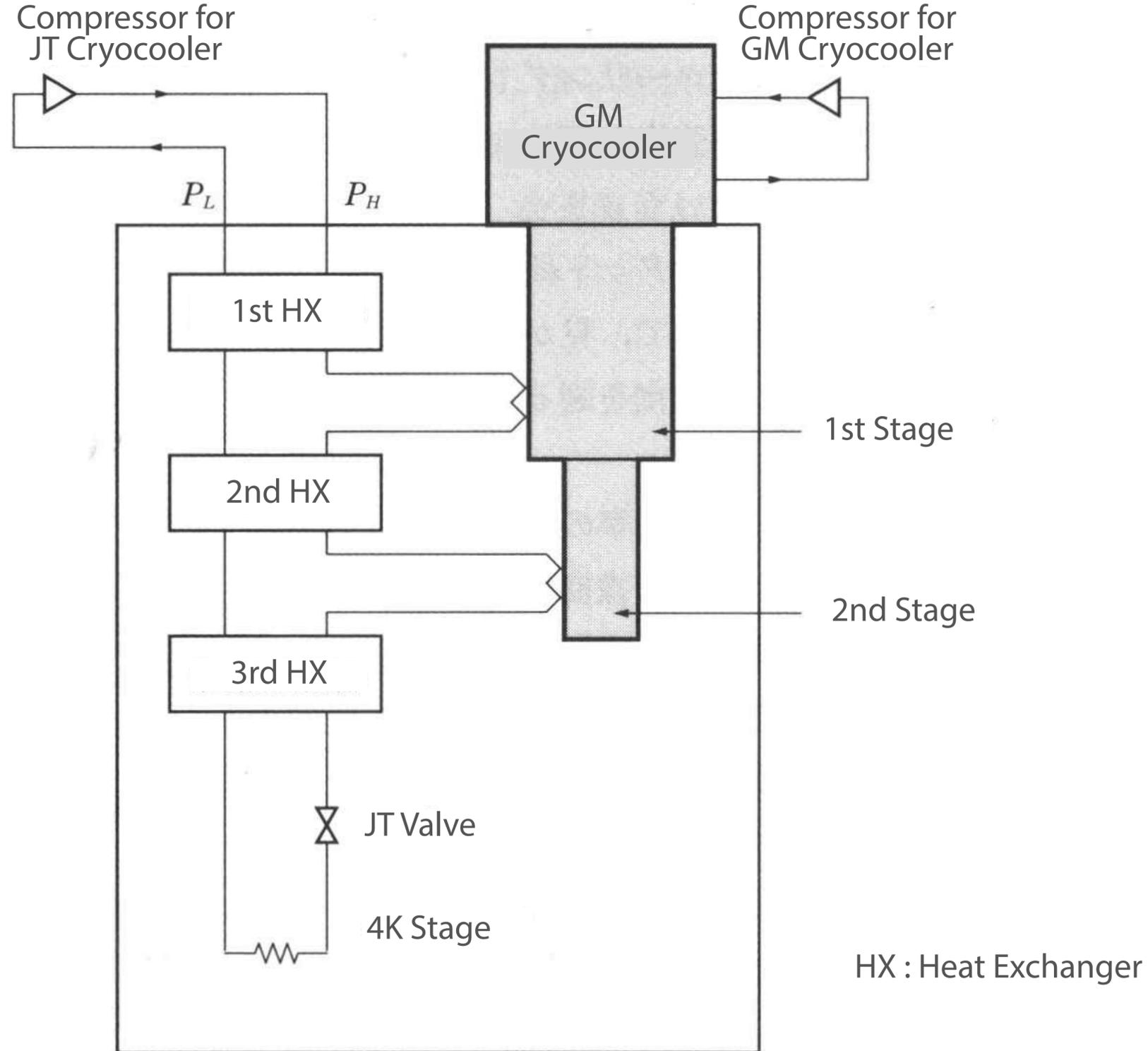
- ◆ Easy handling and operation
 - ◆ Flexible tube connection between cryocooler and compressor
 - ◆ Power line from wall outlet
- ◆ Neither liquid helium nor liquid nitrogen necessary
- ◆ The lower achieving temperature, the smaller cooling capacity

Components of GM Cryocooler



Ikushima, Y., "R&D on Ultra Low Vibration Cryocoolers", SOKENDAI Doctoral Thesis (2009)

Principle of GM-JT Cryocooler



- ◆ 2 compressors necessary
- ◆ for GM cryocooler
- ◆ for JT cryocooler (refrigerator)

Ogiwara, H. ed., "Introduction to Cryogenic Engineering", Tokyo Denki Univeristy Press (1999)

GM-JT Cryocooler of Sumitomo Heavy Industries, Ltd. 4K GM-JT CRYOCOOLER SERIES



Performance Specifications

Model Number	CG304SC	CG308SC	CG310SC
3rd Stage Capacity* Watts @ 4.3 K (50/60 Hz)	1.0/1.2	3.0/3.5	4.2/5.0
Electrical Supply 50/60 Hz	3 phase, 200 V		
Power Consumption 50/60 Hz	4.5/5.4	5.1/6.4	5.1/6.4
Cooling Water L/min. (gal./min.)	5.5-6.5 (1.5-1.7)	8.0-10.0 (2.1-2.6)	8.0-10.0 (2.1-2.6)
Refrigeration Unit Weight kg (lbs.)	18.0 (39.7)	35.0 (77.2)	50.0 (110.2)
Compressor Weight kg (lbs.)	205 (452)	220 (485)	220 (485)
Maintenance Hours	10,000		

Standard Scope of Supply

- V304SC, V308SC or V316SC Cold Head
- U304CWA or U308CWA Compressor
- Helium Vapor Gauge (with CG308SC and CG310SC models)
- Hydrogen Vapor Gauge
- 6 m (20 ft.) Helium Gas Lines
- 6 m (20 ft.) Valve Motor Cable
- Tool Kit

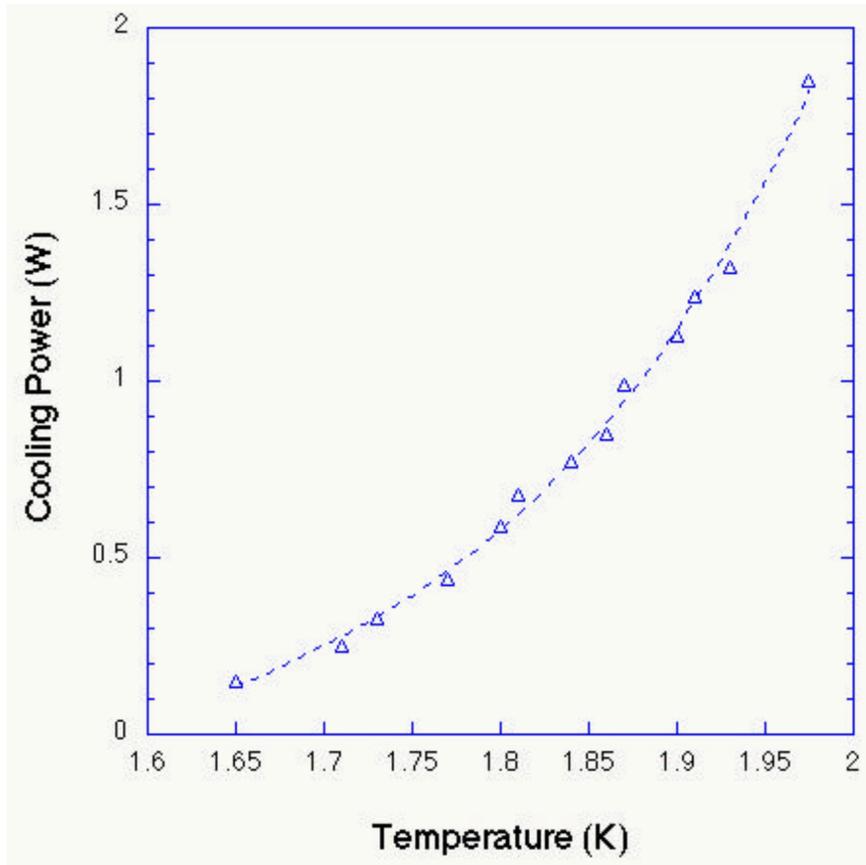
<http://www.shicryogenics.com/wp-content/uploads/2012/11/Cryocooler-Product-Catalogue.pdf>

Development of Small 2K Refrigerator

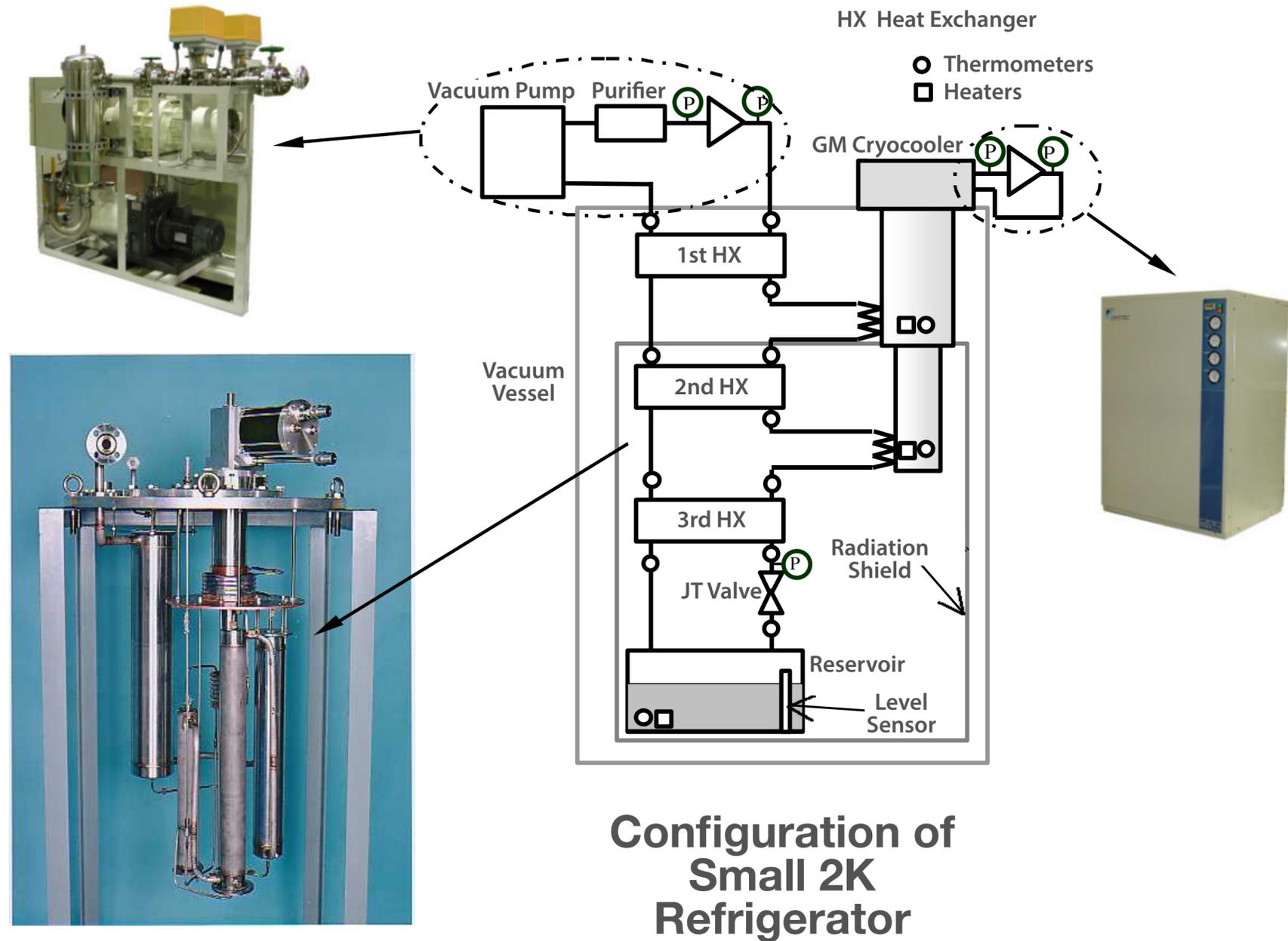
July 2001, National Institute for Materials Science

Cooling Capacity : **2 W @ 2 K** / 0.6 W @ 1.8 K

Input Power : 8.8 kW (GM + JT + Vacuum Pumps)



Temperature dependence of Cooling Power



<https://www.nims.go.jp/news/press/2001/hdfqf100000021bg-att/p200107090.pdf>

2K GM Cryocooler

GM Cryocooler of Sumitomo Heavy Industries, Ltd.

RDC-02K 2K Cryocooler Series

Performance Specifications



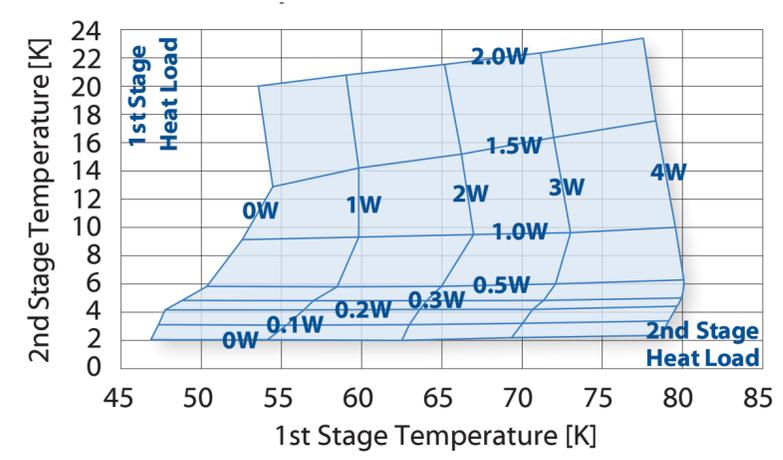
Power Supply	50Hz	60 Hz
2 nd Stage Capacity	0.02 W @ 2.3 K	
1 st Stage Capacity	1.0 W @ 60 K	3.0 W @ 60 K
Minimum Temperature ¹	<2.2 K	
Cooldown Time to 2.3 K ¹	<120 Minutes	
Weight	7.0 kg (15.4 lbs.)	
Dimensions (HxWxD)	351.7 x 130 x 226 mm (13.8 x 5.1 x 8.9 in.)	
Maintenance	10,000 Hours	
Regulatory Compliance	UL/CE, RoHS	

Standard Scope of Supply

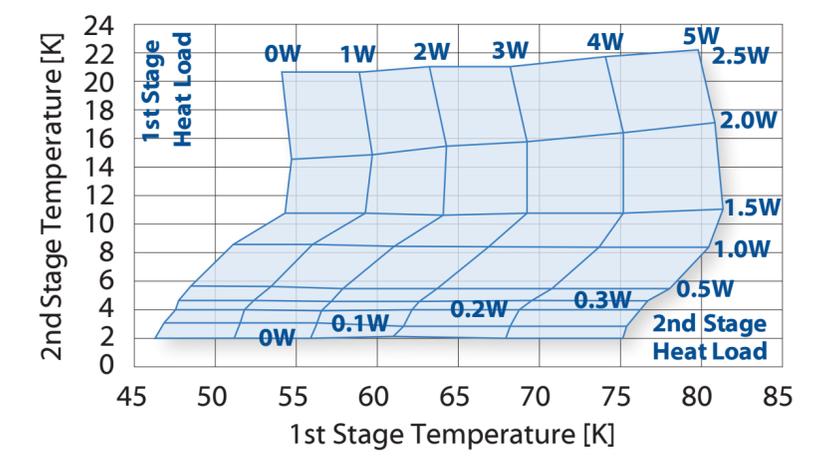
- RDC-02K Cold Head
- CNA-11B/C Compressor
- Helium Gas Lines – 3 m (10 ft.)
- Cold Head Cable – 6 m (20 ft.)
- Power Cable – 5 m (16.5 ft.)
- Tool Kit

¹Lowest temperature and cooldown time are for reference only.

RDC-02K Cold Head Capacity Map (50 Hz)
With CNA-11B Compressor and 3 m (10 ft.) Helium Gas Lines



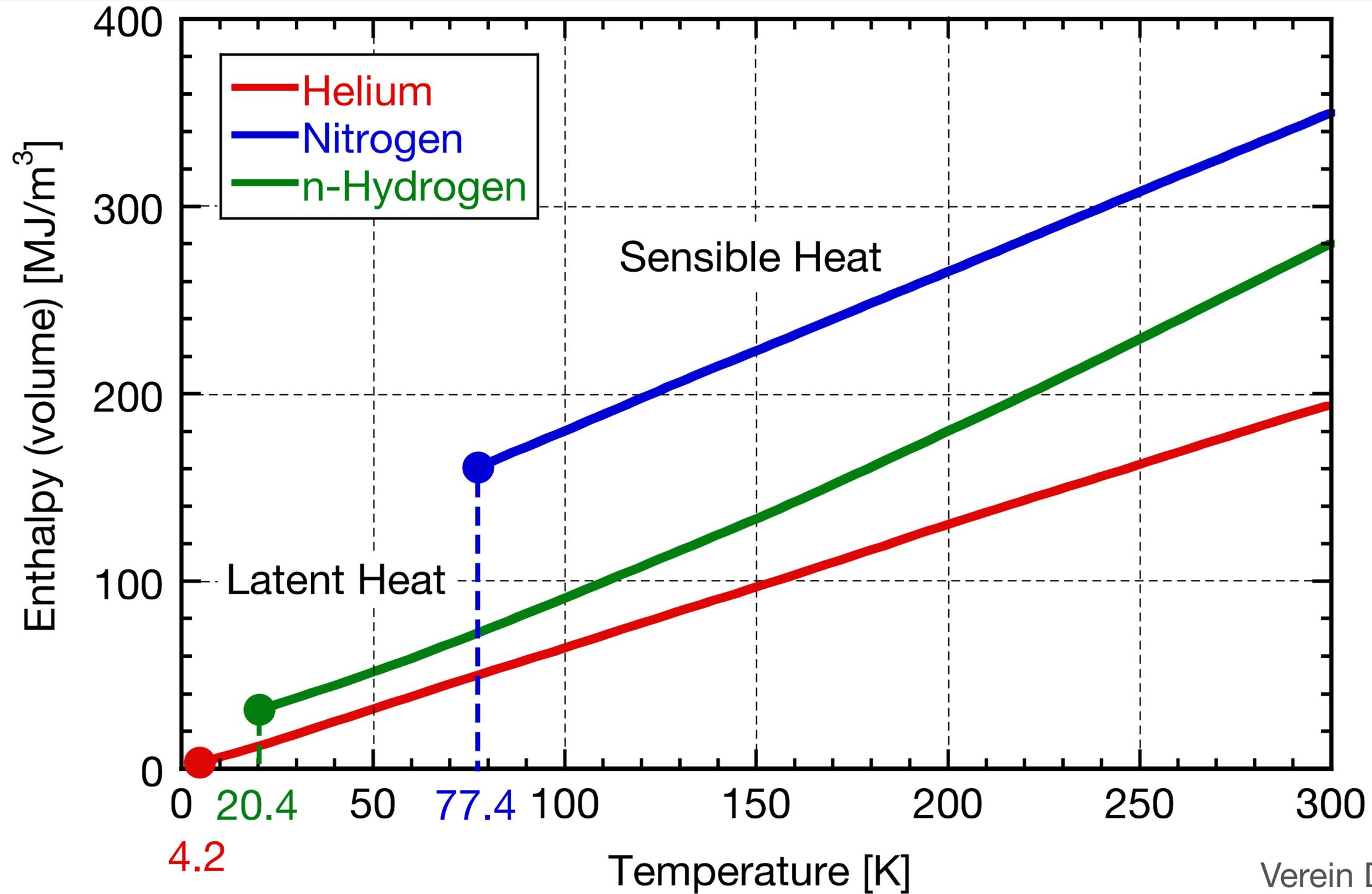
RDC-02K Cold Head Capacity Map (60 Hz)
With CNA-11B Compressor and 3 m (10 ft.) Helium Gas Lines



https://shicryogenics.com/wp-content/uploads/2023/08/Cryocooler_Product_Catalogue_English_A4_06.23.pdf

- ◆ Self-excited oscillation of gas column (acoustic oscillation, Taconis oscillation)
 - ◆ Highly possible in a thin tube whose hot end closed and cold end open
- ◆ Easy occurrence in liquid helium
- ◆ Introduction of heavy heat load
 - ◆ Rapid evaporation of liquid helium
- ◆ Dependence on temperature condition (temperatures at hot and cold ends) and on geometrical condition (diameter, length etc.)
- ◆ Off-resonant conditions by varying length and/or with stuffing inside pipe

Latent Heat and Sensible Heat



Verein Deutscher Ingenieure,
“Lehrgangshandbuch Kryotechnik” (1977)

Summary

- ◆ Recent superconducting accelerators operate at 2 K or lower temperature
- ◆ Higher frequency superconducting cavities require lower operation temperature for moderate cryogenic system
- ◆ Helium — only substance to cool down superconducting devices at 2 K or lower temperature

- ◆ Superfluid helium
 - ◆ One of liquid phases of helium at 2 K or lower temperature
 - ◆ Excellent apparent thermal conductivity — Two-fluid model
- ◆ Superfluid helium cryogenic systems
 - ◆ Another J-T valve and a 2K heat exchanger are essential components to improve superfluid helium production rate
 - ◆ Cold compressors introduced to larger superfluid helium cryogenic systems