IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation NM-4 given at CCA 2021, October 11 – 15, 2021, Virtual.

CCA 2021

A collaborative research to develop a 6 T 230 mm room-temperature bore high temperature superconductor MRI magnet

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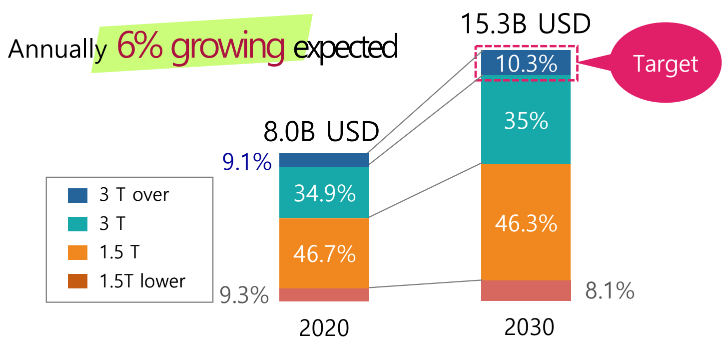
CONTENTS

1. Background(1)- Why we need higher magnetic field MRI

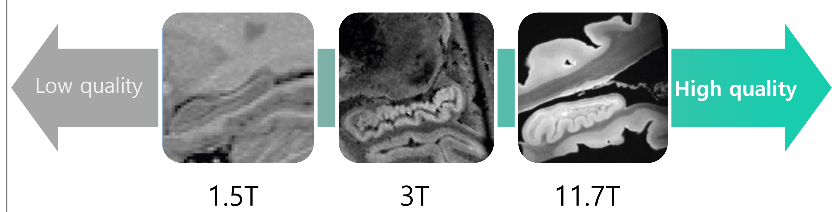
MRI market forecast



MRI market forecast , Future Market Insights, 'MRI Systems Market, Global Industry Analysis

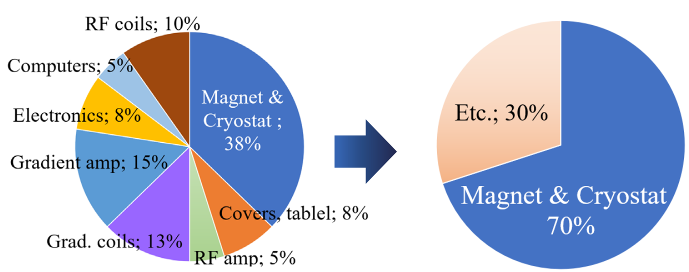
Demand of high resolution MRI

Higher magnetic field magnet provides higher resolution image



Magnet cost

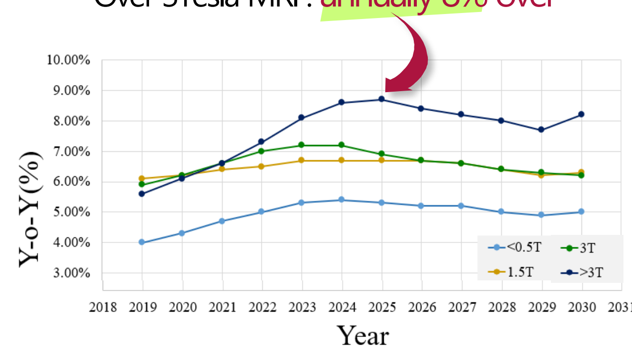
Medium field 1.5 T class : 38%
Ultra high field 7 T over : 70%



Middle field class MRI

High field class MRI

High market growing



MRI market growing (magnetic field)

Ref. Future Market Insights, 'MRI Systems Market, Global Industry Analysis

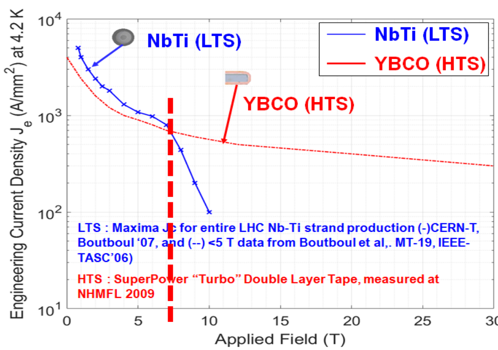
1. Background(2)- Limitation of LTS magnet

Low temperature superconducting materials limitation

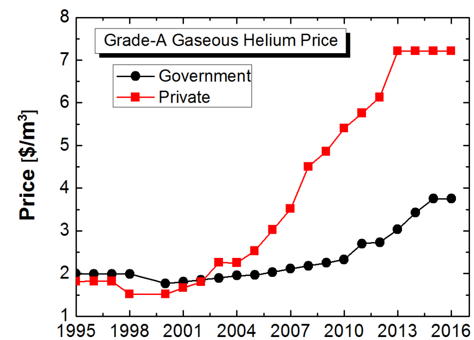
→ Performance degradation under high field applications
→ Low maximum magnetic field
→ HTS materials : better performance at high field

Liquid helium

Helium shortage, cost
→ Expensive operating and maintenance cost



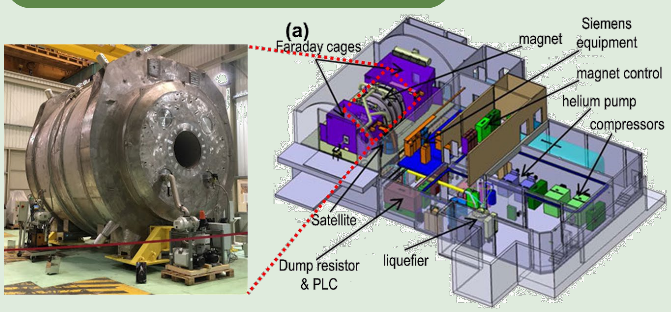
Field properties of LTS & HTS



Increasing liquid helium cost

[1]REF: U. S. Geological Survey (USGS) Website, Helium Statics and Information, 2017.

11.7 T MRI with LTS magnet

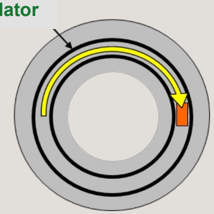
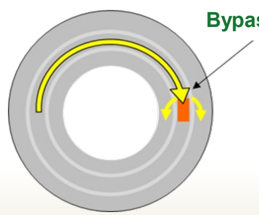


- CEA (Europe)
- Size: 4m x 4m
- Weight : 130 ton
- Superfluid helium 1.8K cooling
- Huge space, building requires

LTS ultra high field MRI
→ Limitation of acceptance to clinical use

1. Background(3)– No insulation HTS magnet

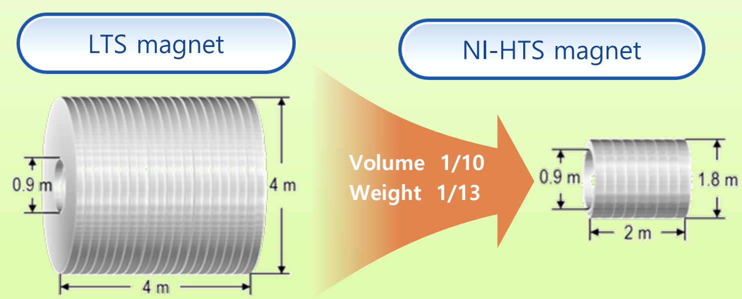
Remove insulation layer: No-insulation magnet technology

Conventional HTS magnet	No-insulation magnet
Quench → losing superconductivity	
	
→ Slow quench propagation → Damaging HTS tape	→ Current bypass → Protecting HTS tape
No detecting method	**Automatically protecting (self protection)**
Low stability	**High stability**
Bottleneck of HTS application	**Unique idea for High field application**

Design comparison

Example : 11.7T MRI magnet
LTS vs. NI-HTS

Design parameter	LTS magnet	NI- HTS magnet
Center field	11.7 T	
Bore size	0.9 m	0.9 m
Outer D	4.0 m	1.8 m
Length	4.0 m	2.0 m
Weight	130 ton	10 ton
Stored E	340 MJ	100 MJ
Operating Temp.	1.8 K	4.2 K



High stability, Ultra high field magnet

2. Project Target

Period	Sep 2020 ~ Dec 2023 (40 months)
Budget	$3.5M (Funded by Korea government)
Collaborators	SuperGenics Co., Ltd. Seoul National University(SNU), Korea Electrotechnology Research Institute(KERI) Kunsan National Univ., ChangWon National Univ., Korea University.

Project Target

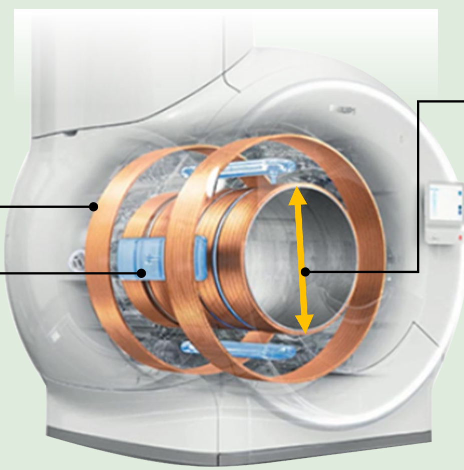
Center field : > 6T | Bore : >200mm (RT) | Helium free

HTS magnet

- Central magnetic field > 6T
- Stable superconducting magnet
- Wire supplier : SuNam
- Quench protection

Conduction cooling

- Operating temperature :20K
- Temperature gradient < 5K

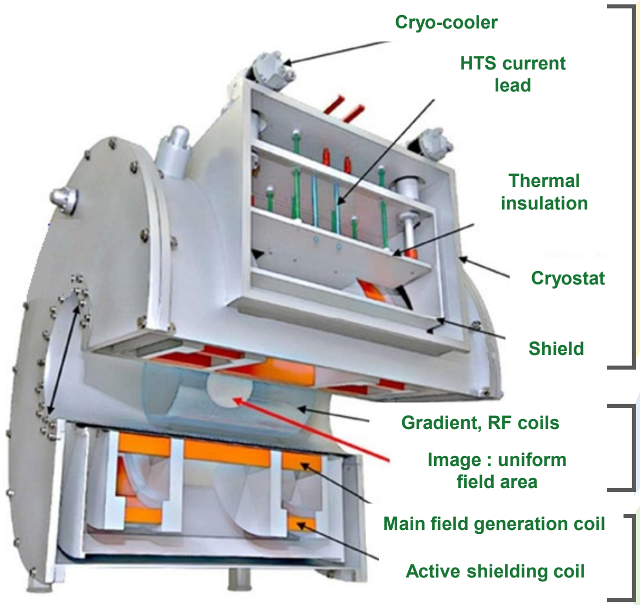


Magnetic field performance

- RT bore >200mm
- Field uniformity : <10 ppm
- Passive shimming
- Distortion by eddy current<10%
- Field drift : <1ppm/hr
- High performance Gradient coil
- Screen current minimize operation

Ref : Google Image 'Phillips Helium free MRI system'

3. Research contents– break through technologies



Existing
Small coil conduction cooling
Cryostat manufacturing
HTS current lead
3-axis gradient coil design
Shim coil design/test
RF coil manufacturing
NMR Ferro shimming
High quality magnetic field design
Multi-physics analysis for Electromagnetic&thermal
Quench analysis Magnet protection system
HTS magnet winding technic
Reducing screening current of small scale HTS magnet
Small magnet operation technic
Short time operation test

Upgrade technic through this project
Large magnet conduction cooling
Minimize temperature gradient
Active shielding gradient coil
Gradient coil water cooling
Induced/screen current reducing
RT shim coil design & operation
Ferro shimming technic for high field magnet
High quality, high magnetic field design for HTS MRI
Electromagnetic, thermal and structure stability under high field
Quench protection system design for high field MRI
Developing precise winding technic for HTS tape
Reducing screening current of large scale HTS magnet
Developing operation protocols for commercial MRI system
Test standard for HTS MRI magnet
Long-time operation reliability

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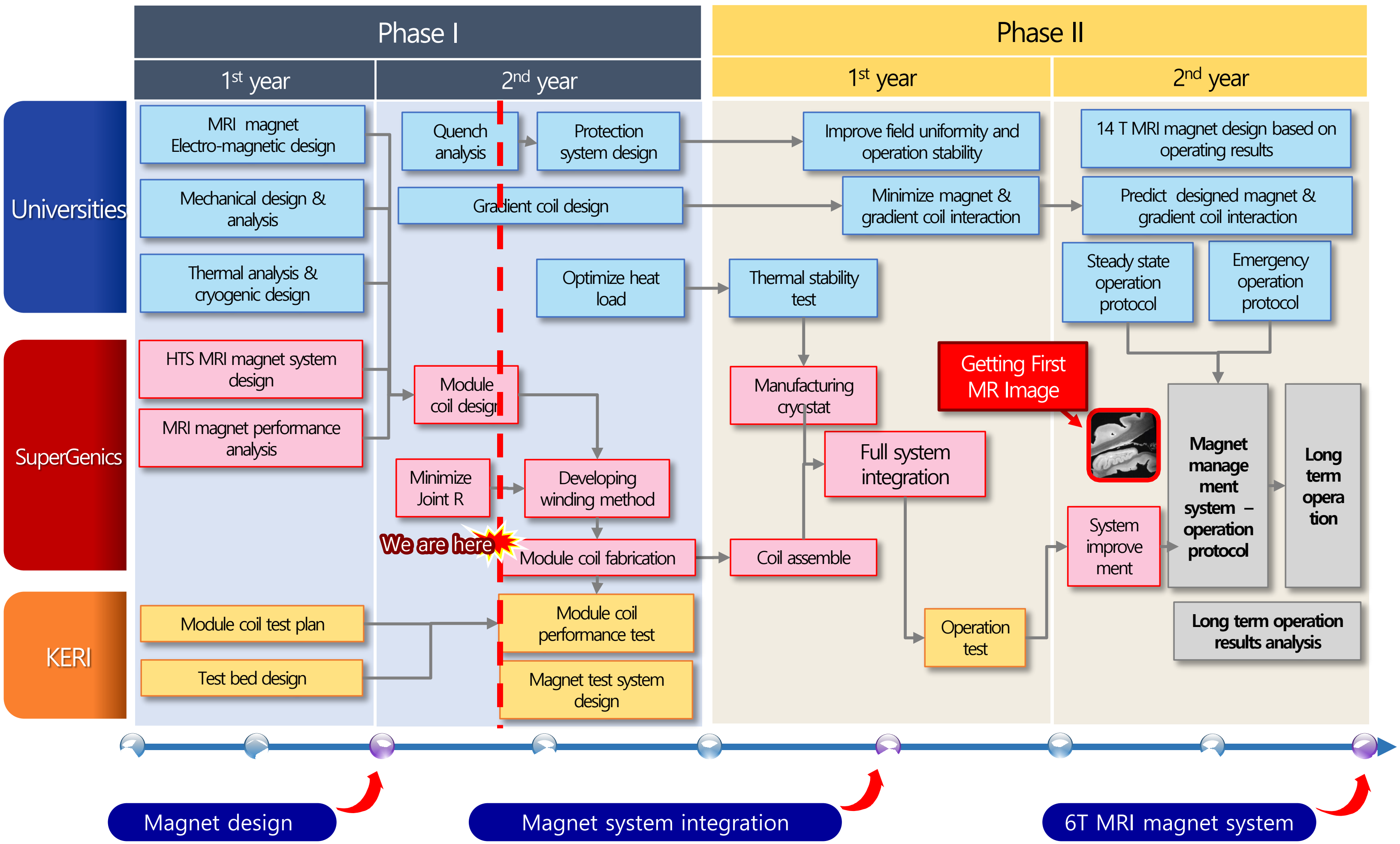
3. Research contents – Road map



4. R&D Team

Seoul National University

Prof. Seungyoung Hahn

- ✓High field HTS magnet expert
- ✓Published Nature magazine (NI-HTS magnet)

Sungkyunkwan University

- ✓Gradient coil expert
- ✓MRI conduction cooling developing experiences at GE
- ✓Commercialize experiences

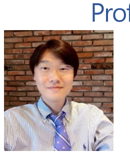
Changwon National University

Prof. Seockho Kim

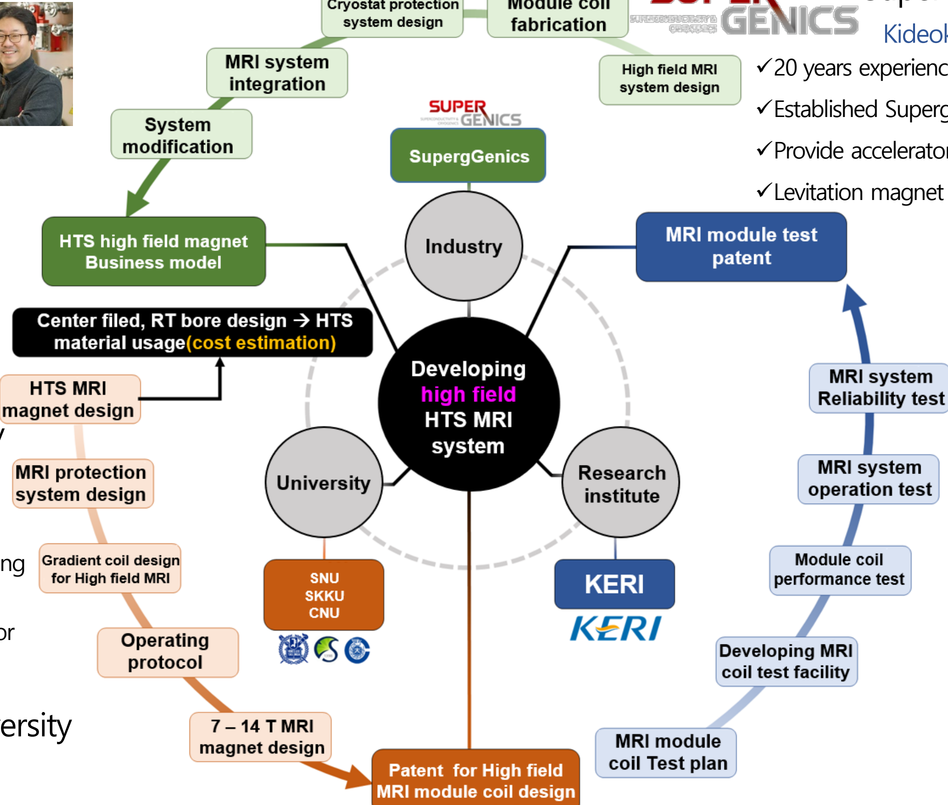
- ✓Cryogenic system expert
- ✓Conduction cooling system developing experiences
- ✓Conduction cooling SMES, accelerator magnet

Kunsan National University

Prof. Min chul Ahn



- ✓Ferro shimming expert
- ✓Shimming technic for HTS NMR



SuperGenics

Kideok Sim, CEO

- ✓20 years experiences of HTS cable at KERI
- ✓Established Supergenics (2017)
- ✓Provide accelerator HTS magnet (IBS)
- ✓Levitation magnet for train (KRRI)

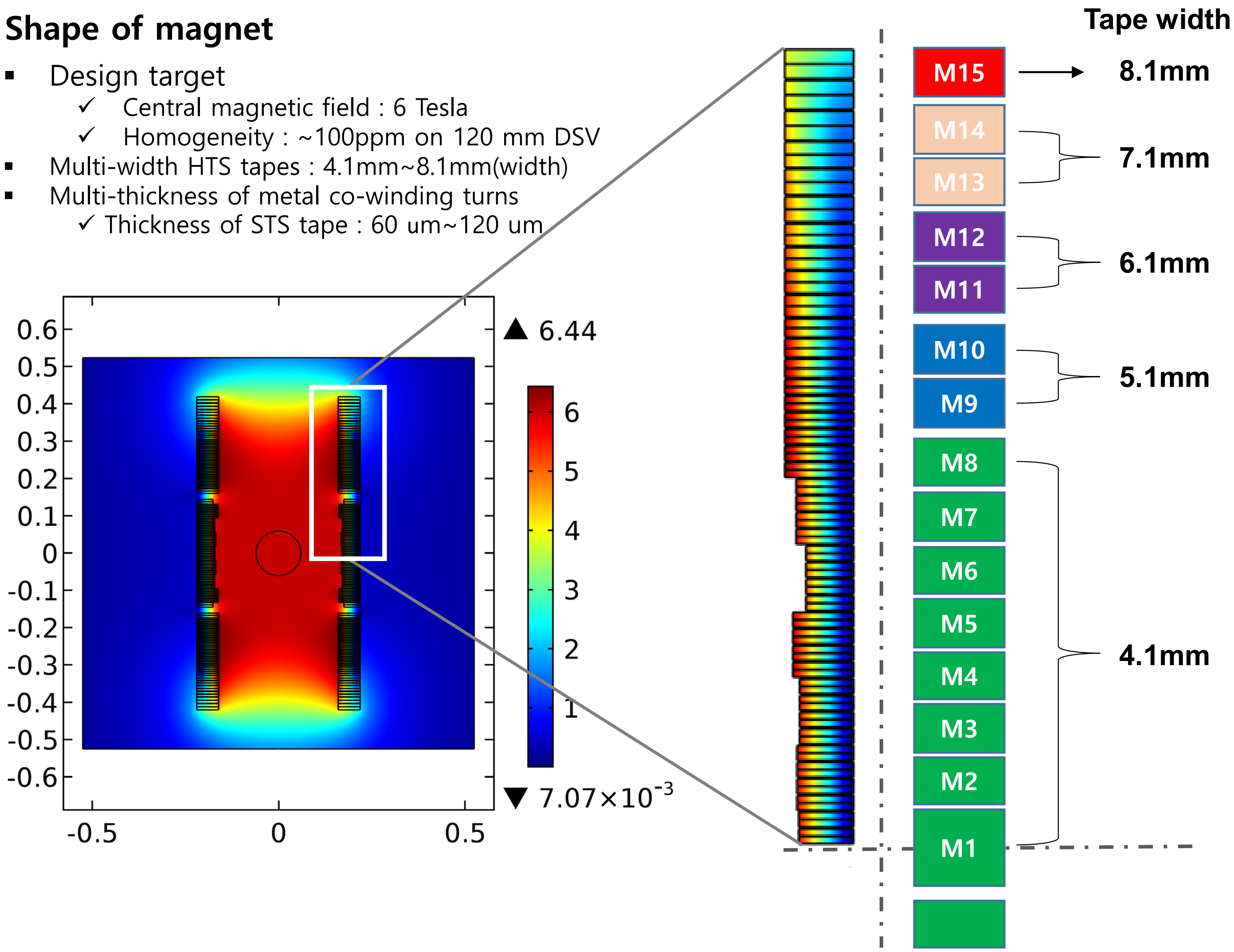
KERI

- ✓40 years superconducting devices R&D
- ✓Superconducting motors, SMES, superconducting cable development
- ✓Superconducting devices test facility

5. Research results - Magnet design

◆ Shape of magnet

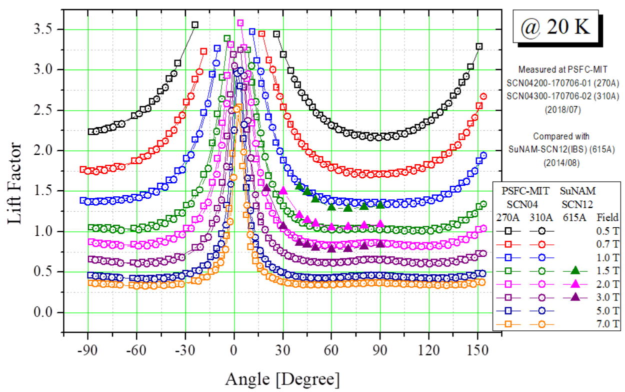
- Design target
  - ✓ Central magnetic field : 6 Tesla
  - ✓ Homogeneity : ~100ppm on 120 mm DSV
- Multi-width HTS tapes : 4.1mm~8.1mm(width)
- Multi-thickness of metal co-winding turns
  - ✓ Thickness of STS tape : 60 um~120 um

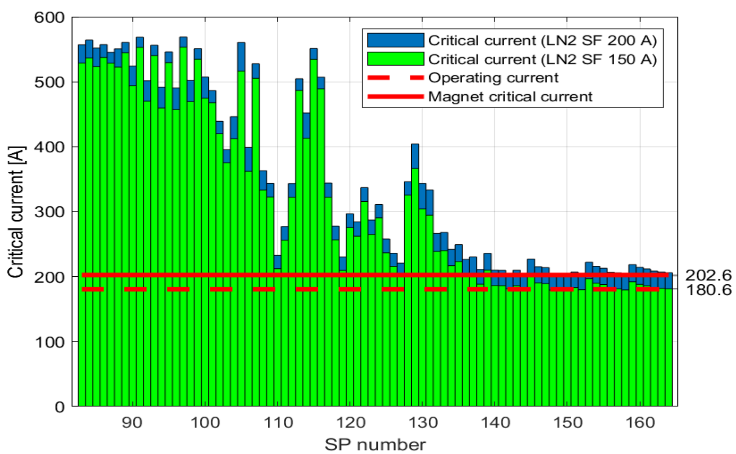


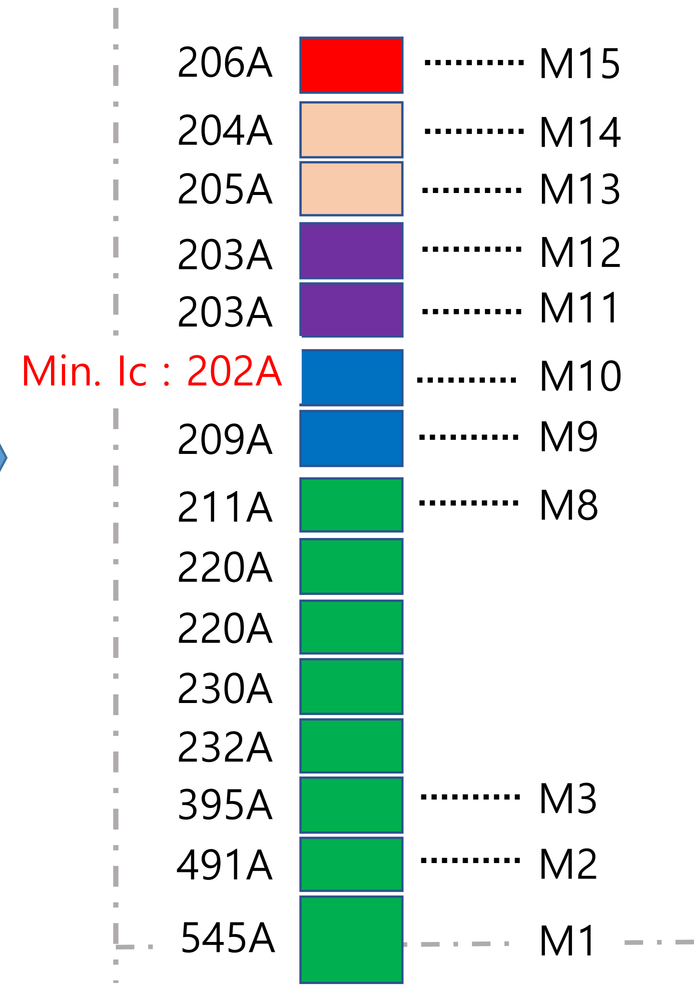
5. Research results - Magnet design

◆ Critical current of magnet

- SuNAM HTS tape
- Ic of HTS tape : 200A @77K SF (4mmW)
- Coil temperature : 20K







5. Research results - Magnet design

◆ Homogeneity of magnetic field

- **Ideal design**

↳ ▪ **Statistically approach**

✓ std error : arise from manufacturing imperfections
✓ Simulated using Monte-Carlo method, assuming standard deviation of tape thicknesses and coil heights are 3 um and 0.2 mm respectively

↳ ▪ **Considering SCIF (Screen Current Induced Field) error**

✓ Arise from non-linear properties of superconducting resistivity
✓ Simulated using FEM (H-formulation with domain homogenization method)

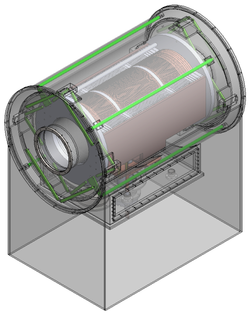
↳ ▪ **Check the change of homogeneity by the thermal contraction after coolong**

Harmonics Error of Magnetic Field (120mm DSV) [ppm]			
Order	Ideal design	std error	SCIF error
1	-	±84.4	-
2	-25.6	±42.5	-70.5
3	-	±19.4	-
4	2.9	±8.2	-0.4
5	-	±3.3	-
6	-0.2	±1.3	0
7	-	±0.5	-

5. Research results - Magnet design

<table>
<tr><th colspan="3">Parameters</th><th>Design Values</th></tr>
<tr><td rowspan="4">Shape of magnet</td><td colspan="2">Inner radius (without bobbin) [mm]</td><td>160~173.2 mm</td></tr>
<tr><td colspan="2">Outer radius [mm]</td><td>202.72 mm</td></tr>
<tr><td colspan="2">Height of magnet [mm]</td><td>898.8 mm</td></tr>
<tr><td colspan="2">Number of DPC</td><td>82</td></tr>
<tr><td rowspan="2">Current</td><td colspan="2">Iop [A] for 6T</td><td>180.6</td></tr>
<tr><td colspan="2">Ic [A] (margin)</td><td>202.6 (10.9%) @20K</td></tr>
<tr><td rowspan="4">Magnetic field</td><td colspan="2">B field (center) [T] @ Iop</td><td>6</td></tr>
<tr><td rowspan="3">Homogeneity (PPM)</td><td>Ideal design</td><td>28.7</td></tr>
<tr><td>Statistically</td><td>±313.6 (95% probability)</td></tr>
<tr><td>SCIF</td><td>70.9</td></tr>
<tr><td rowspan="2">Energy</td><td colspan="2">Stored energy [MJ] @ Iop</td><td>1.292</td></tr>
<tr><td colspan="2">Inductance [H]</td><td>79.2</td></tr>
</table>

◆ Heat load and temperature analysis



Without current
- Radiation
- Conduction through supports
- Conduction through leads

→

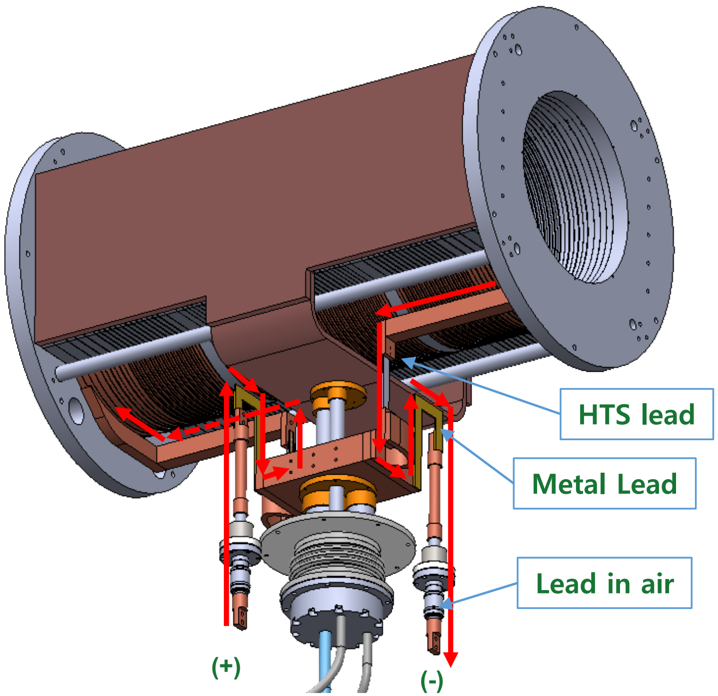
Current operation
- Magnetization loss
- Turn-turn current loss
- Eddy current loss
- Joint and current lead loss

→

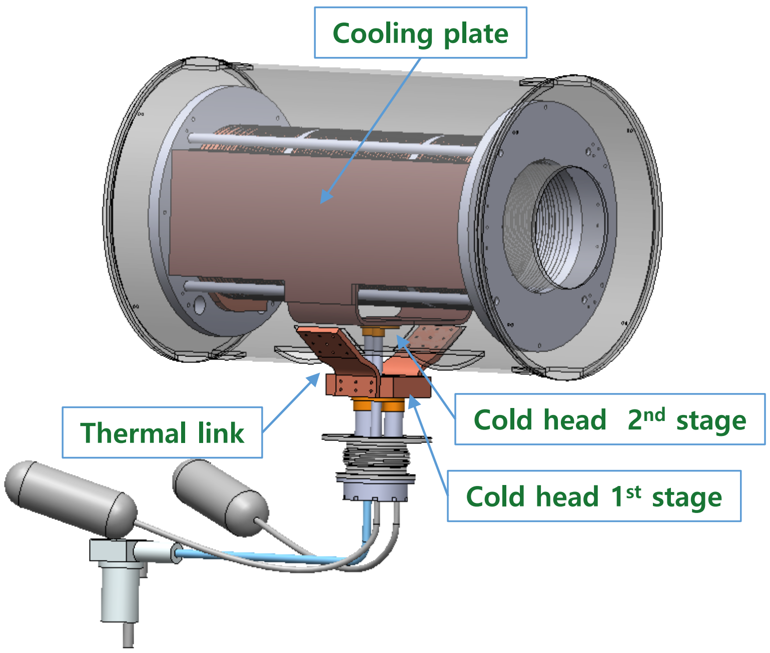
Temperature after Quench

Parts	Heat load [W]								Temperature [K] (min/max/dT)		
	Resist-ance	Radiation	Eddy current	Magnetization	Turn to turn current	Current leads	Support	Total	w/o Current	with Current	After Quench
Radiation Shield	-	21	-	-	-	25	-	46	-	-	-
Magnet	2.17	0.362	5.55m	1.19	2.67	-	2.65	9.05	10.5 / 11.3 / 0.8	13.6 / 17.0 / 3.4	- / 78.6 / 58.6
Cold head	15.1 W @ 20 K (Cooling capacity of cryocooler, 60 Hz)								10.0	12.3	-

5. Research results – System design

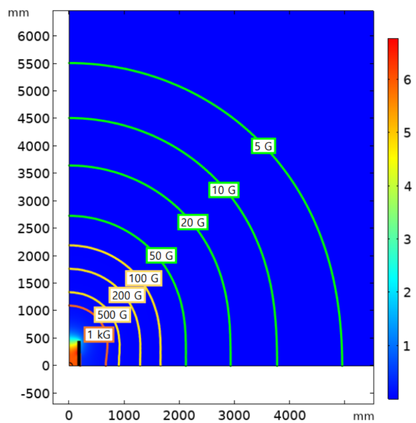


[Current lead of Magnet]

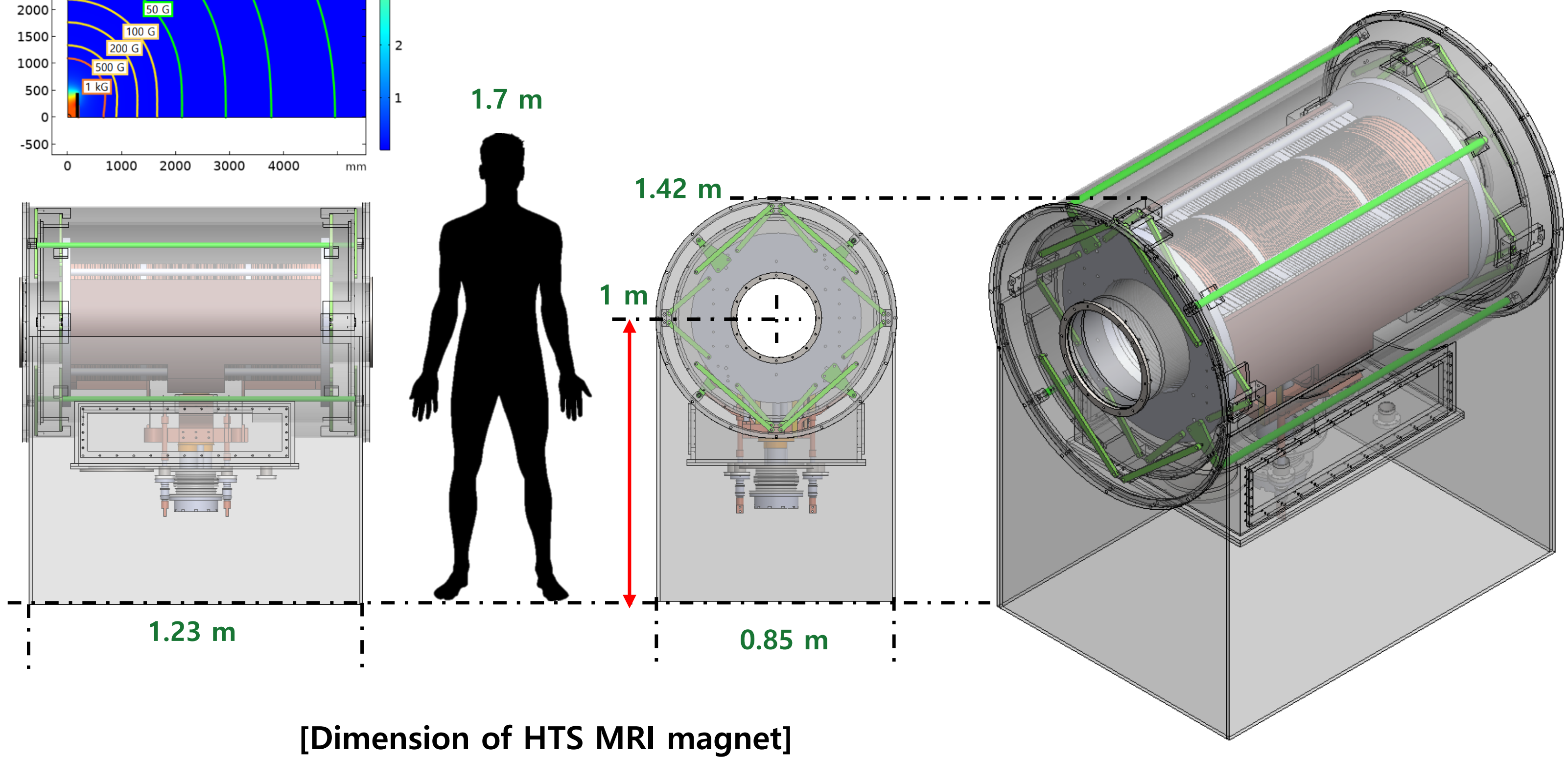


[Cooling path]

5. Research results – System design



- **Magnet center position : 1 m**
- **Foot print : 1.23 m x 0.85 m (1.04 m²)**



[Dimension of HTS MRI magnet]

6. Conclusion

◆ PLAN

- Due to a limited budget, the magnet room temperature bore size was set to be 230mm. Yet, we are expecting the magnet, once successfully completed, to play an important role as a pilot magnet to fulfill our ultimate goal to develop a next-generation ultra-high field (>7 T) all-HTS whole-body (>800 mm) MRI magnet.

- After securing magnet performance in this project, we are planning to collaborate with Seoul National University Hospital to use it for the clinical research of infant brain. Furthermore, there is a possibility that our R&D results will be used in the medical device R&D center construction project planned by the local government (KangWon province).

◆ HTS wire

- For the development of HTS MRI magnet, high magnetic field wire is important, but a wire **with uniform cross-sectional shape** is also important to minimize the effect of winding errors on the field homogeneity.

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Thank you for Attention !