Overview of Recent Progress in No-Insulation REBCO Magnet

25th International Conference on Magnet Technology

NI-REBCO Team[1] and S. Hahn[1,2]

[1]National High Magnetic Field Laboratory
[2]Seoul National University

August 28, 2017

Low Temperature Superconductor (LTS)

Drivers
- Performance (> 23 T)
- Operational Cost (LHe-free)

Challenges
- Operation Reliability
- Conductor Cost

High Temperature Superconductor (HTS)

S. Hahn
<hahnsy@snu.ac.kr>

Low Temperature Superconductor (LTS)

Drivers

- Performance (> 23 T)
- Operational Cost (LHe-free)

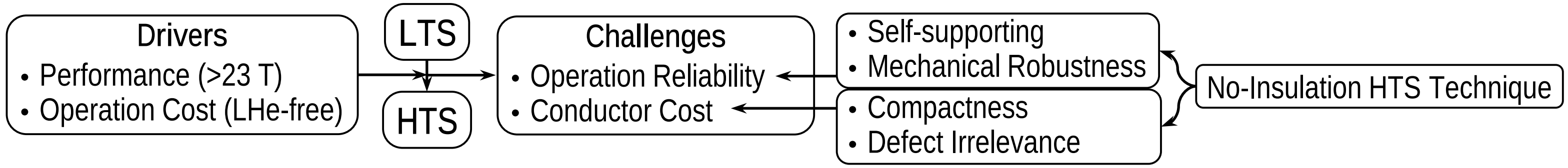
Challenges

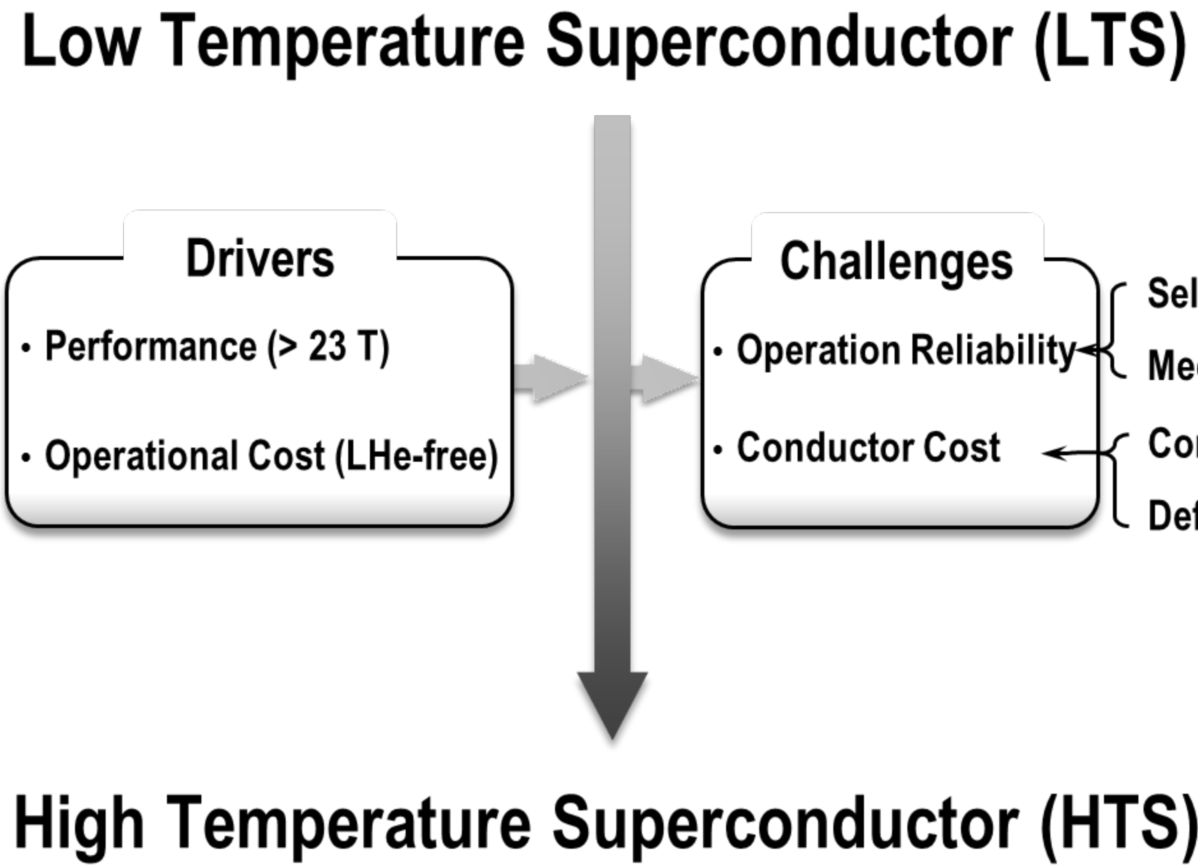
- Operation Reliability
- Conductor Cost

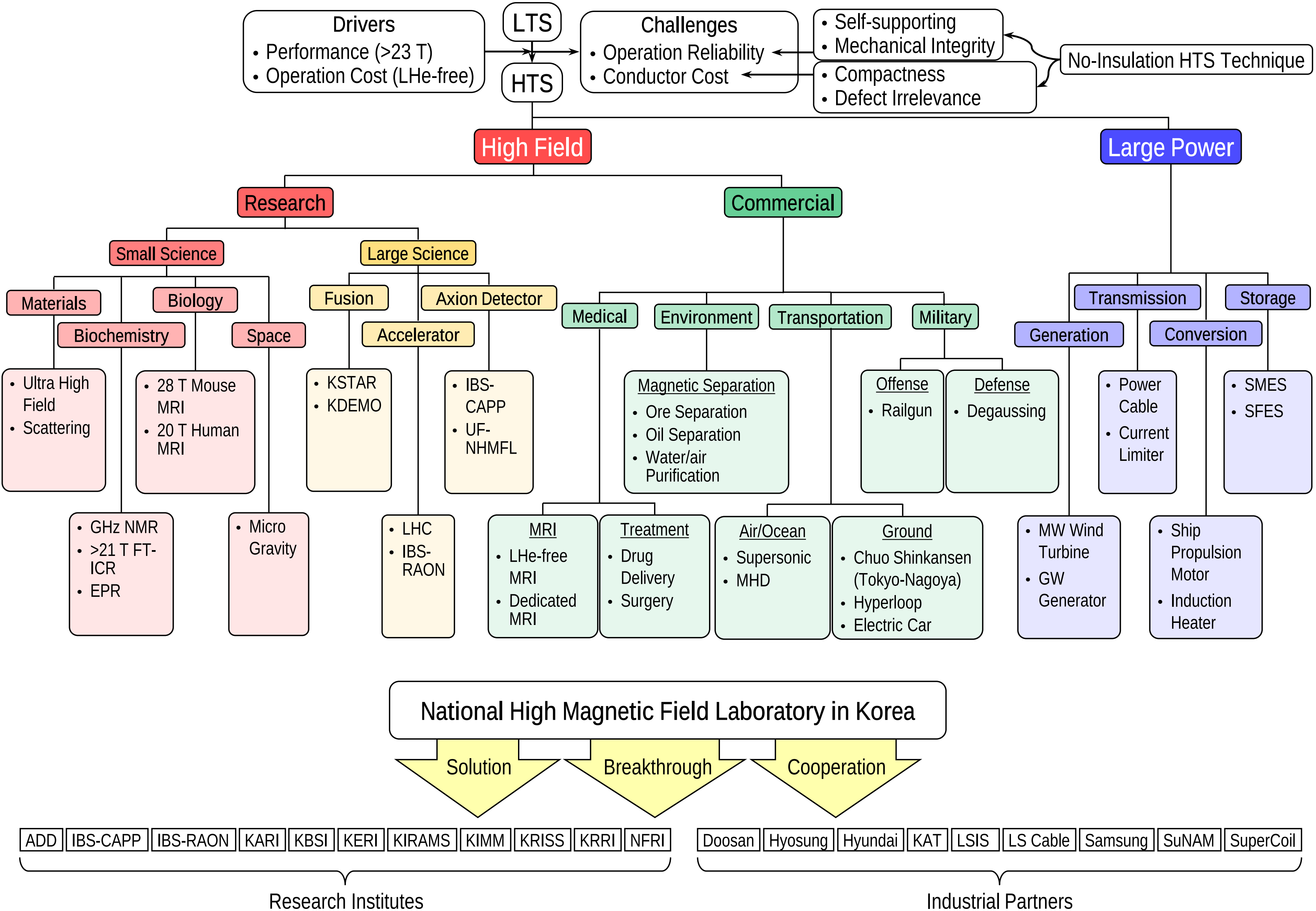
Self-Protecting
Mechanical Integrity
Compactness
Defect Irrelevance

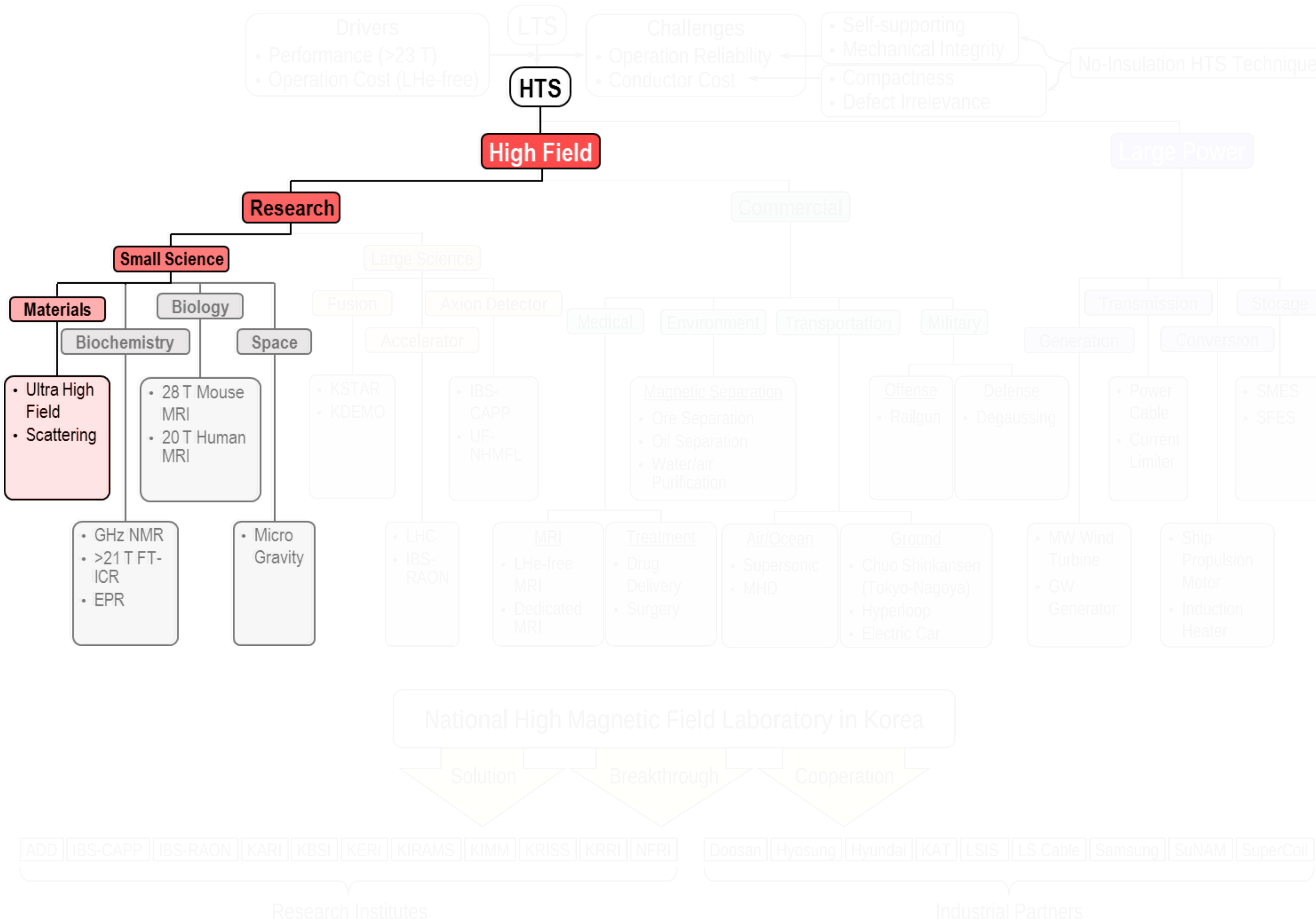
"No-Insulation" HTS Technique

High Temperature Superconductor (HTS)


Drivers
• Performance (>23 T)
• Operation Cost (LHe-free)
LTS
HTS
Challenges
• Operation Reliability
• Conductor Cost
• Self-supporting
• Mechanical Robustness
• Compactness
• Defect Irrelevance
No-Insulation HTS Technique


Low Temperature Superconductor (LTS)
Drivers
• Performance (> 23 T)
• Operational Cost (LHe-free)
Challenges
• Operation Reliability
• Conductor Cost
Self-Protecting
Mechanical Integrity
Compactness
Defect Irrelevance
"No-Insulation" Technique
High Temperature Superconductor (HTS)

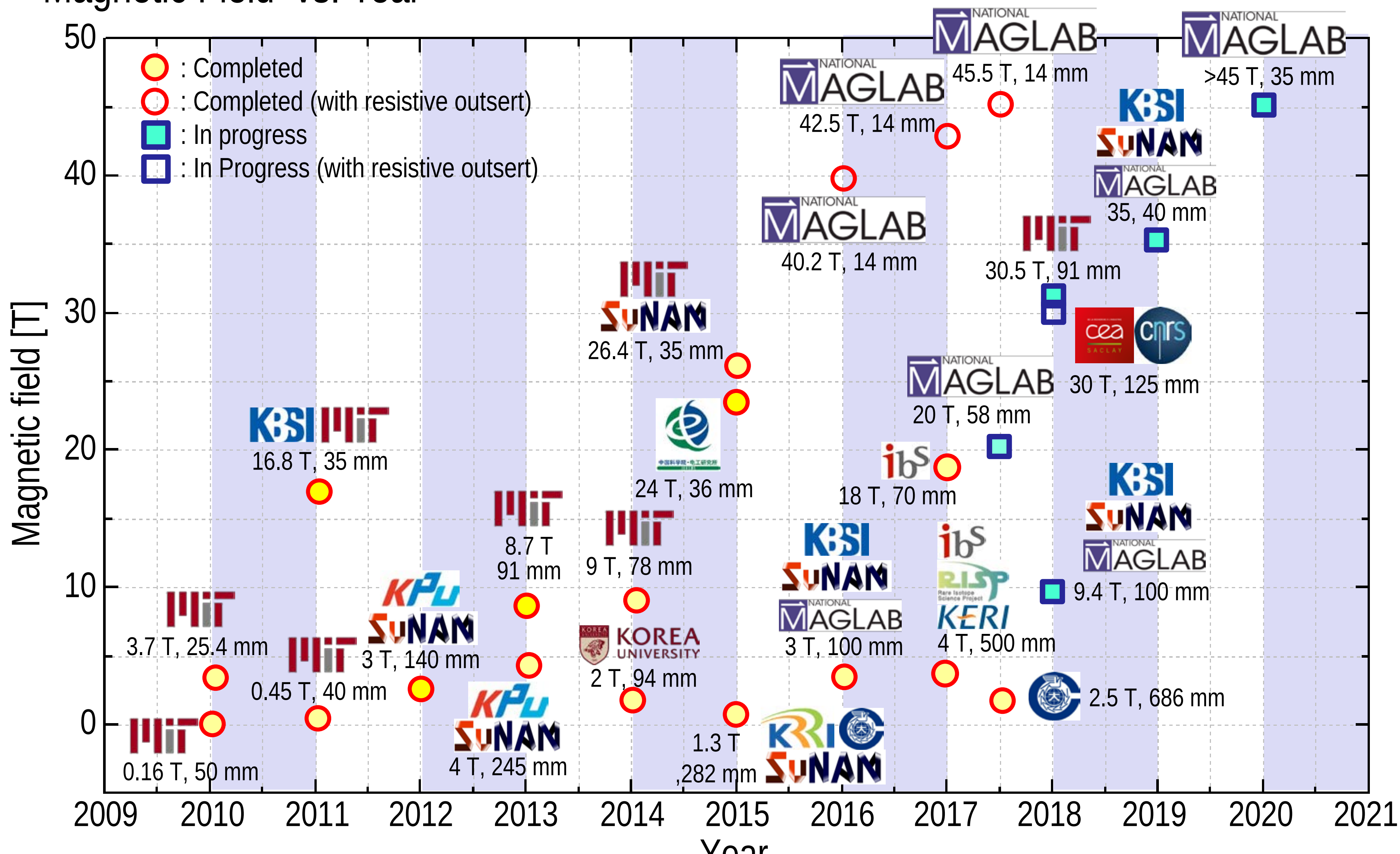

Drivers
• Performance (>23 T)
• Operation Cost (LHe-free)
LTS
HTS
Challenges
• Operation Reliability
• Conductor Cost
• Self-supporting
• Mechanical Integrity
• Compactness
• Defect Irrelevance
No-Insulation HTS Technique
High Field
Large Power
Research
Commercial
Small Science
Large Science
Materials
Biology
Biochemistry
Space
Fusion
Axion Detector
Accelerator
Medical
Environment
Transportation
Military
Transmission
Storage
Generation
Conversion
• Ultra High Field
• Scattering
• 28 T Mouse MRI
• 20 T Human MRI
• KSTAR
• KDEMO
• IBS-CAPP
• UF-NHMFL
Magnetic Separation
• Ore Separation
• Oil Separation
• Water/air Purification
Offense
• Railgun
Defense
• Degaussing
• Power Cable
• Current Limiter
• SMES
• SFES
• GHz NMR
• >21 T FT-ICR
• EPR
• Micro Gravity
• LHC
• IBS-RAON
MRI
• LHe-free MRI
• Dedicated MRI
Treatment
• Drug Delivery
• Surgery
Air/Ocean
• Supersonic
• MHD
Ground
• Chuo Shinkansen (Tokyo-Nagoya)
• Hyperloop
• Electric Car
• MW Wind Turbine
• GW Generator
• Ship Propulsion Motor
• Induction Heater
National High Magnetic Field Laboratory in Korea
Solution
Breakthrough
Cooperation
ADD
IBS-CAPP
IBS-RAON
KARI
KBSI
KERI
KIRAMS
KIMM
KRISS
KRRI
NFRI
Doosan
Hyosung
Hyundai
KAT
LSIS
LS Cable
Samsung
SuNAM
SuperCoil
Research Institutes
Industrial Partners



Drivers
Performance (>23 T)
Operation Cost (LHe-free)
LTS
HTS
Challenges
Operation Reliability
Conductor Cost
Self-supporting
Mechanical Integrity
Compactness
Defect Irrelevance
No-Insulation HTS Technique
High Field
Large Power
Research
Commercial
Small Science
Large Science
Materials
Biology
Biochemistry
Space
Ultra High Field
Scattering
28 T Mouse MRI
20 T Human MRI
GHz NMR
>21 T FT-ICR
EPR
Micro Gravity
Fusion
Axion Detector
Accelerator
KSTAR
KDEMO
IBS-CAPP
UF-NHMFL
LHC
IBS-RAON
Medical
Environment
Transportation
Military
Magnetic Separation
Ore Separation
Oil Separation
Water/air Purification
Offense
Railgun
Defense
Degaussing
MRI
LHe-free MRI
Dedicated MRI
Treatment
Drug Delivery
Surgery
Air/Ocean
Supersonic
MHD
Ground
Chuo Shinkansen (Tokyo-Nagoya)
Hyperloop
Electric Car
Transmission
Storage
Generation
Conversion
Power Cable
Current Limiter
SMES
SFES
MW Wind Turbine
GW Generator
Ship Propulsion Motor
Induction Heater
National High Magnetic Field Laboratory in Korea
Solution
Breakthrough
Cooperation
ADD
IBS-CAPP
IBS-RAON
KARI
KBSI
KERI
KIRAMS
KIMM
KRISS
KRRI
NFRI
Doosan
Hyosung
Hyundai
KAT
LSIS
LS Cable
Samsung
SuNAM
SuperCoil
Research Institutes
Industrial Partners

Progress in NI REBCO Magnet (2009 – 2017)

■ Magnetic Field vs. Year



K. M. Kim (ASC-MagLab)
S. Hahn
<hahnsy@snu.ac.kr>

"Little Big Coil 3 (LBC3)"

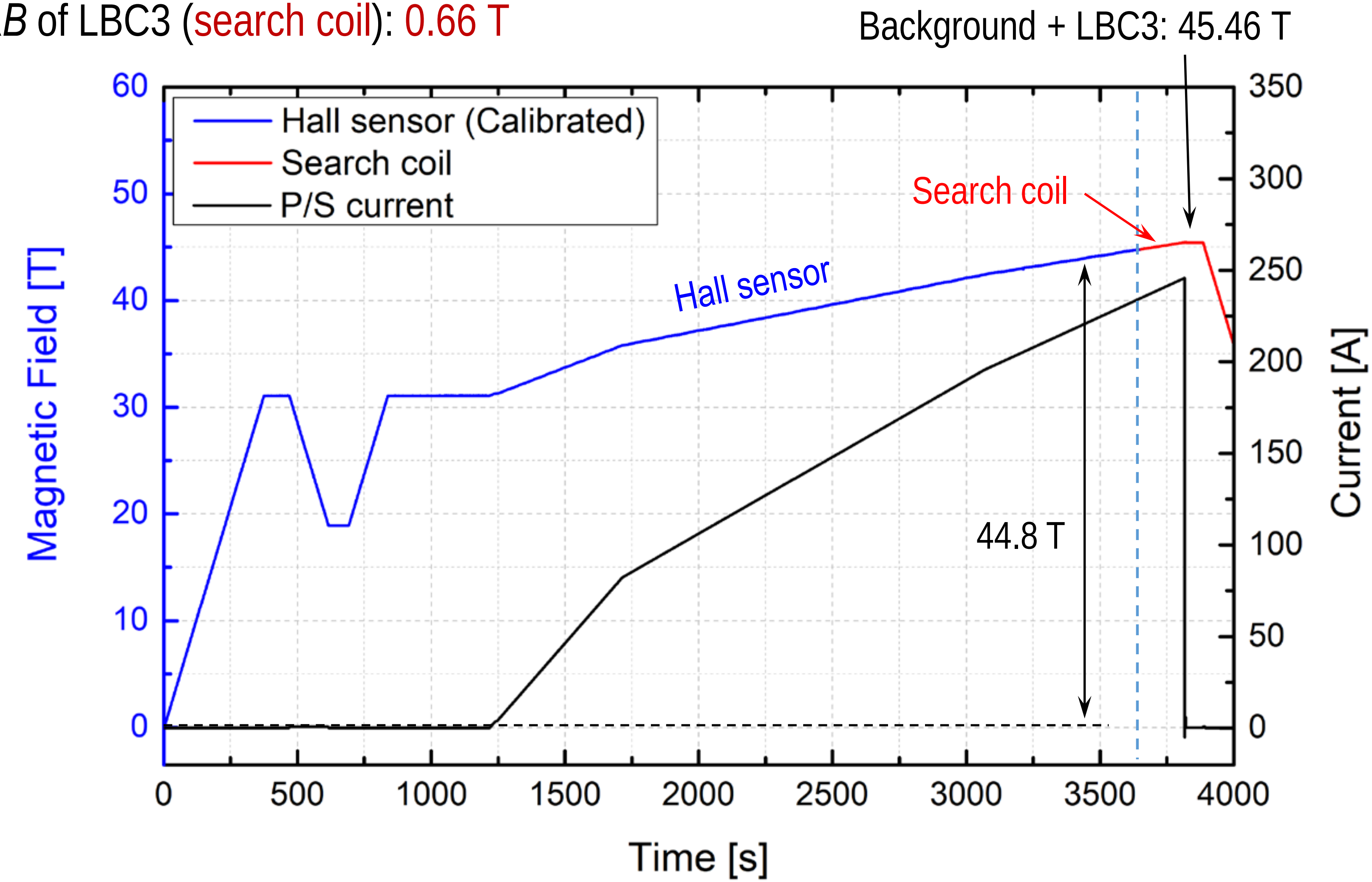
- ID: 14 mm; OD: 34 mm; H: 51 mm
- SuperPower 30 um tape
- Tested in a 31 T resistive magnet

SPC Number	Number of turn	Coil O.D. (mm)
1	229	34.00
2	229	33.95
3	234	34.00
4	229	33.85
5	220	33.83
6	222	33.95
7	222	33.96
8	226	33.75
9	220	33.74
10	229	33.82
11	229	33.84
12	228	34.01

Parameters		Values
REBCO Tape		
Width; thickness	[mm]	4.03; 0.045
Thickness of substrate; copper	[mm]	0.03; 0.01 (5 μm per side)
E_r; E_θ; E_z	[GPa]	69; 144; 144
95-% I_c retention stress	[MPa]	720 (0.5 % strain)
Little Big Coil		
Winding ID; OD; height	[mm]	14; 34; 51
Number of pancakes		12
Turn per single pancake		226.4 (average)
Total turns of LBC		2717
REBCO tape per pancake	[m]	16.7
Total REBCO length	[m]	200.4
Self Inductance of DP	[mH]	3.66 (DP3) – 4.01 (DP2)
Total inductance	[mH]	50.6
Magnet constant	[mT/A]	60.2 (calculated, actual)
Tape current density (J_t) at 100 A	[A/mm^2]	551
Coil current density (J_e) at 100 A	[A/mm^2]	533
$L_s+\sum L_M$ for DP1 (Top) - DP6(Bottom)	[mH]	7.22; 9.13; 9.14; 9.24; 8.74; 7.14
R_c (R_{ct}=50.0 $\mu\Omega$·cm^2 from 0 T LHe test)	[mΩ]	47.1
τ_c ($= L/R_c$)	[s]	1.07
31 T Background Magnet (Cell 7)		
Overall winding ID; OD; height	[mm]	38; 600;400
Magnet constant	[mT/A]	0.8432
B_c at I_{op} of 37.0 kA	[T]	31.197
Self inductance	[mH]	4.30
Mutual inductance with LBC	[mH]	1.07
Operation		
I_c of DP1 (T) - DP6 (B) at 45.5 T	[A]	576; 505; 526; 513; 502; 577
ϵ_{bend} at $r = a_1$; a_2	[%]	0.21; 0.090
$\epsilon_{mag}(r = a_2)$ at 40 T; 45 T; 48 T	[%]	0.23, 0.40, 0.50
V_{DP}; V_{LBC} at 10 A/min	[mV]	1.2 - 1.5; 8.4
I_{leak} at 10 A/min	[A]	0.2
Overall Joule heating at 10 A/min	[mW]	<10

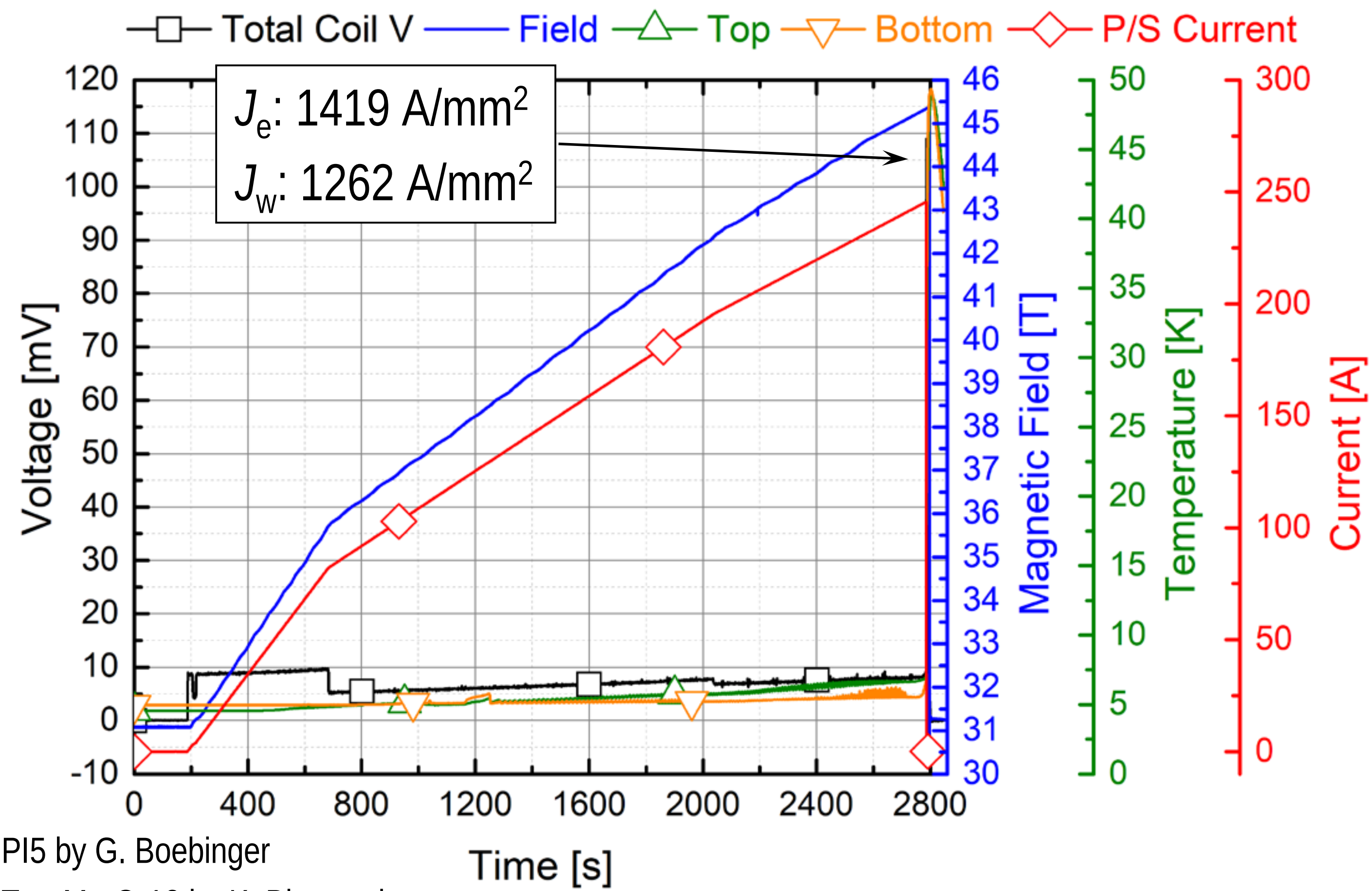
Generation of 45.46 T in 31.08 T Background Field (ΔB = 14.38 T)

- Field Measurement: (1) Calibrated Hall Sensor (<45 T); (2) Search Coil (>45 T)
  - Calibrated magnetic field (Hall sensor): 44.80 T
  - Δ*B* of LBC3 (search coil): 0.66 T



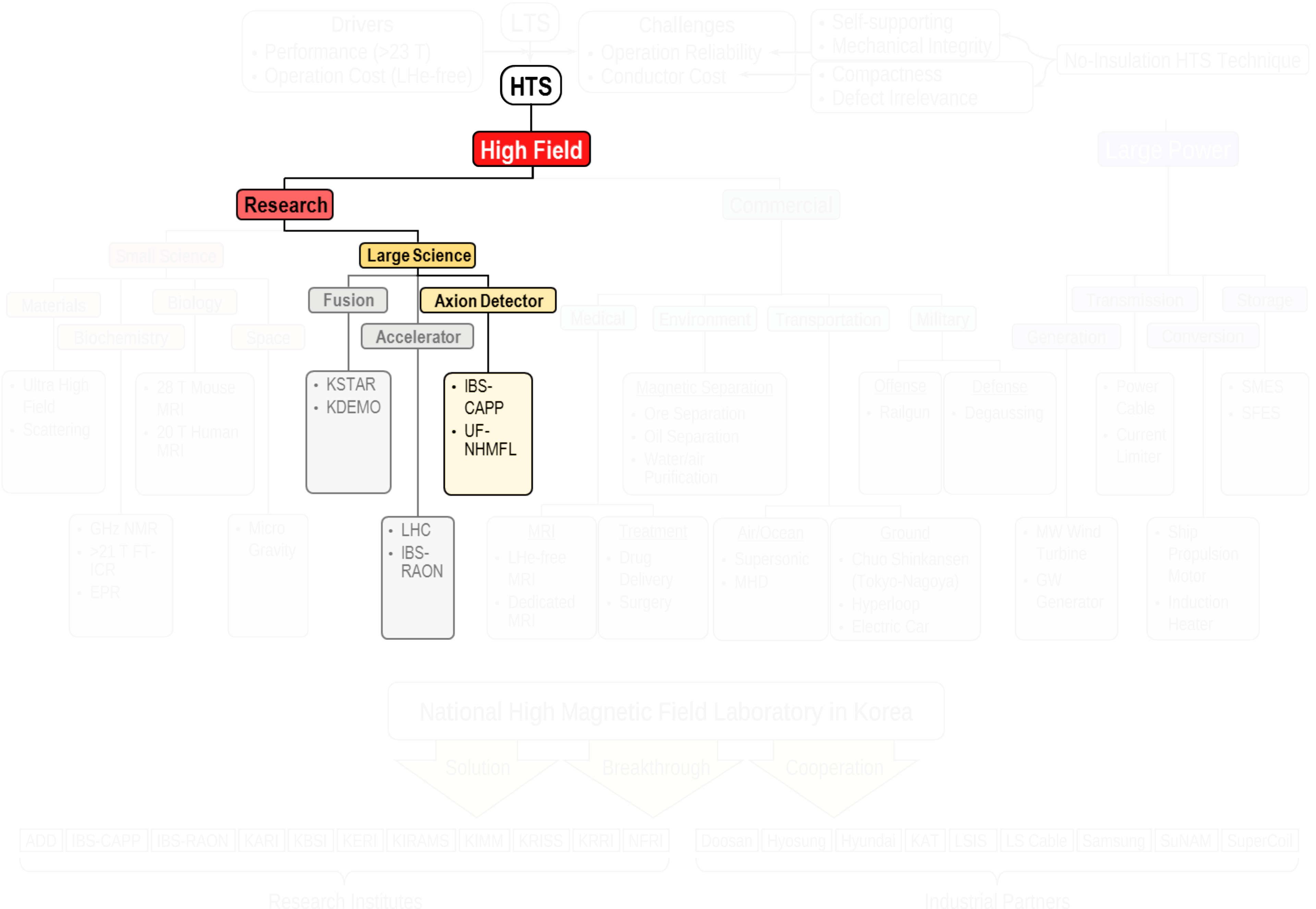
Generation of 45.46 T: 1400 A/mm^2 and 700 MPa at >7 K

- Key Operation Parameters at 45.46 T (After Survival from Unexpected 31 T Trip)
  - Actual coil current: 245.3 A → tape J_e: 1419 A/mm^2; winding J_w: 1262 A/mm^2
  - Peak magnetic stress: ~700 MPa; Peak total strain: 0.38 % (compressive bending included)
  - Operating temperature: >7 K (due to the helium bubble trap issue)



Overview: Wed-Mo-PI5 by G. Boebinger

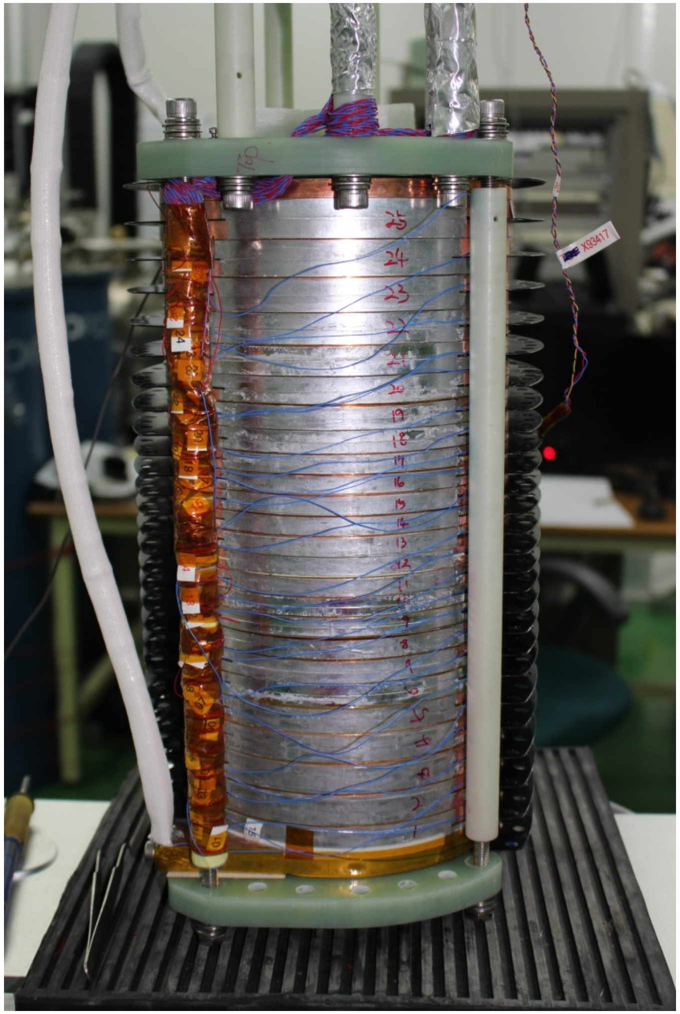
Quench simulation: Tue-Mo-Or12 by K. Bhattarai



S. Hahn
<hahnsy@snu.ac.kr>

26-T/35-mm MW-NI All-REBCO Magnet (2015, SuNAM-MIT-MagLab)

- Multi-Width No-Insulation Magnet in Liquid Helium at 4.2 K
  - Designed by MIT, constructed by SuNAM, and tested by SuNAM and MagLab



Parameter		M1	M2	M3	M4	M5
Magnet Configuration						
Average tape width	[mm]	4.1	5.1	6.1	7.1	8.1
Average tape thickness	[μm]	146	145	135	138	135
Pancake-pancake spacer	[mm]	0.2				
Coil i.d.; o.d.	[mm]	35.0; 171.9				
Overall height	[mm]	327				
Number of DP		10	4	4	4	4
Turn per DP		914	916	996	968	984
Conductor per DP	[m]	297	298	324	315	320
Total conductor	[km]	3.0	1.2	1.3	1.3	1.3
Operation and Performance						
Magnet constant	[mT/A]	109.2				
Operating temperature	[K]	4.2 (liquid helium)				
Current density at 26.4 T	[A/mm^2]	404	327	293	247	221
Inductance, L	[H]	12.79				
Peak $B_\perp$	[T]	1.54	1.59	1.82	2.08	3.68
Time constant (77 K), τ_c	[sec]	947 (12.79 H/13.5 mΩ)				
Peak hoop stress at 26.4 T	[MPa]	286				

Ref: S. Yoon, et al., "26 T 35 mm all-GdBa2Cu3O7-x multi-width no-insulation superconducting magnet," *Supercond. Sci. Technol.*, 29 (2016), 04LT04.

26-T/35-mm MW-NI All-REBCO Magnet (2015, SuNAM-MIT-MagLab)

- The First Scientific User Experience in HTS Magnet (24 T at 4.2 K)

SciRate beta   Sign in   Sign up

Magnetoresistance in copper in high magnetic fields: The first scientific application of a no-insulation HTS magnet

Saebyeok Ahn, Sung Woo Youn, Jonghee Yoo, Dong Lak Kim, Junu Jeong, Moohyun Ahn, Jongkuk Kim, Doyu Lee, Jiyoung Lee, Taehyeon Seong, Yannis K. Semertzidis

In halo dark matter axion search experiments, cylindrical microwave cavities are typically employed to detect signals from the axion-photon conversion. To enhance the conversion power and reduce the noise level, cavities are placed in strong solenoid magnetic fields at sufficiently low temperatures. Exploring high mass regions in cavity-based axion search experiments requires high frequency microwave cavities and thus understanding cavity properties at high frequencies in extreme conditions is deemed necessary. We present a study of the magnetoresistance of copper using a cavity with a resonant frequency of 12.9 GHz in magnetic fields up to 15 T at the liquid helium temperature of 4.2 K. The observations are interpreted with the anomalous skin effect and size effect. For this study we utilize a second generation high temperature superconducting magnet designed with no-insulation and multi-width techniques. This measurement of magnetoresistance in high magnetic fields (> 10 T) is the first application of the high temperature superconducting technologies ever to a scientific study.

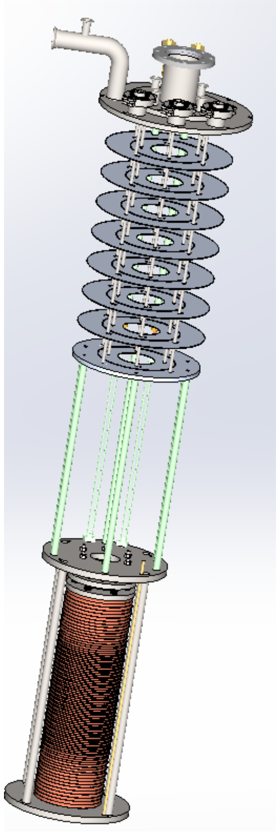
Submitted 12 May 2017 to **Instrumentation and Detectors** [physics.ins-det]
Published 16 May 2017
Subjects: physics.ins-det hep-ex
Author comments: 6 pages, 5 figures
http://arxiv.org/abs/1705.04754
http://arxiv.org/pdf/1705.04754.pdf

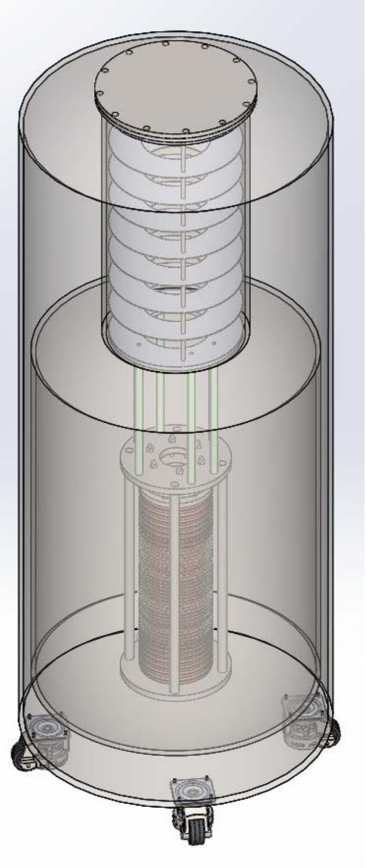
REF: Center for Axion and Precision Physics Research, Institute of Basic Science (2017)

18 T 70 mm NI-REBCO Magnet by SuNAM for IBS-CAPP

- The First Commercial HTS Magnet in Korea
  - Design, construction, and test by the SuNAM, Co., Ltd. in collaboration with SNU.
  - Multi-width no-insulation REBCO type

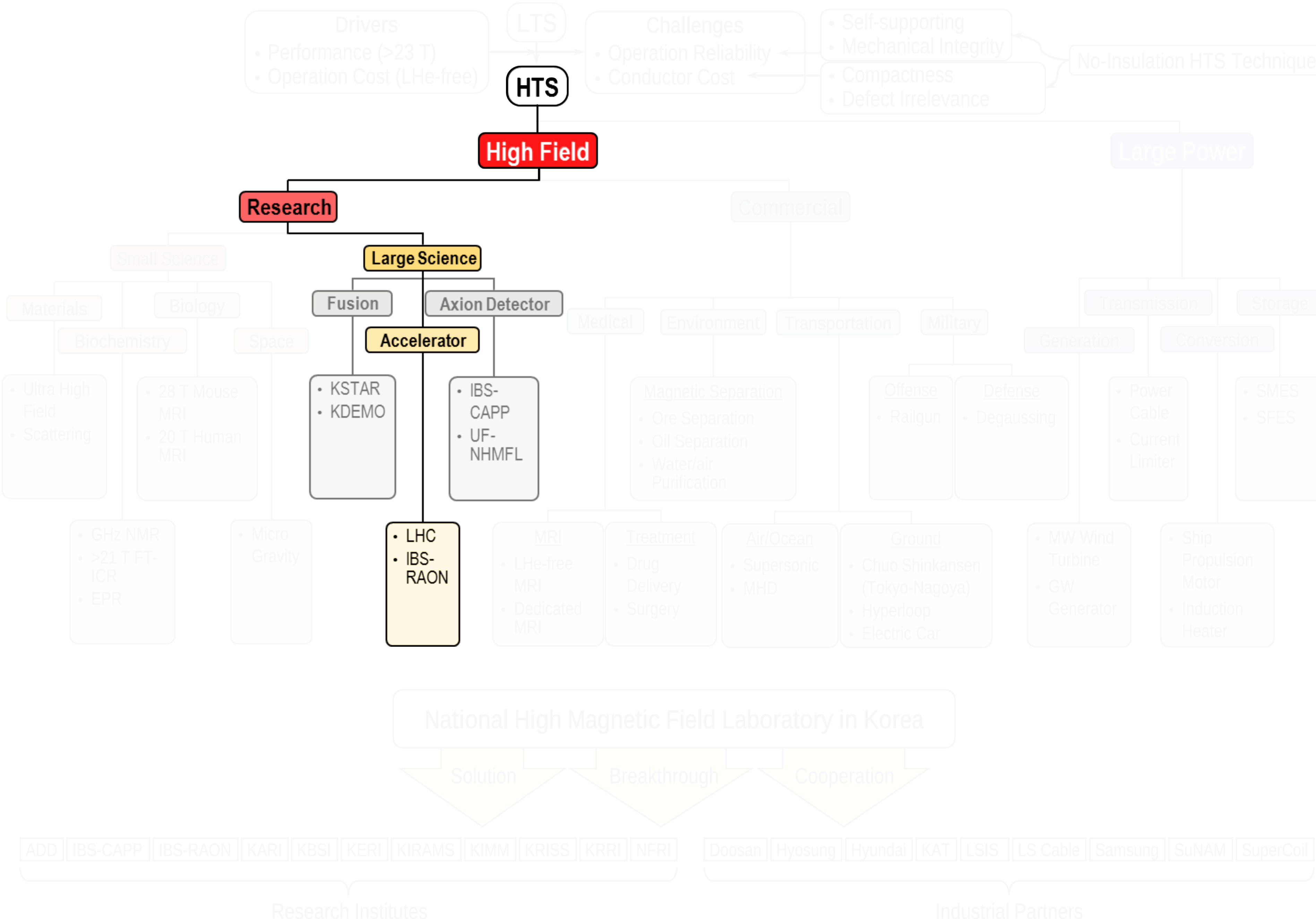
Parameter	Unit	M4	M5	M6	M7	M8
Coil Configuration						
I_C (77K, S.F., 4.1mmW, 0.12mmT)	[A]	200				
Cold Bore; Magnet Height	[mm]	70; 476				
Winding I.D.; O.D.	[mm]	74.0; 155.6				
Spacer SP-SP; DP-DP	[mm]	0.2; 0.6				
Number of DPC		28	4	4	4	4
Total DPC; Turn per SPC		44; 340				
Equivalent Conductor L (4mmW)	[km]	13.24				
Magnet operation						
Homogeneity* (r < ±25mm, z < ±100mm)	[%]	92.5				
I_{OP}; $I_{C,\ Coil}$ (Margin [%])	[A]	199.2; 249.3 (20.1)				
Inductance	[H]	18.9				
Critical Current of Modules, $I_{C,\ Module}$	[A]	249	284	325	346	304
Perp. Field on HTS (B//c) @ $I_{C,\ Coil}$	[T]	2.5	2.6	2.5	2.7	4.8
Magnetic Hoop Stress (BJR; FE)	[MPa]	276; 362				





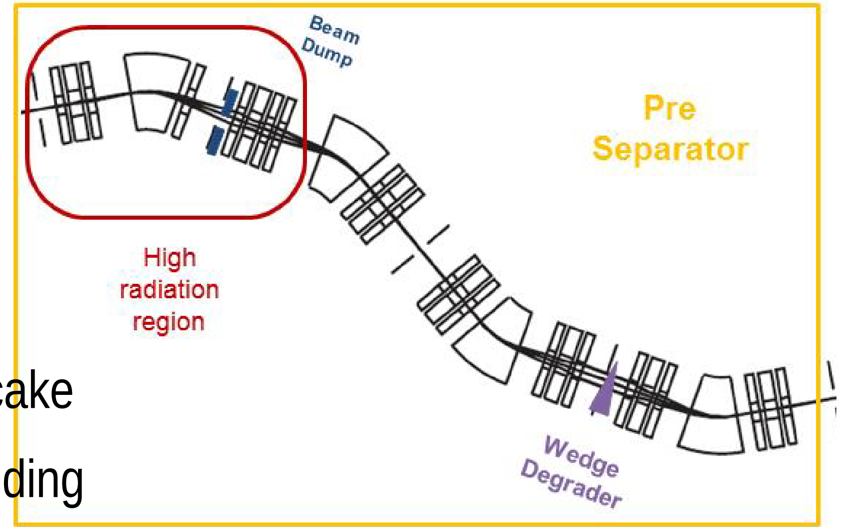
* 90% Homogeneity Requirement in Cavity Space

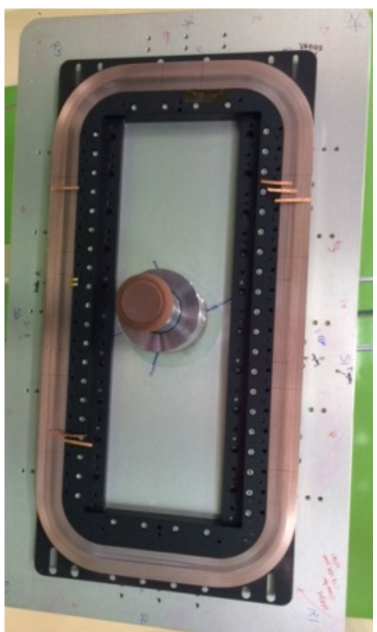
Courtesy to K. Cheon (SuNAM)

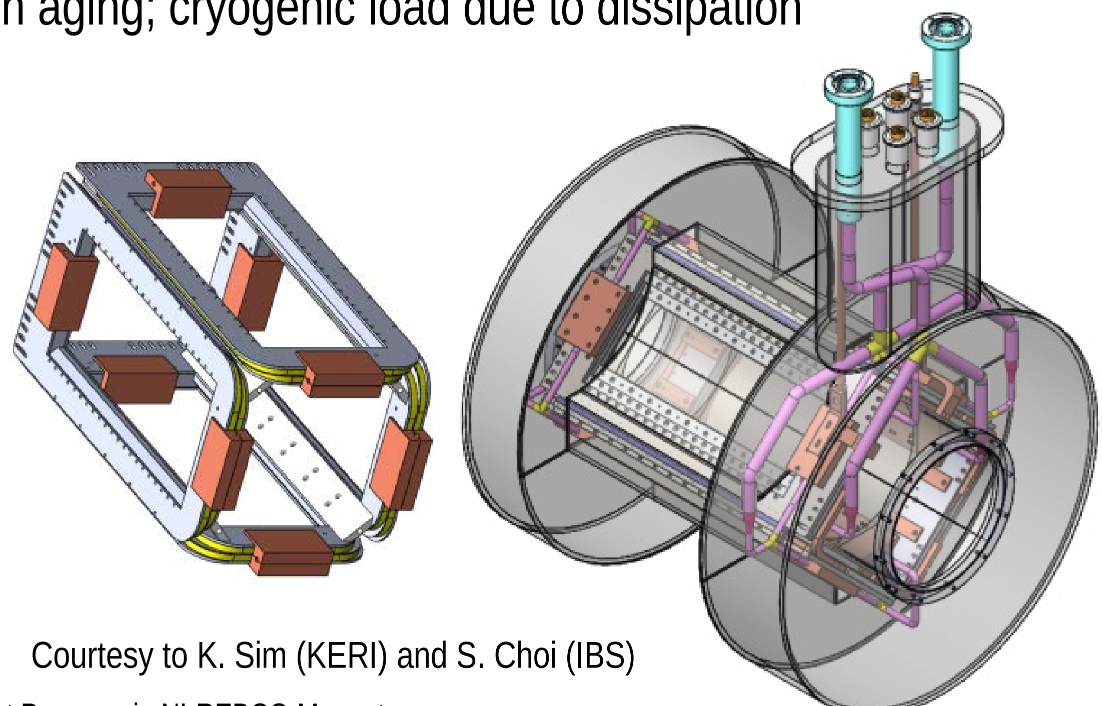

Drivers
Performance (>23 T)
Operation Cost (LHe-free)
LTS
Challenges
Operation Reliability
Conductor Cost
Self-supporting
Mechanical Integrity
Compactness
Defect Irrelevance
No-Insulation HTS Technique
HTS
High Field
Large Power
Research
Commercial
Small Science
Large Science
Materials
Biology
Biochemistry
Space
Fusion
Axion Detector
Accelerator
Ultra High Field
Scattering
28 T Mouse MRI
20 T Human MRI
KSTAR
KDEMO
IBS-CAPP
UF-NHMFL
LHC
IBS-RAON
GHz NMR
>21 T FT-ICR
EPR
Micro Gravity
Medical
Environment
Transportation
Military
Magnetic Separation
Ore Separation
Oil Separation
Water/air Purification
Offense
Railgun
Defense
Degaussing
MRI
LHe-free MRI
Dedicated MRI
Treatment
Drug Delivery
Surgery
Air/Ocean
Supersonic
MHD
Ground
Chuo Shinkansen (Tokyo-Nagoya)
Hyperloop
Electric Car
Transmission
Storage
Generation
Conversion
Power Cable
Current Limiter
SMES
SFES
MW Wind Turbine
GW Generator
Ship Propulsion Motor
Induction Heater
National High Magnetic Field Laboratory in Korea
Solution
Breakthrough
Cooperation
ADD
IBS-CAPP
IBS-RAON
KARI
KBSI
KERI
KIRAMS
KIMM
KRISS
KRRI
NFRI
Doosan
Hyosung
Hyundai
KAT
LSIS
LS Cable
Samsung
SuNAM
SuperCoil
Research Institutes
Industrial Partners

4 T Quadruple Magnet for Rare Isotope Accelerator (2021, IBS-KERI)

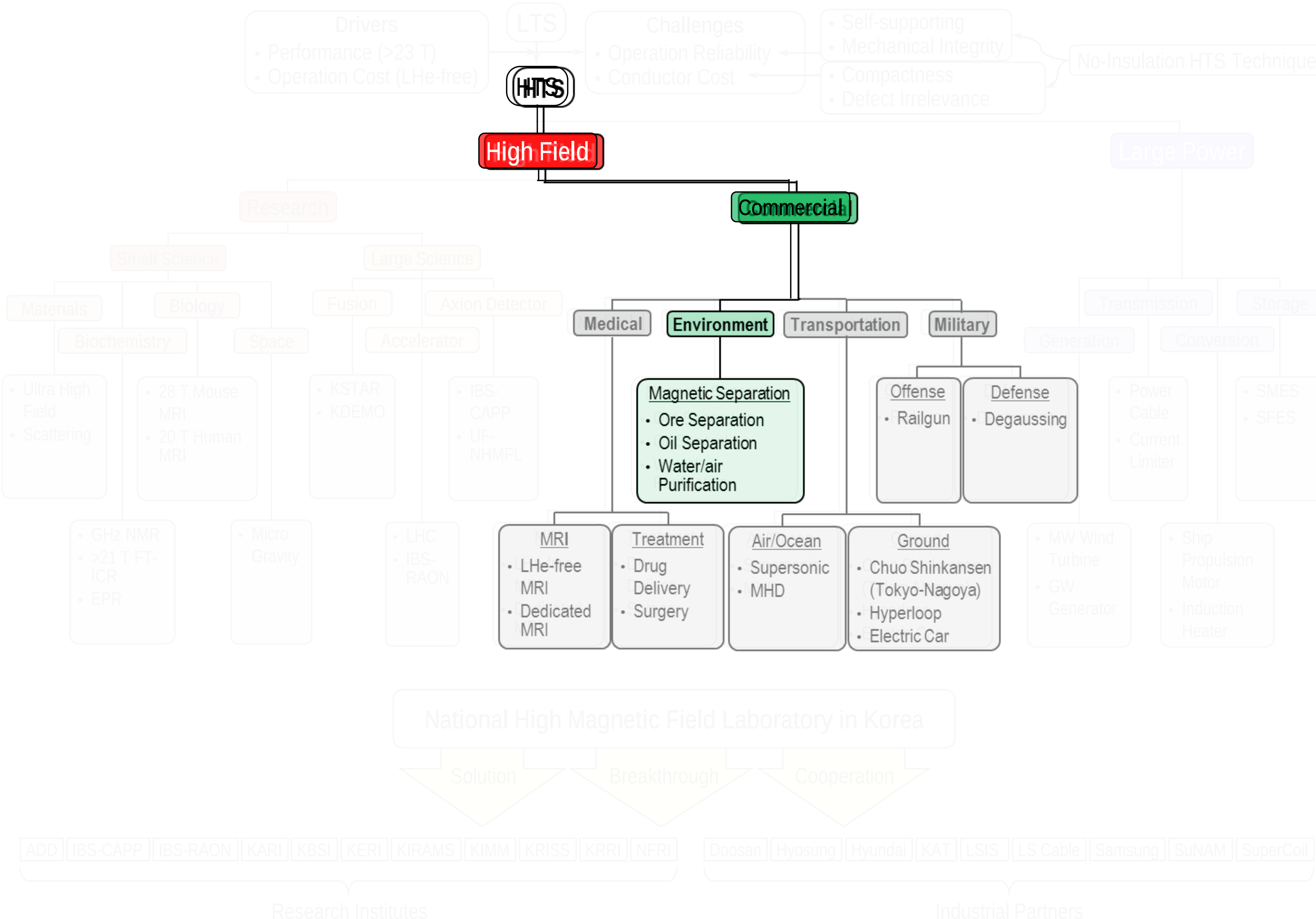
- *First MI REBO Coil for Actual Accelerator*
  - REBCO magnet for high radiation region
  - Large temperature margin of HTS
  - LHe-free operation (40 K, GHe)
  - 550 mm x 150 mm “window-frame” double-pancake
  - SuNAM & SuperPower, 12 mm wide; SS co-winding
  - Major challenges: I_c degradation in aging; cryogenic load due to dissipation





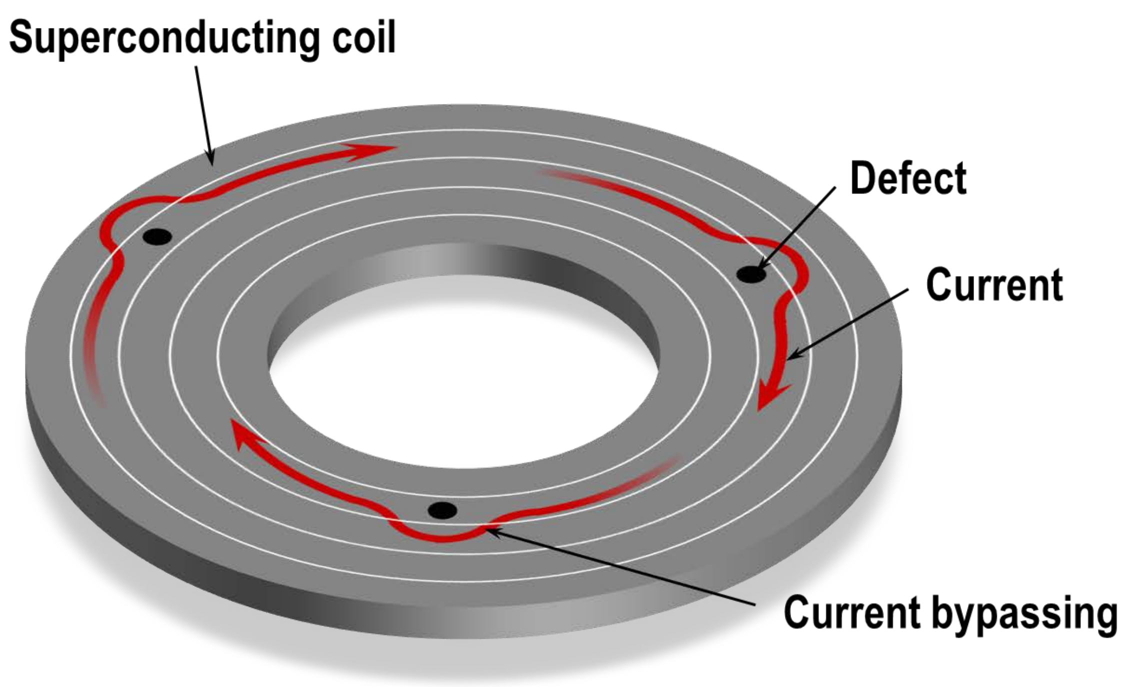


Courtesy to K. Sim (KERI) and S. Choi (IBS)


HTS
High Field
Commercial
Medical
Environment
Transportation
Military
Magnetic Separation
• Ore Separation
• Oil Separation
• Water/air Purification
Offense
• Railgun
Defense
• Degaussing
MRI
• LHe-free MRI
• Dedicated MRI
Treatment
• Drug Delivery
• Surgery
Air/Ocean
• Supersonic
• MHD
Ground
• Chuo Shinkansen (Tokyo-Nagoya)
• Hyperloop
• Electric Car

Defect Irrelevant Winding (DIW)

- Key Concept
  - An REBCO NI coil having multiple defects (or even discontinuity)



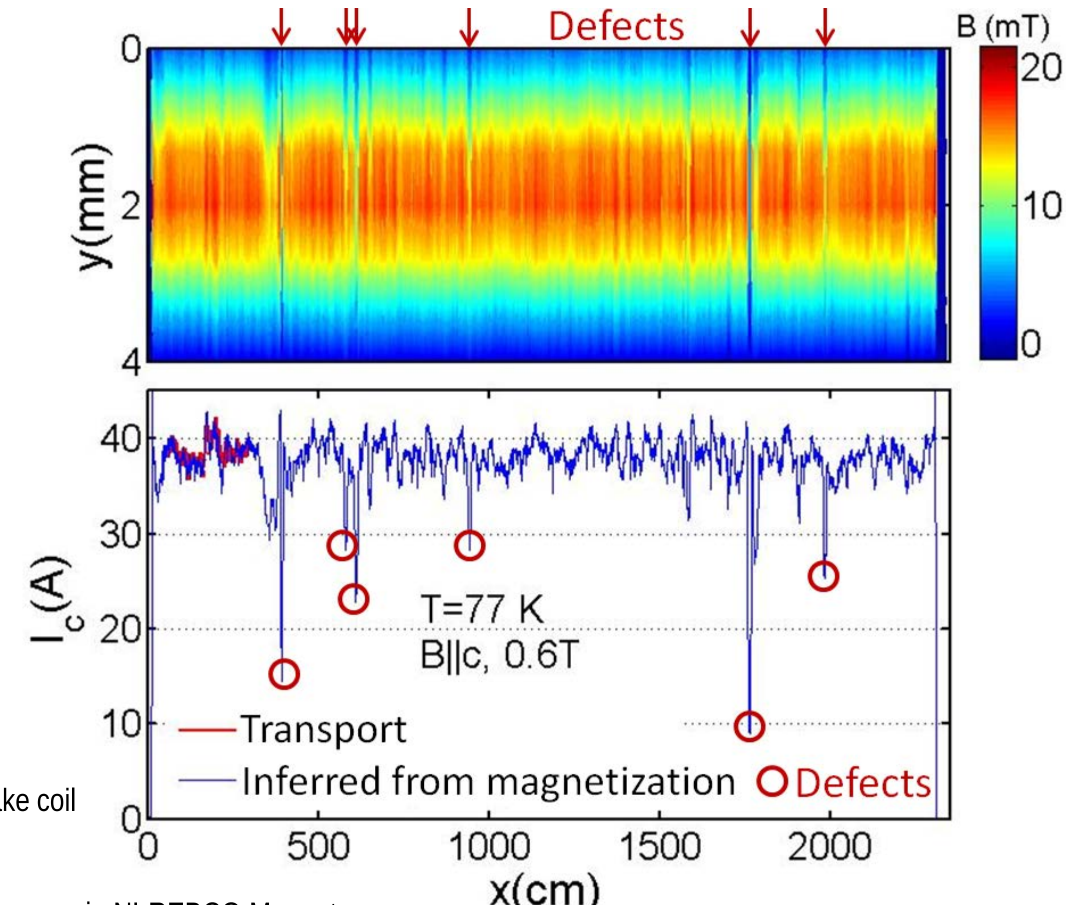
Ref: S. Hahn, et al., "Defect-irrelevant behavior of a no-insulation pancake coil wound with REBCO tapes containing multiple defects," *Supercond. Sci. Technol.*, **29**: 105017, 2016.

The First DIW Test Coil: 6 Major Defects

- **Single Pancake Test Coil**
  - a_1: 20 mm; a_2: 34.5 mm; Turns: 135; ~23 m
  - Peak B_r: 2.38 mT/A (z=1 mm);
    4.72 mT/A (z=2 mm)
  - B_0: 3.18 mT/A

Ref: S. Hahn, et al., "Defect-irrelevant behavior of a no-insulation pancake coil wound with REBCO tapes containing multiple defects," *Supercond. Sci. Technol.*, 29 (105017), 2016.

- **I_c Measurement by the Yatestar**
  - *6 "major" defects*, i.e., local I_C is less than 80 % of the lengthwise average



Operational Reliability Test of an NI HTS Coil by KERI

- HTS Coil Operation under "Mechanically Extreme Conditions"
  - 3 types of extreme conditions: (1) hammering; (2) nailing; and (3) drilling
    → barely discernible degradation of the coil performance.

Courtesy: M. Son, K. Sim, and the KERI Superconductivity Lab., 2016.

Operational Reliability Test of an NI HTS Coil by KERI

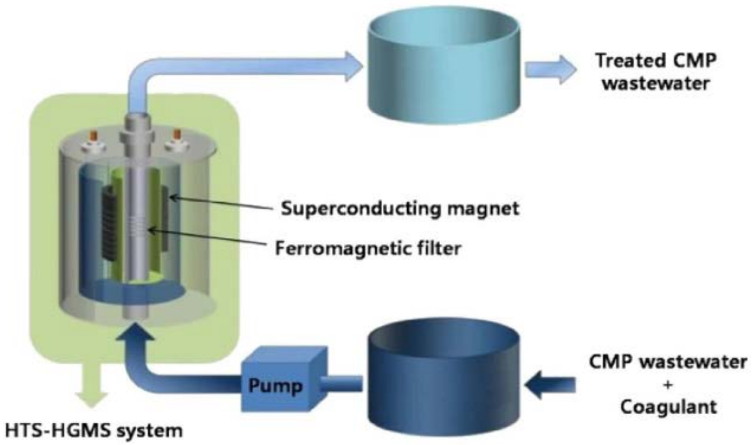
- HTS Coil Operation under "Mechanically Extreme Conditions"
  - 3 types of extreme conditions: (1) hammering; (2) nailing; and (3) drilling
    → barely discernible degradation of the coil performance.

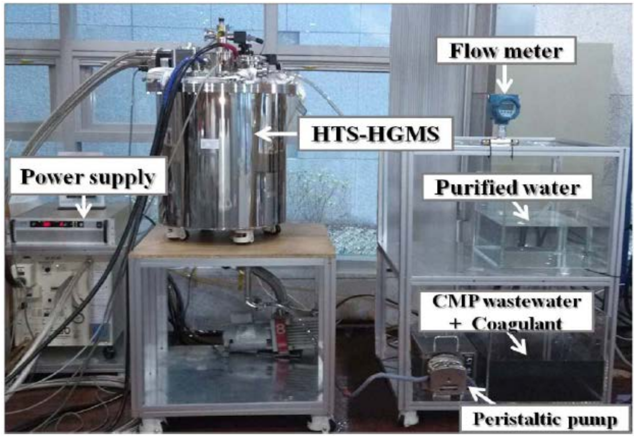
Courtesy: M. Son, K. Sim, and the KERI Superconductivity Lab., 2016.

S. Hahn
<hahnsy@snu.ac.kr>

NI REBCO Magnet for Magnetic Separation (2014, Korea U.)

- 2 T 94 mm All-REBCO NI Magnet for Water Purification[1]

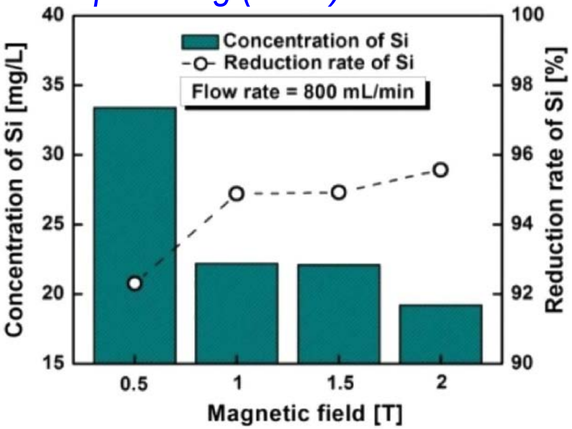




Schematic drawing (a) and photograph (b) of the high gradient magnetic separation (HGMS) system for the purification of chemical mechanical polishing (CMP) wastewater

- 18 NI REBCO DP (tapes by SuNAM)
- *20 K solid nitrogen* by use of a cryocooler
- 95.5 % reduction of Si concentration after 800 mL/min filteration at 2 T[2]

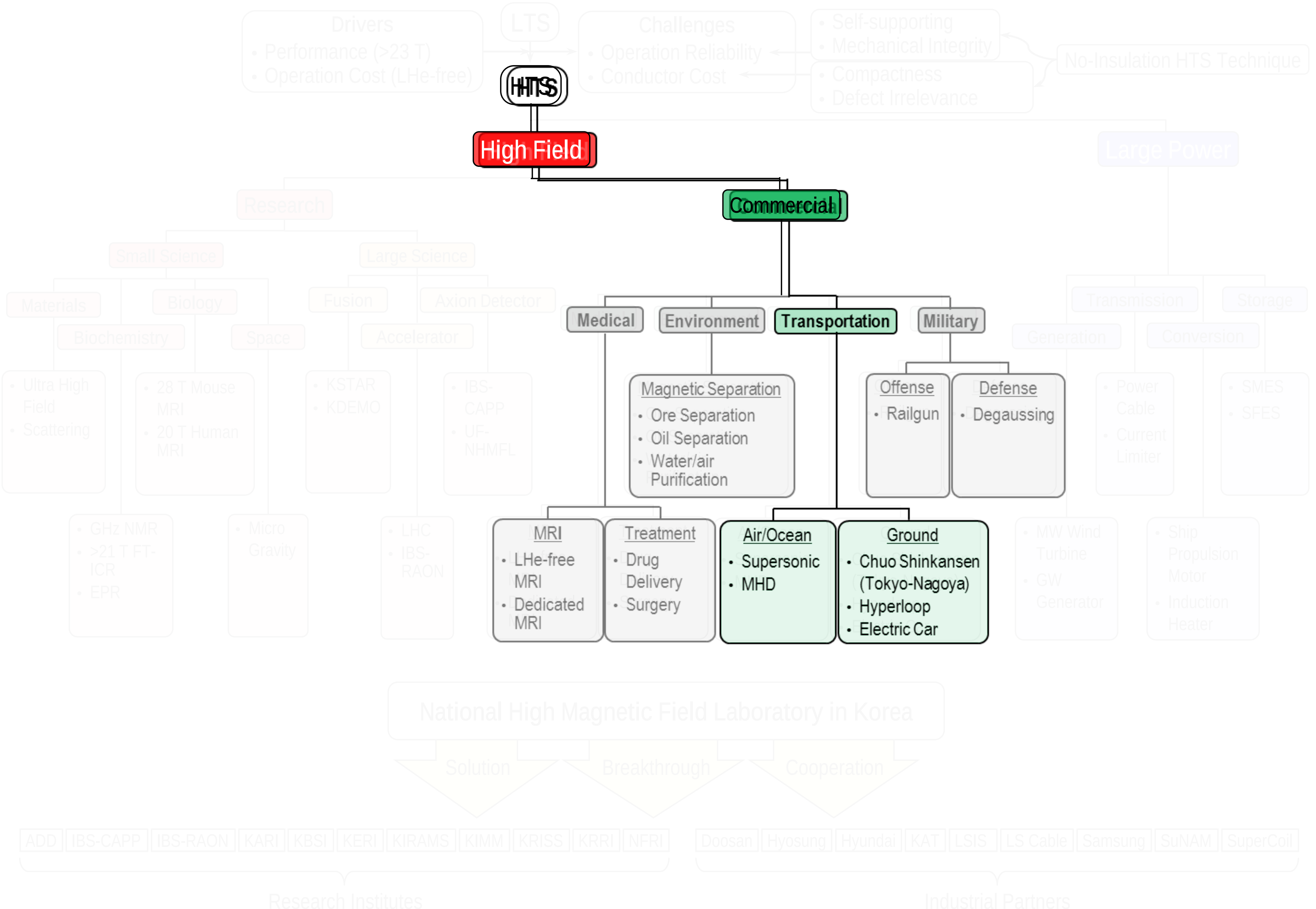
REBCO double pancake coil (left) and HGMS's magnet assembled with 18 NI DP coils (right)



Concentration and reduction rate of Si in wastewater samples

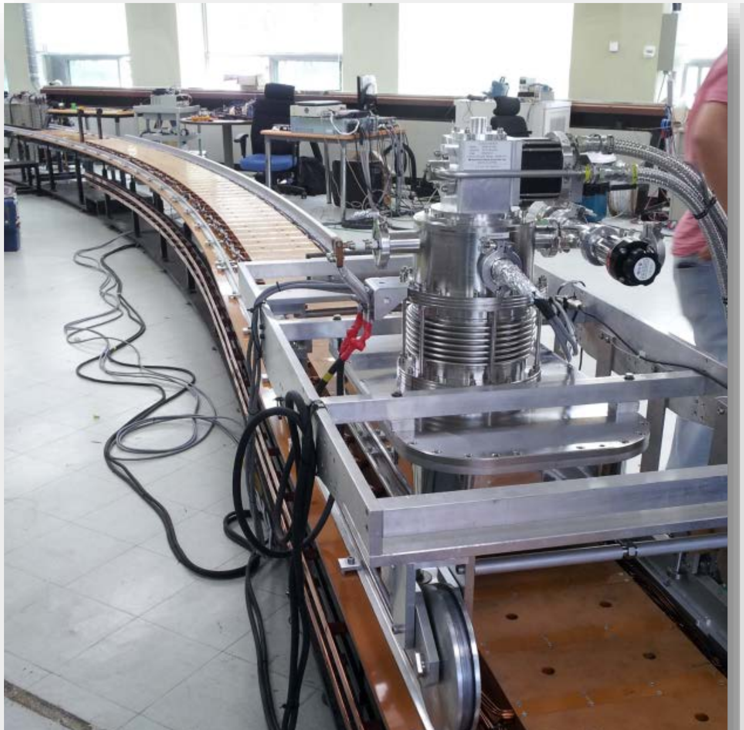
[1]J. B. Song, et al., "High-Tc Superconducting High Gradient Magnetic Separator Using Solid Nitrogen Cooling System for Purification of CMP Wastewater," *IEEE. Trans. Appl. Supercond*. 23 (2013), 3700505.

[2]Y. G. Kim, et al., "Purification of Chemical Mechanical Polishing Wastewater via Superconducting High Gradient Magnetic Separation System With Optimal Coagulation Process" *IEEE. Trans. Appl. Supercond.* 25 (2015), 3700205.

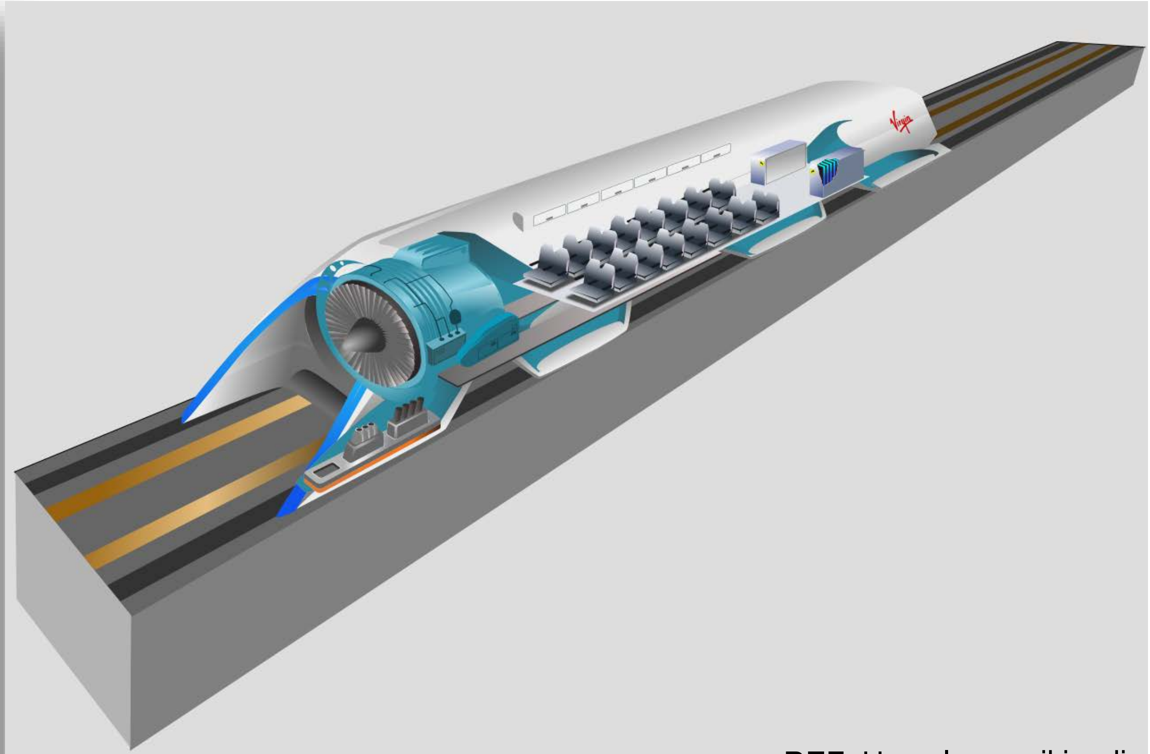

HTS
High Field
Commercial
Medical
Environment
Transportation
Military
Magnetic Separation
• Ore Separation
• Oil Separation
• Water/air Purification
Offense
• Railgun
Defense
• Degaussing
MRI
• LHe-free MRI
• Dedicated MRI
Treatment
• Drug Delivery
• Surgery
Air/Ocean
• Supersonic
• MHD
Ground
• Chuo Shinkansen (Tokyo-Nagoya)
• Hyperloop
• Electric Car

"Vacuum Tube MagLev": Hyperloop

- On-going Collaboration with KRRI, Changwon National University, and SuNAM
  - No-Insulation HTS linear synchronous motor
  - Construction and successful operation completed in 2015.
  - A scale-up project under preparation in collaboration with KRRI, KERI, CNU and SuNAM.

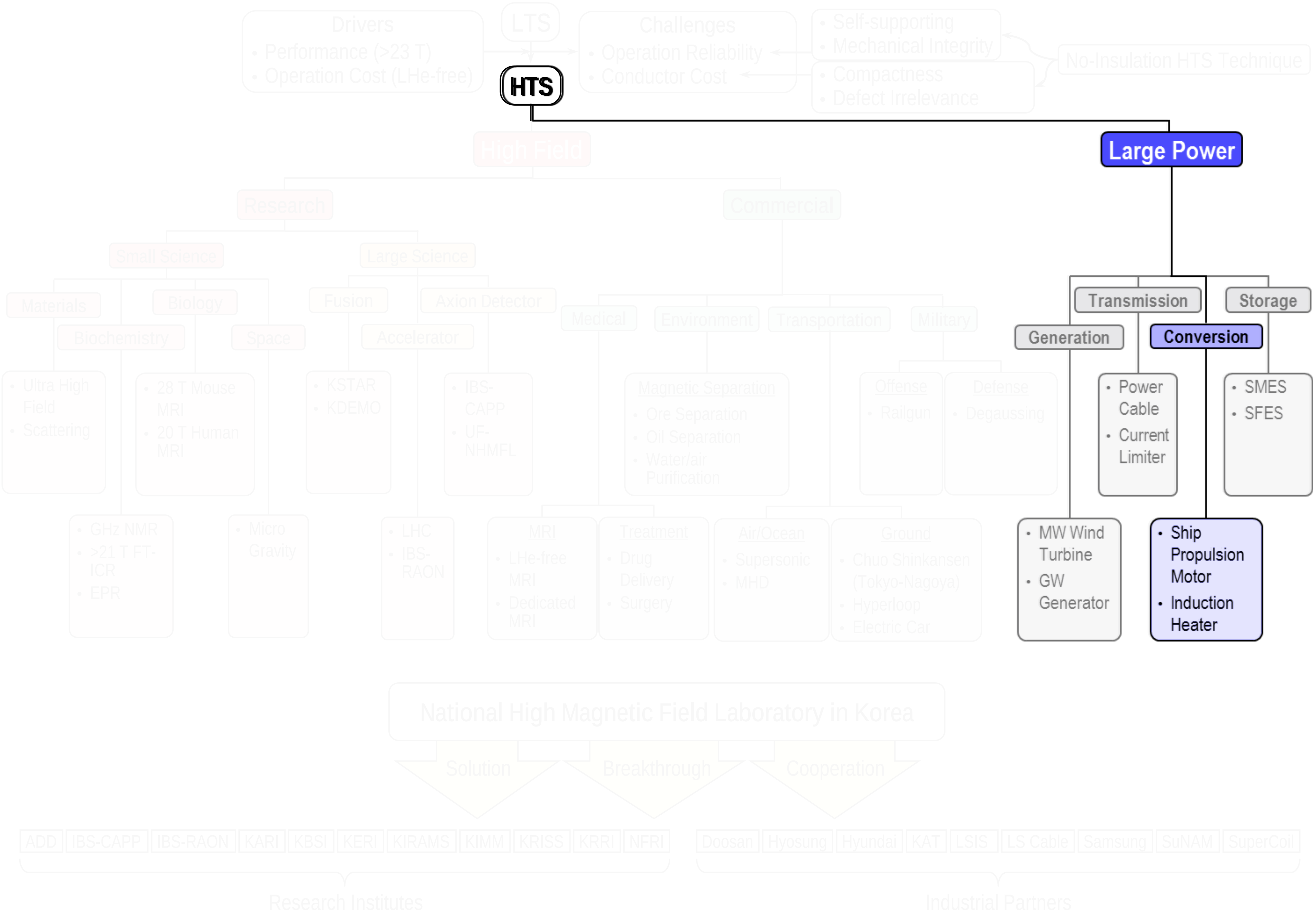


Courtesy: C. Lee (KRRI) and S. Kim (CNU)



REF: Hyperloop, wikipedia

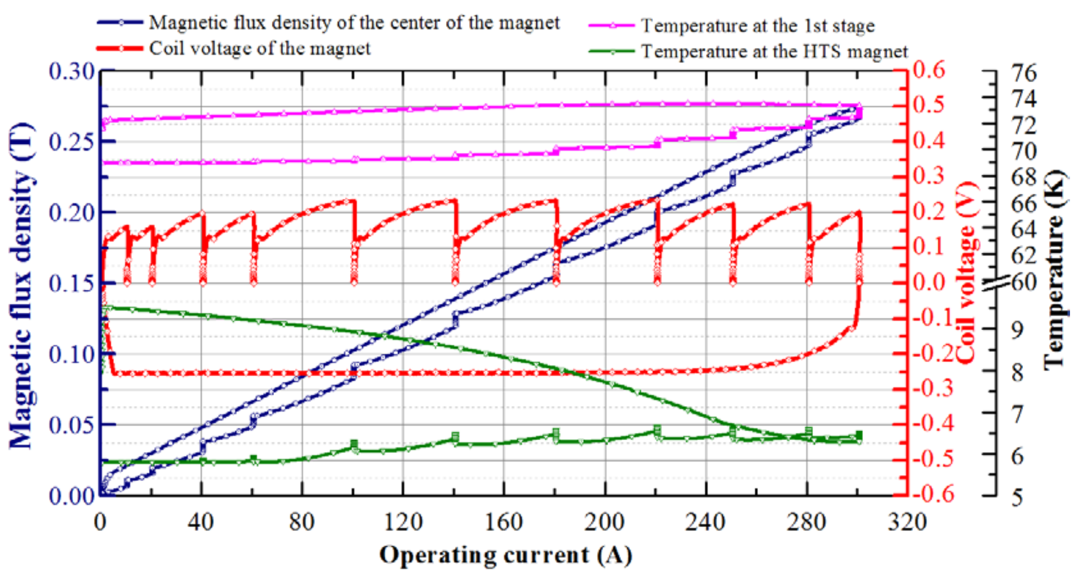
S. Hahn
<hahnsy@snu.ac.kr>



S. Hahn
<hahnsy@snu.ac.kr>

300 kW 1.2 m x 0.6 m MI Magnet for Induction Furnace (2017, CNU)

- *"Largest Bore-Size" NI-class Magnet*
  - "10 kW" success in 2015 (full demonstration)
  - SuNAM REBCO tape (12mmx 0.1mm), 3.4 km
  - Stainless steel tape co-winding
  - 528 mH without iron core; ~1 hr charging
  - 250 A/mm^2 at 7 K (conduction-cooled)
  - *To be installed at SuperCoil, Co., Ltd., in Korea*



Characteristic Curves of the HTS MI Magnet Fabricated

The Developed 2G HTS Magnet for HTS DC IF.

Excitation Ceremony of the 2G HTS MI Magnet

Ref: Jongho Choi, Minwon Park, Sangho Cho, Development of the large HTS magnet for a 300 kW HTS DC Induction furnace, Excitation Ceremony, 2016. Aug.

Summary

- Significant Progress of NI-REBCO Magnet Technology since 2010

- High Field Research Magnet (Completed)
  - *"Little Big Coil": Record High DC Field of 45.46 T at 1400 A/mm^2 and 700 MPa*
  - *First user experience by IBS-CAPP: 24 T SuNAM/MIT/MagLab Magnet*
  - *First commercial high-field user magnet in Korea: 18 T SuNAM/SNU for IBS-CAPP*
  - *4 T 550 mm x 150 mm quadruple magnet by KERI for IBS-RISP (accelerator)*

- Industrial Applications (Completed)
  - *"Defect-Irrelevant" Behavior → Significant Enhancement in Operation Reliability*
  - *High Gradient Magnetic Separation by Korea University*
  - *Vacuum Tube Maglev by KRRI, CNU, and SuNAM*
  - *Induction Heater (1.2 m x 0.6 m) by Supercoil and CNU*

Application of the NI-REBCO technology is expanding to more challenging systems