ICEC29/ICMC2024

Development of 4K-GM cryocooler and its applications for superconducting magnets

TOSHIBA

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2024.07.24

Contents

01

Introduction

“THE QUEST FOR ABSOLUTE ZERO”

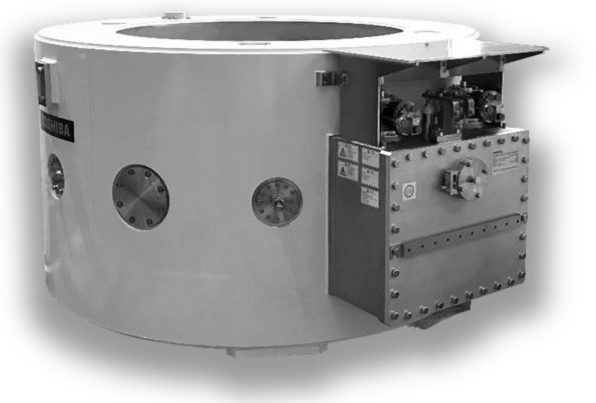
by K. MENDELSSOHN,

PUBLISHED BY WEIDENFELD AND NICOLSON, 1966

translated by K. Oshshima, Kodansha 1971

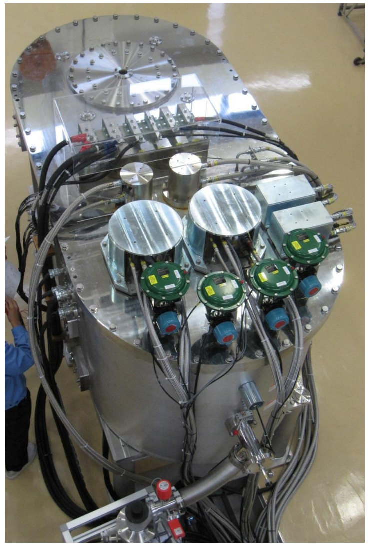
Development of Superconducting Magnets in Toshiba

- Industry/Medical
    - Silicon Single Crystal Puller
    - Rotating Gantry
    - Maglev
- Energy
    - ITER
    - SMES
- Basic Science
    - Magnet for Accelerator
    - High Magnetic Field Magnet



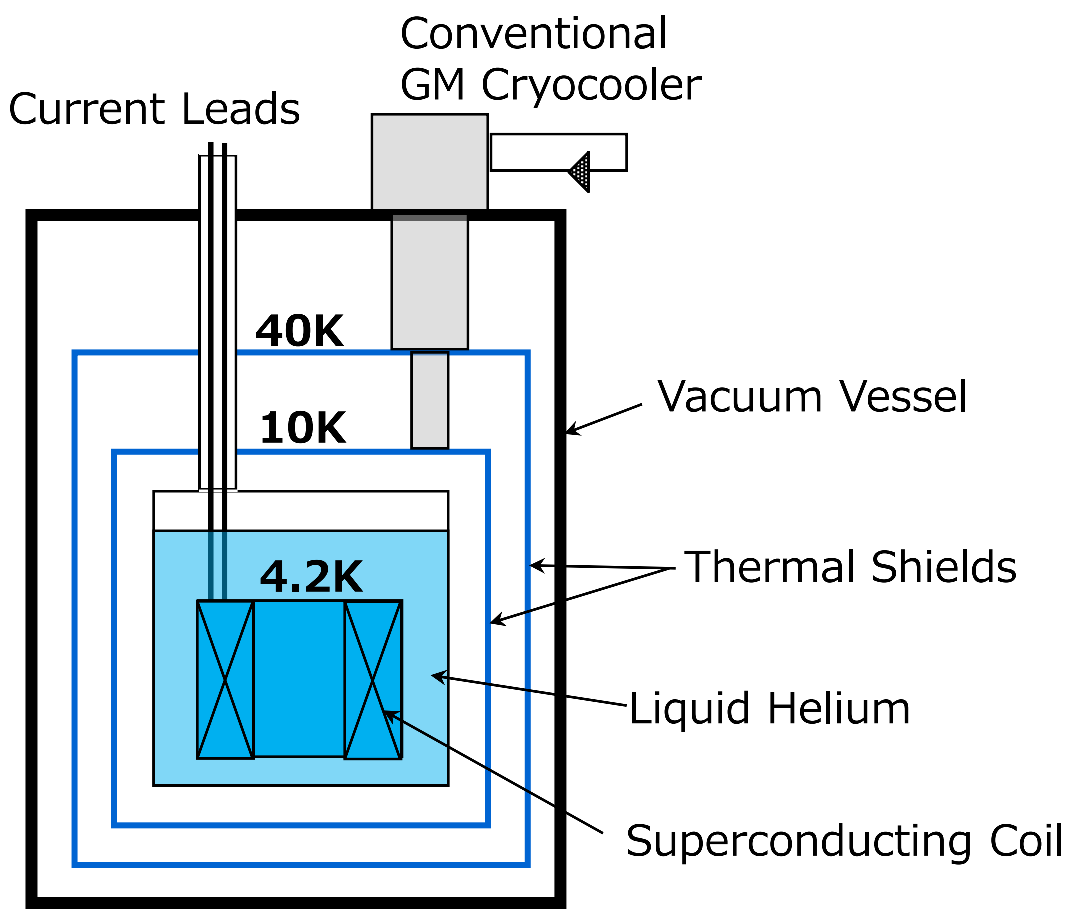
Courtesy of National Institutes for Quantum Science and Technology

Courtesy of Osaka University



Courtesy of Tohoku University

Conventional Superconducting Magnet in 1980's



GM : Gifford-McMahon

MRI Magnet with GM Cryocooler

GM Cryocooler replaced Liquid N_2 for thermal shields cooling

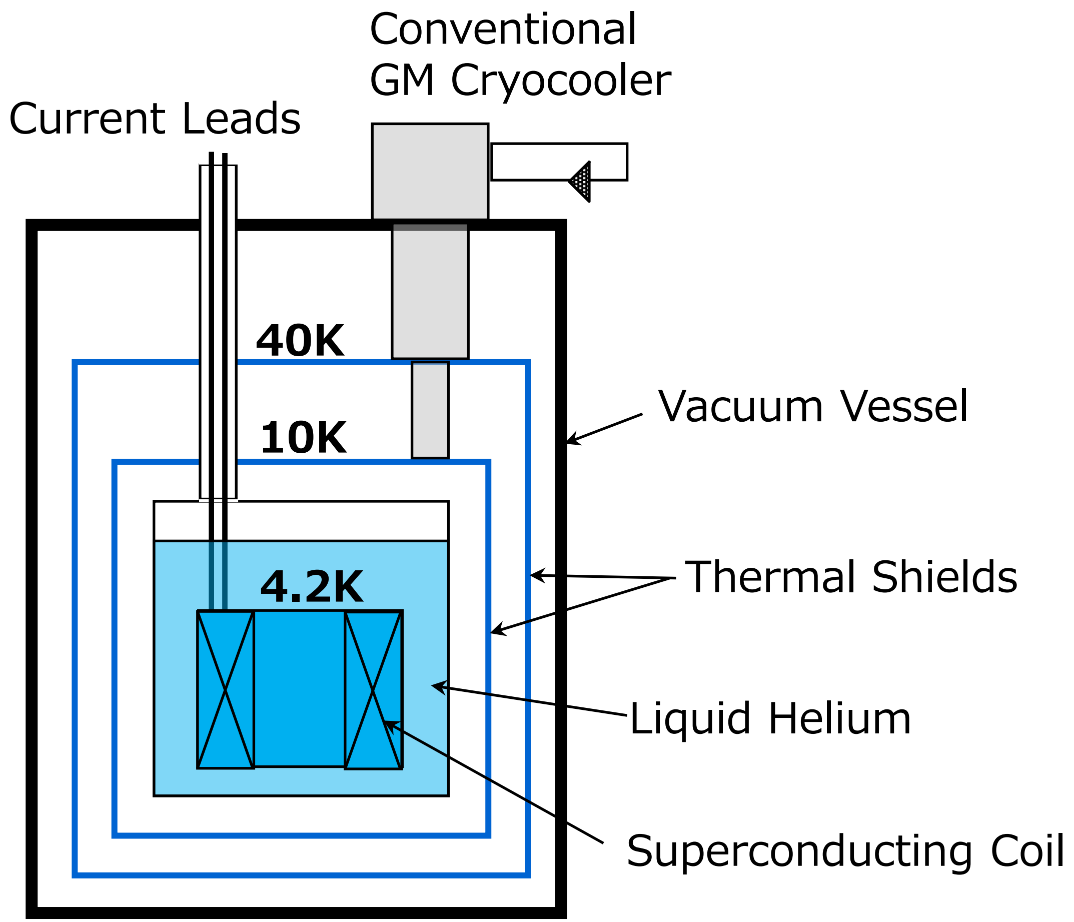
Motivation to Lower the Temperature of GM Cryocooler

Cost of Liquid Helium was Expensive

Strong Requirement to reduce
Evaporation Ratio of Liquid Helium

Limitation of 2nd Thermal Shield
Temperature around 10-12 K

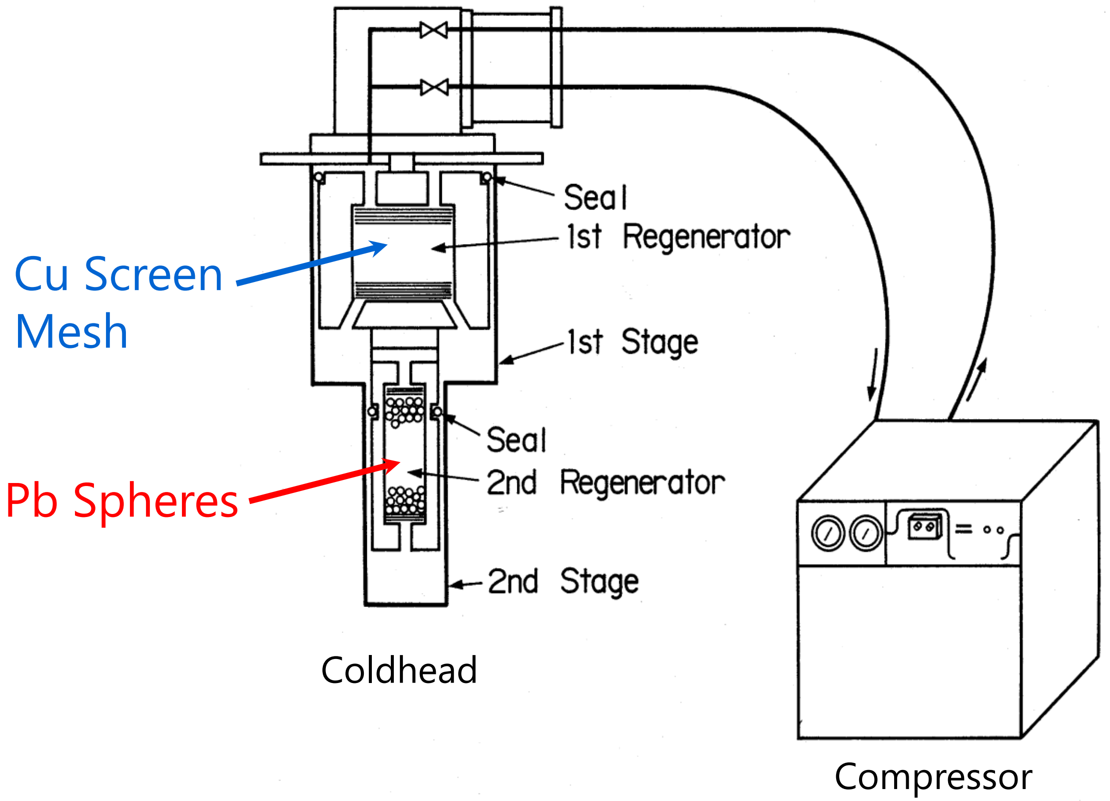
GM Cryocooler's Lowest Temperature Limit



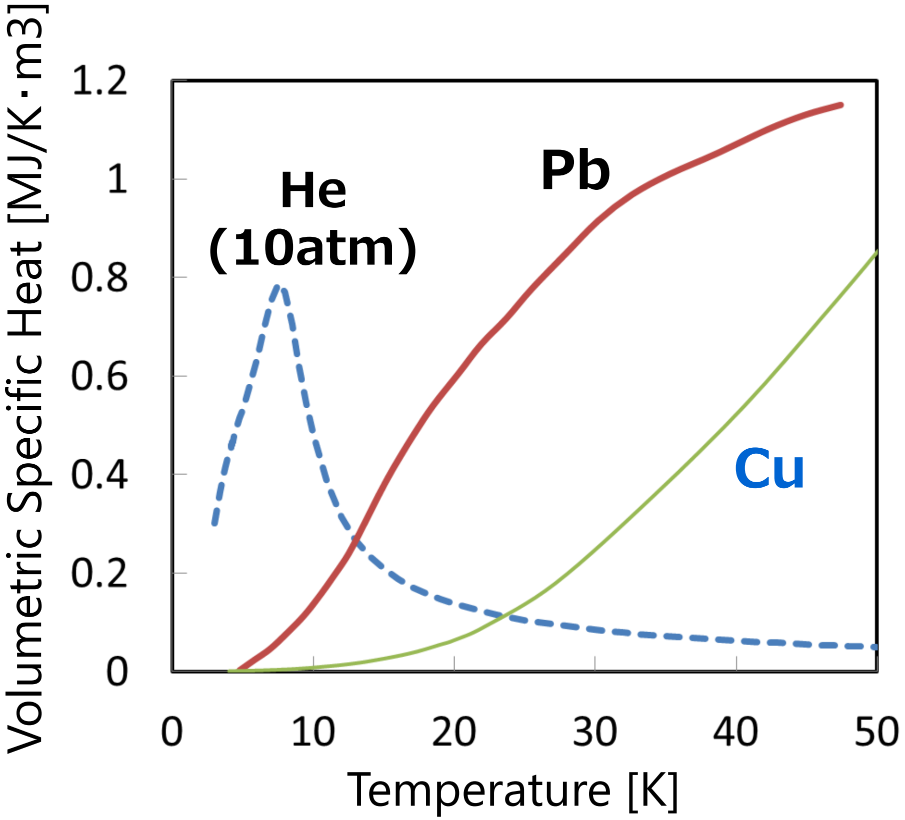
02

4K-GM Cryocooler

Why lowest temperature of GM cryocooler was limited around 10K ?



Configuration of two-stage GM Cryocooler



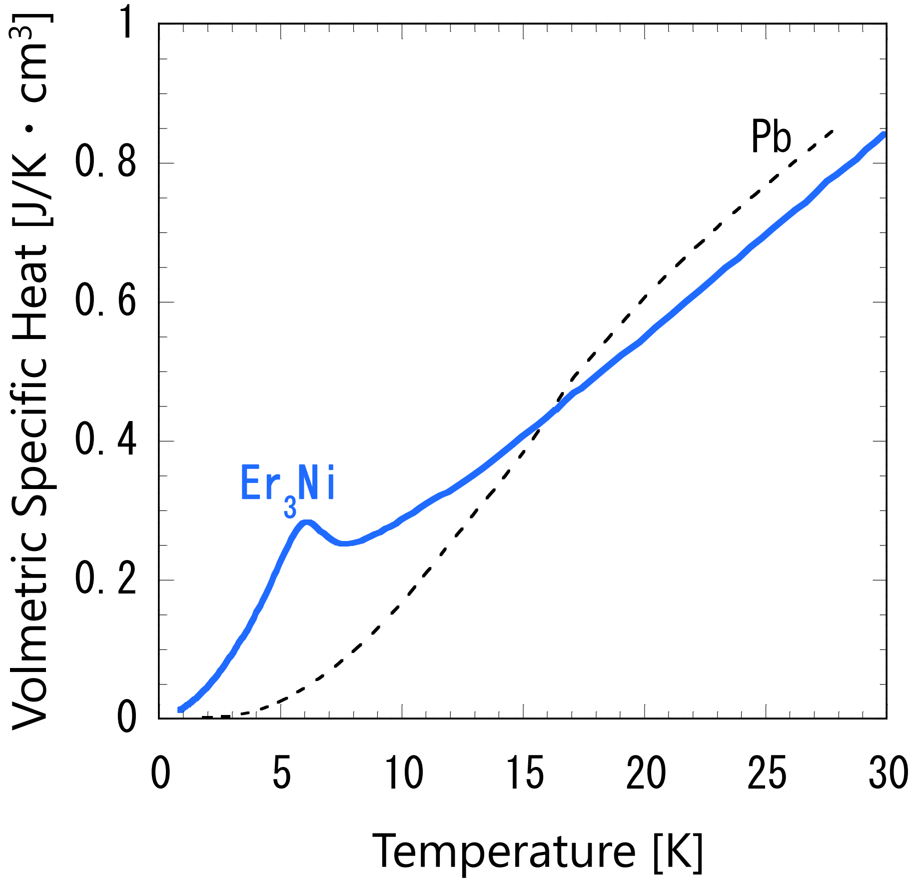
Needs for New Materials with Large Heat Capacity below 10 K

Search for New Regenerator Materials

(1)Large Heat Capacity below 10 K

(2) Heat capacity approximately equal to
that of Pb at temperatures above 10 K

(3)Antiferromagnetic Materials
for Superconducting Magnet Cooling



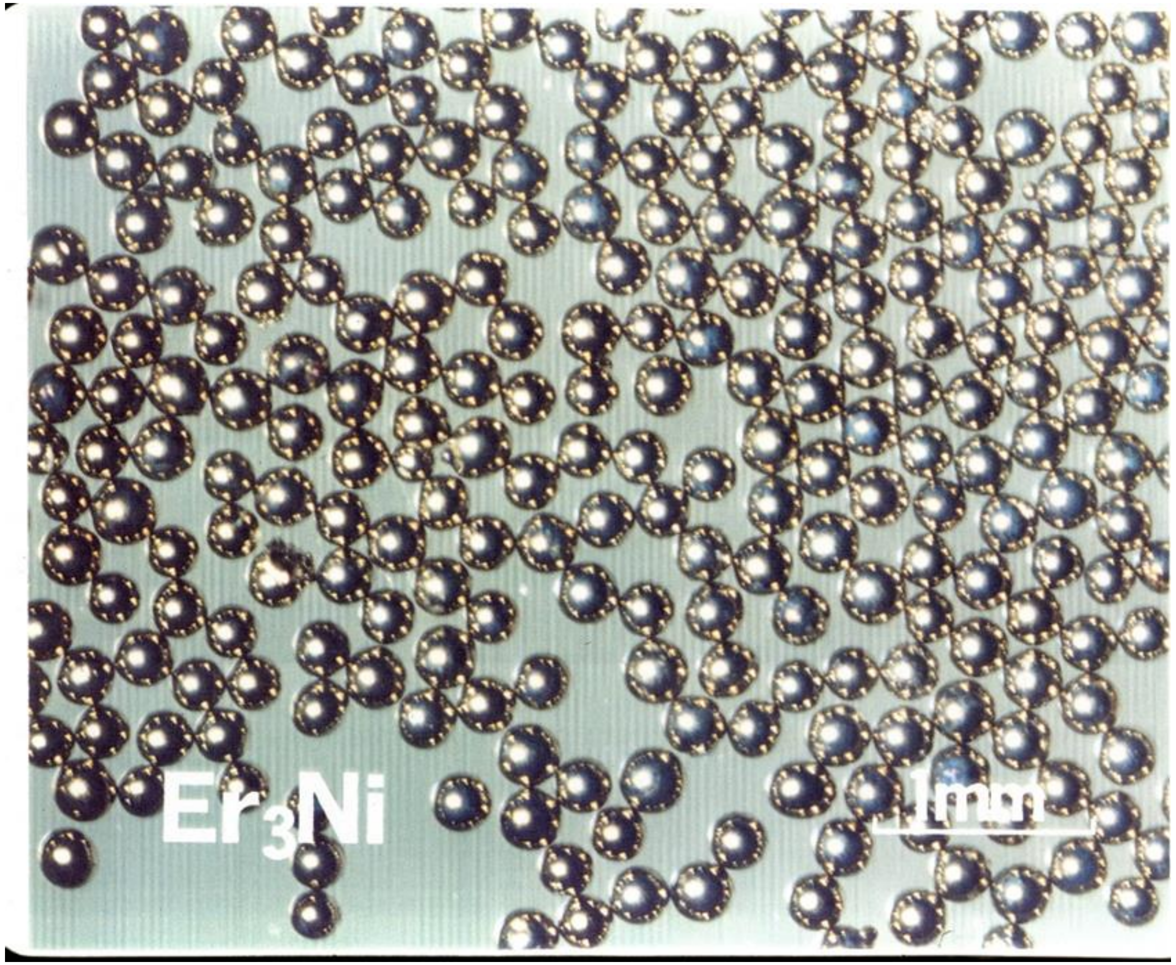
Courtesy of Toshiba Materials Co., Ltd

New Magnetic Regenerator Material of Er_3Ni was found in 1988

Other Efforts to 4K Cooling - Spheres for Regenerator –

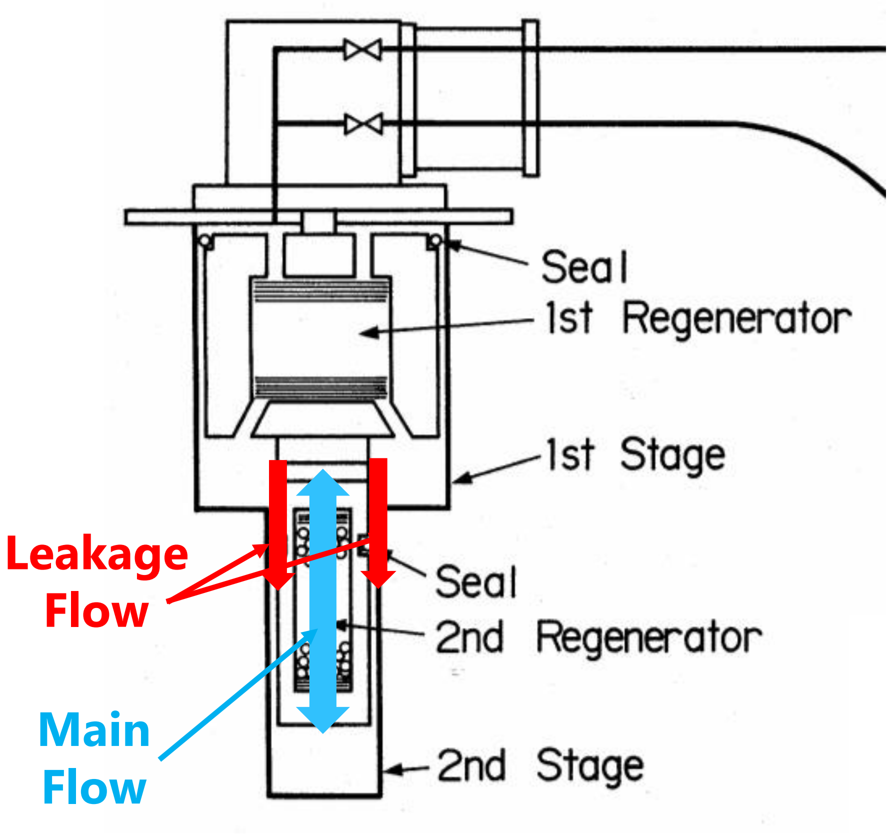
Make Spheres for Regenerator
φ150 – 300 μm

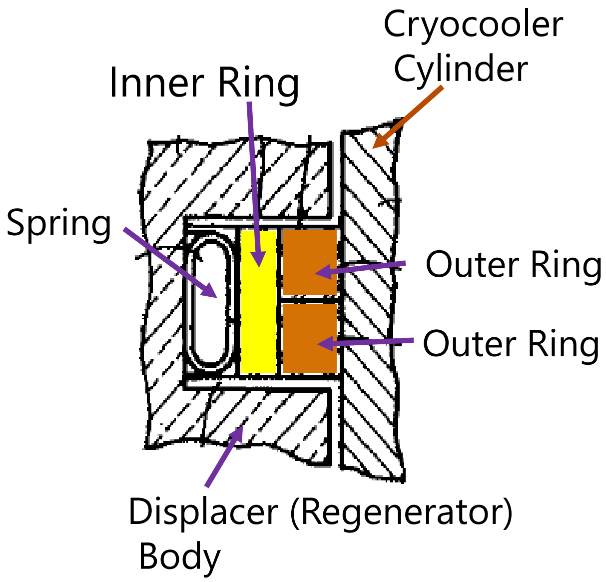
Uniform Helium Flow
Low Porosity
Good Heat Transfer with Helium

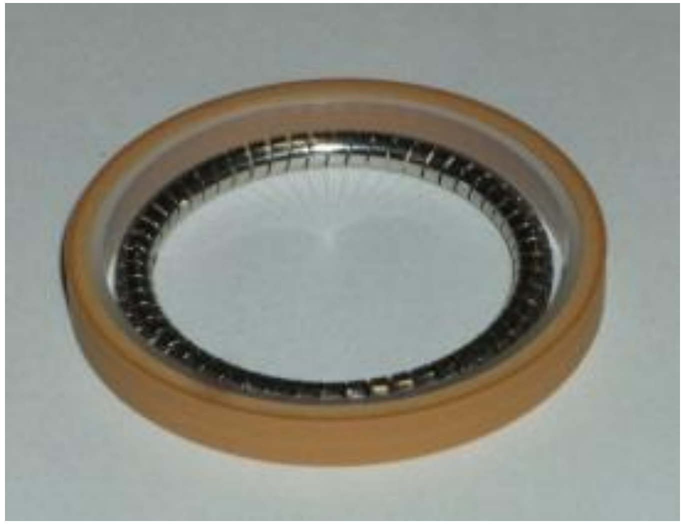


Courtesy of Toshiba Materials Co., Ltd

Other Efforts to 4K Cooling -Reduce Seal Leakage at 2nd Displacer -







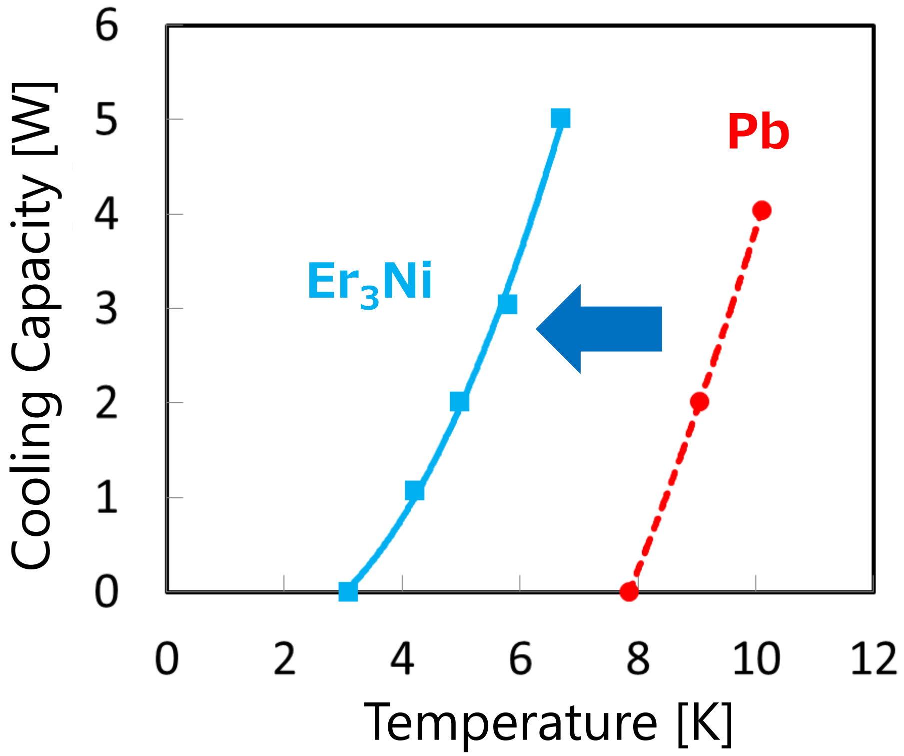
Configuration and Photo of New Seal

Seal Leakage became 1/10 by the new Seal

Achieve 4 K Cooling by two Stage GM Cryocooler

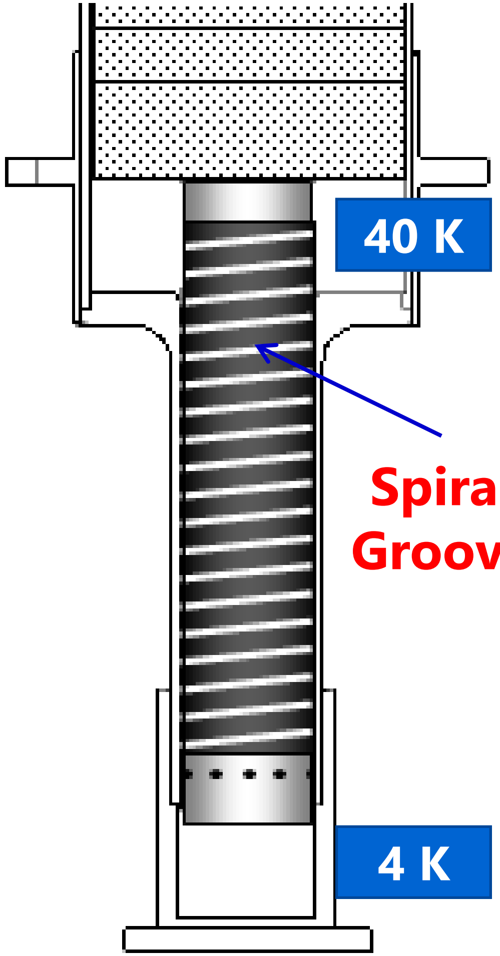
Pb

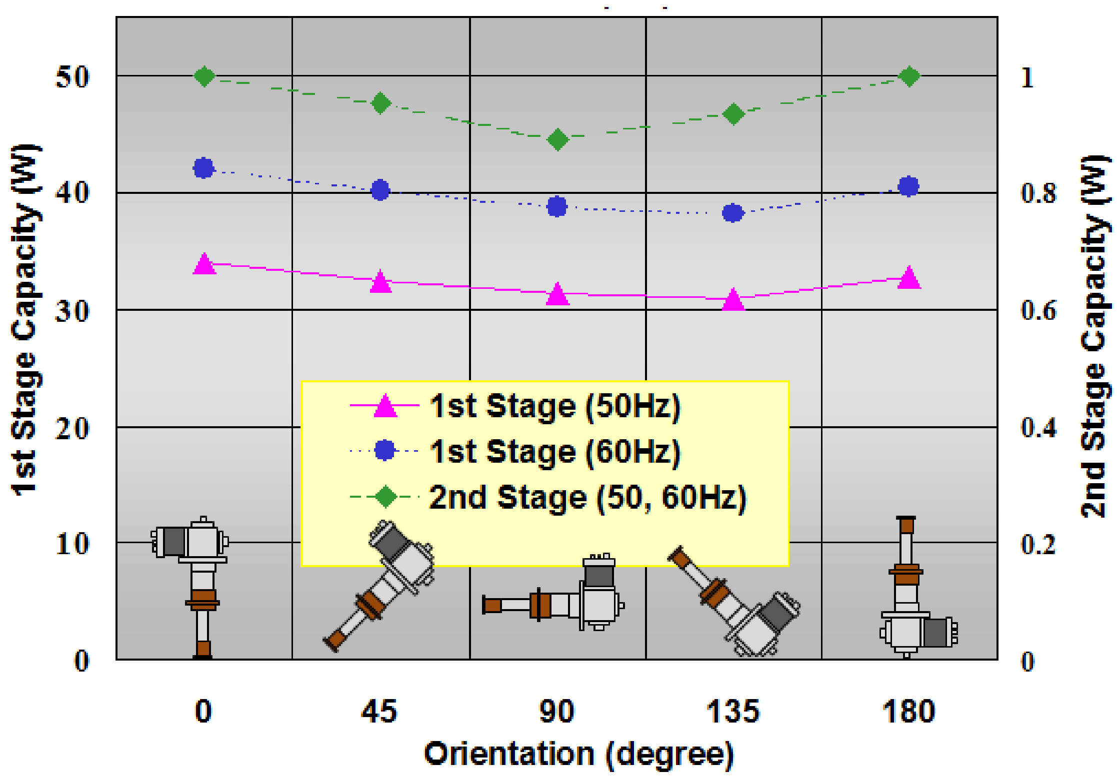
Er_3Ni



Achieved 4.5 K (1989)、1 W cooling Capacity at 4.2K (1991)

Dependence of Coldhead Orientation -Clearance Seal with Spiral Groove-





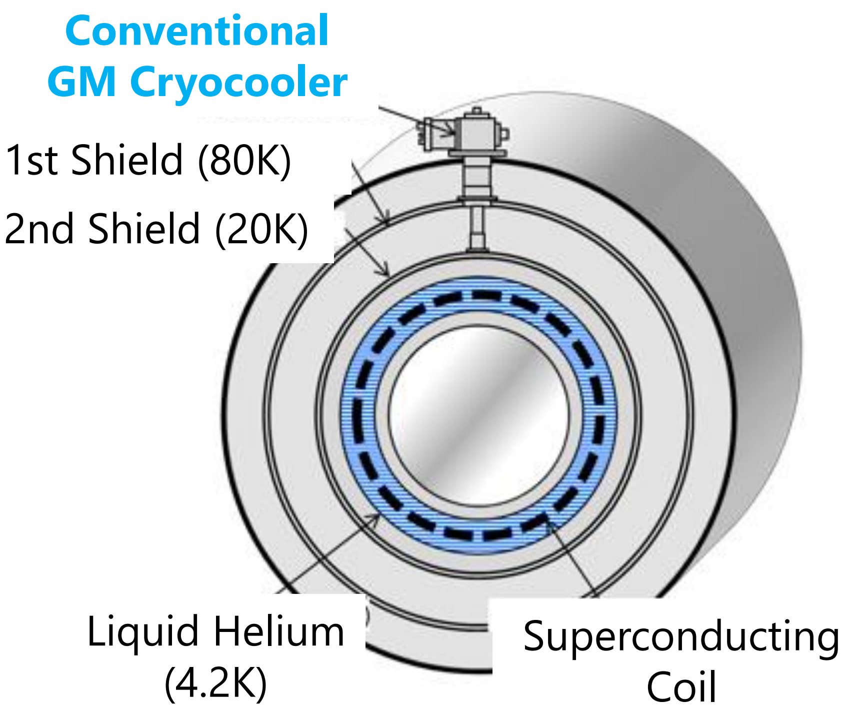
Courtesy of Sumitomo Heavy Industries, Ltd

Sumitomo Heavy Industry (SHI) solved the Orientation Issue

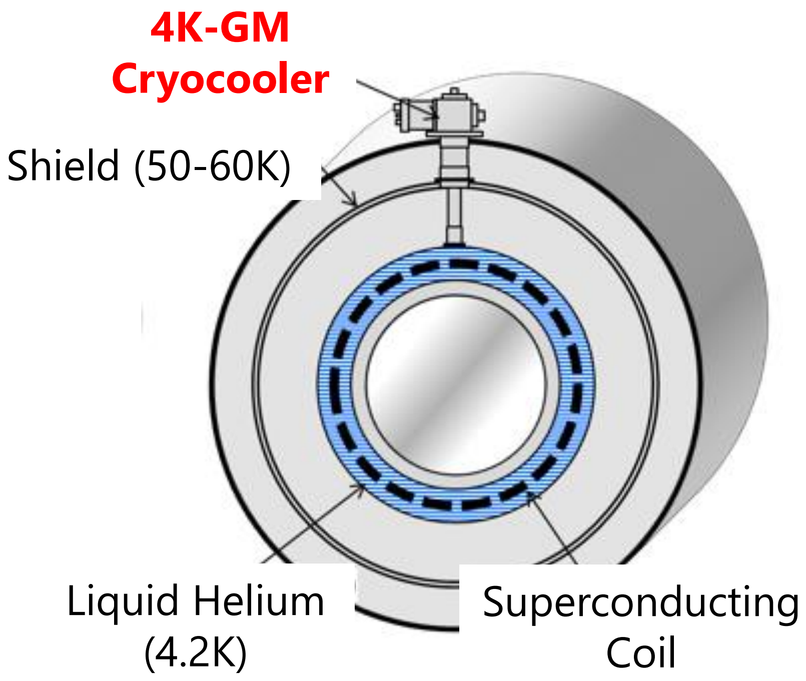
03

Cryocooler-cooled Superconducting Magnet

4K-GM Cryocooler application for SCM -Re-Condensation-



Thermal Shield Cooling



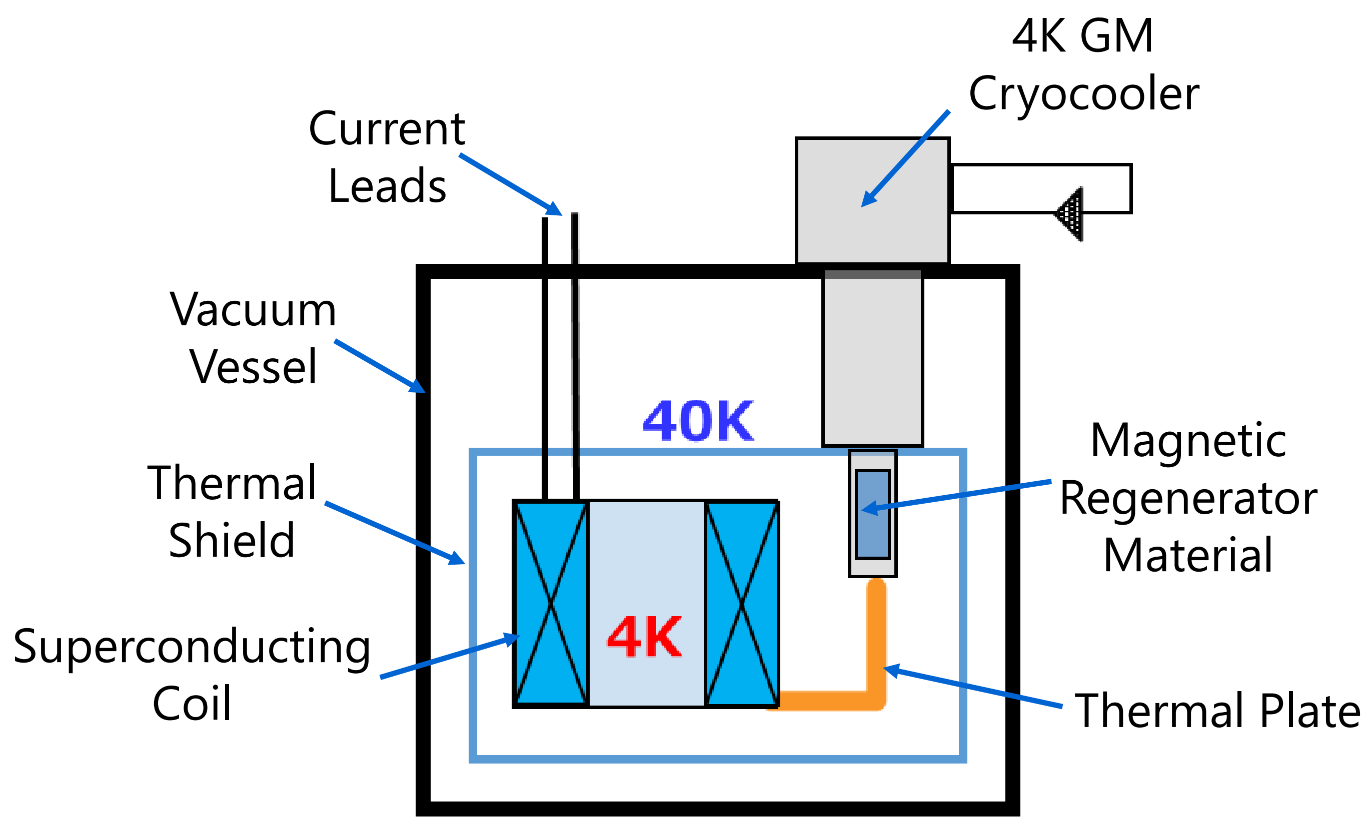
Helium re-condensation

Configuration of MRI Magnet with GM Cryocooler

Courtesy of Sumitomo Heavy Industries, Ltd

Almost All MRI Magnet has become re-condensation type Magnet

4K-GM Cryocooler application for SCM –Conductive Cooling-



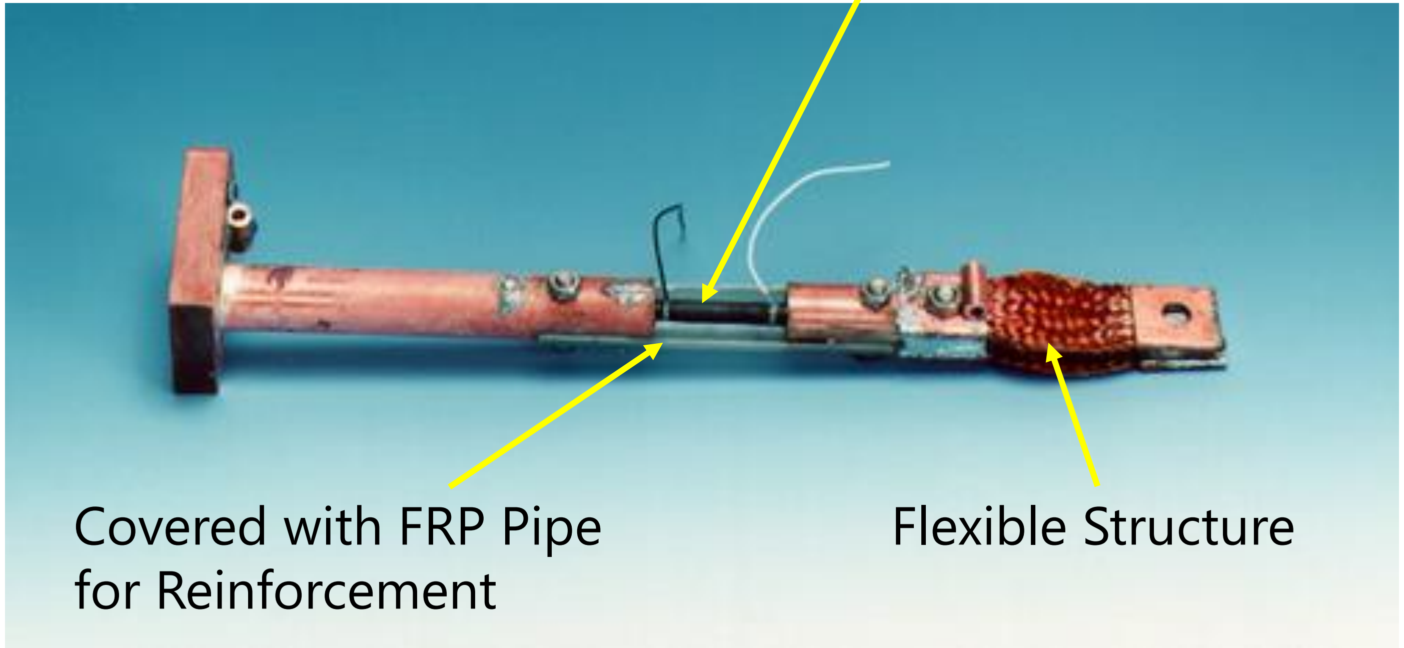
Large Heat Load through Current Leads

＞1W by 100 A Current Leads

1986 High Tc Superconductor was Found !!
High Tc Current Lead was developed

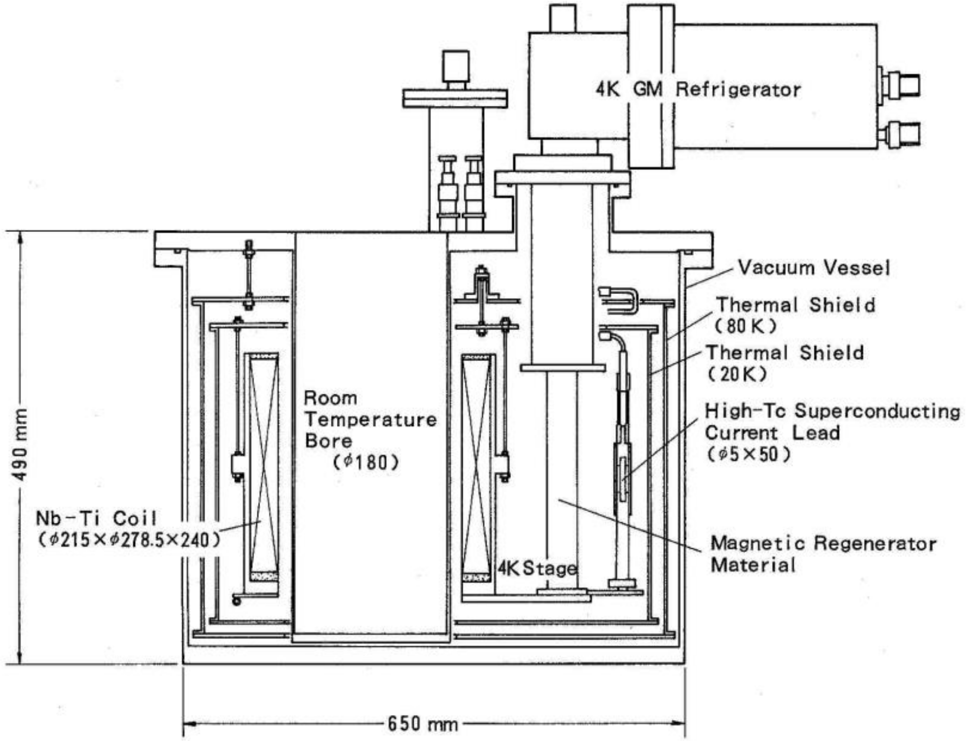
Breakthrough Technologies 4K-GM Cryocooler + HTS Current Lead

High Tc Superconducting Current Lead developed by Toshiba



Heat Load through Current Leads < 0.1W by 100 A

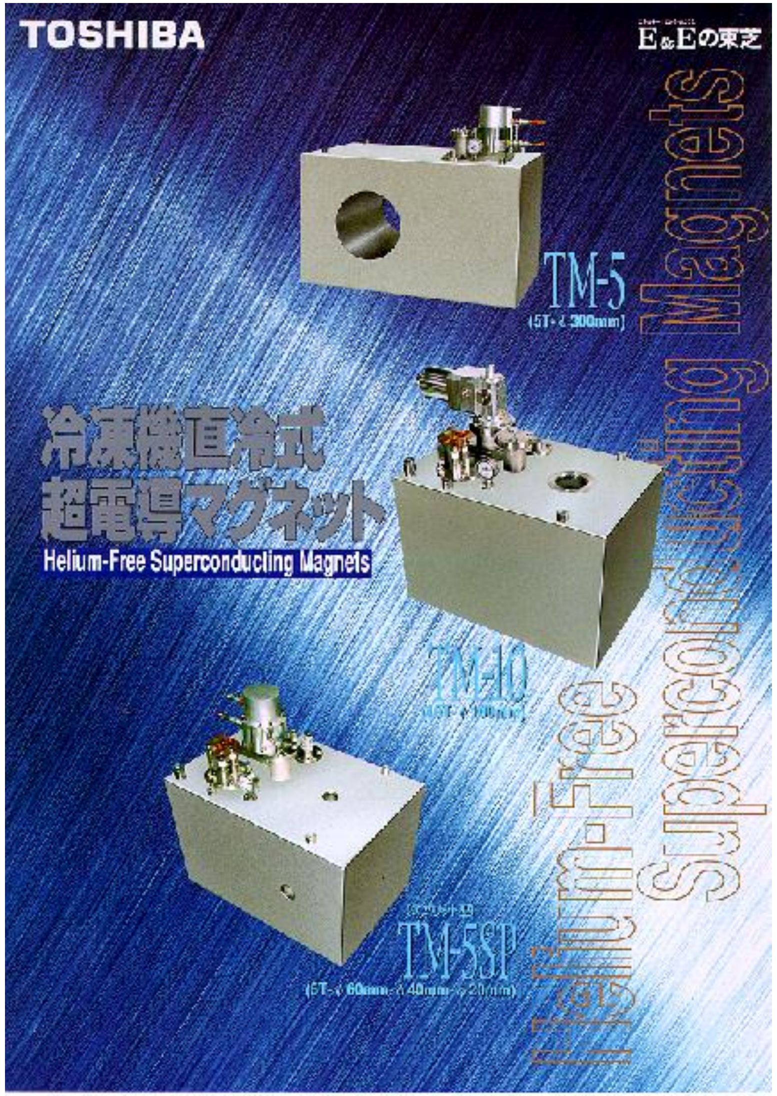
First Liquid Helium Free SCM cooled by 4K-GM Cryocooler



Presented at International Cryogenic Engineering Conference (ICEC15), June, 1994, Genova, Italy

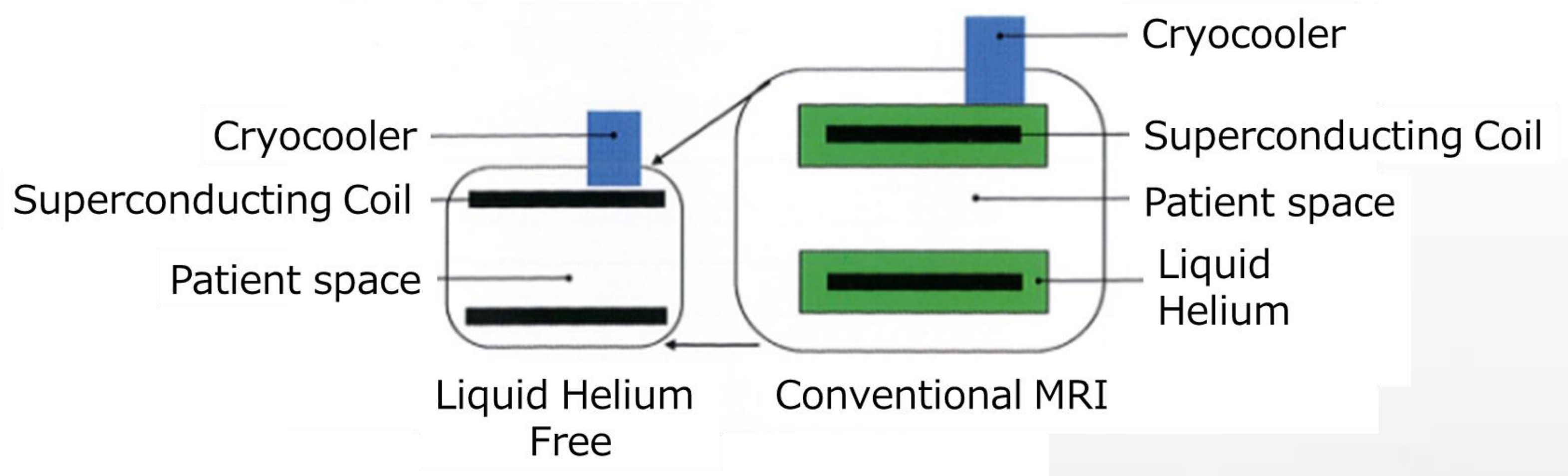
NbTi Coil was first cooled by 4K-GM Cryocooler (6T at φ180mm)
Nb_3Sn coil was added later(10T at φ100mm)

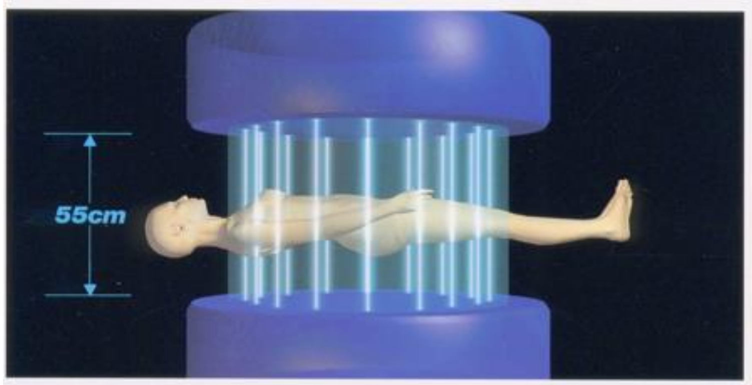
Commercialized Cryocooler-Cooled SCM for Research Use (1995)

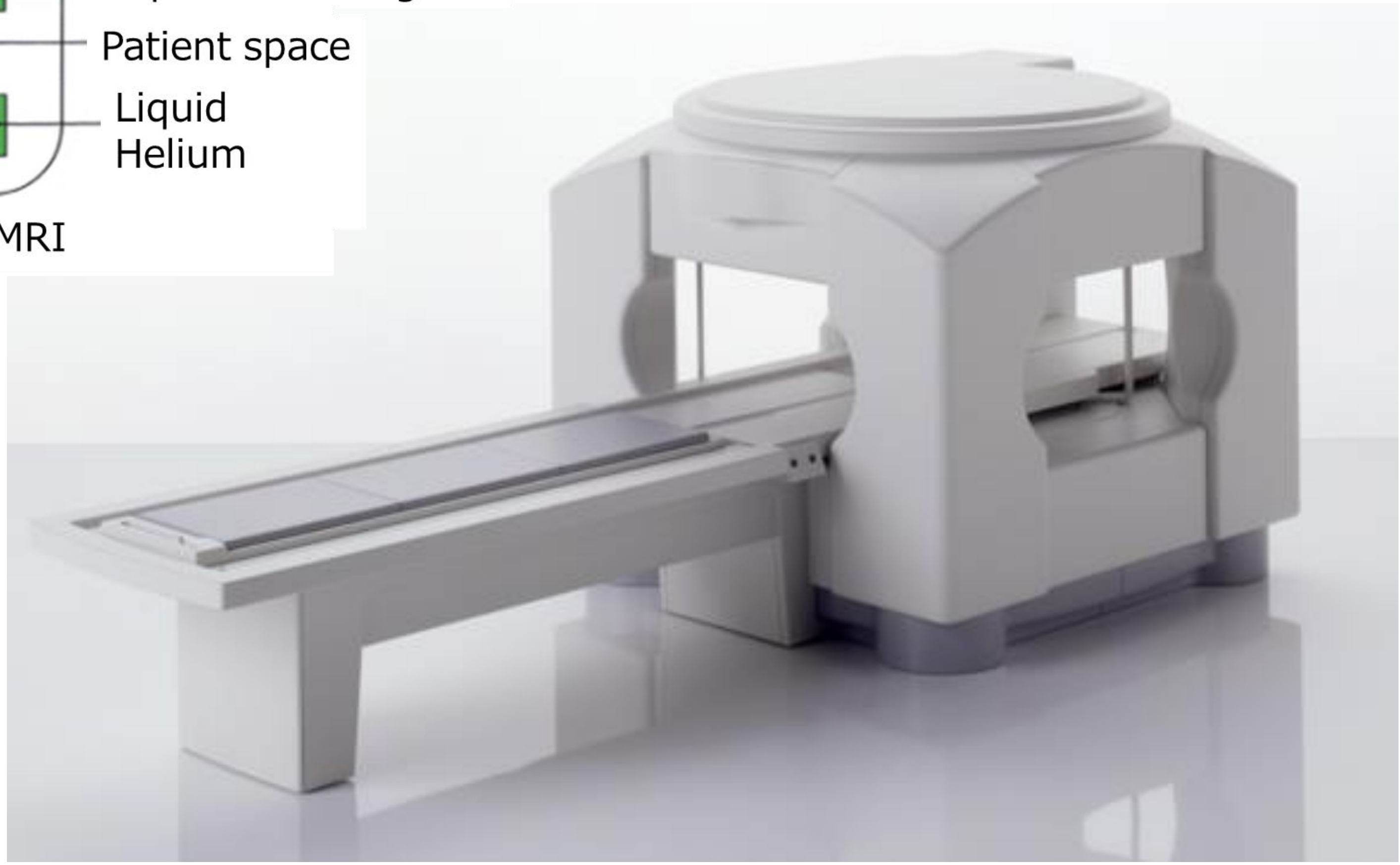


Liquid Helium Free, Easy Operation, Low Running Cost, Safety

Conductive cooled Superconducting Open MRI (1997)







Compact but Wide & Open, Liquid Helium Free

Courtesy of Canon Medical Systems Corporation

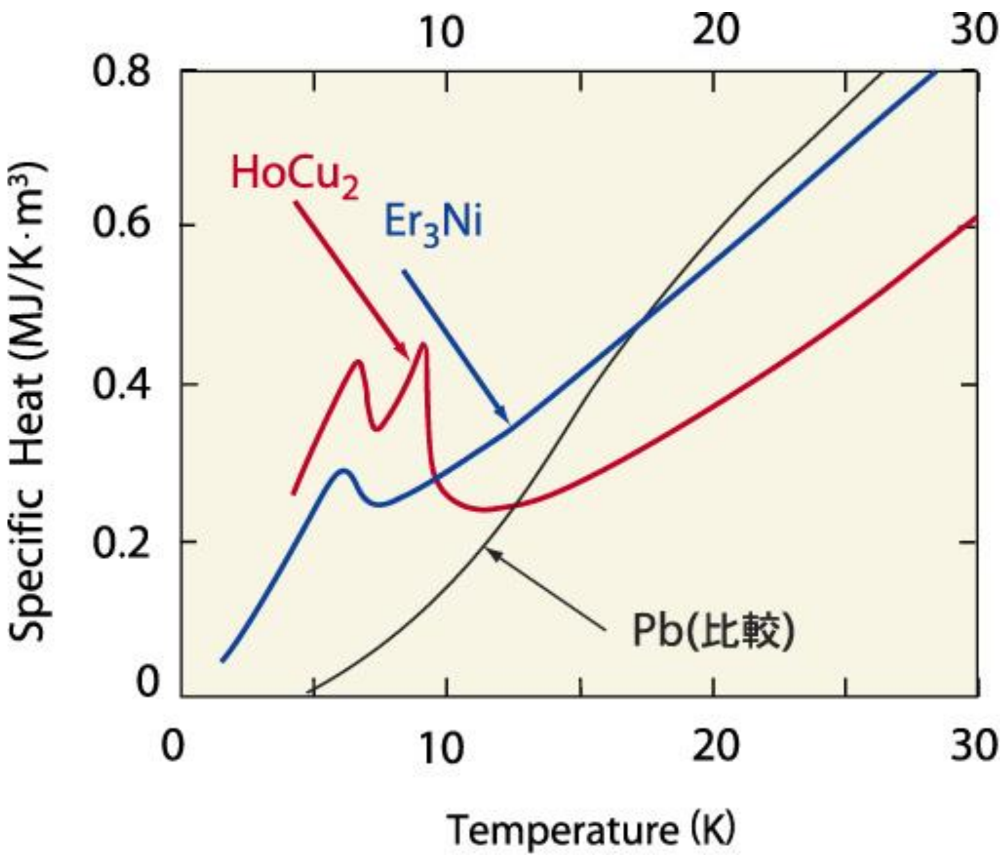
Conductive cooled Superconducting Open MRI

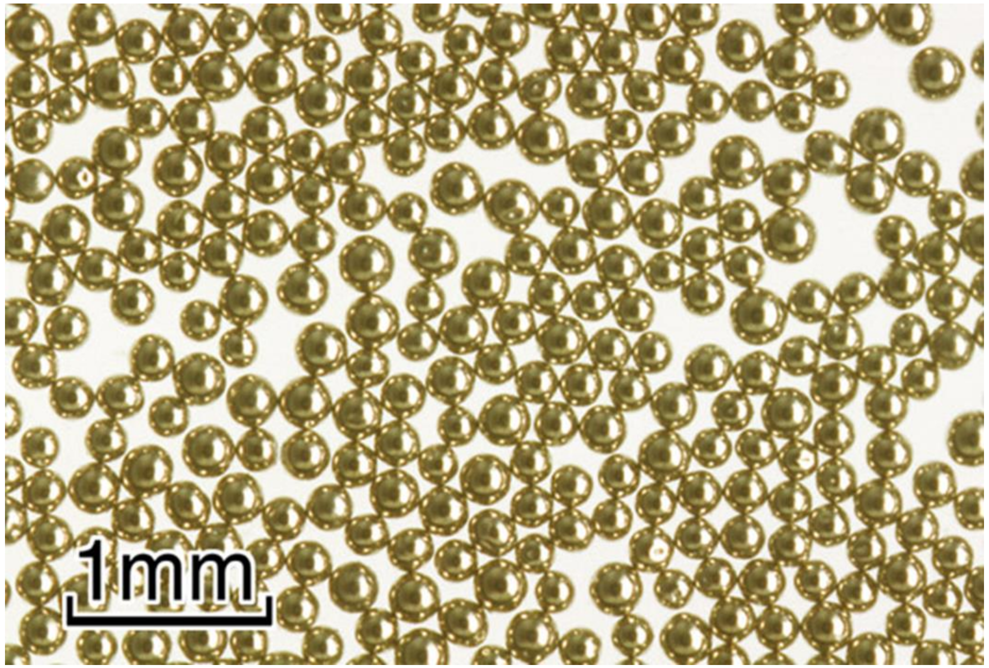
Courtesy of Canon Medical Systems Corporation

04

Recent Progress

Progress of Magnetic Regenerator Material (1)



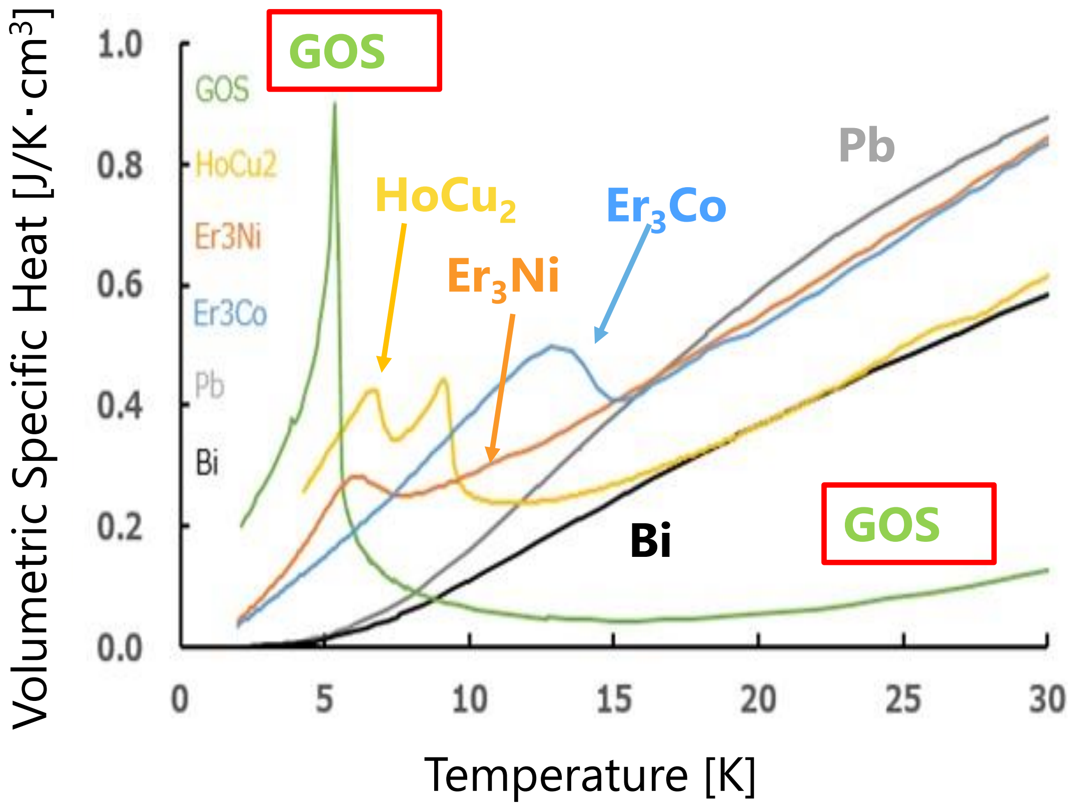


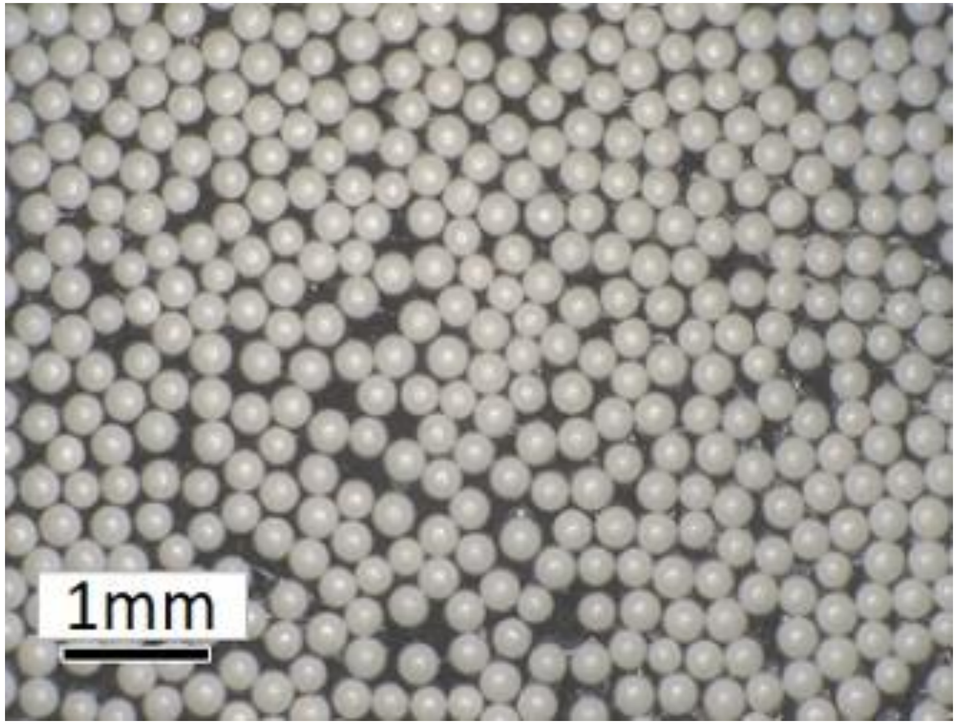
$HoCu_2$ Spheres

Courtesy of Toshiba Materials Co., Ltd

$HoCu_2$ replaced Er_3Ni

Progress of Magnetic Regenerator Material (2)



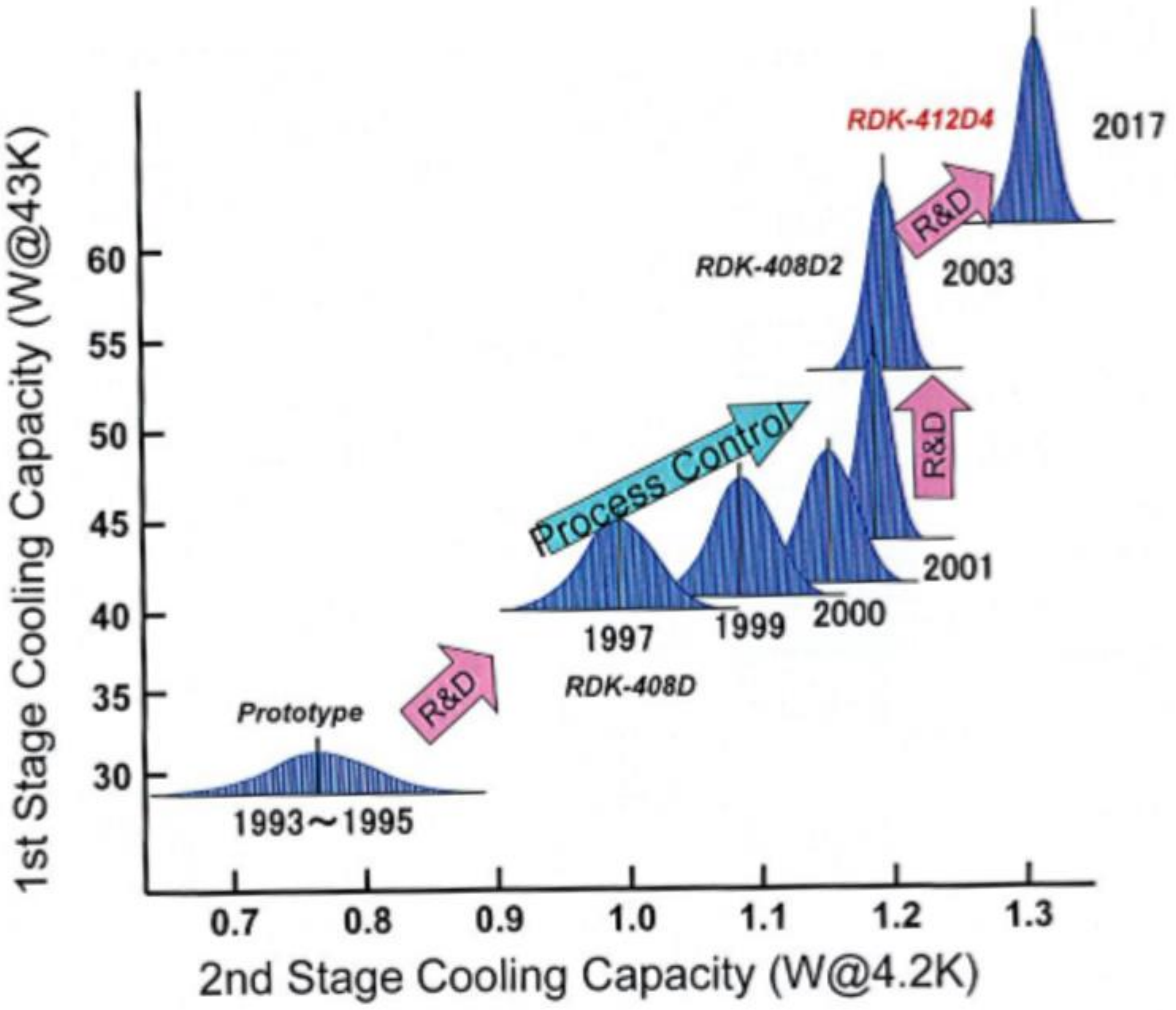


GOS(Gd_2O_2S) Spheres

Courtesy of Toshiba Materials Co., Ltd

GOS (Gd_2O_2S) is used at Bottom End of 2nd Regenerator

Progress of 4K-GM Cryocooler Performance by SHI



Courtesy of Sumitomo Heavy Industries, Ltd

Cooling Capacities Improved by R&D and Manufacturing Process Control

4K-GM Cryocooler by Sumitomo Heavy Industry

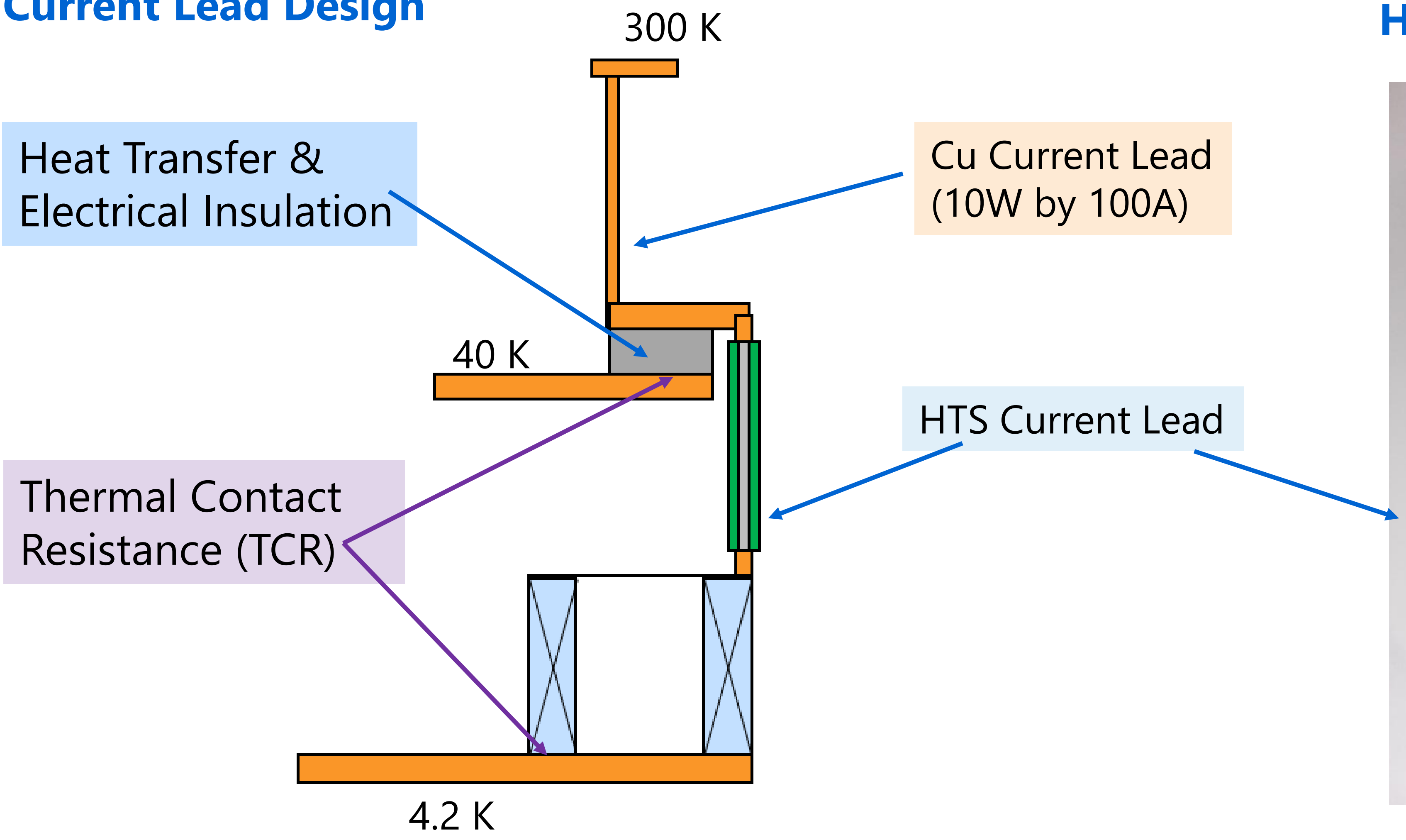
0.2W, 0.4W, 0.5W,
1.0W, 1.25, 2.0W @4.2K

30Hz – 60Hz (Compressor)
40Hz – 70Hz (Coldhead)

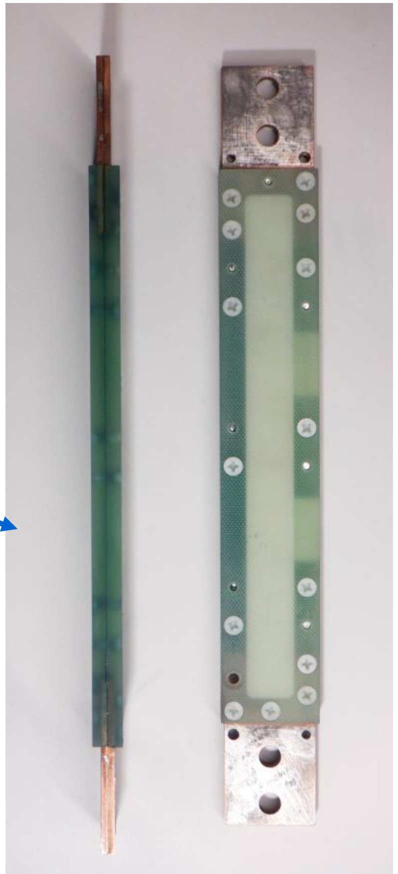
Courtesy of Sumitomo Heavy Industries, Ltd

Progress of Thermal Design for Conductive-cooled SCM

Current Lead Design



HTS Current Lead



Progress of Thermal Design for Conductive-cooled SCM

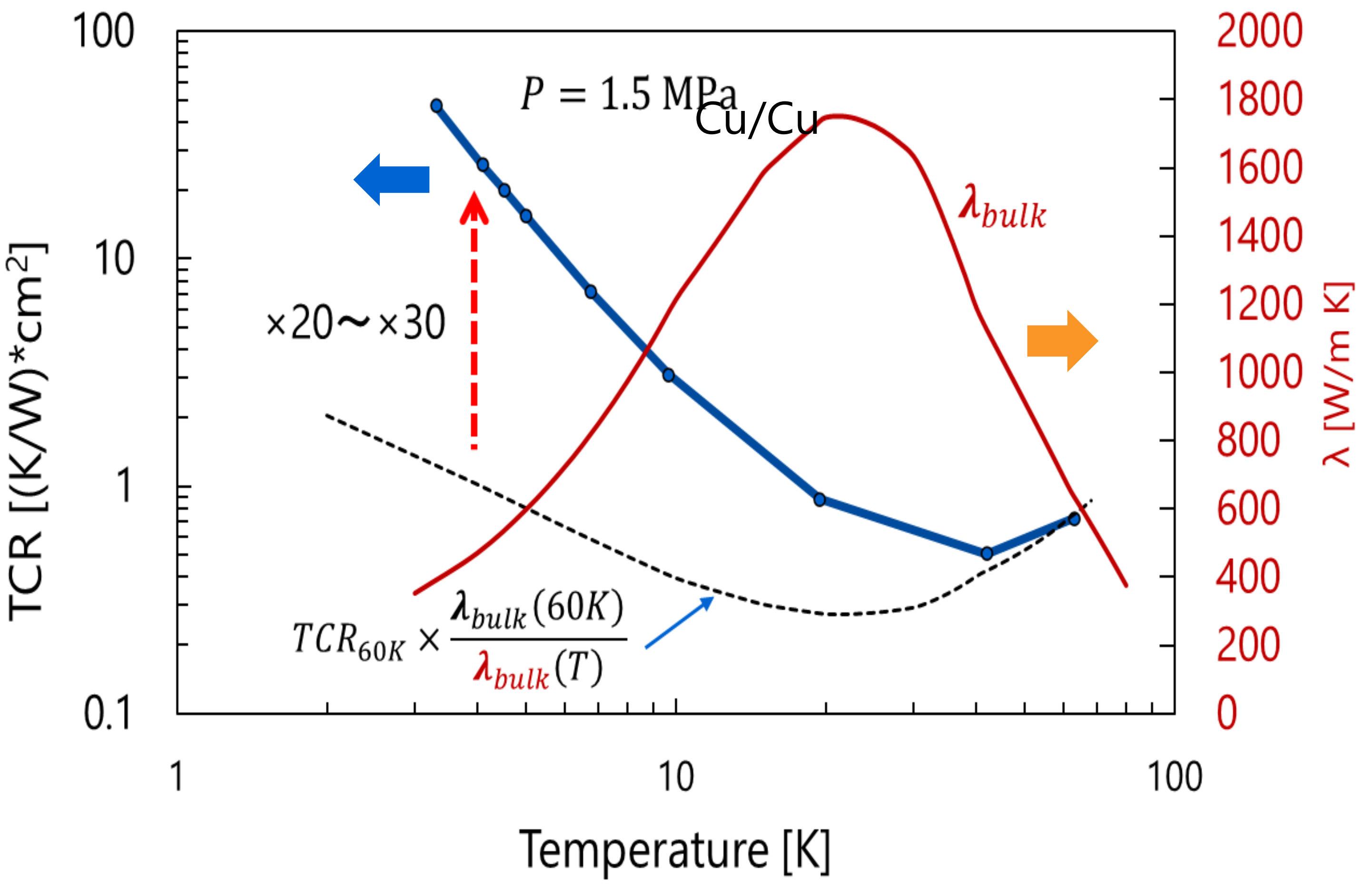
Thermal Contact Resistance (TCR)

$$TCR \propto \delta^a \times P^b \times \frac{1}{\lambda}$$

δ: Surface Roughness

P: Surface Pressure

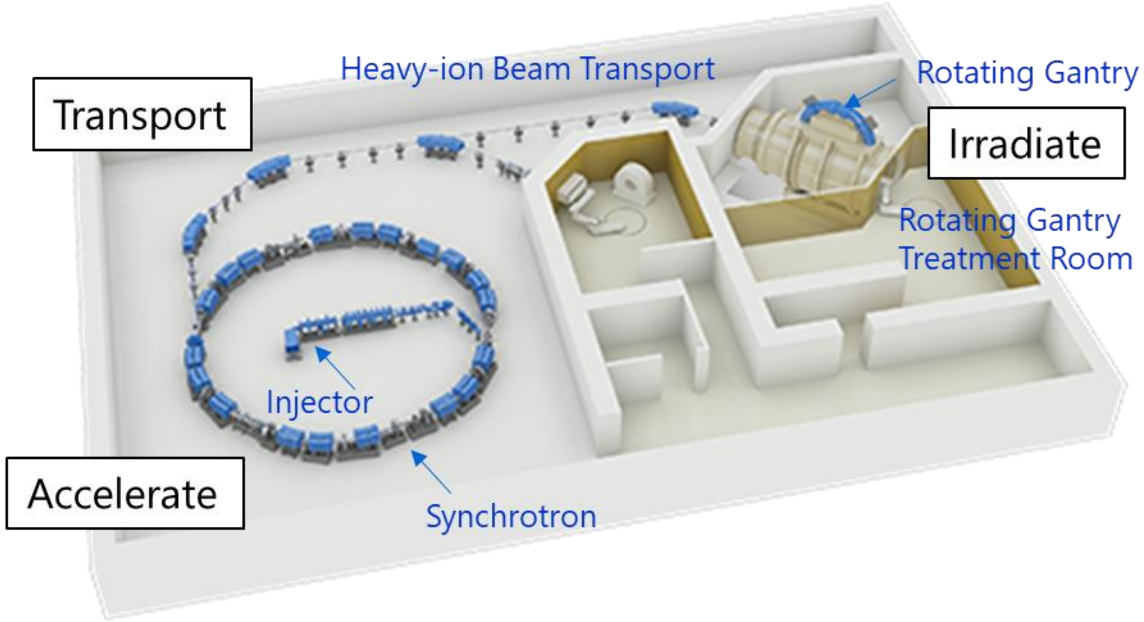
λ: Thermal Conductivity



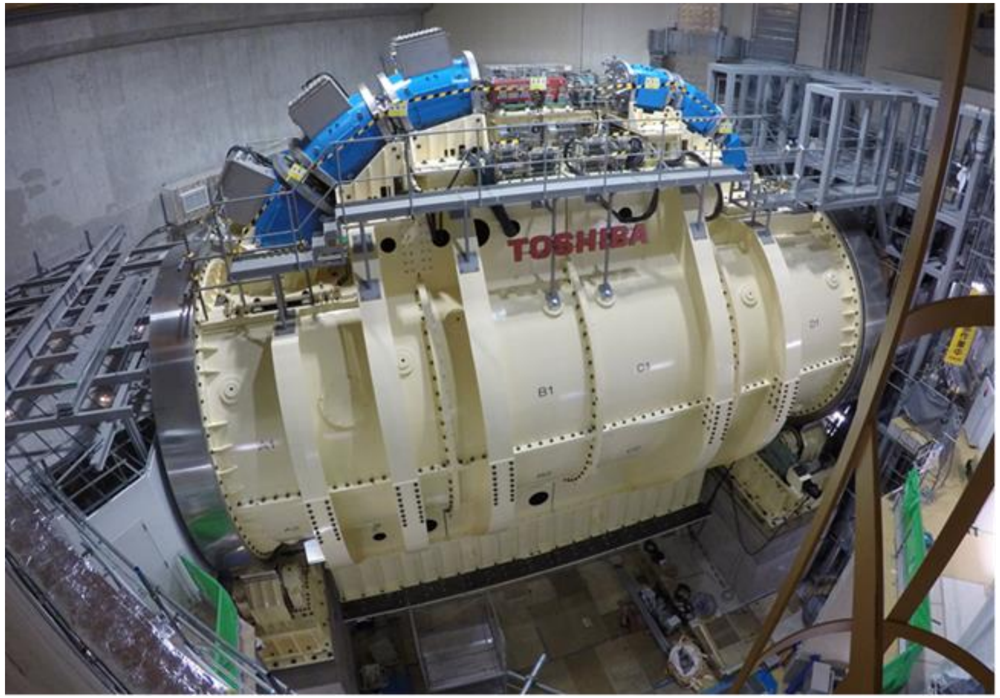
Temperature Dependence of Thermal Contact Resistance (TCR)

Superconducting Rotating Gantry for Heavy-Ion Radiotherapy System

Heavy-ion Radiotherapy System



Superconducting Rotating Gantry



-Length: 14m

-Radius: 3.5m

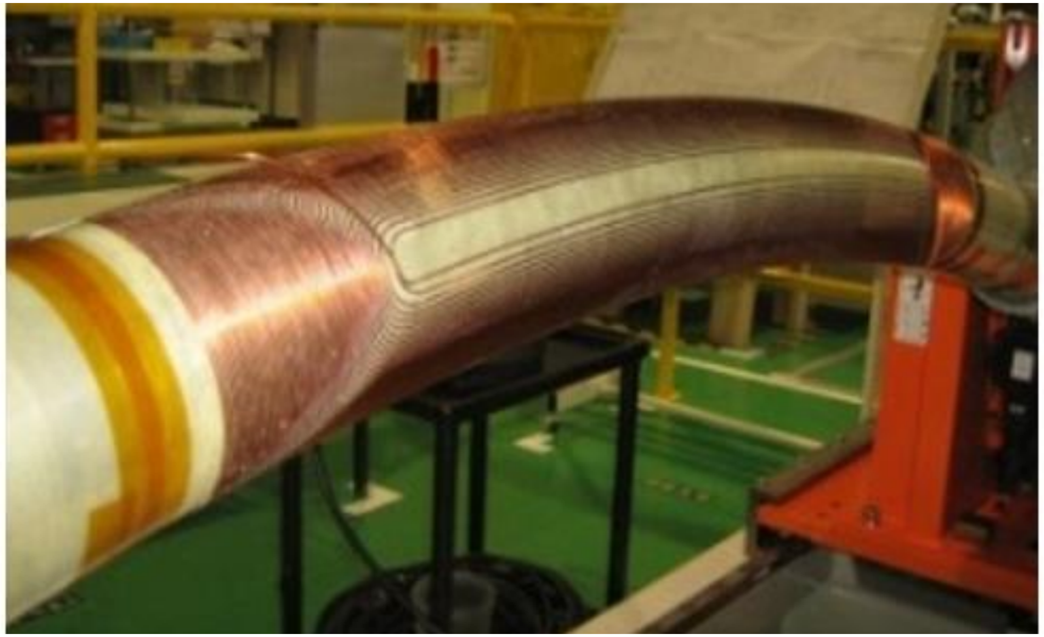
-Weight: 300ton Approx.

Courtesy of National Institutes
for Quantum Science and Technology

Superconducting Rotating Gantry for Heavy-Ion Radiotherapy System

Compact Superconducting Magnet

Surface Winding Method
Automatic and Precise Winding



Courtesy of National Institutes
for Quantum Science and Technology

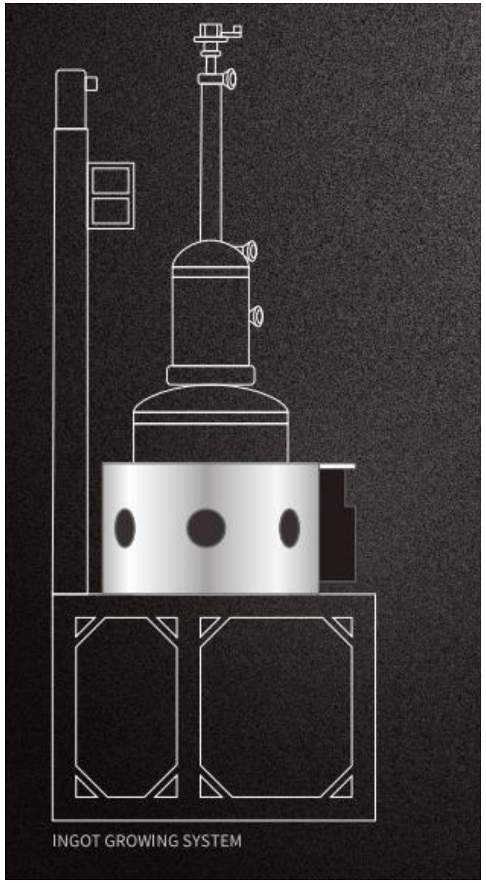
Superconducting Rotating Gantry for Heavy-Ion Radiotherapy System

Movie

Courtesy of National Institutes
for Quantum Science and Technology

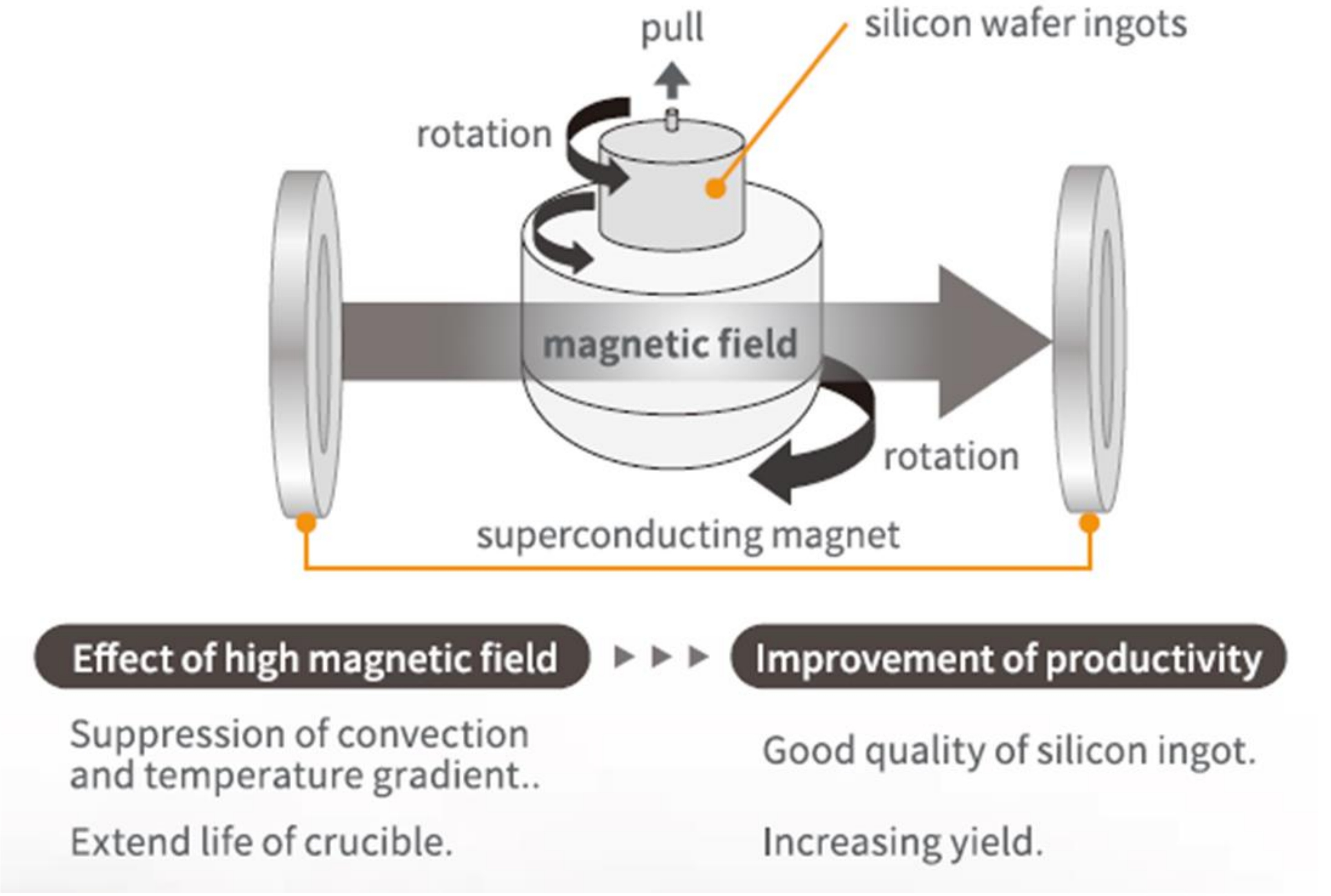
Superconducting Magnet for Silicon Single Crystal Puller

Toshiba has manufactured superconducting magnets for Silicon Single-Crystal Pullers since 1988. Recently, liquid Helium free magnets are dominant.



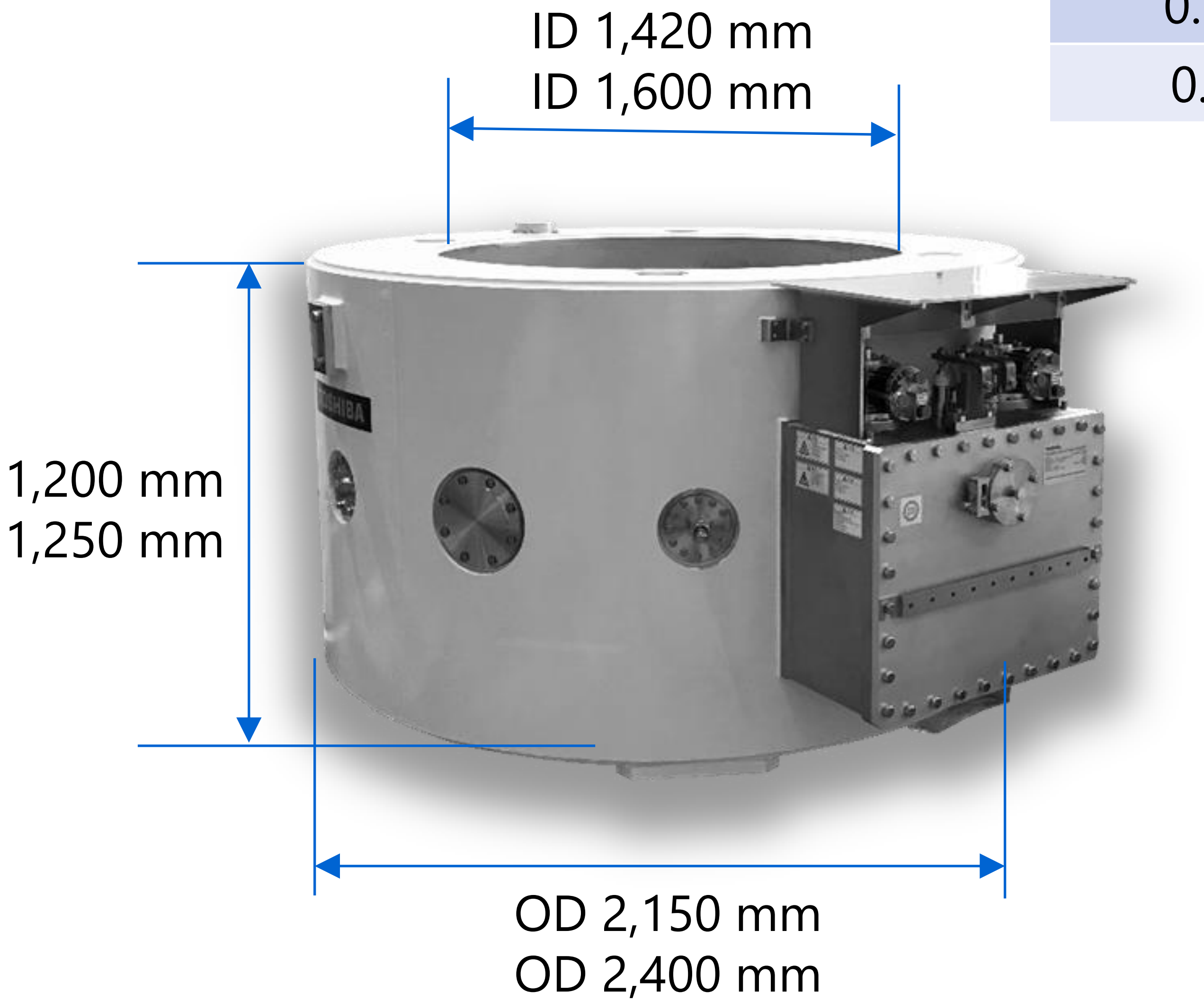
Overview of Silicon Single Crystal Puller

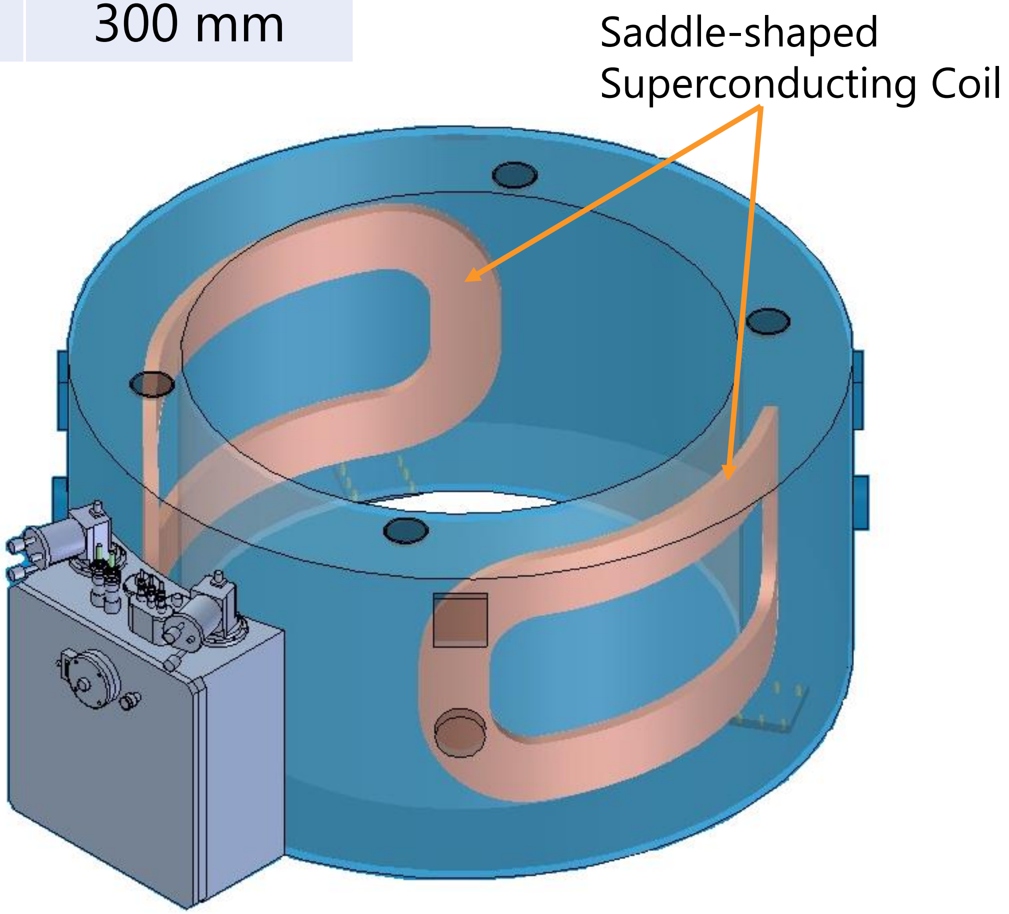
Effect of Magnetic Field



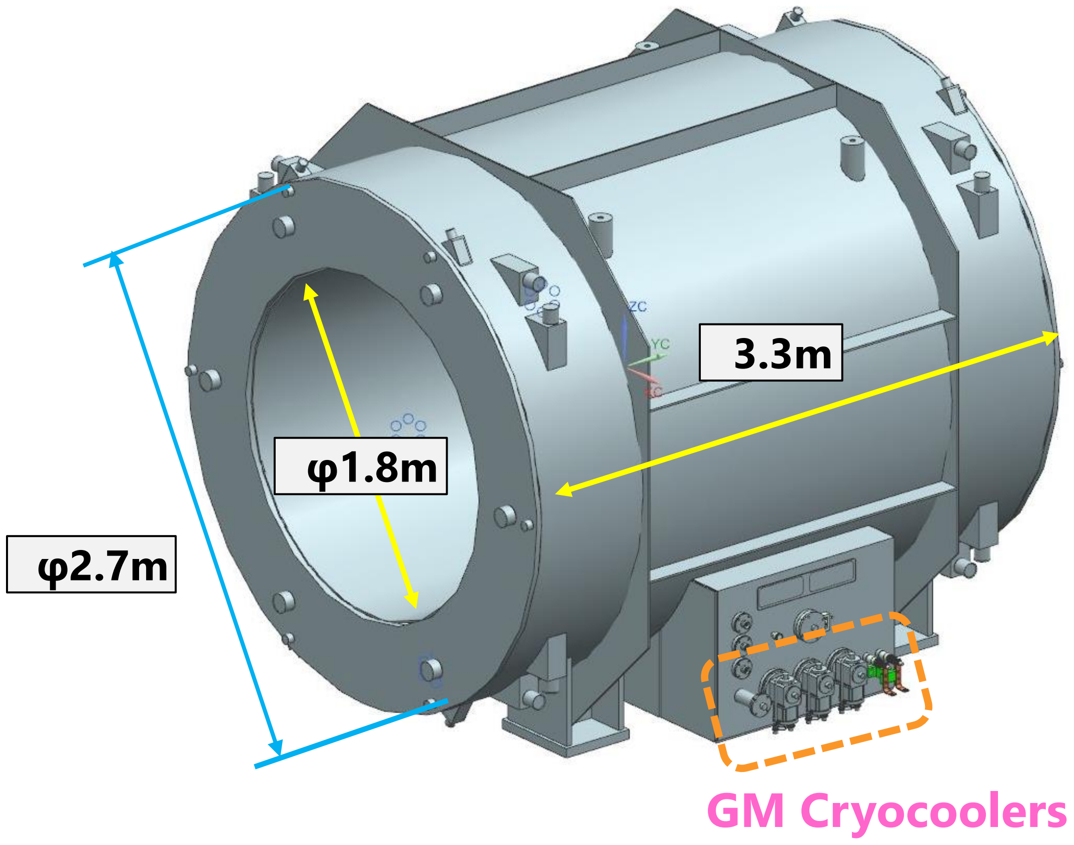
Superconducting Magnet for Single Crystal Puller

Center Field	Wafer Size
0.3 T	200 mm
0.4 T	300 mm





Large Detector Magnet for Osaka University



Central Filed	T	1.0
Stored E	MJ	4.2
Coil ID	m	2.1
Coil Length	m	2.9
Current	A	189
Coil No	P	14
Conductor	mm	Φ1.2/NbTi-Cu
Cryocooler	W	1.5W @4.2K ×3 35W @50K ×3

Courtesy of Osaka University

Large Detector Magnet for Osaka University

Courtesy of Osaka University

25 T Cryogen Free SCM for Tohoku University

NbTi/Nb3Sn Coils 4.2K
GM/JT Cryocooler

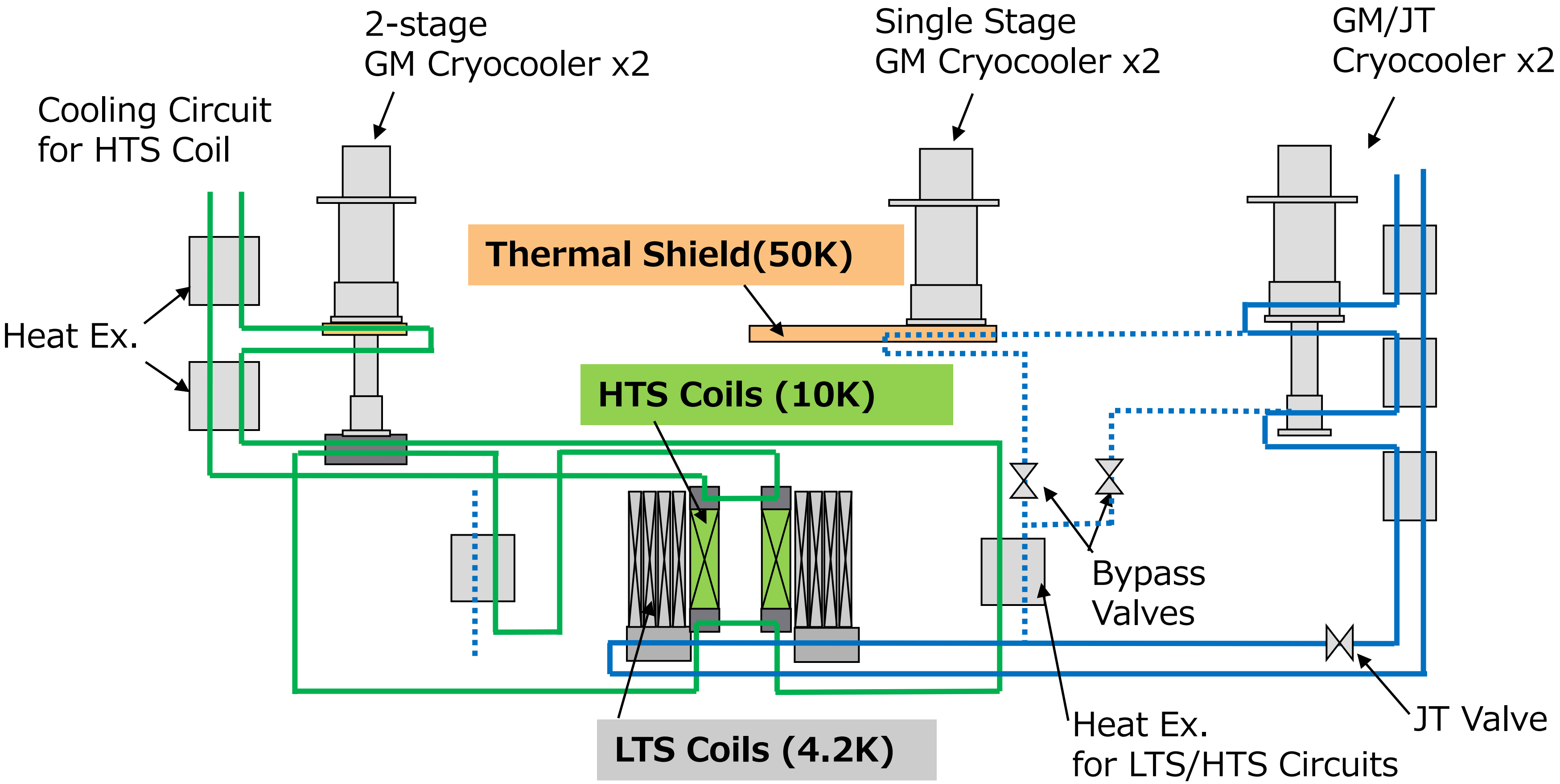
HTS Coils 10K
Two Stage GM Cryocooler

Thermal Shield 50K
Single Stage GM Cryocooler

Courtesy of Tohoku University

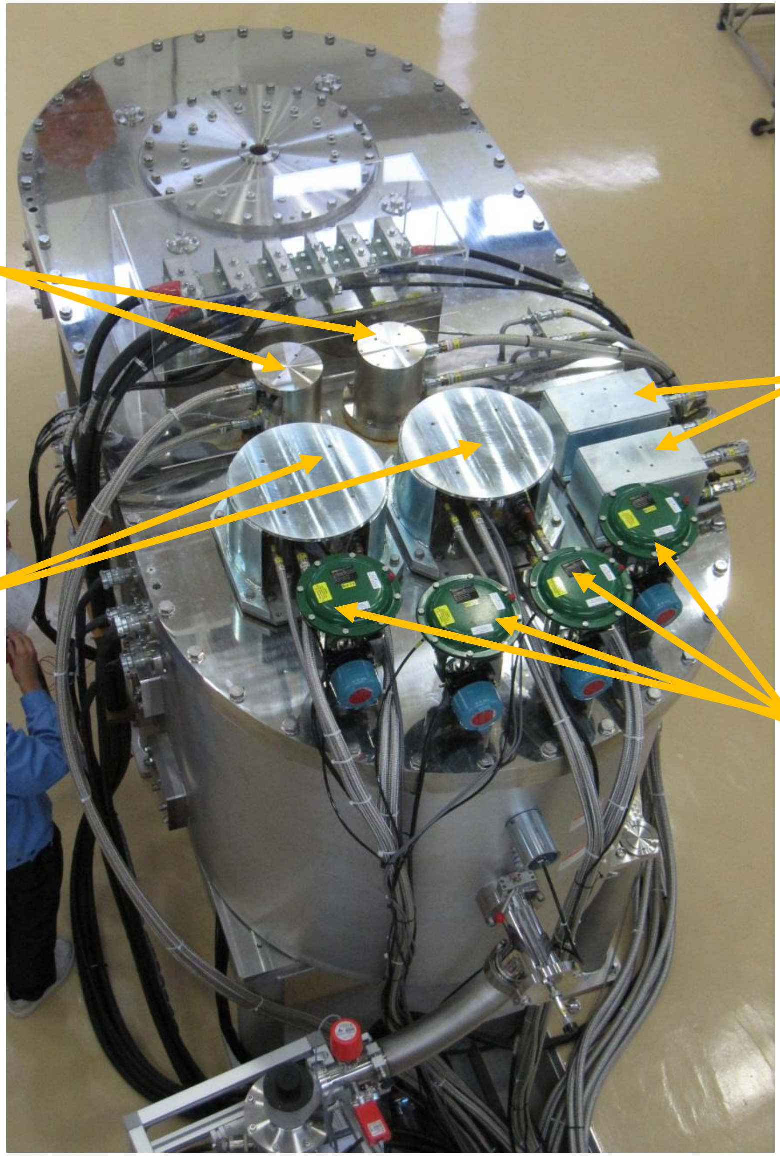
25 T Cryogen Free SCM for Tohoku University

Helium Gas Circulation and Conductive Cooling



Courtesy of Tohoku University

25 T Cryogen Free SCM for Tohoku University



Single Stage
GM Cryocoolers
for Thermal Shield

2-stage
GM Cryocoolers
for HTS Coil

GM/JT
Cryocoolers
for LTS Coil

Bypass Valves
for Initial Cooling

Courtesy of Tohoku University

05

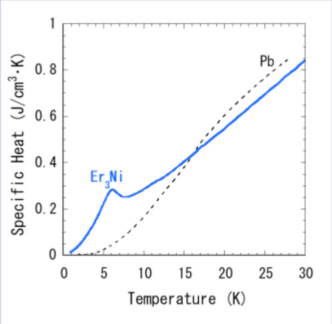
Summary

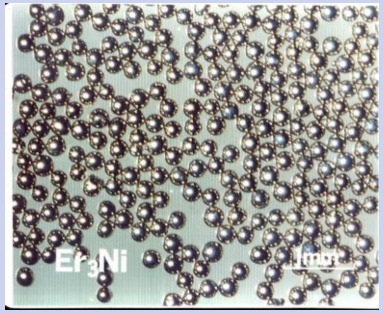
Summary

The Breakthrough technologies created cryocooler-cooled superconducting magnets

Magnetic Regenerator Materials	4K-GM Cryocooler	Cryocooler-Cooled SCM

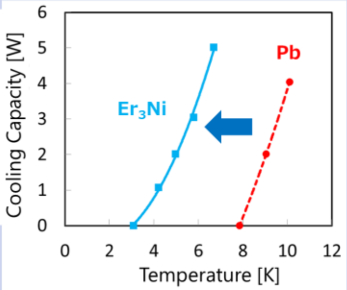
Magnetic Regenerator Materials



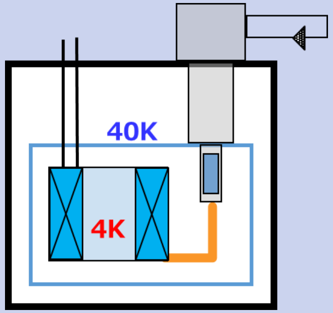


Courtesy of Toshiba Materials Co., Ltd

4K-GM Cryocooler

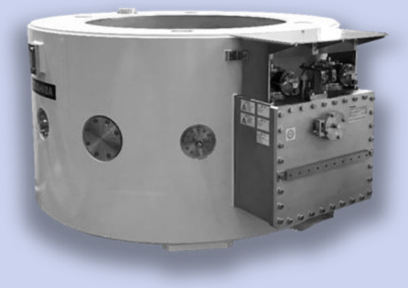


Cryocooler-Cooled SCM



Contribute to the Protection of Helium Resources and the Development of Industry and Academia

Industry



Silicon Single Crystal Puller

Medical

Superconducting Rotating Gantry
Courtesy of National Institutes for Quantum Science and Technology

Academia/Basic Science

Large Detector Magnet
Courtesy of Osaka Univ.

High Magnetic Field Magnet
Courtesy of Tohoku Univ.

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