The 6th Asian School on Superconductivity and Cryogenics for Accelerators

Institute of High Energy Physics, Chinese Academy of Science, China

Superfluid Helium Cryogenics and Superfluid Helium Cryogenic Systems

High Energy Accelerator Research Organization (KEK)
Accelerator Laboratory

NAKAI Hirotaka, Ph.D.

March 29, 2025

Contents of This Lecture

Introduction

Accelerators and Cryogenics

- Higher energy accelerators
  - Limitations of copper devices (input power and heat generation)
- Superconducting magnets : NbTi, Nb_3Sn
  - Dipole (beam bending)
  - Quadrupole (beam focusing)
- Superconducting RF cavities : Nb
  - Accelerating cavities
  - Crab cavities

Operation Temperature of SC Accelerators

- 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

Surface Resistance of Nb Superconducting Cavities

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

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 $T < T_c/2$

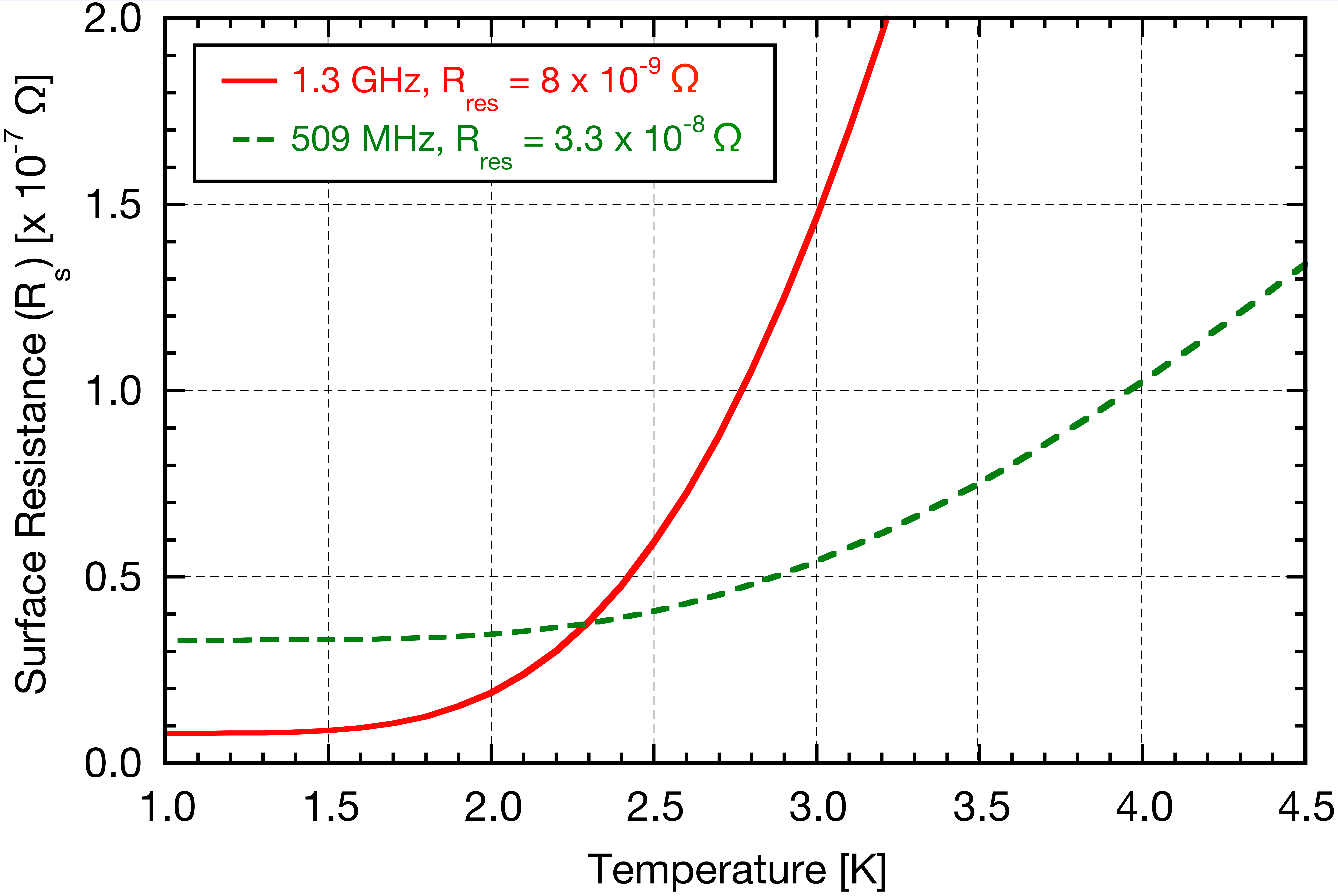
$$R_{BCS} = 2x10^{-4} \frac{1}{T} \left(\frac{f}{1.5} \right)^2 \exp\left(-\frac{17.67}{T} \right)$$

T : Operation temp.

f : Frequency

Padamsee, H. *et al.* “RF Superconductivity for Accelerators”, John Wiley & Sons, 1998

Temperature Dependence of Surface Resistance



Operation Temperature of Superconducting Cavities

- 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

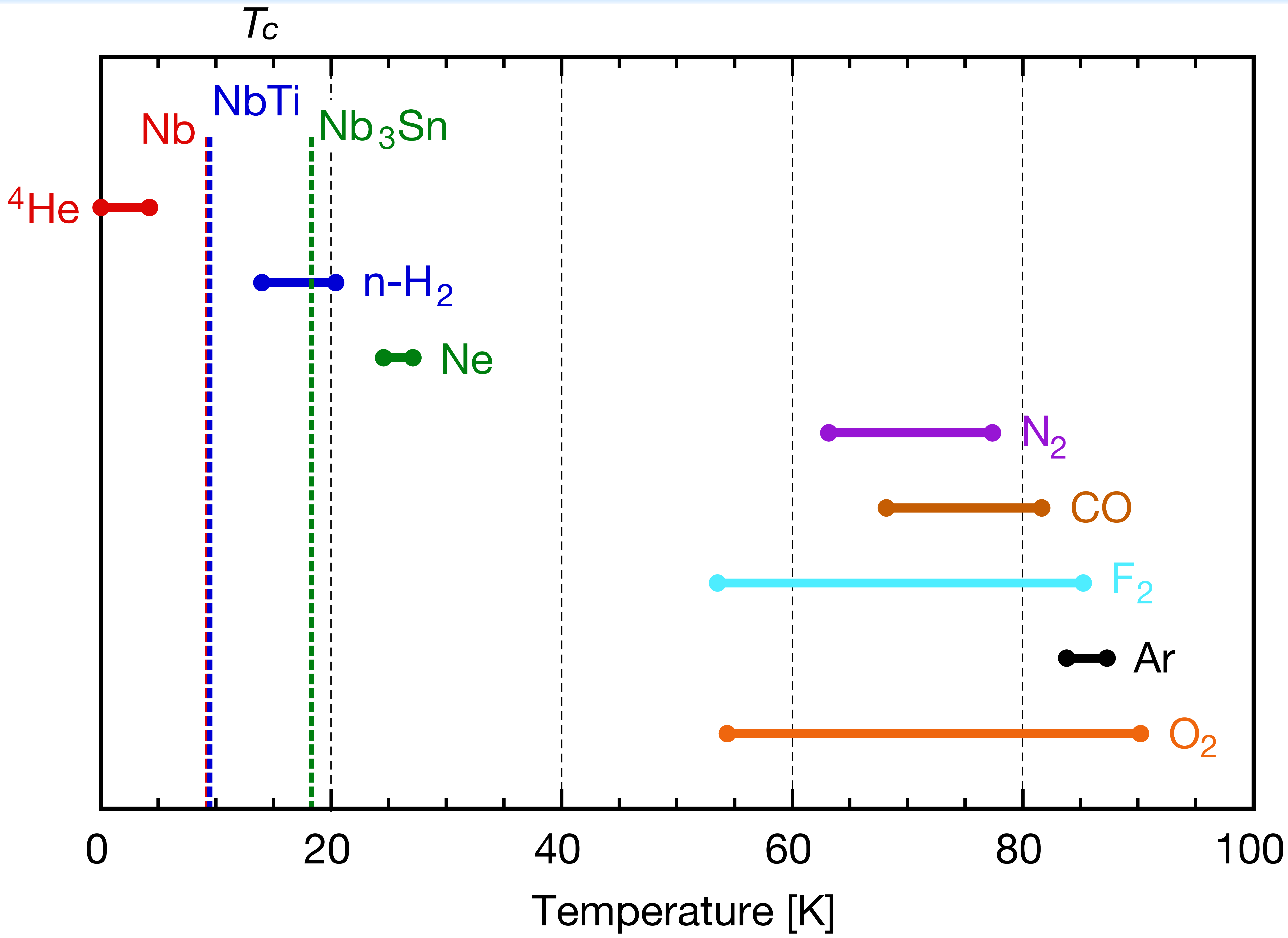
Superfluid Helium

Liquid Phase Temperature Range

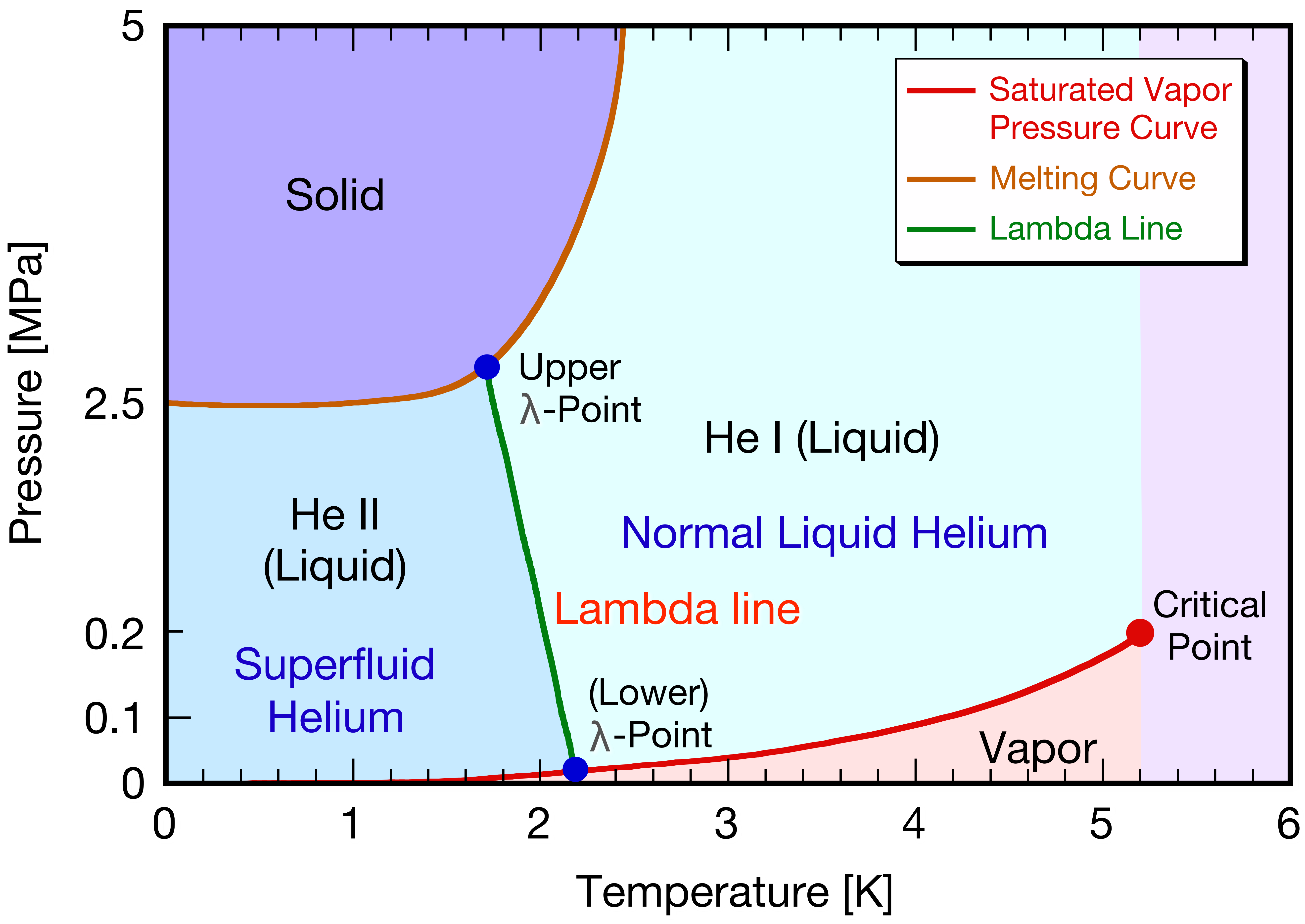
Substance	Triple Point [K]	Boiling Point# [K]
^4He	2.1773*	4.224
p-H_2	13.813	20.278
n-H_2	13.96	20.39
Ne	24.55	27.092
N_2	63.148	77.347
CO	68.14	81.62
F_2	53.48	85.24
Ar	83.78	87.290
O_2	54.361	90.185

Under Atmospheric Pressure   * Lambda Point Temperature

Boiling and Triple Points, Transition Temperatures

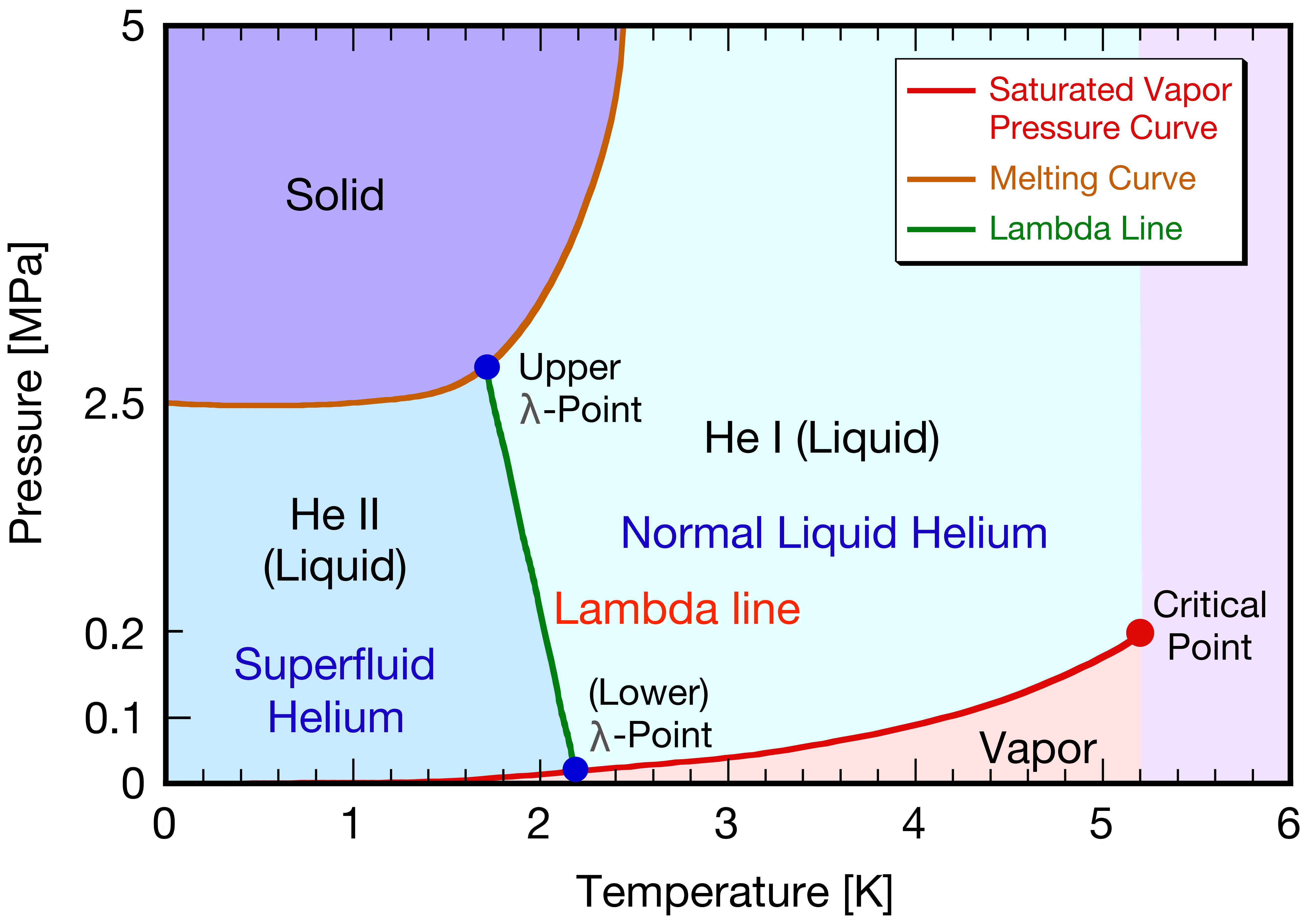


Phase (State) Diagram of Helium



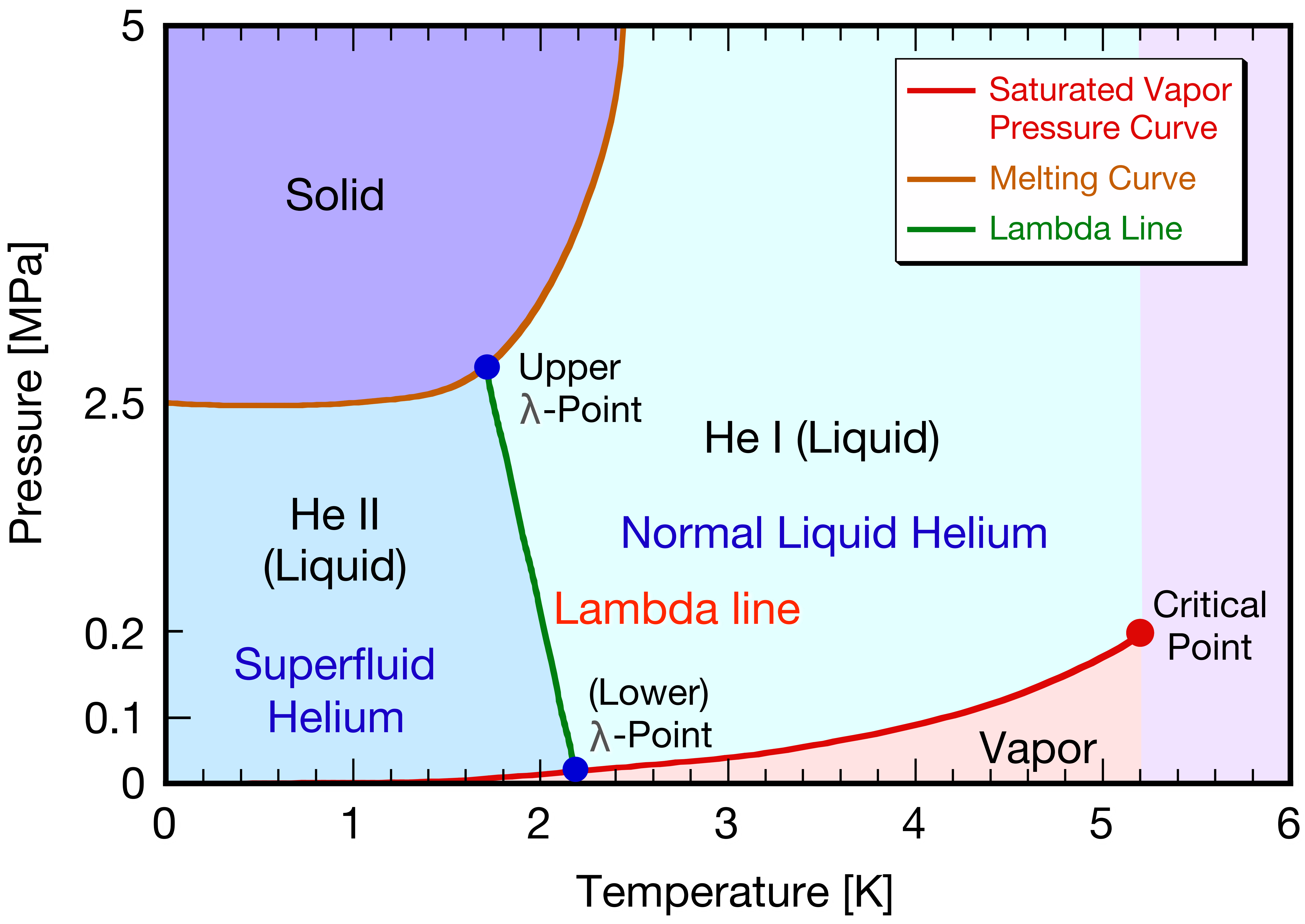
- Liquid phase remains even at 0 K
- Solid appears only under high pressure (above 2.5 MPa)
- Two different liquid phases
  - He I ('ordinary' liquid helium, normal fluid phase)
  - He II (superfluid helium, superfluid phase)
- Lambda line — border of these two liquid phases

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)

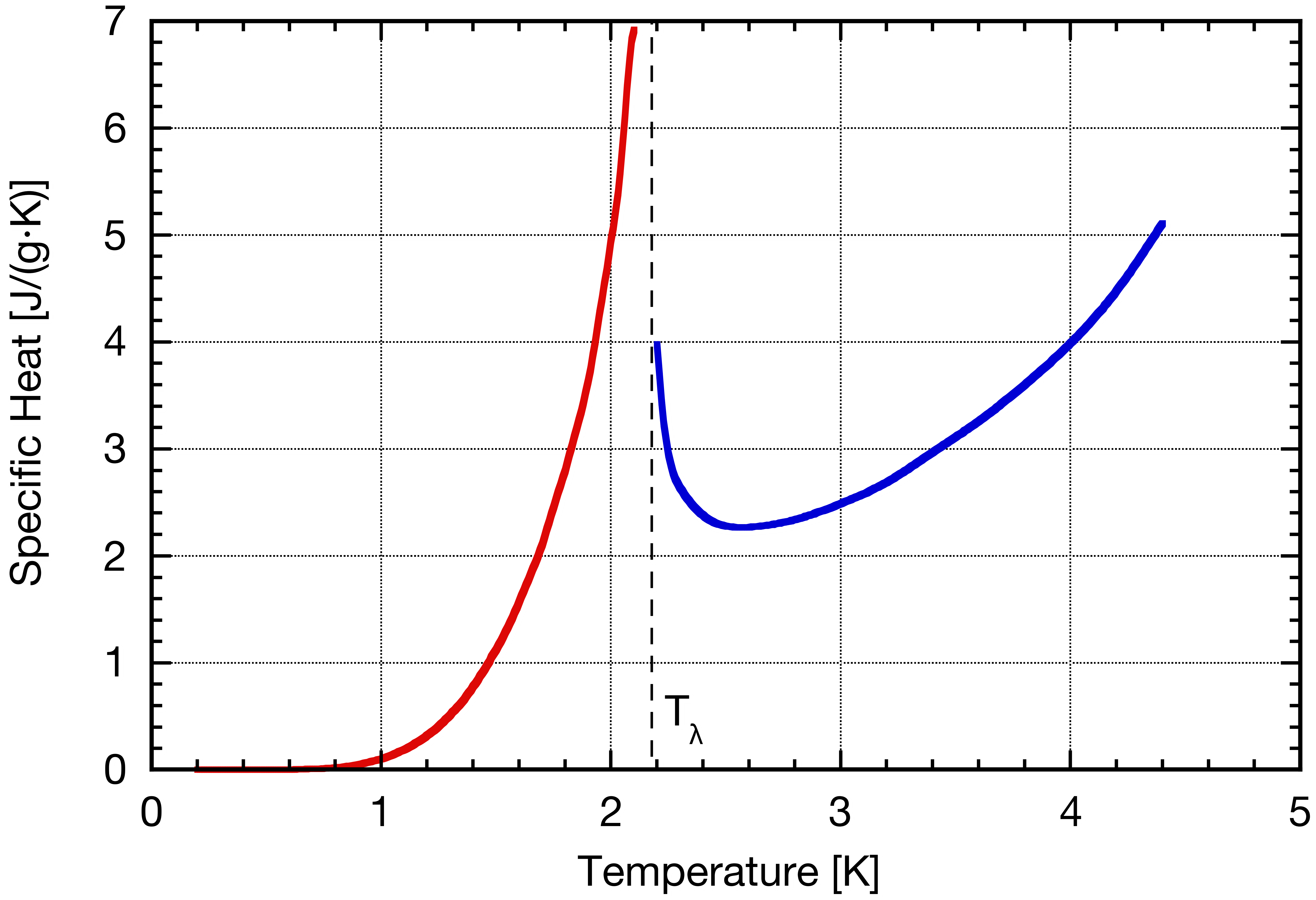
Phase (State) Diagram of Helium (cont'd)



- 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

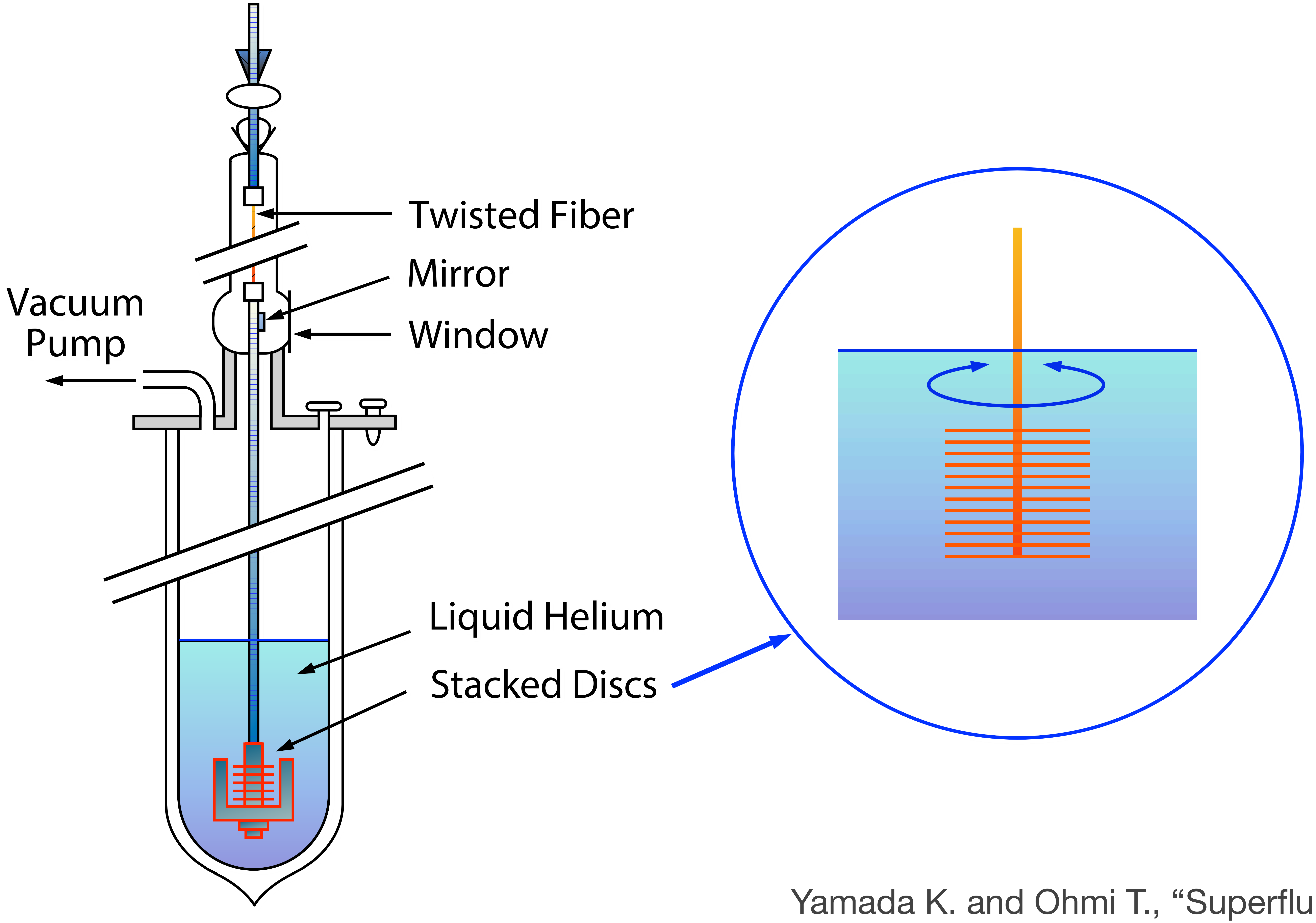
(Figures may vary among references)

Specific Heat of Liquid Helium



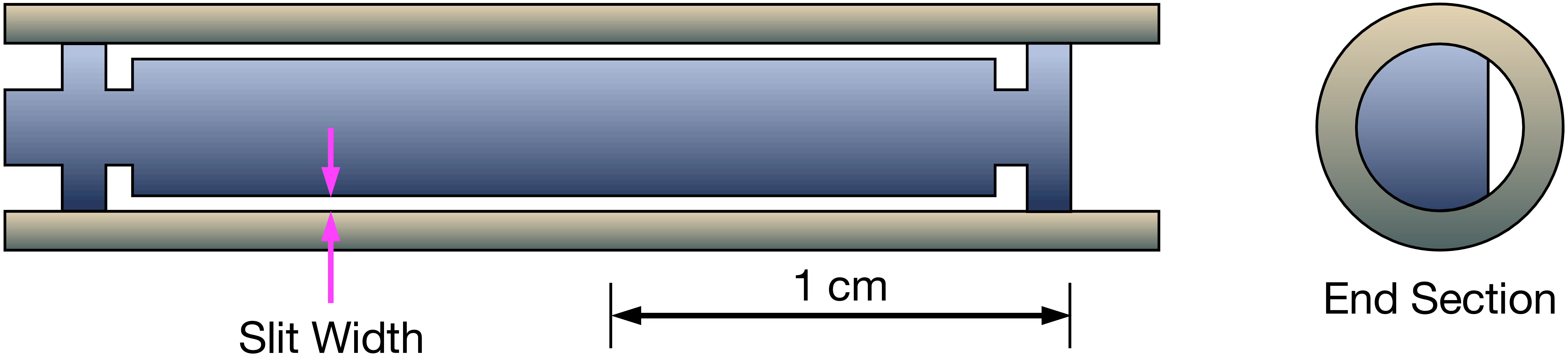
Schmidtchen, U., Private Communication (1984)

Rotational Viscometer



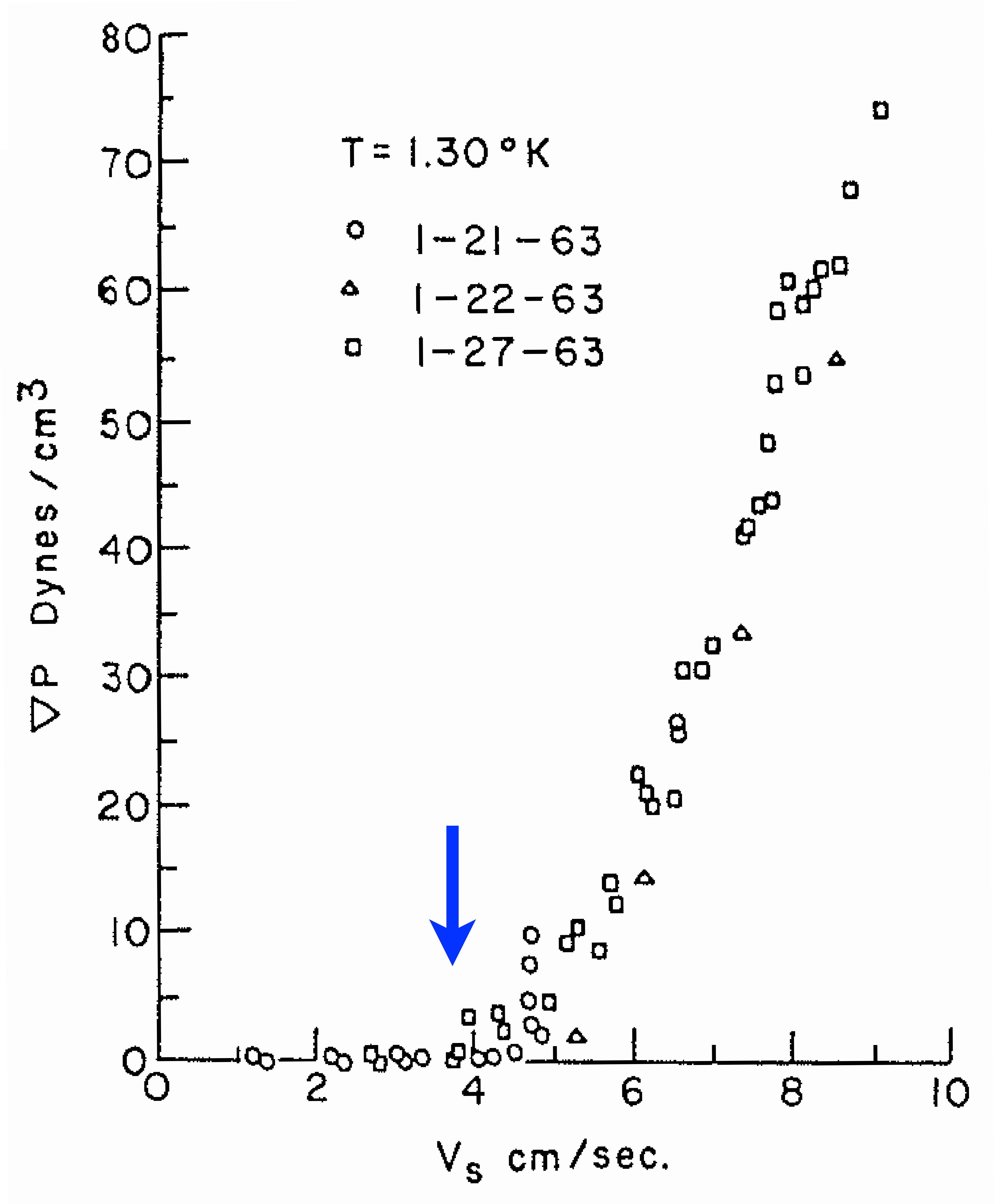
Yamada K. and Ohmi T., “Superfluidity”, Baifukan (1995)

Flow Through Slit (1)



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

Flow Through Slit (2)



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

Poiseuille Flow

Radius of Flow Path

Pressure Difference

Mean Velocity

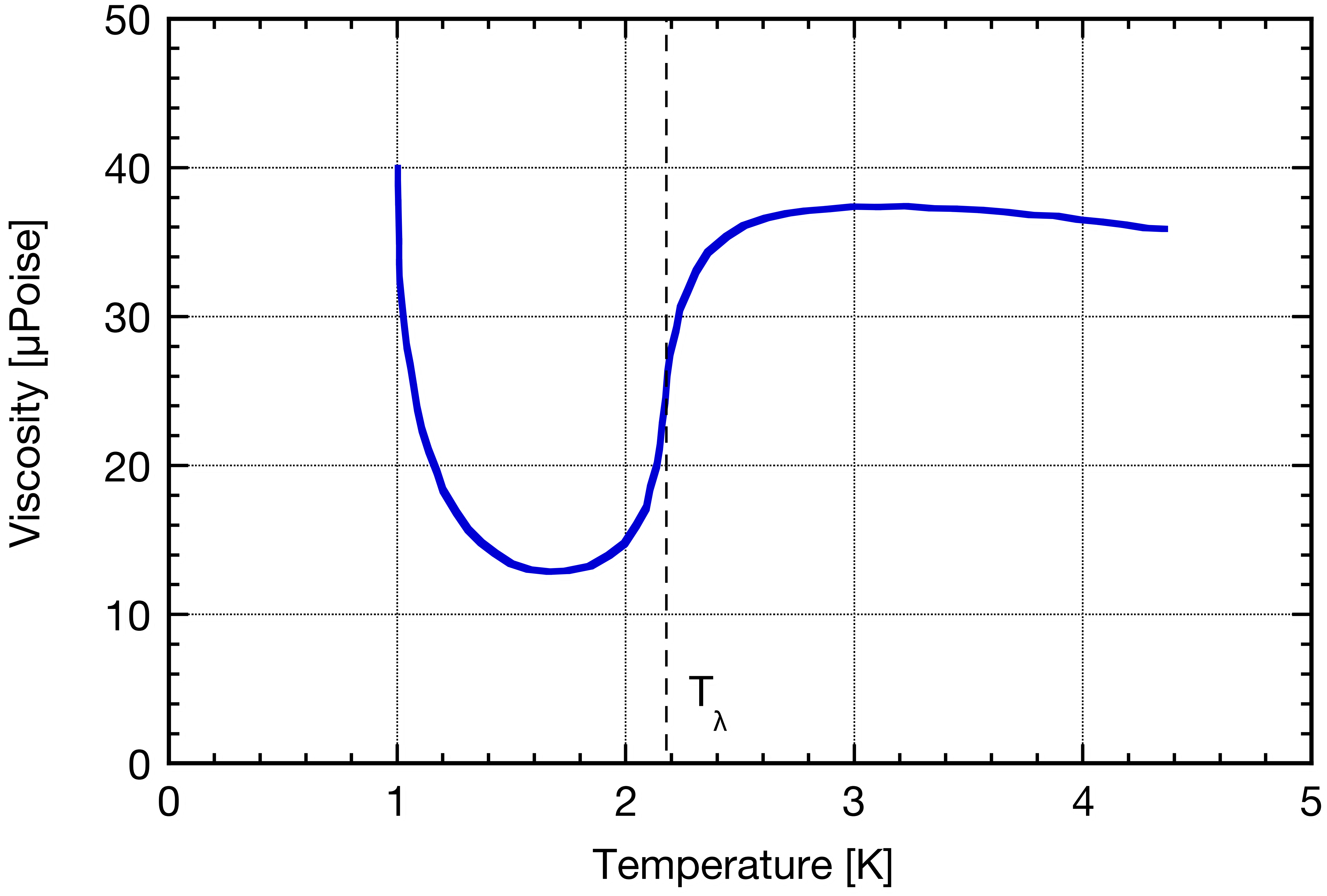
$$V = \frac{a^2}{8L\eta}\Delta P$$

Path Length

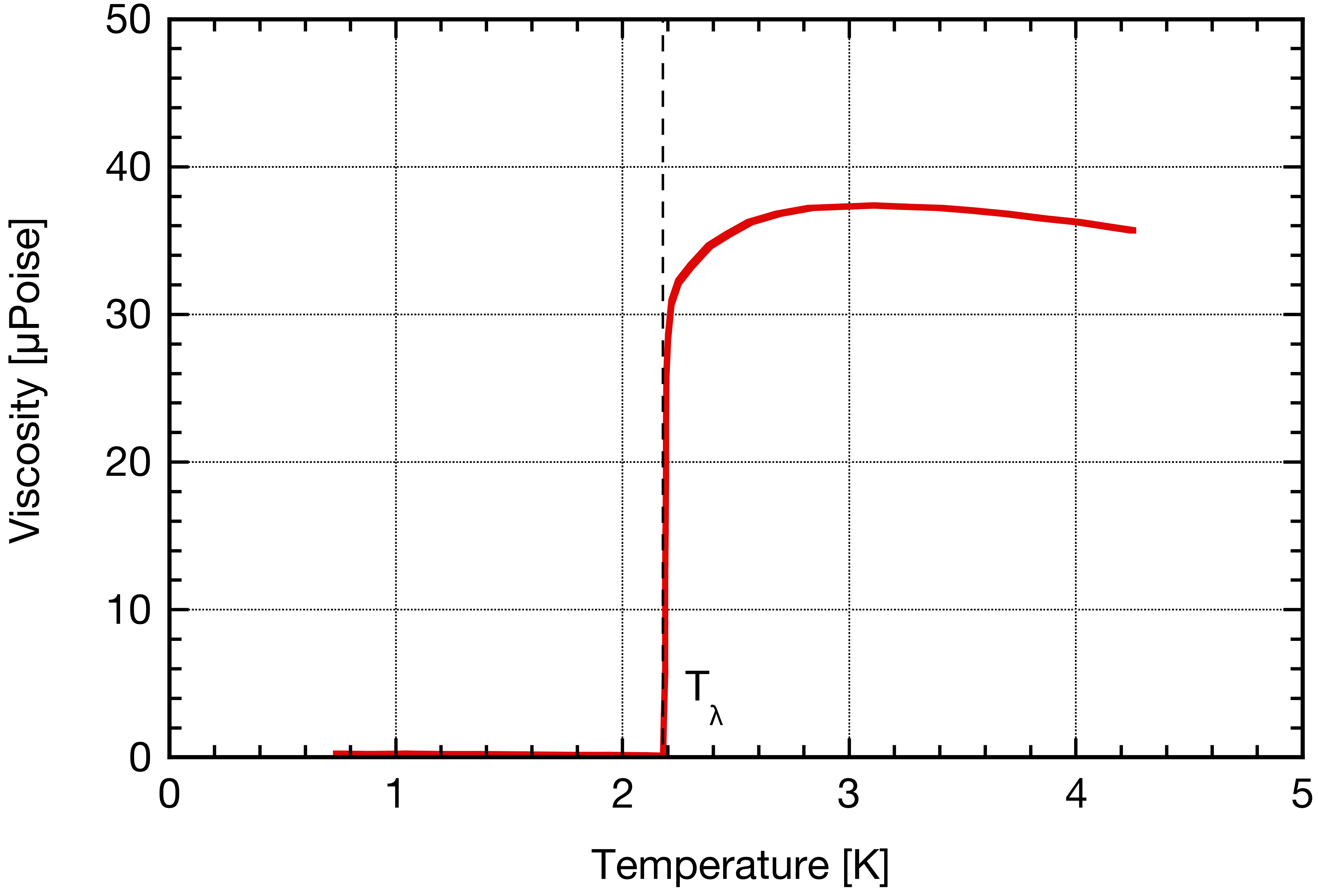
Viscosity of Fluid

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

Two Different Results of Viscosity Measurement



Rotational Viscometer



Poiseuille Flow in Capillary

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

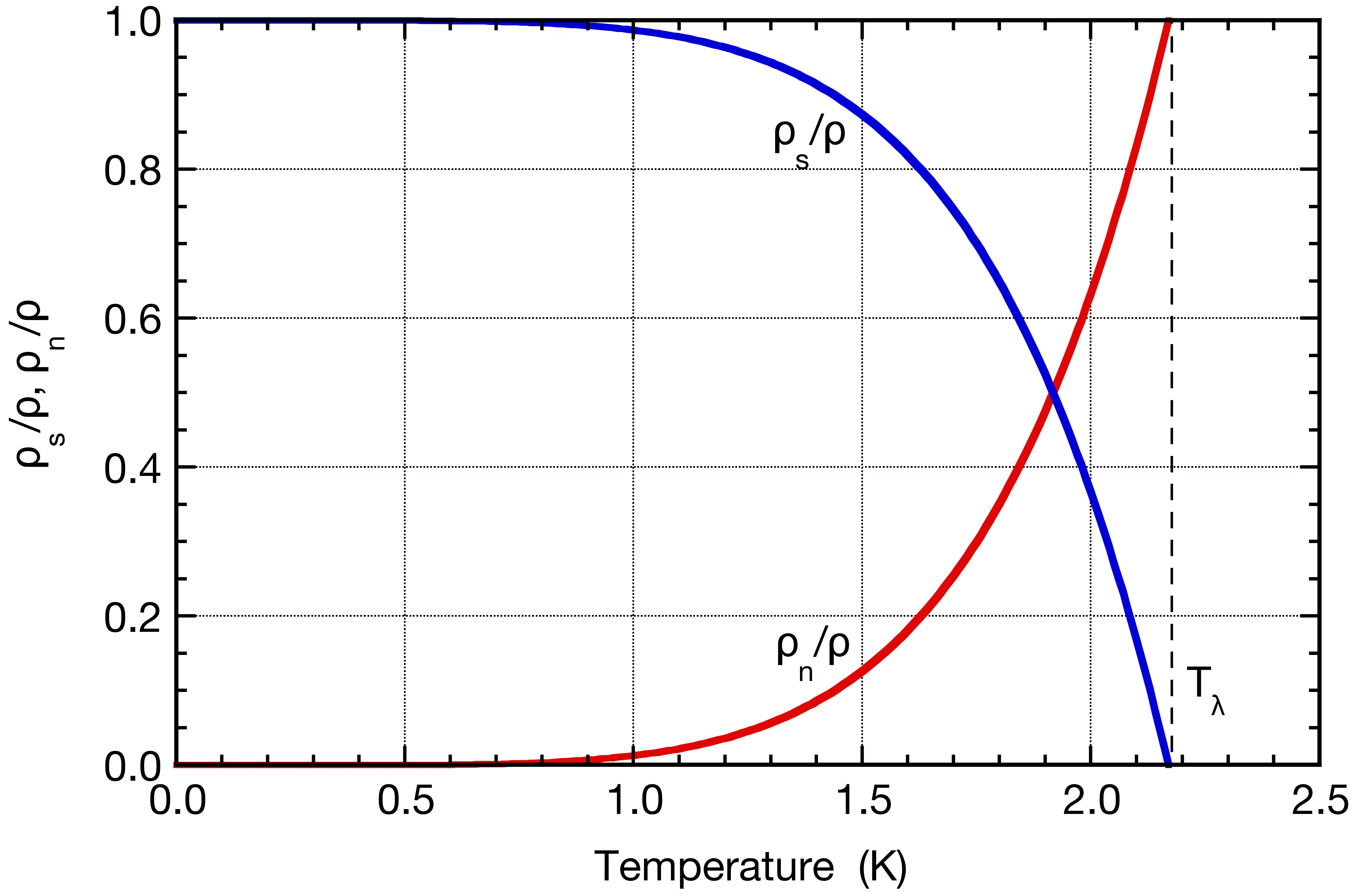
Two-fluid Model (1)

- 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”)

Two-fluid Model (2)

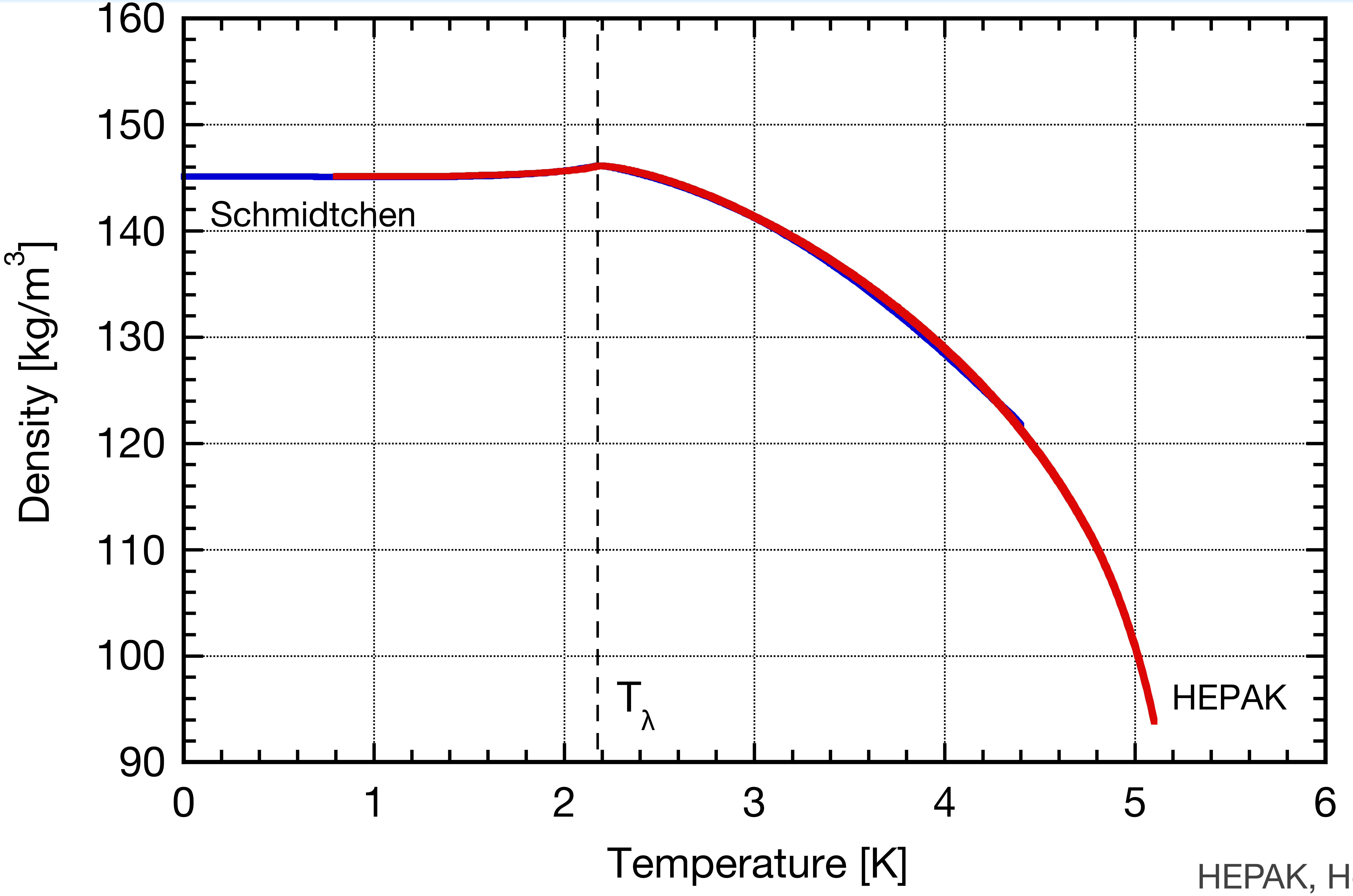
	Normal Fluid Component Normal Fluid	Superfluid Component Superfluid
Density	ρ_n	ρ_s
Viscosity	μ	0
Entropy Transport	Yes	No
Driving Force	Pressure Difference	Temperature Difference

Two-fluid Model (3)



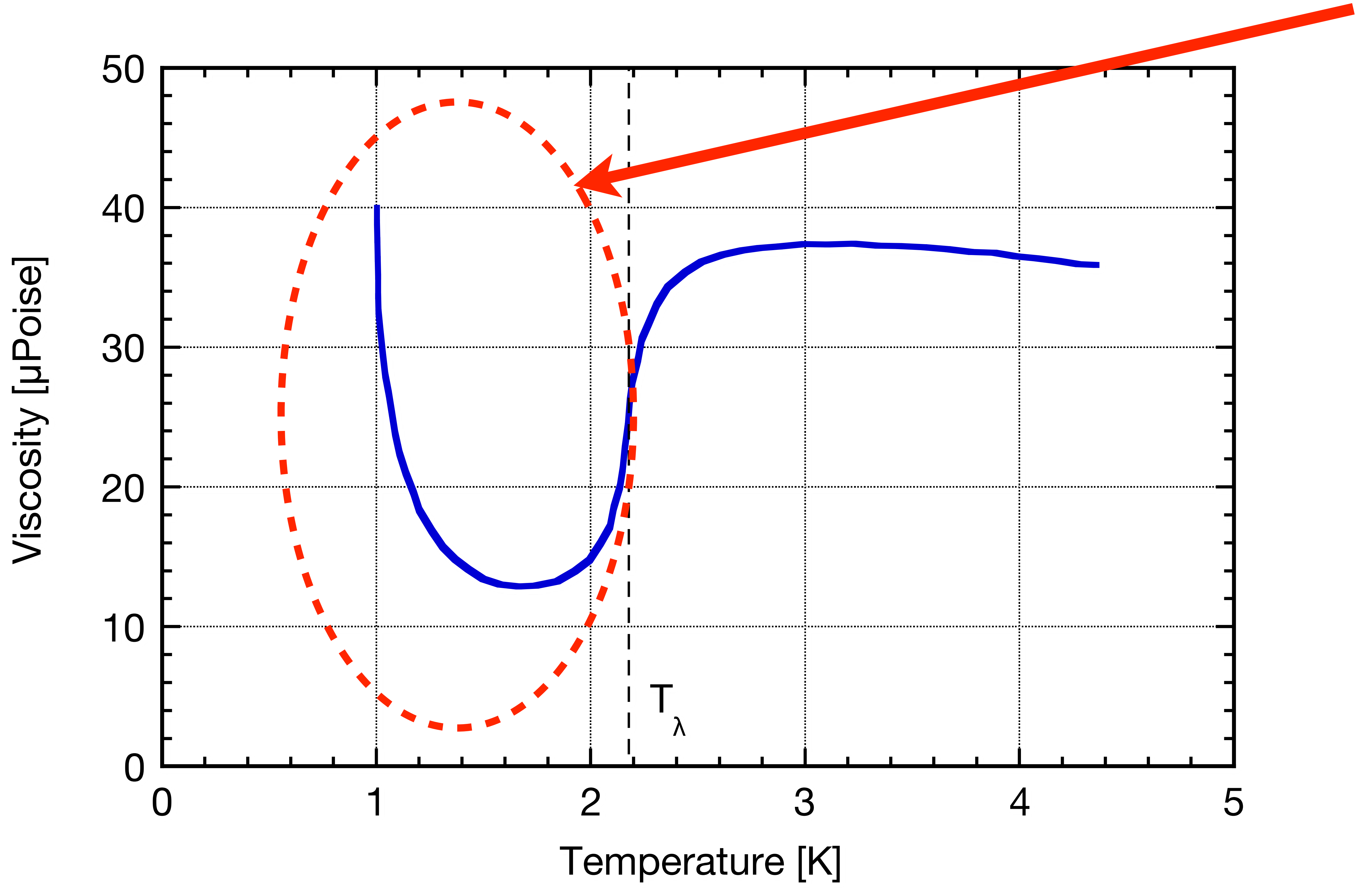
- Overall density is sum of densities of each components
- Density ratios (ρ_s/ρ, ρ_n/ρ) depend on temperature
- Each component makes independent flow field
- No interaction between each component flows

Density of Liquid Helium

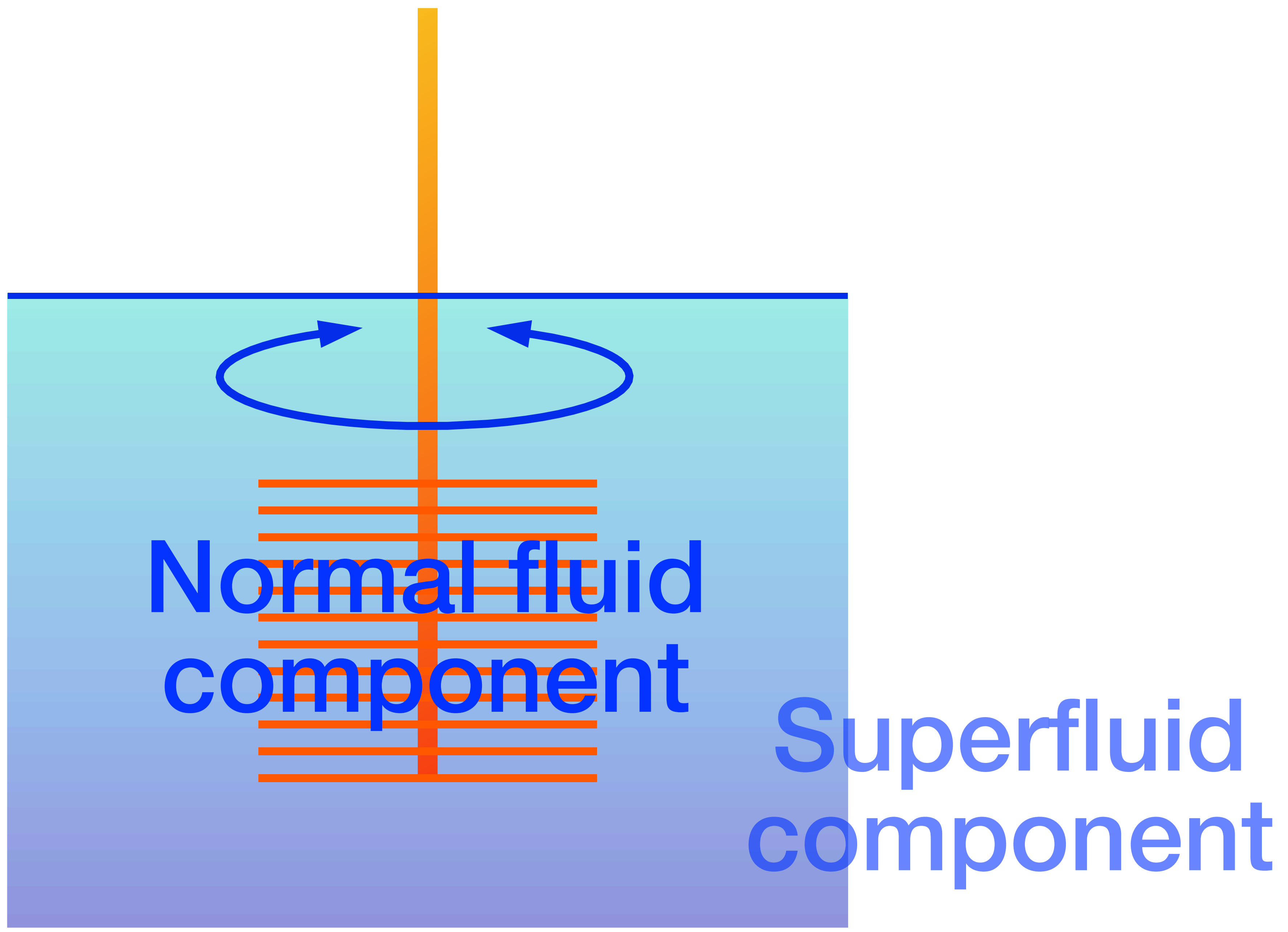


HEPAK, Horizon Technologies
Schmidtchen, U., Private Communication (1984)

Rotational Viscometer Result

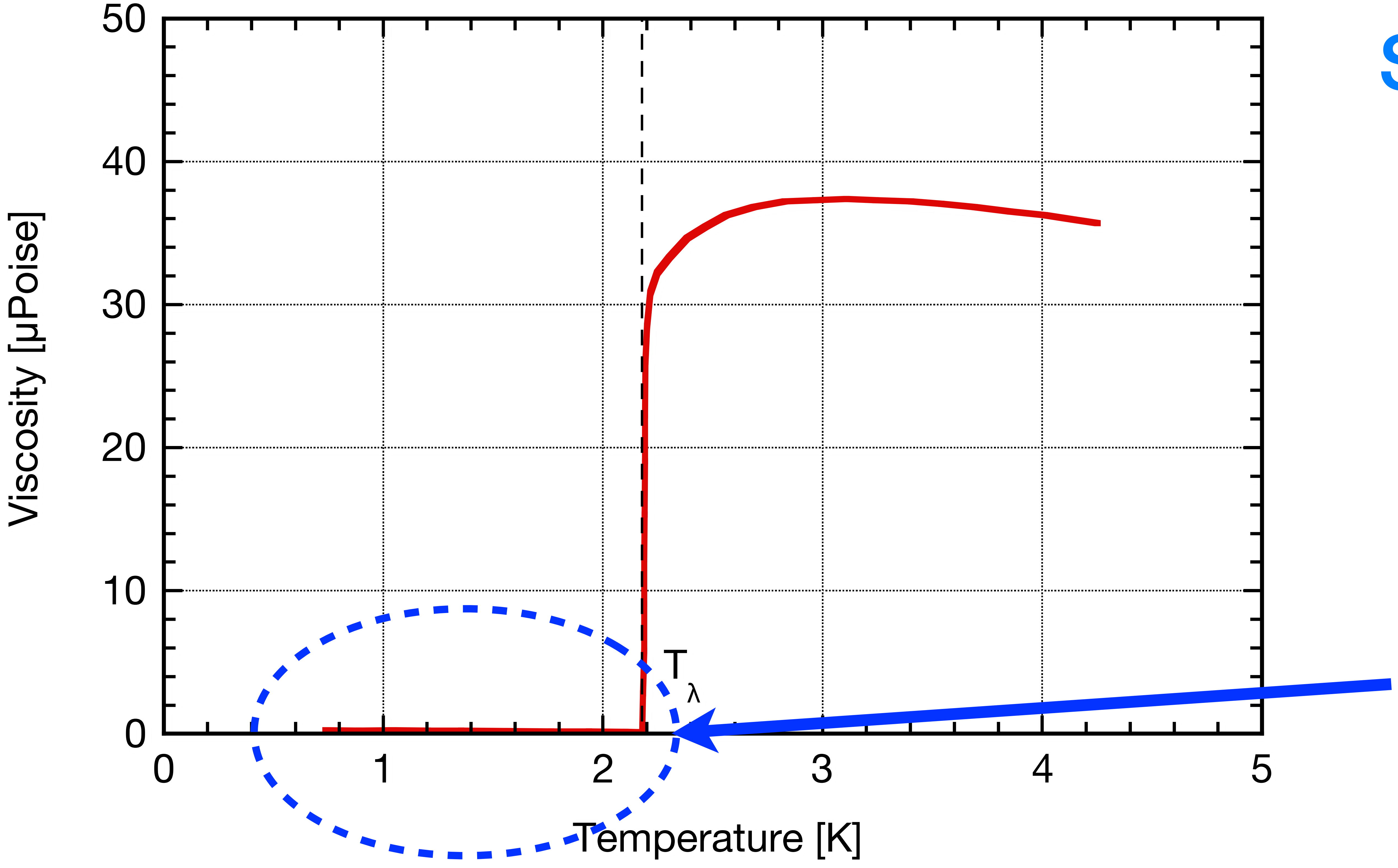


Normal fluid component motion with disks because of its viscosity

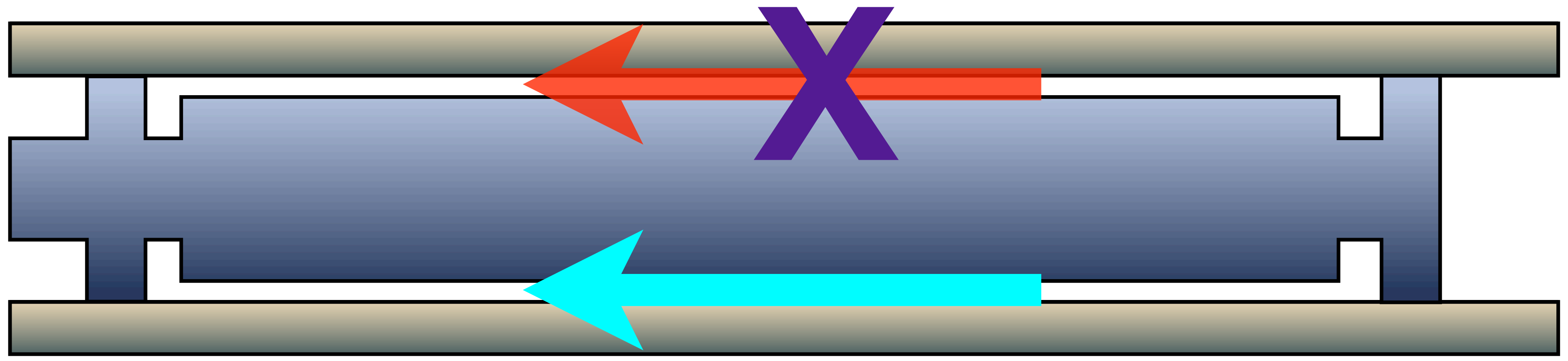


Superfluid component unrelated with disk motion

Flow-Through-Slit Result



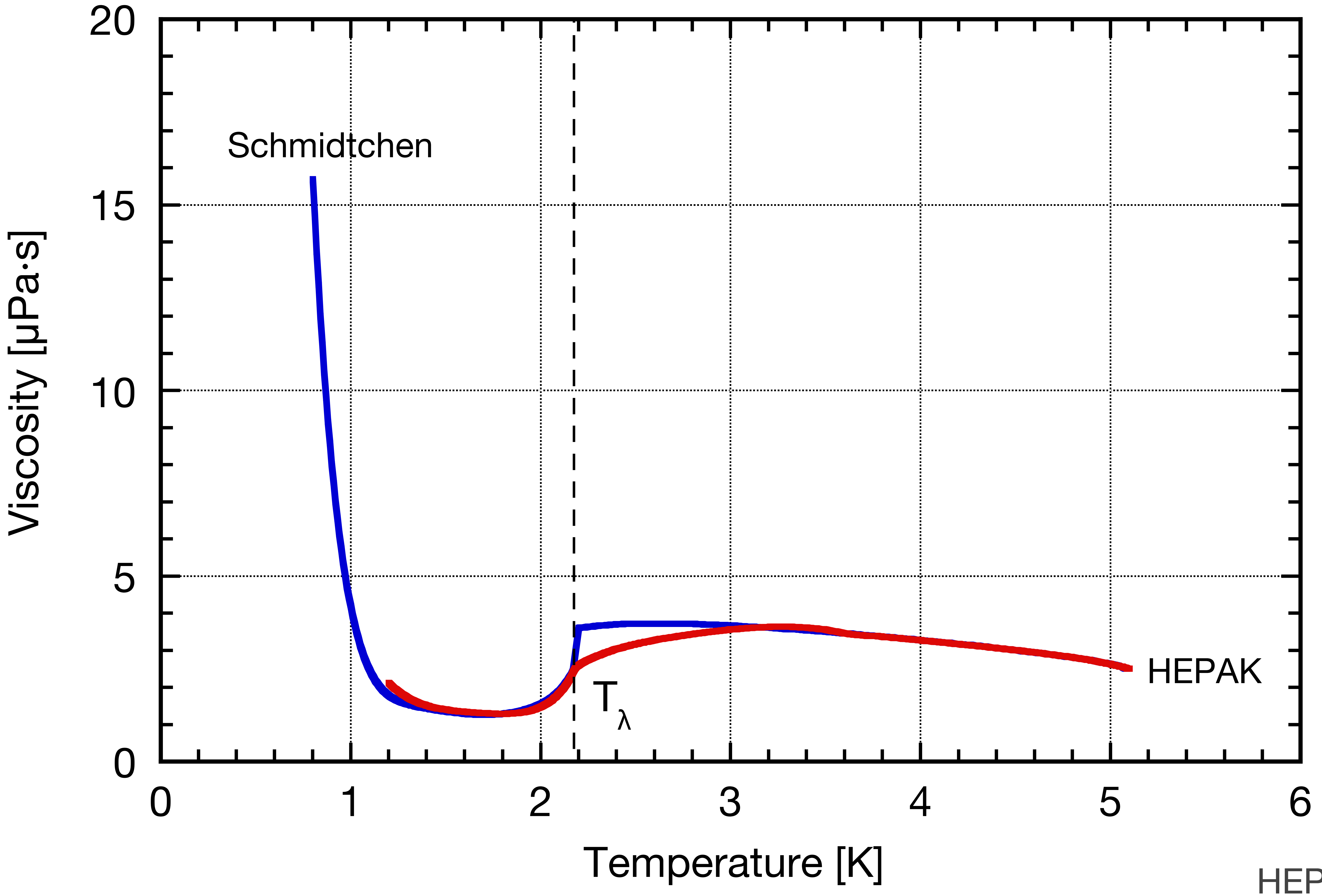
Stagnant normal fluid flow in the slit because of its viscosity



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)

Two-fluid Model (4)

Density of Superfluid Component

Density of Normal Fluid Component

Overall Density

Overall Momentum Density

$$\rho = \rho_s + \rho_n$$

$$\mathbf{j} = \rho_s \mathbf{v}_s + \rho_n \mathbf{v}_n$$

Velocity Field of Superfluid Component

Velocity Field of Normal Fluid Component

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

Equations of Continuity and Momentum Conservation

Total Fluid Continuity Equation

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

Total Fluid Momentum Equation

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

Vendramini, C. A., Séminaires du SACM, Irfu, CEA (2015)

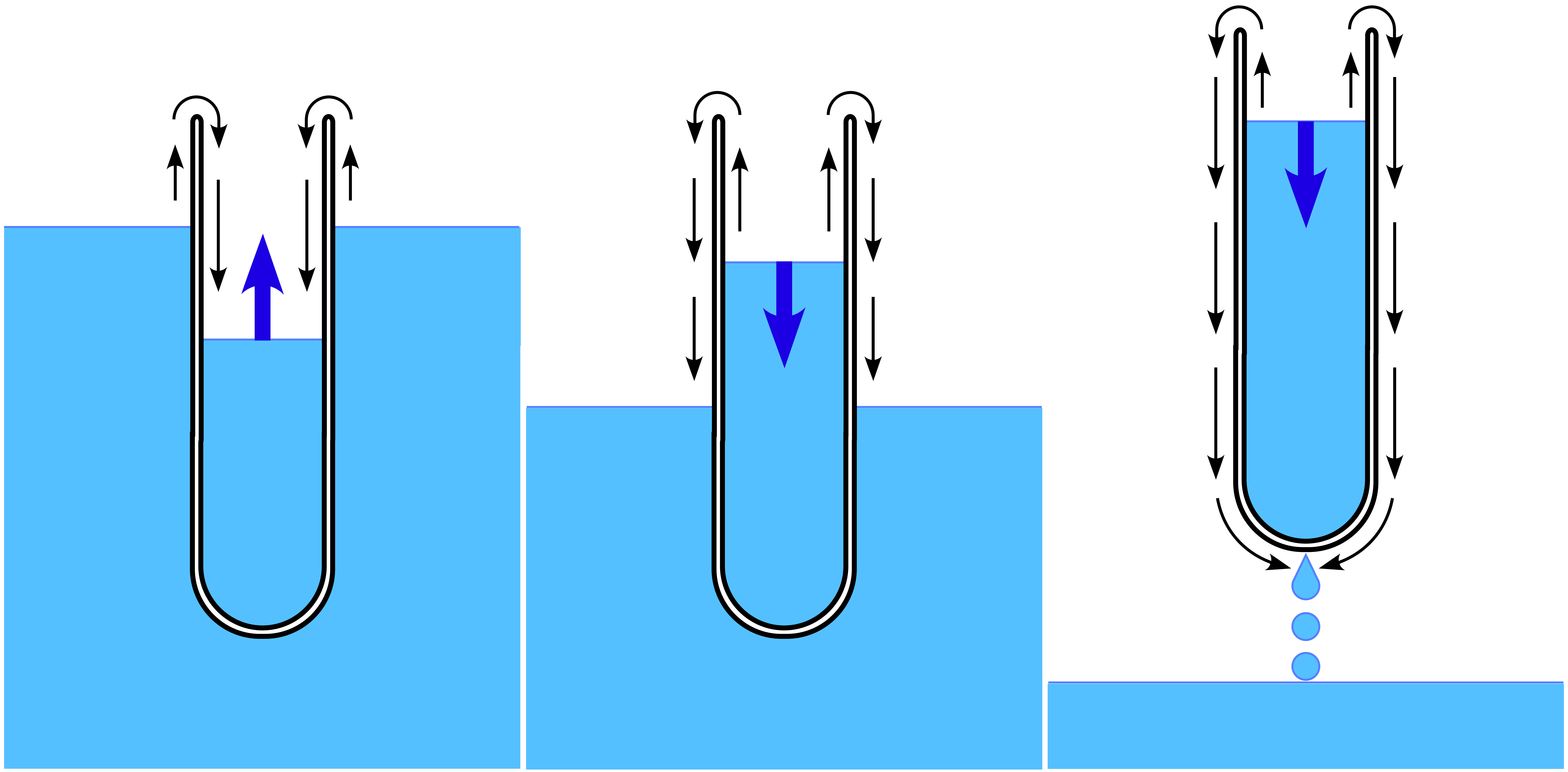
Momentum Equations for Each Component

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

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

Vendramini, C. A., Séminaires du SACM, Irfu, CEA (2015)

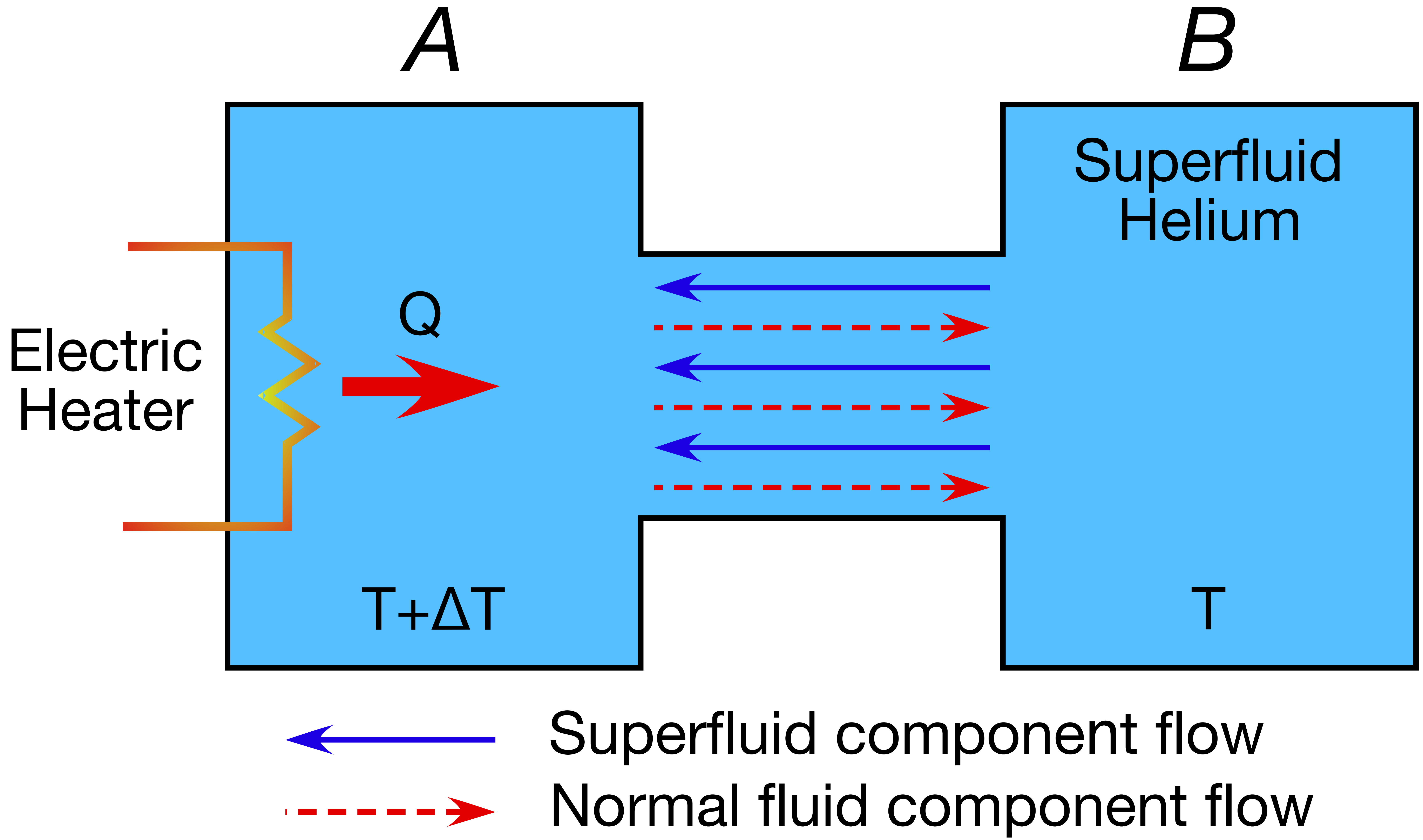
Film Flow



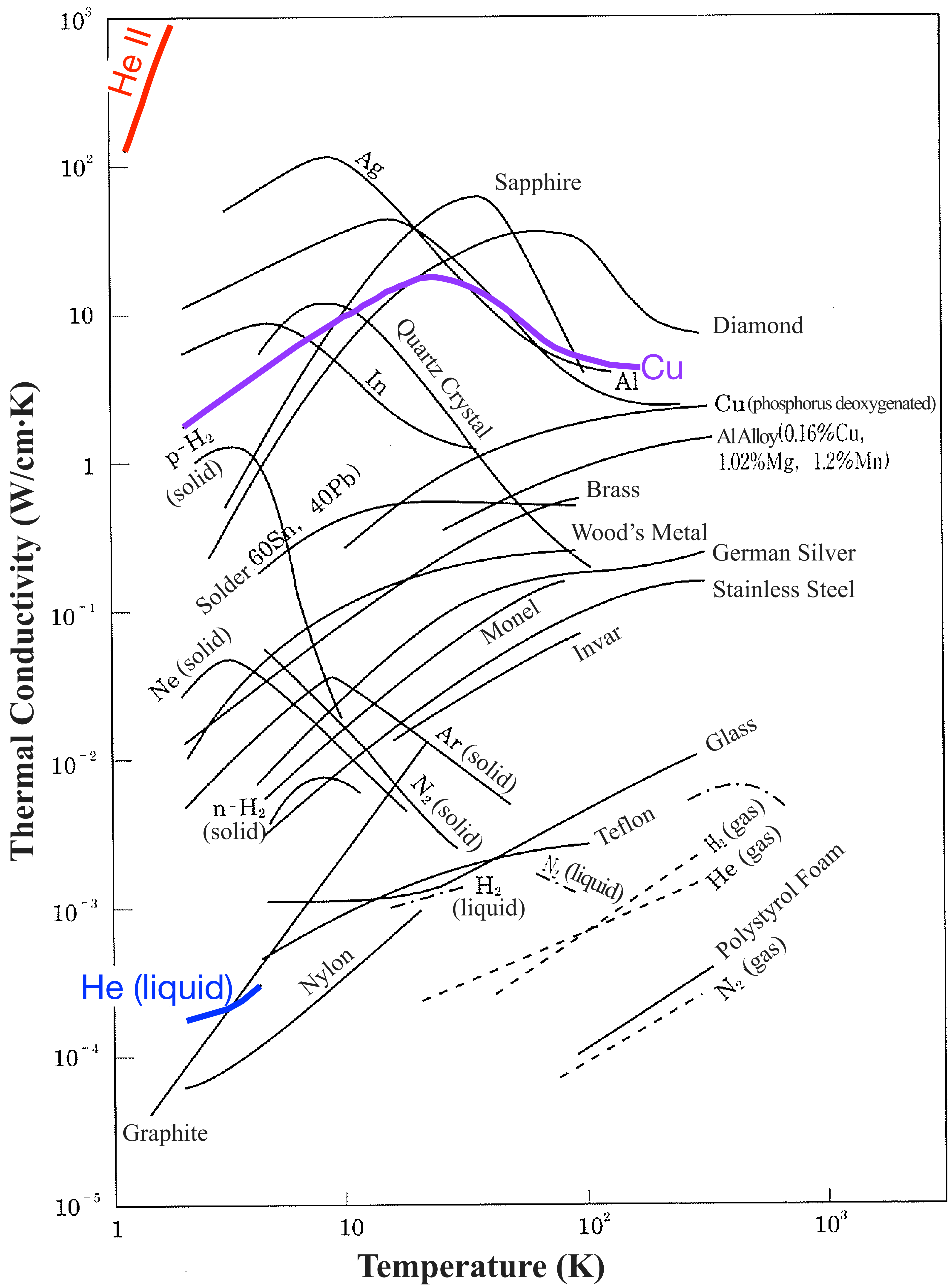
(A) (B) (C)

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)

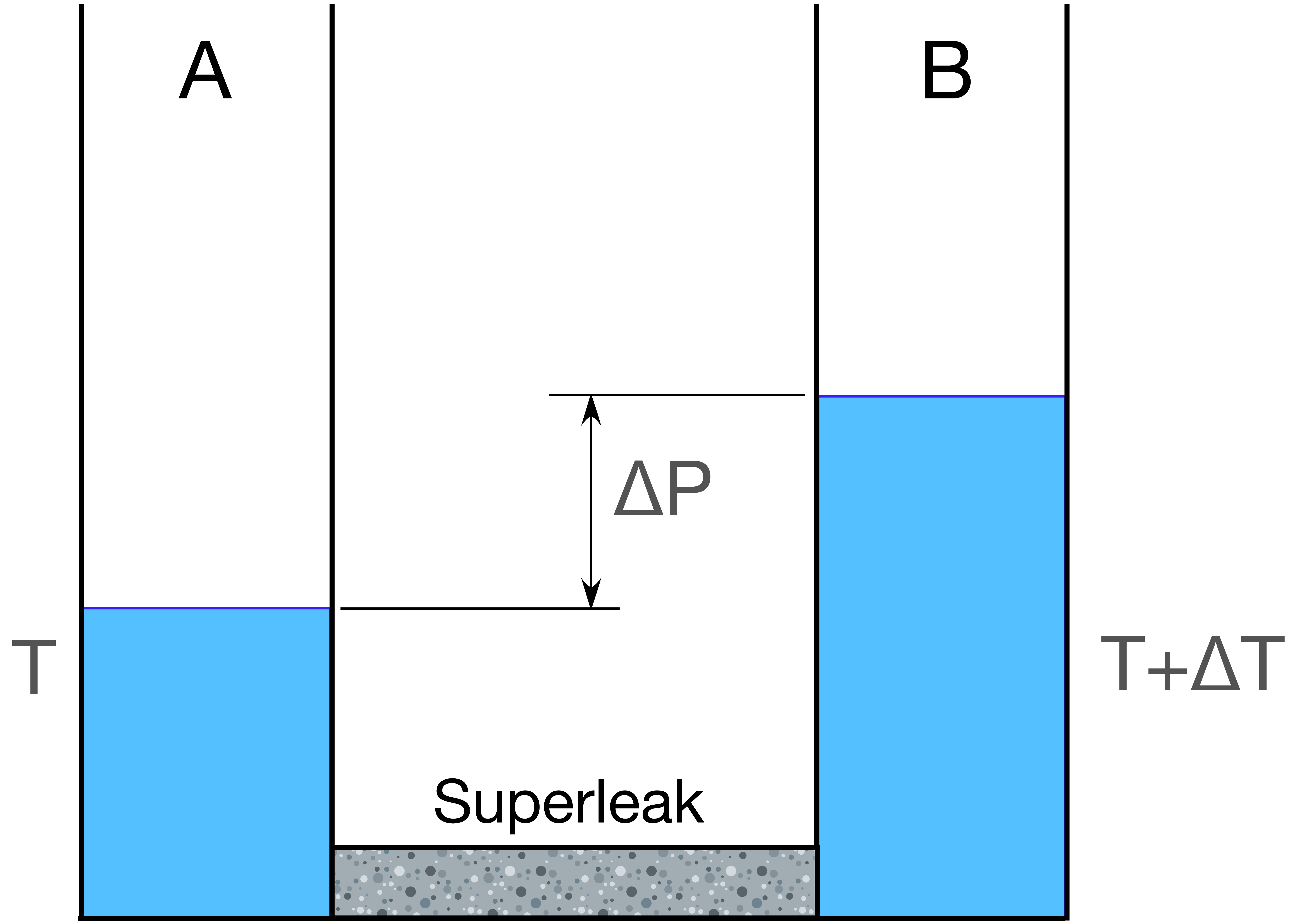


Thermal Conductivity

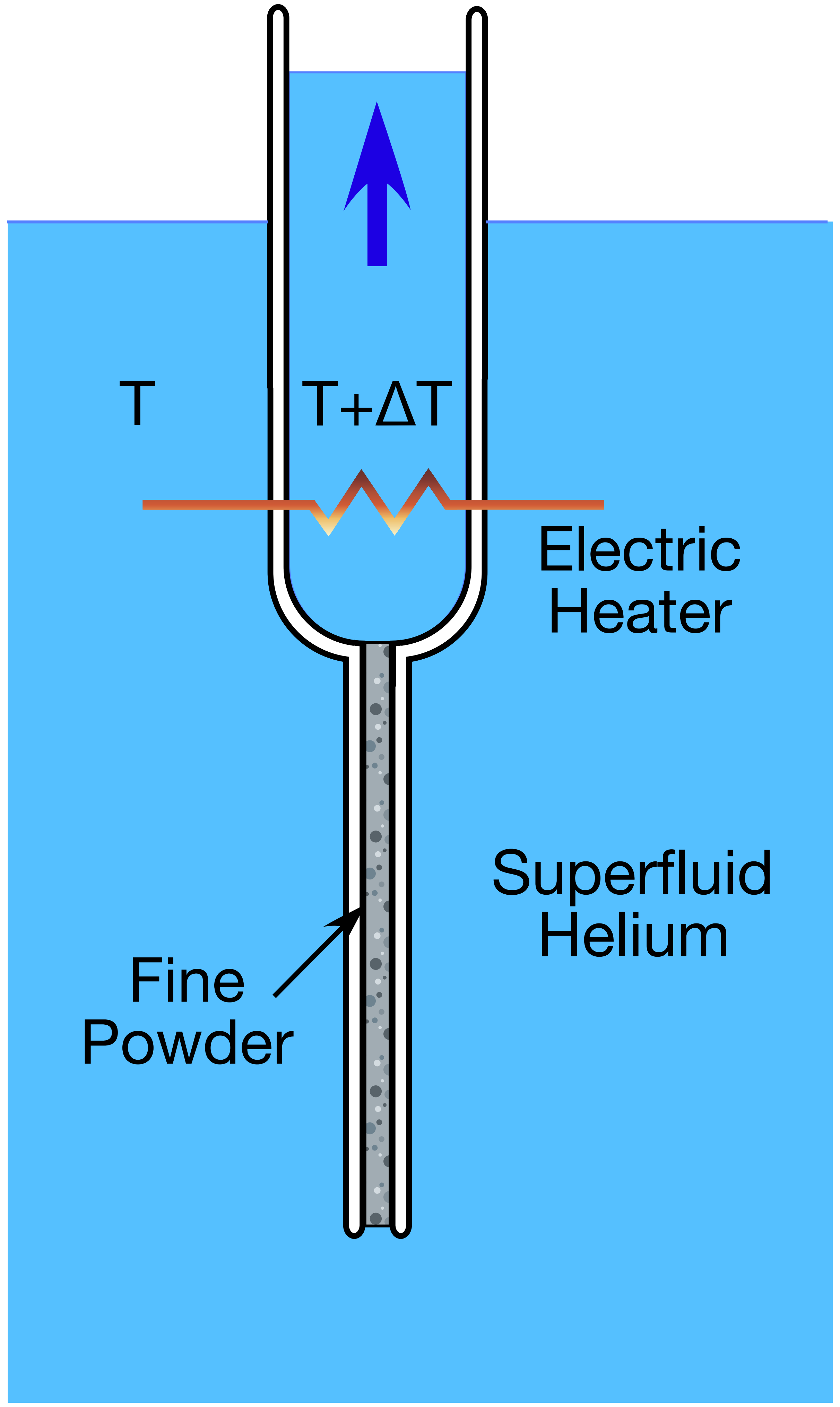
- (Apparent) thermal conductivity of superfluid helium
  - Much larger than that of pure copper
  - Different mechanism of other substances and materials

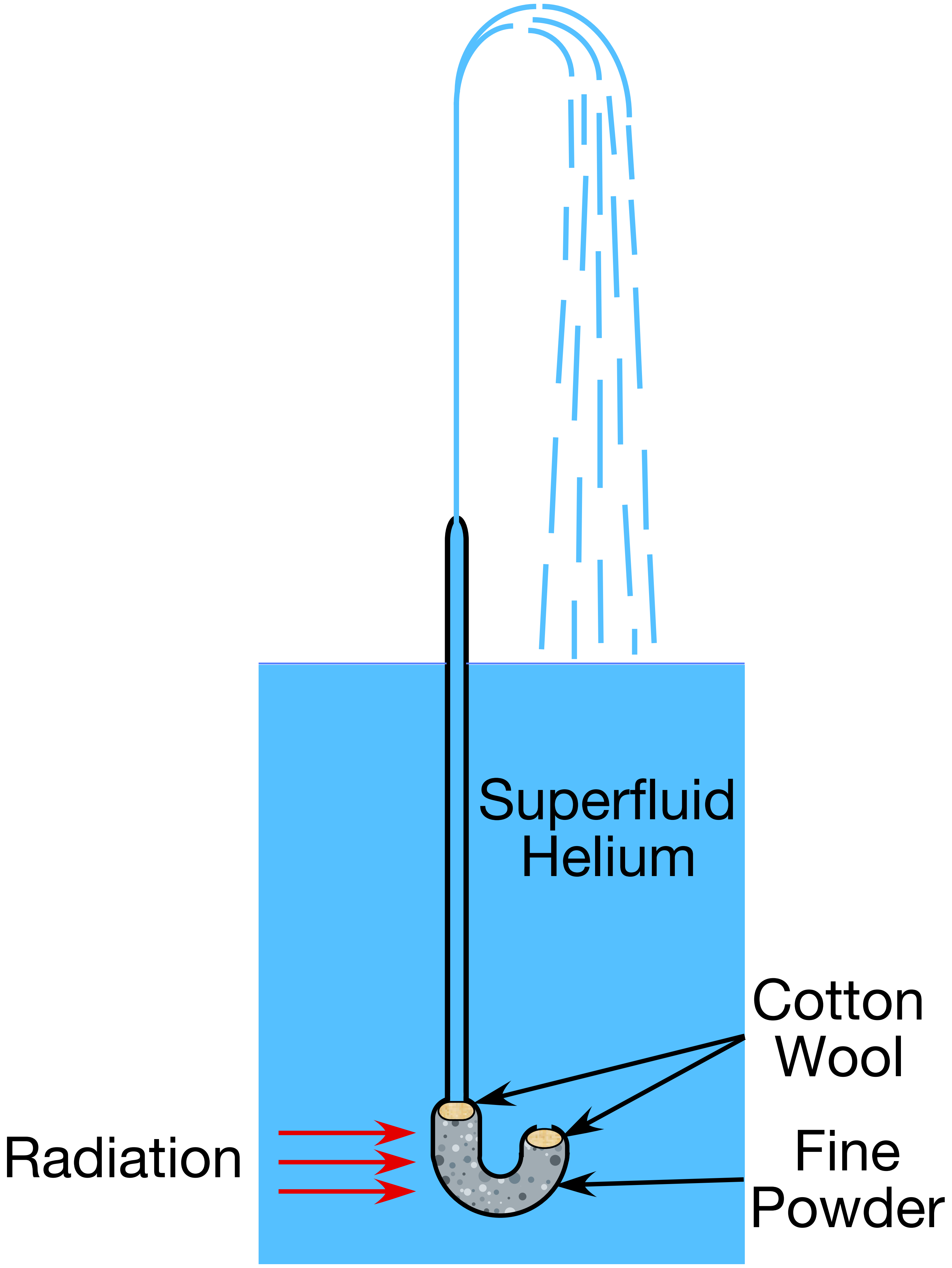
Verein Deutscher Ingenieure, "Lehrgangshandbuch Kryotechnik" (1977)

Thermomechanical Effect (1)



Thermomechanical Effect (2)





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

London's Relation

Density

Entropy

Pressure Difference

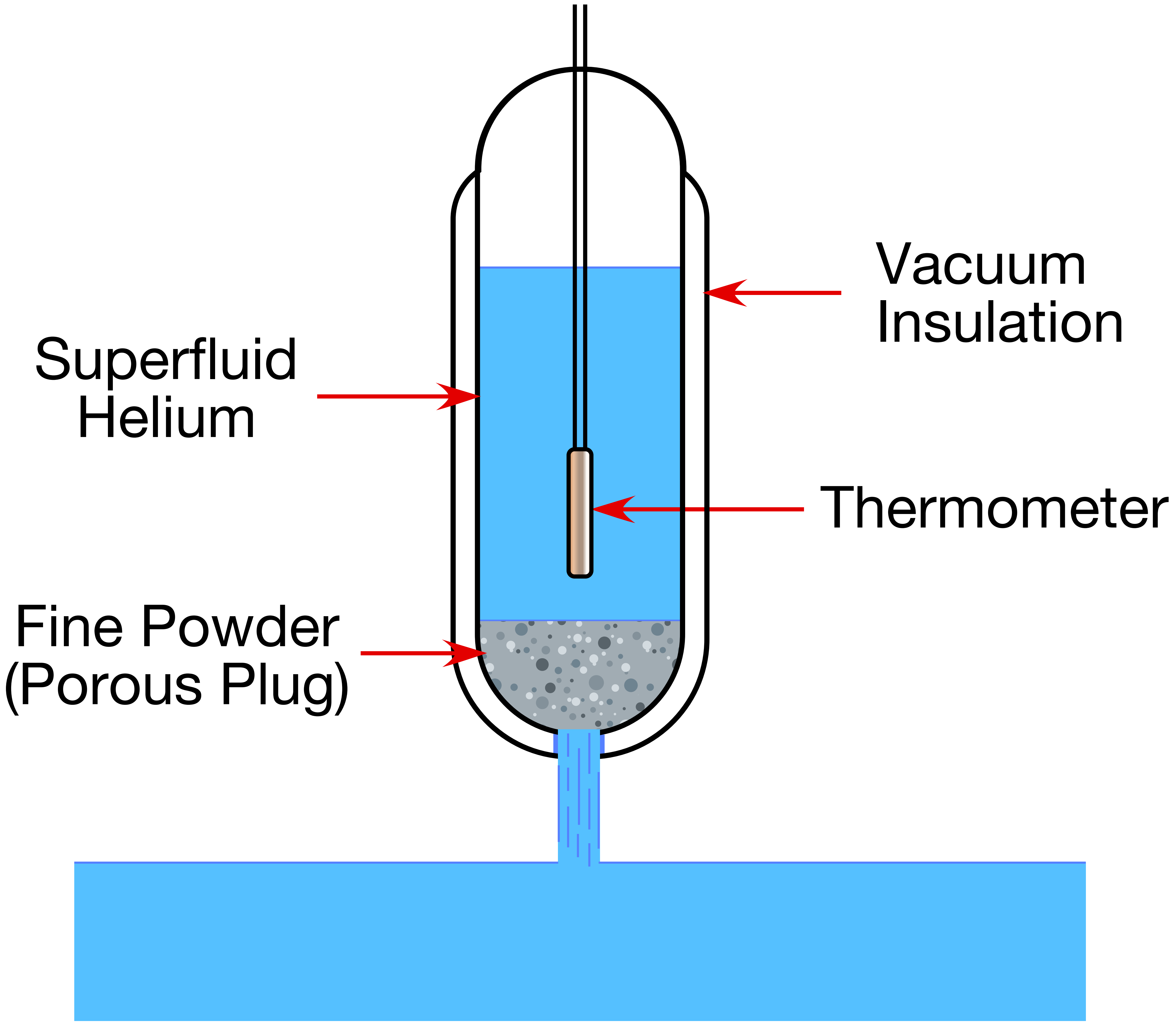
$$\Delta P = \rho s \Delta T$$

Temperature Difference

Fountain Effect

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

Mechanocaloric Effect



Entropy Filter

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

Superfluid Helium

- Superfluidity
  - Superfluid helium can flow through a capillary without any friction
- Super thermal conductivity
  - Apparent thermal conductivity is more than 100 times of that of pure copper
- Film flow
  - Superfluid helium can flow through an adsorbed film whose thickness is just a few atoms (20–30 nm)

Superfluid Helium and Superconducting Devices

- 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

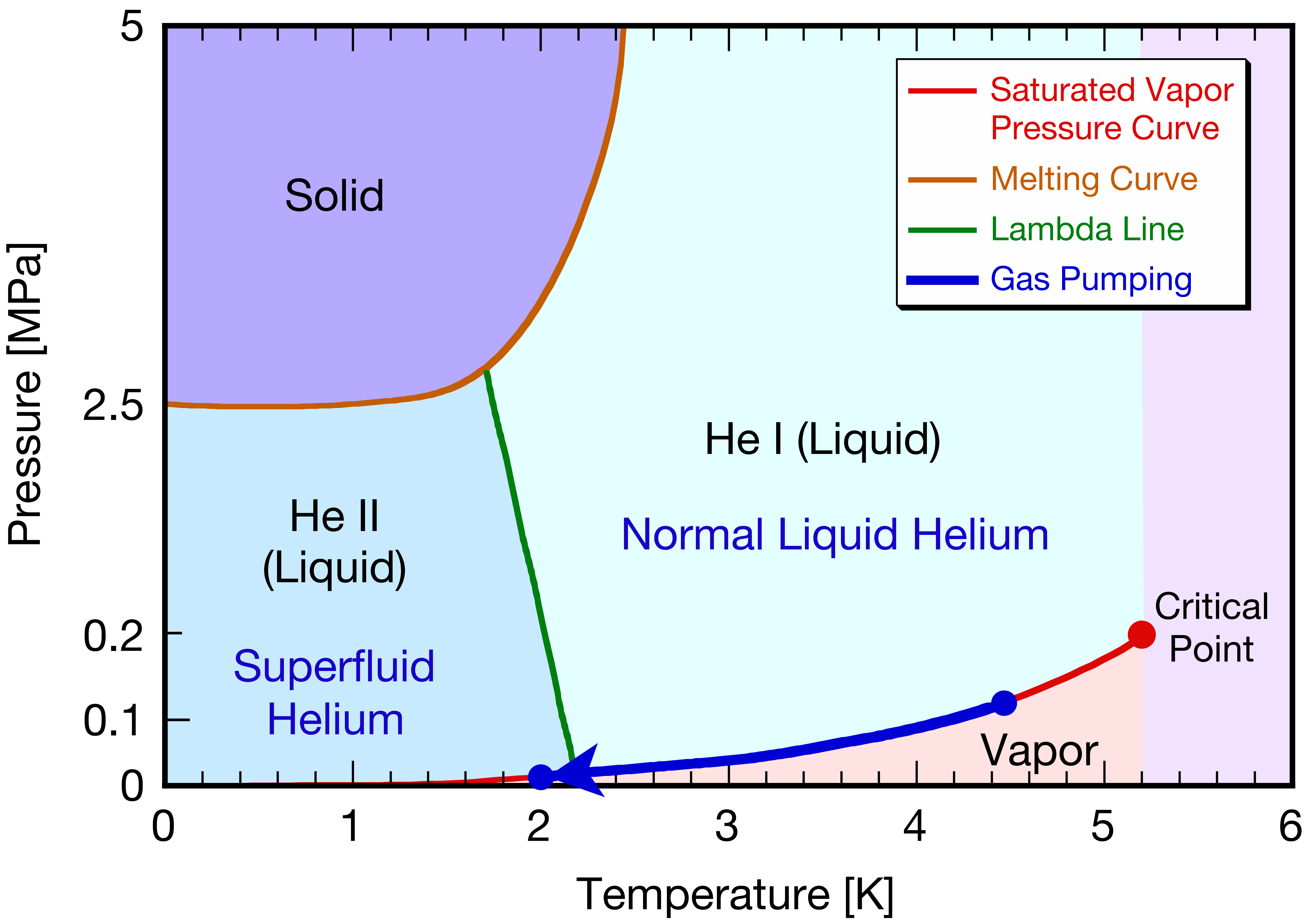
Superfluid Helium Cryogenic Systems

Classification of Cryogenic Refrigerators

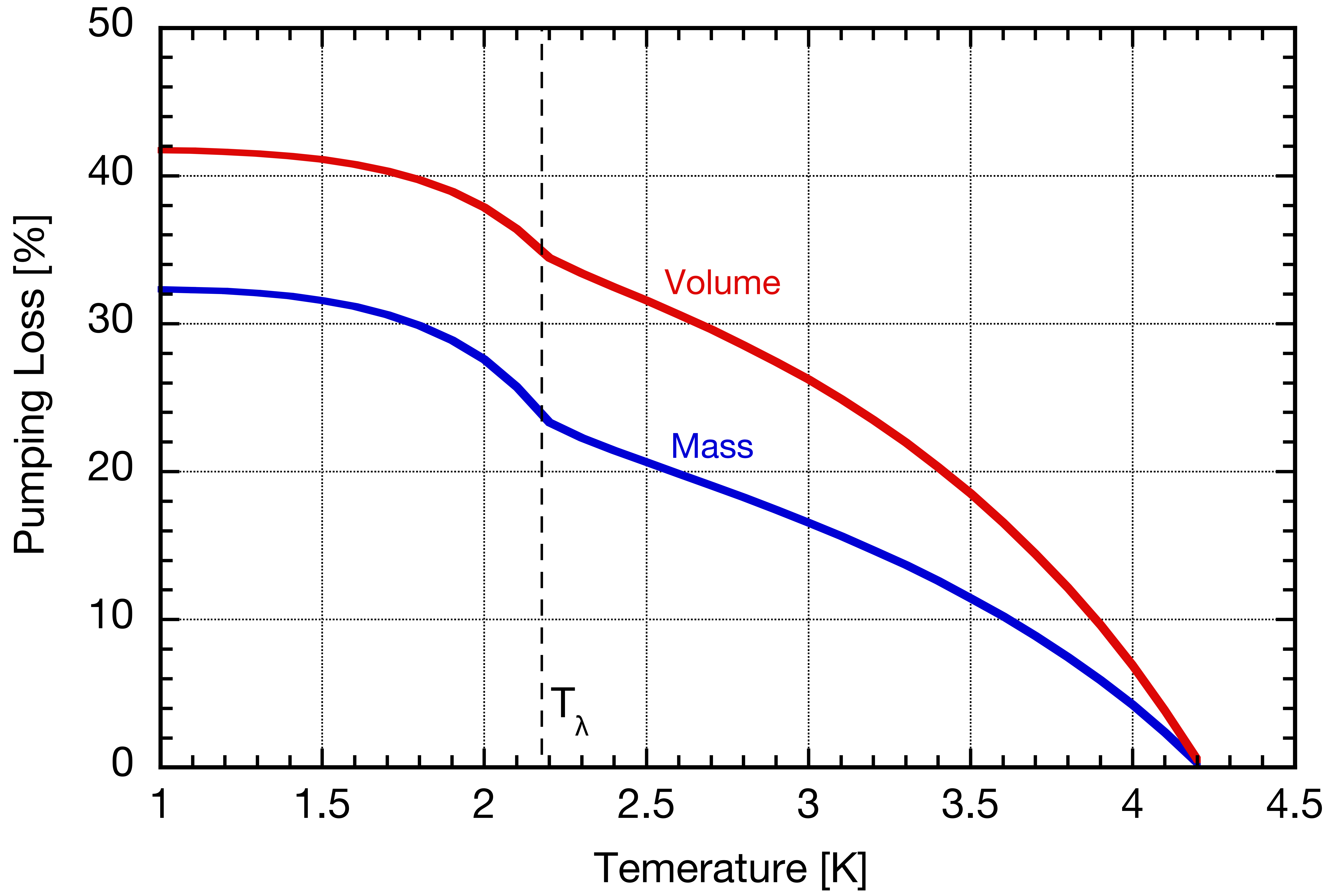
Scale	Heat Exchanger	Expansion	Refrigerator	Capacity
Small (Cryocooler)	Regenerative	Isothermal	Vuilleumier	
			Stirling	
		Simon	Gifford-McMahon (GM)	0.1 - 1 W @ 4.2 K
			Solvay	
			Pulse Tube	
	Counterflow	Joule-Thomson (Isenthalpic)	Joule-Thomson (JT)	1 - 10 W @ 4.2 K
Medium - Large		Isentropic	Claude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

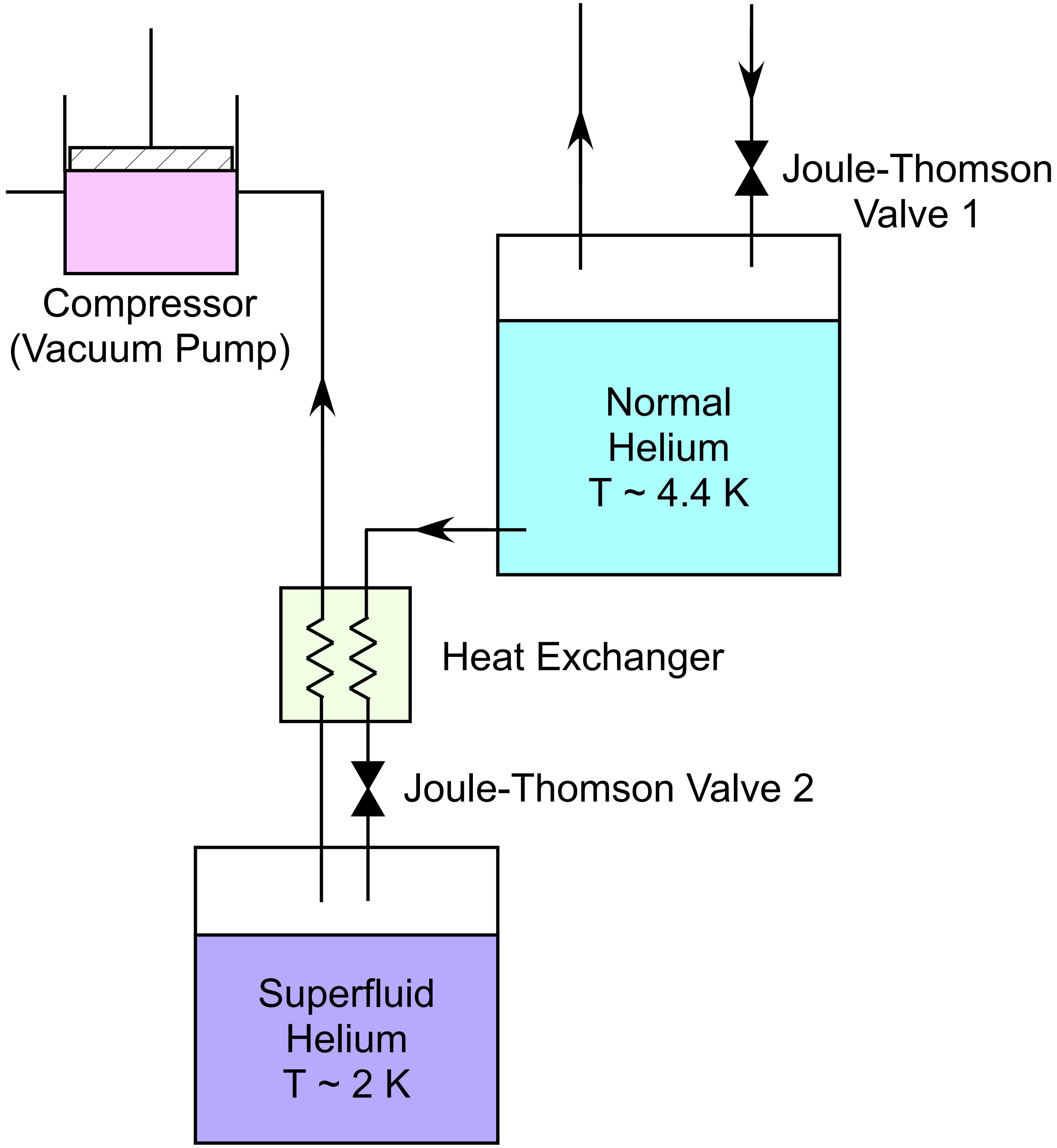


Liquid Helium Loss by Pressure Reduction



Schmidtchen, U., Private Communication (1984)

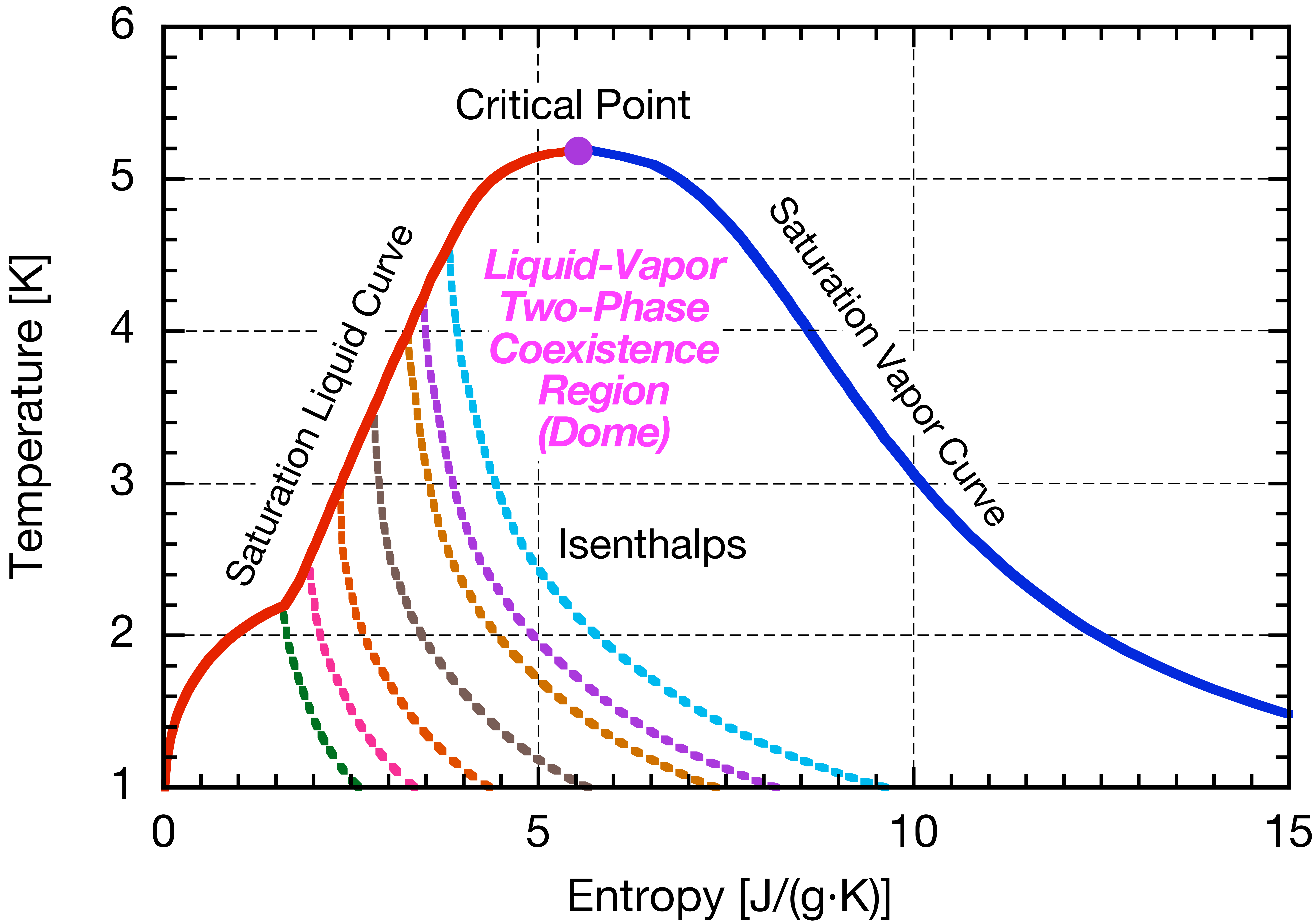
Continuous Production of Superfluid Helium



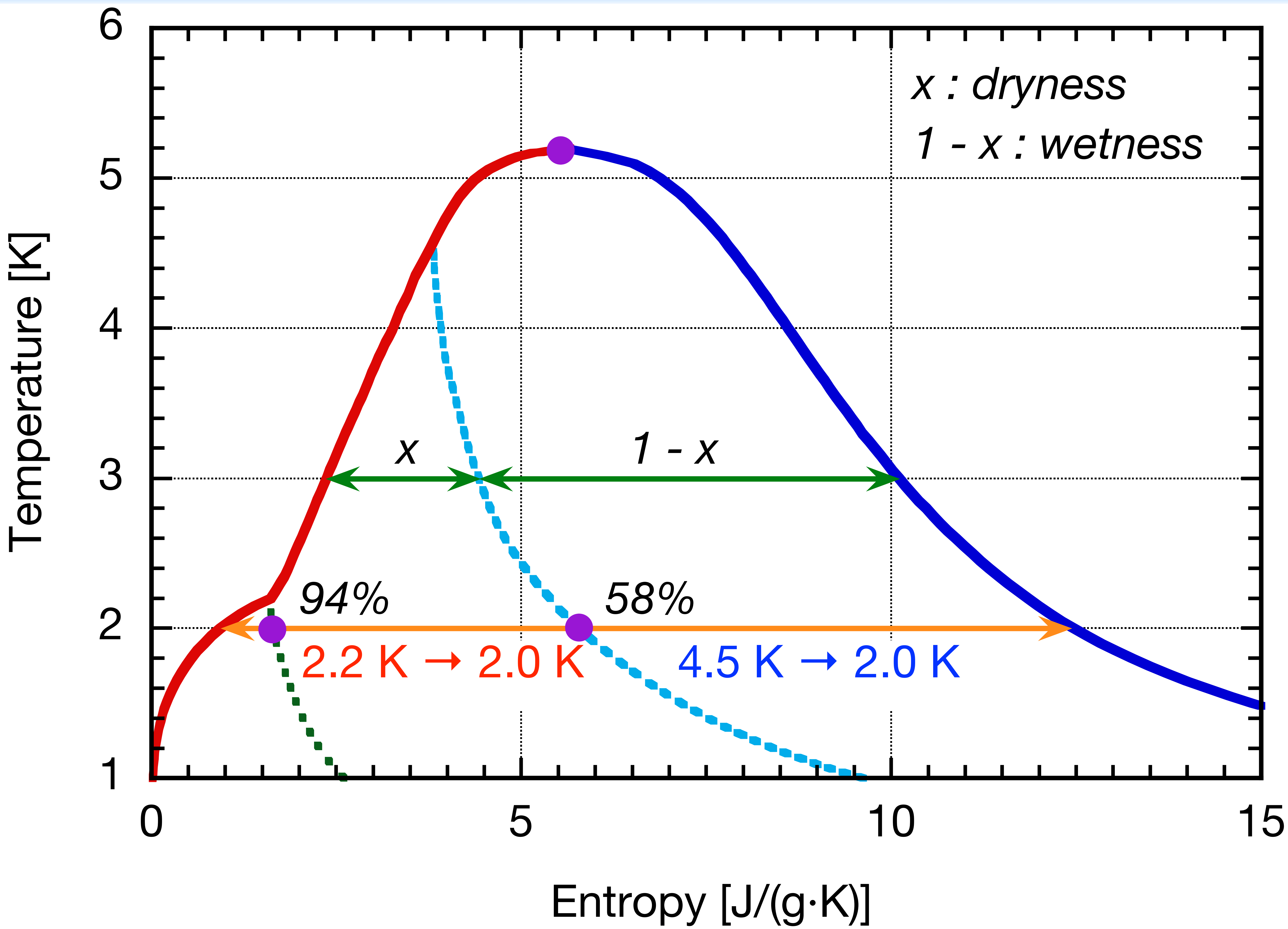
- Production of liquid helium
  - Joule-Thomson valve 1
- Cooling of liquid helium
  - Heat exchanger
- Isenthalpic expansion
  - Joule-Thomson valve 2
- Production of superfluid helium
- Compression of evaporated helium gas
  - Compressors
  - Vacuum pumps

Van Sciver, S. W., “Helium Cryogenics,” PlenumPress (1986)

Temperature-Entropy (T-s) Diagram of Helium



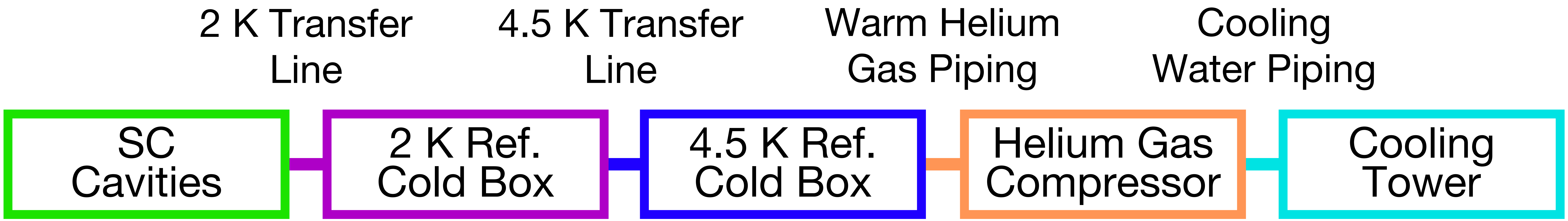
Dryness (vapor quality) & Wetness



2K Refrigerator (2K Cold Box)

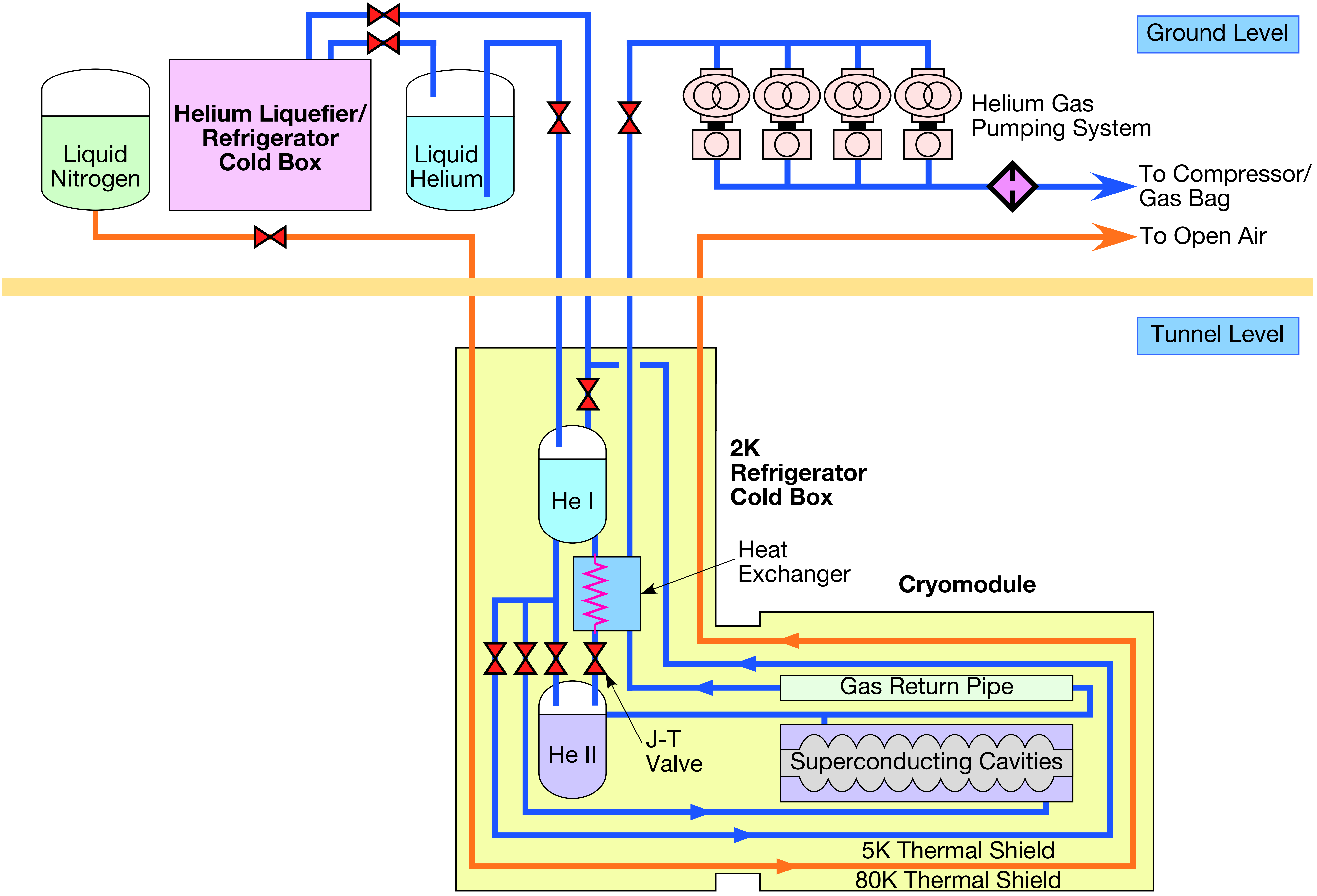
- Heat exchangers
  - To improve liquefaction rate (wetness) by reducing inlet liquid helium temperature
- Joule-Thomson valves
  - To control flow rate of liquid helium (throttle)
  - Less heat load from ambient required
- Compressors/Vacuum pumps
  - Cooling capacity at operation temperature determined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

Concept of Superfluid Helium Cryogenic System

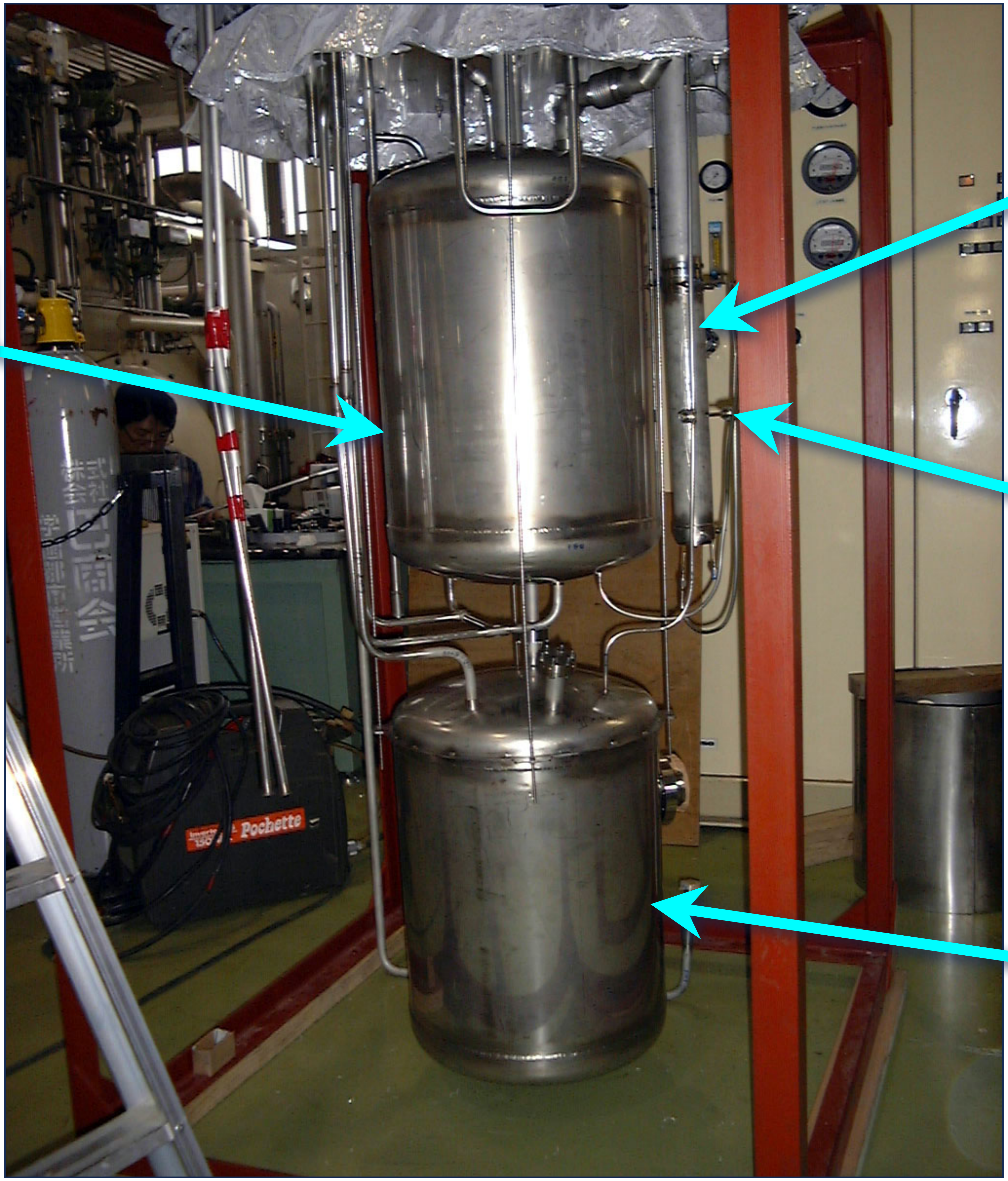


- Liquid helium production from helium gas at room temperature
  - Helium liquefier/refrigerator (4.5K cold box)
  - Helium compressors
- Superfluid helium production from liquid helium
  - 2K refrigerator (2K cold box)
  - Vacuum pumps/cold compressors

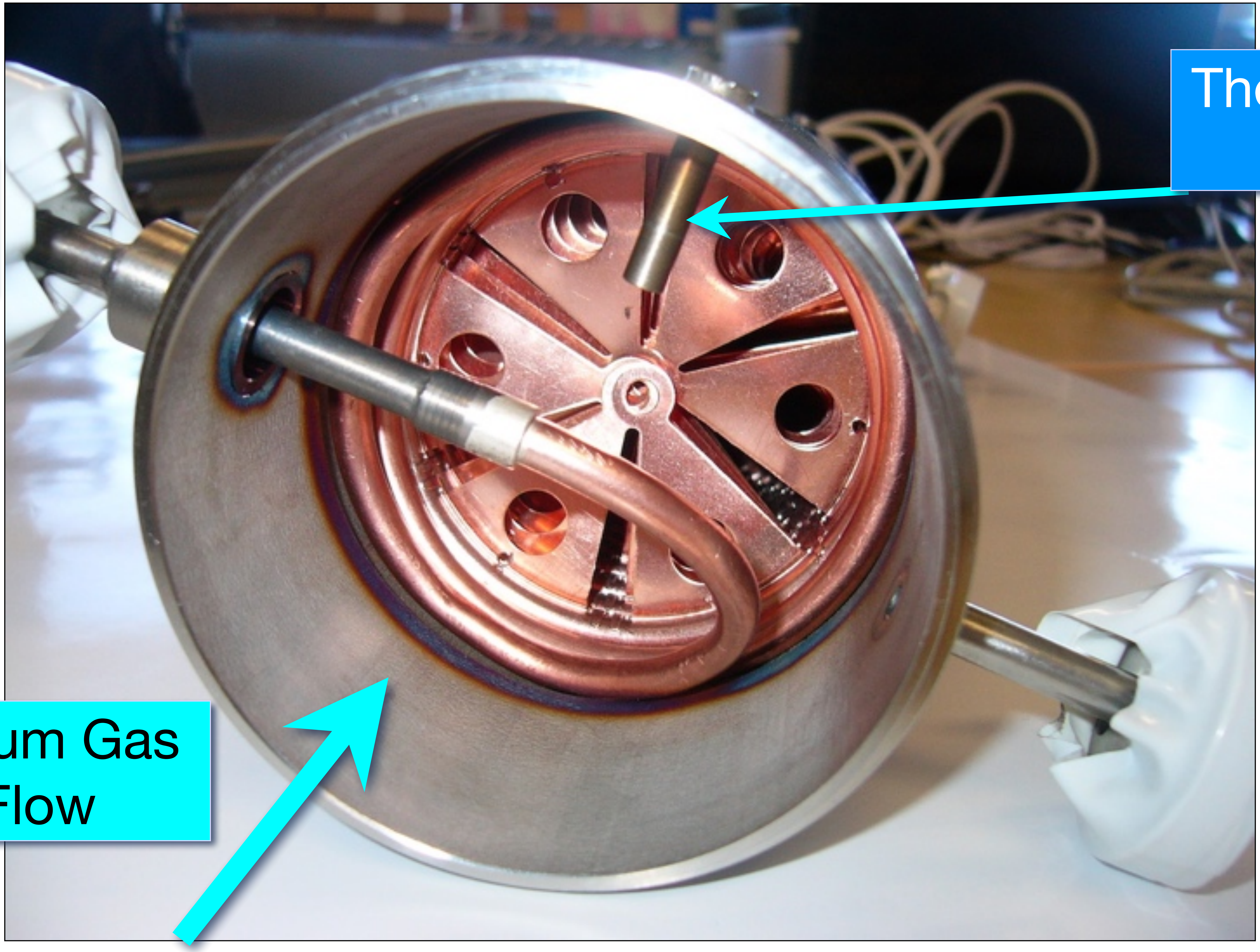
Cryogenic System at Superconducting RF Test Facility



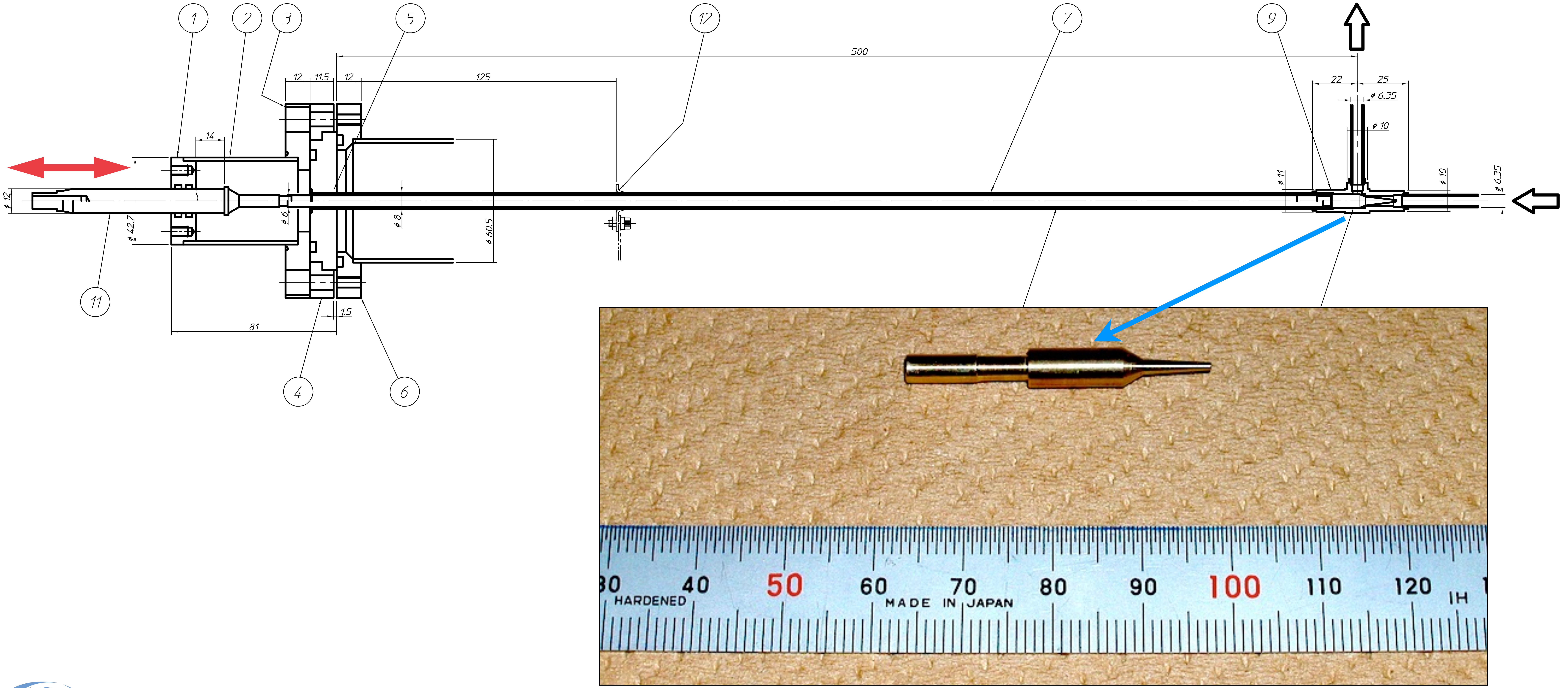
2K Refrigerator Cold Box



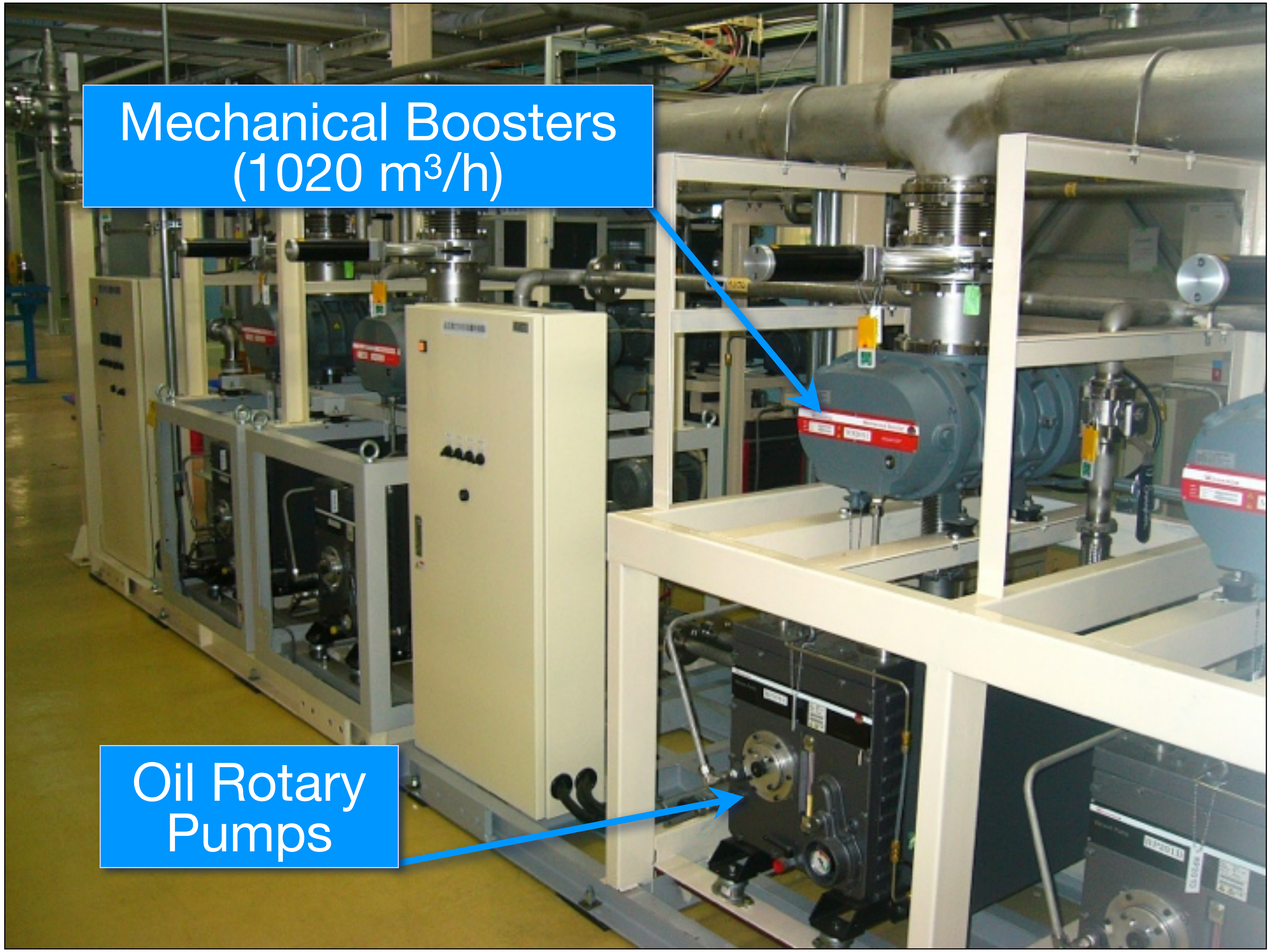
2K Heat Exchanger



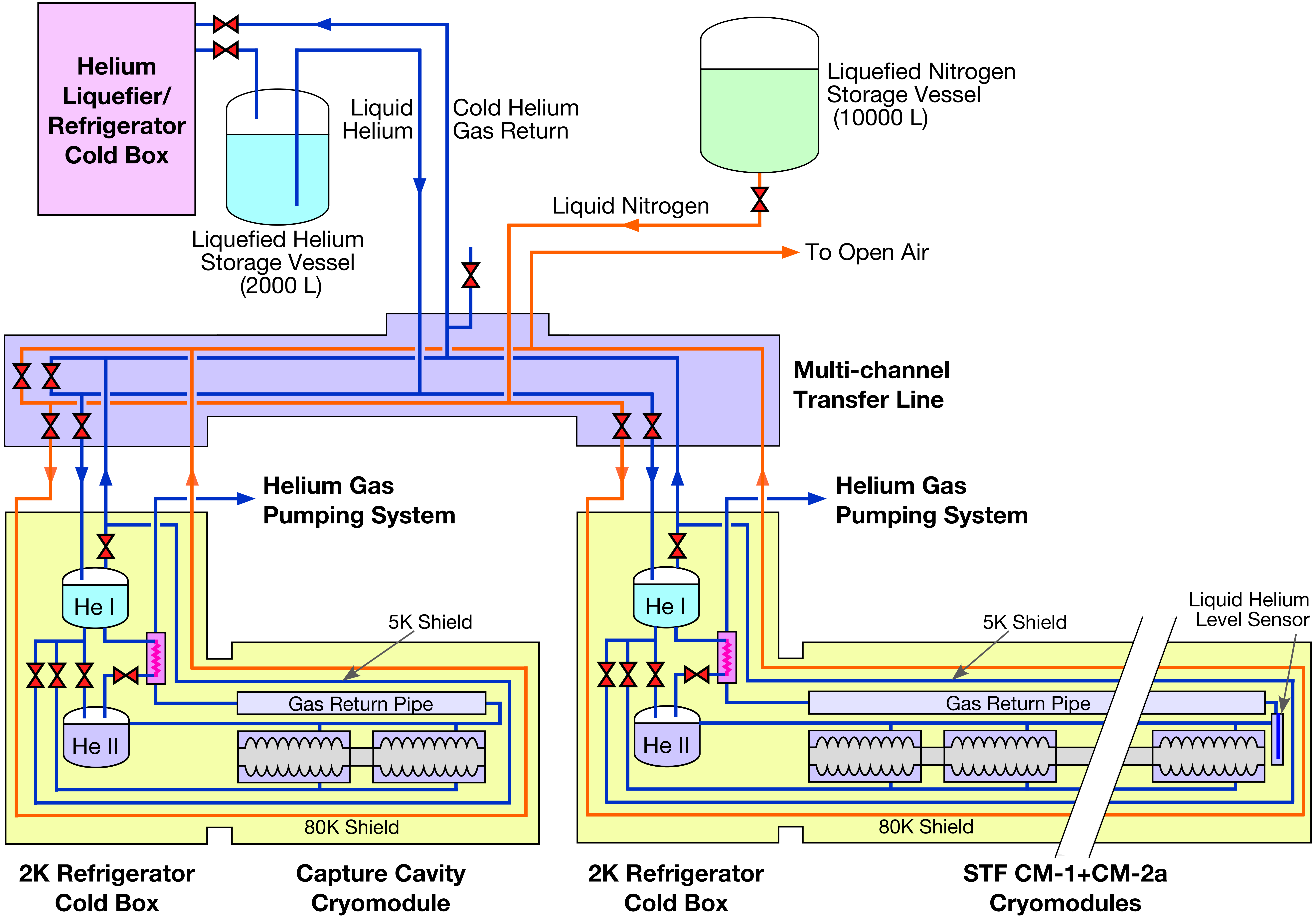
Joule-Thomson Valve for 2K Heat Exchanger



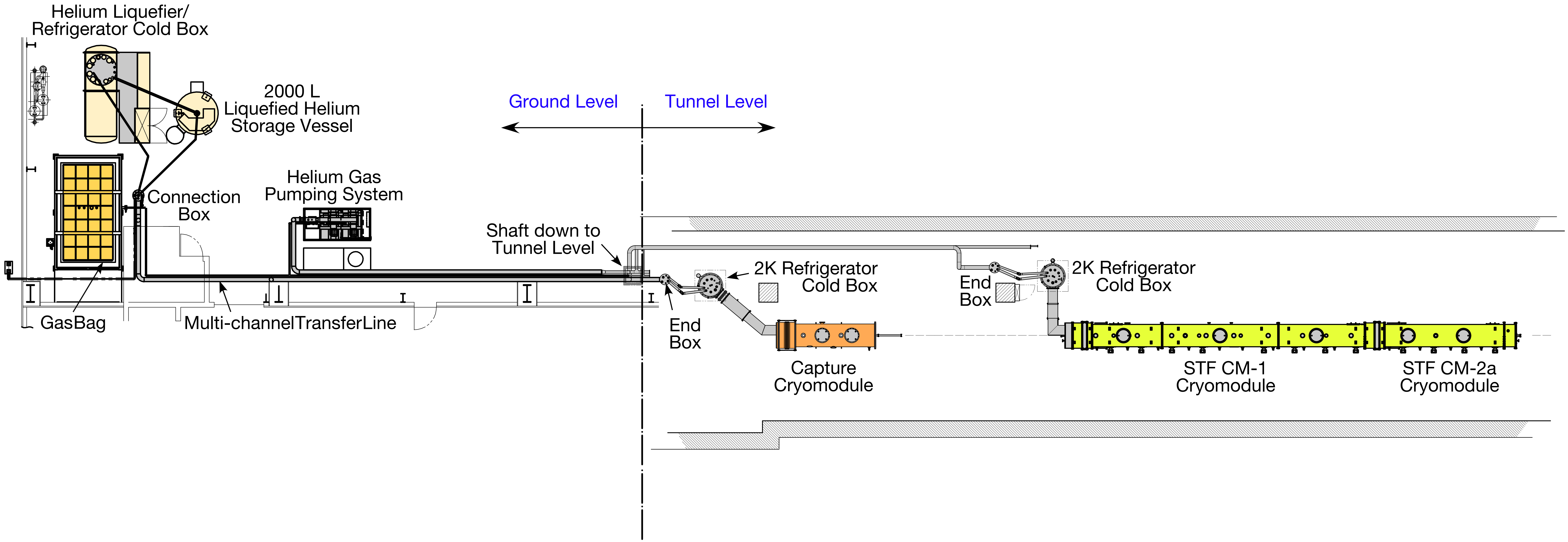
Helium Pumping System



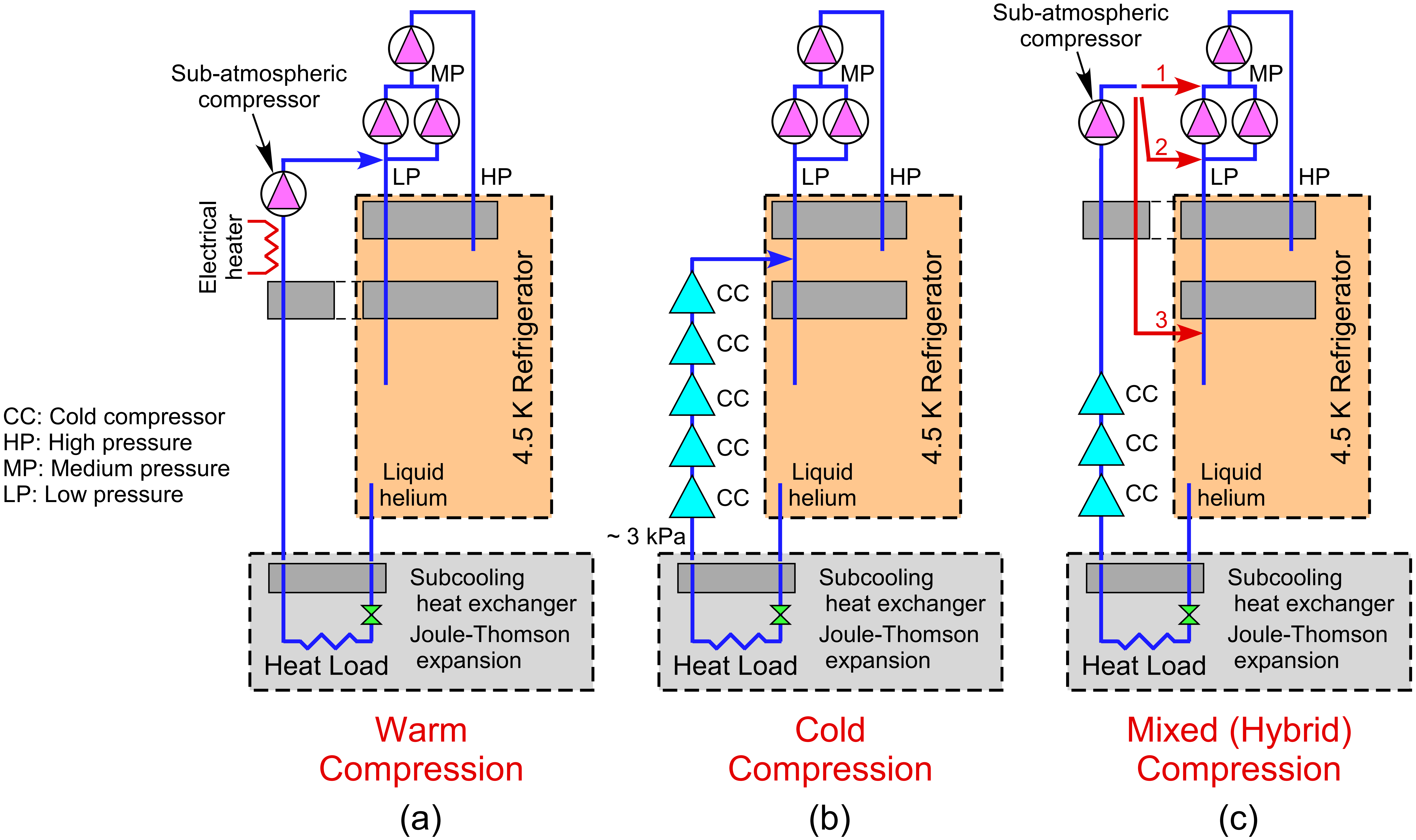
STF 2K Superfluid Helium Cryogenic System



STF Cryogenic System Configuration

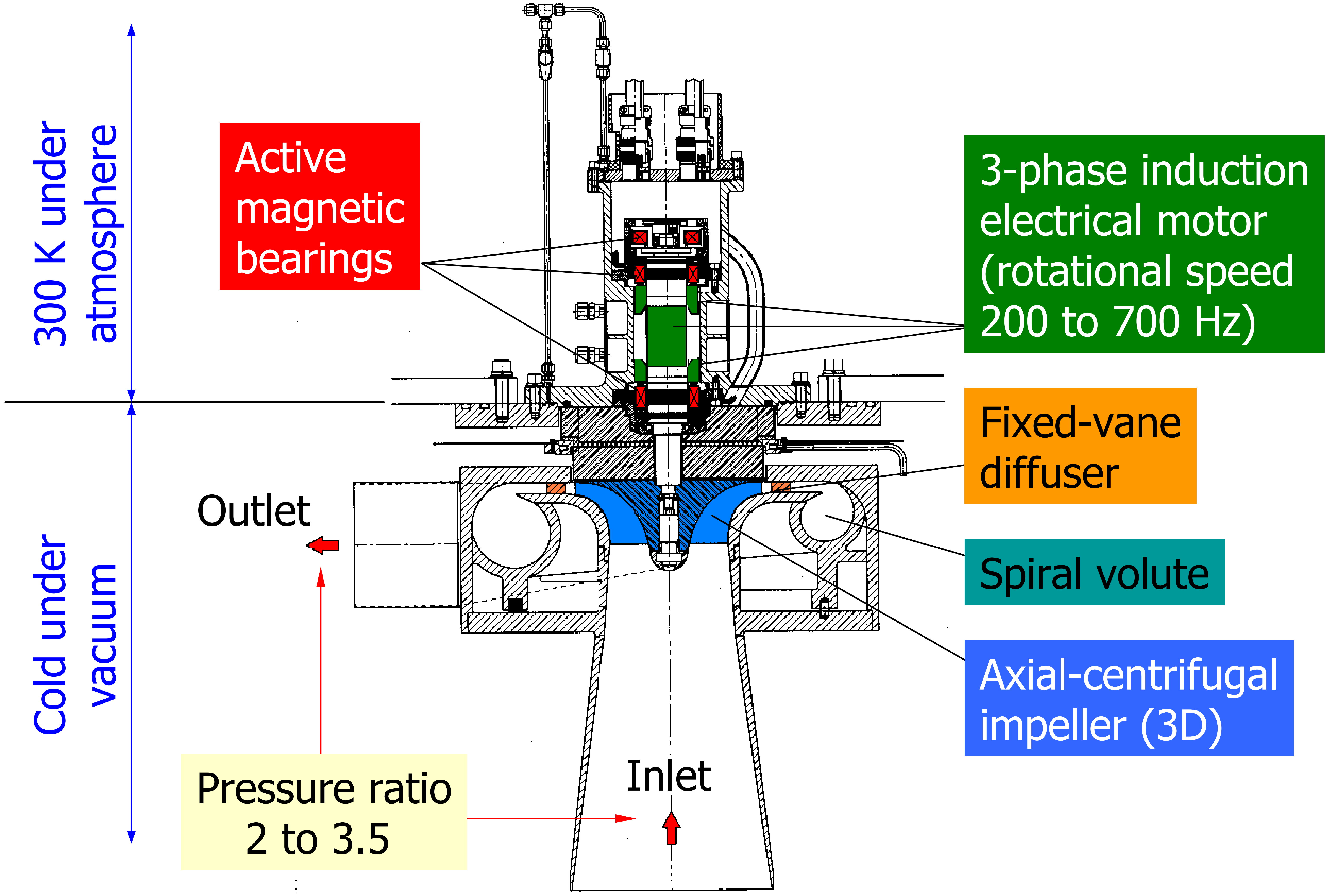


Pressure Reduction of Liquid Helium



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)

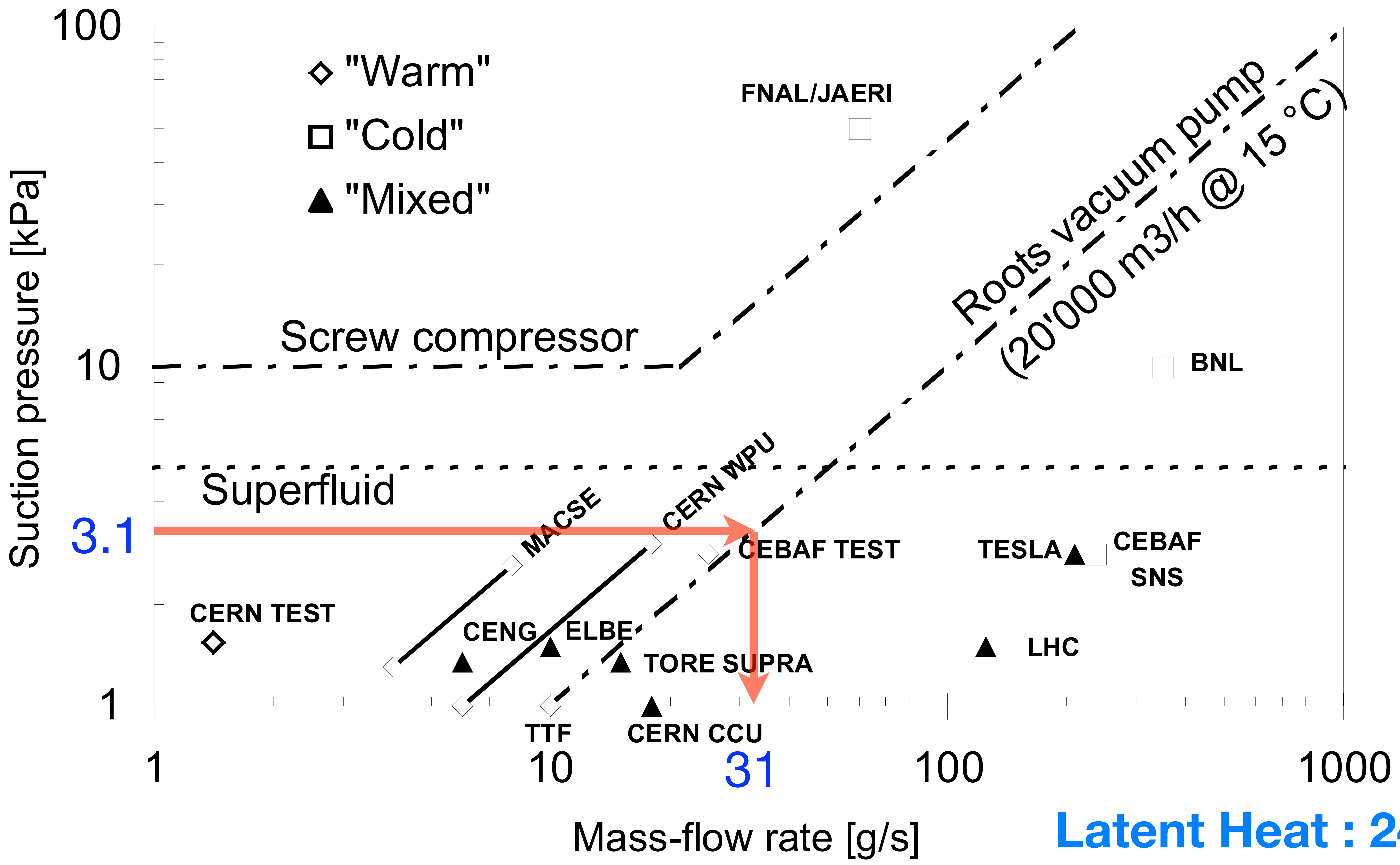
Cold Compressors for CERN-LHC

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

Classification of Cryogenic Refrigerators

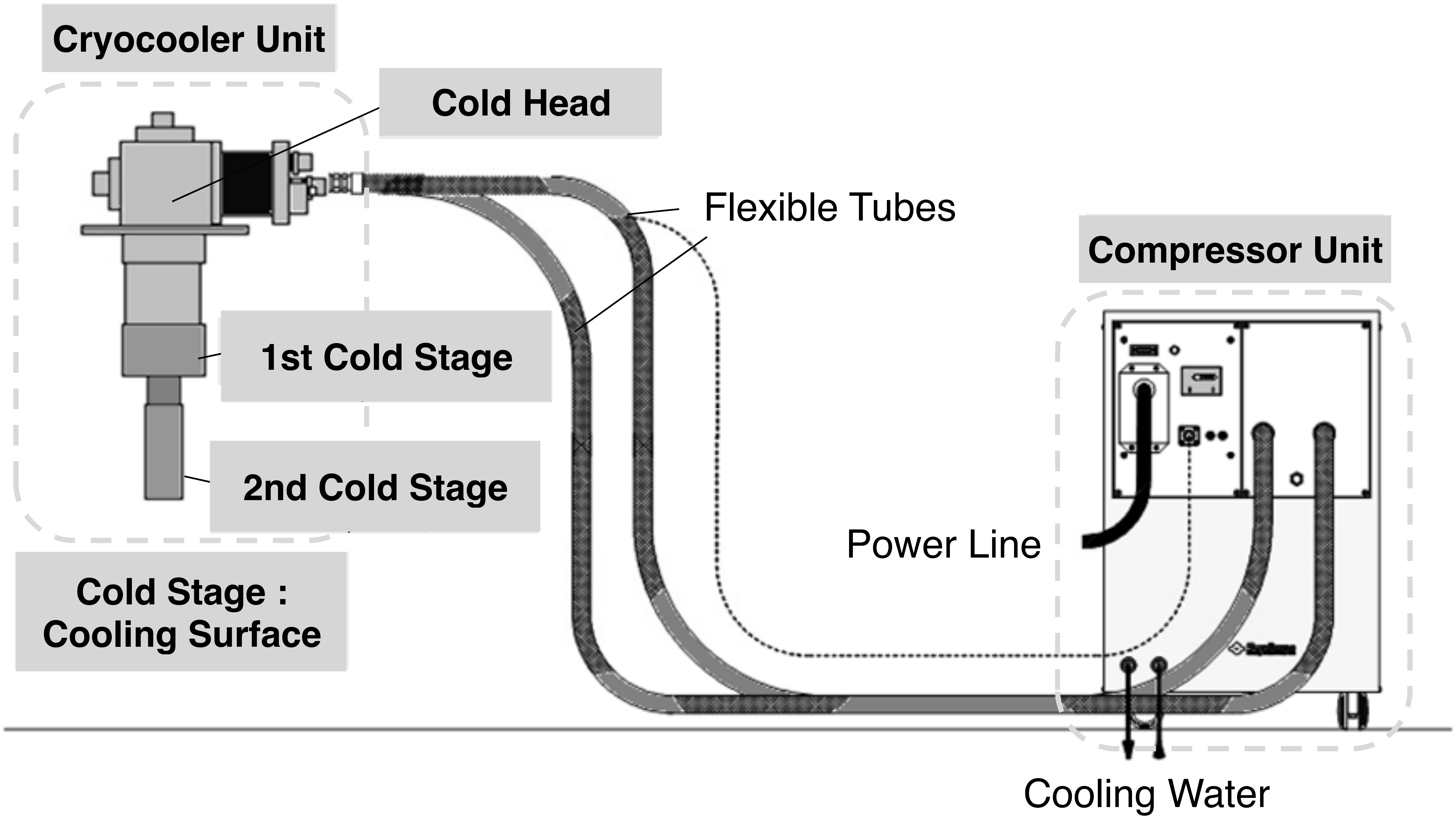
Scale	Heat Exchanger	Expansion	Refrigerator	Capacity
Small (Cryocooler)	Regenerative	Isothermal	Vuilleumier	
			Stirling	
		Simon	Gifford-McMahon (GM)	0.1 - 1 W @ 4.2 K
			Solvay	
			Pulse Tube	
	Counterflow	Joule-Thomson (Isenthalpic)	Joule-Thomson (JT)	1 - 10 W @ 4.2 K
Medium - Large		Isentropic	Claude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

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

Characteristics of Cryocoolers

- 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)

GM Cryocooler of Sumitomo Heavy Industries, Ltd.

SRDK-415D 4K CRYOCOOLER SERIES

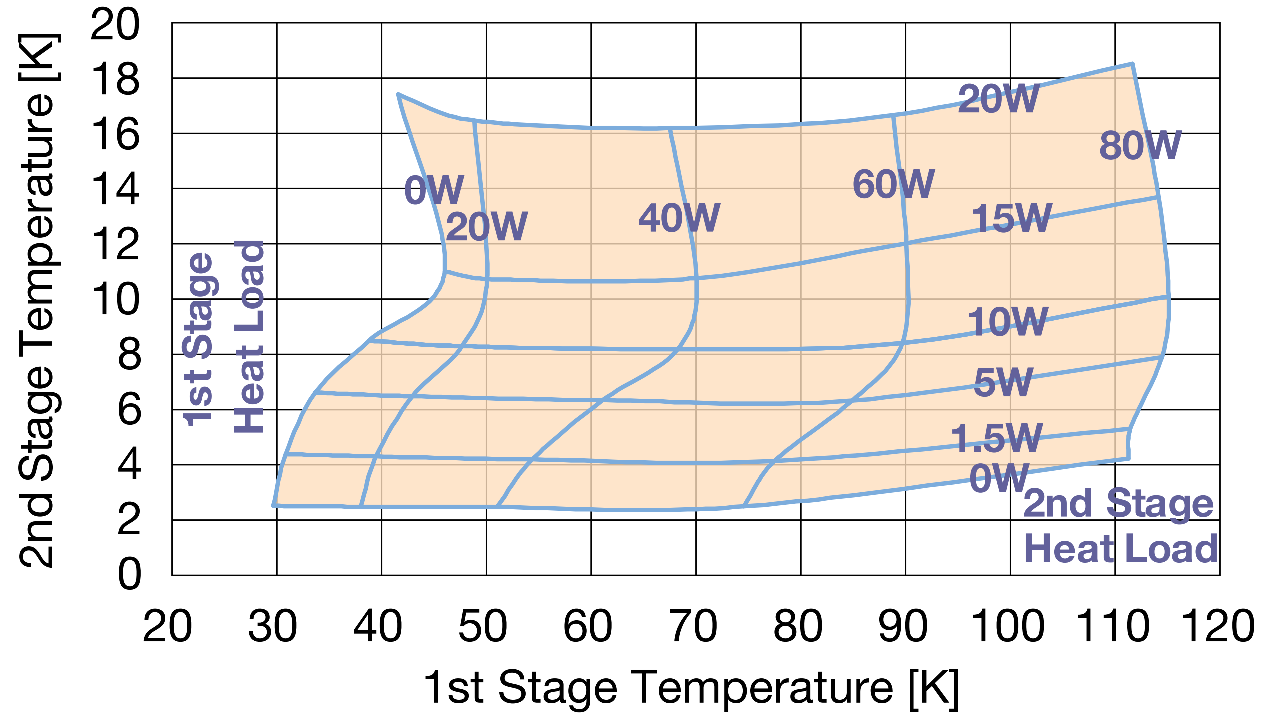
Performance Specifications

Power Supply Hz	50	60
2nd Stage Capacity Watts @ 4.2 K	1.5	1.5
1st Stage Capacity Watts @ 50 K	35	45
Cooldown Time to 4.2 K Minutes	60	60
Weight kg (lbs.)	18.5 (40.8)	
Maintenance Hours	10,000	

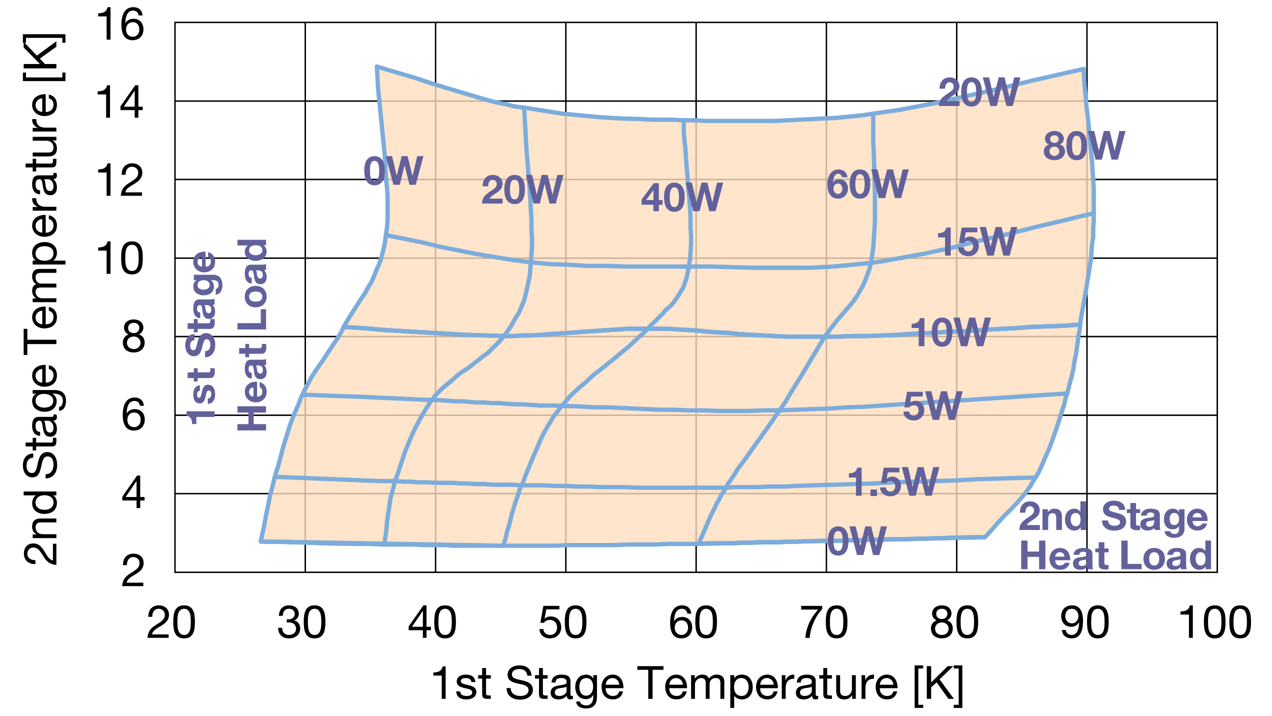
Standard Scope of Supply

- RDK-415D Cold Head
- CSA-71A, F-50L/H, F-70L/H, CNA-61C/D Compressor
- 20 m (66 ft.) Helium Gas Lines or 6 m (20 ft.) Helium Gas Lines with Buffer Tank [10 m (33 ft.) with CNA-61C/D Compressor]
- 6 m (20 ft.) Cold Head Cable [10 m (33 ft.) with CNA-61C/D Compressor]
- Tool Kit

SRDK-415D Cold Head Capacity Map (50 Hz)



SRDK-415D Cold Head Capacity Map (60 Hz)



Note: Capacity maps for reference only.

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

Pulse Tube Cryocooler of Sumitomo Heavy Industries, Ltd.

SRP-082B 4K PULSE TUBE SERIES

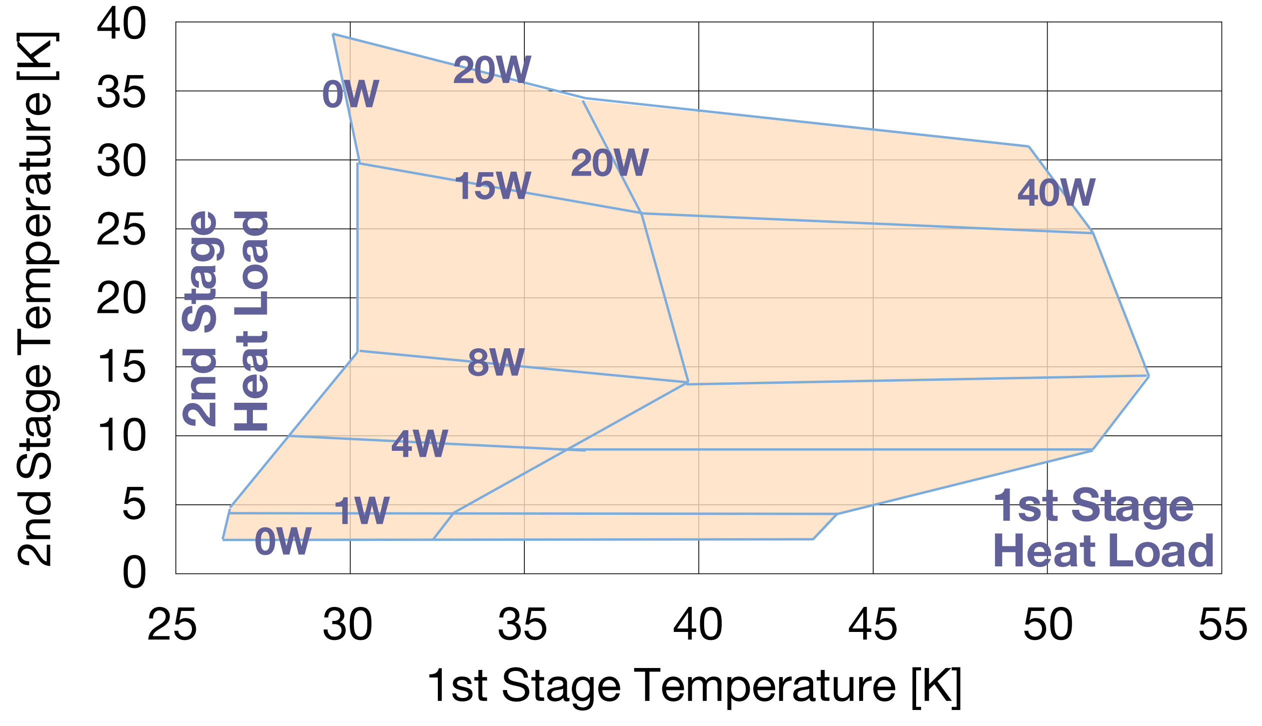
Performance Specifications

Power Supply Hz	50	60
2nd Stage Capacity Watts @ 4.2 K	1.0	1.0
1st Stage Capacity Watts @ 45 K	40	40
Cooldown Time to 4.2 K Minutes	80	80
Weight kg (lbs.)	26.0 (57.3)	
Maintenance Hours	20,000	

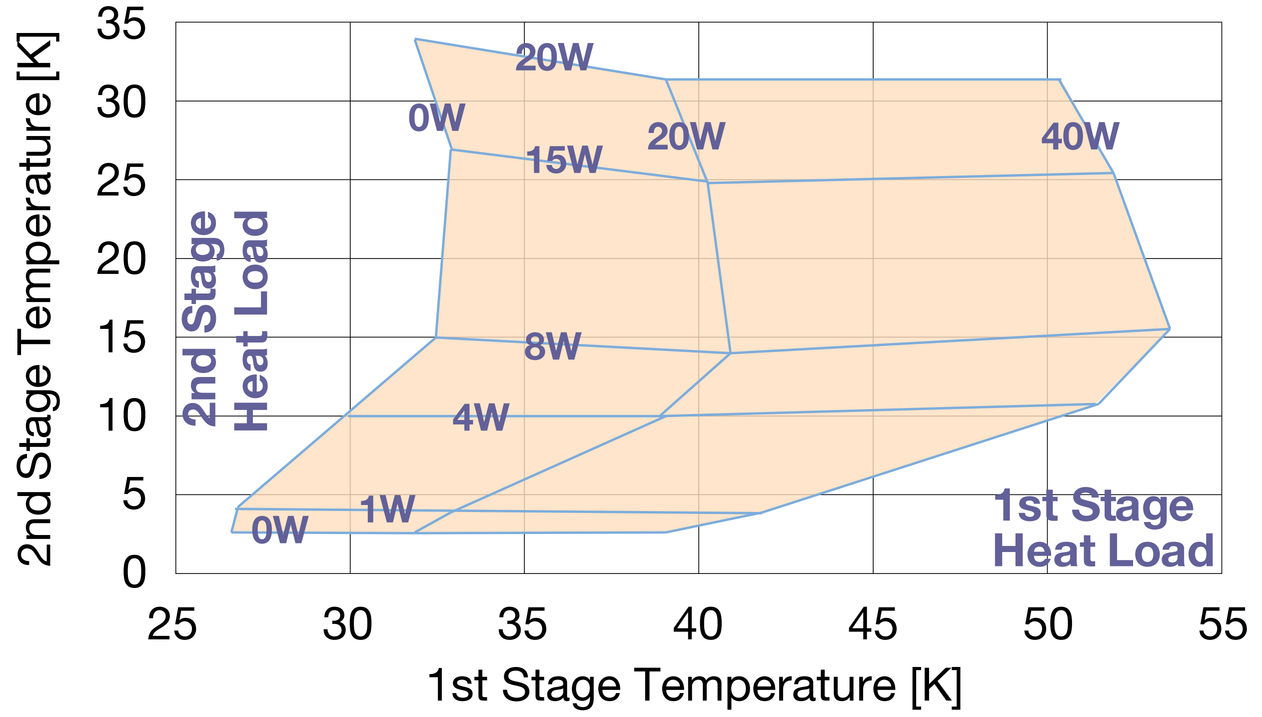
Standard Scope of Supply

- RP-082B Pulse Tube
- F-70LP/H Compressor
- 20 m (66 ft.) Helium Gas Lines
- 20 m (66 ft.) Cold Head Cable
- Tool Kit
- Optional Split Valve Unit

SRP-082B Pulse Tube Capacity Map (50 Hz)

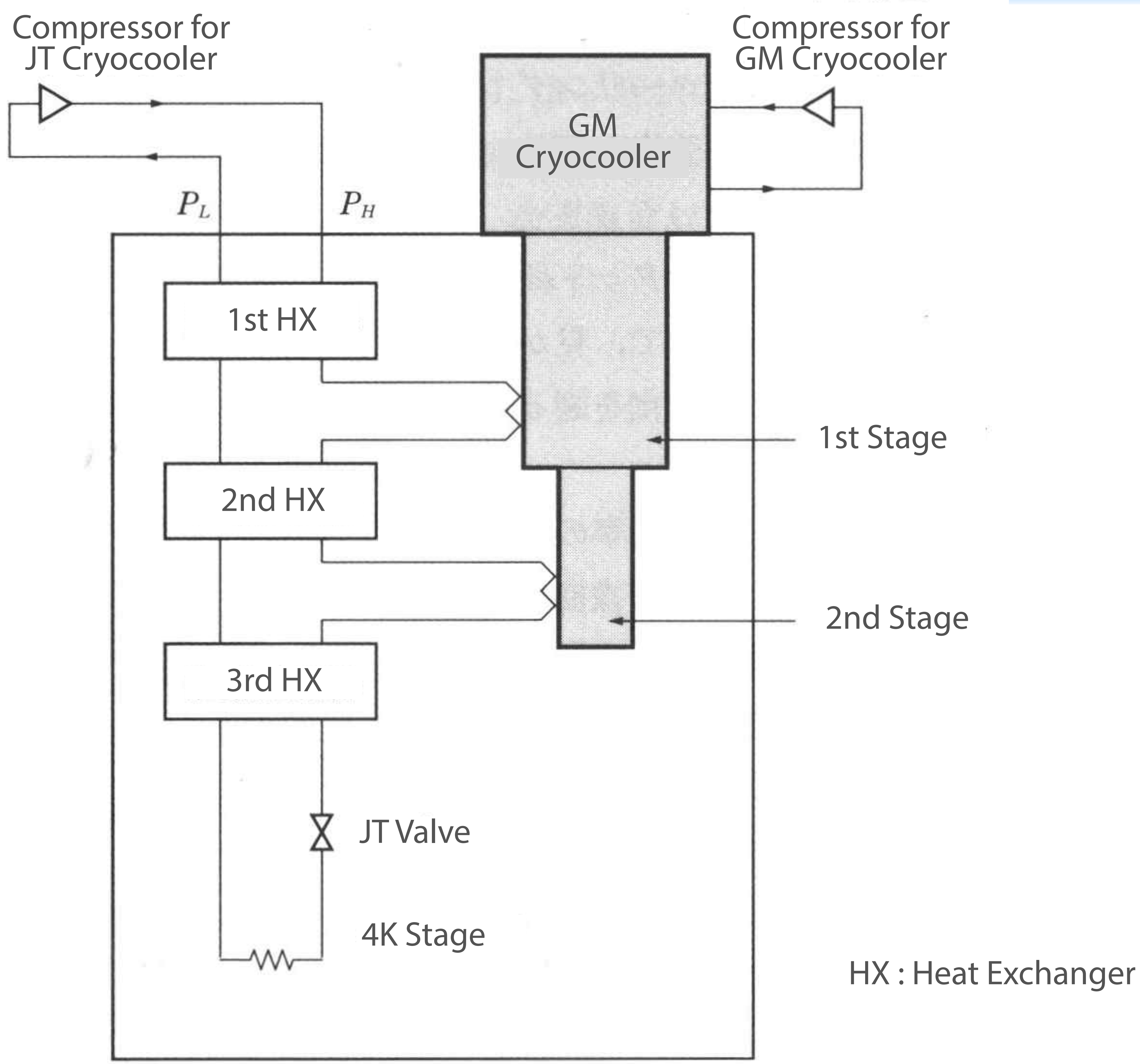


SRP-082B Pulse Tube Capacity Map (60 Hz)



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

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

Cryocoolers

- 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

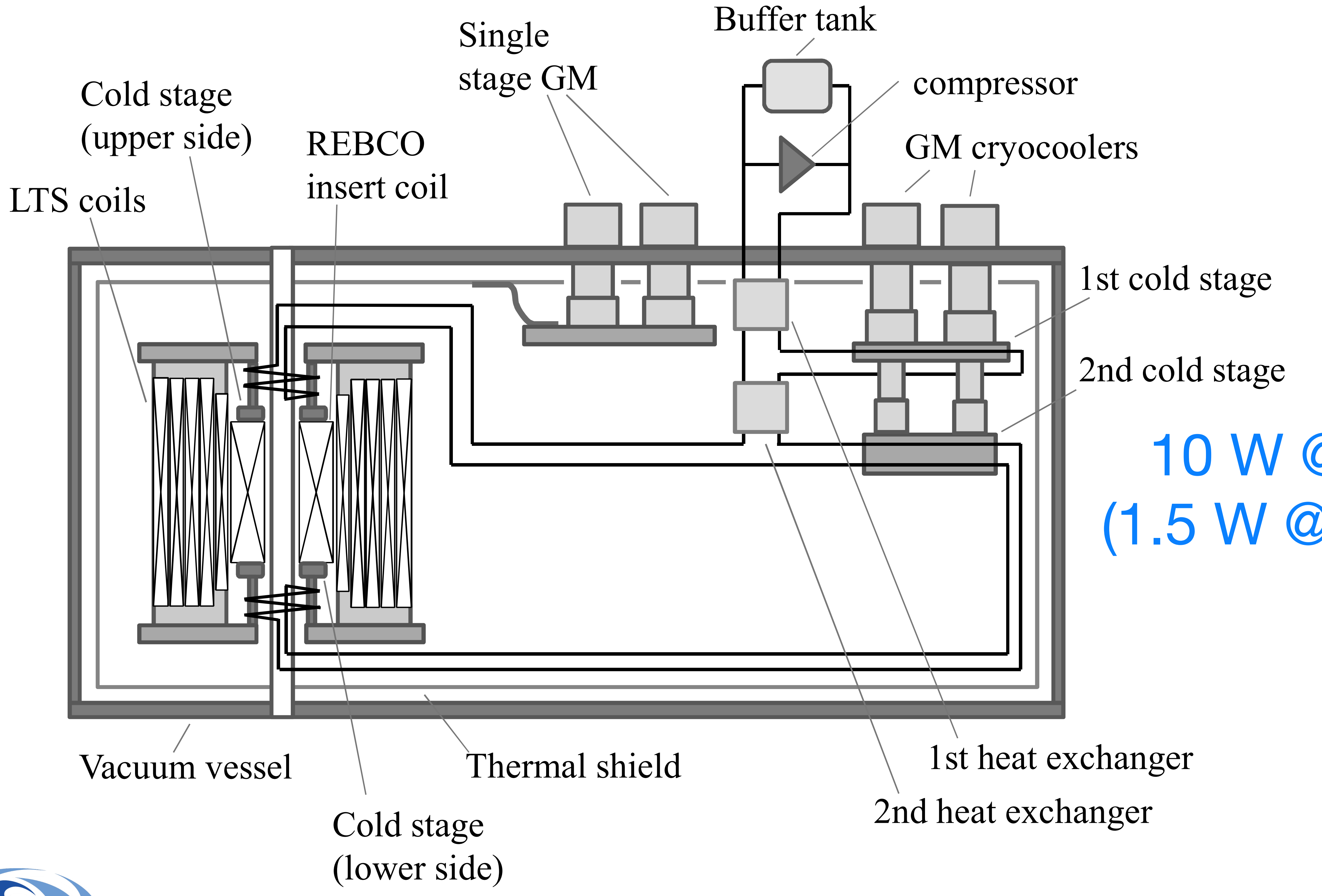
Superconducting Magnet Cooled with Cryocooler

Concept of a Cryogenic System for a Cryogen-free 25 T Superconducting Magnet

S. Iwai, M. Takahashi et al. (Toshiba and Tohoku University)

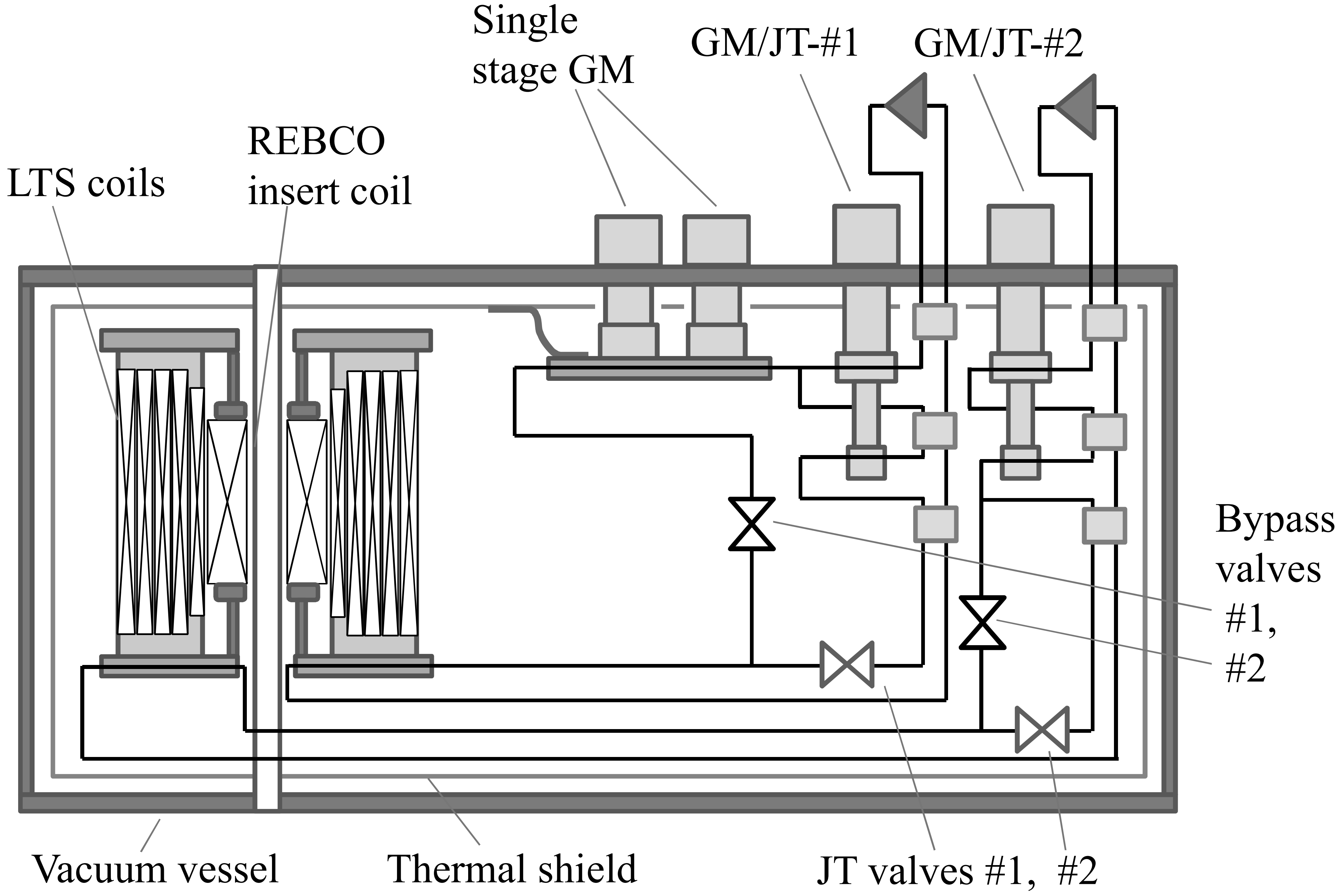
Physics Procedia ***67*** *(2015) 326-330, Proc. 25th Int'l Cryog. Eng. Conf. (2014)*

Conduction Cooling Only with Cryocoolers



10 W @ 8 K
(1.5 W @ 4.2 K)

4.2 W @ 4.3 K



https://www.sciencedirect.com/science/article/pii/S1875389215004769

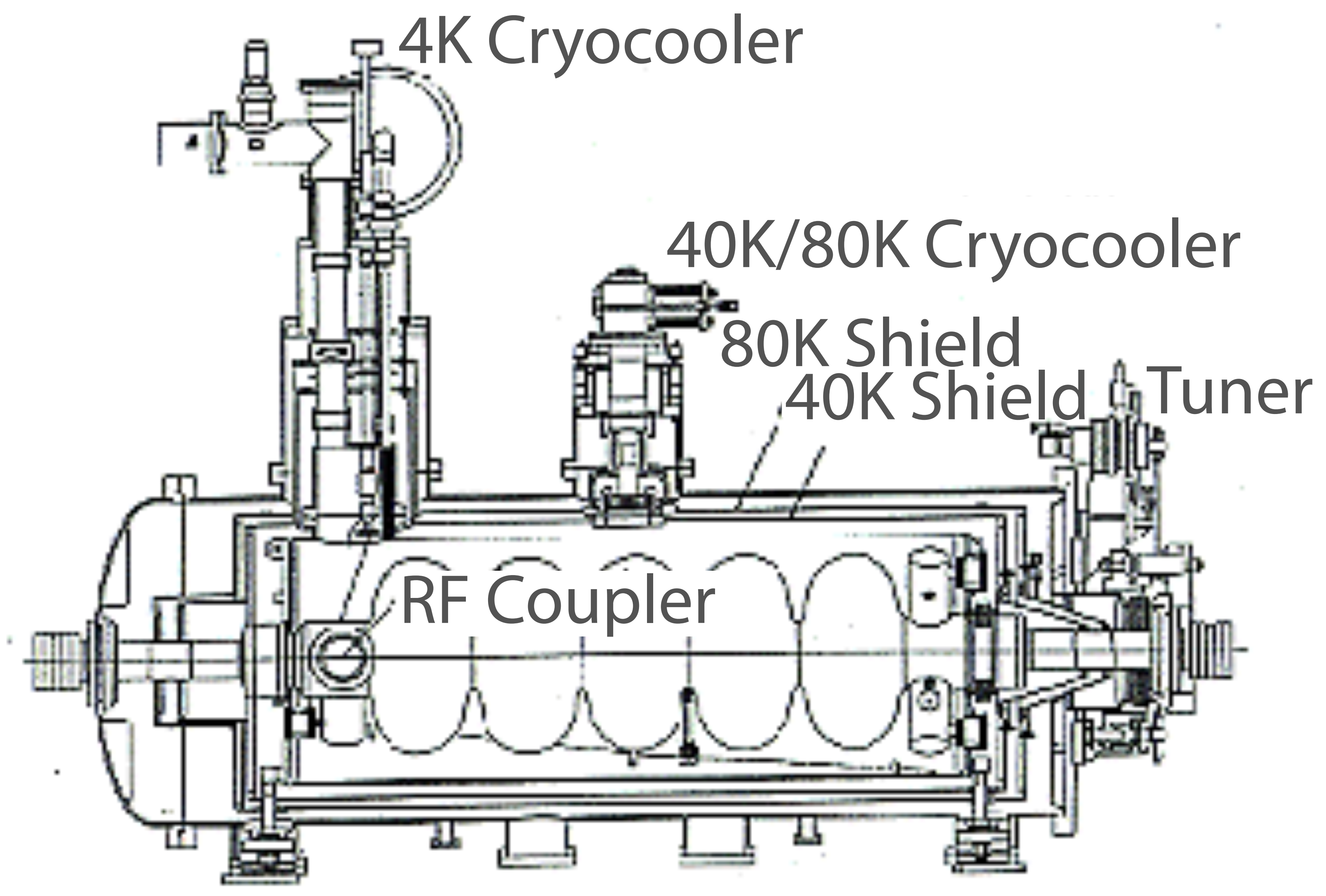
Superconducting RF Cavity Cooled with Cryocooler

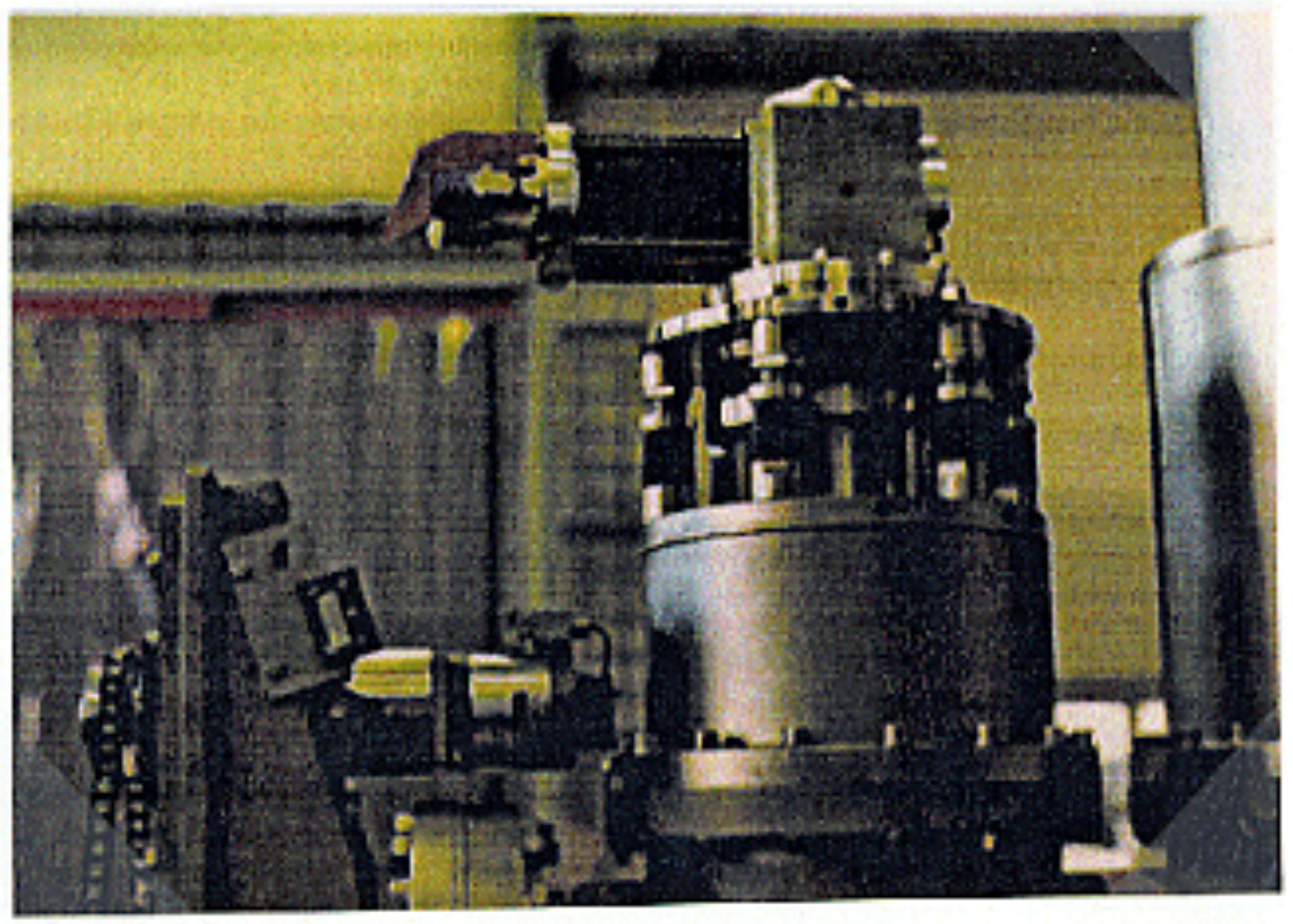
Atomic Energy Fundamental Technology Database : 2000/01/20 by E. Minehara

Objective : **Development of Cryocoolers for Free Electron Laser Driven by CW (Continuous Wave) High Power Superconducting Lineac**

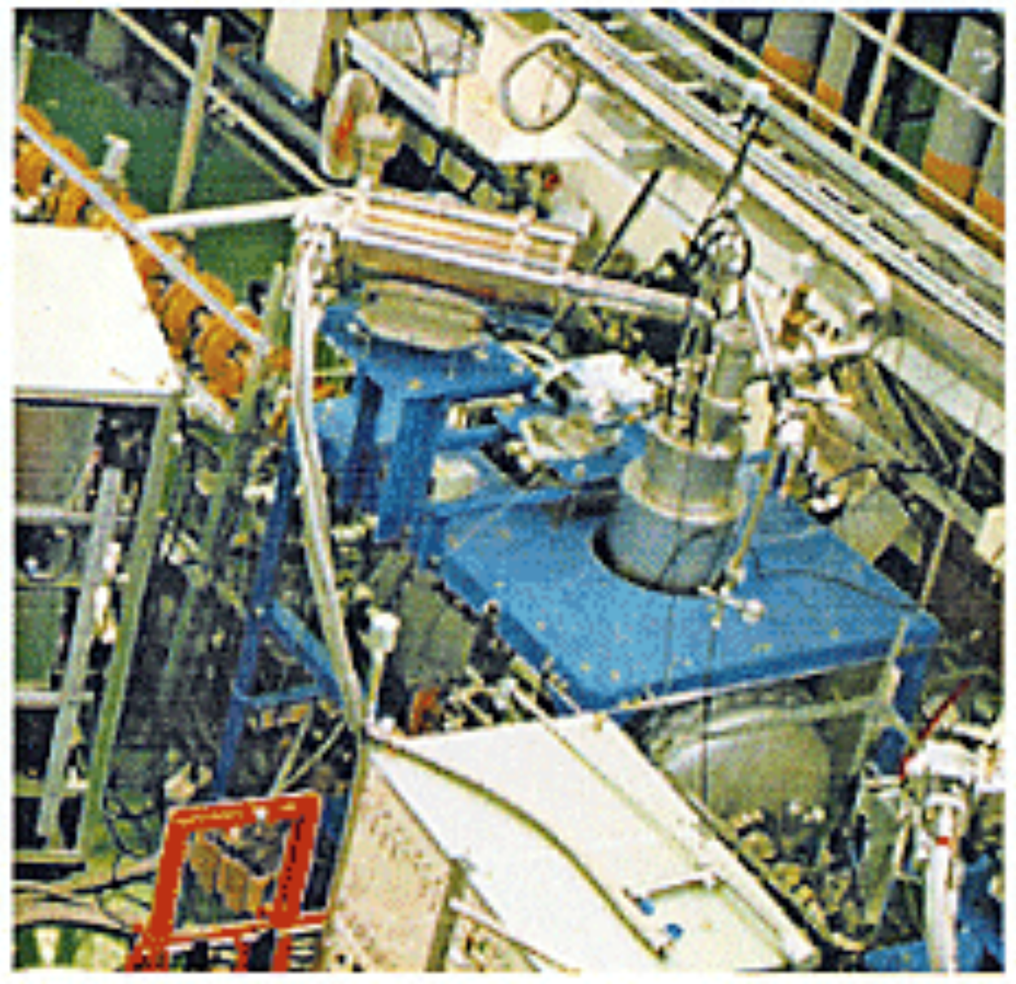
Research Institutes : Japan Atomic Energy Research Institute, Tokai Research Institute
Thomas Jefferson National Accelerator Facility

Helium Re-condensation with Cryocoolers





40K/80K GM Cryocooler
20 W @ 20 K + 140 W @ 80 K

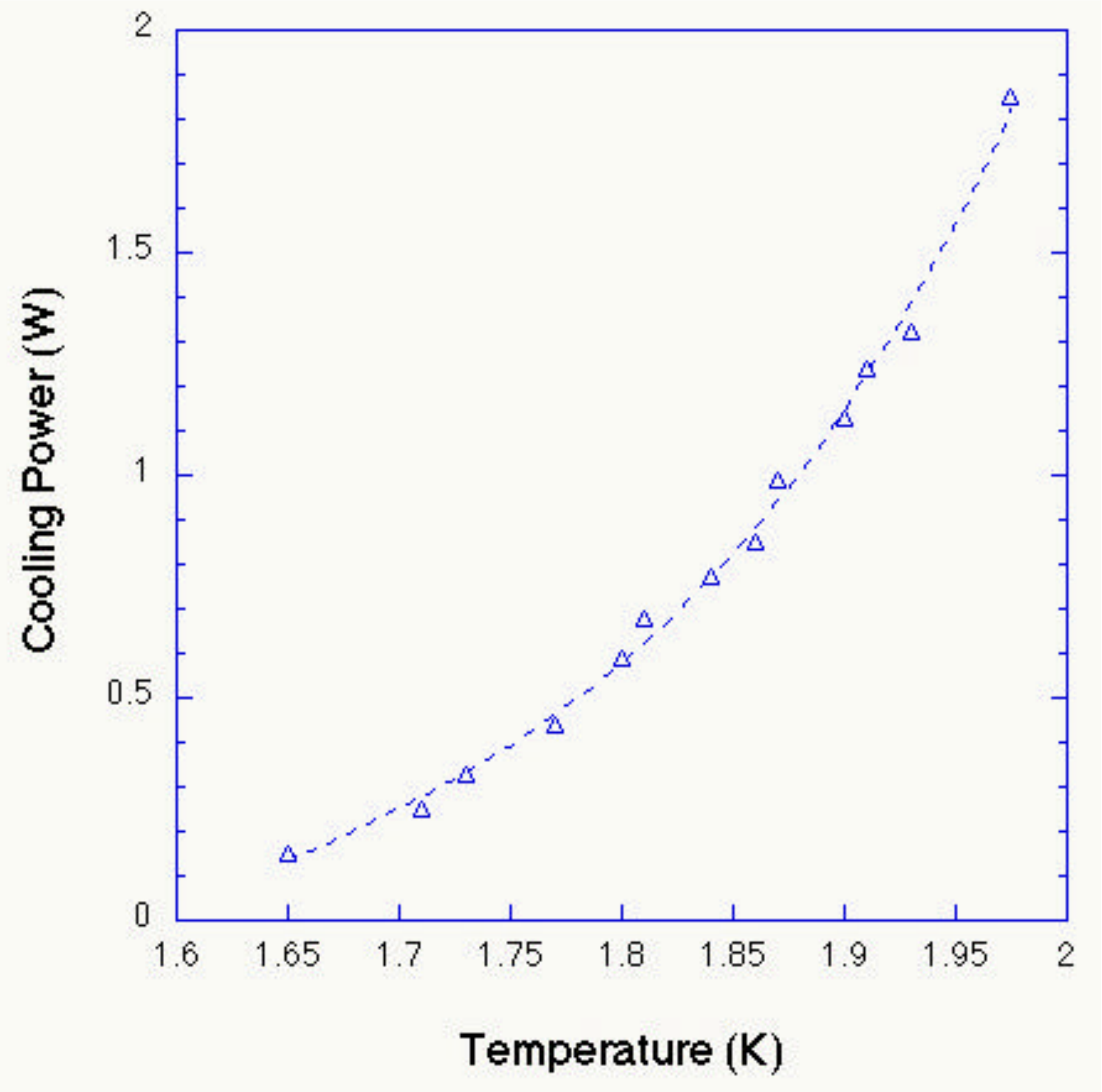


4K GM/JT Cryocooler
12 W @ 4 K

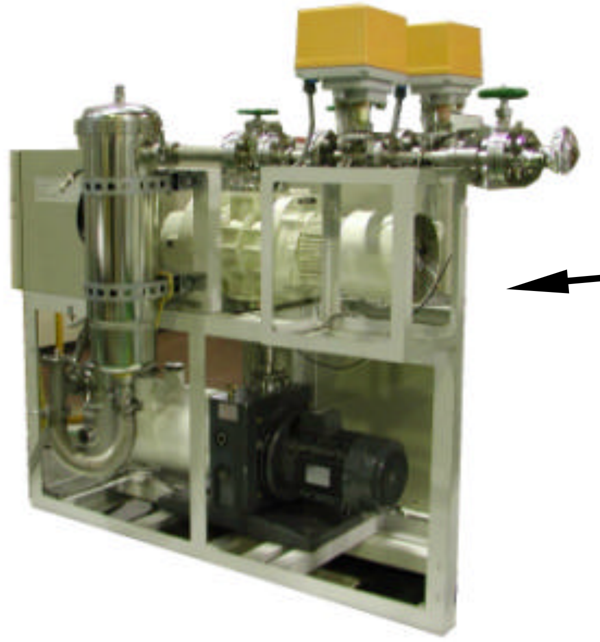
http://www.rada.or.jp/database/home3/normal/ht-docs/member/synopsis/140023.html

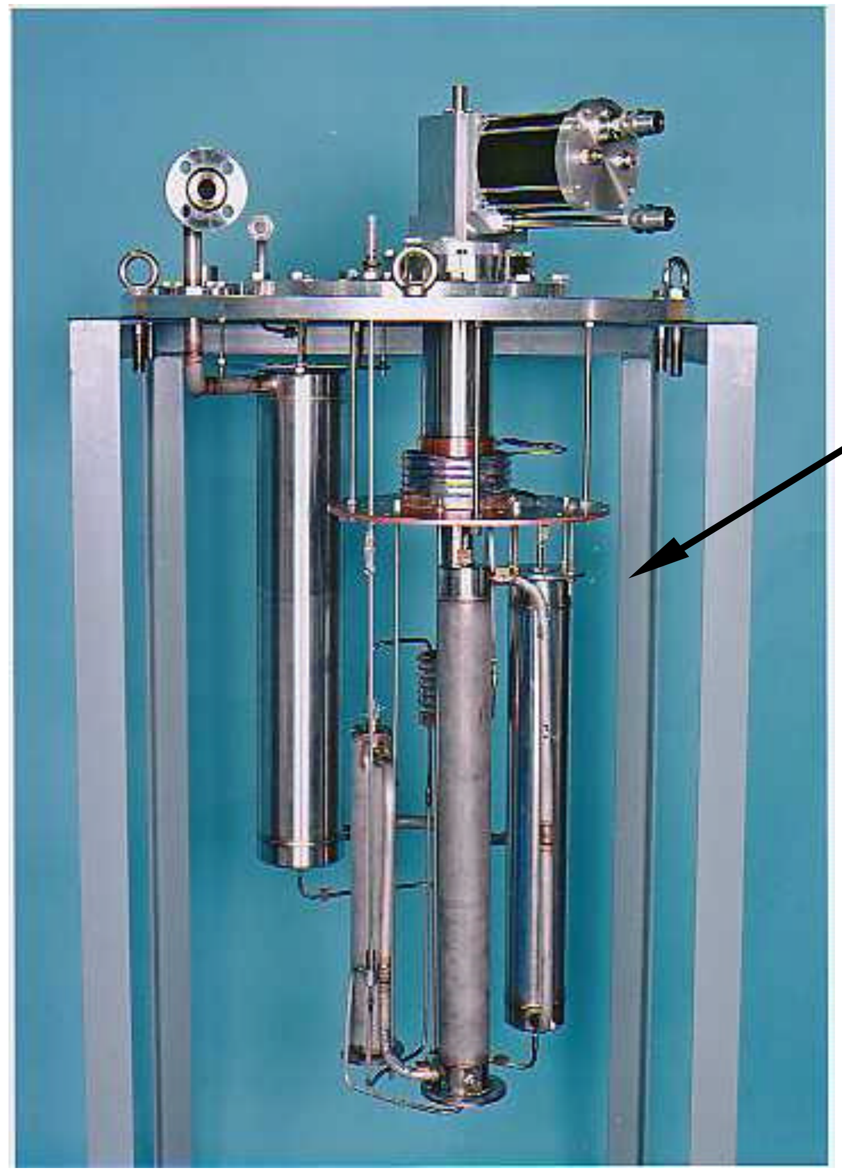
Development of Small 2K Refrigerator

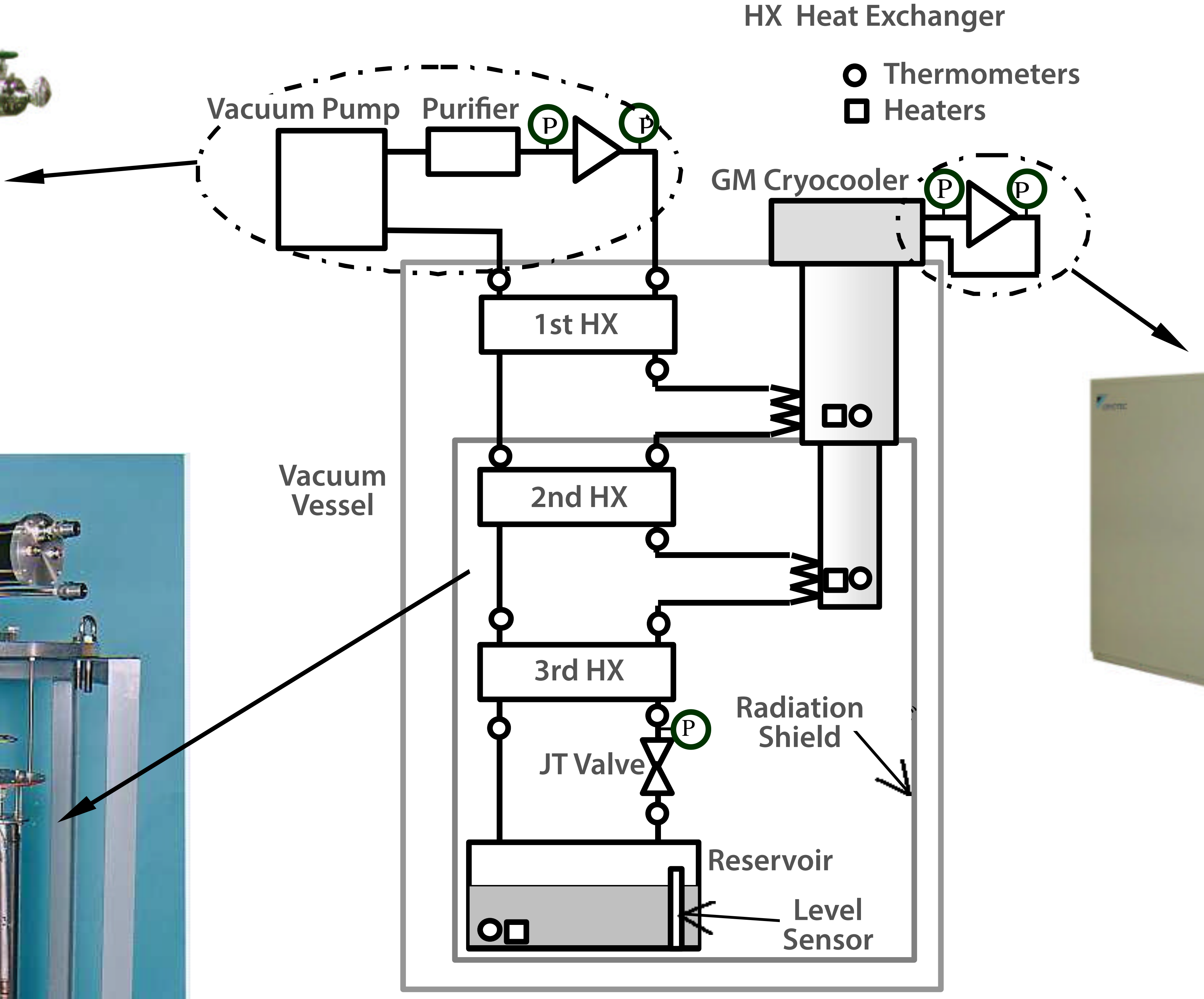
July 2001, National Institute for Materials Science
Cooling Capacity : **2 W @ 2 K** / 0.6 W @ 1.8 K
Input Power : 8.8 kW (GM + JT + Vacuum Pumps)



Temperature dependence of Cooling Power







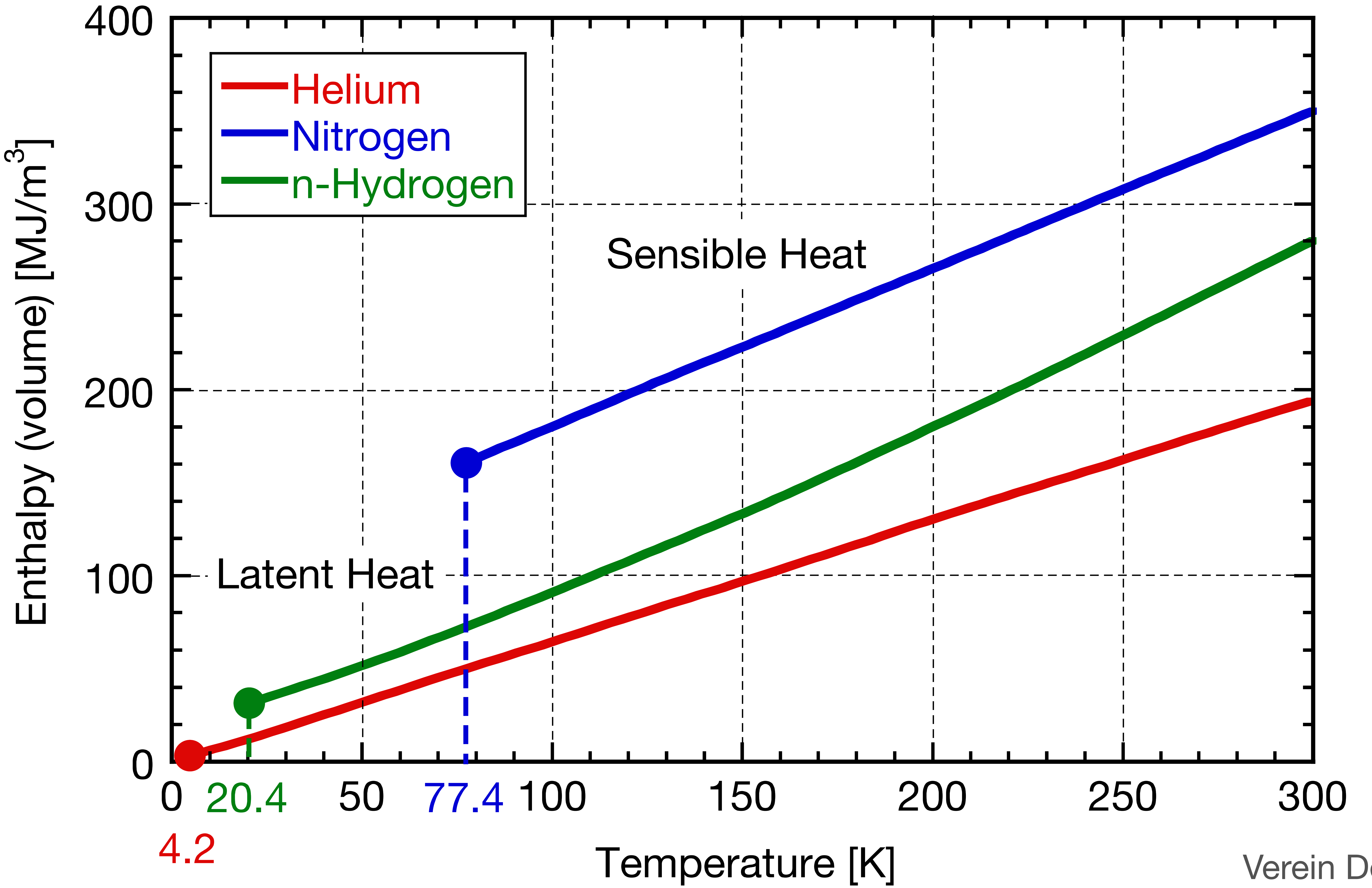
Configuration of Small 2K Refrigerator

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

Thermal Oscillation

- 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

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

Summary (cont'd)

- 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