Achievements, Progress, and Issus in No-Insulation HTS Coils

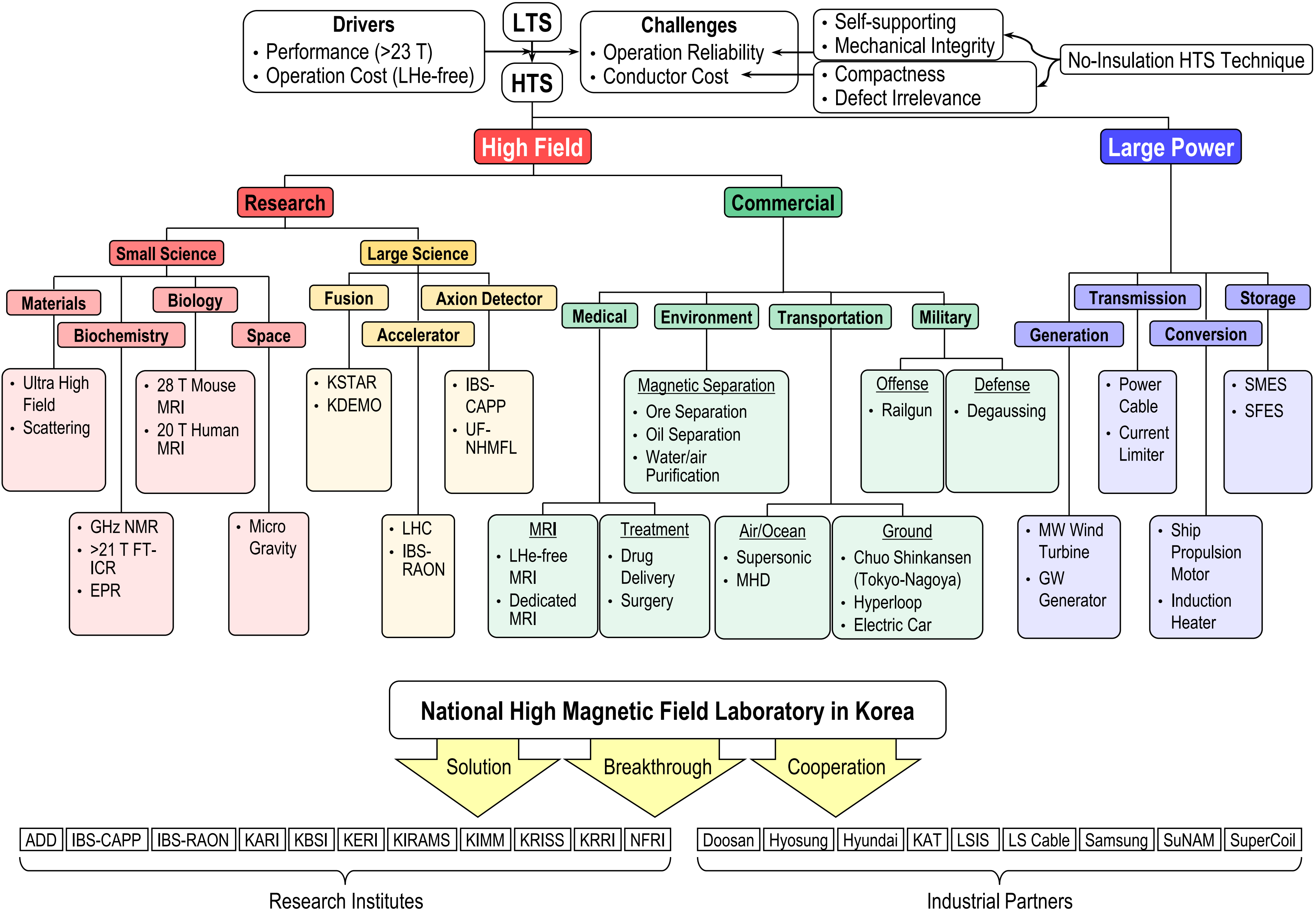
13th European Conference on Applied Superconductivity

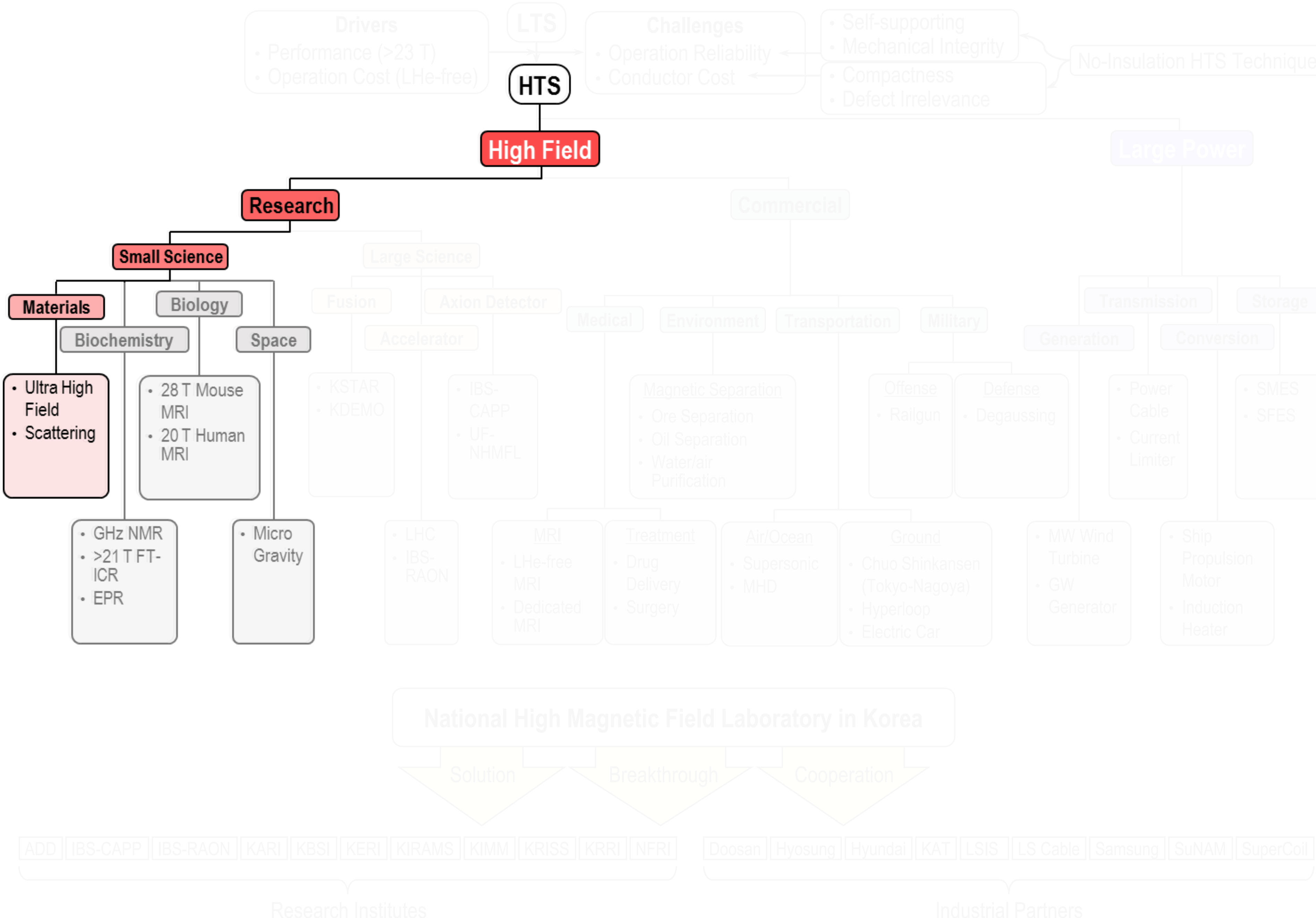
NI-REBCO Team[1] and S. Hahn[1,2]

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

September 20, 2017

Contents

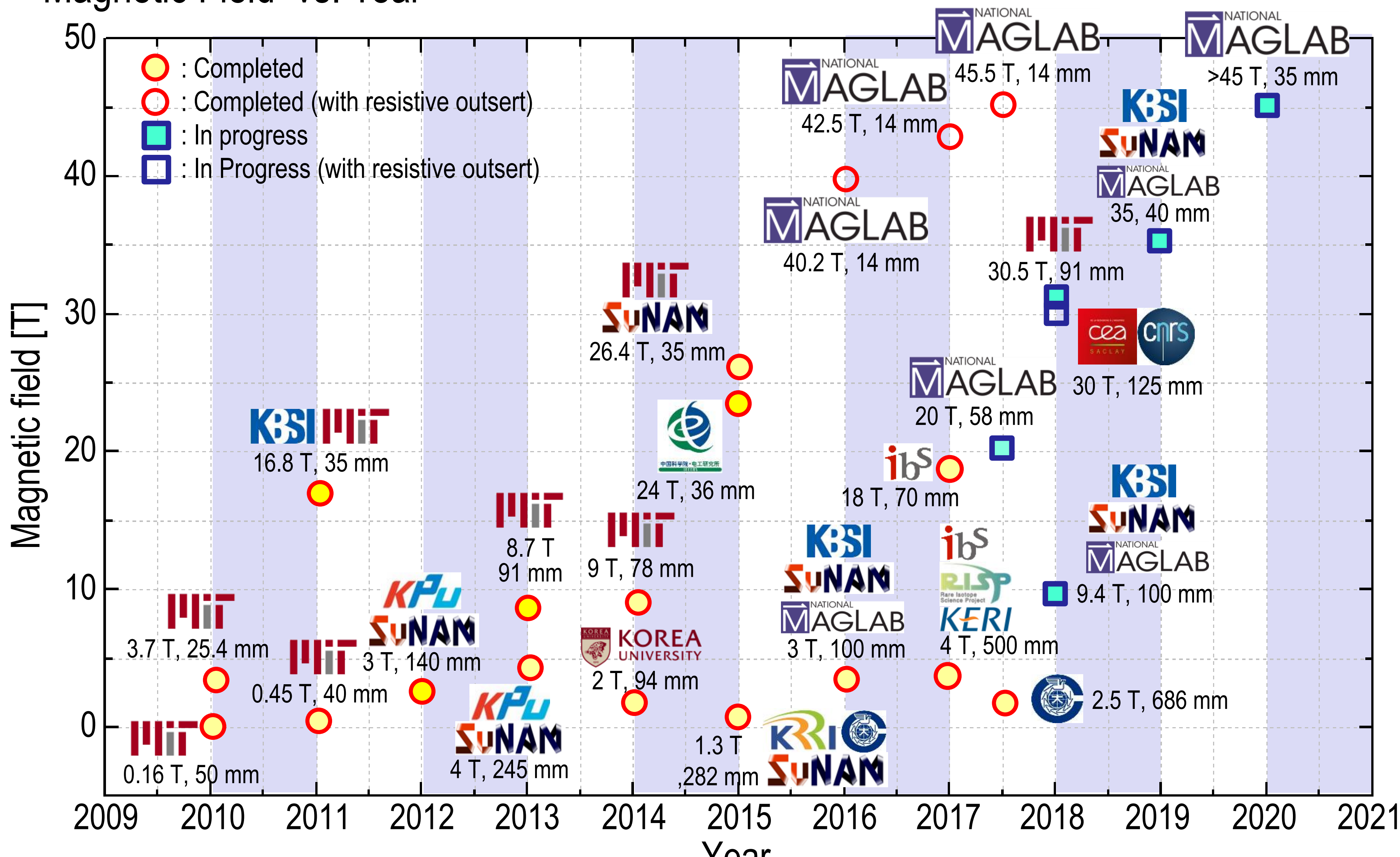

Drivers
• Performance (>23 T)
• Operation Cost (LHe-free)
LTS
HTS
Challenges
• Operation Reliability
• Conductor Cost
• Self-supporting
• Mechanical Integrity
• Compactness
• Defect Irrelevance
No-Insulation HTS Technique
High Field
Large Power
Research
Commercial
Small Science
Large Science
Materials
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



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
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)"

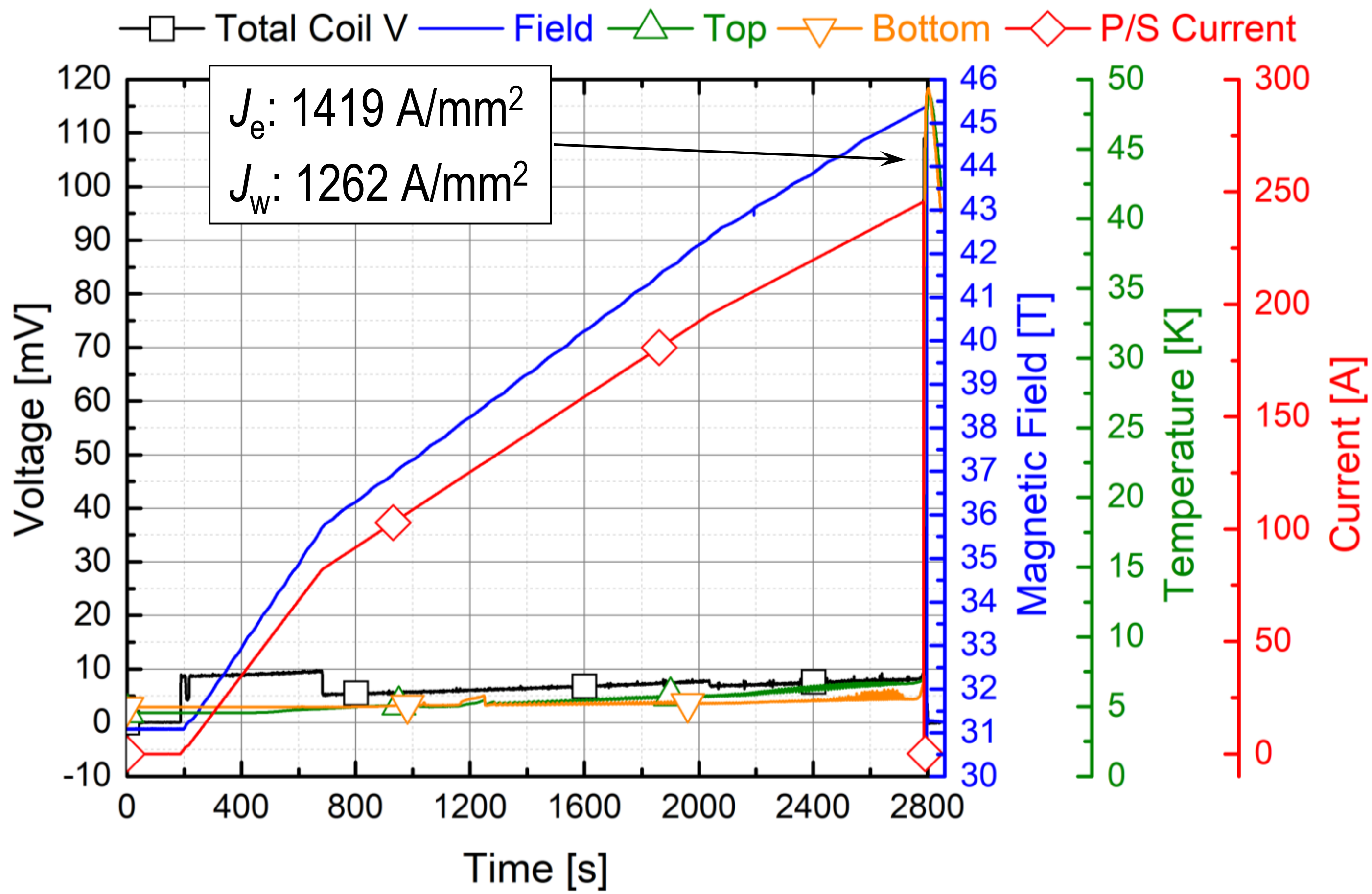
- ID: 14 mm; OD: 34 mm; H: 51 mm
- SuperPower 30 um tape
- Tested in a 31 T resistive magnet

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

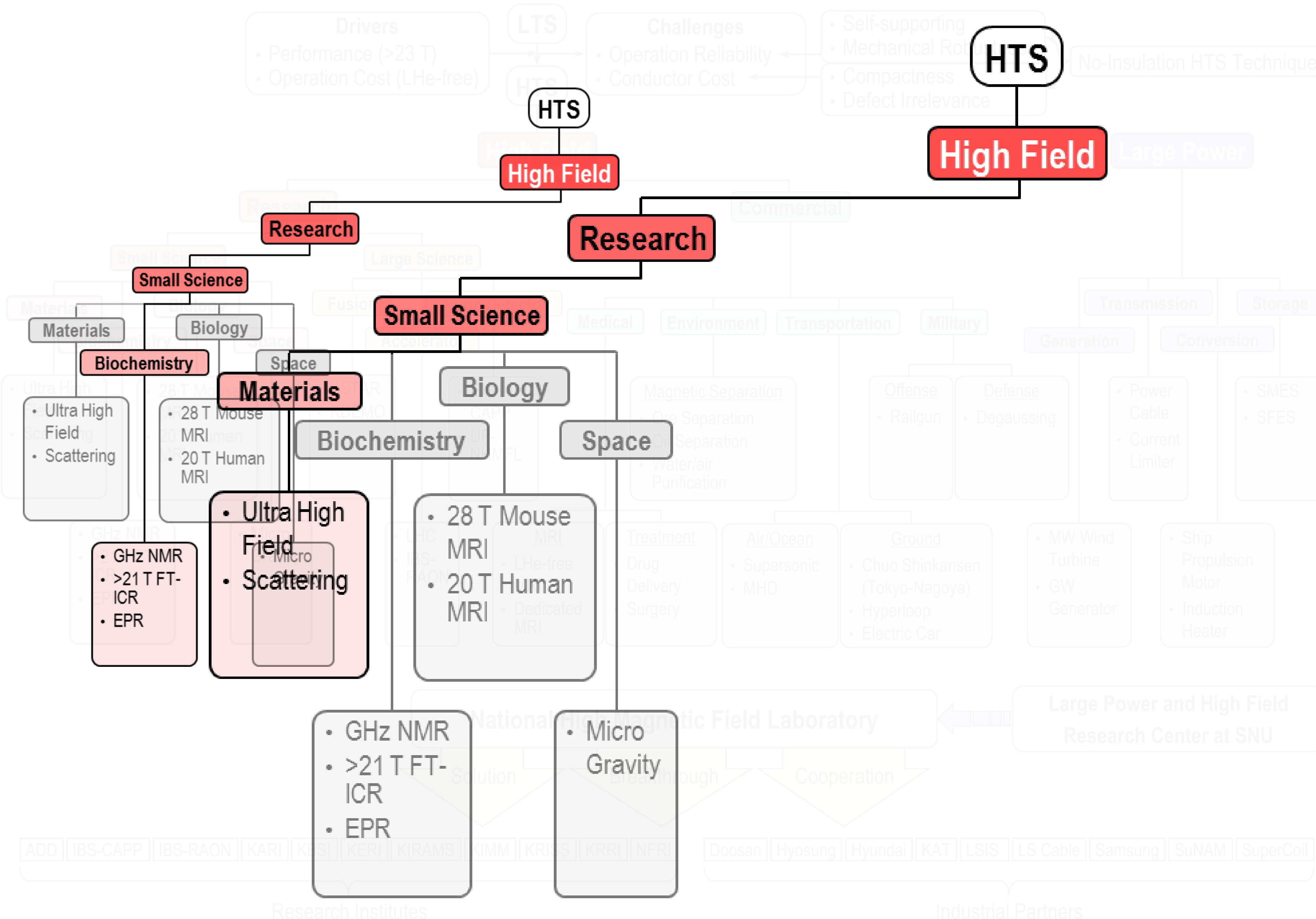
Parameters		Values
REBCO Tape		
Width; thickness	[mm]	4.03; 0.045
Thickness of substrate; copper	[mm]	0.03; 0.01 (5 μm per side)
E_r; E_θ; E_z	[GPa]	69; 144; 144
95-% I_c retention stress	[MPa]	720 (0.5 % strain)
Little Big Coil		
Winding ID; OD; height	[mm]	14; 34; 51
Number of pancakes		12
Turn per 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: 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)

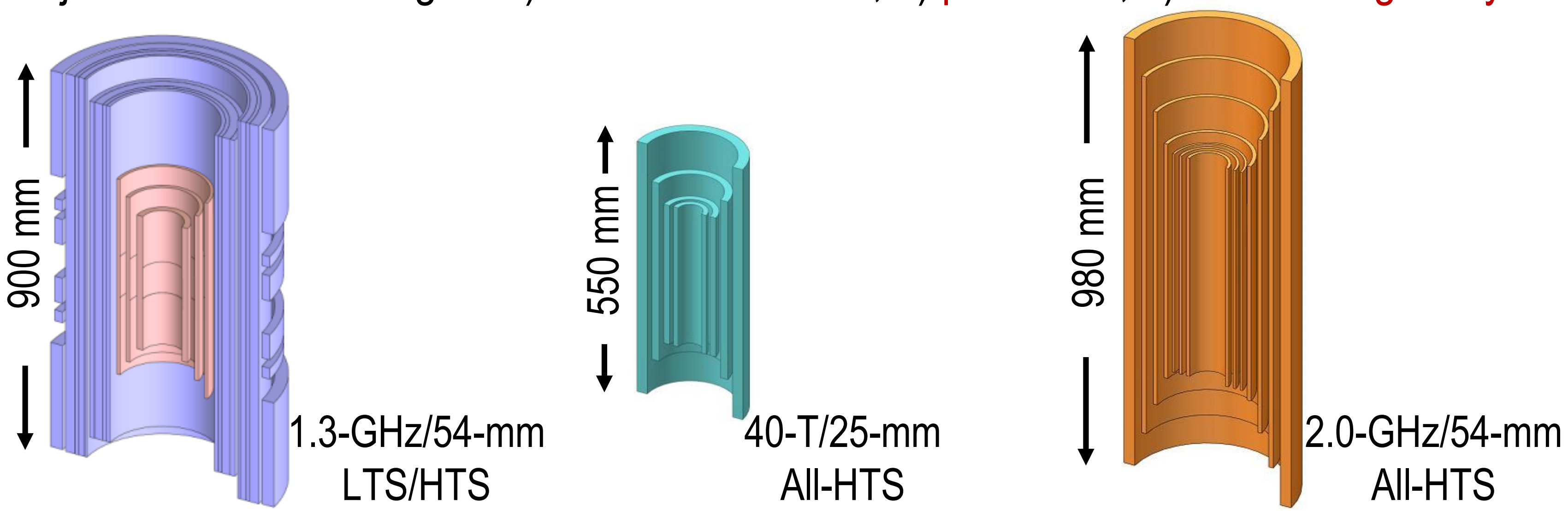


S. Hahn
<hahnsy@snu.ac.kr>


HTS
High Field
Research
Small Science
Materials
Biochemistry
Biology
Space
• Ultra High Field
• Scattering
• GHz NMR
• >21 T FT-ICR
• EPR
• 28 T Mouse MRI
• 20 T Human MRI
• Micro Gravity
HTS
High Field
Research
Small Science
Materials
Biochemistry
Biology
Space
• Ultra High Field
• Scattering
• GHz NMR
• >21 T FT-ICR
• EPR
• 28 T Mouse MRI
• 20 T Human MRI
• Micro Gravity

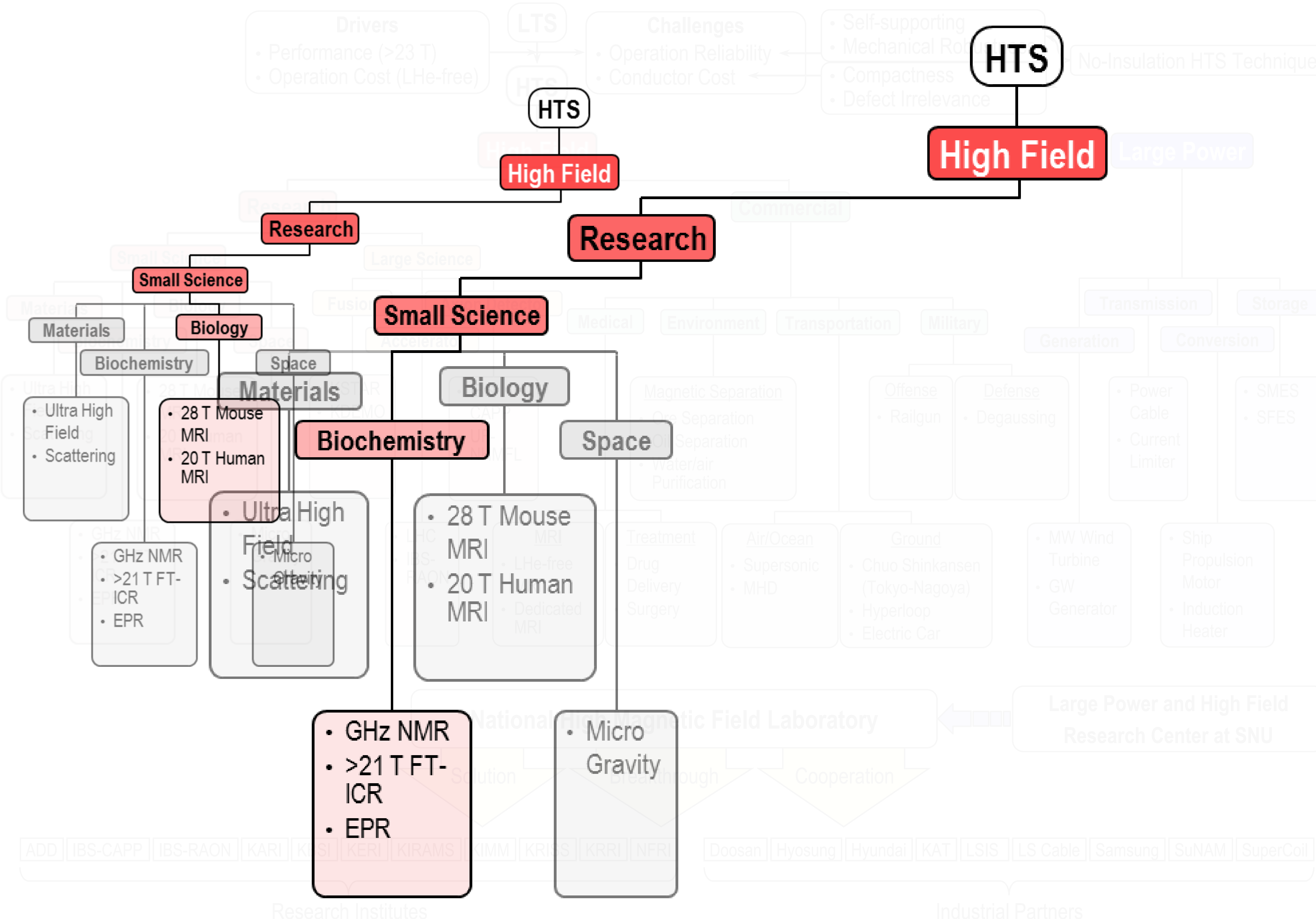
GHz-Class (>23 T) All-HTS High-Resolution NMR Magnet

- Future of HTS NMR Magnet: GHz-NMR
  - HTS conductor cost becomes less pressing for GHz-class NMR magnets.
  - Major technical challenges: 1) mechanical stress; 2) protection; 3) field homogeneity.



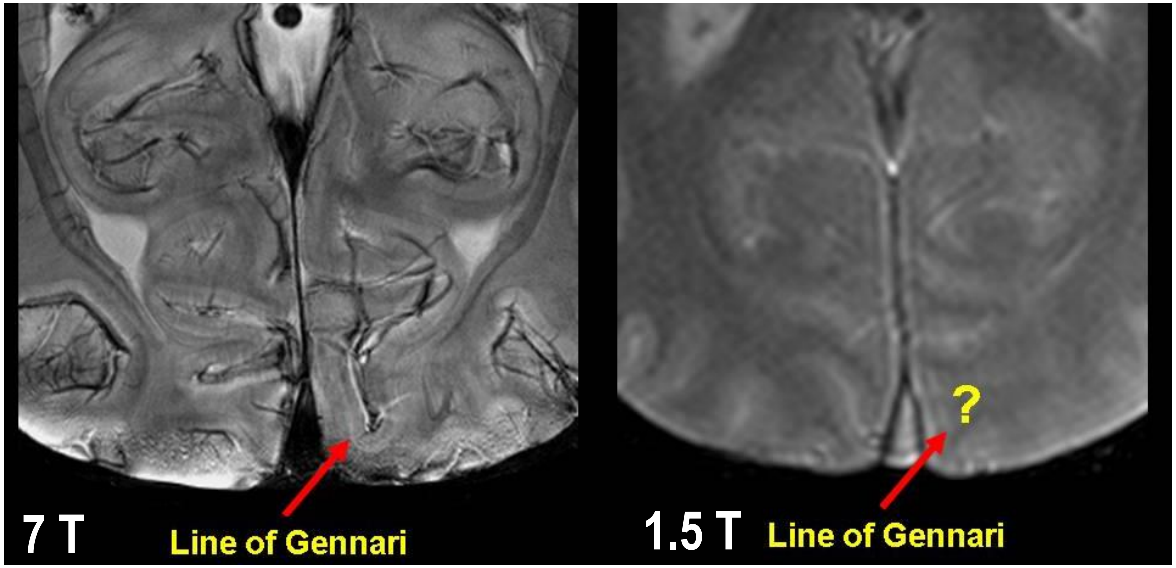
Frequency (LTS/HTS)[GHz]	Field [T]	Bore [mm]	HTS Tape (6-mm) [km]	HTS Tape [USD]	LTS Magnet [USD]	Remark
1.3 (0.5/0.8)	30.5	54	12	$0.60M	$1.0M	MIT on-going program, high-resolution
1.7 (0/1.7)	40.0	25	20	$1.0M	--	Low homogeneity, 300 ppm@2-cm DSV
2.0 (0/2.0)	47.0	54	70	$3.5M	--	High-resolution

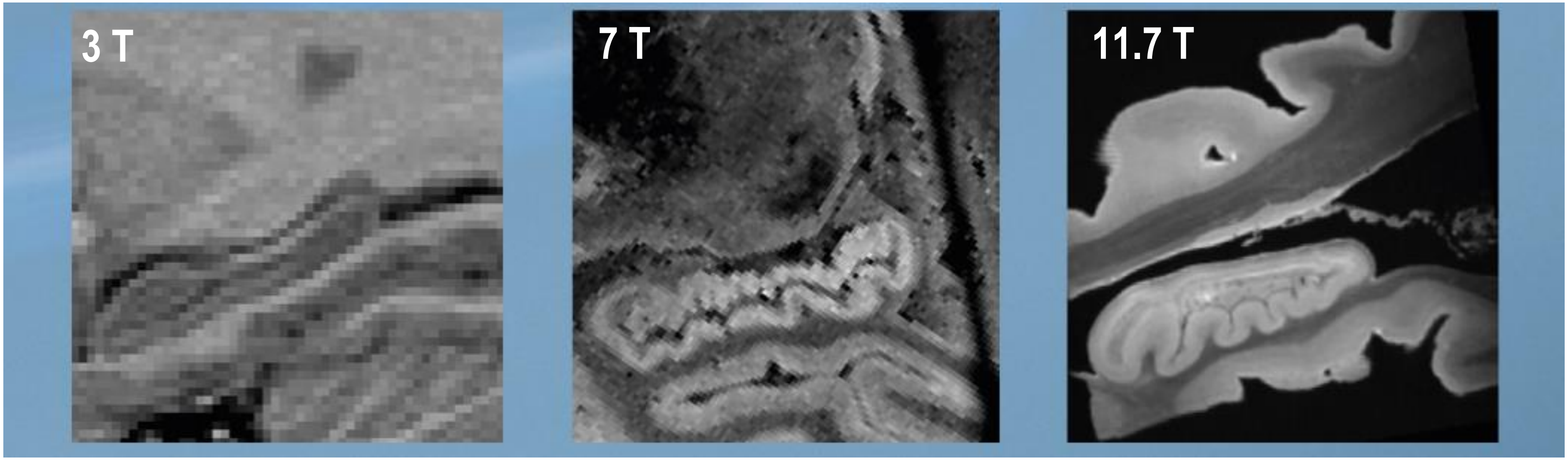
S. Hahn
<hahnsy@snu.ac.kr>


HTS
High Field
Research
Small Science
Biology
Biochemistry
Space
Materials
28 T Mouse MRI
20 T Human MRI
GHz NMR
>21 T FT-ICR
EPR
Micro Gravity
Ultra High Field
Scattering

Importance of “High Field” for MRI

- Comparison of MRI Images: 3 T, 7 T, and 11.7 T



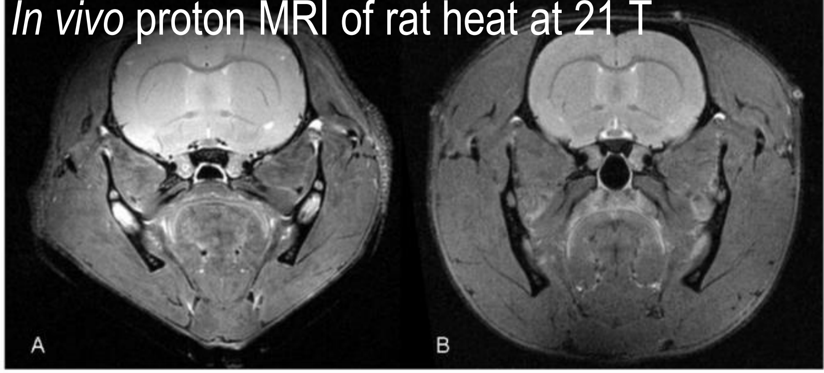


*REF: http://www.cea.fr/english/Pages/News/voyage-aimant-IRM-projet-iseult.aspx

28 T Mouse Brain MRI Magnet

- NI HTS Design (NHMFL)
  - State-of-the-art: 21 T 105 mm magnet at NHMFL.
  - 28 T 120 mm winding ID; 100mm RT bore

In vivo proton MRI of rat heat at 21 T

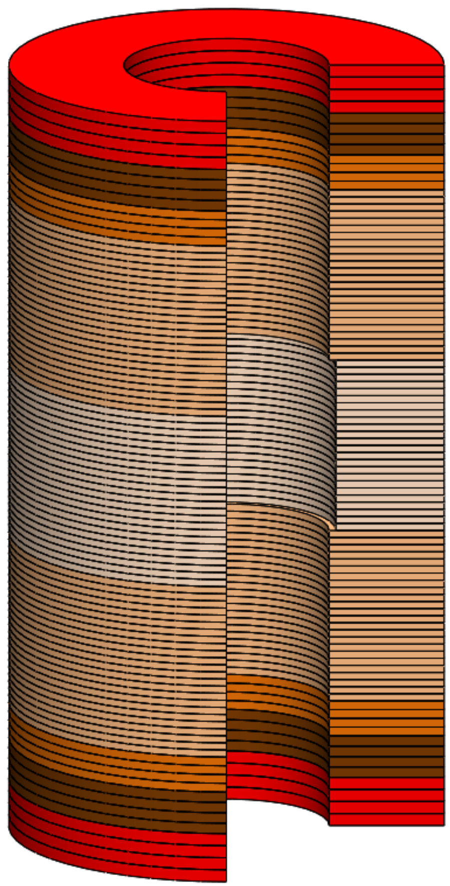


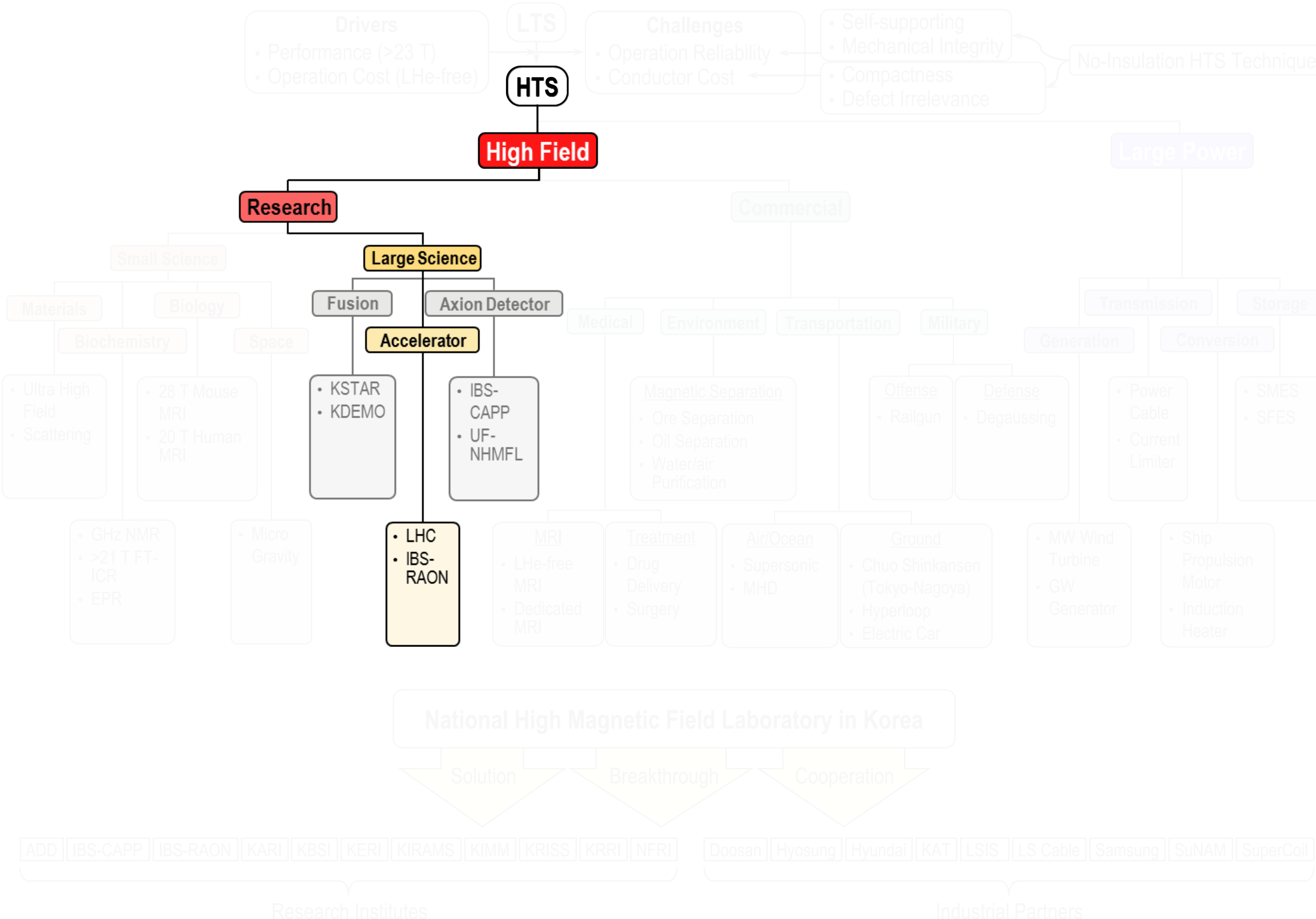
REF: V. Shepkin, et al., *Magn. Reson. Imaging*, 28 (2010), pp. 400-407

Parameters	M1	M1N	M2	M3	M4
REBCO Width [mm]	4.1	4.1	5.1	6.1	7.1
REBCO Thickness [mm]			0.12		
E_r; E_h; E_z [GPa]			107; 173;173		
I_c at 77 K, self [A]	150	150	188	225	263
I_c of 4.1 mm tape at 4.2 K and $B_\perp$ of 5 T [A]			>		
REBCO Insert					
Winding ID [mm]	127.9	120.0	120.0	120.0	120.0
Winding OD [mm]			254.4		
z_1; z_2 [mm]	-51.6; 51.6	51.6; 154.8	154.8; 176.0	176.0; 201.2	201.2; 230.4
Number of double-pancake (DP) coils	12×1	12×2	2×2	2×2	2×2
Turn per "single" pancake coil	527	560			
REBCO tape per DP [m]	633	659			
REBCO tape per module [km]	7.60	15.82			
Total REBCO tape [km]			35.2 (4.1 mm equivalent)		
Inductance [H]			153		
28 T Operation					
Center field [T]			28		
Operating current, I_{op} [A]			197.47		
Conductor current density at I_{op} [A/mm^2]	401	401	323	270	232
B1; B2 at 28 T [T]			28.0;-1.99		
$B_\perp$ (parallel to c-axis) at 28 T [T]	0.8	4.7	5.3	6.0	7.8
Peak bending strain ($r = a_1$) [%]			0.083		
Peak magnetic strain ($r=a_1$) [%]			0.33		
Total mag.+bend. strain at $r=a_1$ [%]			0.42		
Z2 [T/cm^2]			0.267×10^{-3}		
Z4 [T/cm^4]			-0.125×10^{-2}		
Z6 [T/cm^6]			-0.118×10^{-2}		
Overall field homogeneity in $\|z\| < 3$ cm [ppm]			<3		

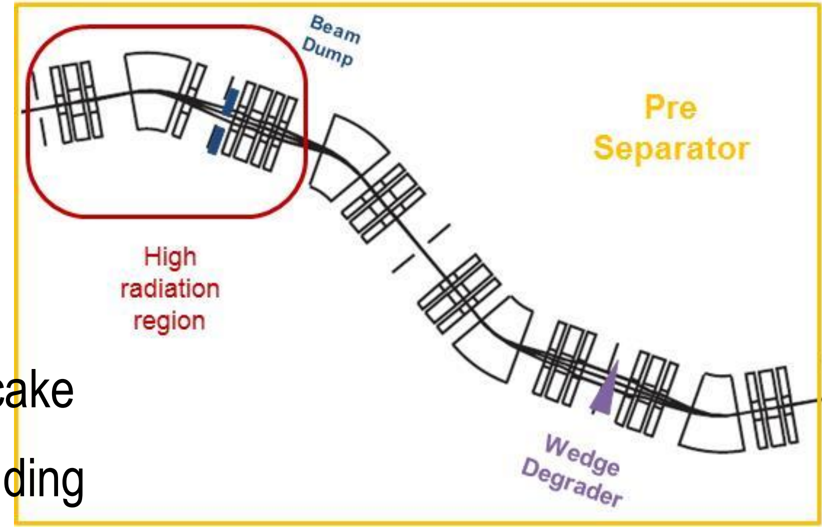
255 mm OD

35 km, 4.1 mm tape

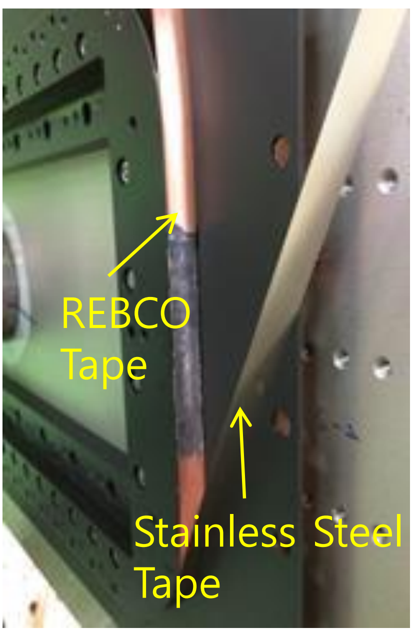


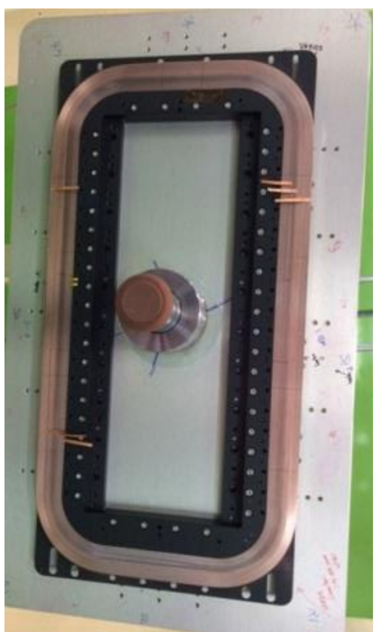

Drivers
• Performance (>23 T)
• Operation Cost (LHe-free)
LTS
Challenges
• Operation Reliability
• Conductor Cost
• Self-supporting
• Mechanical Integrity
• Compactness
• Defect Irrelevance
No-Insulation HTS Technique
HTS
High Field
Large Power
Research
Commercial
Small Science
Large Science
Materials
Biology
Biochemistry
Space
Fusion
Axion Detector
Accelerator
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

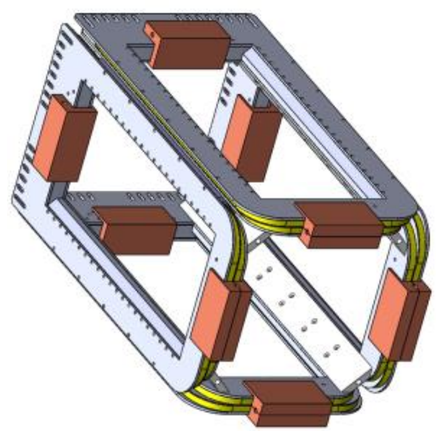
4 T Quadruple Magnet for Rare Isotope Accelerator (2021, IBS-KERI)

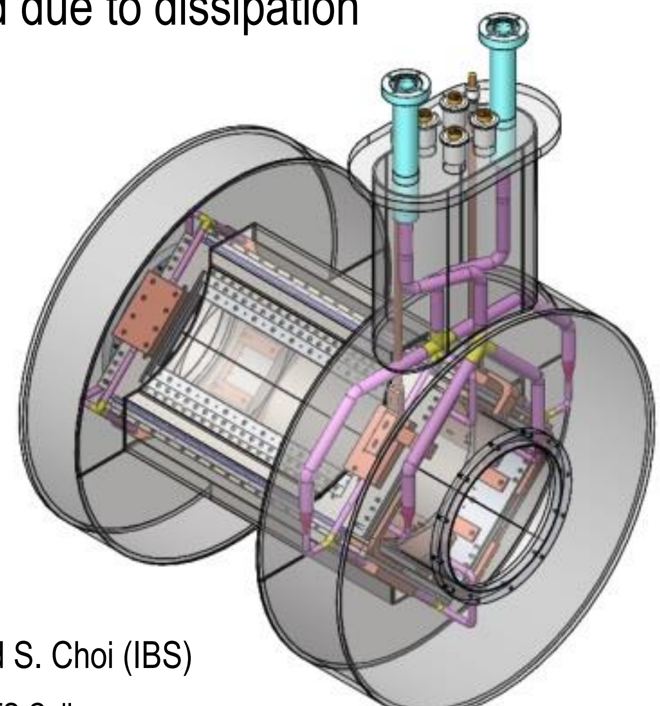


- ***First MI REBO Coil for Actual Accelerator***
  - REBCO magnet for high radiation region
  - Large temperature margin of HTS
  - LHe-free operation (40 K, GHe)
  - 550 mm x 150 mm “window-frame” double-pancake
  - SuNAM & SuperPower, 12 mm wide; SS co-winding
  - Major challenges: I_c degradation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

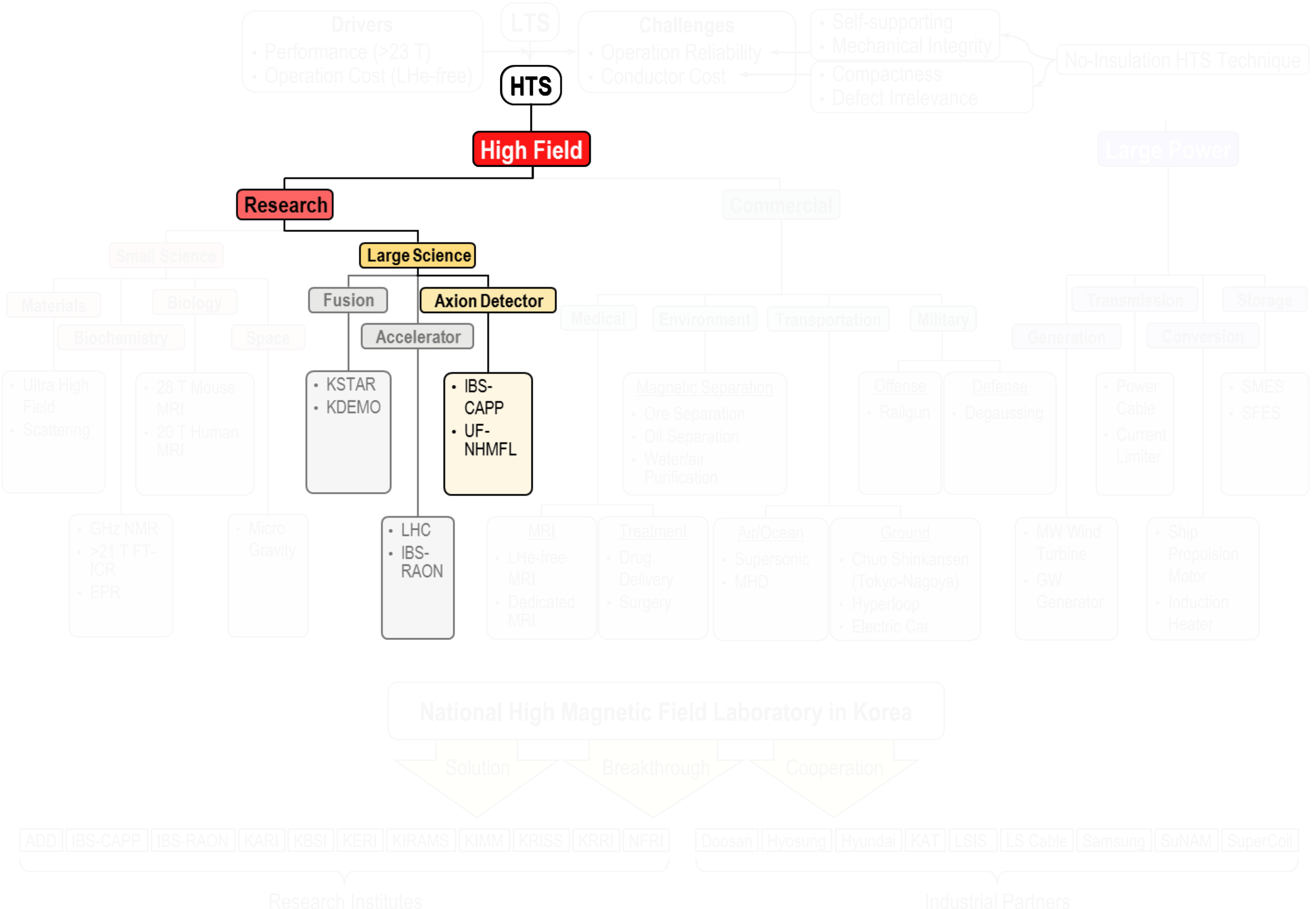






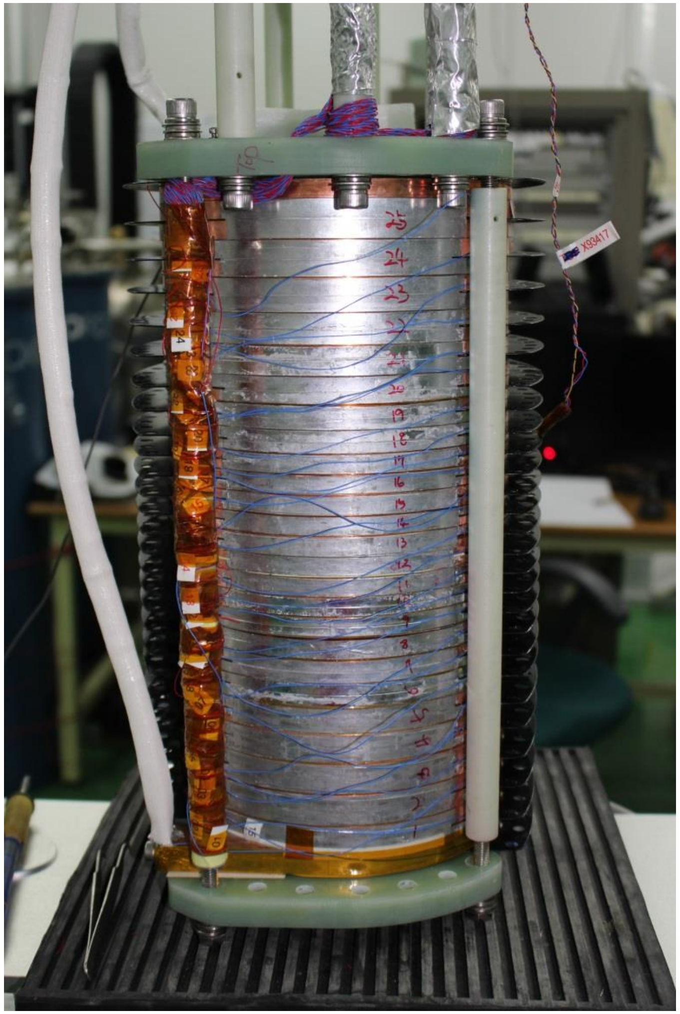


Courtesy to K. Sim (KERI) and S. Choi (IBS)


HTS
High Field
Research
Large Science
Fusion
Accelerator
Axion Detector
• KSTAR
• KDEMO
• IBS-CAPP
• UF-NHMFL
• LHC
• IBS-RAON

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.

24-T/35-mm MW-NI All-REBCO Magnet (2017, 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)

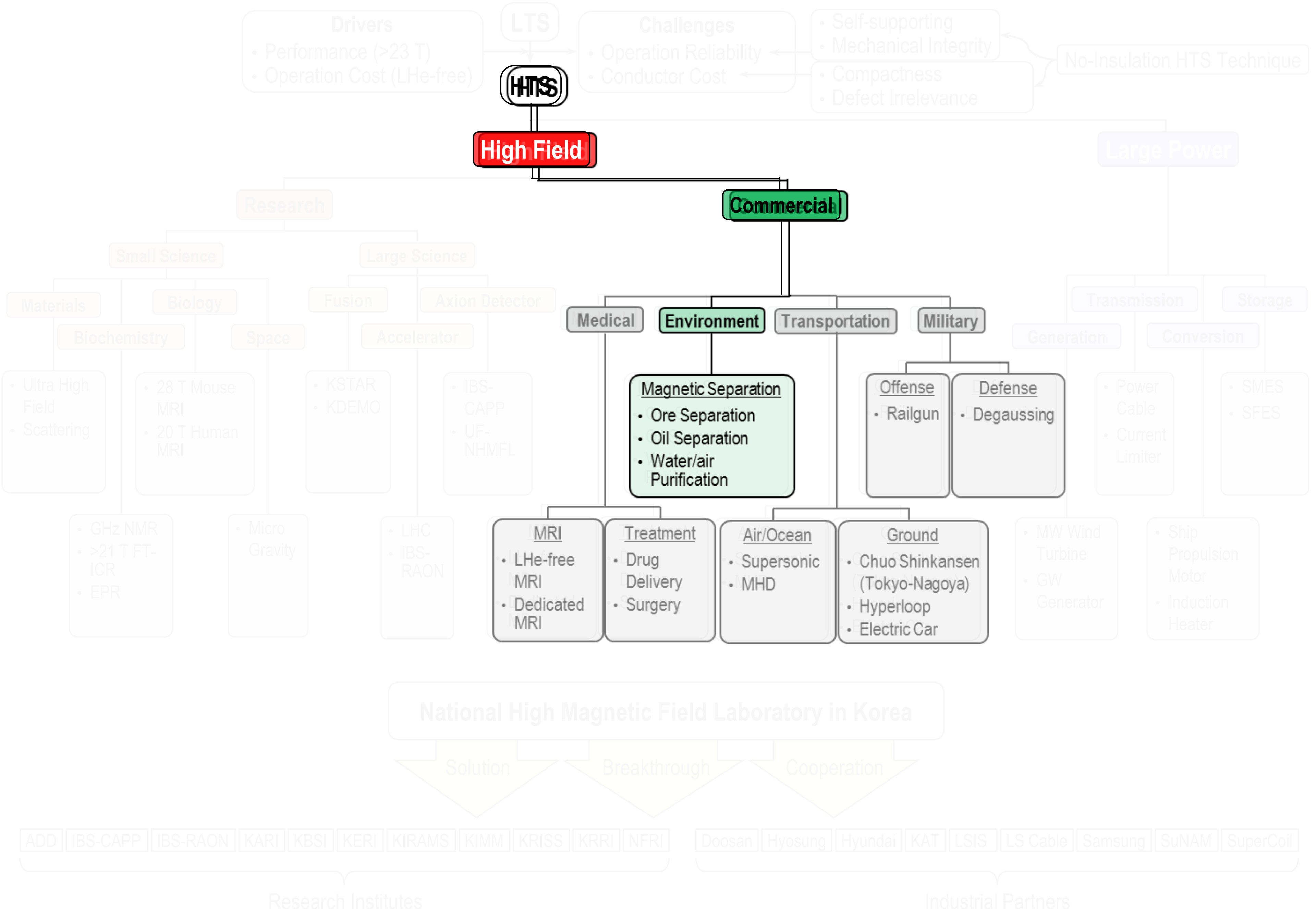
18 T 70 mm NI-REBCO Magnet by SuNAM for IBS-CAPP

- The First Commercial HTS Magnet in Korea
  - Completed in 2 months after design and delivered to the IBS in August 2017
  - Total heat input + generation: ~1 W (1.4 L/hr LHe consumption)

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

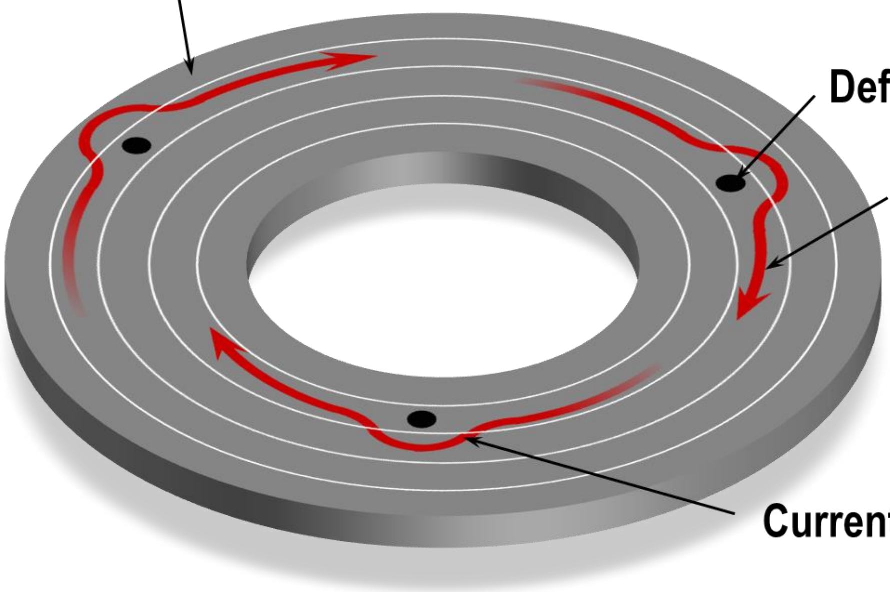
Courtesy to SuNAM, Co., Ltd.



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

Defect Irrelevant Winding (DIW)

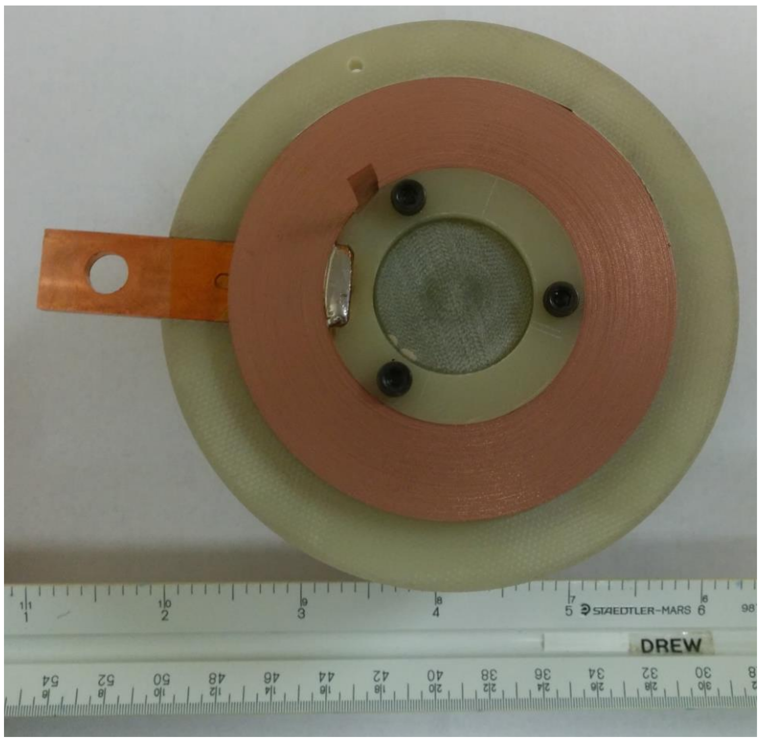
- Key Concept
  - An REBCO NI coil having multiple defects (or even discontinuity)



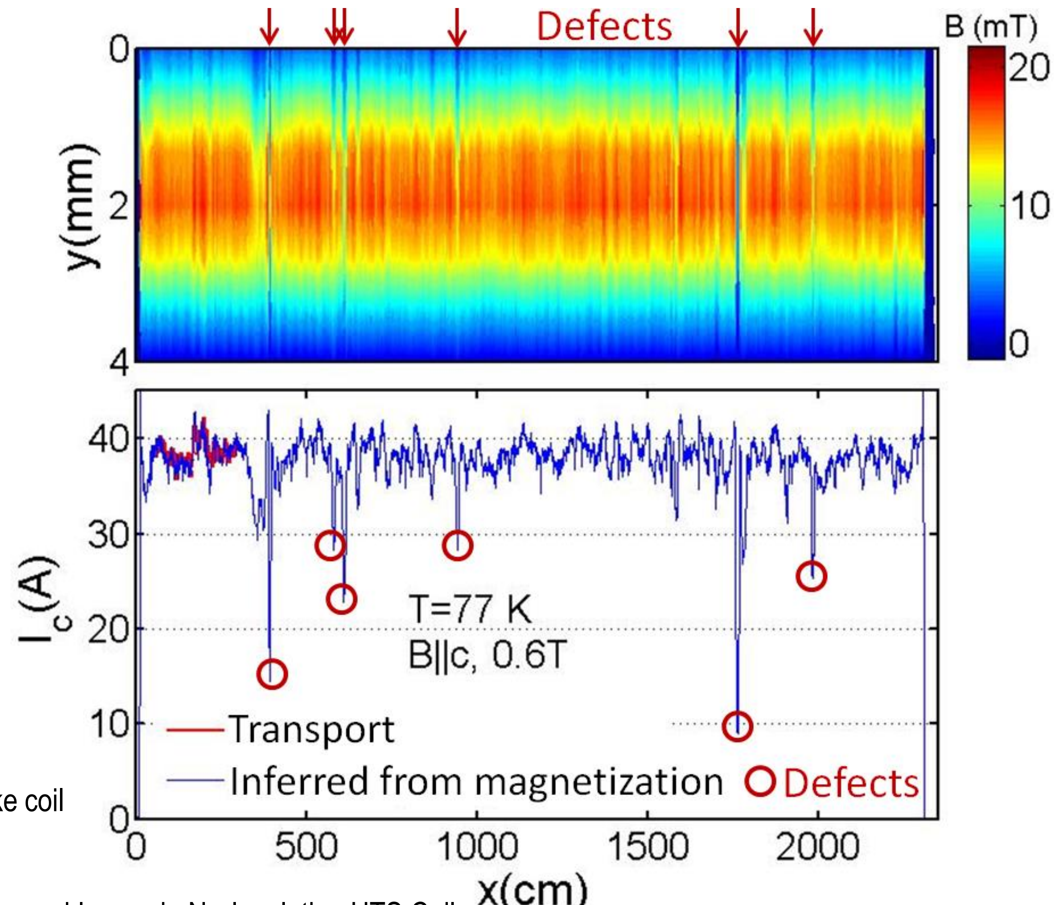
Ref: S. Hahn, et al., "Defect-irrelevant behavior of a no-insulation pancake coil wound with REBCO tapes containing multiple defects," *Supercond. Sci. Technol.*, **29**: 105017, 2016.

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



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



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.

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

Operational Reliability Test of an NI HTS Coil by KERI

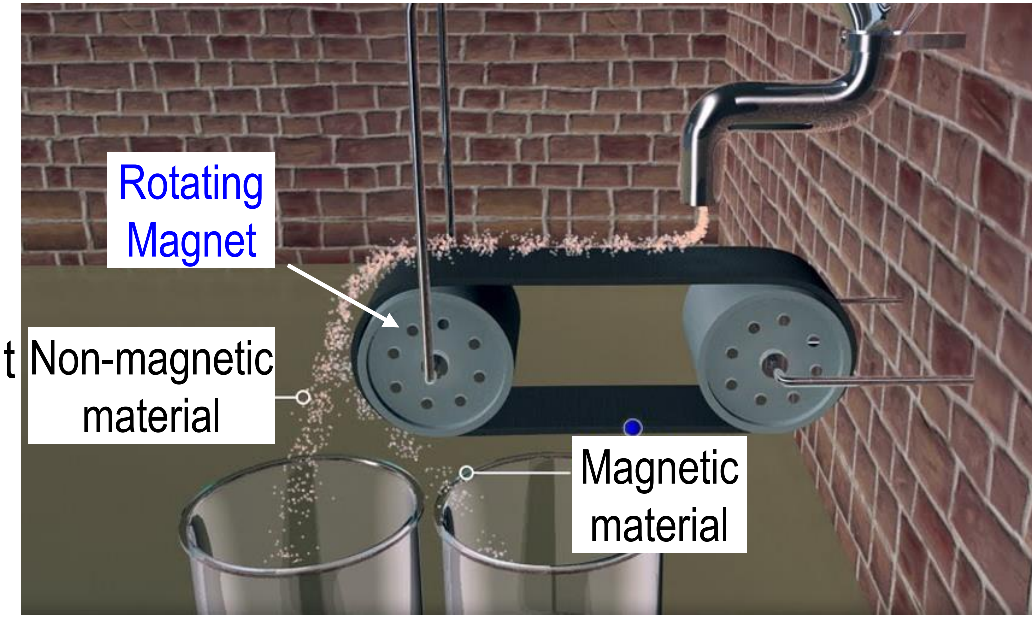
- HTS Coil Operation under “Mechanically Extreme Conditions”
  - 3 types of extreme conditions: (1) hammering; (2) nailing; and (3) drilling
    → barely discernible degradation of the coil performance.

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

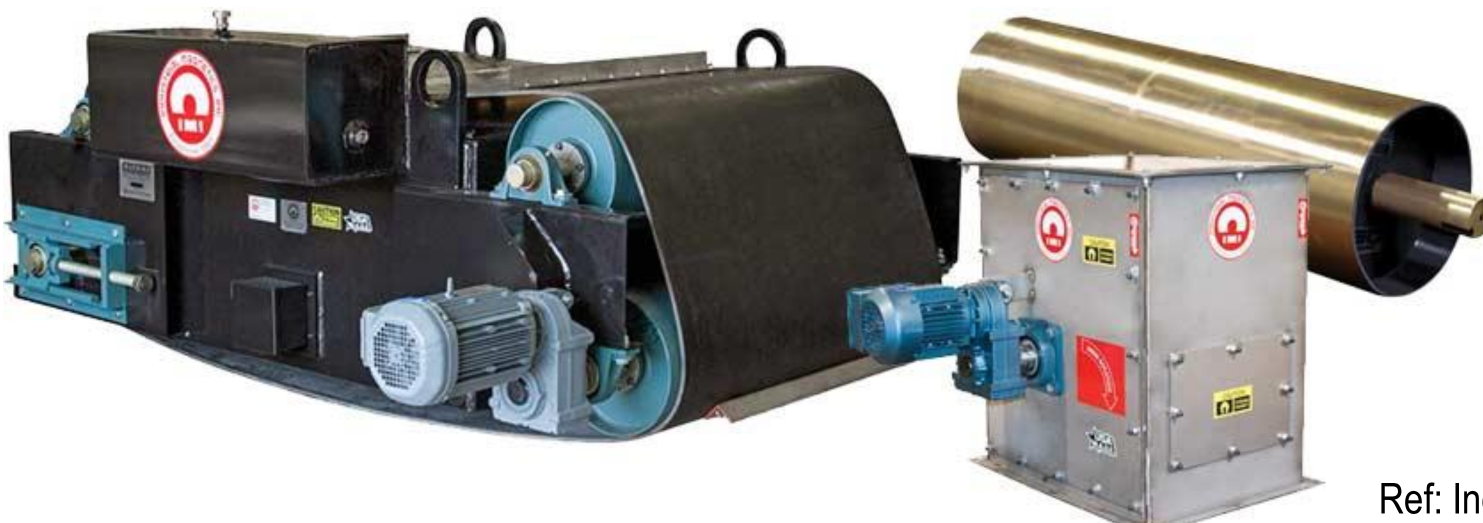
Mining Industry: Concentration of Ores

- Magnetic Separation of Ores
  - Separation of magnetic ores from non-magnetic ores
  - Commonly used in mining industry
  - Size and power limits of the conventional system with permanent or electromagnets
  - Superconducting system: low operation cost but high device cost

Basic Concept: Magnetic Separation of Ores



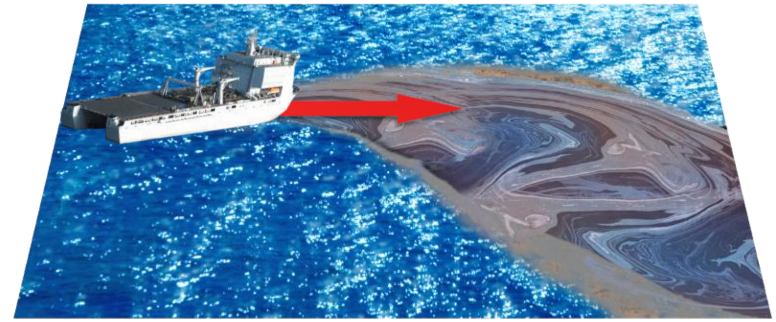
Ref: 7 Active Studio

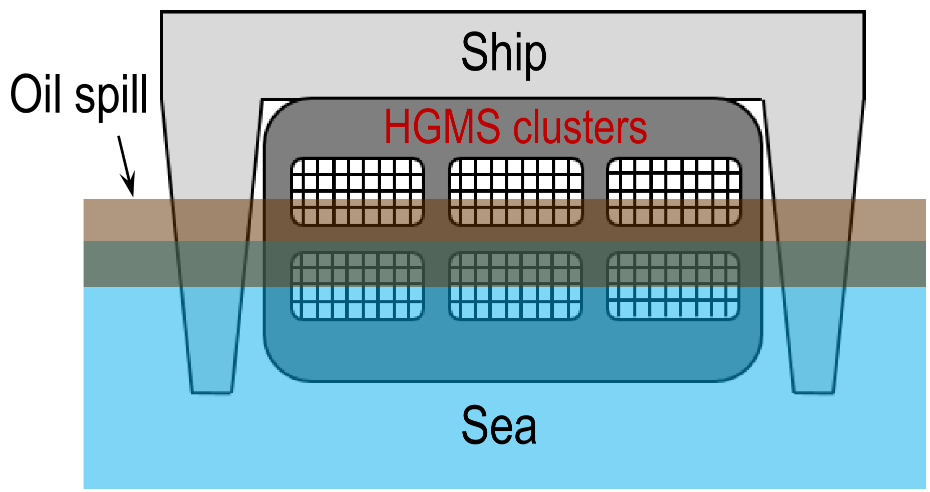


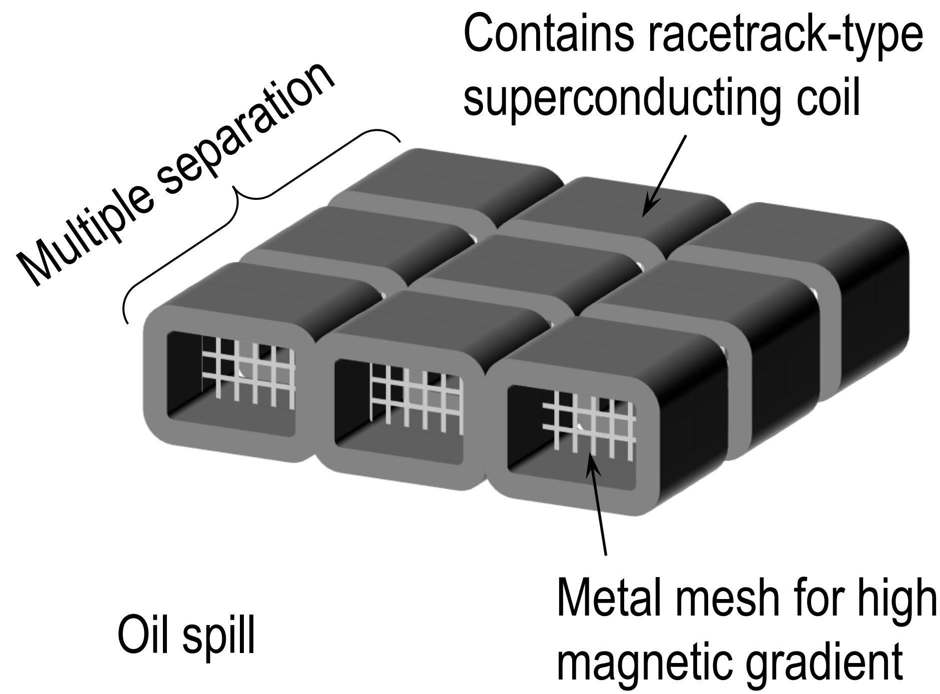
Ref: Industrial Magnetics, Inc.

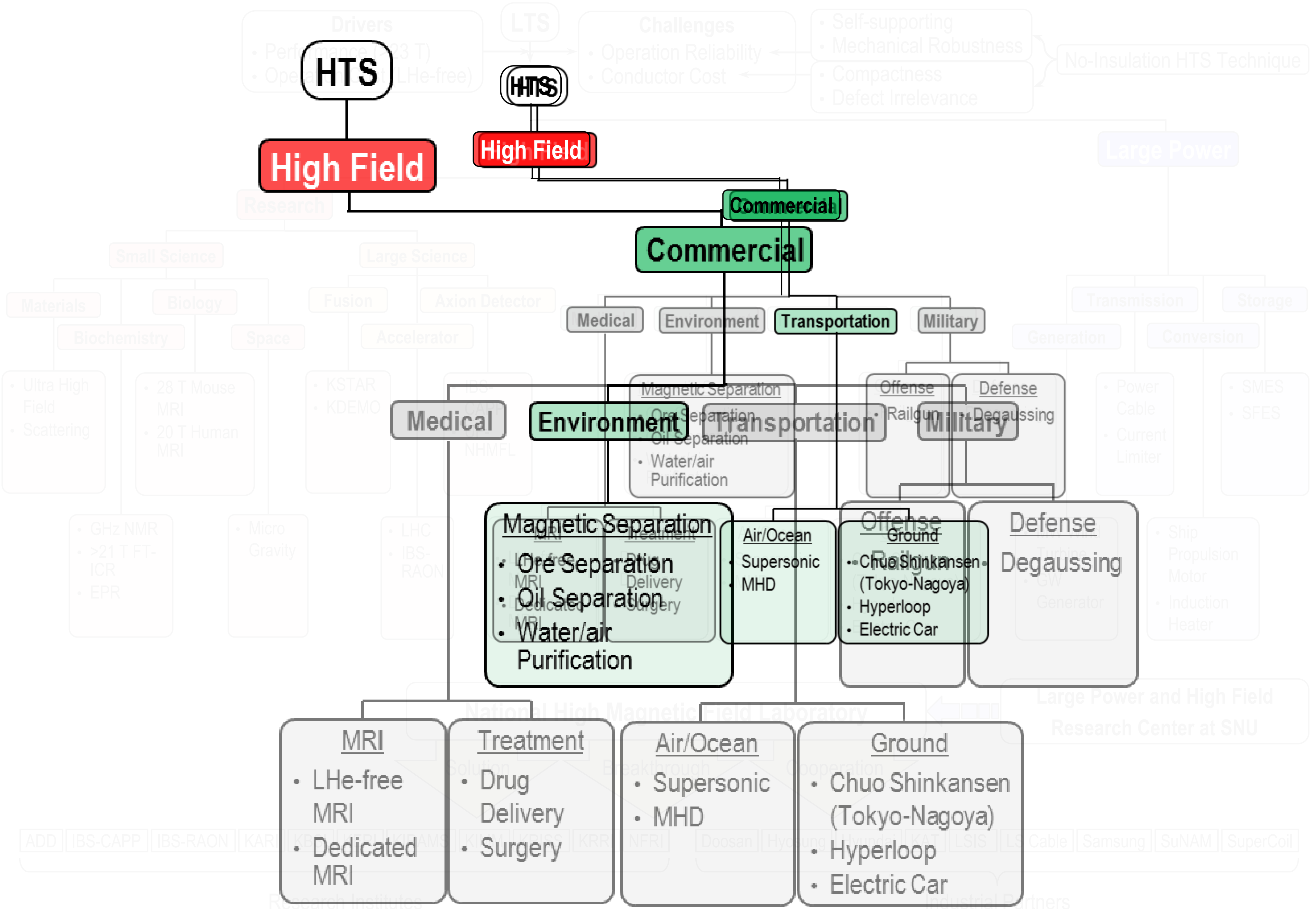
Magnetic Oil Spill Separation

- Compact "Honeycomb" NI-HTS Magnet Array
  - Cleanup and recovery of oil spill in ocean
  - Use of a compact "honeycomb" NI-HTS magnet array with ferrous nanoparticles
  - "Defect-Irrelevant-Winding" to significantly reduce the magnet construction cost (patent submitted).





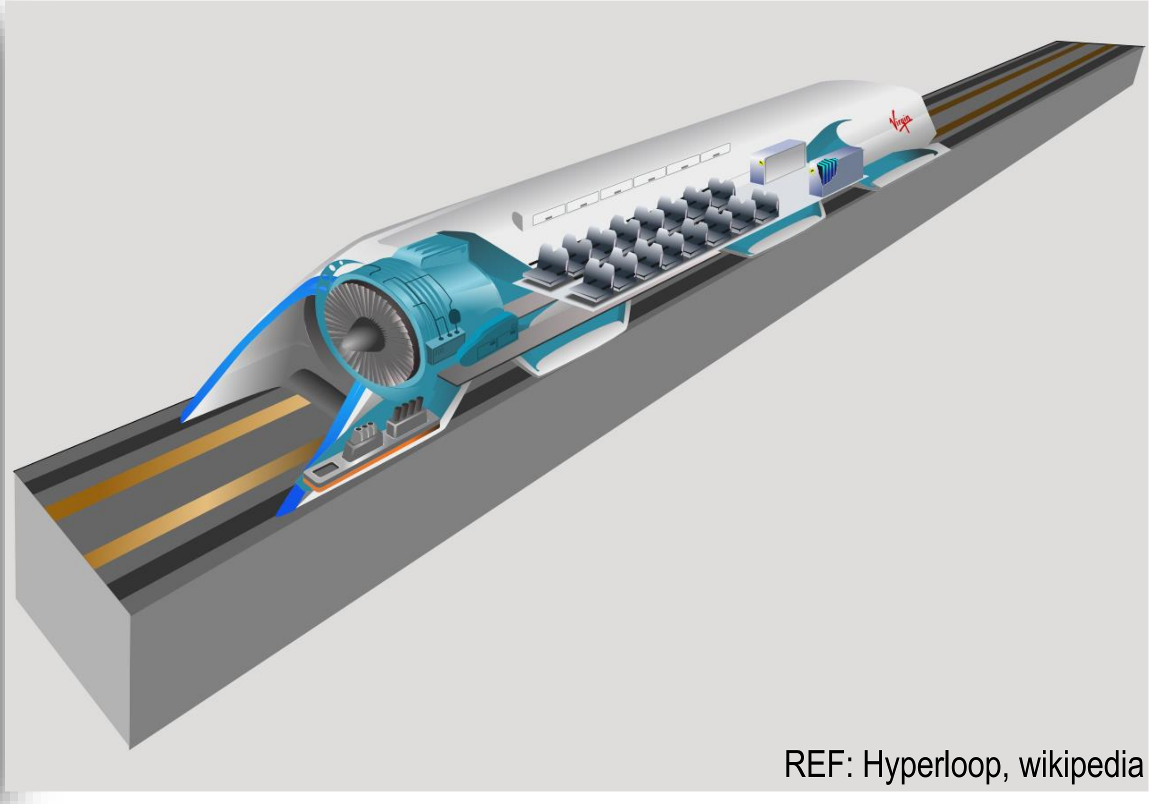


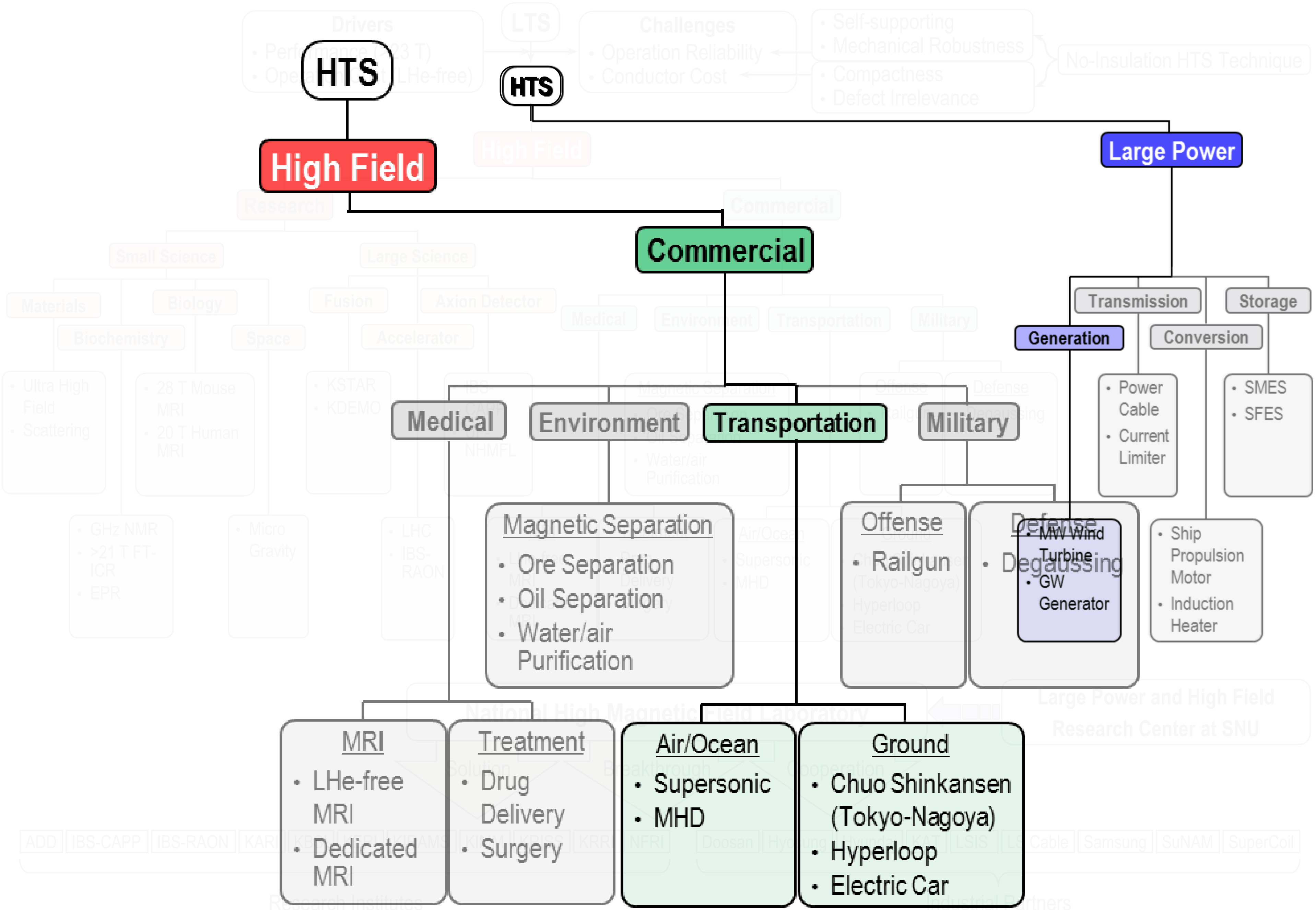

HTS
High Field
Commercial
Medical
Environment
Transportation
Military
Magnetic Separation
Ore Separation
Oil Separation
Water/air Purification
Air/Ocean
Supersonic
MHD
Ground
Chuo Shinkansen (Tokyo-Nagoya)
Hyperloop
Electric Car
Offense
Railgun
Defense
Degaussing
MRI
LHe-free MRI
Dedicated MRI
Treatment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

"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.

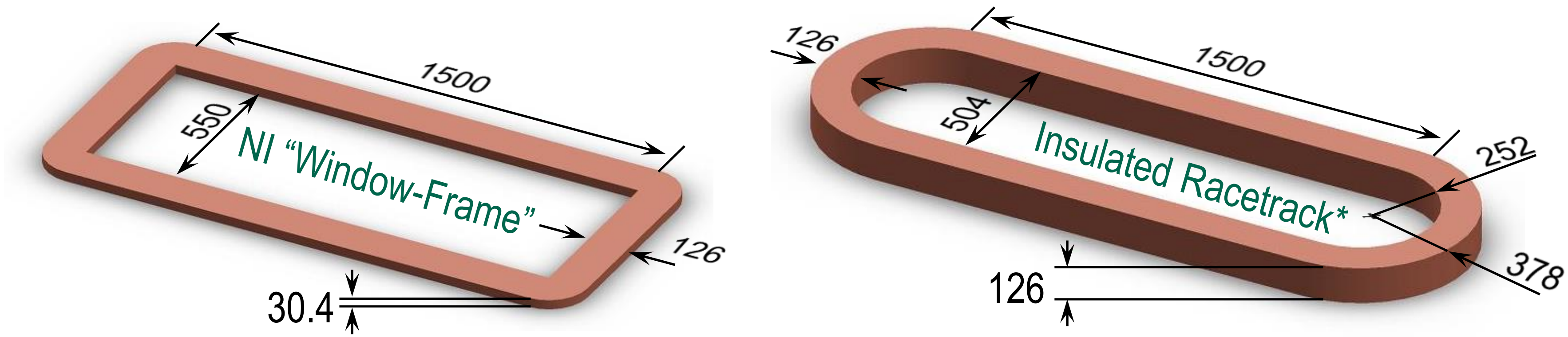

Courtesy: C. Lee (KRRI) and S. Kim (CNU)


REF: Hyperloop, wikipedia


HTS
HTS
High Field
Large Power
Commercial
Transmission
Storage
Generation
Conversion
Power Cable
Current Limiter
SMES
SFES
Medical
Environment
Transportation
Military
Magnetic Separation
Ore Separation
Oil Separation
Water/air Purification
Offense
Railgun
Defense
Degaussing
MW Wind Turbine
GW Generator
Ship Propulsion Motor
Induction Heater
MRI
LHe-free MRI
Dedicated MRI
Treatment
Drug Delivery
Surgery
Air/Ocean
Supersonic
MHD
Ground
Chuo Shinkansen (Tokyo-Nagoya)
Hyperloop
Electric Car

No-Insulation Field Coil for MW-Class HTS Wind Generators

- HTS Field Coils for 10-MW Generator, No-Insulation vs. Insulated
  - NI features: compact, mechanically robust and self-protecting
  - Efficient conduction cooling owing to reduced thermal contact resistance

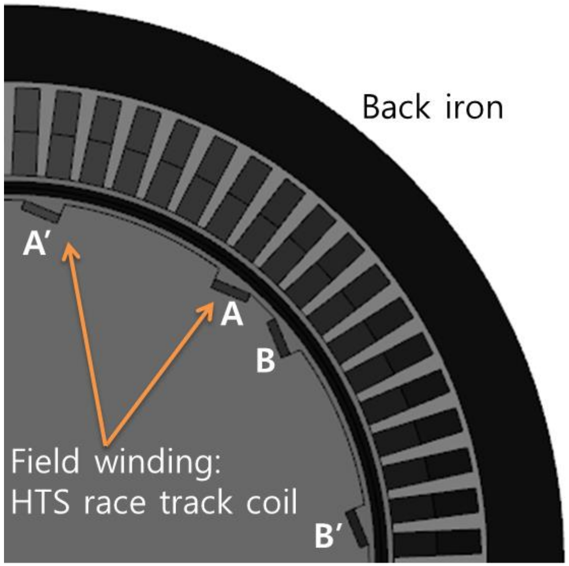


Parameters		NI	Insulated
Winding cross-section	[mm^2]	126 x 30.4	126 x 126
Operating temperature	[K]	20	20
Overall current density	[A/mm^2]	586	168

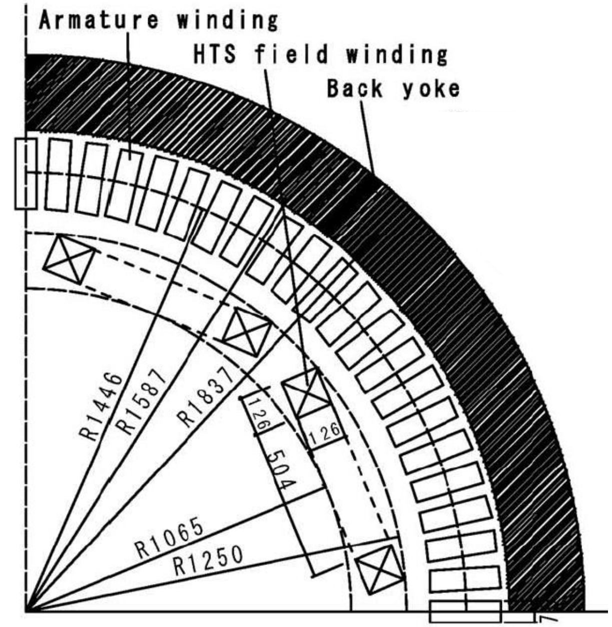
*REF: S. Fukui, et al., "Study of 10 MW-Class Wind Turbine Generators With HTS Field Coils," *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 1151 – 1154, 2011.

Design Comparison of 10-MW HTS Wind Generator, NI vs. Insulated

- NI "Window-Frame" HTS Field Coil

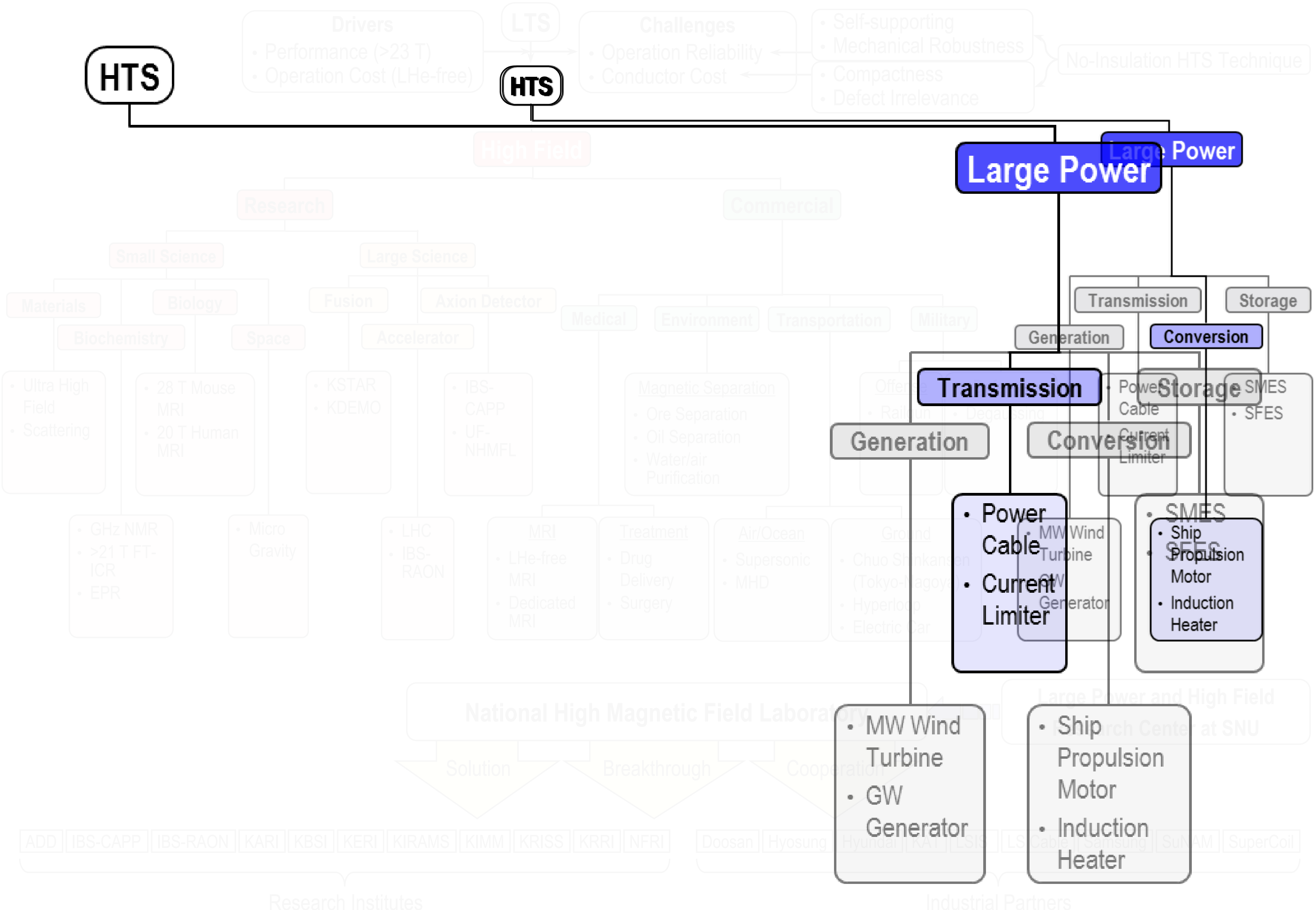


- Insulated Racetrack HTS Field Coil*



Parameters		**NI**	**Insulated**
Rated power	[MW]	10.3	10.2
Rated rotating speed	[rpm]	10	10
Rated phase voltage; line current	[kV; kA]	3.27; 1.81	3.30; 1.75
Total HTS conductor	[ton]	1.8	8.7

*REF: S. Fukui, et al., "Study of 10 MW-Class Wind Turbine Generators With HTS Field Coils," *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 1151 – 1154, 2011.

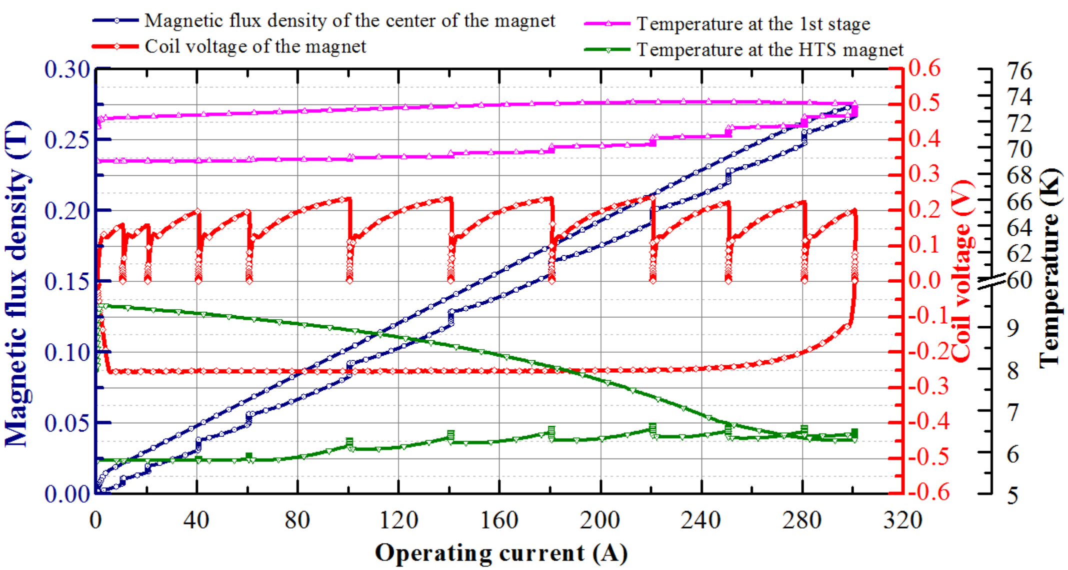


S. Hahn
<hahnsy@snu.ac.kr>

300 kW Induction Furnace (2017, Supercoil & CNU)

- *"1.2 m x 0.6 m" Metallic Insulation Coil*
  - SuNAM 12-mm wide tape
  - Stainless steel tape co-winding
  - 528 mH without iron core; ~1 hr charging
  - Coil survived (self-protecting) after an unexpected quench that led to mechanical failure.

The Developed 2G HTS Magnet for HTS DC IF.



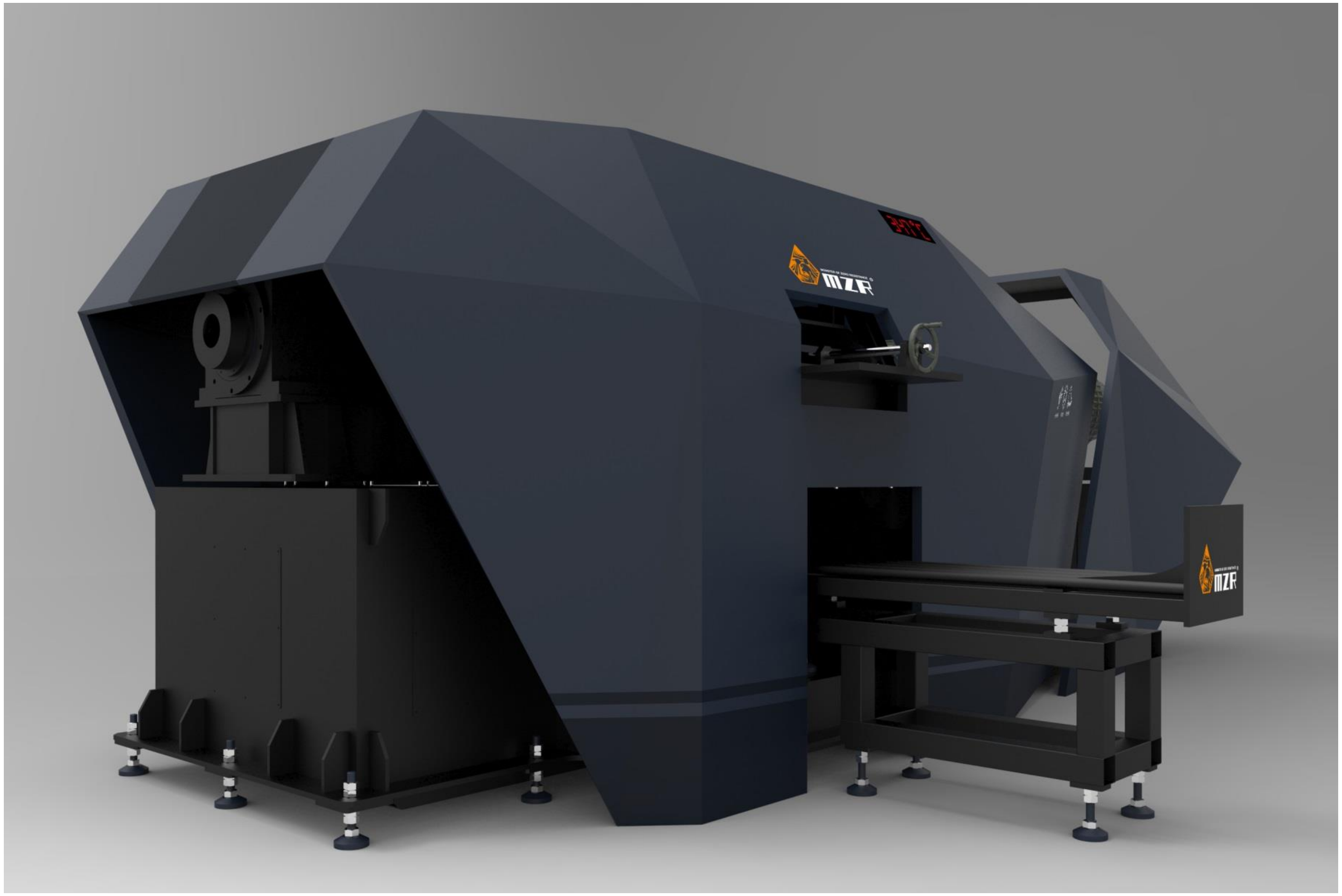
Characteristic Curves of the HTS MI Magnet Fabricated

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.

300 kW Induction Furnace (2017, Supercoil & CNU)

- The First Commercial Industrial Product using HTS (in service since August, 2017)
  - >90 % efficiency vs. 20 – 50 %, conventional
  - ½ footprint and $0.3M less annual operation cost → estimated break-even in 1.5 years.

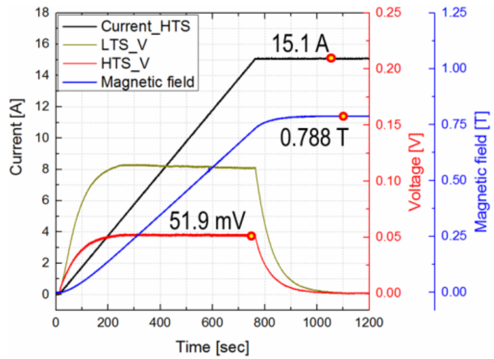


Courtesy to Jongho Choi (SuperCoil, Co. Ltd.)

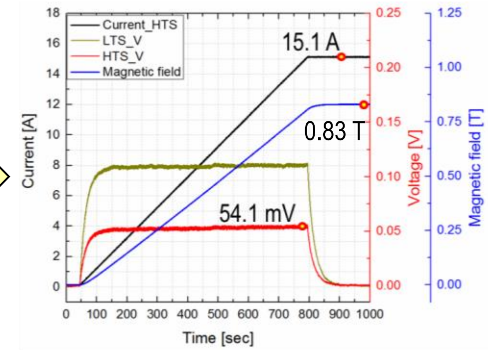
Contents

Lessons Learned with No-Insulation (REBCO) Coils

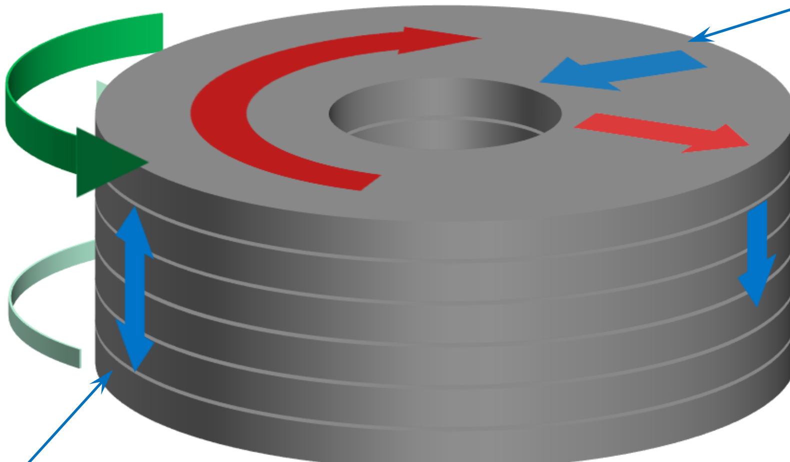
- Challenges in No-Insulation Coils
  - Characteristic resistance (R_c) variation
  - Overstress due to magnetic induction
  - Unbalanced force during quench
  - Unbalanced torque during quench

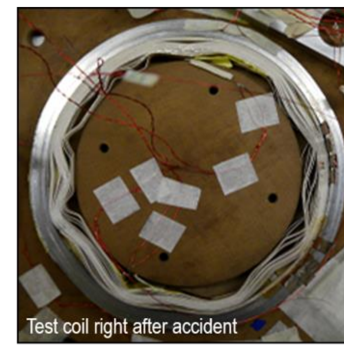


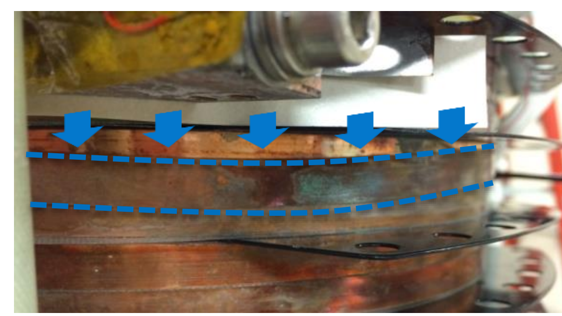
R_c = 47.4 mΩ (R_{ct} = 51.8 μΩ·cm^2)



R_c = <u>116.2</u> mΩ (R_{ct} = <u>127</u> μΩ·cm^2)







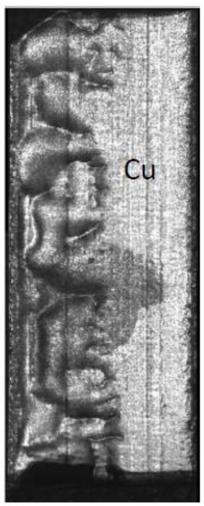
No-Insulation Coils

Lessons Learned with No-Insulation (REBCO) Coils

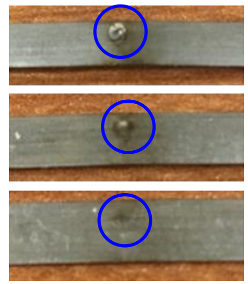
- Construction and Operation Issues
  - Physical deformations of the tape
  - Joint degradation
  - Metallic insulation arcing
  - LHe trap and bubbling

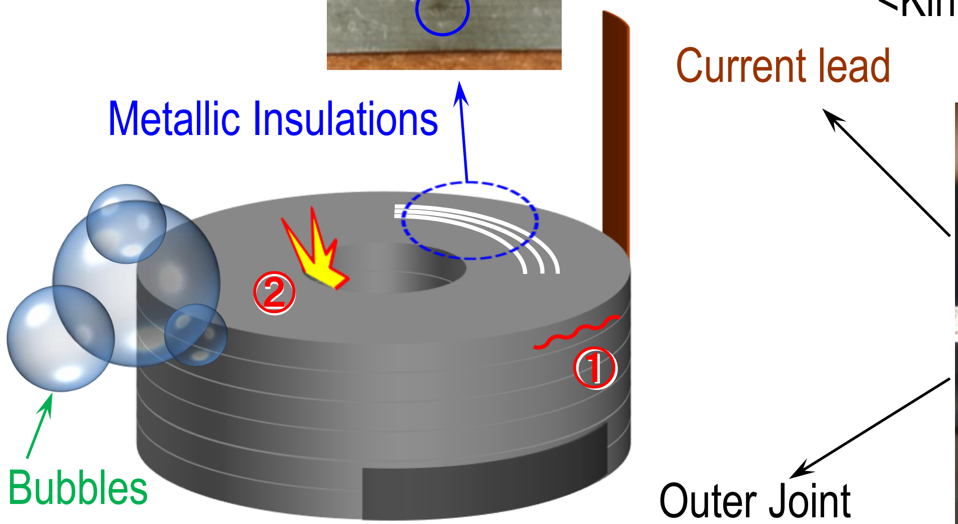
<Tape crumpling>

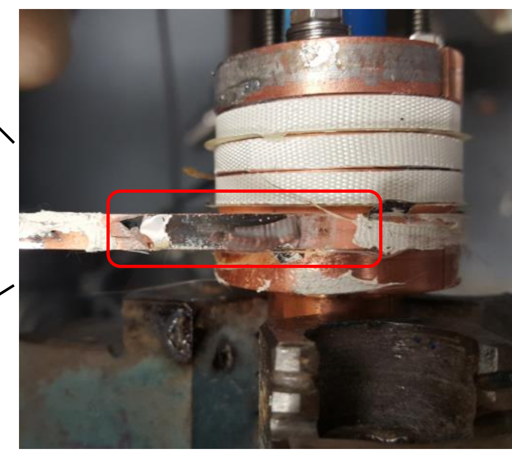
<Kinks in coil turns>



Surface-optical,
Cu-delamination







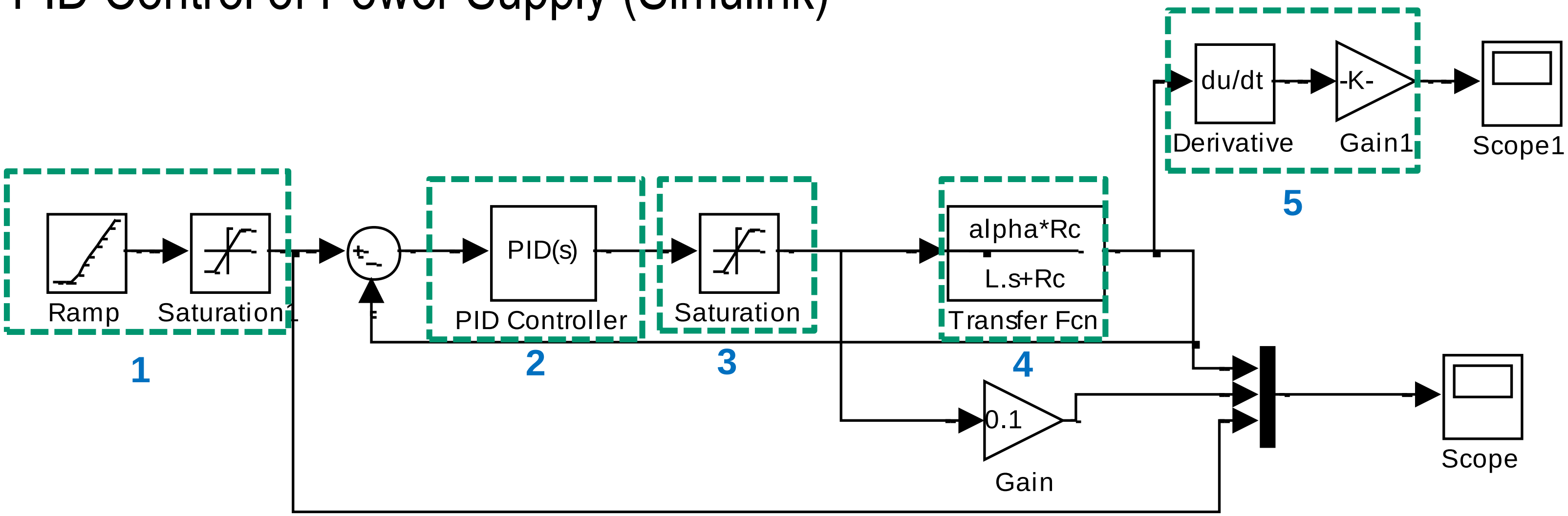
No-Insulation Coils

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

Contents

Feedback Control of 7 T 78 mm NI All-REBCO Magnet in LN2

- PID Control of Power Supply (Simulink)



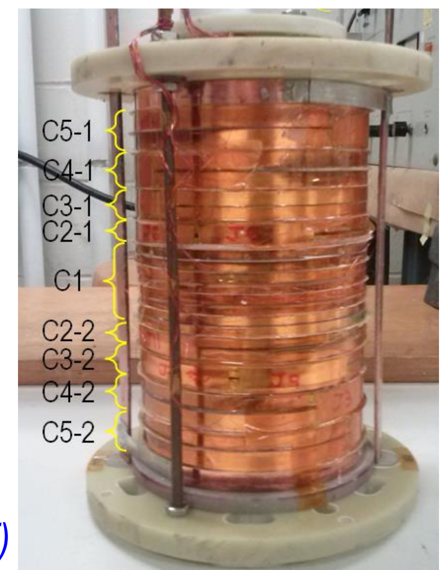
1 : Making reference signal for magnetic field → Linear ramp up 0.5 T with 2.5 mT/s

2 : PI controller → P-gain = 5000, I-gain = 25

3 : Limit the max. P/S current → Protect the coil : set as 40 A

4 : Transfer function → Input : P/S current, Output : magnetic field

5 : Get magnet voltage

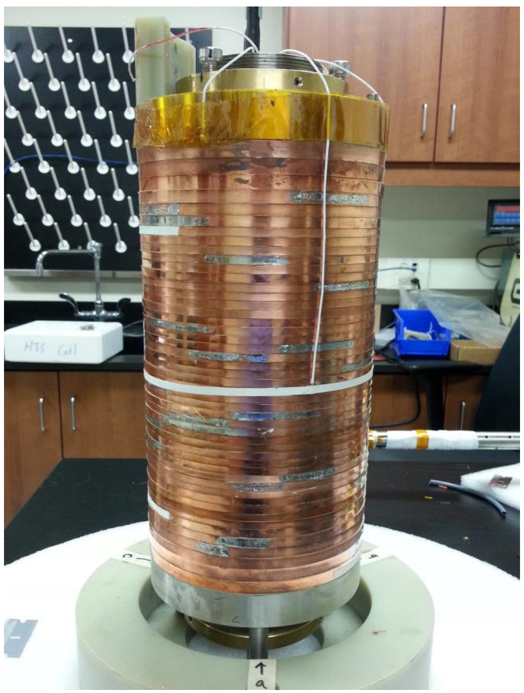


7 T 78 mm NI-REBCO Magnet (MIT)

Ref: S. Kim, S. Hahn, K. Kim, and D. Larbalestier, “Active feedback control of a no-insulation REBCO magnet for fast tracking of target field at 77 K,” submitted for publication in 2016.

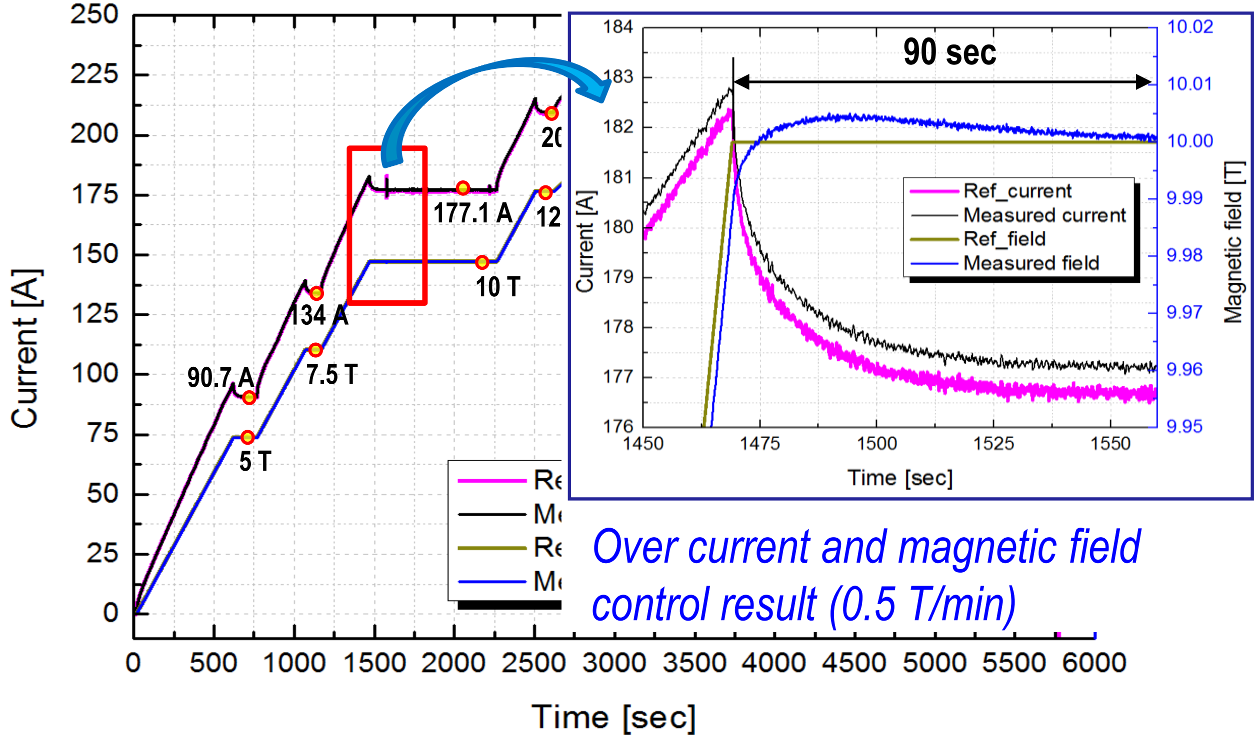
Active Control: Final Controlled Ramp to 13 T

- 13 T NI REBCO insert: 0 → 13 T charging test
- Ramp rate: 0.5 T/min (0 T → 12 T), 0.25 T/min (12 T → 13 T)
- Over current values: 6 A(1.7%)@ 0.5 T/min, 3.2 A(1.4%)@ 0.25 T/min
- Magnet charging time constant: 304 s → expected charging time: ~15 minutes
- 99 % field settlement in 90 seconds with active control.



13 T NI HTS insert

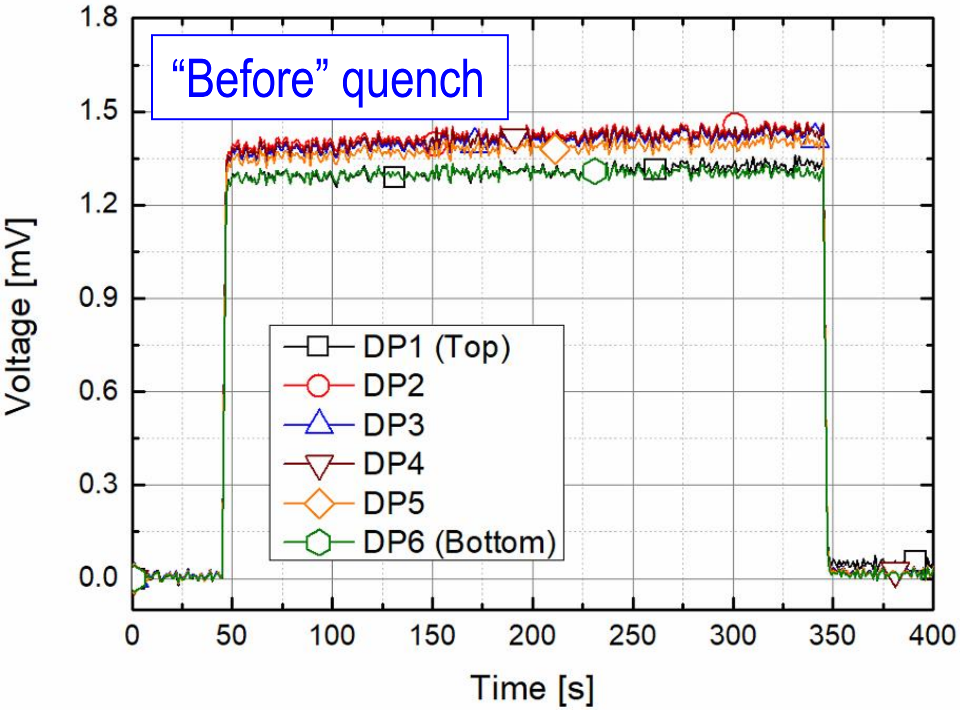
Active control results to 13 T

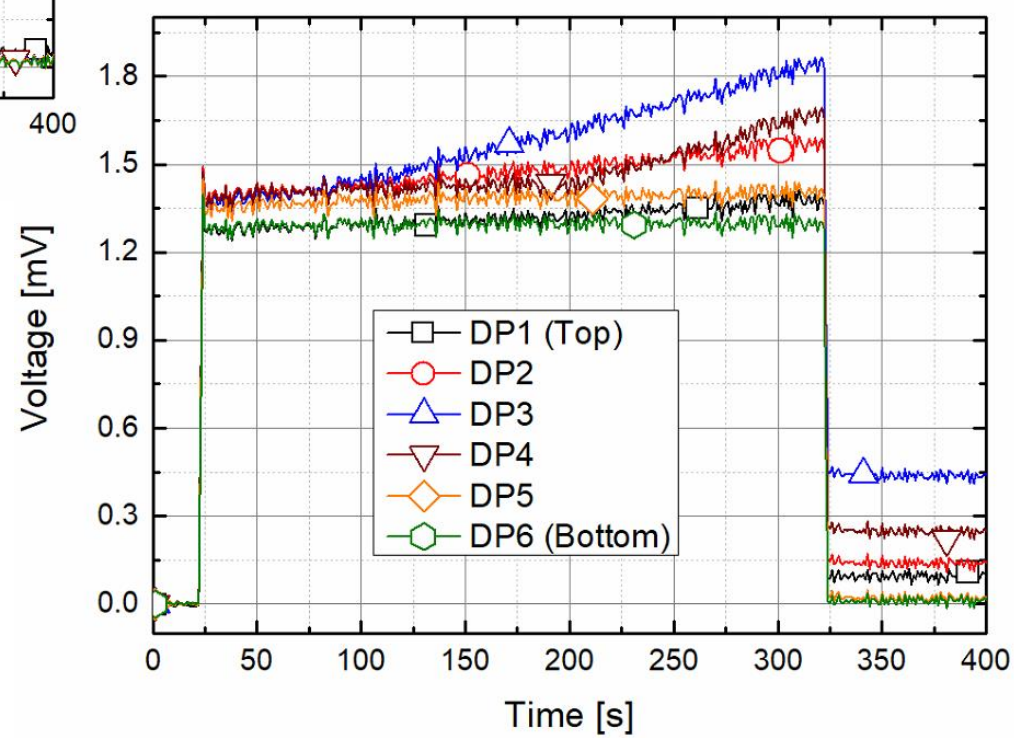


Over current and magnetic field control result (0.5 T/min)

Contents

LBC Retest in LN2 after 45.5 T





- Voltage rise observed in **DP2**, **DP3** and **DP4** of LBC at lower currents in its LN2 test after the 45.5 T run.

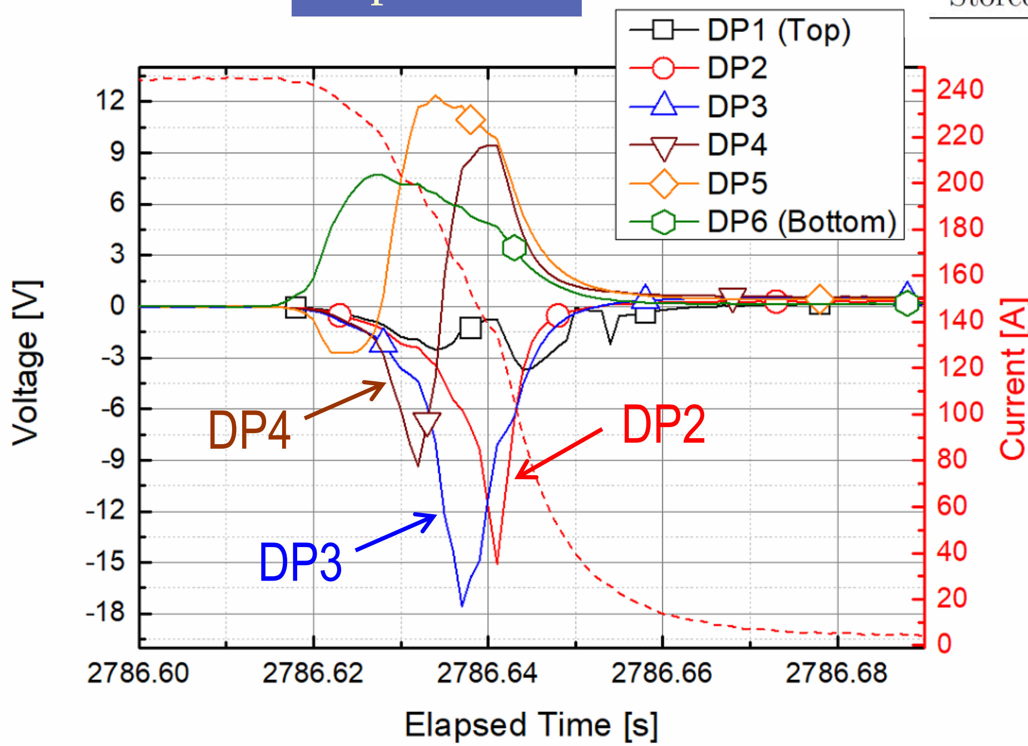
Lumped Circuit Simulation (2017, NHMFL)

- Simulation of 14.4 T NI Insert in 31.1 T Background Magnet (45.5 T)
  - Quench was initiated in DP6 (bottom)

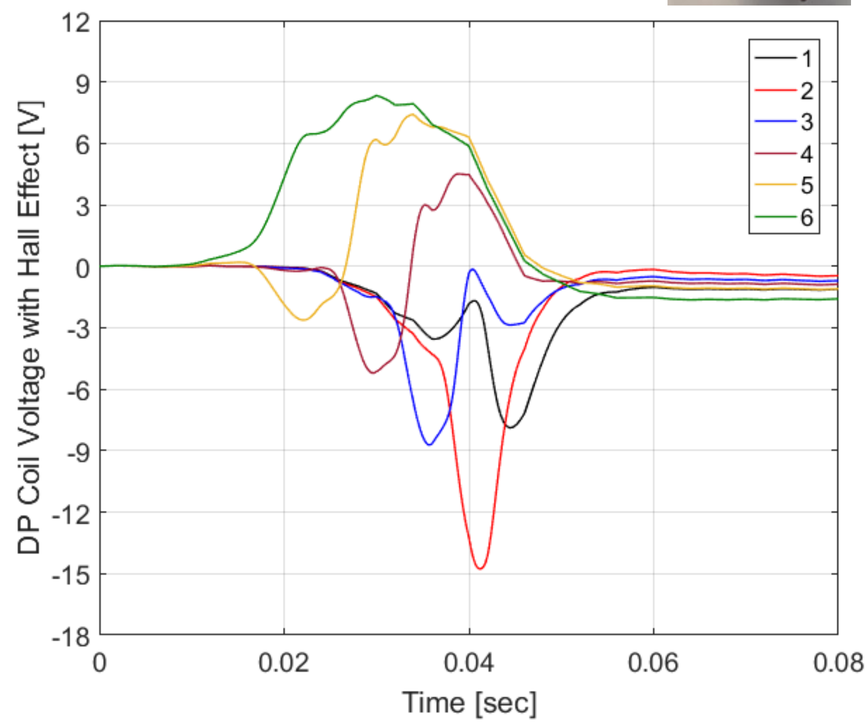
Table 1: Key Magnet Parameters

Parameters	Value
Inner radius [mm]	7
Outer Radius [mm]	17
Height [mm]	51
Time Constant [sec]	1.07
Quench Current [A]	245
Stored Energy [kJ]	1.512

Experiment



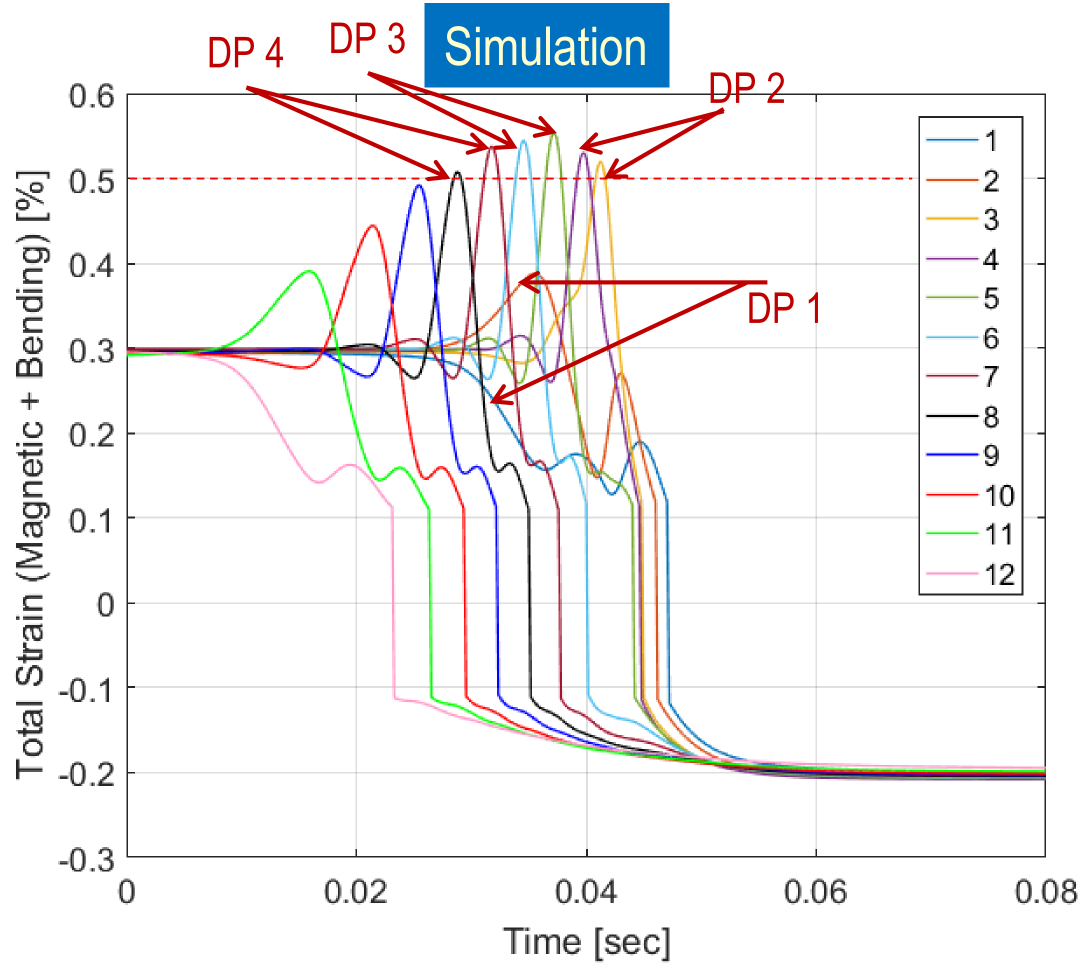
Simulation



K. Bhattarai with the Applied Superconductivity Center (ASC), NHMFL (Tue-Mo-Or12-06, MT-25, Netherlands, Amsterdam, August, 2017)

Lumped Circuit Simulation (2017, NHMFL)

- Total hoop strain (magnetic + bending) on the REBCO layer.



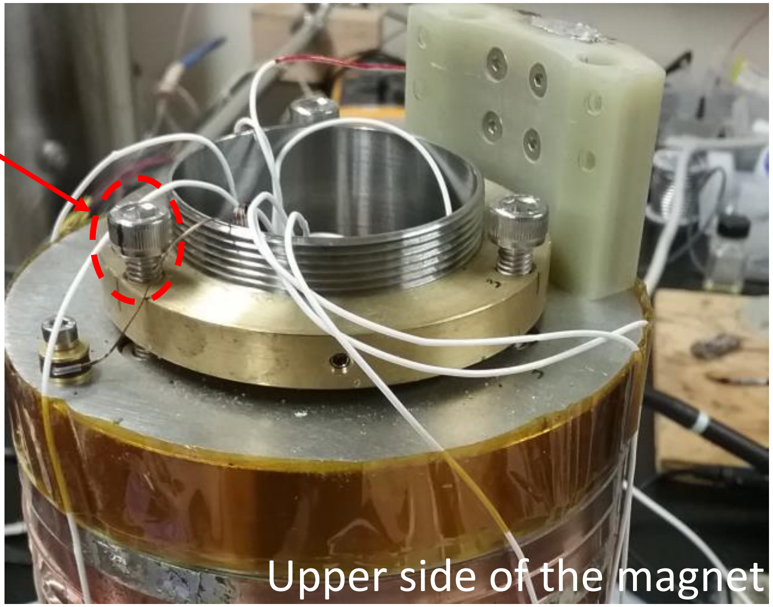
- Simulation demonstrated that the hoop strain of DPs 2,3,4 exceeded 0.5% limit.
- Post mortem analysis shows overstrain degradation in DPs 2, 3, 4 **and 5**

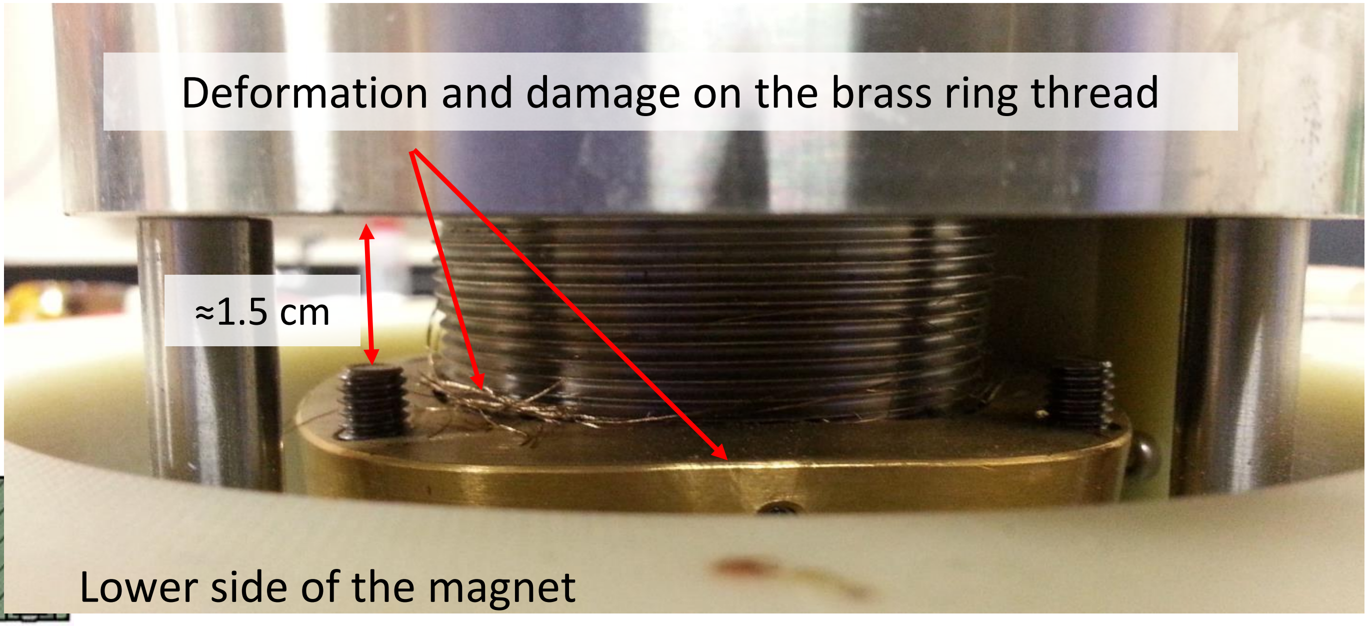
13 T NI REBCO Insert for 19 T: Inspection after 19 T Quench

- Brass ring (Magnet Bottom)

✓ The screw loosened without deformation

✓ No damage on the brass ring thread





Summary: Achievements and Progress

- Significant Progress of NI-REBCO Magnet Technology since 2010 (MIT)

- 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*
  - *Vacuum Tube Maglev by KRRI, CNU, and SuNAM*
  - *The first commercial industrial NI-HTS product: 300 kW Induction Heater by Supercoil and CNU*

Summary: Technical Issues

- Issues Identified
  - *Temporal variation of charging behavior → active control*
  - *Overstrain due to magnetic induction → precise modeling in "magnet" level*
  - *Unbalanced force → better reinforcement after accurate simulation*
  - *"Unknown unknowns", still.*

Thank you for your attention.