The 4th Asian School on Superconductivity and Cryogenics for Accelerators
Korea University Sejong Campus, Sejong, Korea

Superfluid Helium Cryogenics and Superfluid Helium Cryogenic Systems

High Energy Accelerator Research Organization (KEK)
Accelerator Laboratory

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February 18, 2023

Contents of This Lecture

1. Introduction

Accelerators and Cryogenics

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

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 …

2. 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

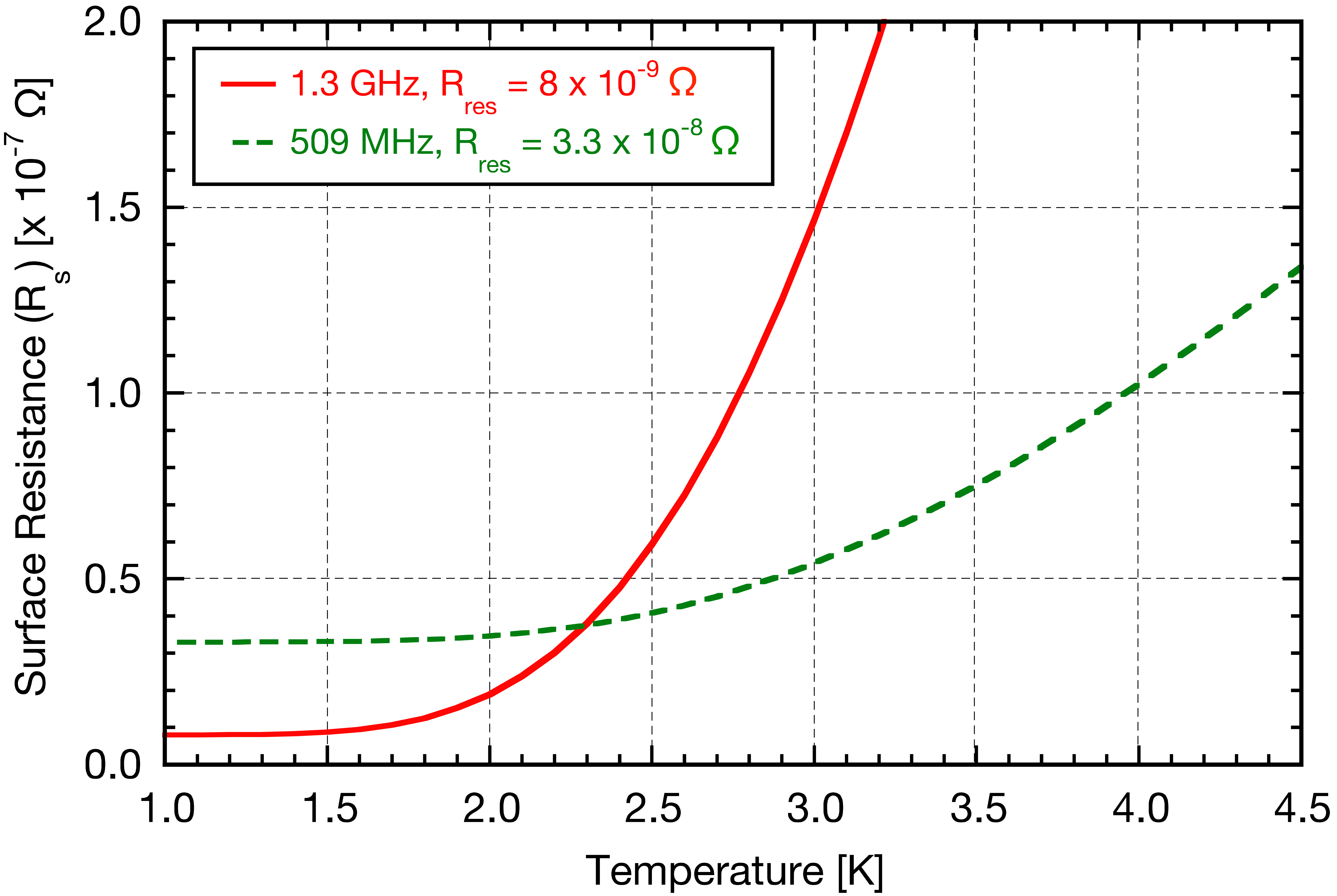
Semi-empirical equation for BCS theoretical value of niobium at temperature $T < T_c/2$

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

T : Operation temp.
f : Frequency

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

Temperature Dependence of Surface Resistance

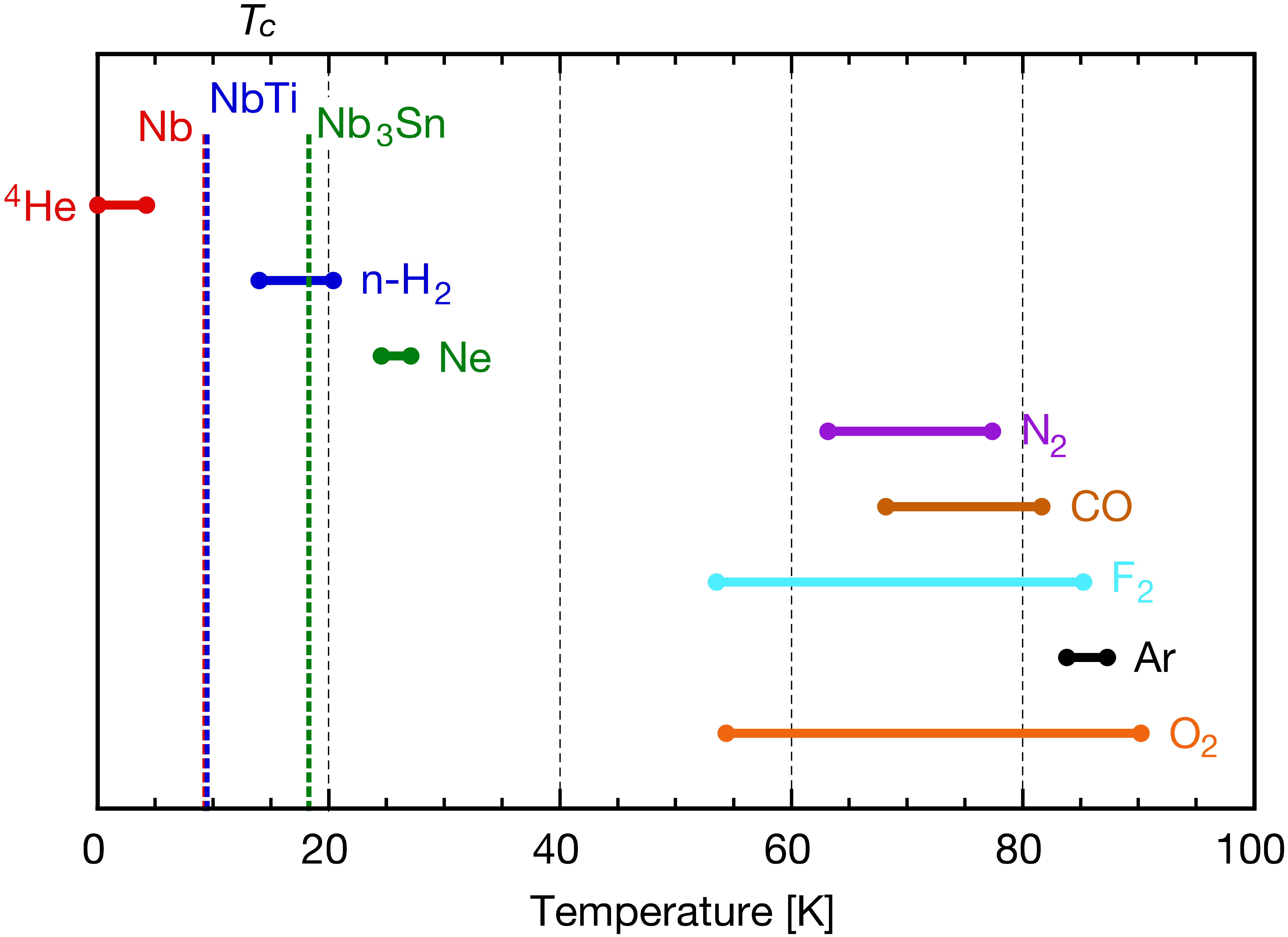


Operation Temperature of Superconducting Cavities

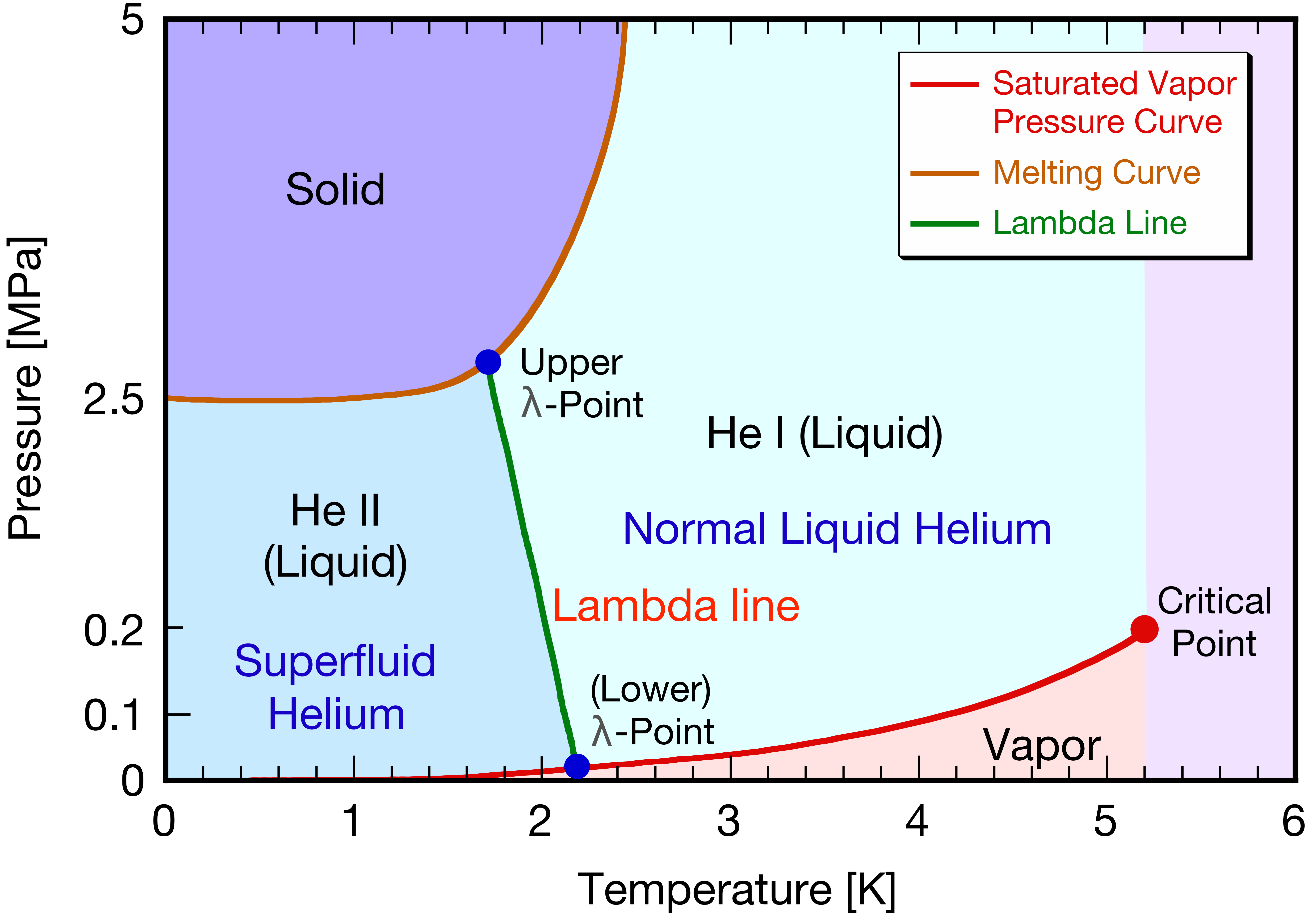
- Heat generated from cavity (cavity loss, RF loss) is proportional to surface resistance
- Surface resistance is sum of BCS resistance and residual resistance
- BCS resistance depends on operation temperature
- The higher resonant frequency the lower operation temperature
  - 509 MHz SC cavities → operated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

3. Superfluid Helium

Boiling and Triple Points, Transition Temperatures

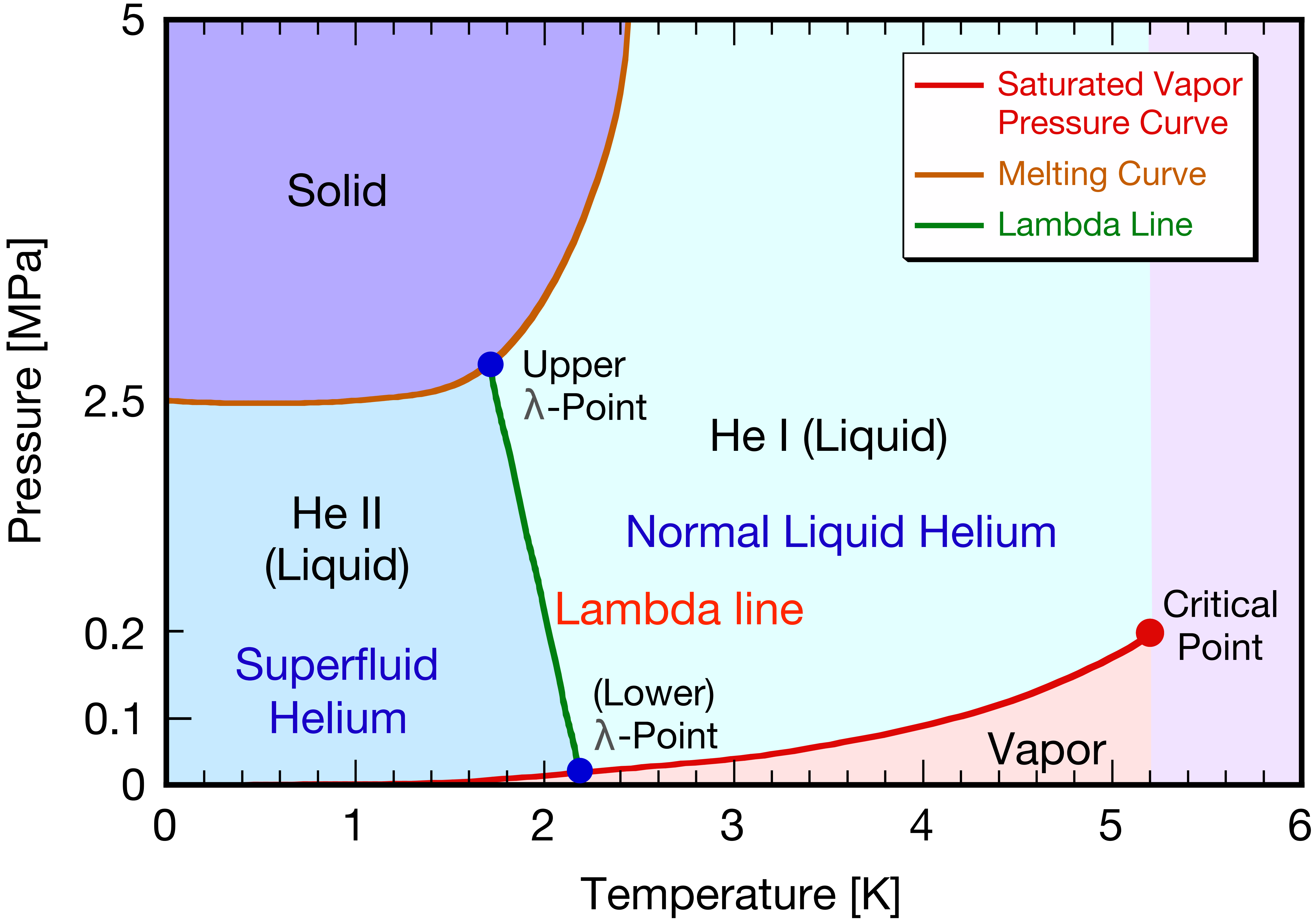


Phase (State) Diagram of Helium



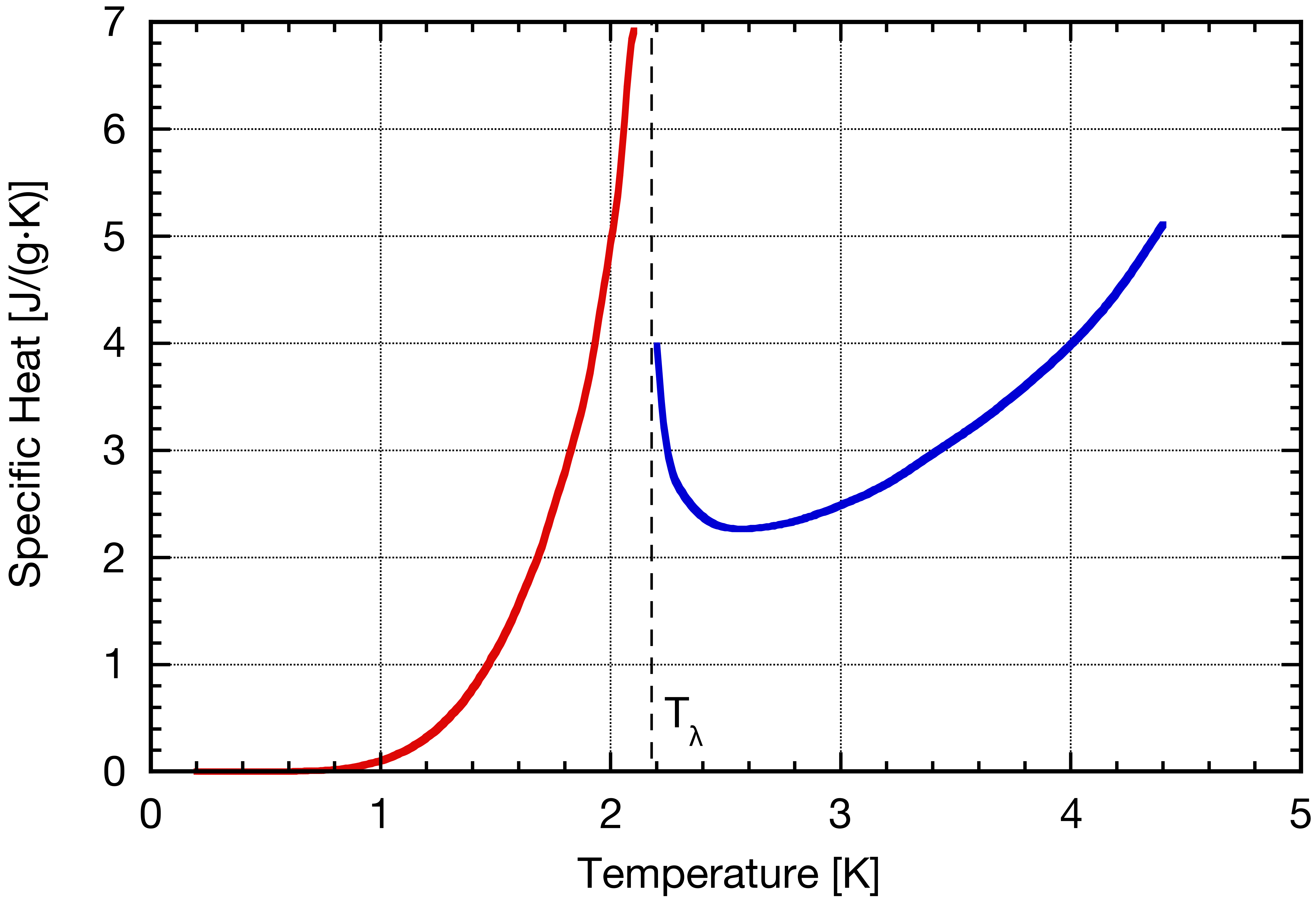
- Liquid phase remains even at 0 K
- Solid appears only under high pressure (above 2.5 MPa)
- Two different liquid phases
  - He I ('ordinary' liquid helium, normal fluid phase)
  - He II (superfluid helium, superfluid phase)
- Lambda line : border of these two liquid phases

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)

Specific Heat of Liquid Helium



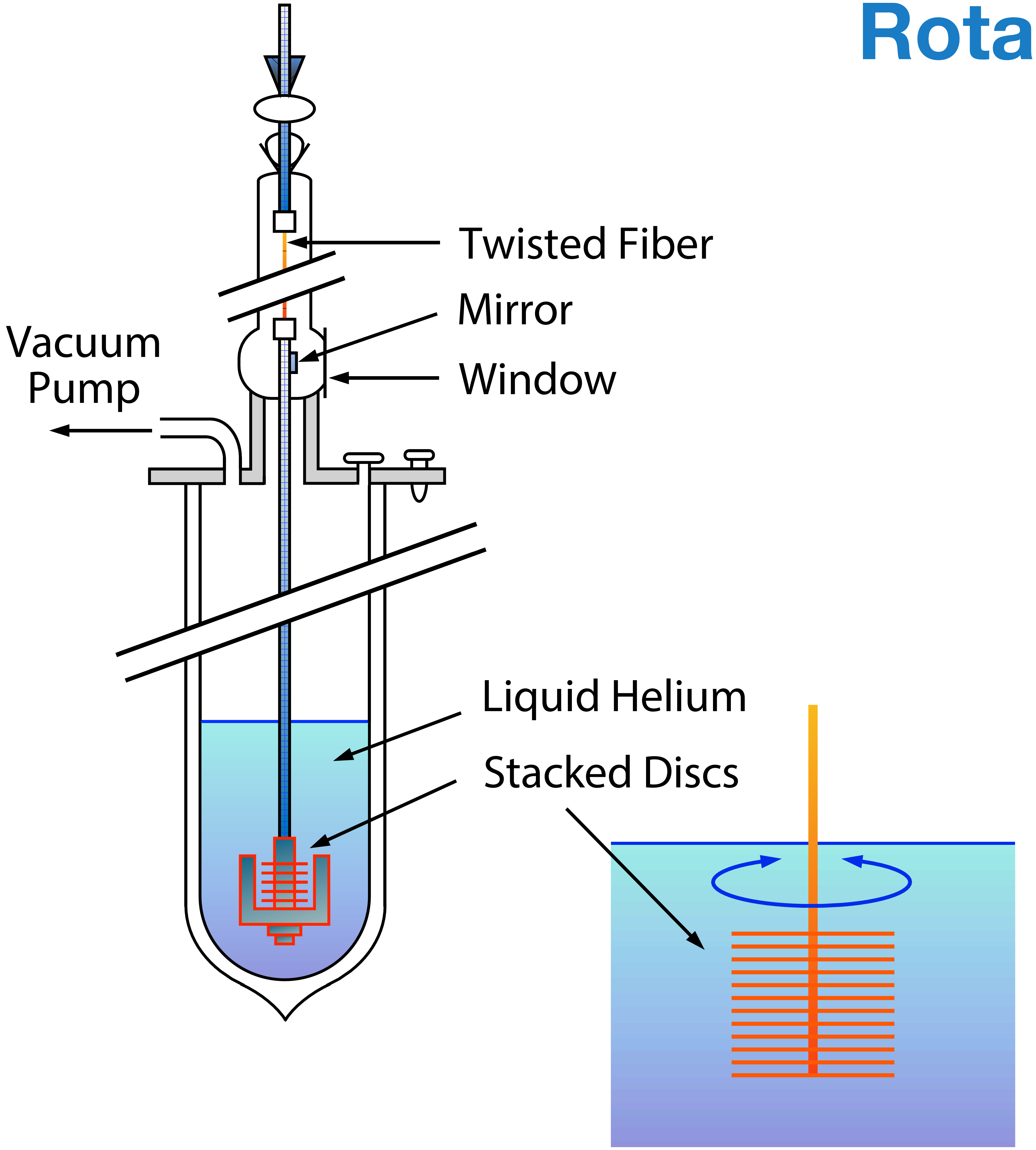
Schmidtchen, U., Private Communication (1984)

Major Thermodynamic State Points

- Lambda point (λ-point)
  - Temperature : T_λ = 2.1768 K
  - Pressure : P_λ = 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

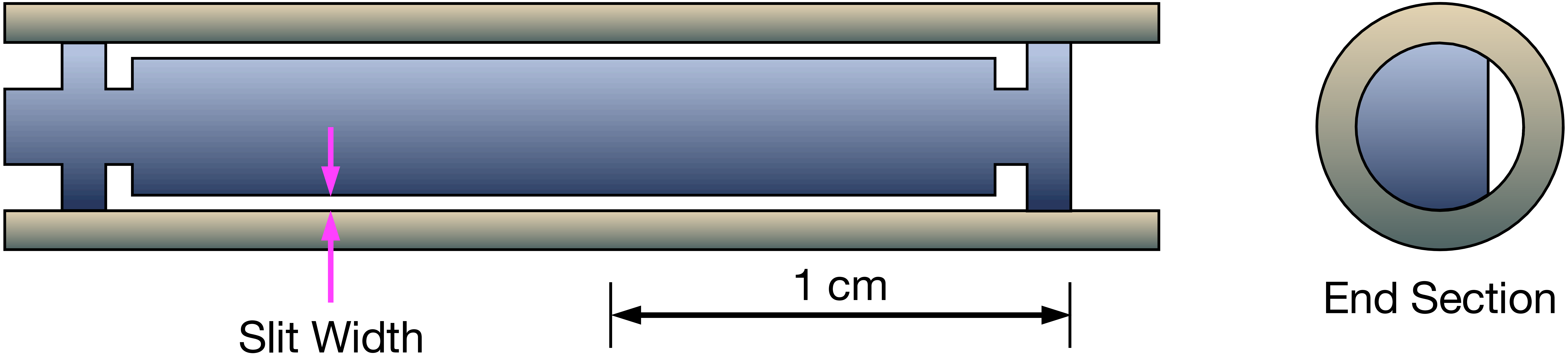
（Figures may vary among references）

Rotational Viscometer



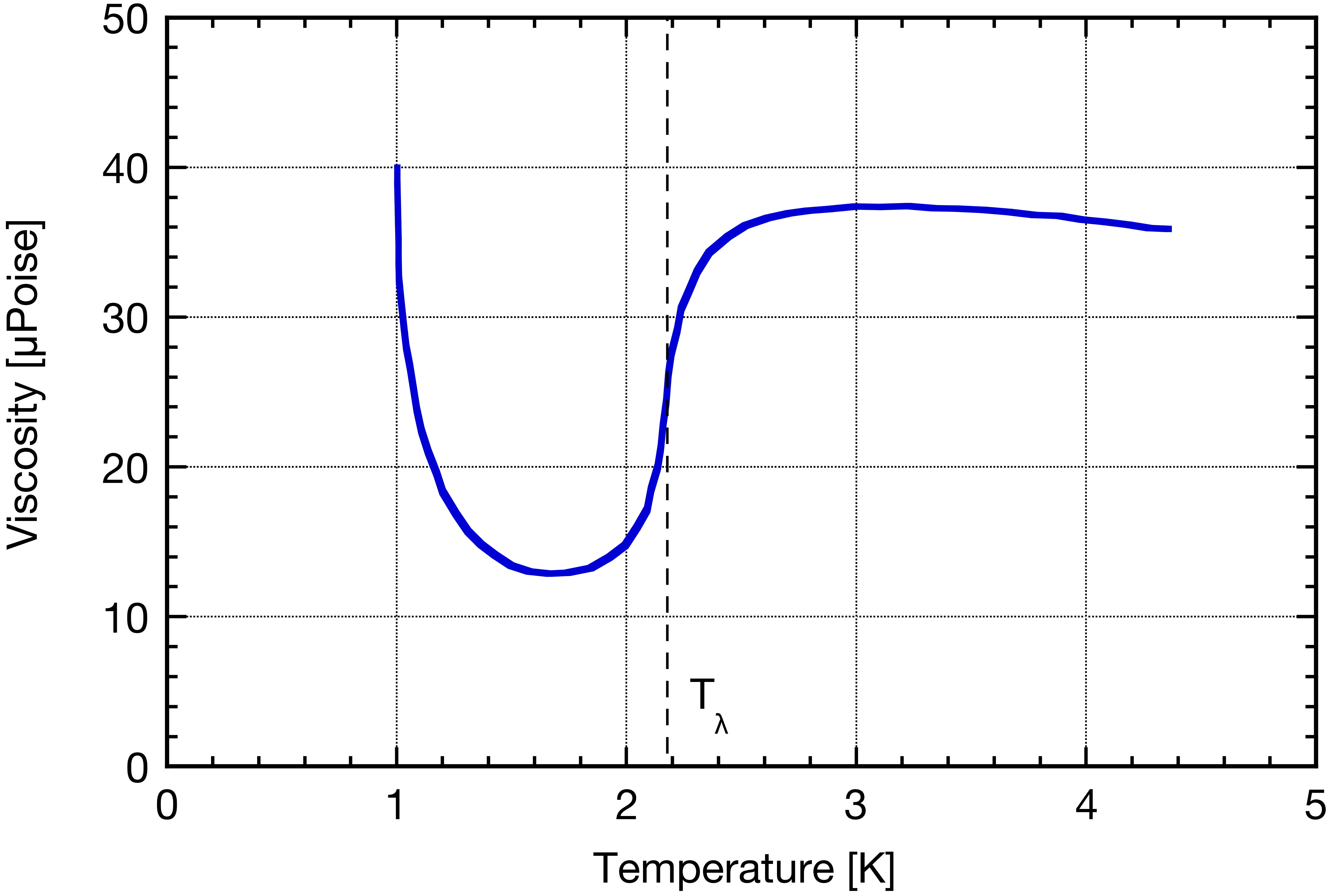
Yamada K. and Ohmi T., “Superfluidity”, Baifukan (1995)

Flow Through Slit (1)

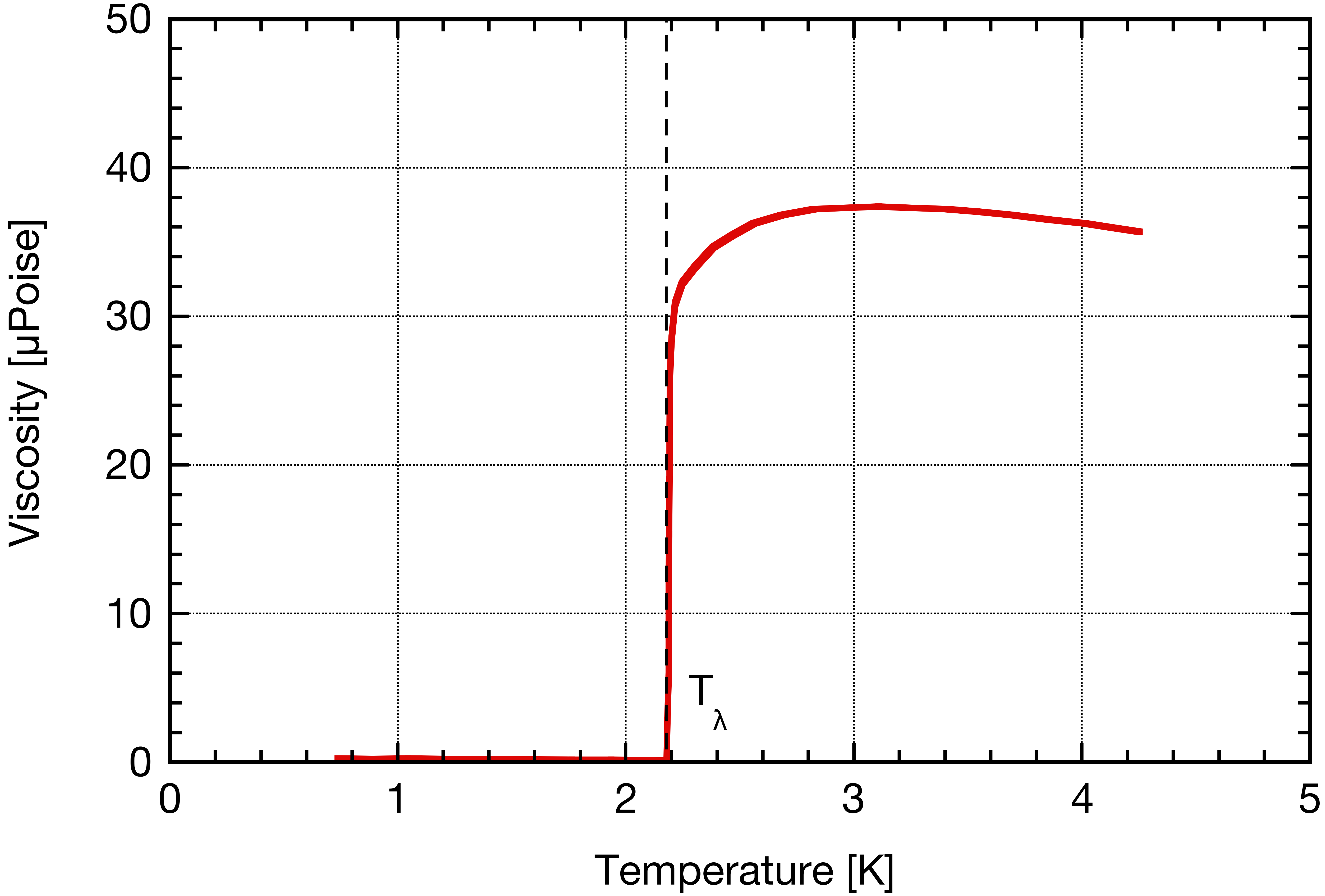


Donnelly, R. J., “Experimental Superfluidity”, University of Chicago Press (1967)

Two Different Methods for Viscosity Measurement



Rotational Viscometer



Poiseuille Flow in Capillary

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

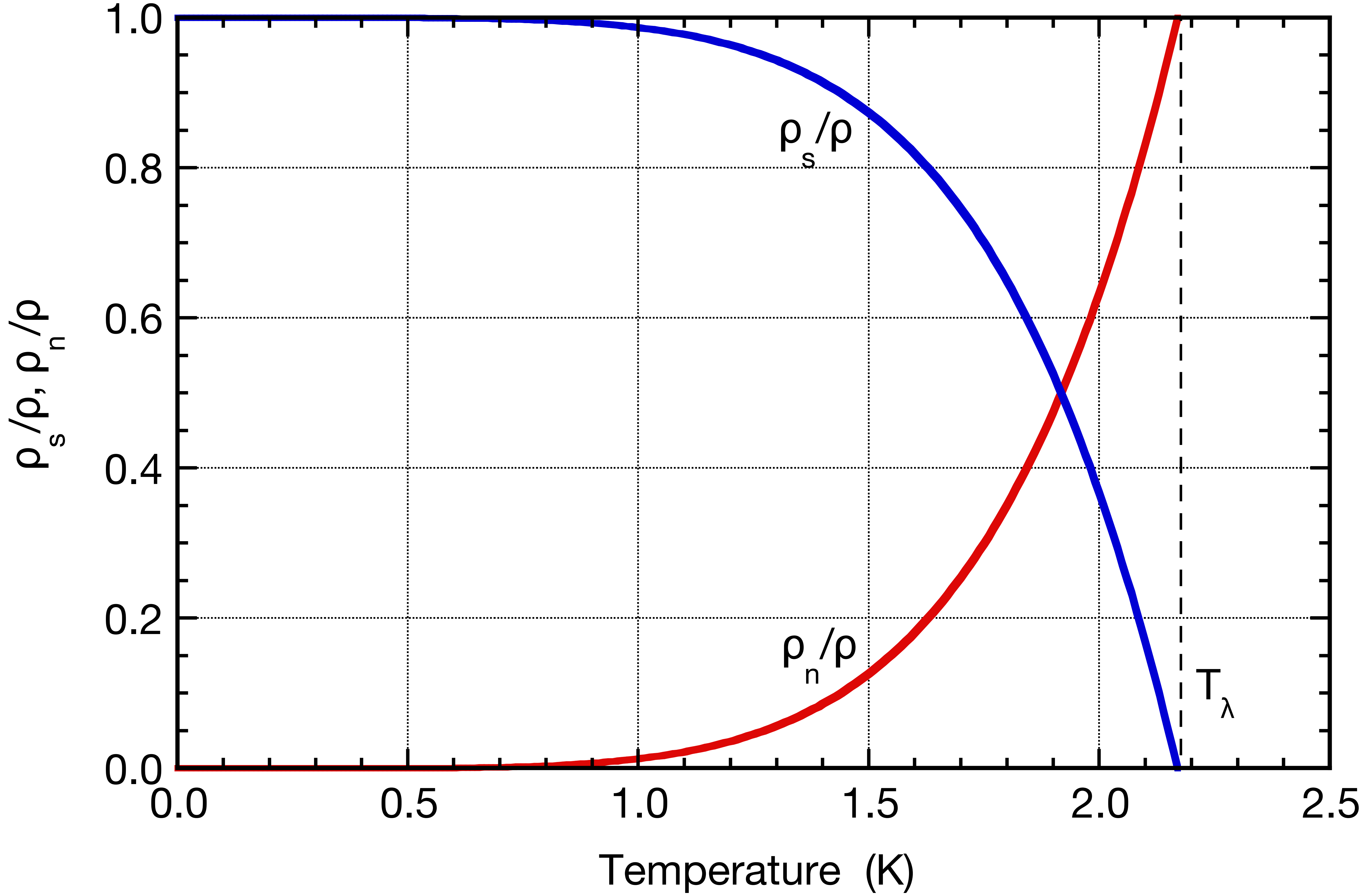
Two-fluid Model (1)

- 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)



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

Two-fluid Model (4)

Density of Superfluid Component

Density of Normal Fluid Component

Overall Density

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

Overall Momentum Density

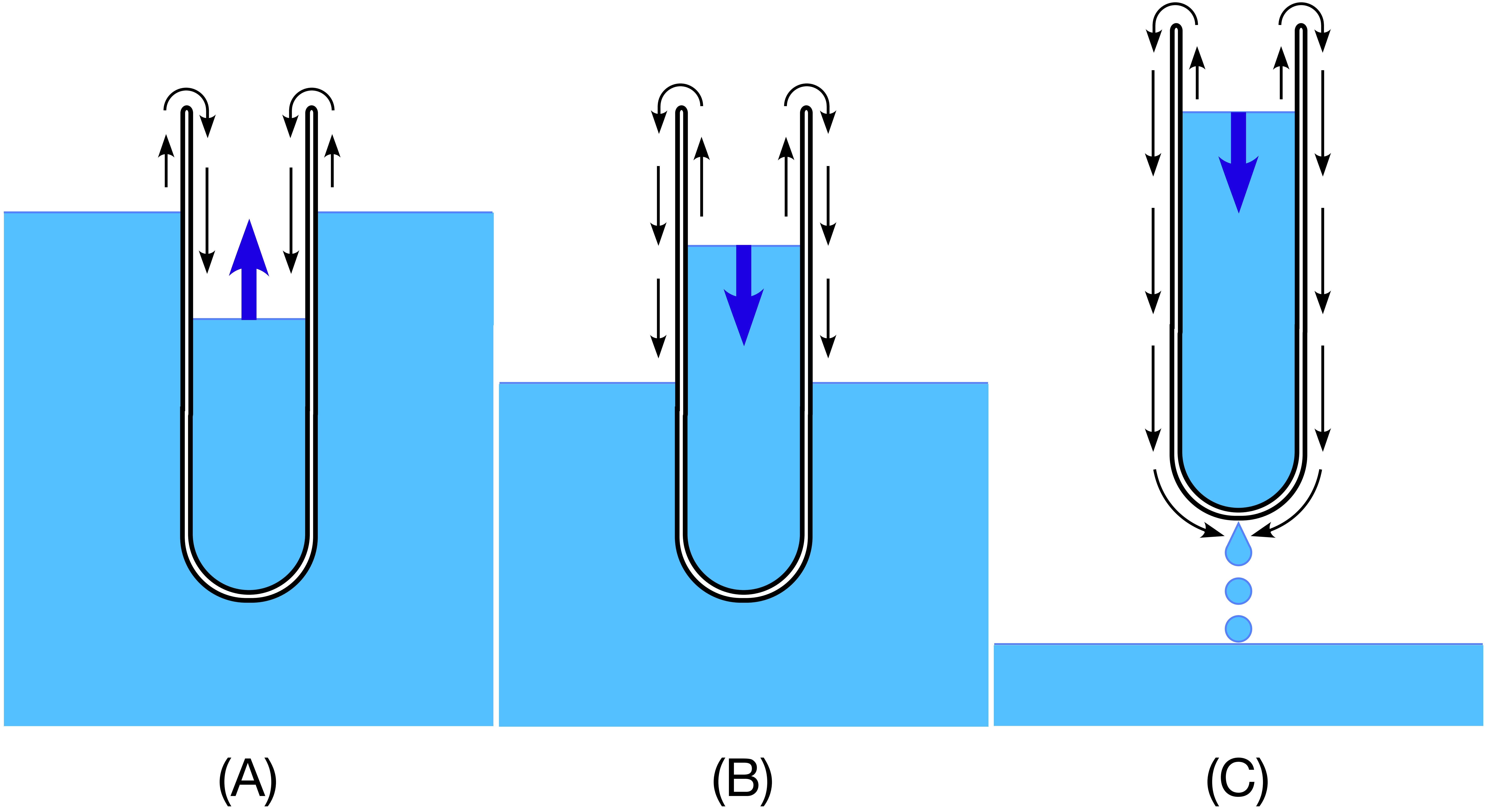
$$\mathbf{j} = \rho_s \mathbf{v}_s + \rho_n \mathbf{v}_n$$

Velocity Field of Superfluid Component

Velocity Field of Normal Fluid Component

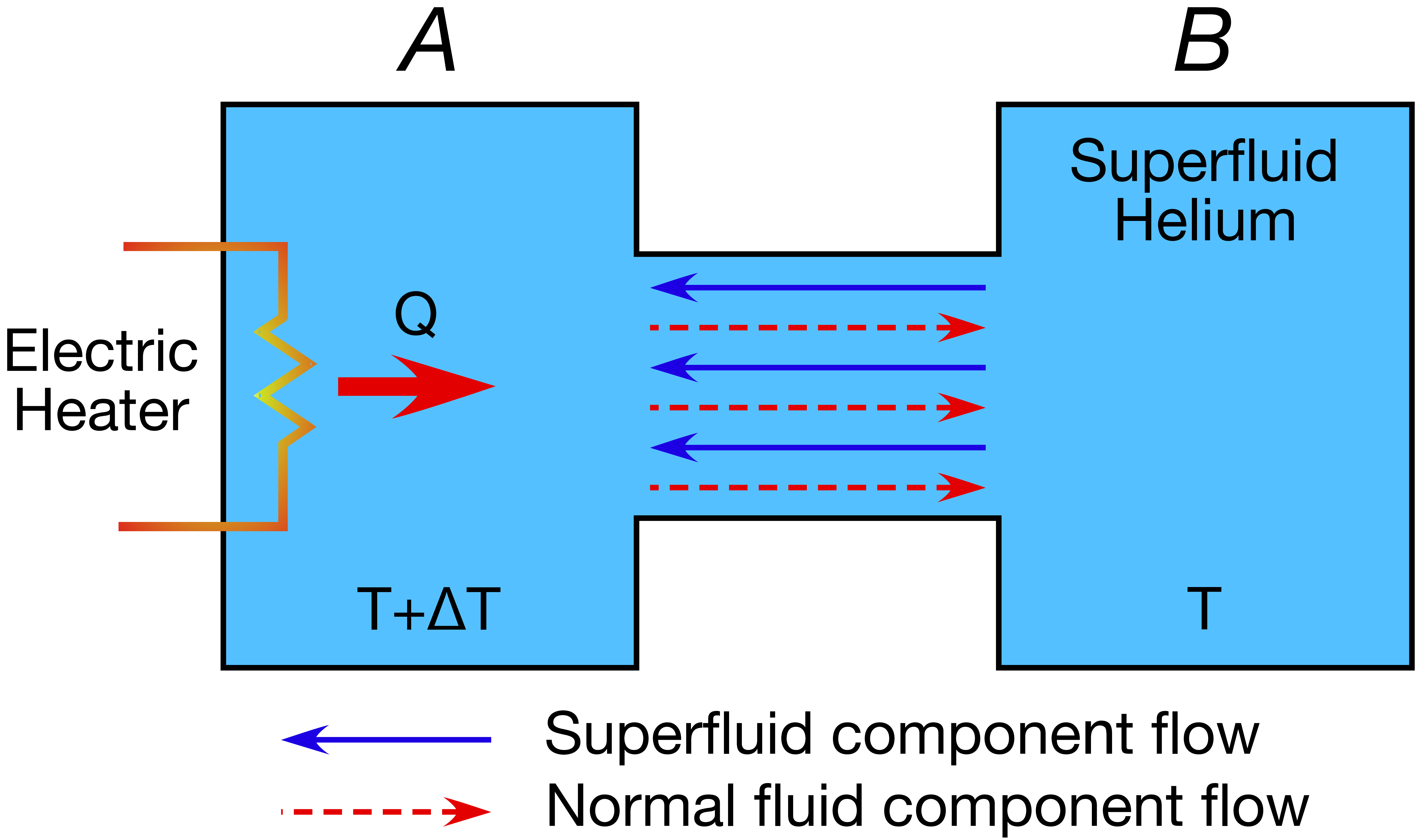
Yamada K. and Ohmi T., “Superfluidity”, Baifukan (1995)

Film Flow



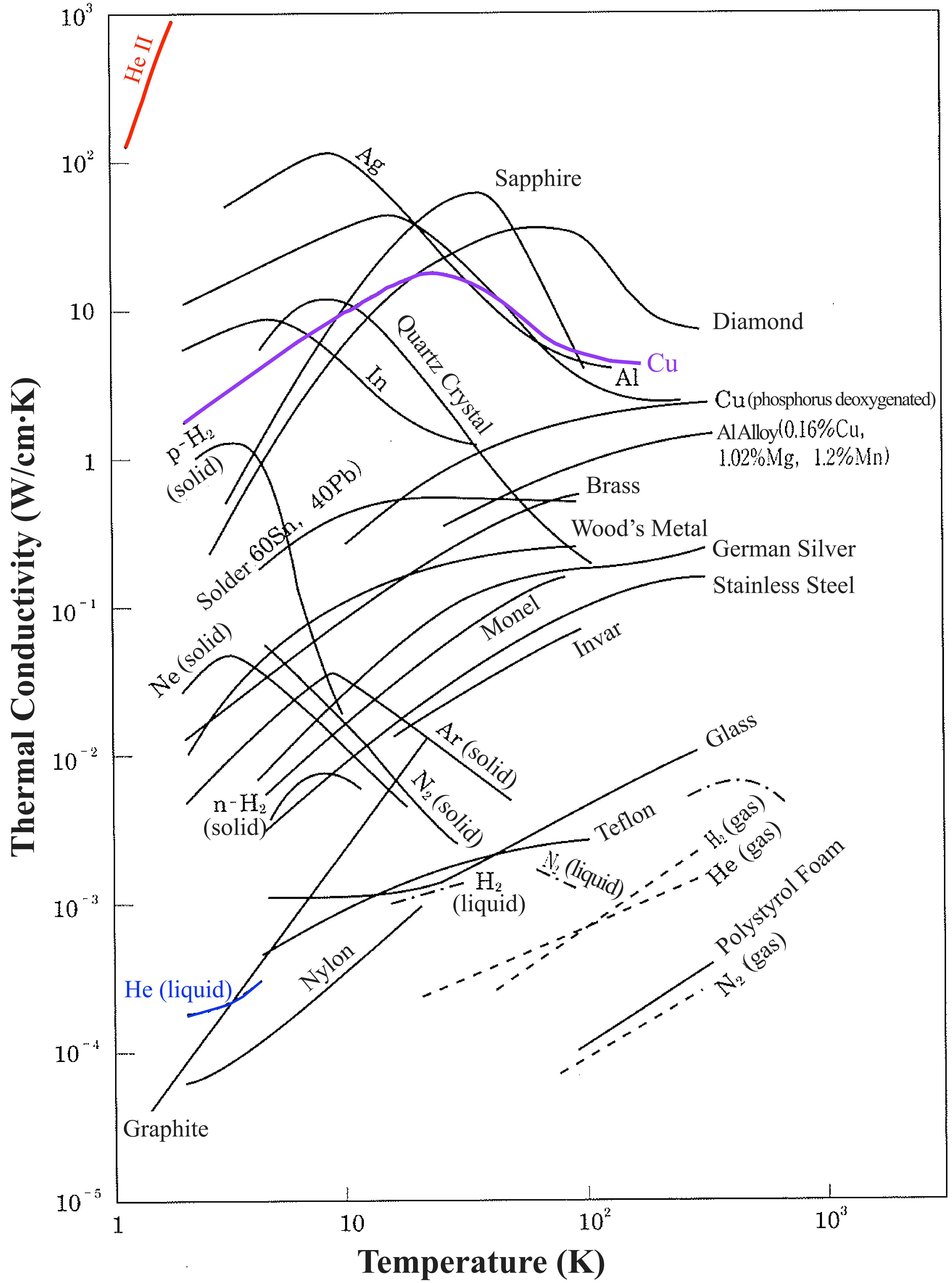
Donnelly, R. J., “Experimental Superfluidity”, University of Chicago Press (1967)

Heat Transfer of Superfluid Helium



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

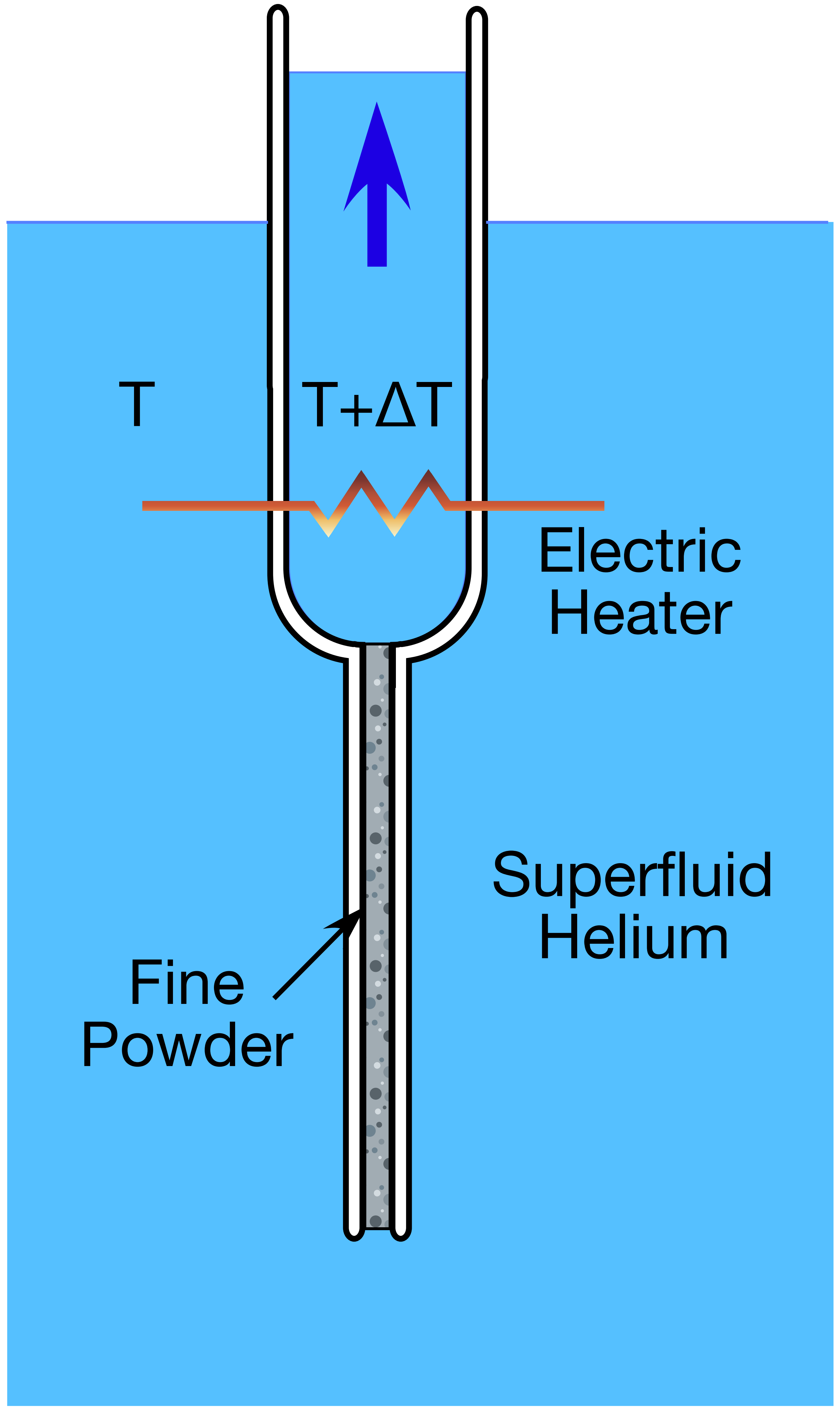
Thermal Conductivity

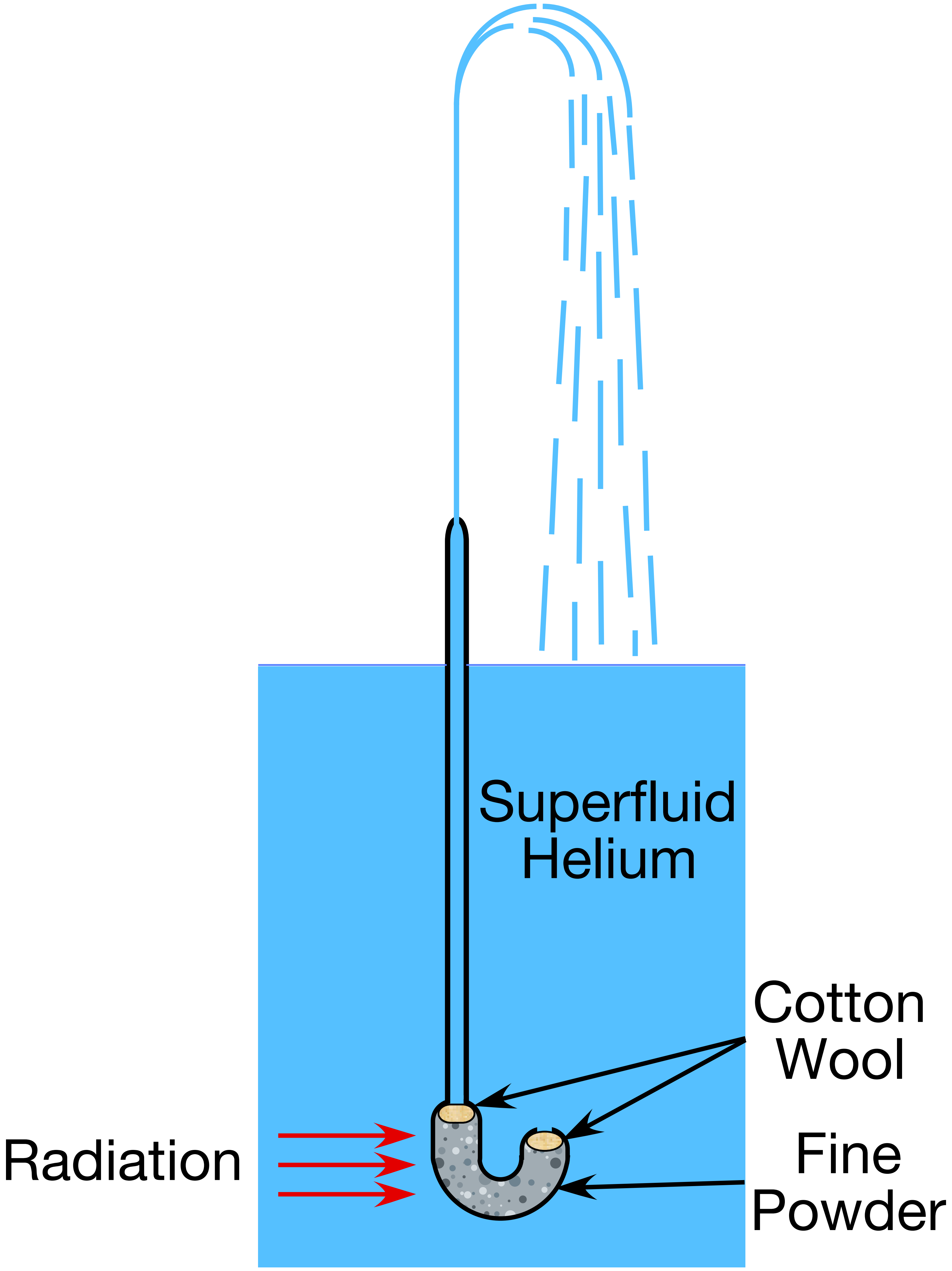


- (Apparent) thermal conductivity of superfluid helium
  - Much larger than that of pure copper
  - Different mechanism of other substances and materials

Verein Deutscher Ingenieure, "Lehrgangshandbuch Kryotechnik" (1977)

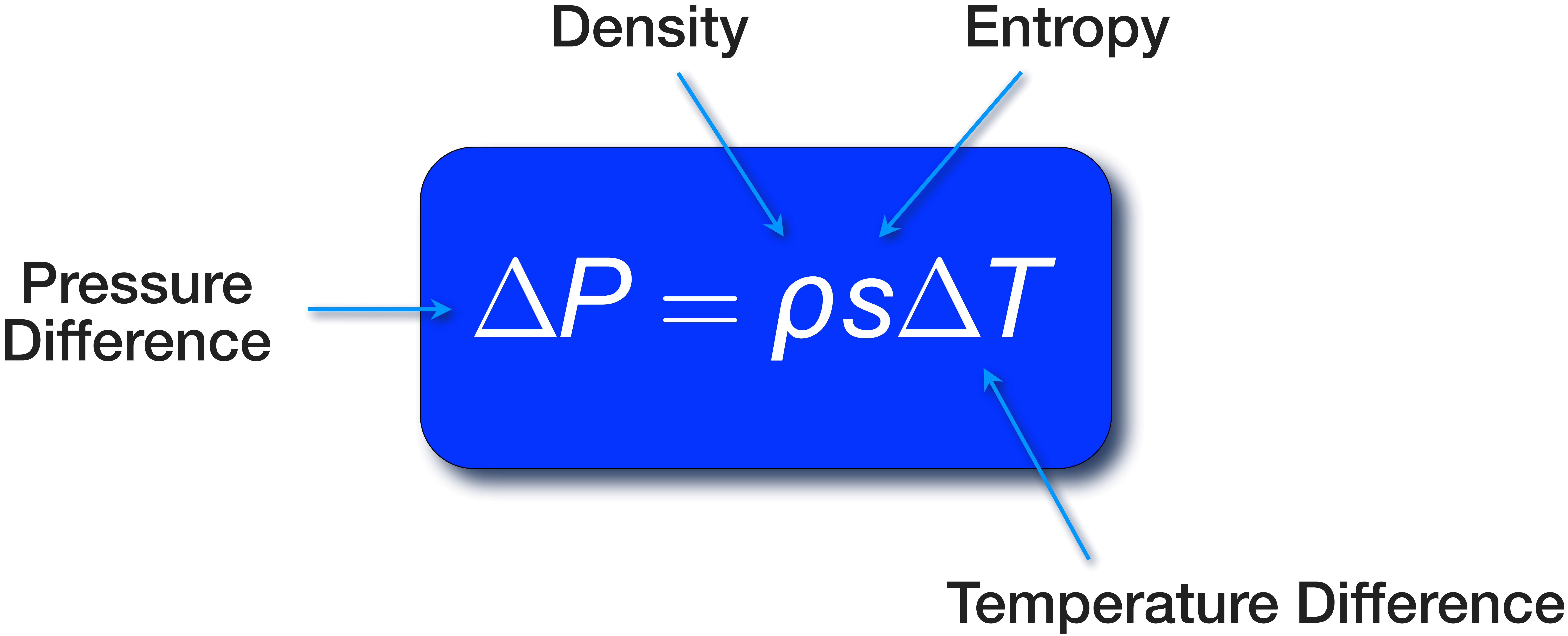
Thermomechanical Effect





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

London’s Relation



Density

Entropy

Pressure Difference

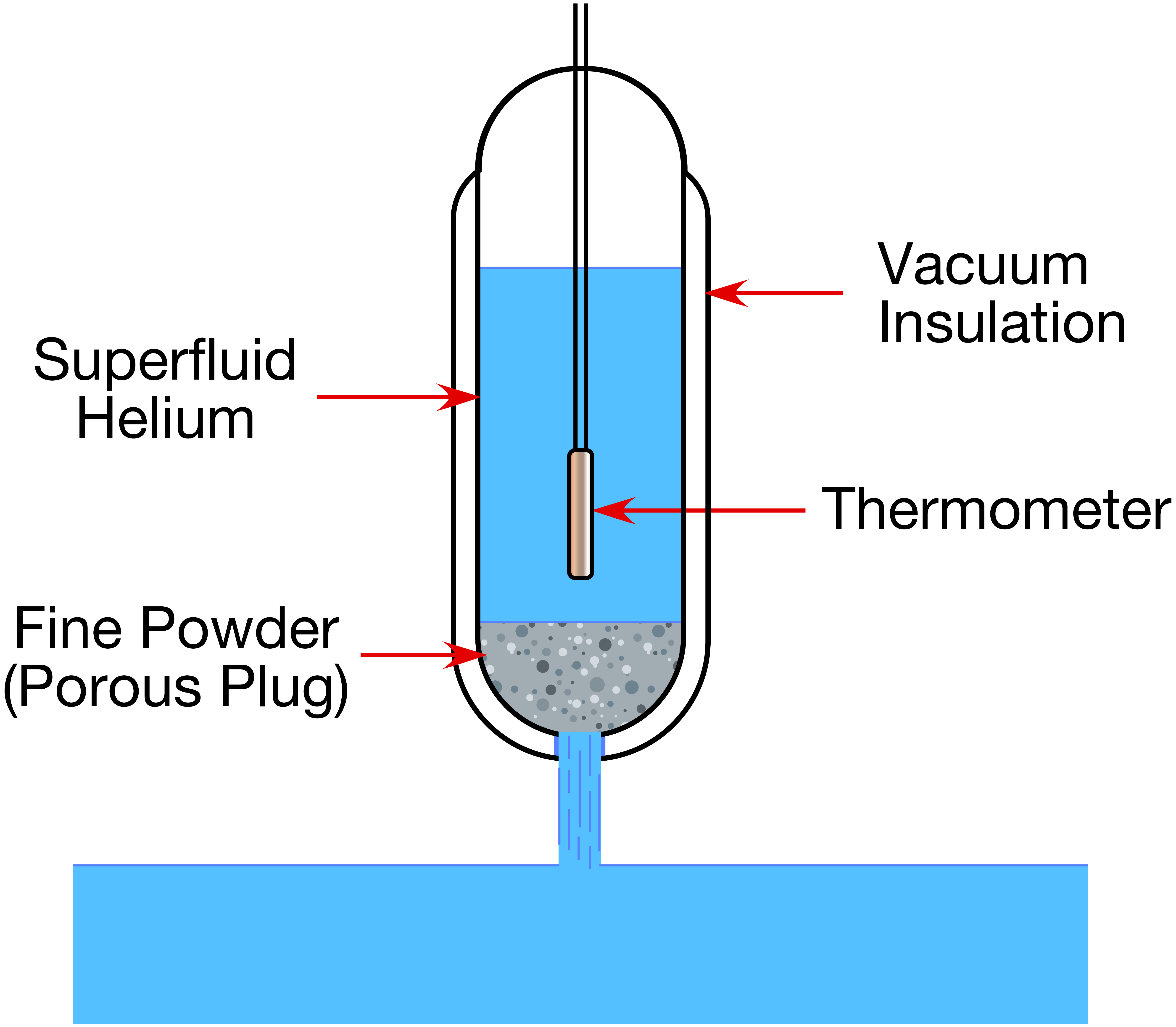
$$\Delta P = \rho s \Delta T$$

Temperature Difference

Fountain Effect

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

Mechanocaloric Effect



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

Superfluid Helium

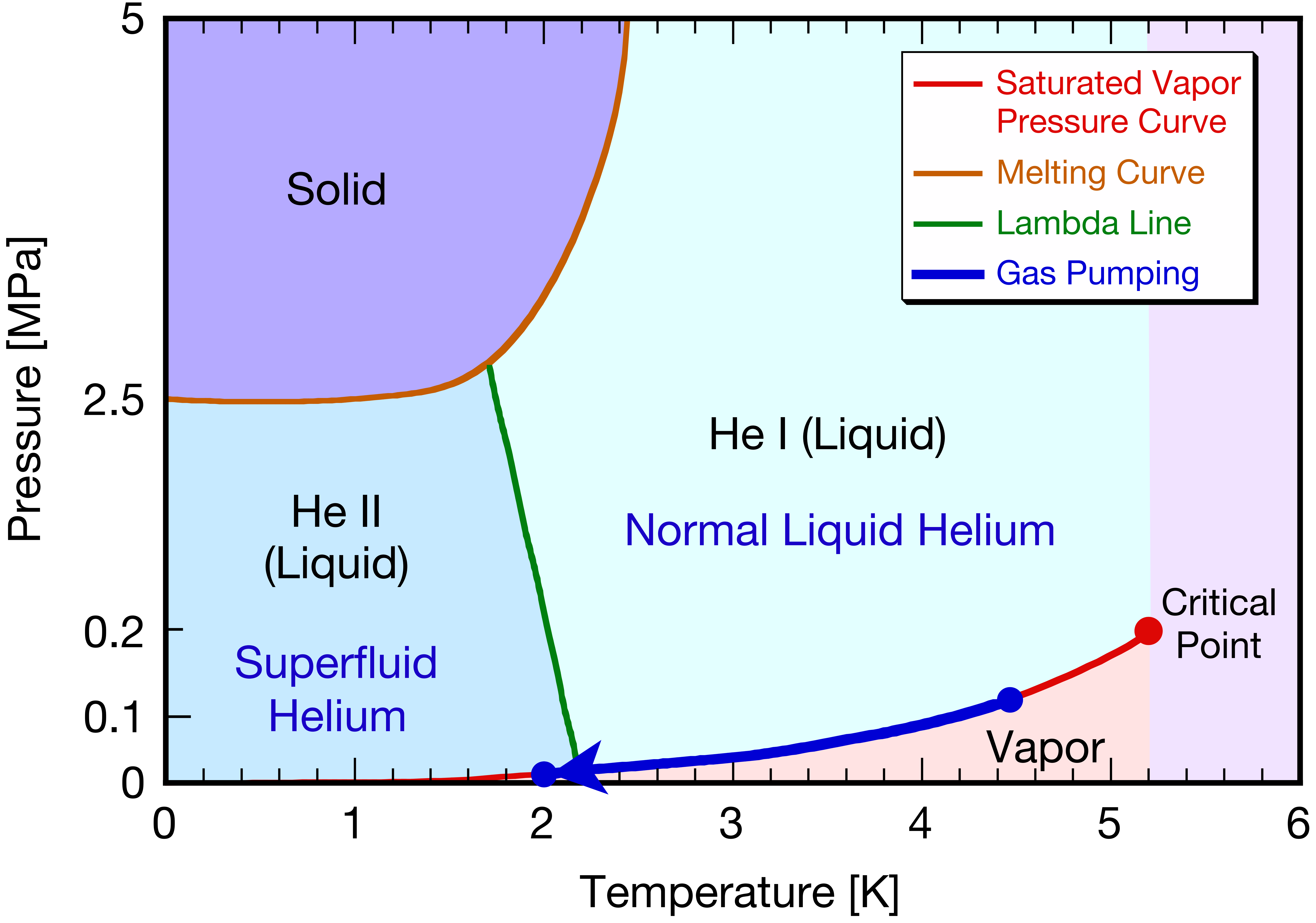
- Superfluidity
  - Superfluid helium can flow through a capillary without any friction
- Super thermal conductivity
  - Apparent thermal conductivity is more than 100 times of that of pure copper
- Film flow
  - Superfluid helium can flow through an adsorbed film whose thickness is just a few atoms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

Superfluid Helium and Superconducting Devices

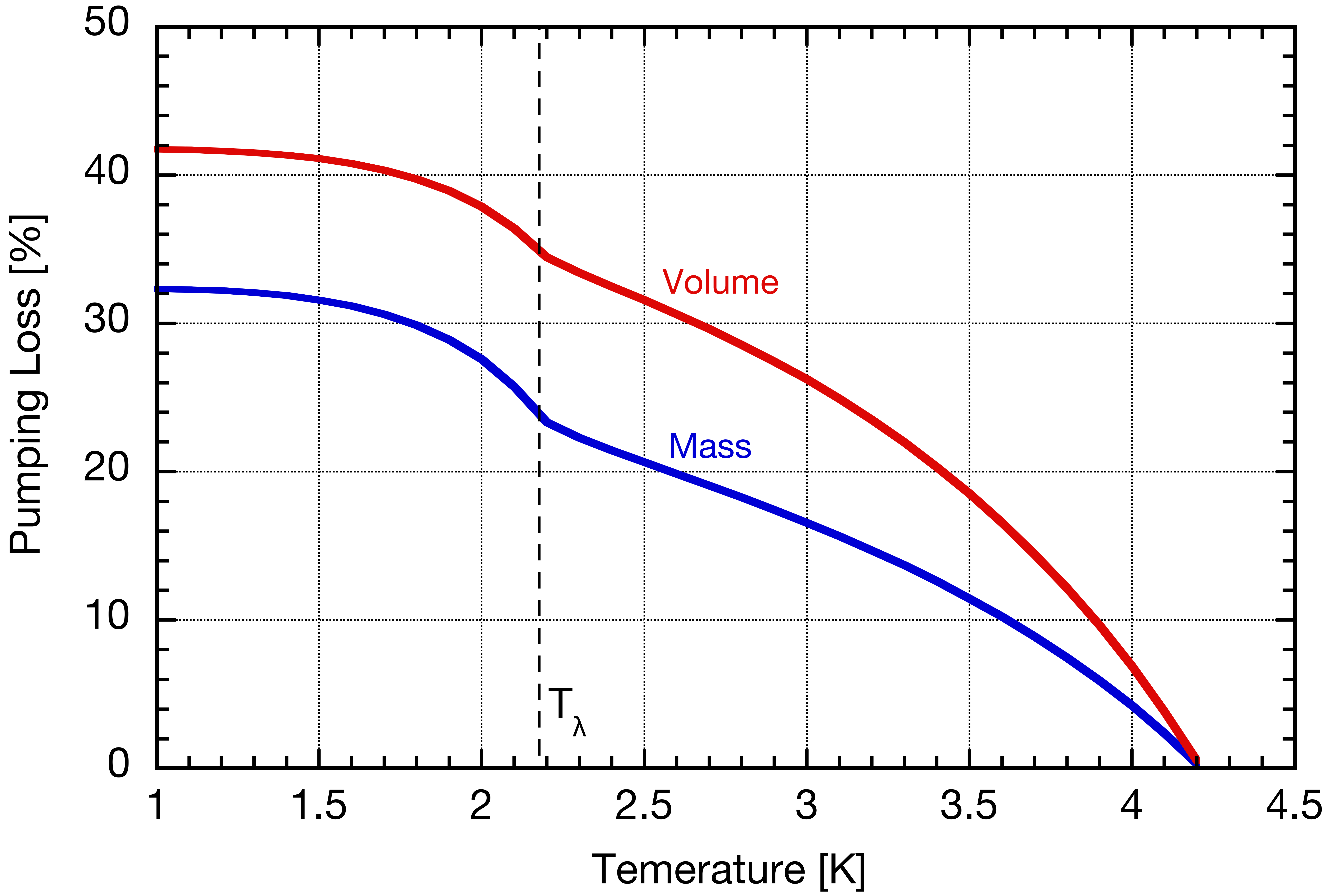
- High (apparent) thermal conductivity
  - No boiling → no gas on superconducting devices
- Superfluidity
  - Filling narrow gaps in superconducting magnet structure, cable strands, etc.
  - Good thermal contact with superconducting devices

4. Superfluid Helium Cryogenic Systems

Production of Superfluid Helium

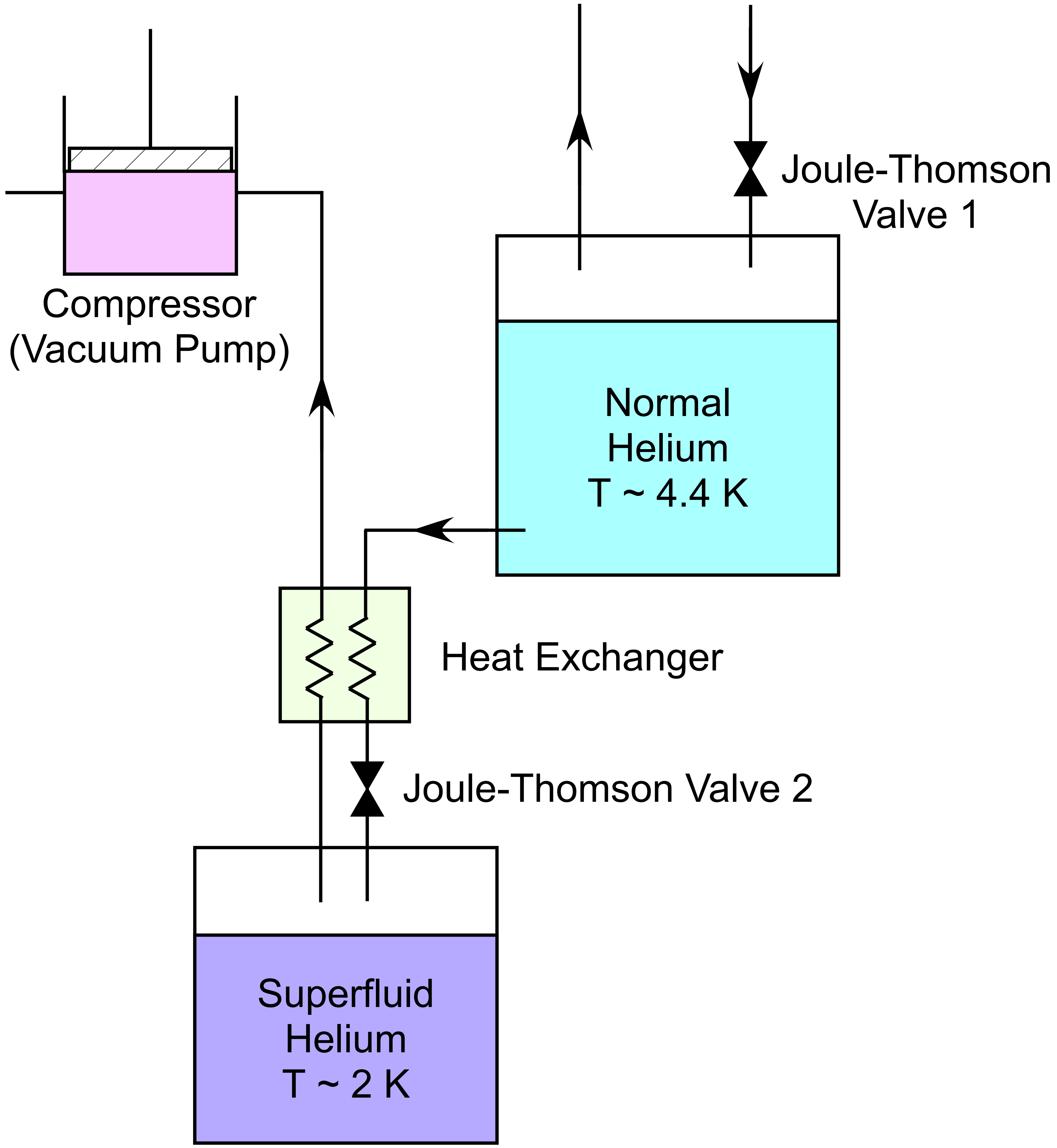


Liquid Helium Loss by Pressure Reduction



Schmidtchen, U., Private Communication (1984)

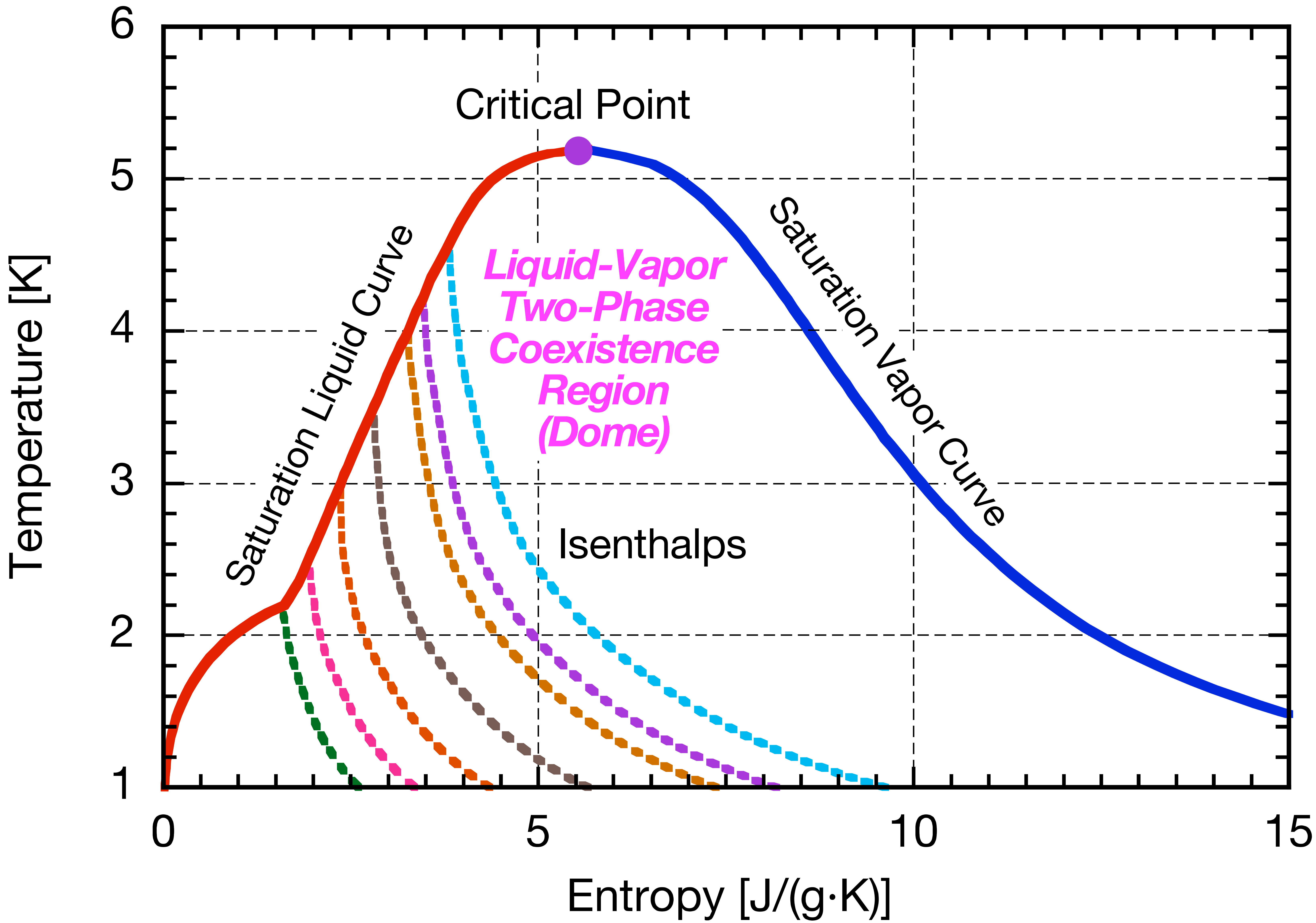
Continuous Production of Superfluid Helium



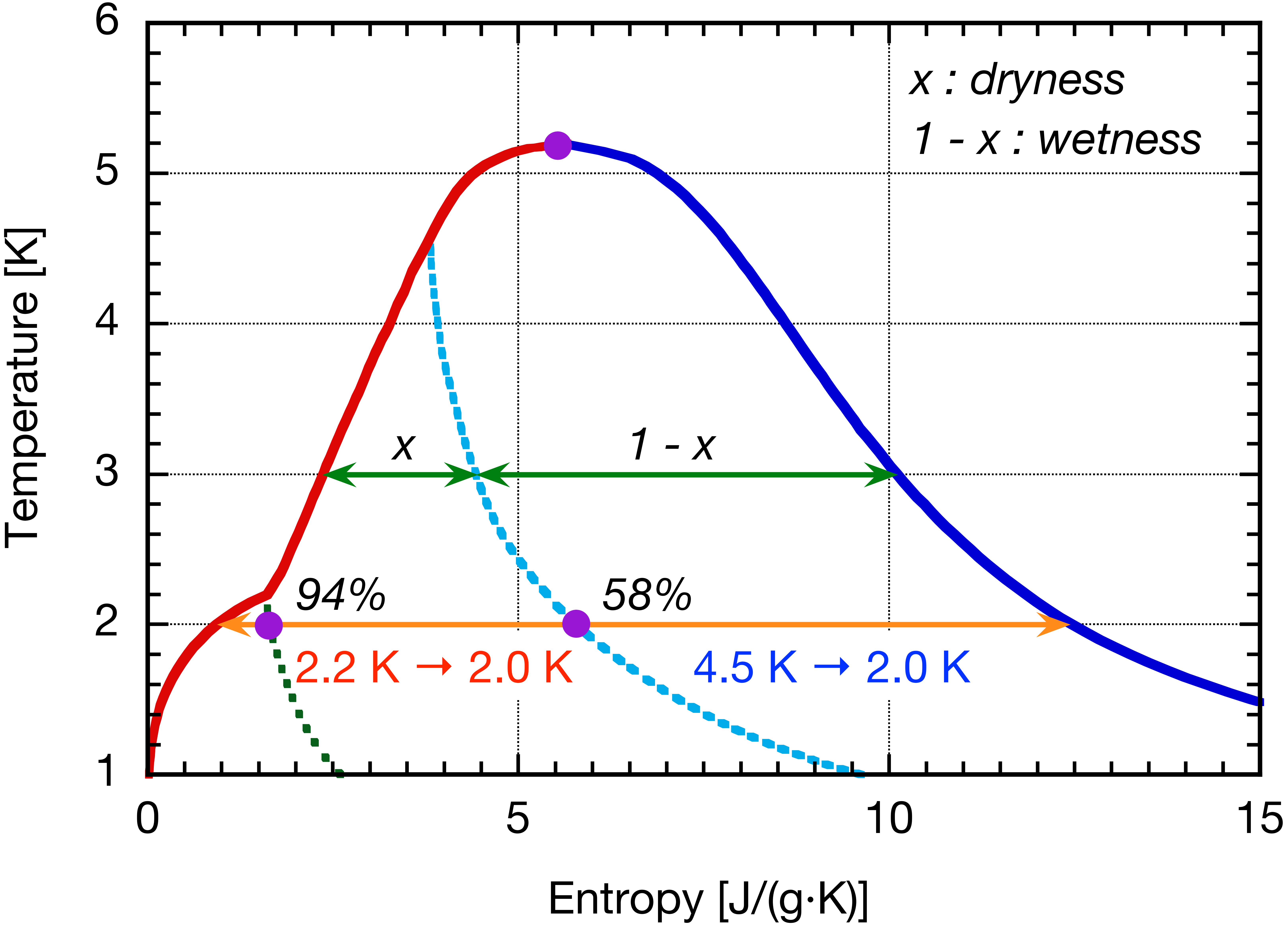
- Production of liquid helium
    - Joule-Thomson valve 1
- Cooling of liquid helium
    - Heat exchanger
- Isenthalpic expansion
    - Joule-Thomson valve 2
- Production of superfluid helium
- Compression of evaporated helium gas
    - Compressors
    - Vacuum pumps

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

Temperature-Entropy (T-s) Diagram of Helium



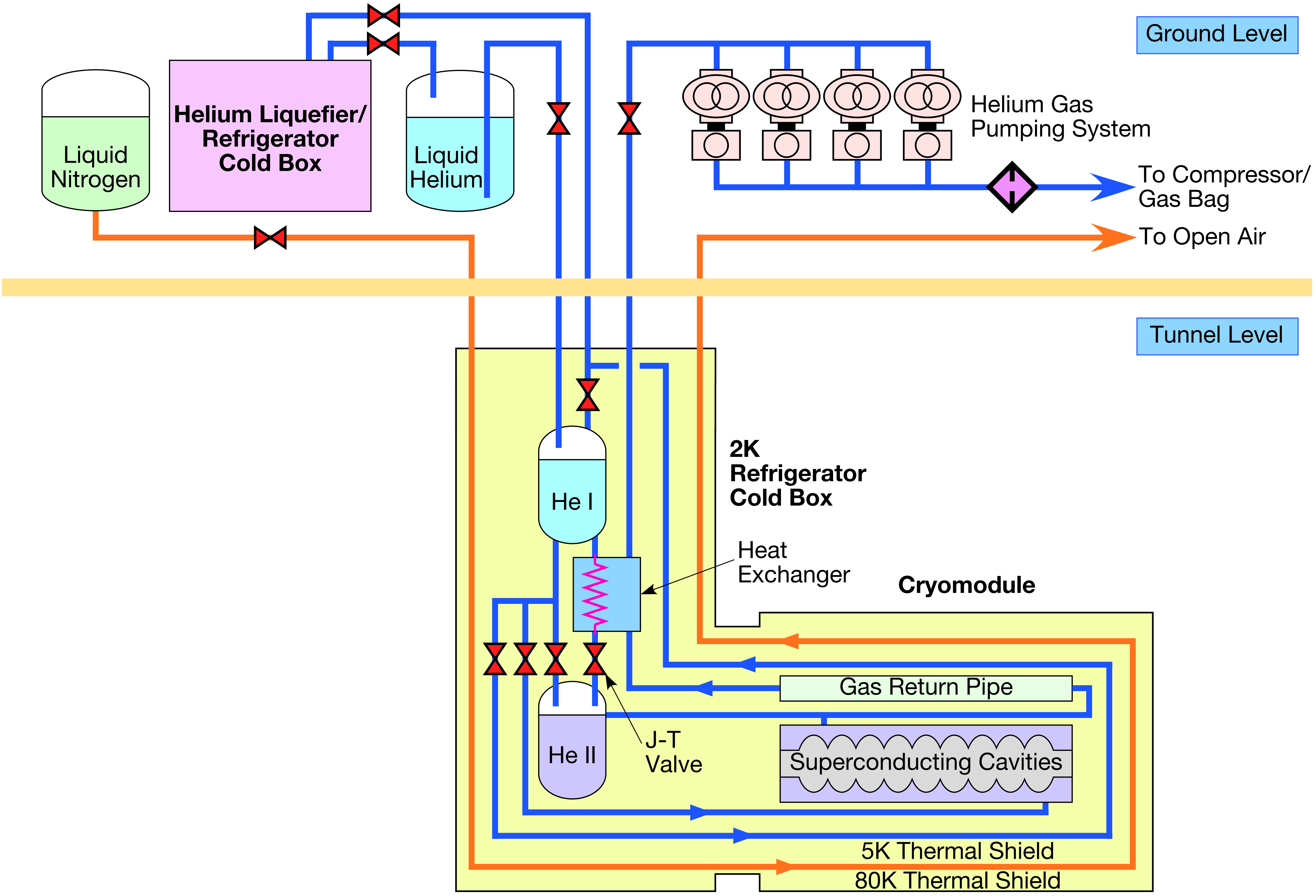
Dryness & Wetness



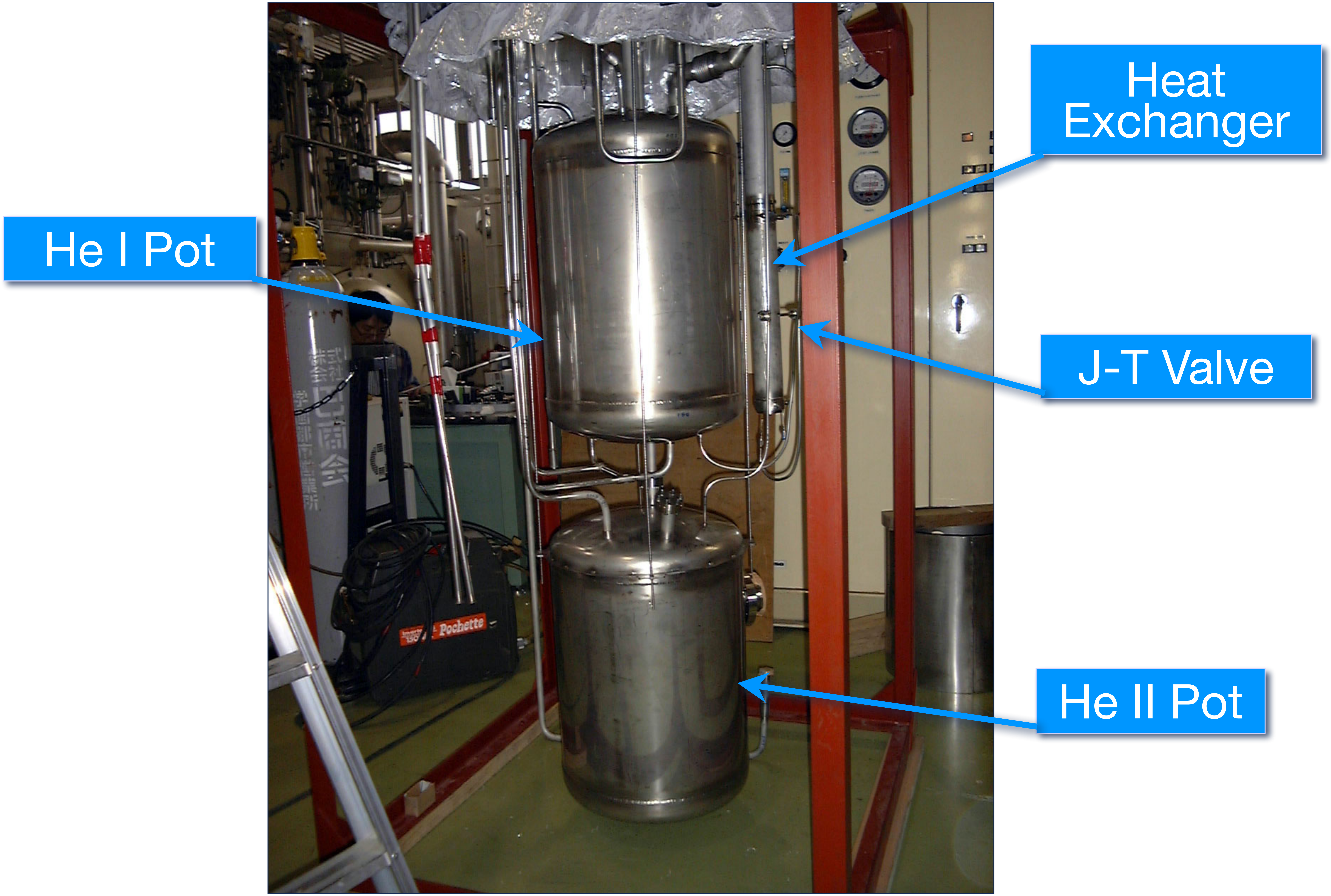
2K Refrigerator (2K Cold Box)

- 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

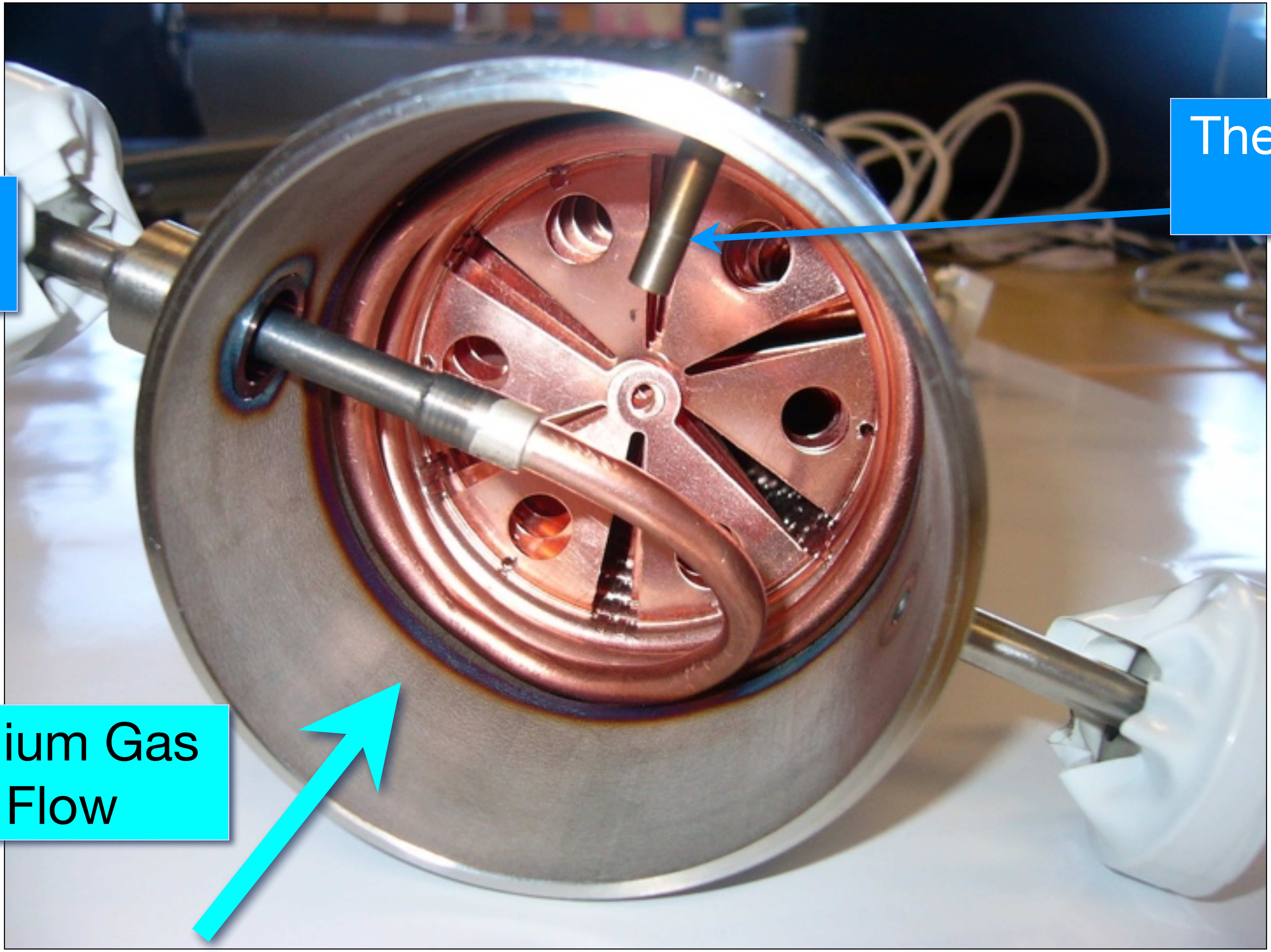
Cryogenic System at Superconducting RF Test Facility



2K Refrigerator Cold Box



2K Heat Exchanger

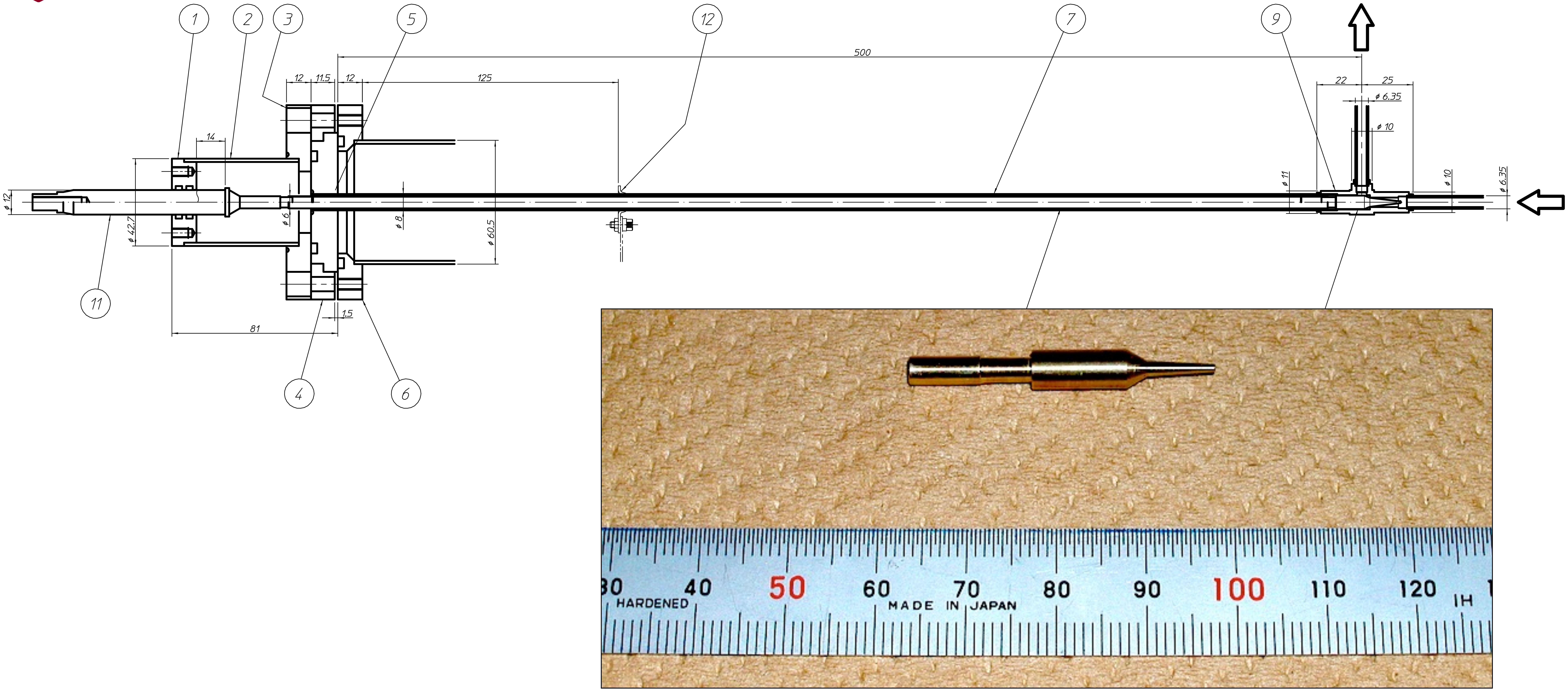


Liquid Helium Port

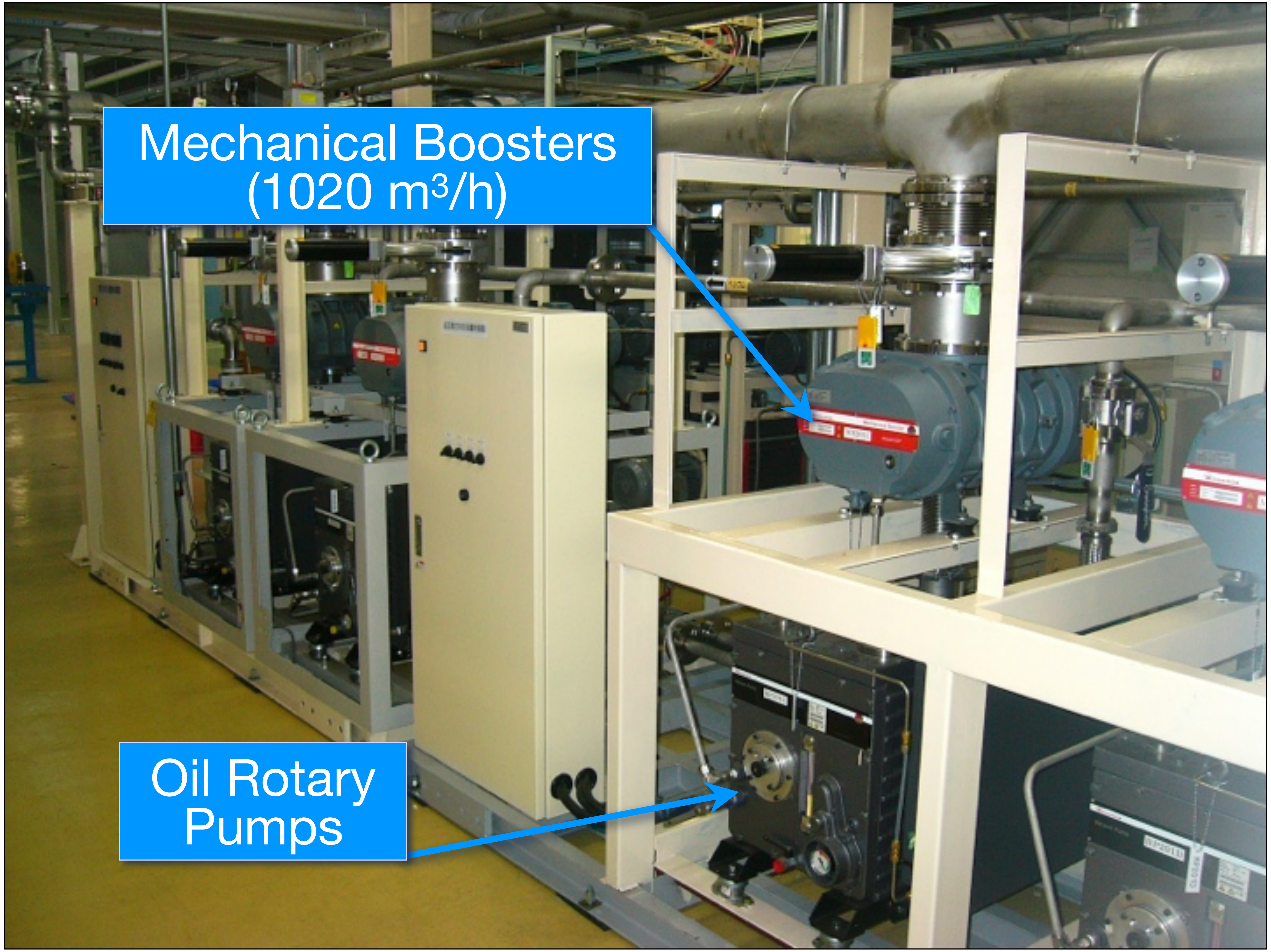
Thermometer Port

Helium Gas Flow

Joule-Thomson Valve for 2K Heat Exchanger

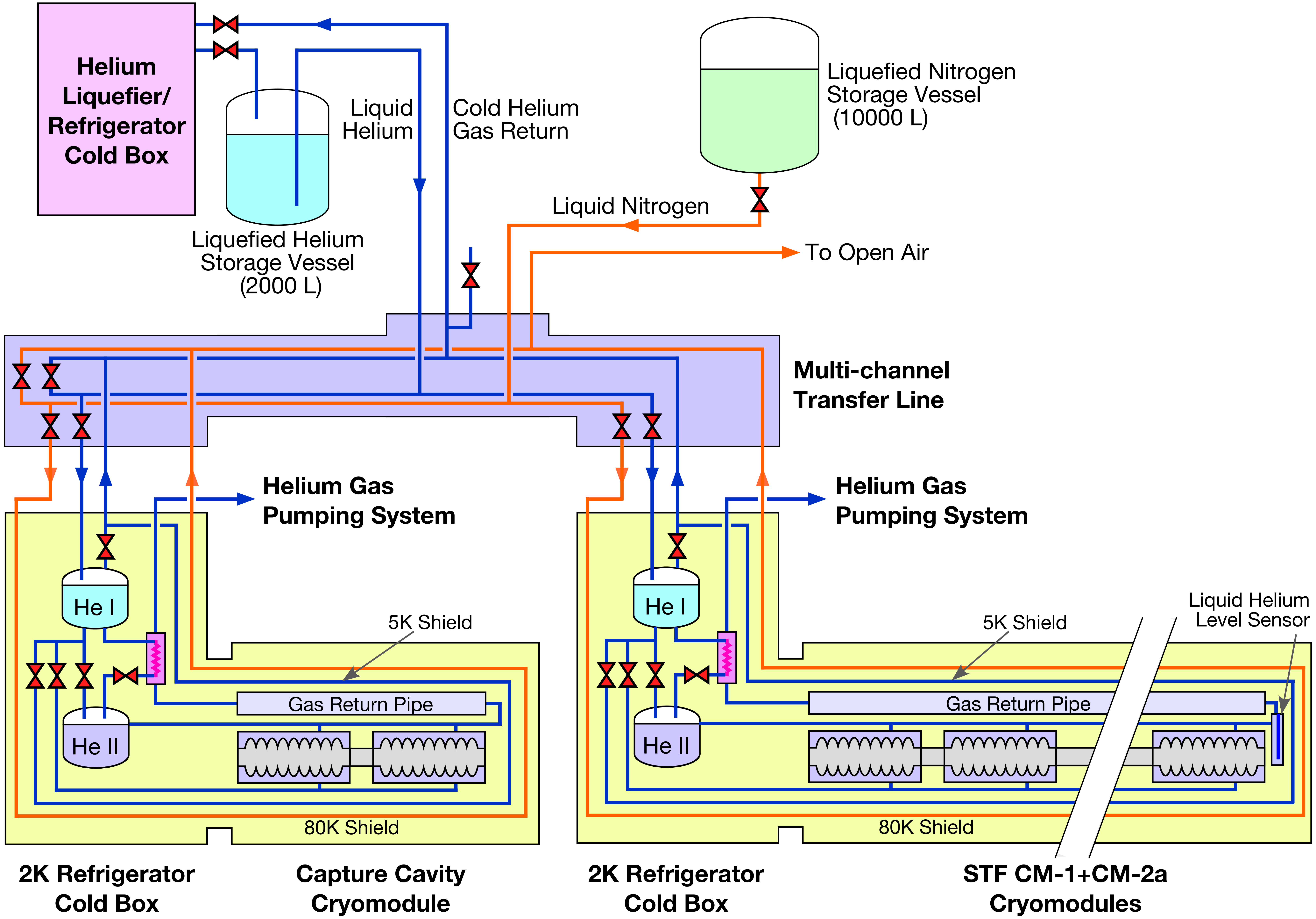


Helium Pumping System

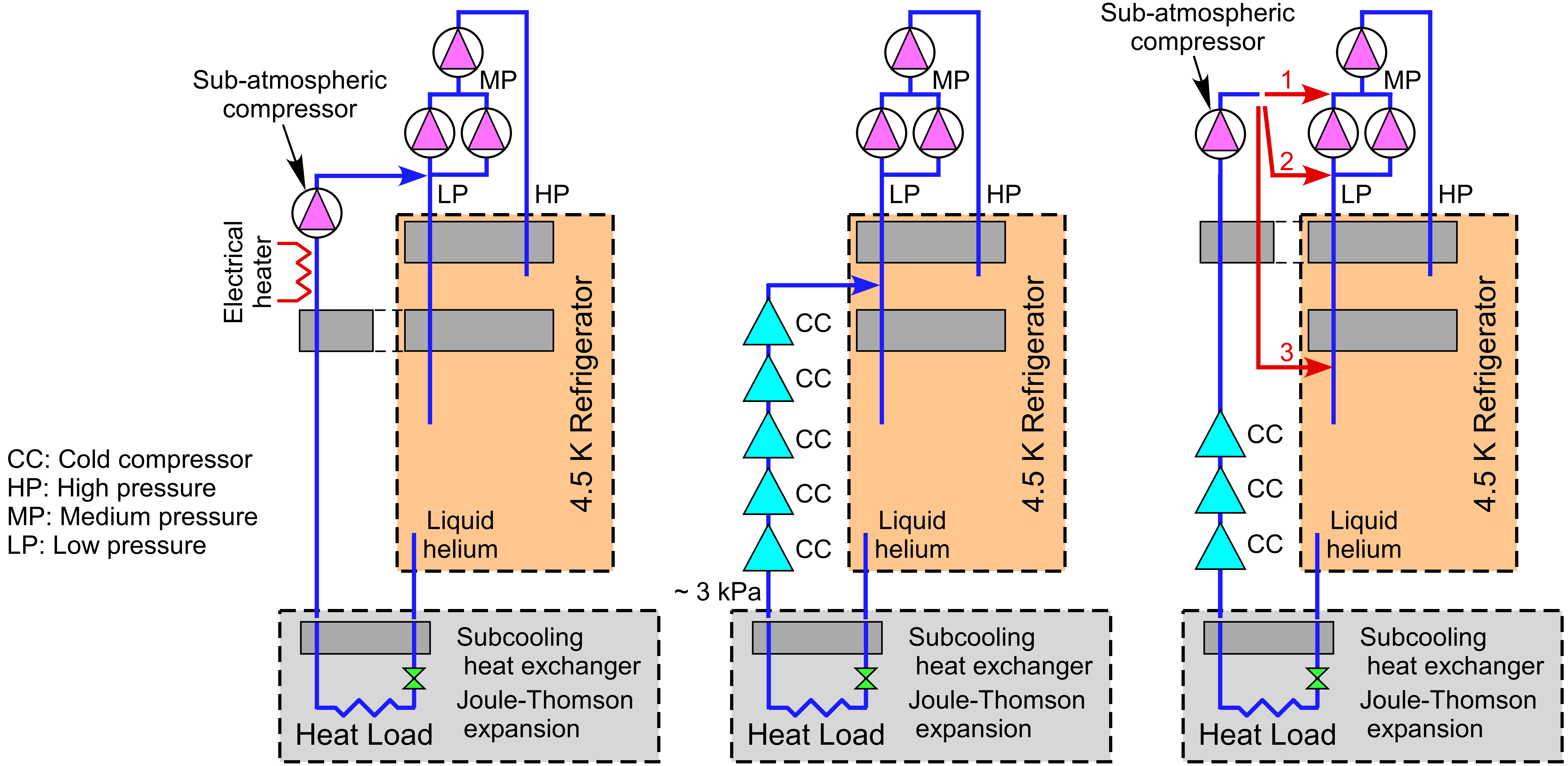

Mechanical Boosters (1020 m³/h)

Oil Rotary Pumps

STF 2K Superfluid Helium Cryogenic System



Pressure Reduction of Liquid Helium



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

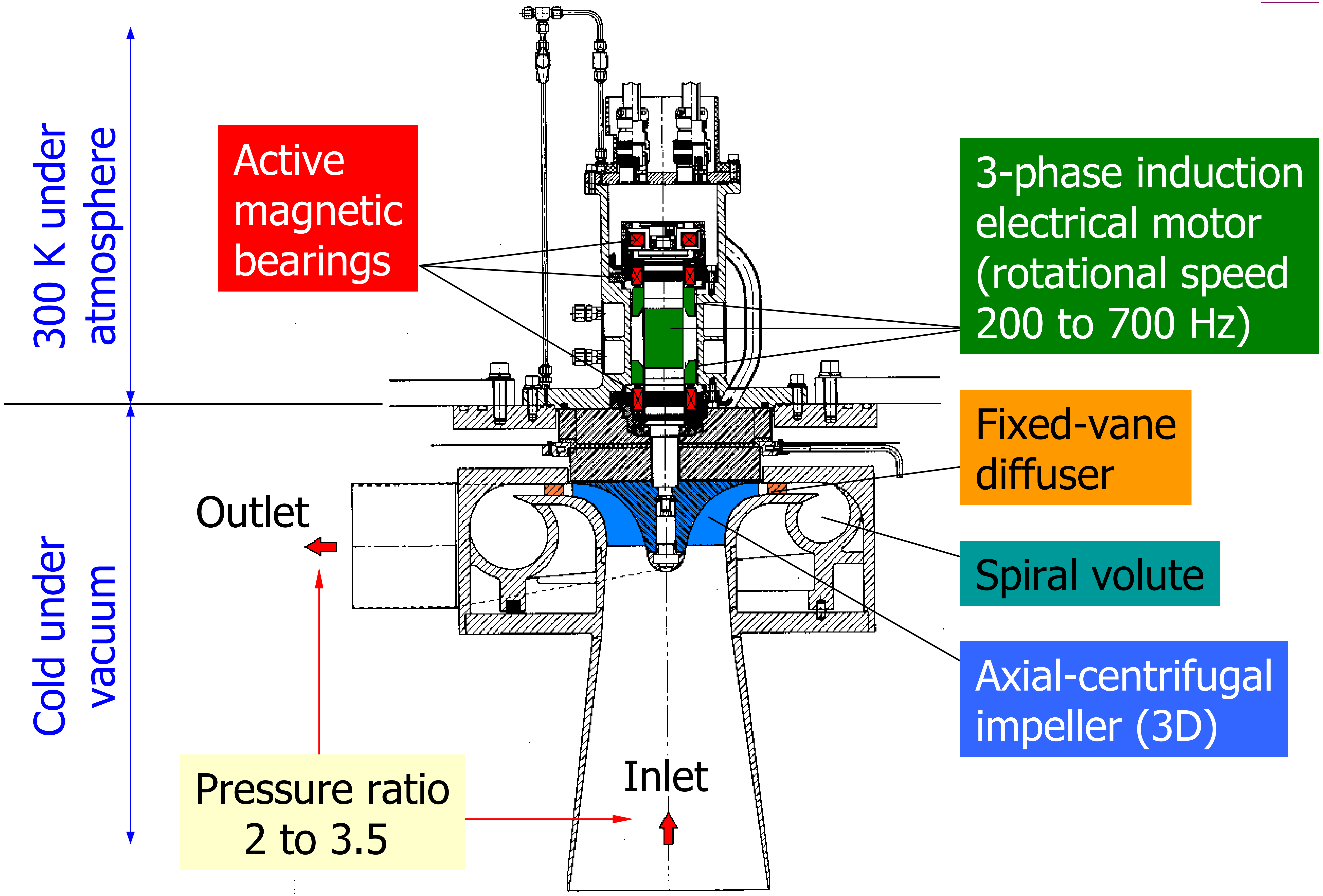
Warm Compression
(a)

Cold Compression
(b)

Mixed (Hybrid) Compression
(c)

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

Structure of Cold Compressor



Active magnetic bearings

3-phase induction electrical motor (rotational speed 200 to 700 Hz)

Fixed-vane diffuser

Spiral volute

Axial-centrifugal impeller (3D)

Pressure ratio 2 to 3.5

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

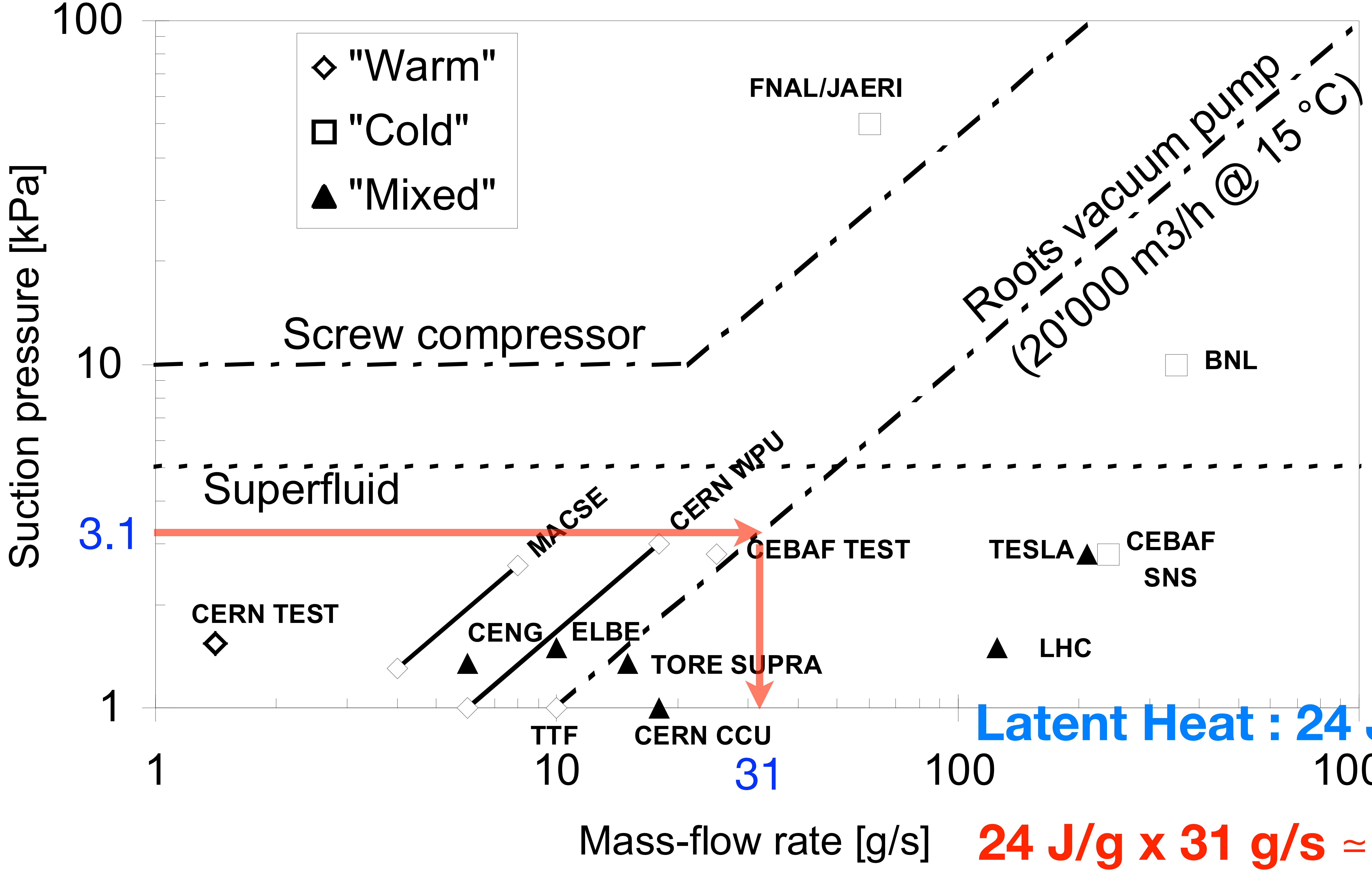
Cold Compressors for CERN-LHC

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)

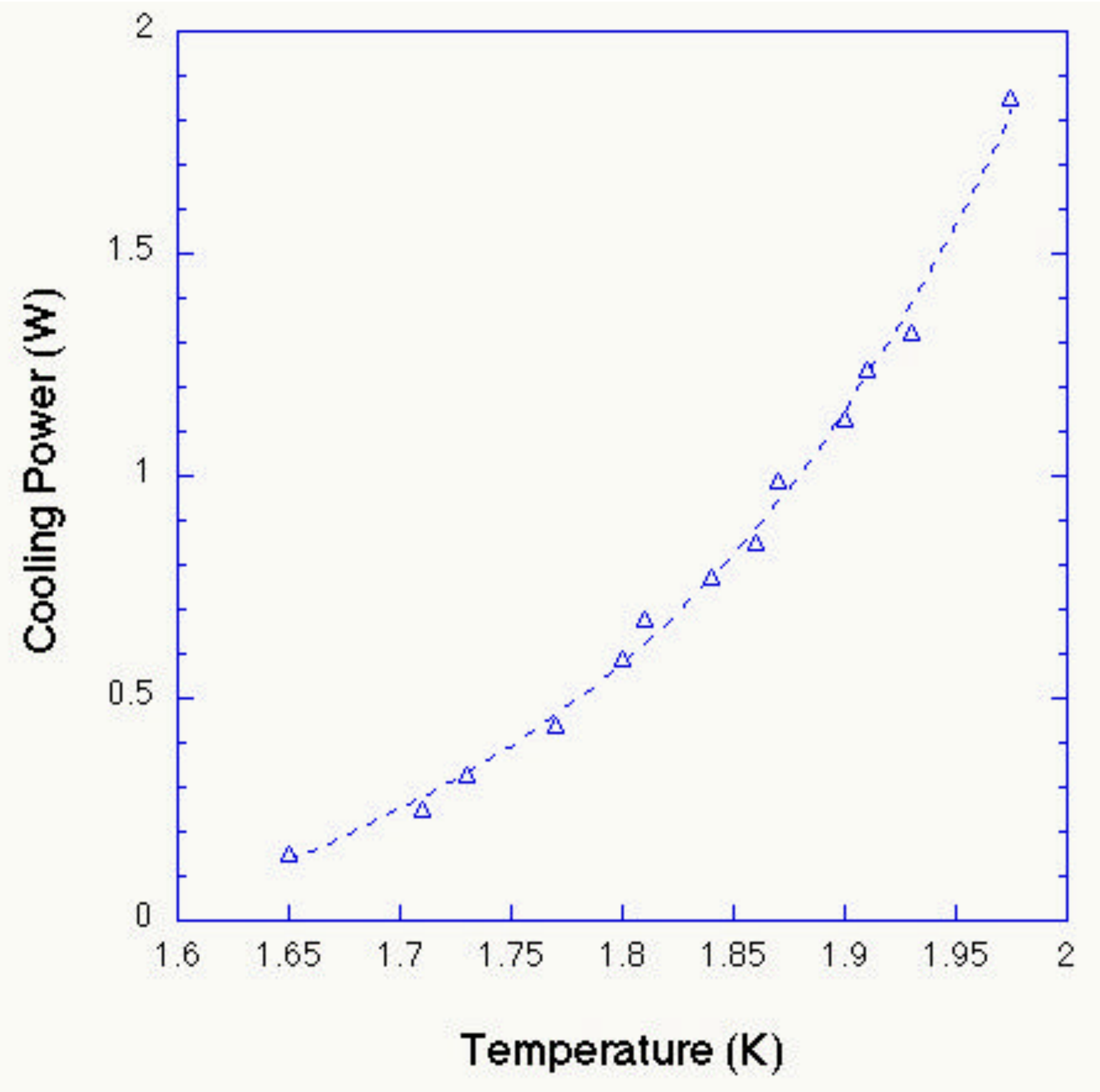
Progress in GM/JT Cryocooler

Development of Small 2K Refrigerator

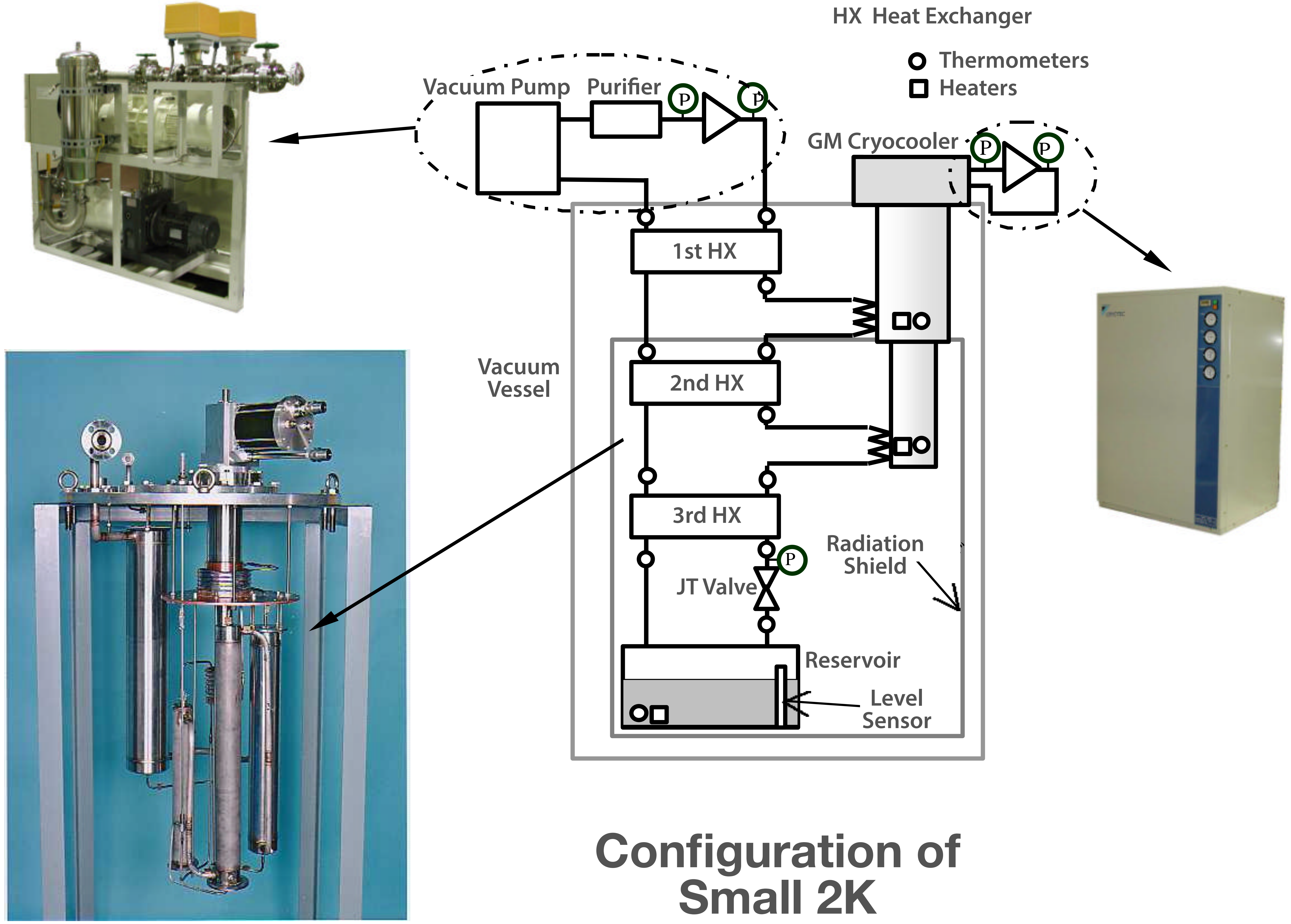
July 2001, National Institute for Materials Science

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

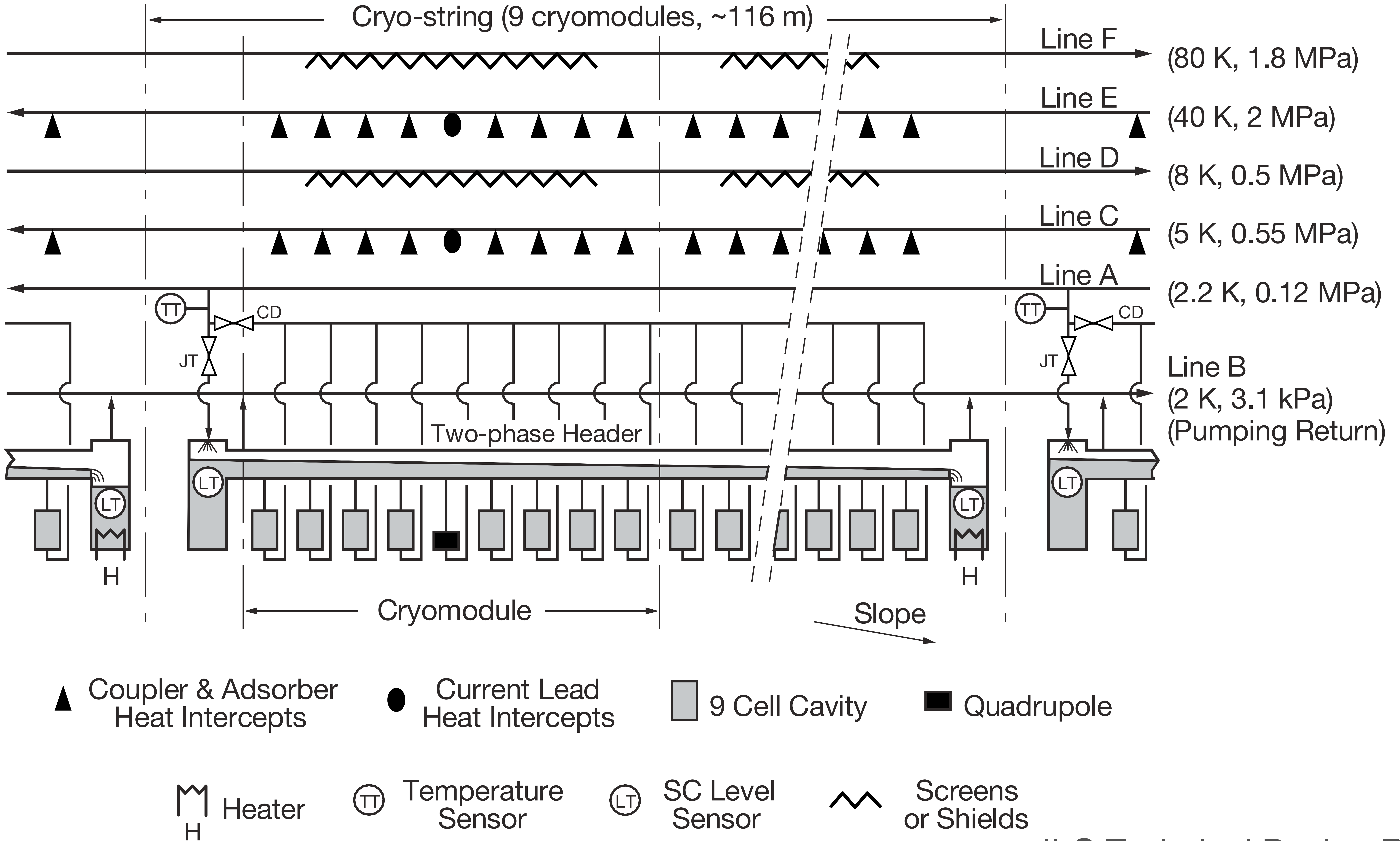


Configuration of Small 2K Refrigerator

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

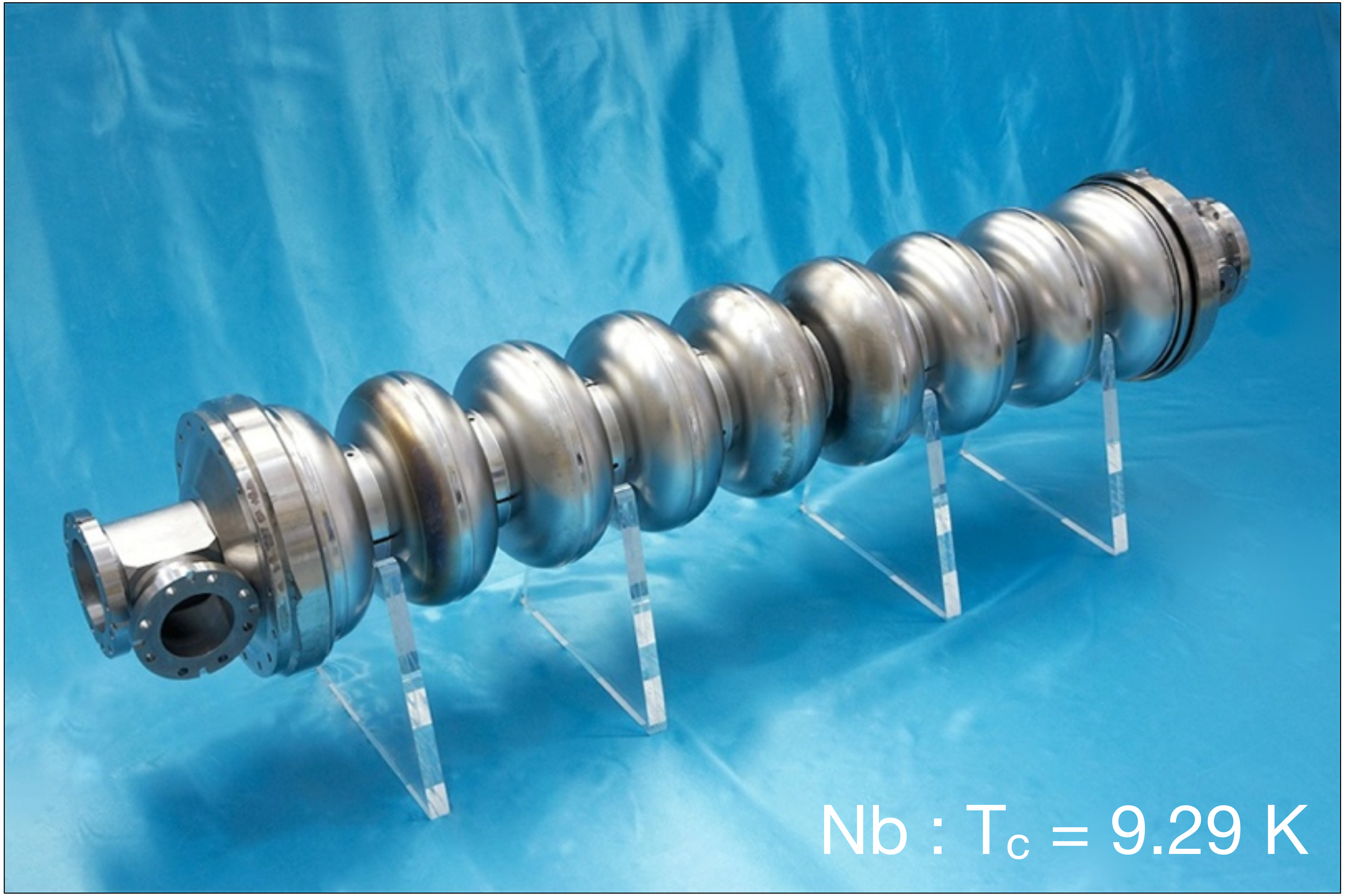
5. Structure of 2K Cryomodules

Cooling scheme of ILC Cryomodule



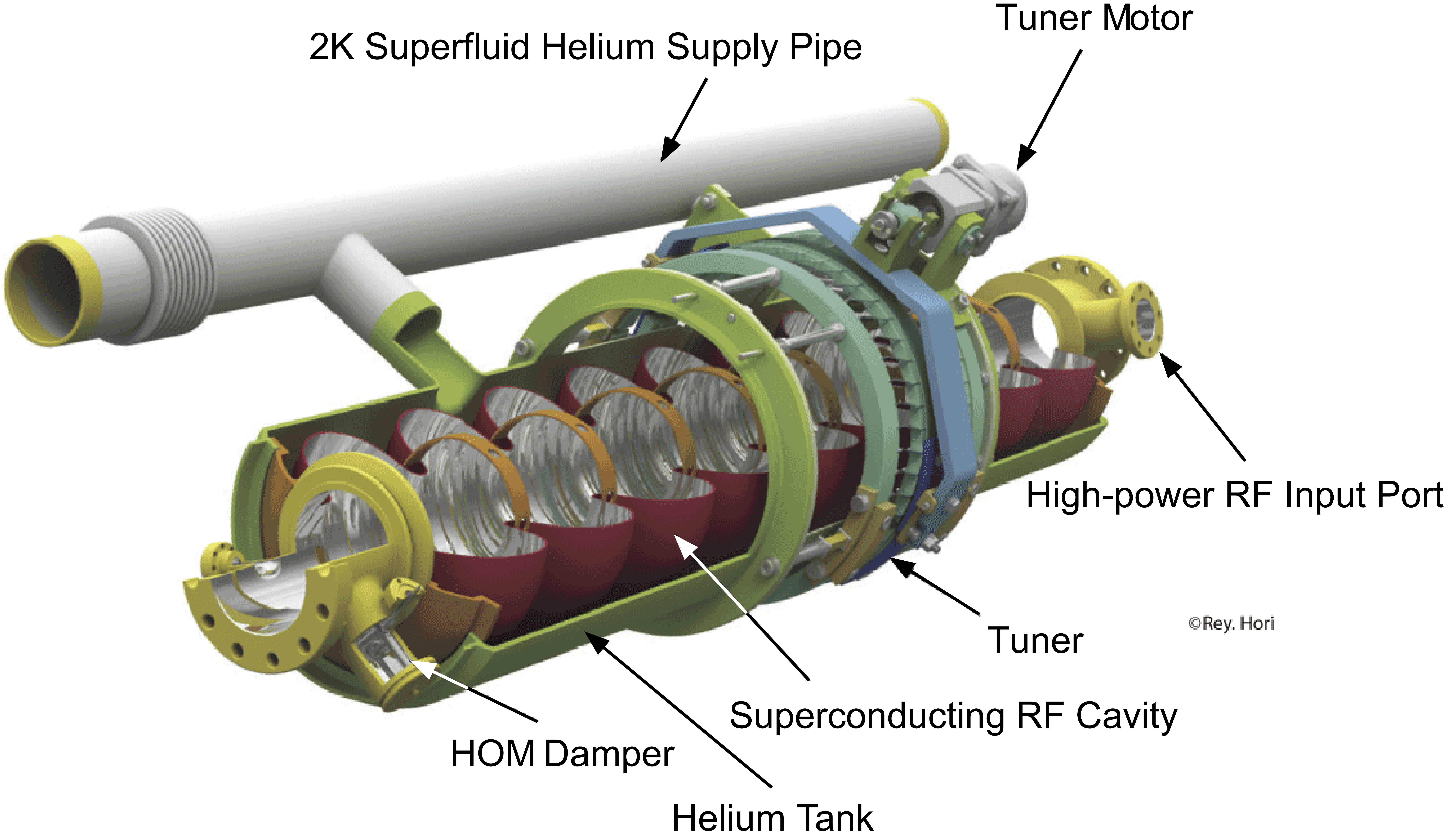
ILC Technical Design Report (2013)

1.3 GHz 9-Cell Superconducting RF Cavity



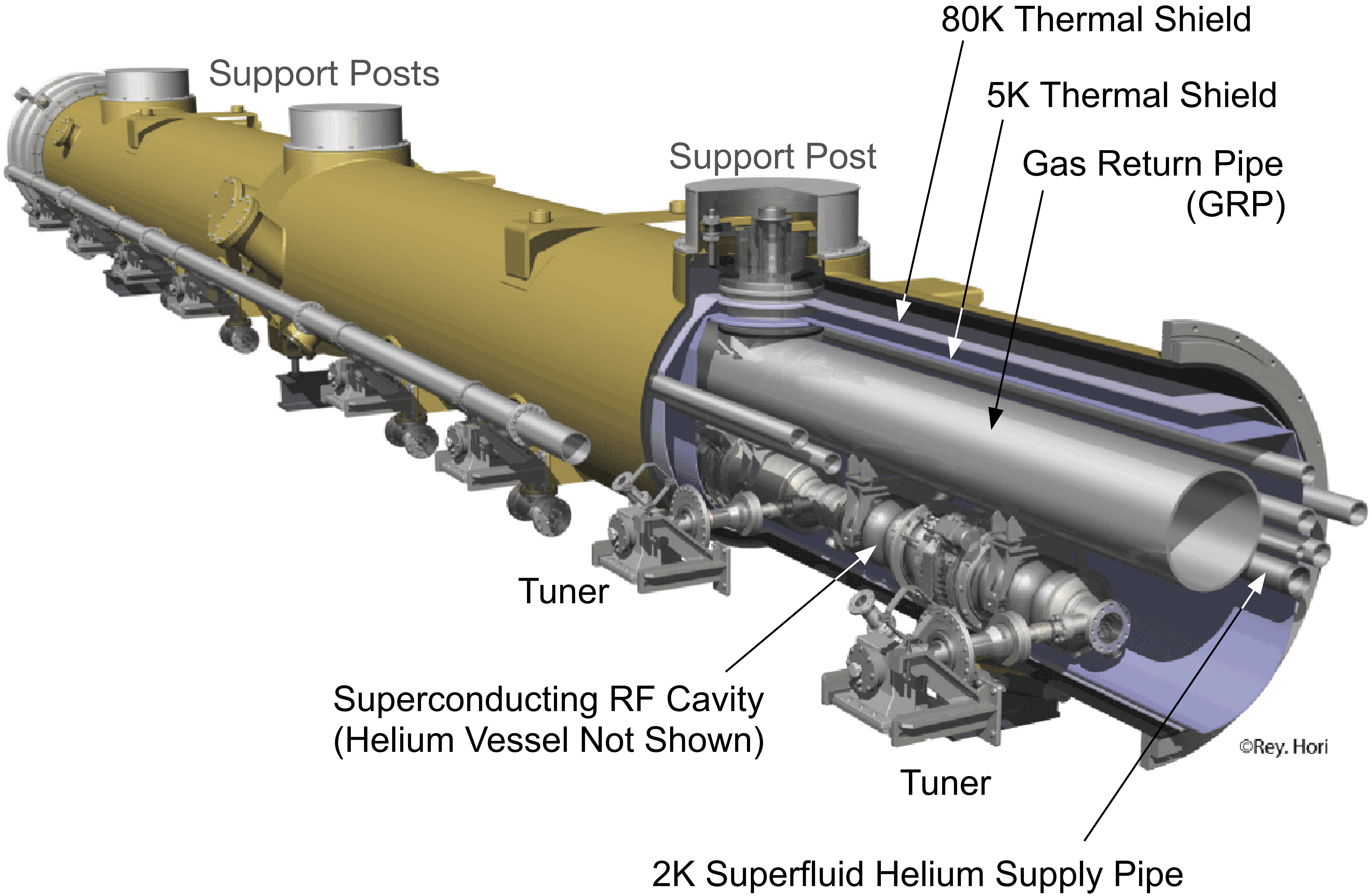
Nb : $T_c = 9.29$ K

ILC Superconducting RF Cavity

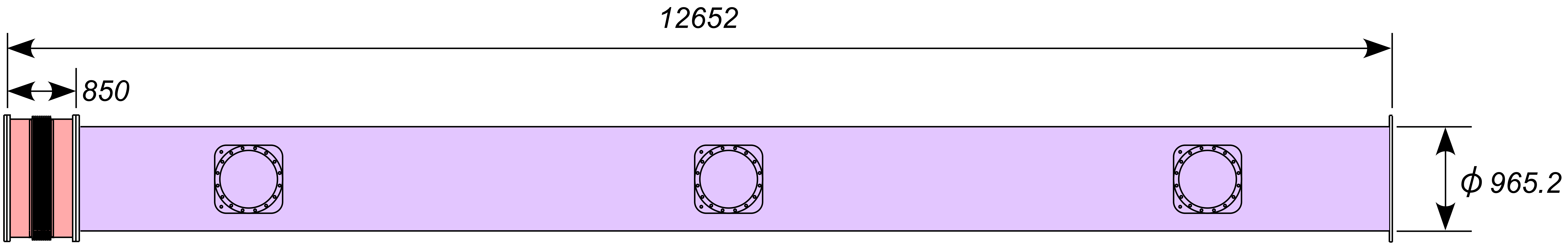


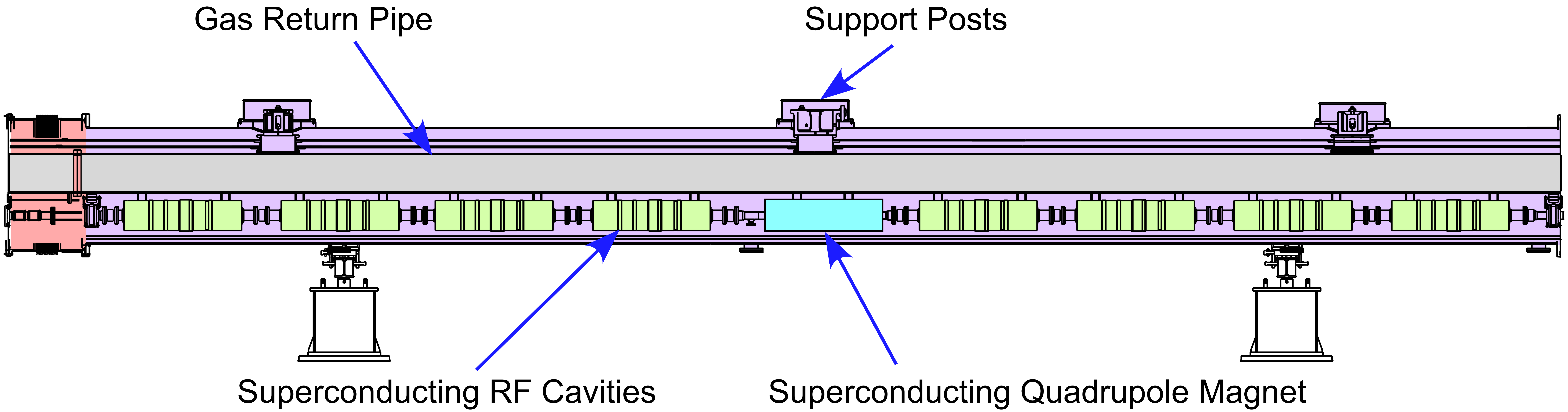
Connection of 4 Superconducting Cavities

ILC Cryomodule



Major Dimensions of ILC Cryomodule





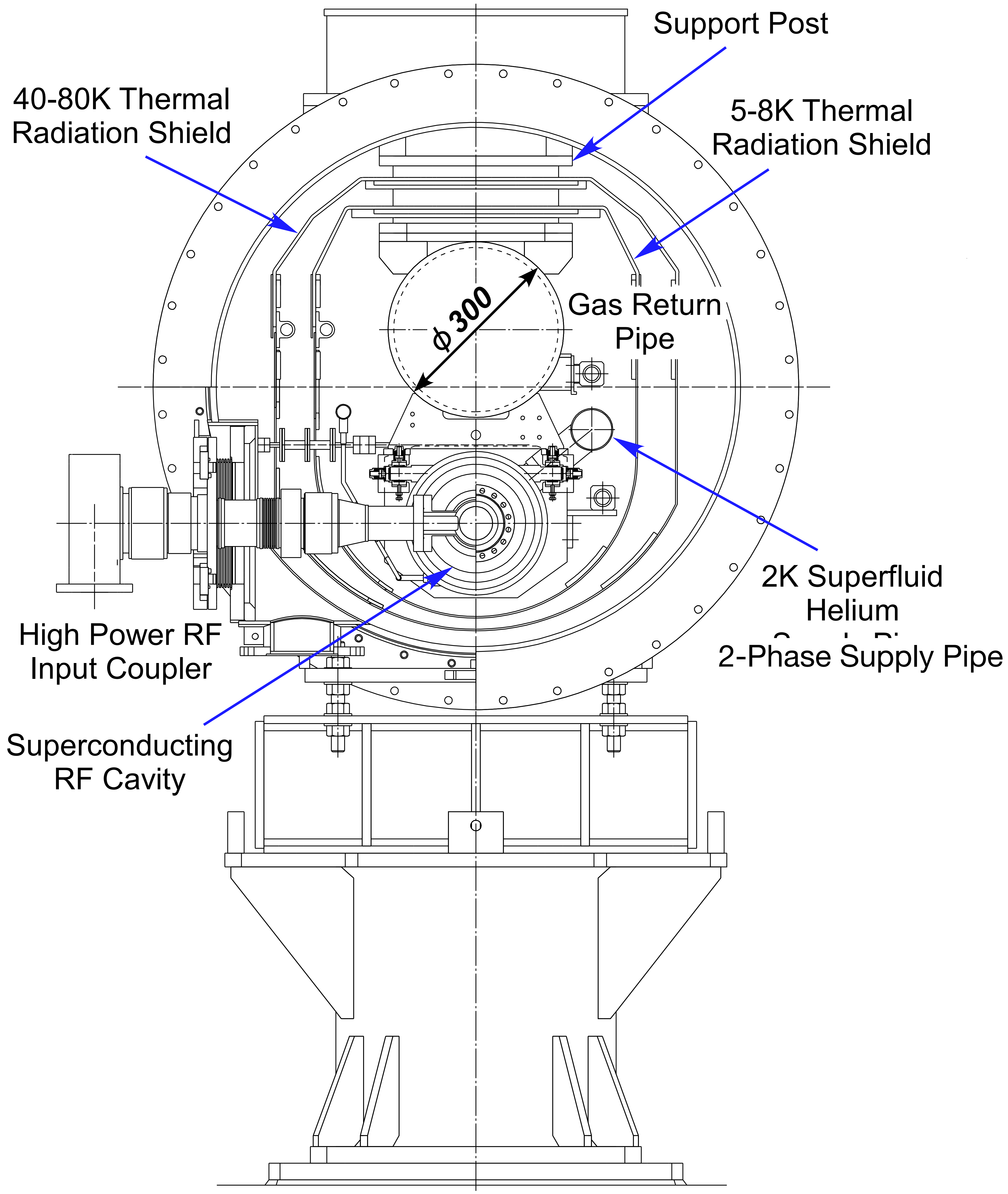
Gas Return Pipe

Support Posts

Superconducting RF Cavities

Superconducting Quadrupole Magnet

Cross Section of STF Cryomodule

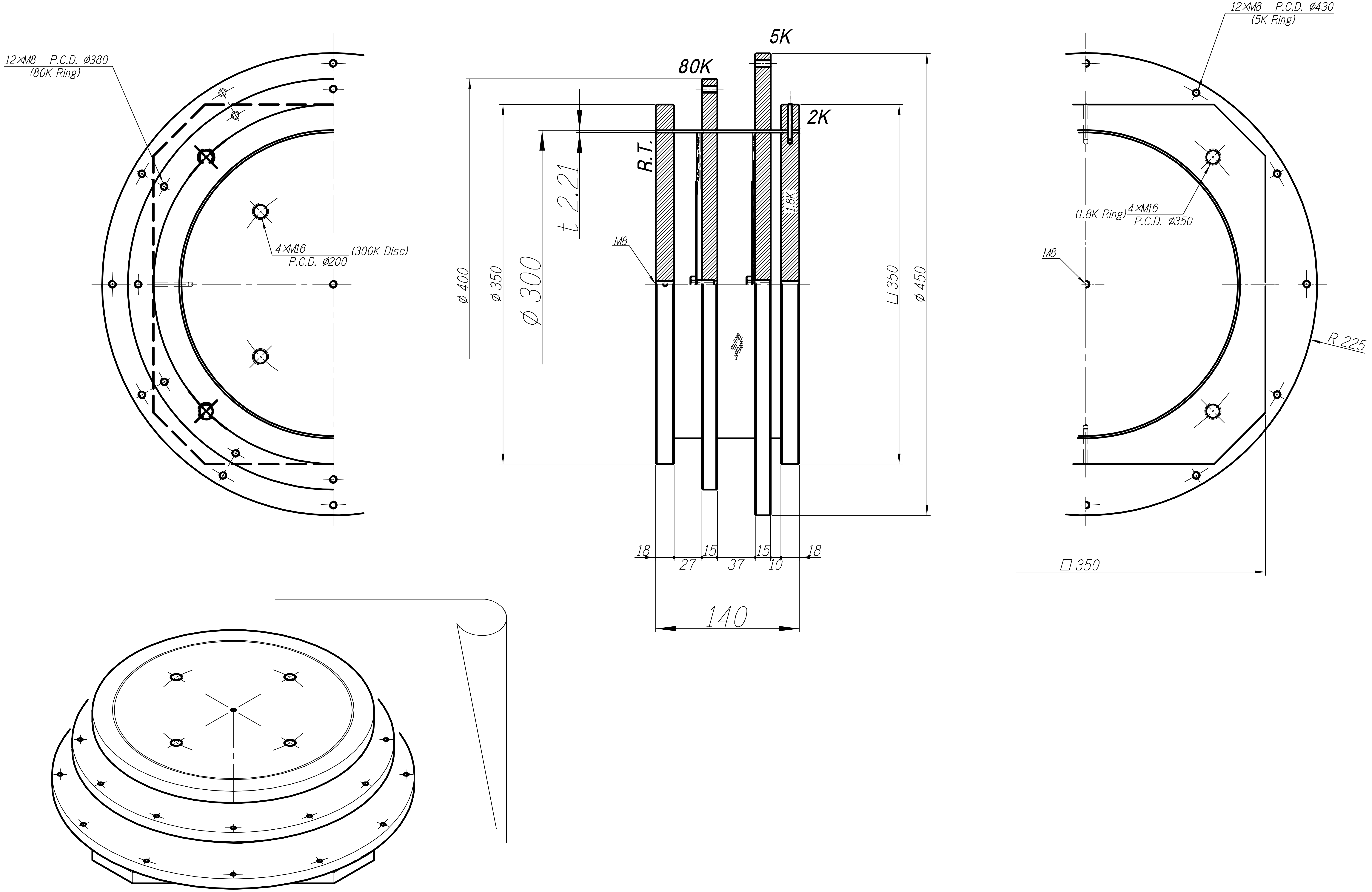


2-phase supply pipe
2 K helium gas return pipe

5 K supply line
8 K return line
(5 K thermal radiation shield)

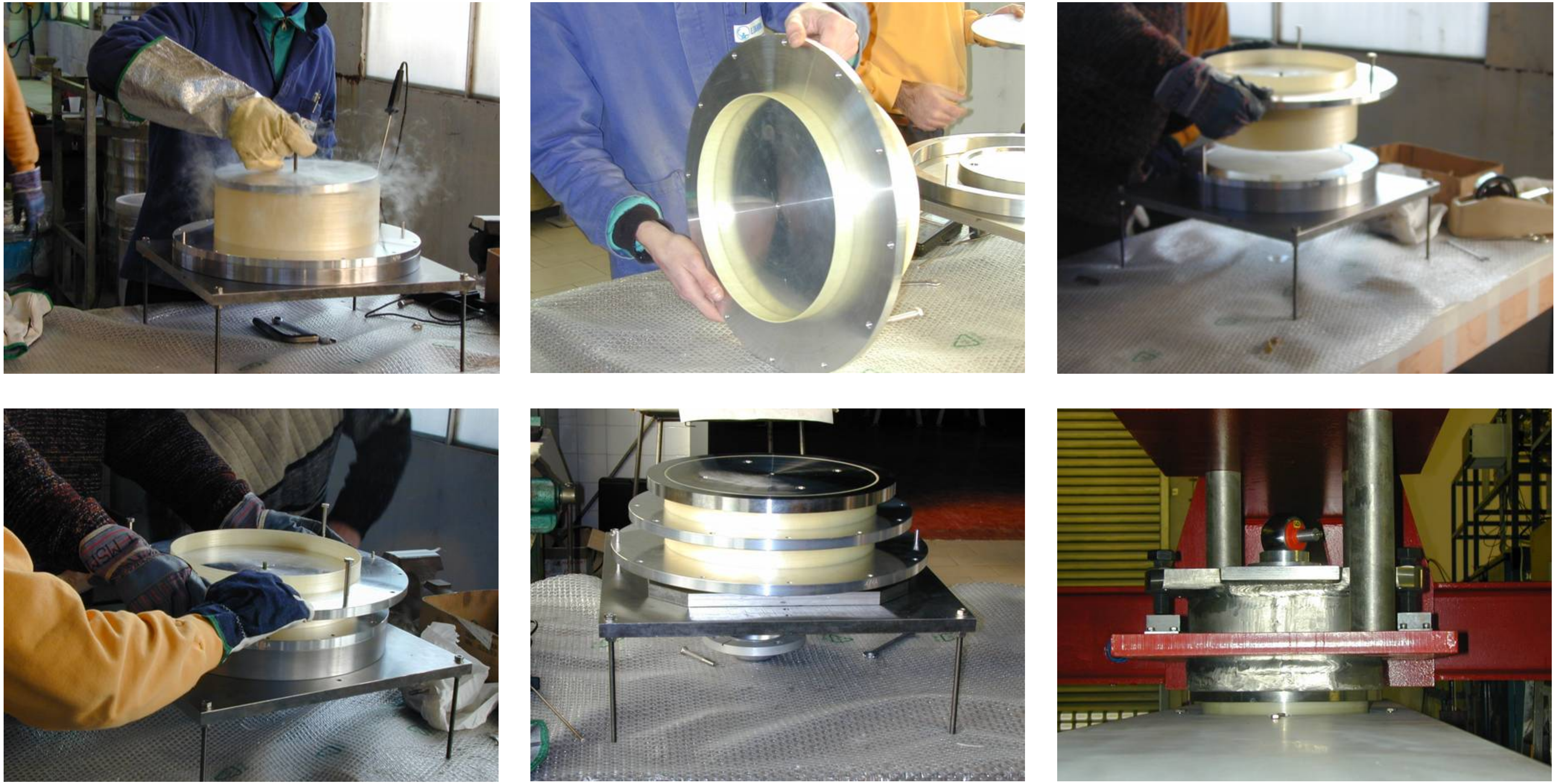
40 K supply line
80 K return line
(40 K thermal radiation shield)

Support Post (1)



Support Post (2)

Cooling Fit of Support Posts

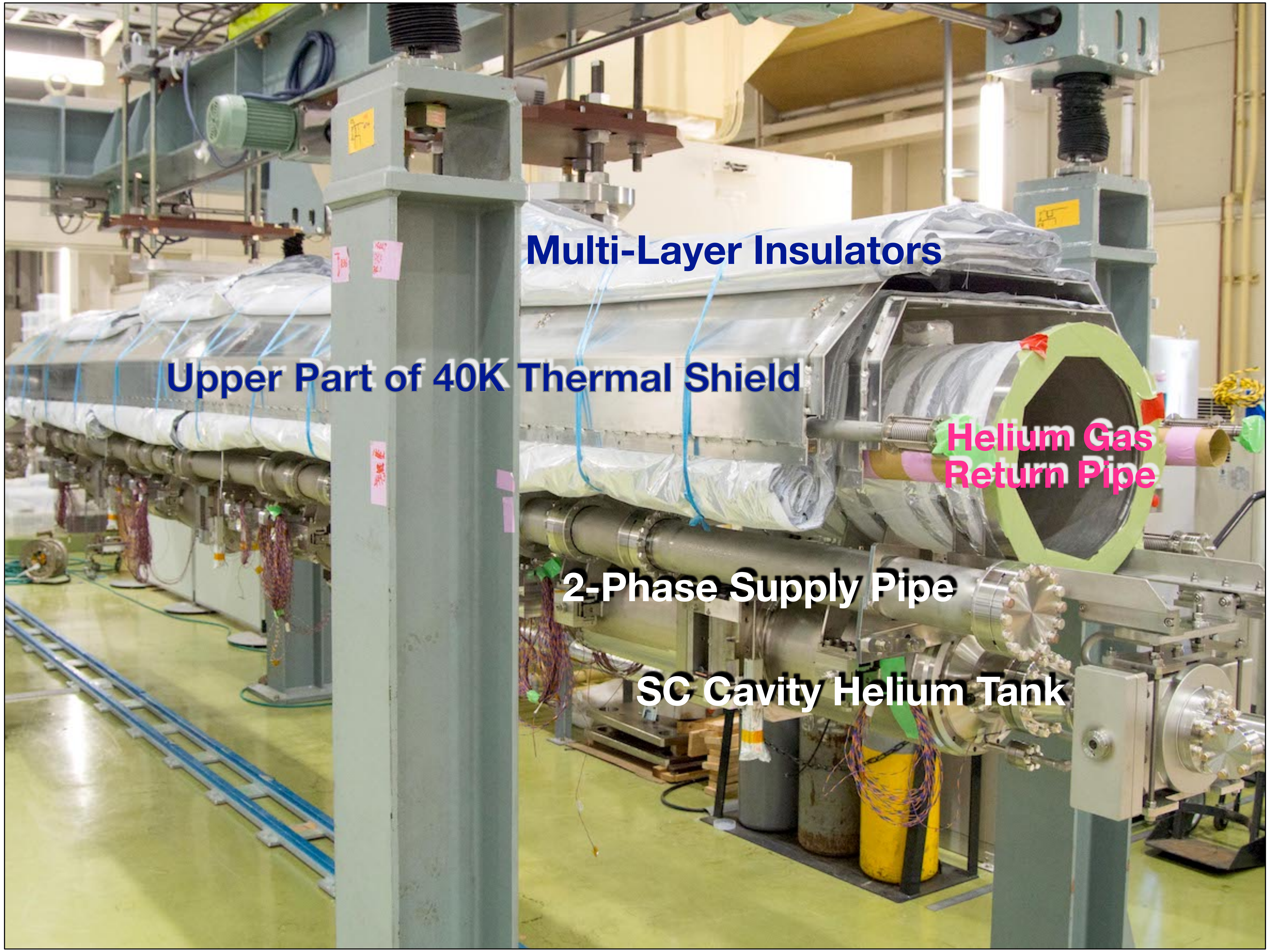


Pagani C., “Current Cryomodules and Changes for ILC”, Snowmass (2005)

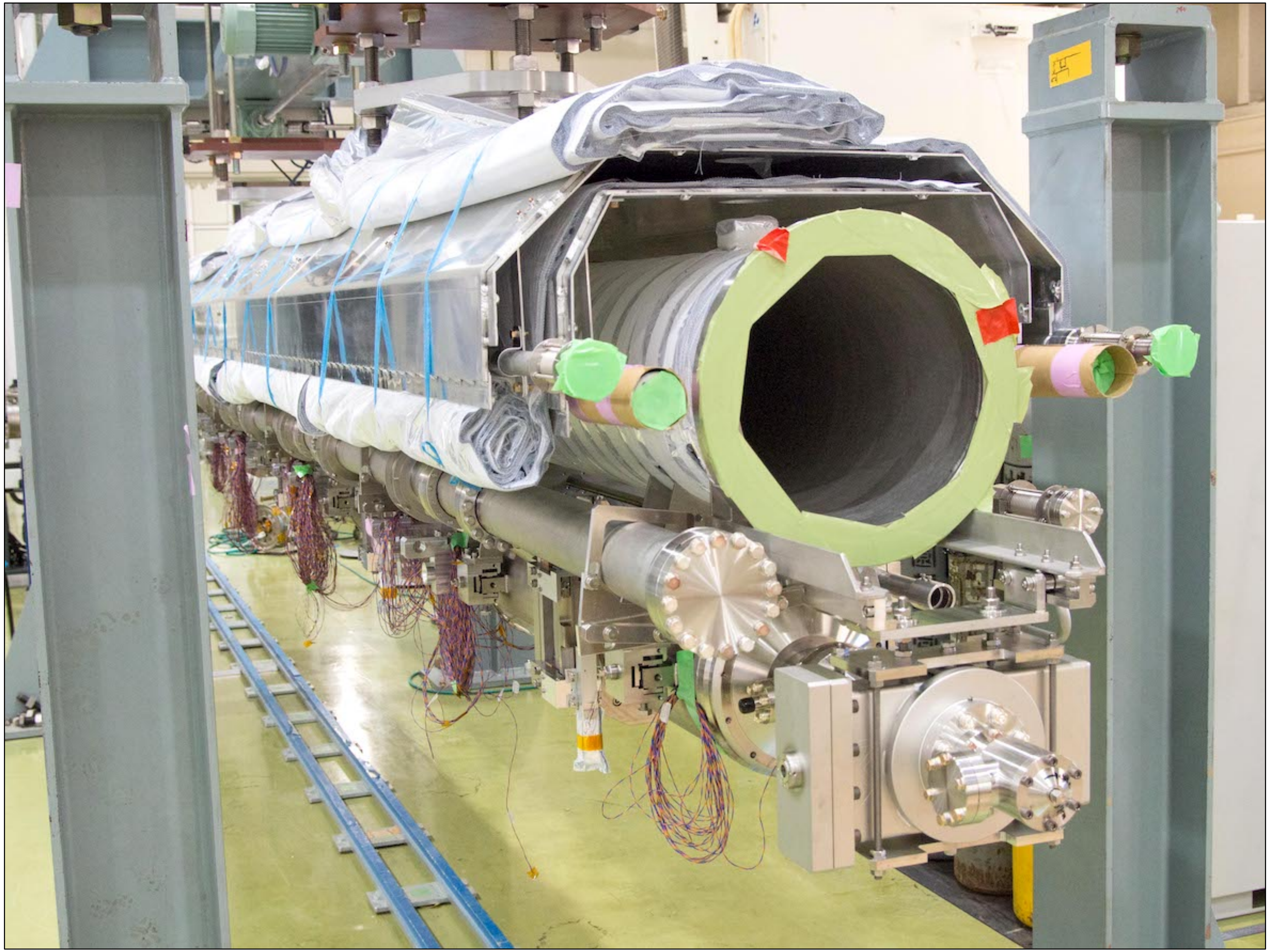
Support Post and Gas Return Pipe (GRP)

2K Gas Return Pipe (GRP)

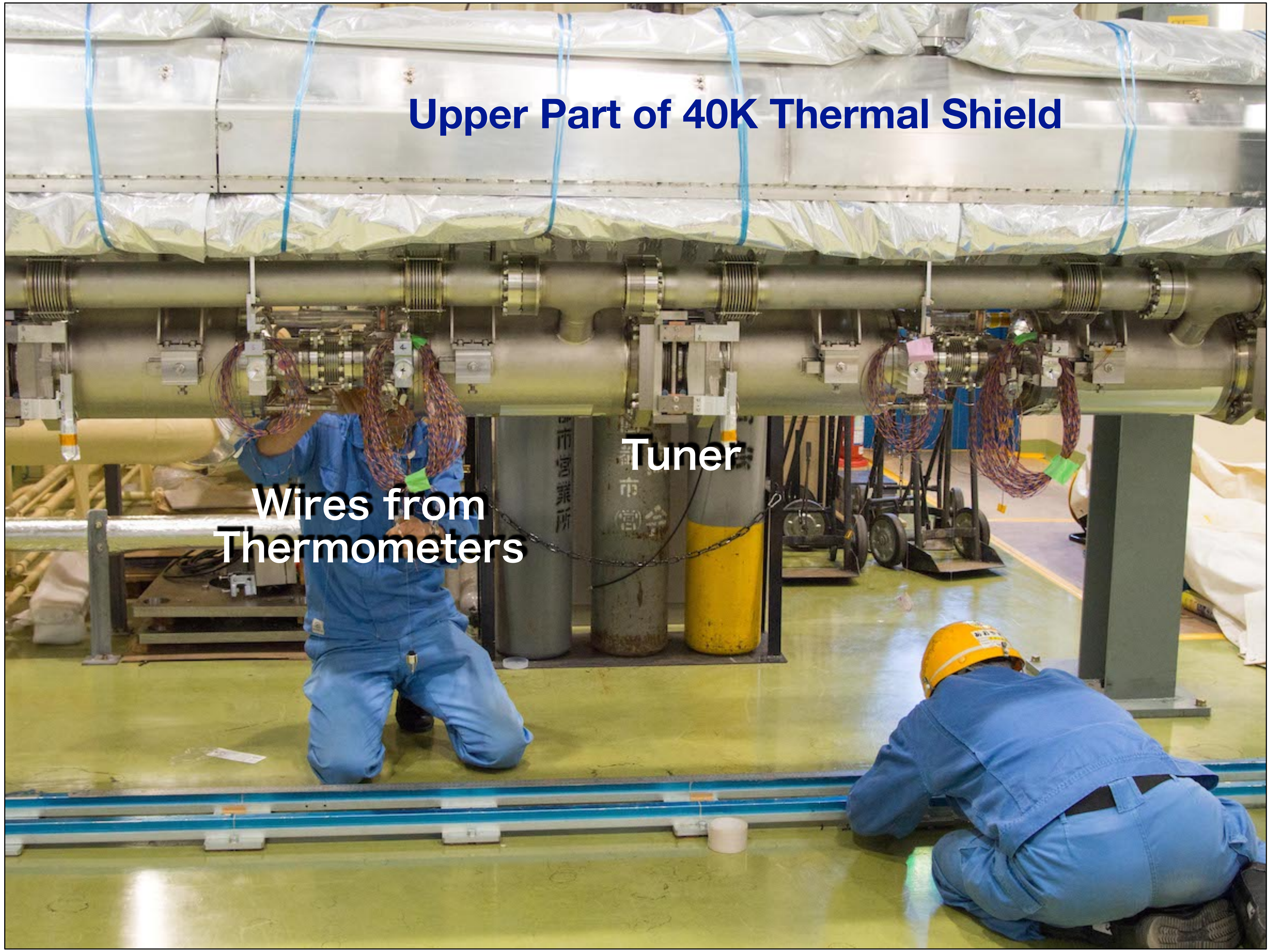
SC Cavities and 2-Phase Supply Pipe (1)



Multi-Layer Insulators



SC Cavities and 2-Phase Supply Pipe (2)



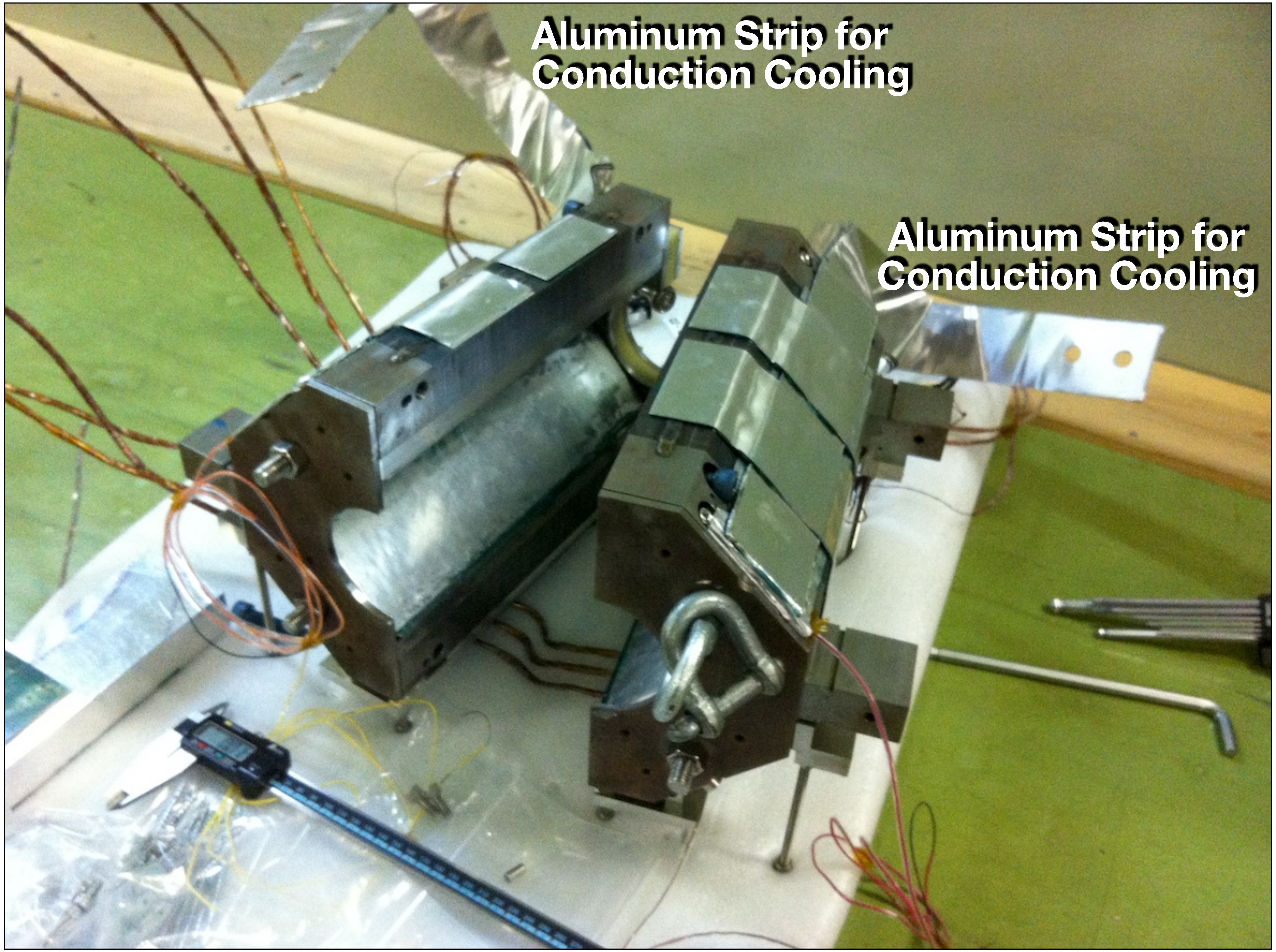
Multi-Layer Insulators

Multi-Layer Insulators

2-Phase Supply Pipe

SC Cavity Helium Tank

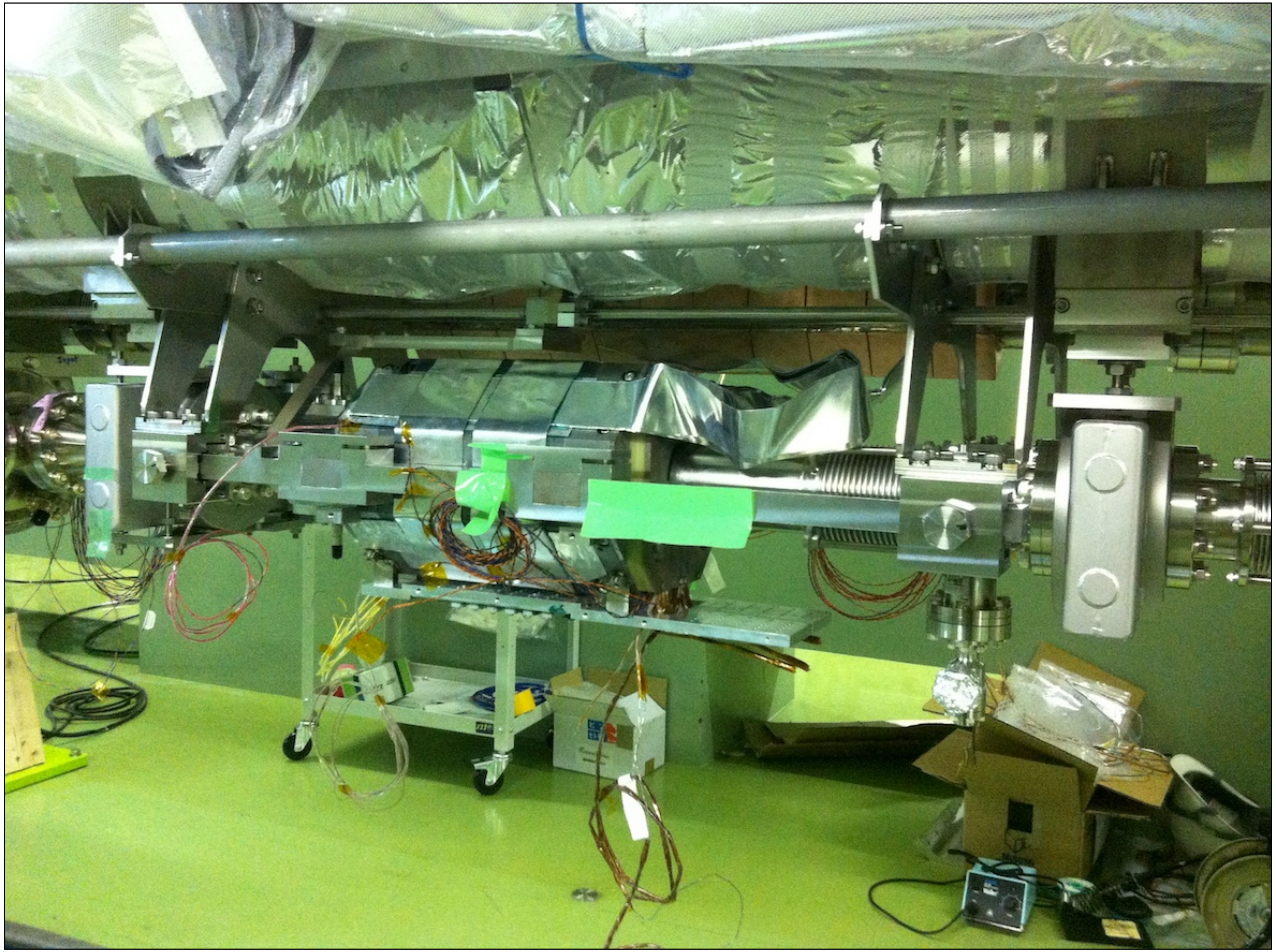
SC Quadrupole Magnet (Separated Vertically)



Aluminum Strip for Conduction Cooling

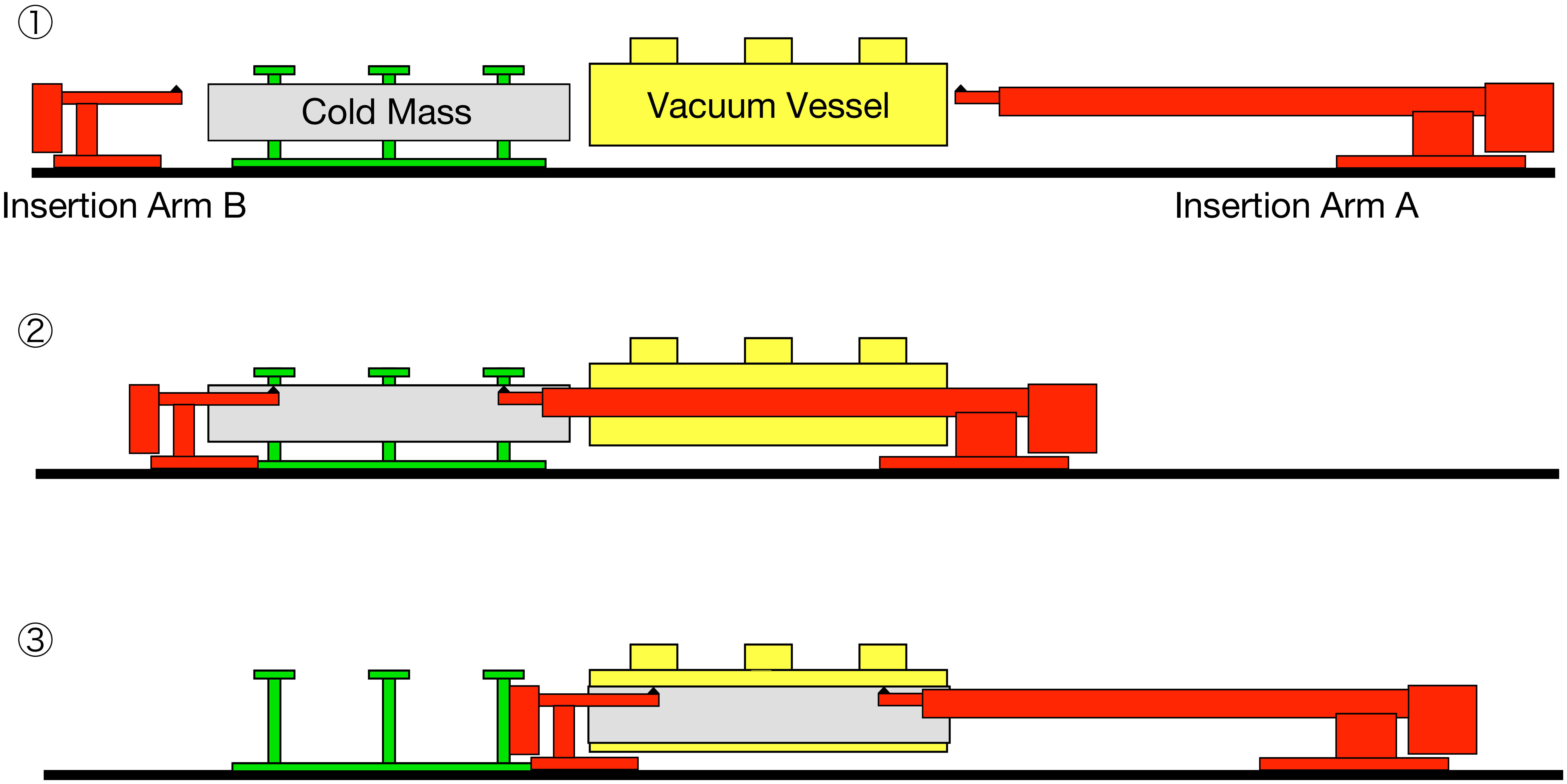
Aluminum Strip for Conduction Cooling

Assembled SC Quadrupole Magnet



Insertion of SC Cavities into Cryomodule Vacuum Vessel

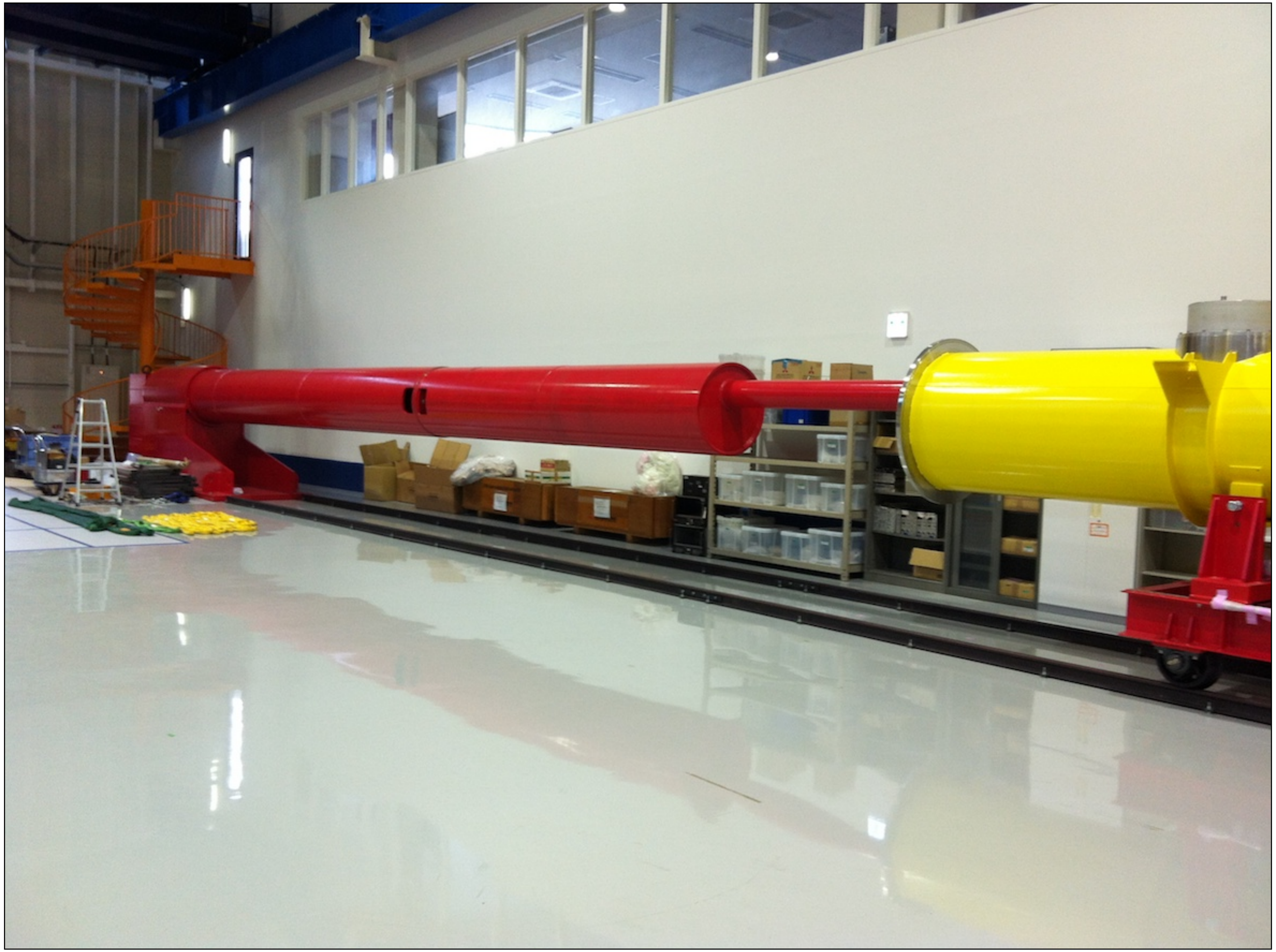
Side View



TESLA-CDR

Insertion Arm B

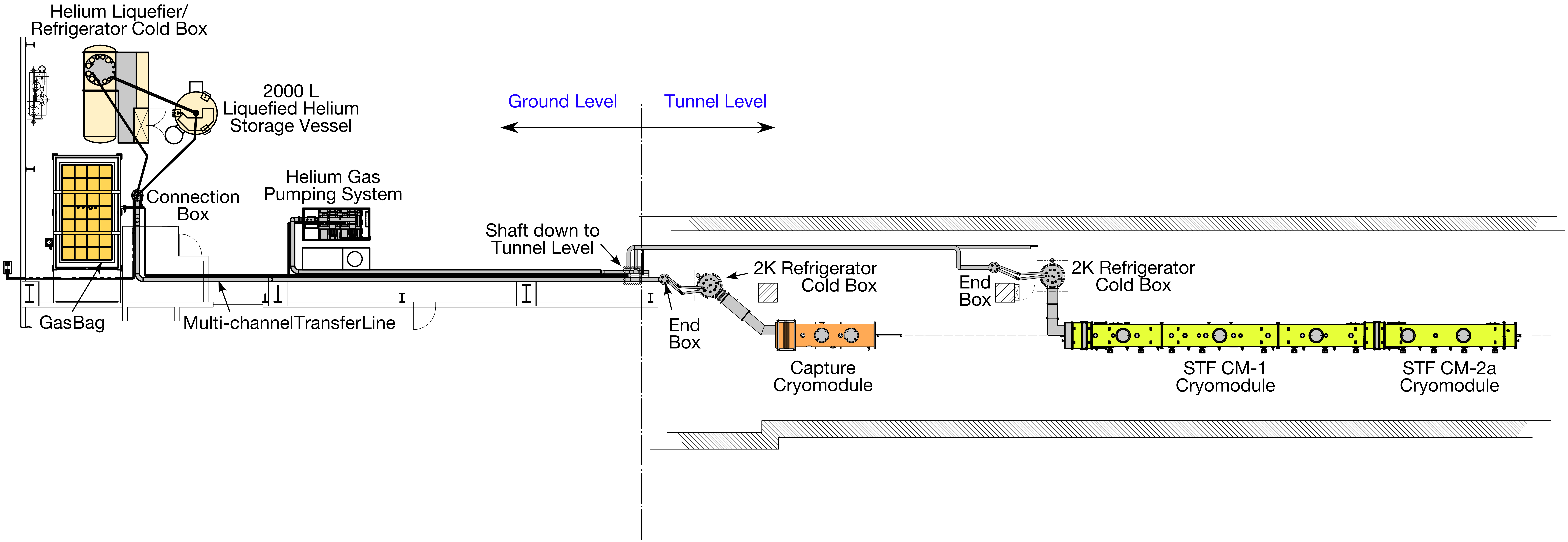
Insertion Arm A



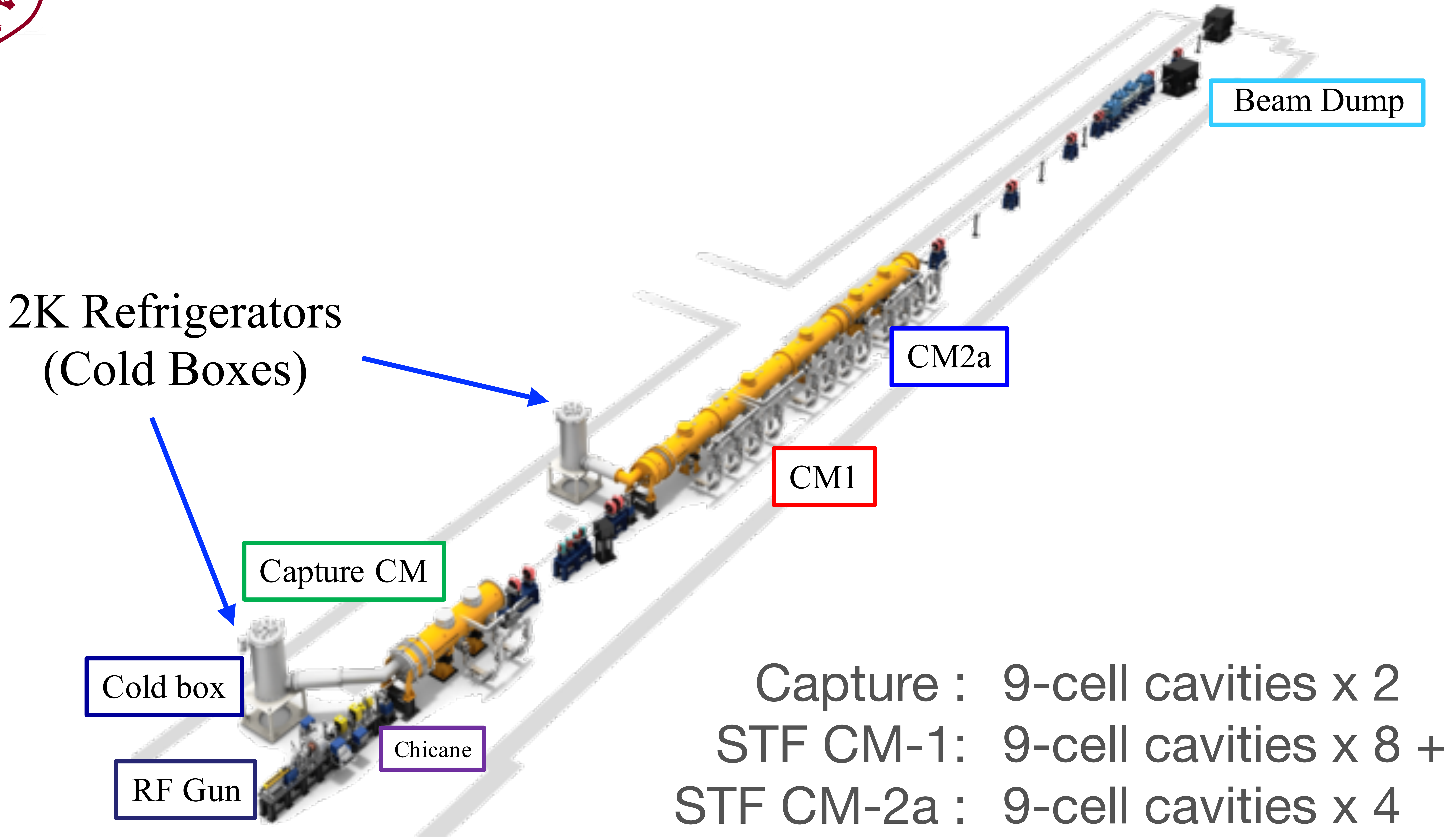
Cryomodule Vacuum Vessel and Insertion Arm-A (2)

Assembly of STF CM-1

STF Cryogenic System Configuration



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 Capture Cryomodule

STF CM-1 + CM-2a

Summary

Summary

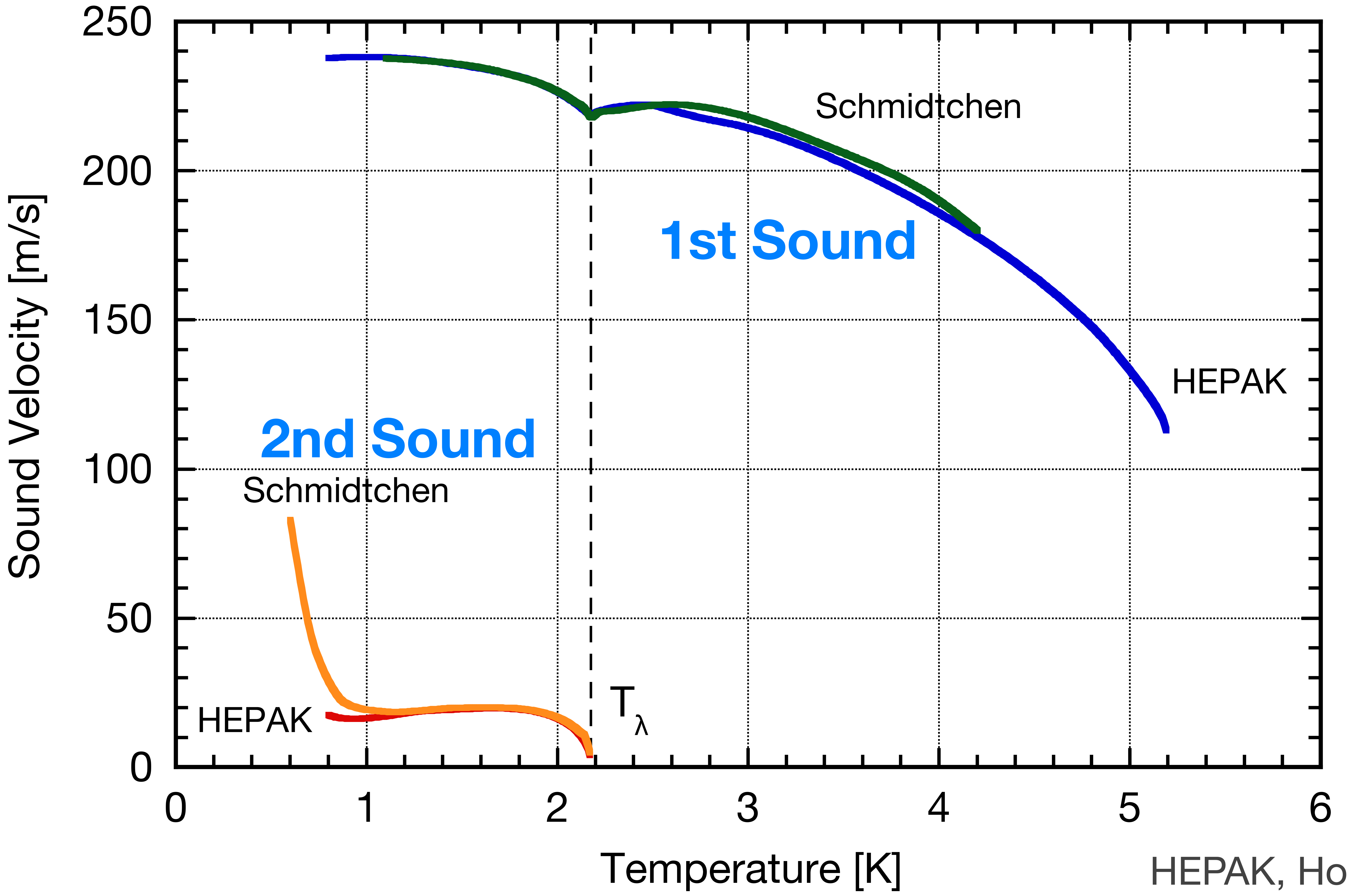
- Recent superconducting accelerators operate at 2 K or lower temperature
  - Higher frequency superconducting cavities require lower operation temperature for moderate cryogenic system
  - Helium - only substance to cool down superconducting devices at 2 K or lower temperature

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

Extra Slides

Speeds of Sound in Liquid Helium



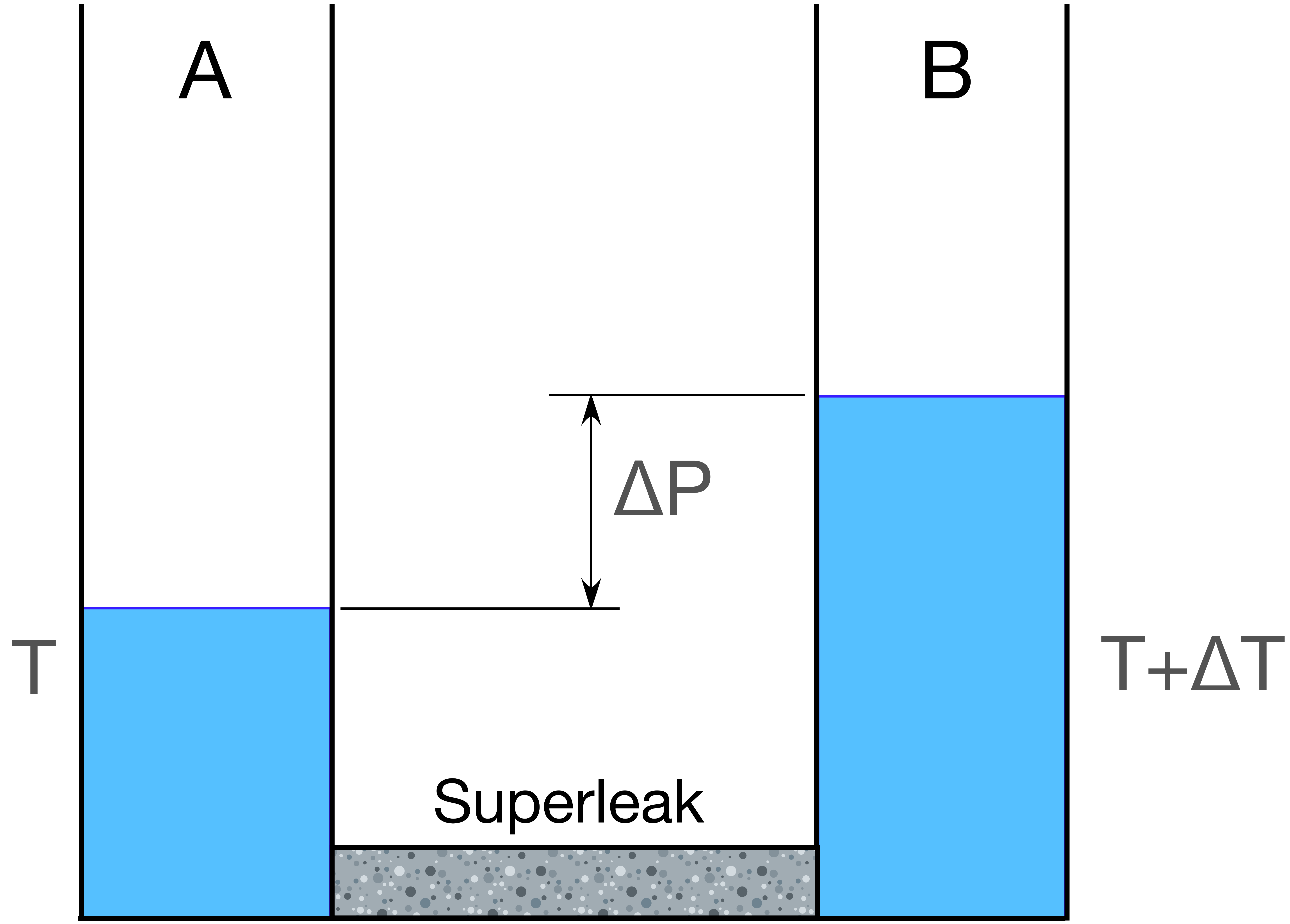
HEPAK, Horizon Technologies

Schmidtchen, U., Private Communication (1984)

Superfluid Helium Flow

- Ideal state
  - Two-fluid model
  - London's relation (fountain effect) valid
- Superfluid turbulence
  - Relative velocity of two components higher than some limit one (critical velocity)
  - Interaction of two flow fields (mutual friction)

Thermomechanical Effect (1)



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

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

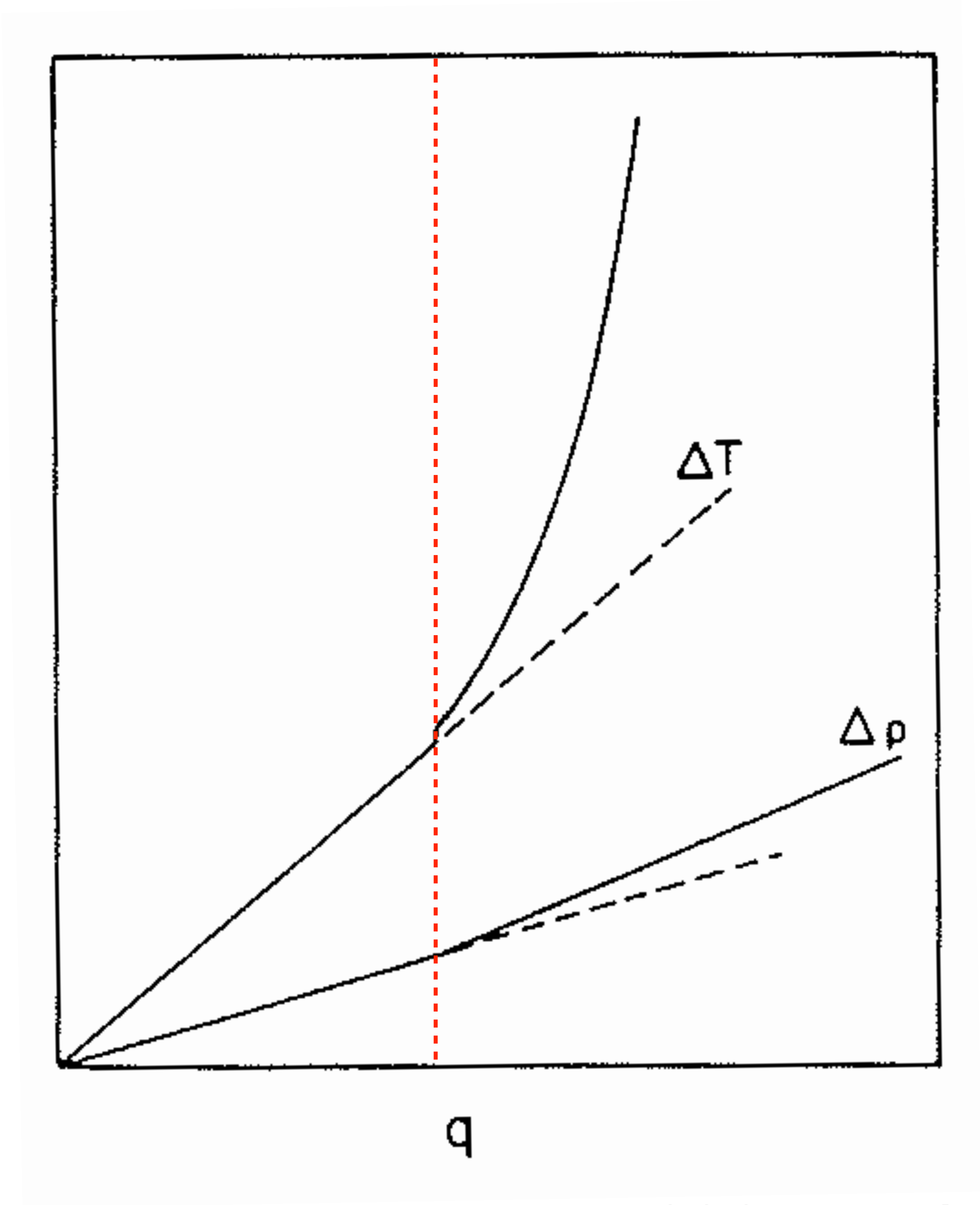
$$\frac{\partial(\rho_n \mathbf{v}_n)}{\partial t} + \nabla(\rho_n \mathbf{v}_n \mathbf{v}_n) = -\frac{\rho_n}{\rho}\nabla P - \rho_s s \nabla T + \mu \nabla^2 \mathbf{v}_n$$

Thermomechanical Effect

$$F_{TM} = \rho_s s \nabla T$$

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

Critical Velocity and Temperature, Pressure Differences



Heat

$$q^3 = -\frac{\rho_s{}^3 s^4 T^3}{A_{GM}\rho_n}\Delta T$$

Temperature Difference

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

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

Heat and Temperature Difference

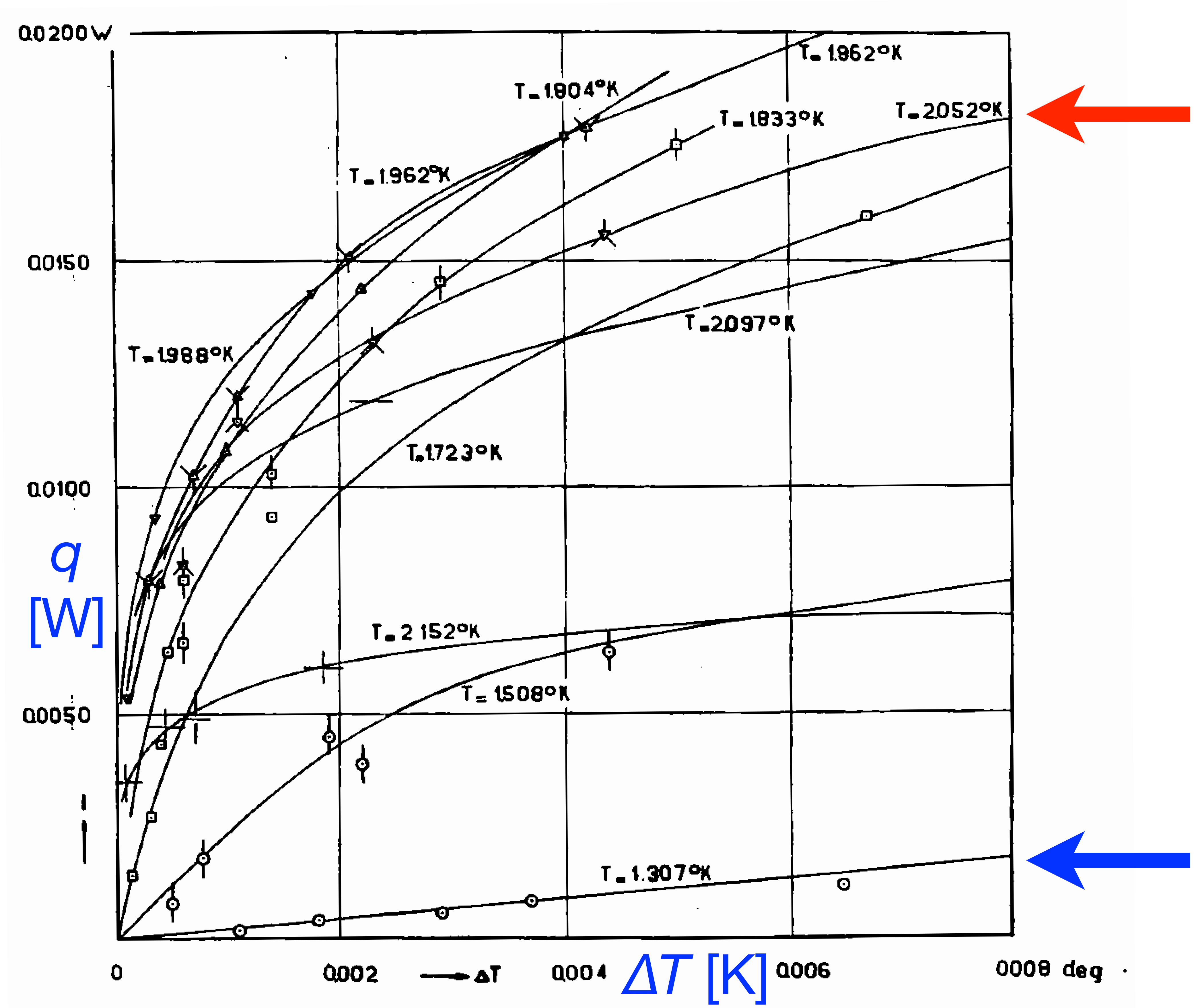


Fig. 1. Total heat flow against difference of temperature at constant bath temperatures. Width of the slit: 10.5 micron.

⊙ $T = 1.307°K$
⊙ $T = 1.508°K$
⊡ $T = 1.723°K$
⊡ $T = 1.833°K$
△ $T = 1.904°K$
△ $T = 1.962°K$
▽ $T = 1.988°K$
▽ $T = 2.052°K$
—·— $T = 2.097°K$
–¦– $T = 2.152°K$

- Large heat and temperature difference
  - Heat almost proportional to cubic root of temperature difference

$$Q \propto \sqrt[3]{\nabla T}$$

- Small heat and temperature difference
  - Heat proportional to temperature difference

Gorter, C. J. and Mellink J. H., Physica 15 (1949) 285-304

Momentum Equations with Interaction

$$\frac{\partial\left(\rho_s \mathbf{v}_s\right)}{\partial t}+\nabla\left(\rho_s \mathbf{v}_s \mathbf{v}_s\right)=-\frac{\rho_s}{\rho}\nabla P+\rho_s s\nabla T-A_{GM}\rho_n\rho_s\left|\mathbf{v}_n-\mathbf{v}_s\right|^2\left(\mathbf{v}_n-\mathbf{v}_s\right)$$

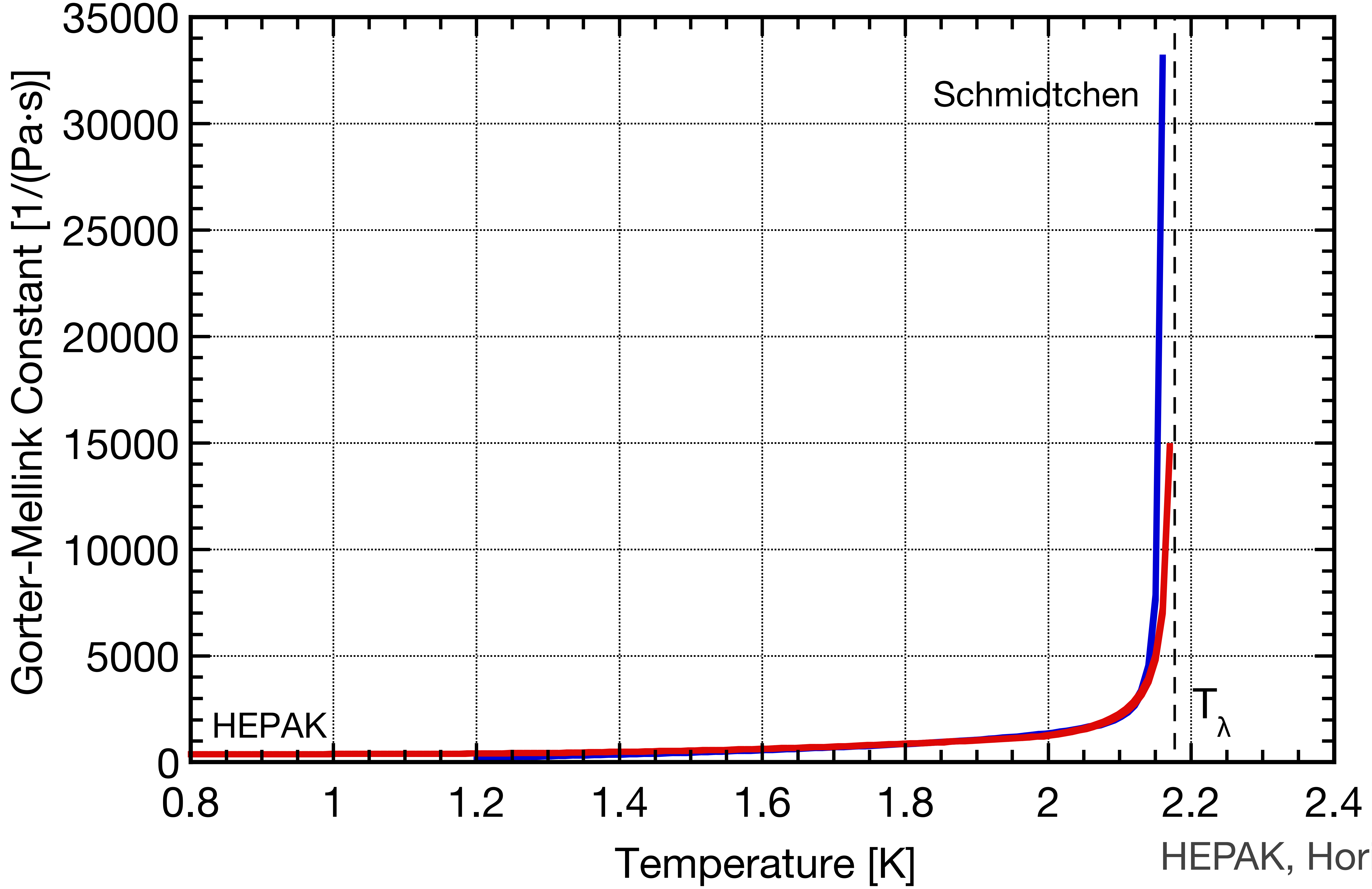
$$\frac{\partial\left(\rho_n \mathbf{v}_n\right)}{\partial t}+\nabla\left(\rho_n \mathbf{v}_n \mathbf{v}_n\right)=-\frac{\rho_n}{\rho}\nabla P-\rho_s s\nabla T+A_{GM}\rho_n\rho_s\left|\mathbf{v}_n-\mathbf{v}_s\right|^2\left(\mathbf{v}_n-\mathbf{v}_s\right)+\mu\nabla^2\mathbf{v}_n$$

Mutual Friction

$$F_{sn}=A_{GM}\rho_n\rho_s\left|\mathbf{v}_n-\mathbf{v}_s\right|^2\left(\mathbf{v}_n-\mathbf{v}_s\right)$$

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

Gorter-Mellink Coefficient (A_{GM})



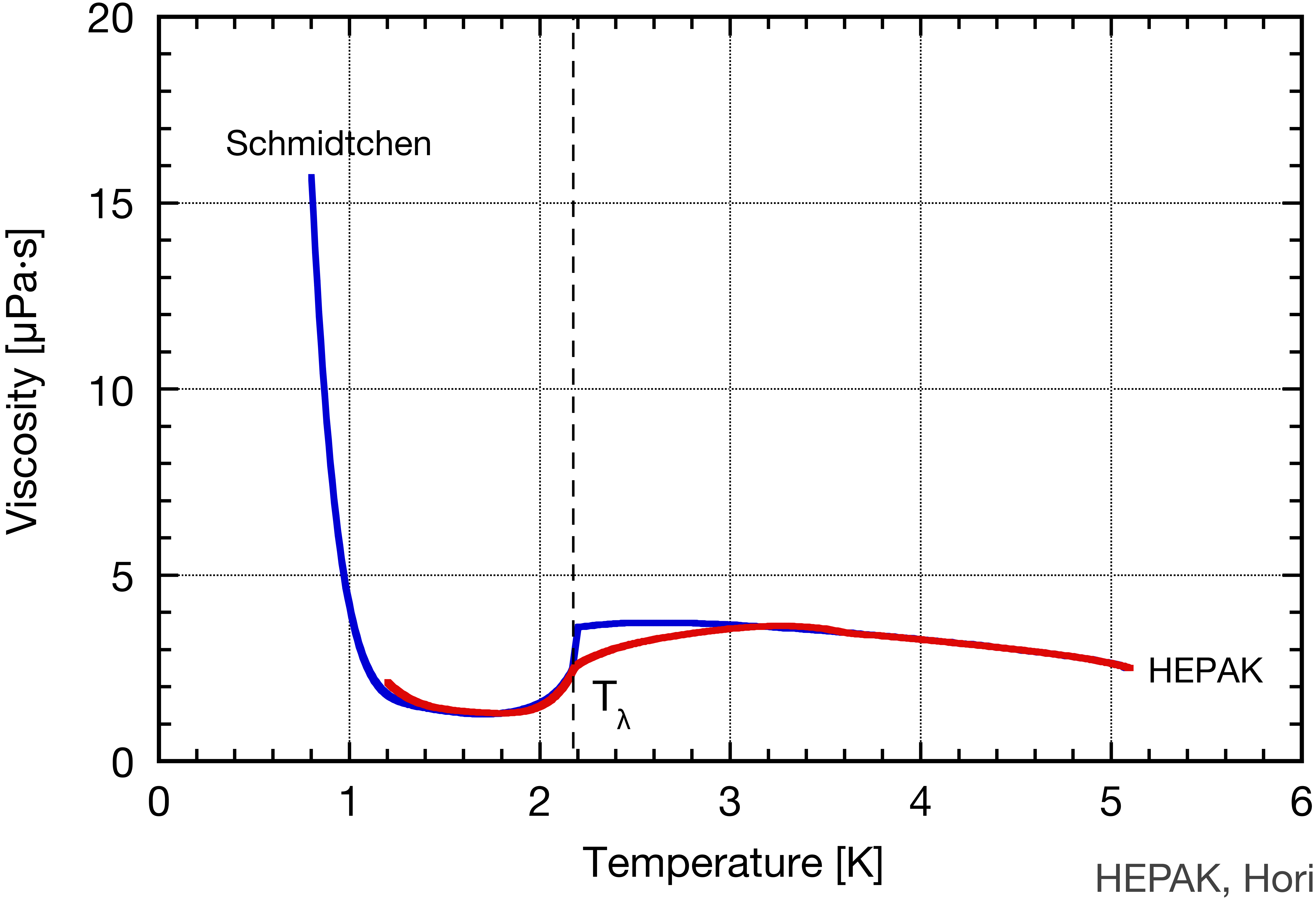
HEPAK, Horizon Technologies

Schmidtchen, U., Private Communication (1984)

Superconducting Cavities Cooling Method

- Operation temperature of 4.4 K (KEKB/SuperKEKB) : 509 MHz
  - 80 K thermal shields cooled with liquid nitrogen
  - Cavities cooled with liquid helium
- Operation temperature of 2 K (STF, cERL) : 1.3 GHz
  - 80K thermal shields cooled with liquid nitrogen
  - 5K thermal shields cooled with liquid helium
  - Cavities cooled with superfluid helium

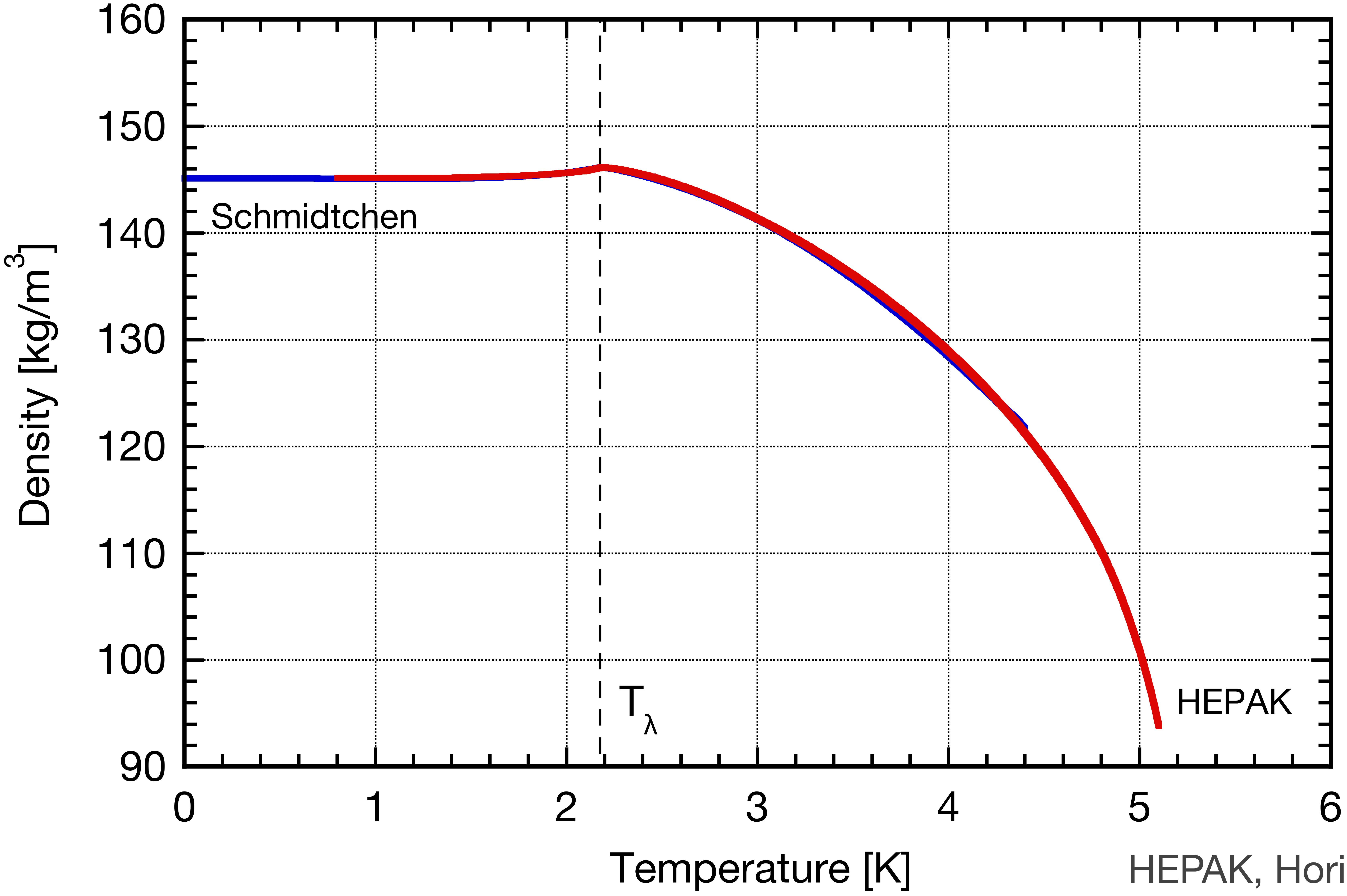
Viscosity of Liquid Helium



HEPAK, Horizon Technologies

Schmidtchen, U., Private Communication (1984)

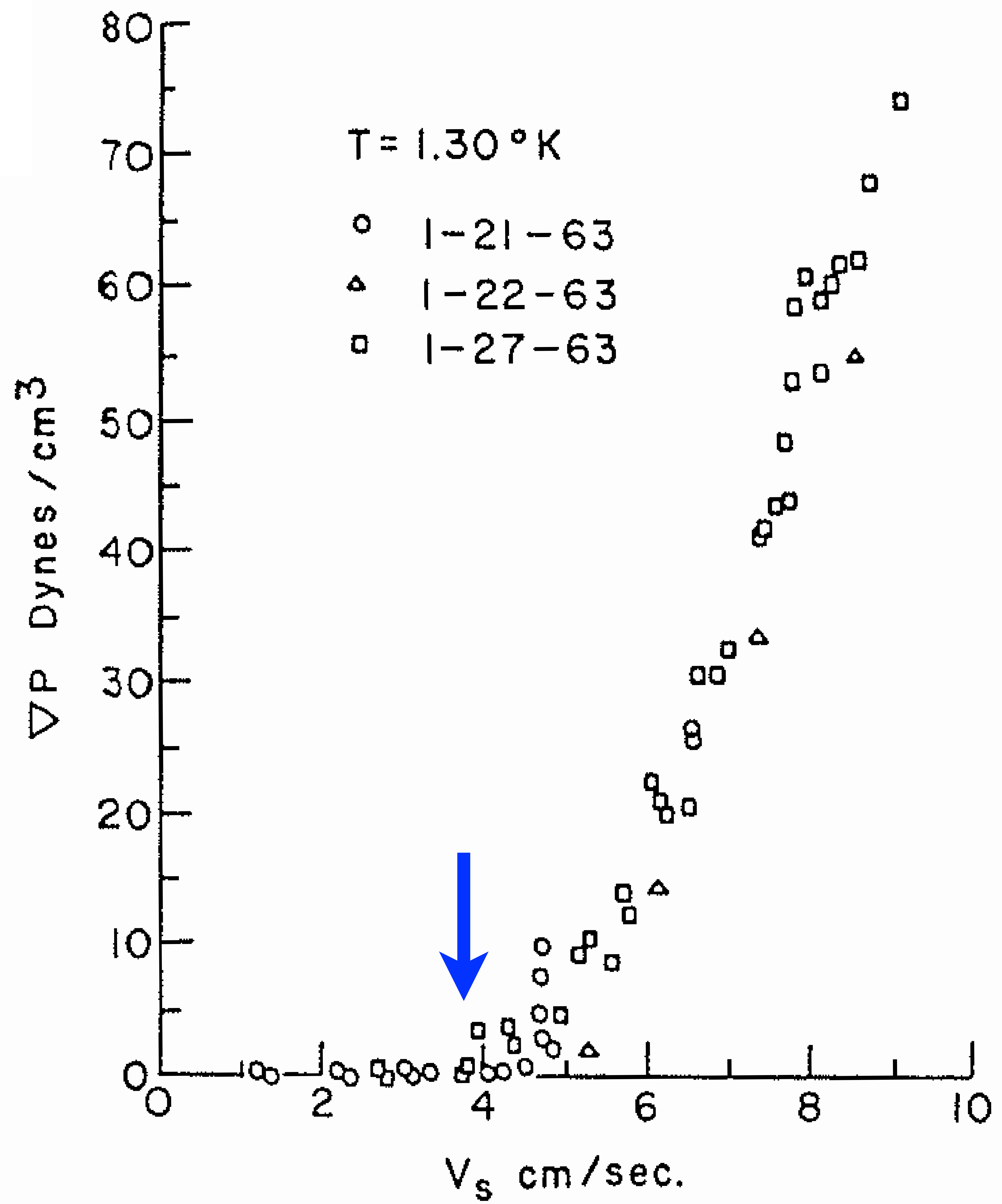
Density of Liquid Helium



HEPAK, Horizon Technologies

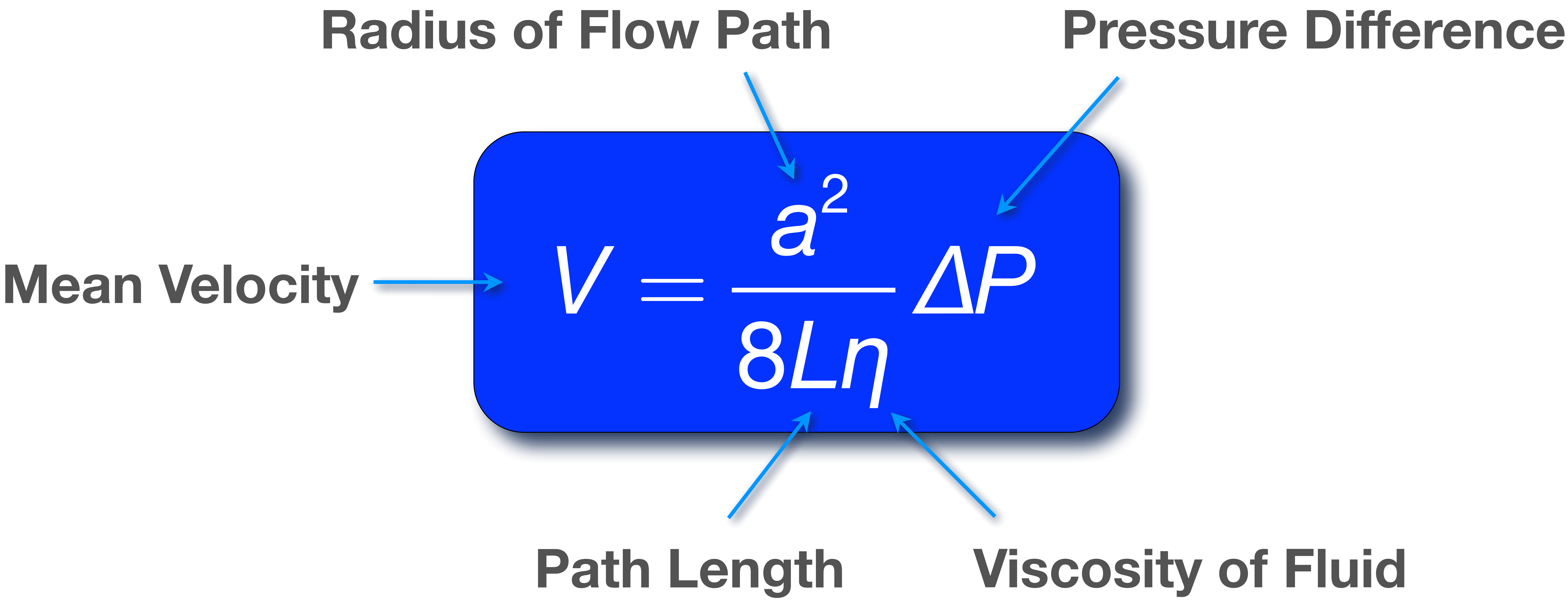
Schmidtchen, U., Private Communication (1984)

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

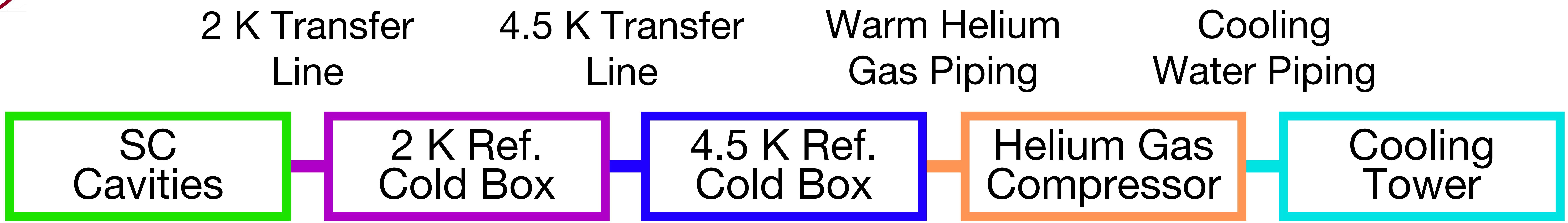
Yamada K. and Ohmi T., “Superfluidity”, Baifukan (1995)

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

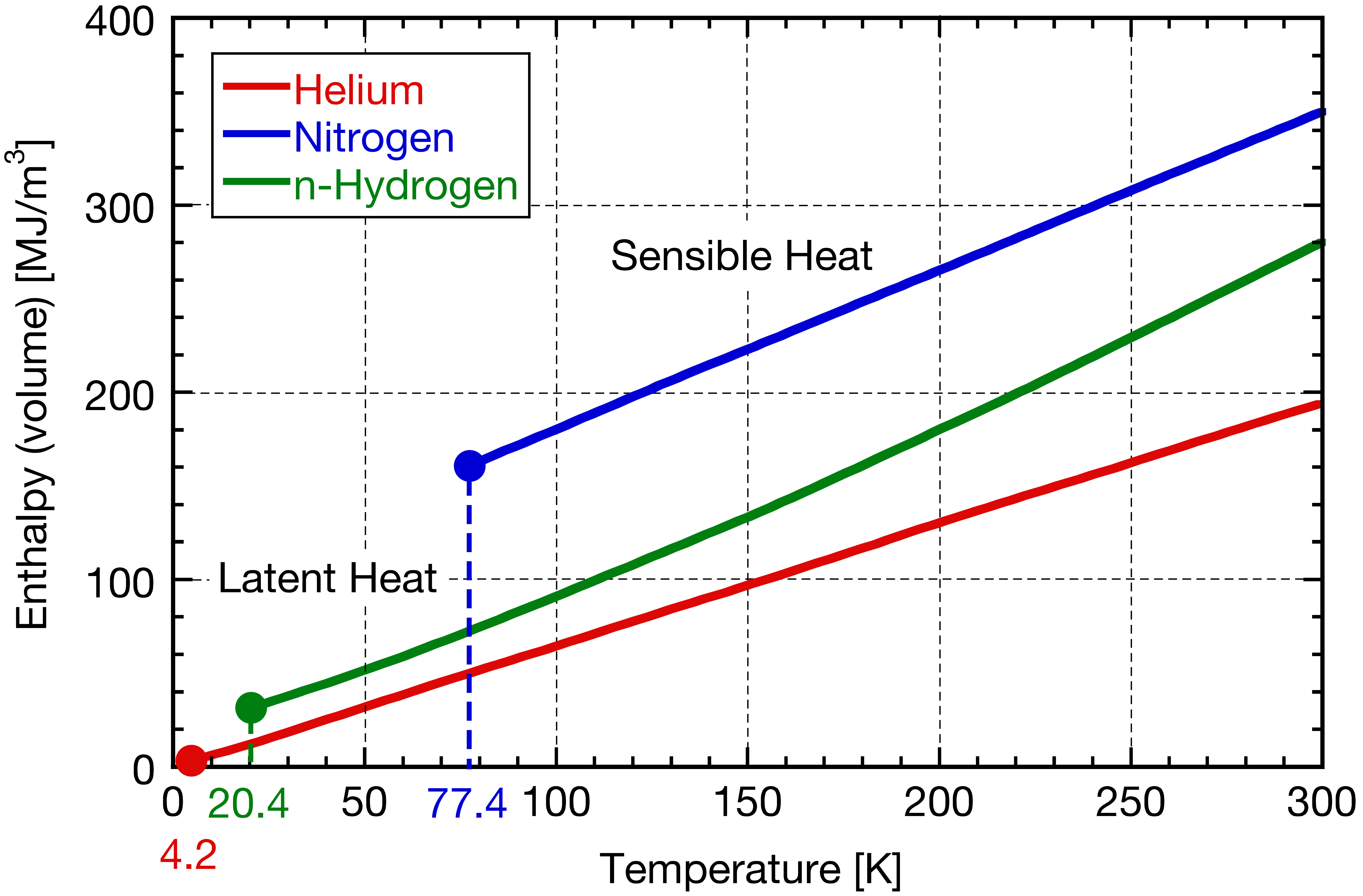
Under Atmospheric Pressure * Lambda Point Temperature

Concept of Superfluid Helium Cryogenic System



- Liquid helium production from helium gas at room temperature
  - Helium liquefiers/refrigerators (4.5K cold boxes)
  - Helium compressors
- Superfluid helium production from liquid helium
  - 2K refrigerators (2K cold boxes)
  - Vacuum pumps/compressors

Latent Heat and Sensible Heat



Verein Deutscher Ingenieure, “Lehrgangshandbuch Kryotechnik” (1977)

Cryogenic Temperature Sensors

Sensor overview

	Temperature range	Standard curve	Below 1 K	Can be used in radiation	Performance in magnetic field
Diodes					
Silicon	1.4 K to 500 K	×			Fair above 60 K
GaAlAs	1.4 K to 500 K				Fair
Positive temperature coefficient RTDs					
Platinum	14 K to 873 K	×		×	Fair above 30 K
Rhodium-iron	0.65 K to 500 K		×	×	Fair above 77 K
Negative temperature coefficient RTDs					
Cernox™	0.10 K to 420 K		×	×	Excellent above 1 K
Germanium	0.05 K to 100 K		×	×	Not recommended
Ruthenium oxide*	0.01 K to 40 K	×	×	×	Good below 1 K
Other					
Thermocouples	1.2 K to 1543 K	×			Fair
Capacitance	1.4 K to 290 K				Excellent

*RX-102B not recommended for use in magnetic fields

Lake Shore Cryotronics, Inc.

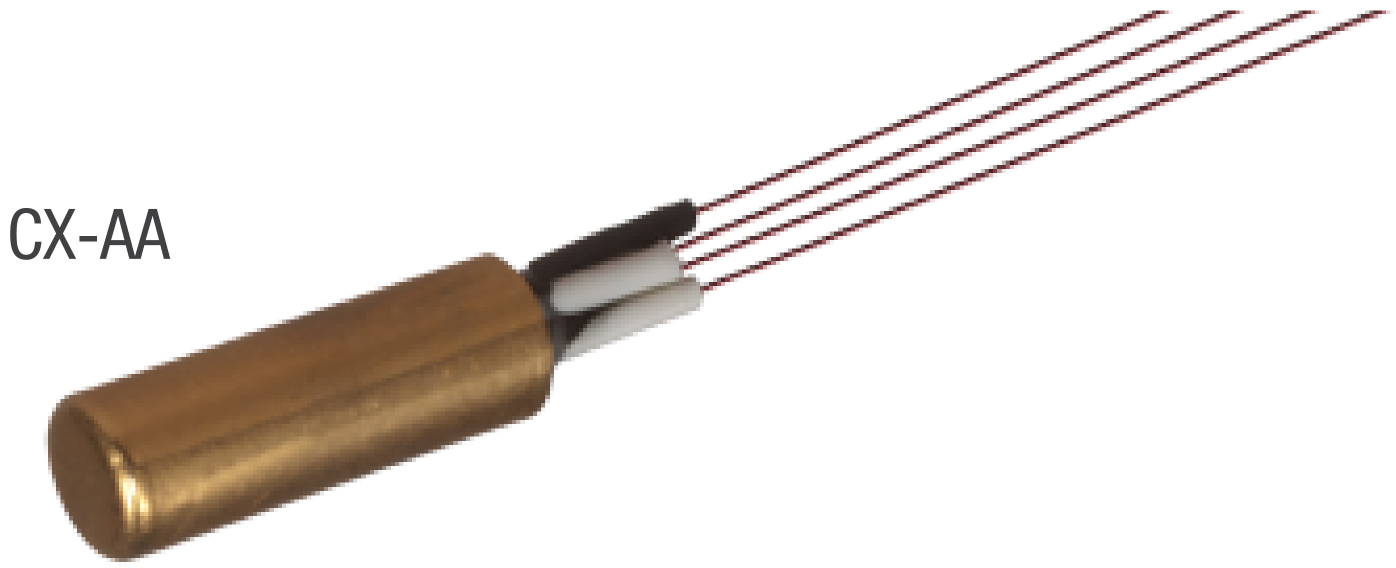
Major Temperature Sensors Employed at KEK

- Cernox® resistance temperature sensors
  - Calibration required due to individual difference
  - Precise measurement at superfluid helium temperature range
- Silicon diode temperature sensors
  - Wide temperature range
  - No calibration required in effect due to very small individual difference
- Platinum-cobalt (Pt-Co) resistance temperature detectors
  - Wide temperature range
  - Slight individual difference

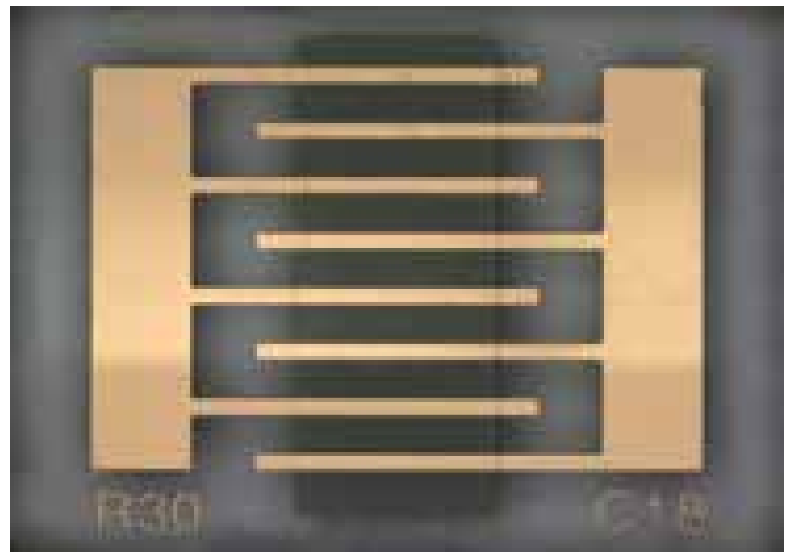
Cernox® Resistance Temperature Sensors

CX-SD

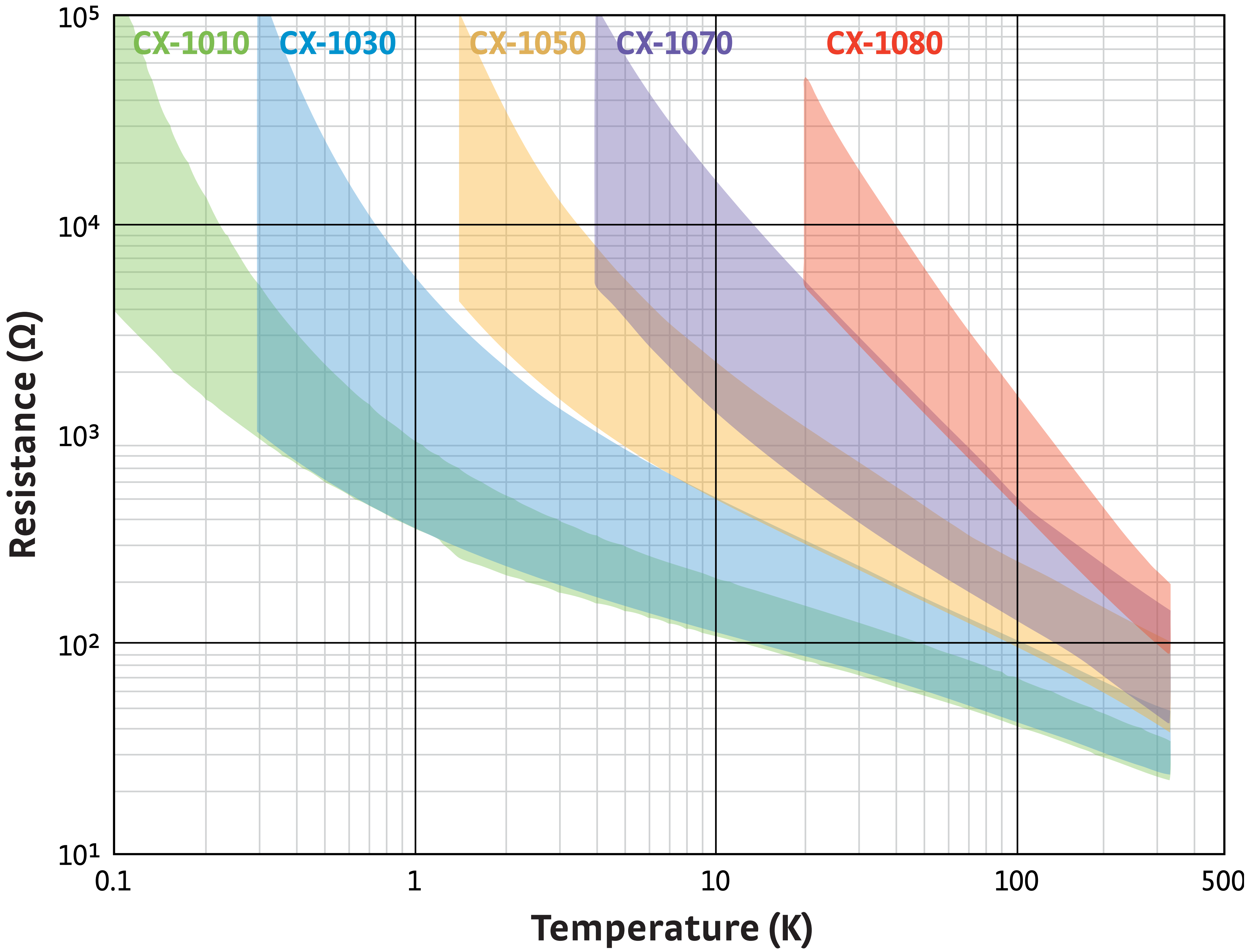
CX-AA



CX-BR



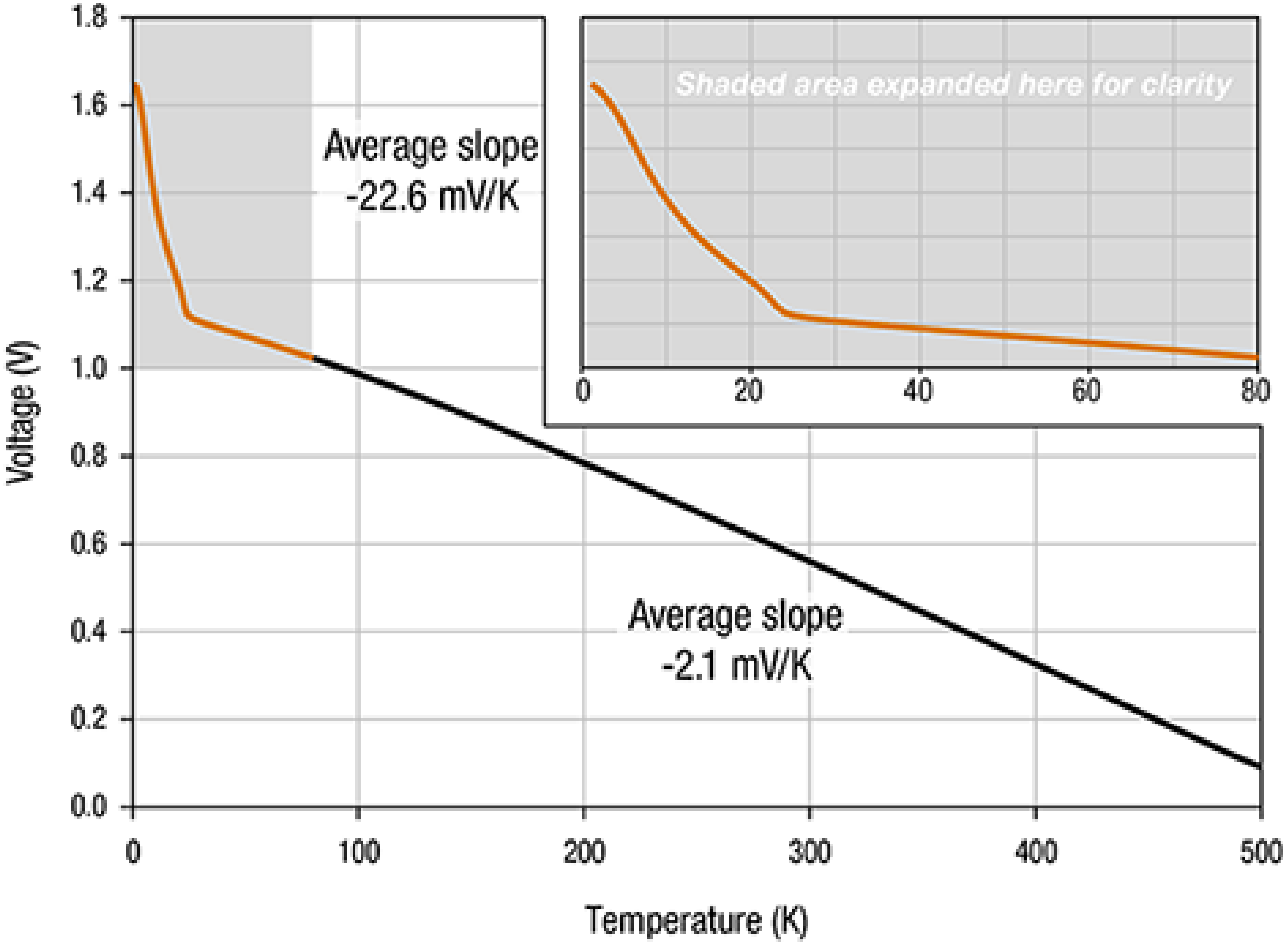
Typical Cernox™ resistance



Lake Shore Cryotronics, Inc.

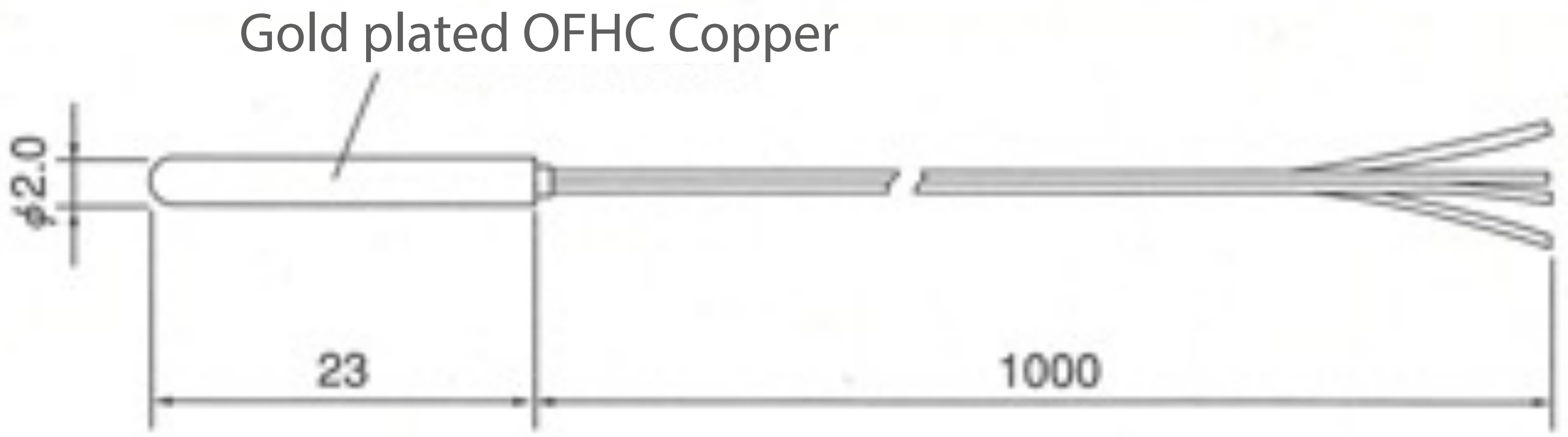
Silicon Diode Temperature Sensors

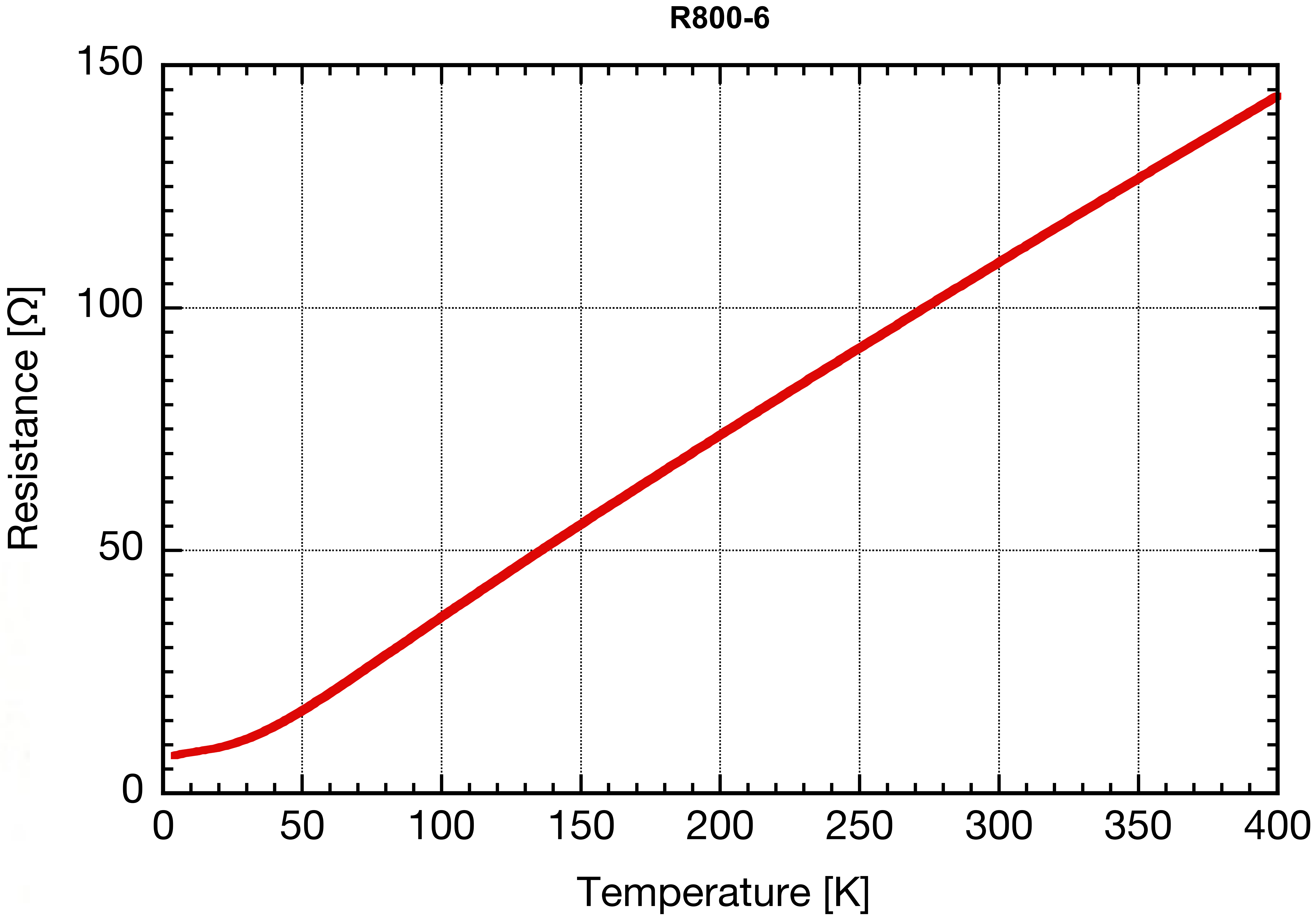
DT-670 Temperature Response Curve



Lake Shore Cryotronics, Inc.

Platinum-Cobalt (Pt-Co) Resistance Temp. Detectors





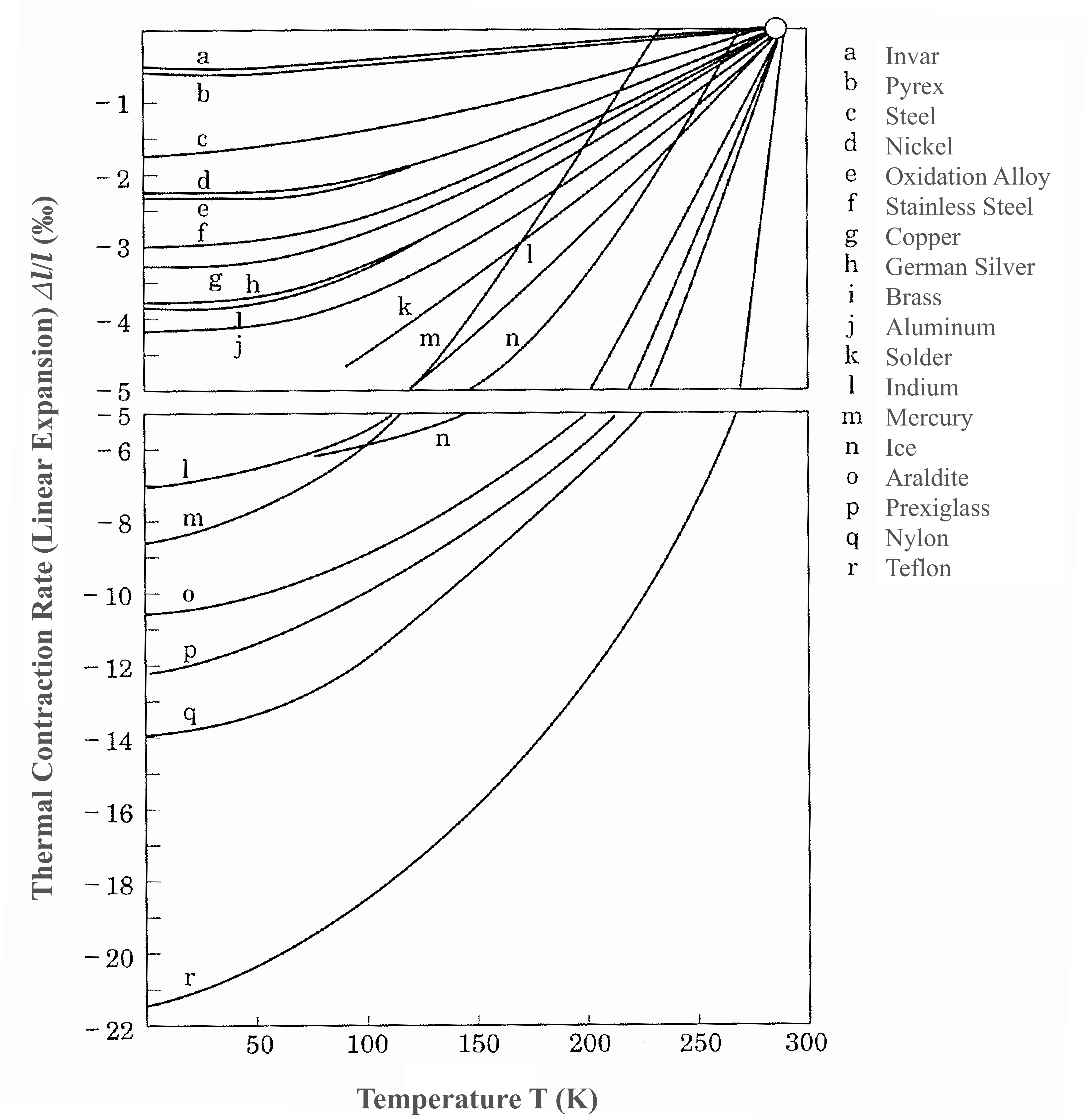
CHINO

STF CM-1 + CM-2a Configuration

Thermometry at Low Temperature

- Measurement with 4-wire method (4 leads from 1 sensor)
  - Wires covered with materials which are not fragile at low temperature
  - Mainly Teflon and fluorocarbon polymers (with care of resistance to radiation)
- Reduction of heat load through wires
  - Thermal anchors employed (wires attached or fixed at low temperature surface)
  - Wiring in insulation vacuum (no heat of wire released in vacuum)

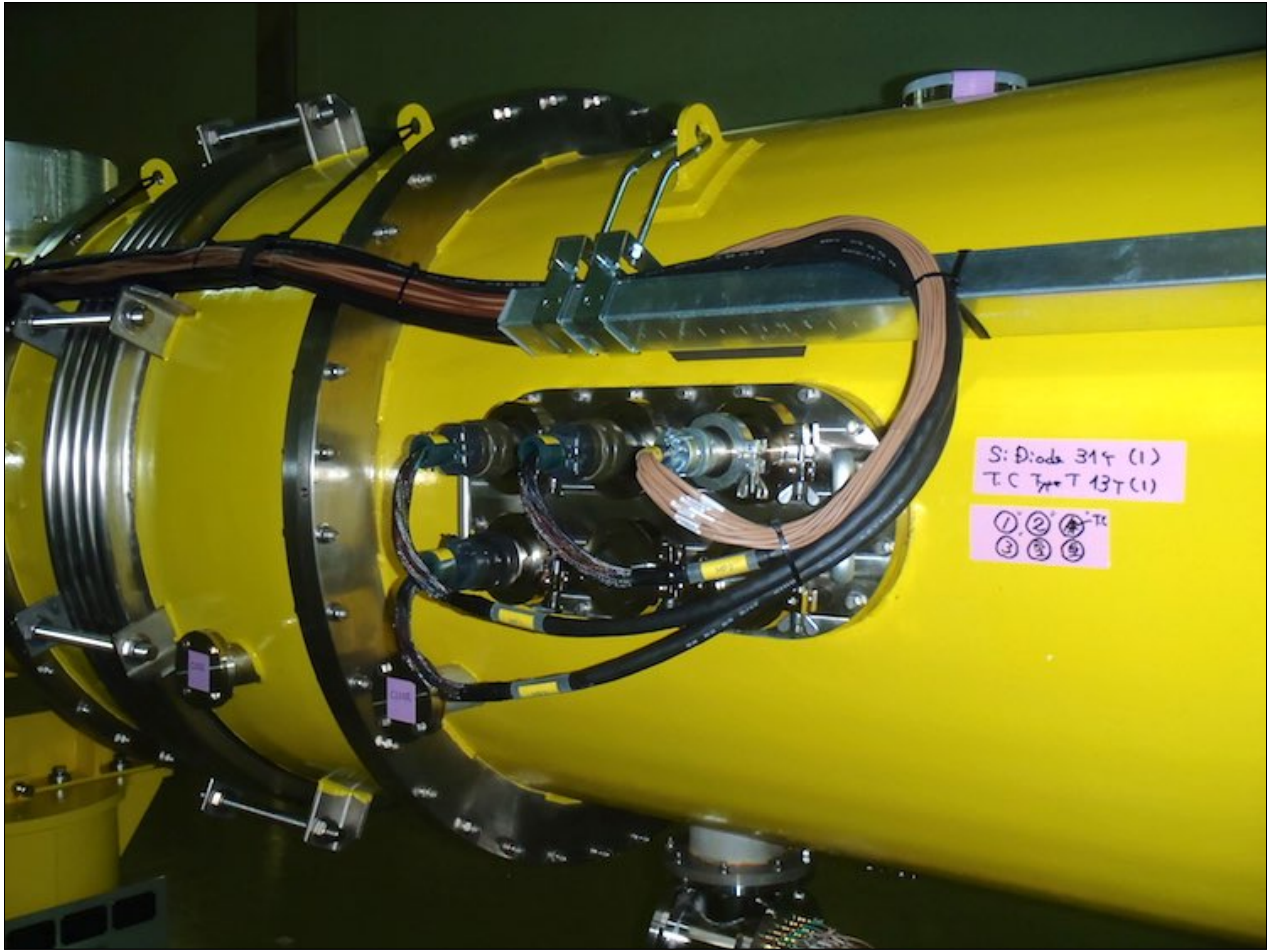
Thermal Shrinkage



- **Linear expansion : length variation of solid with heat**
- **Linear expansion coefficient : increment rate of material length with 1 K increment of temperature**
- **Thermal contraction rate : contraction rate of material length with 1 K increment of temperature**

Verein Deutscher Ingenieure,
“Lehrgangshandbuch Kryotechnik” (1977)

Feed-through of Temperature Sensors



Liquid Helium Level Sensors

- Mechanical level sensors employing thermal oscillation
  - Maximum amplitude of gas column oscillation at free surface of liquid helium
  - Oscillation detection with a rubber membrane and a Bourdon tube (gauge)
- Superconducting level sensors
  - Vertical superconducting wire
  - Superconducting state of wire only in liquid helium
  - Ratio of superconducting and normal state of wire determined from total electrical resistance of wire

End Unit Design

Downstream Side View

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.)
- Avoid resonant conditions by varying length or with stuffing inside pipe