Massachusetts Institute of Technology

A Tabletop, Liquid Helium-Free, Persistent-Mode 1.5-T MgB_2 "Finger" MRI Magnet: Small-Scale Test Coil Results and Final Design Review

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Outline

- Project Goal & Development Progress Overview (2017~2020)
- Small-Scale Magnet Coil Test Results
- ½-scale MgB_2 MRI magnet: Design and Construction, (Operation)
- Full-scale Tabletop 1.5-T MgB_2 Osteoporosis MRI Magnet Design
- Conclusion

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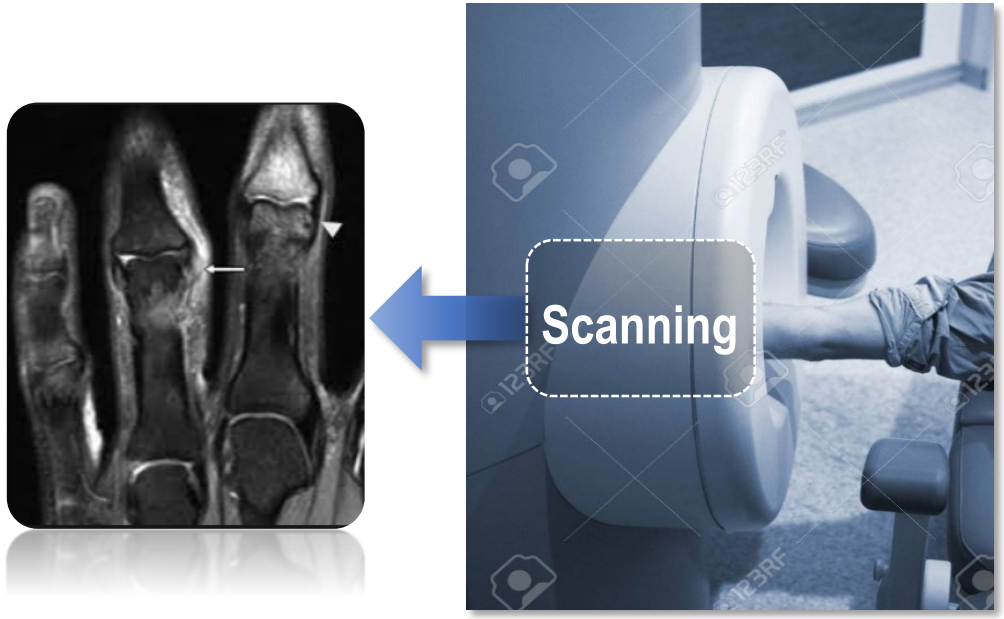
Project Goal

[1] Pushpender Gupta, et al., "High-Resolution 3-T MRI of the Fingers: Review of Anatomy and Common Tendon and Ligament Injuries", *AJR*, Vol. 204, No. 3, March. 2015, p. W314-W323.

▌Tabletop LHe-Free "Finger" MRI for Osteoporosis Screening

** Metabolic bone disease generally systemic*



< An example of an MR scanning for fingers[1] >

< Design Requirement of "Finger" MRI Magnet >

Finger MRI Magnet	Requirement
Field strength	1.5 T
Magnet bore	≥9 cm
Region of Interest (ROI)	2.5 cm in DSV
Homogeneity (Peak-to-Peak)	<5 ppm
Temporal Stability	<0.1 ppm/hr
5-Gauss Fringe Field Radius	<0.5 m
Operating Temperature Range	10 – 15 K

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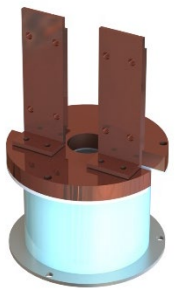
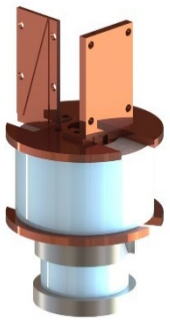
Development Progress Overview

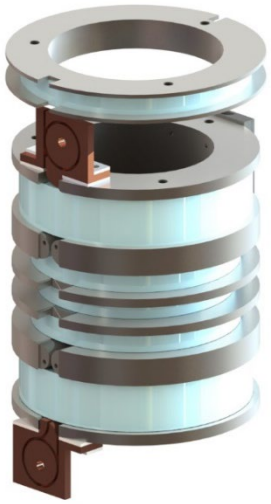
▌MgB_2 magnet validation progress



(2017)
SN_2-cooled single coil with use of 76-m wire



(2018-2019)
SN_2-cooled, Persistent two-coil magnet With 86-m wire



Construction completed
Operation Now in Progress

(2019)
SN_2-cooled, persistent, MRI-field quality 1.5T/54mm magnet with 580-m wire

(2020)
Final 1.5T/(RT)90mm magnet uses 1.3-km MgB_2 wire, 43-kg Silicon Steel

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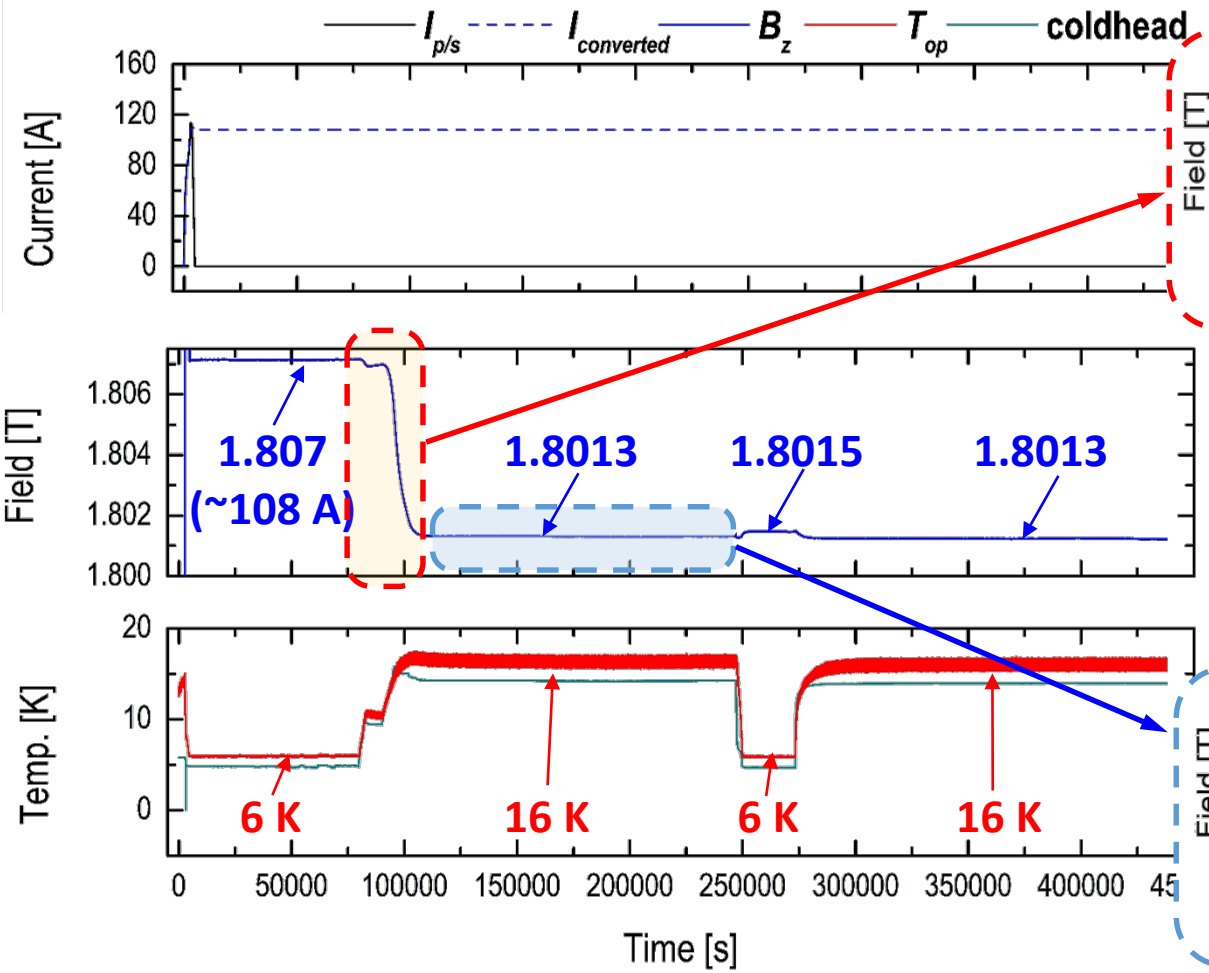
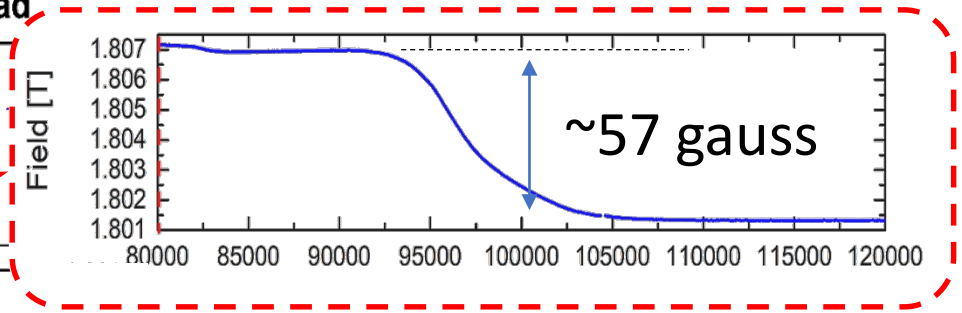
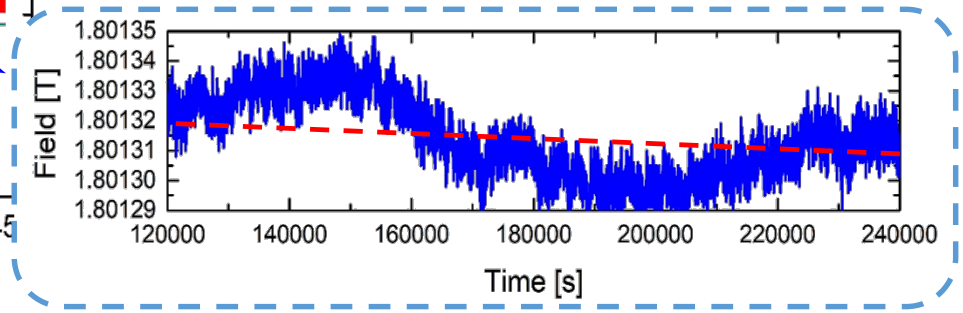
Small Two Coil Magnet Test Results

▮ Demonstration Persistent-mode (PM) in Solid-Nitrogen (SN_2) (6 K & 16 K)







Field decrease during 6 K → 16 K

J_c distribution was changed by T_{op}.

- Target -

I_{op} = 108 A

T_{op} = ~15 K

B_{max} = 2 T

< Energization and operation in persistent>

$R_{calculated}$ = 1.45x10^{-13} Ω (for 33 hrs)

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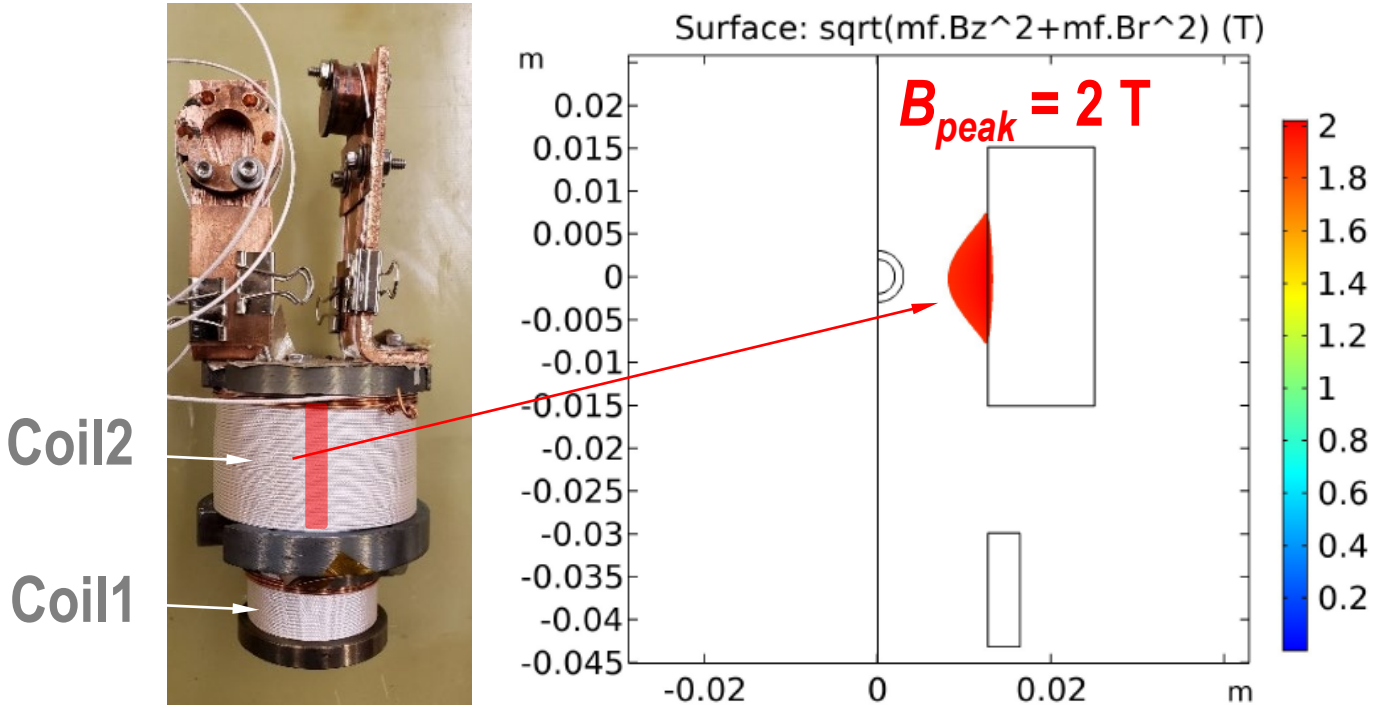
Noticeable Phenomenon

▮ B_z with respect to T_{op} (i.e., J_c)



< Modeling with 22 turns >

- *In* $B_{external}$ = 2 *T*,
- $J_c \rightarrow 0.5J_c$ (I_c vs. B(T))
- Governing Equation:

  1) Maxwell Equation;

  2) Superconducting power law;

$$\mu\frac{\partial \mathbf{H}}{\partial t} + \nabla \times \mathbf{E} = 0$$

$$\mathbf{E} = \rho\mathbf{J};$$

$$\mathbf{J} = \nabla \times H,$$

$$\rho = \frac{E_c}{E_z}\left|\frac{J_z}{J_c}\right|^{n-1}$$

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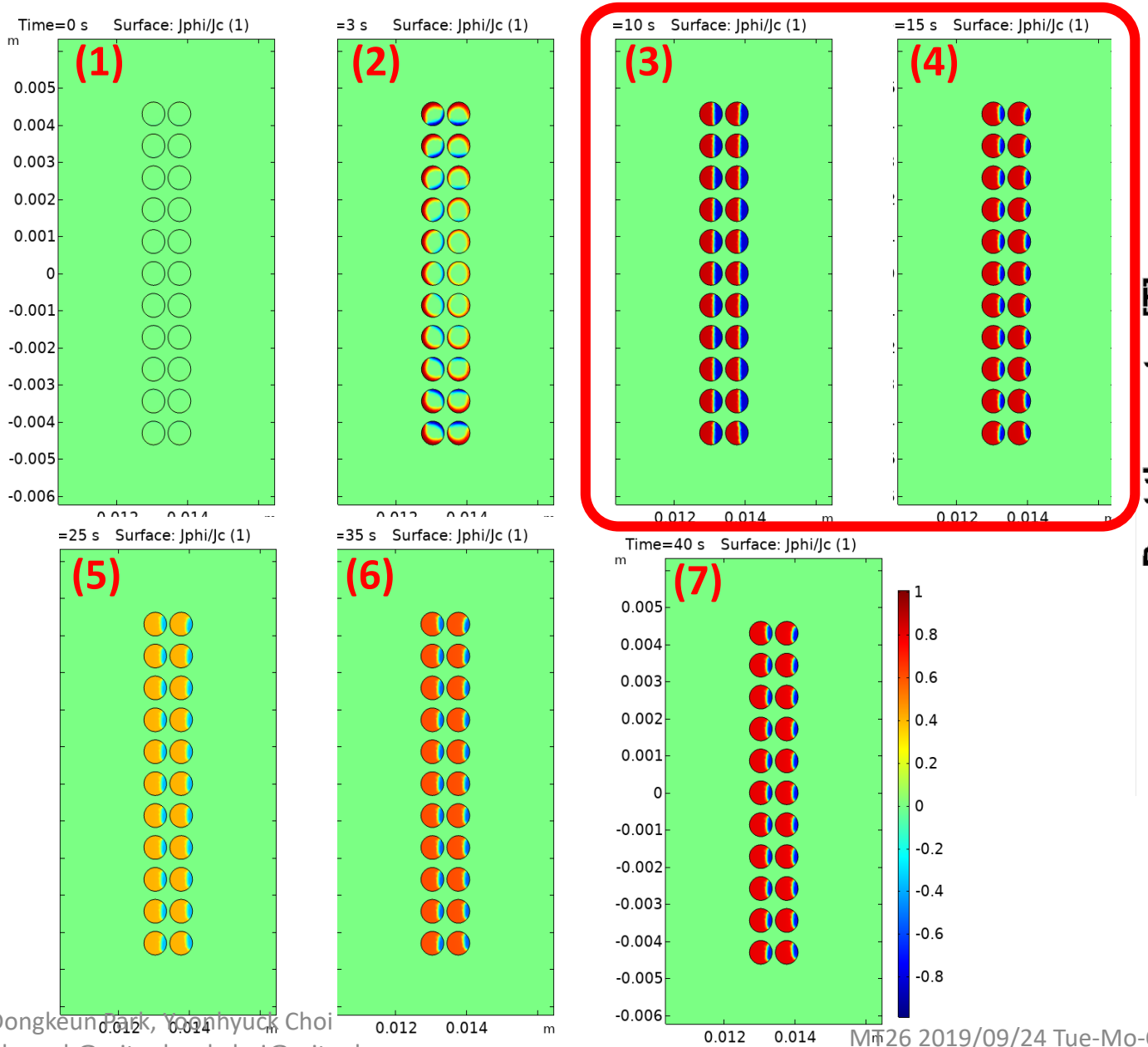
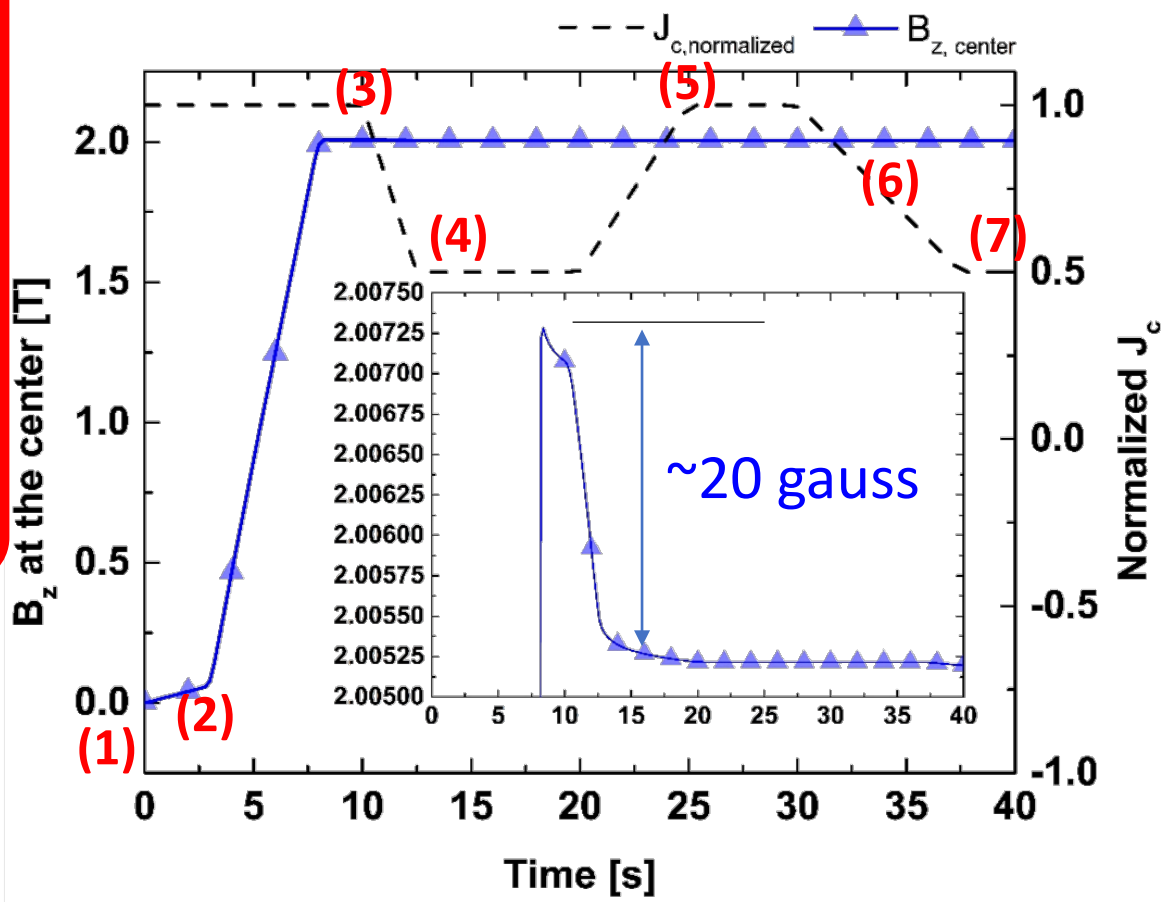
Noticeable Phenomenon





< B_z changes with respect to J_c >

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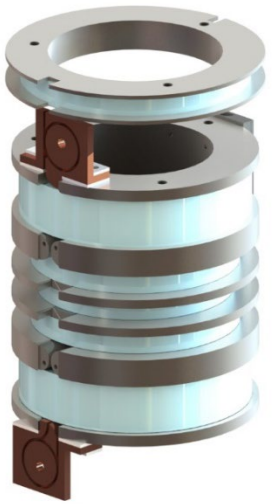
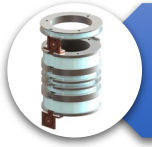
Design of ½-scale MgB_2 Magnet



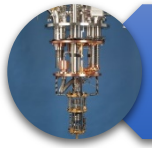
What we expect to learn:

1) **Winding;**
2) **Solid nitrogen cooling;**
3) **MgB_2 field performance in coil;**
4) **Persistent switch and joint;**
5) **Homogeneity vs. Temperature;**
6) **Quench parameters.**



Magnet & Former

Persistent Mode



Cryostat

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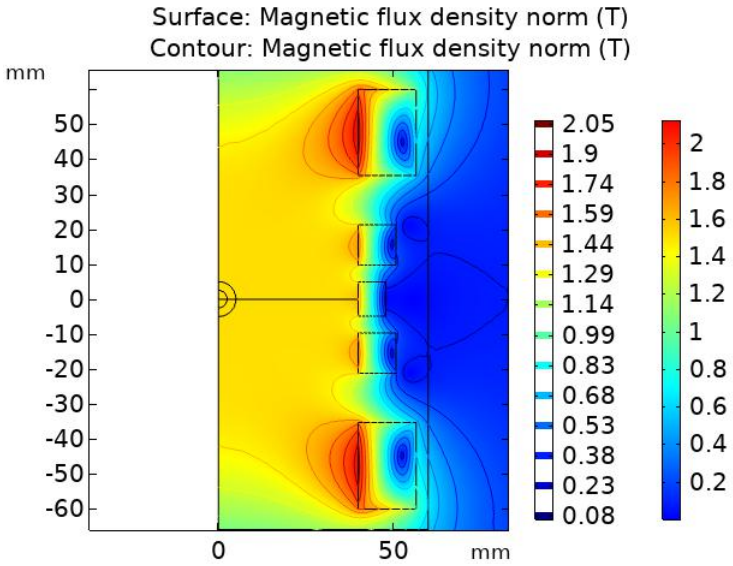
Magnet & Former

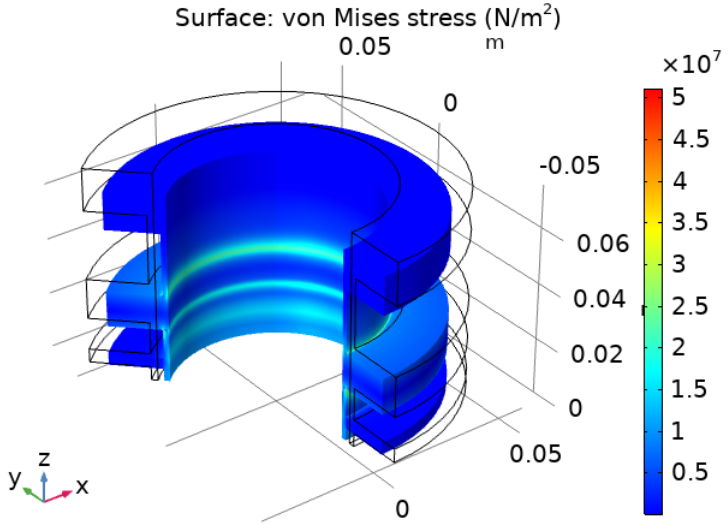
1.5-T/80-mm cold-bore & 600-m long wire

< Parameters of ½-scale MgB_2 test magnet >

Coil section		Coil 1	Coil 2-1	Coil 3-1
Wire (insulated)	[mm]	0.82 mm x 0.72 mm		
a1; *a2*	[mm]	40.00; 47.92	40.00; 50.80	40.00; 56.56
b1; *b2*	[mm]	-4.920; 4.92	9.73; 21.20	35.40; 60.00
# of turns; layers		12; 11	14; 15	30; 23
Wire length	[m]	36	60	209
I_{op}	[A]	**112.2**		
T_{op}	[K]	10; 15		
Center field	[T]	1.5		
Max field	[T]	1.56	1.66	**2.09**
Total inductance	[mH]	172		
Homogeneity @ 10 mm-DSV	[ppm]	**1.2 (Vrms),16 (Pk-Pk)**		

< Analyses for magnet & former designs >





Former deformation (Δa, Δb)

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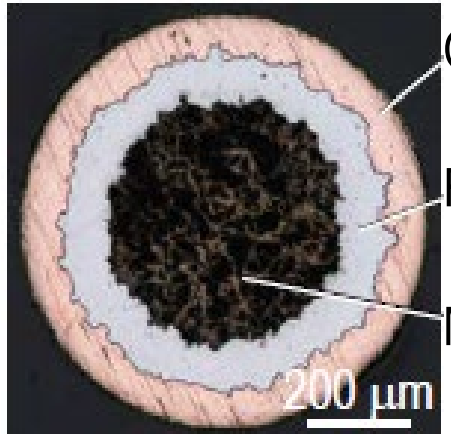
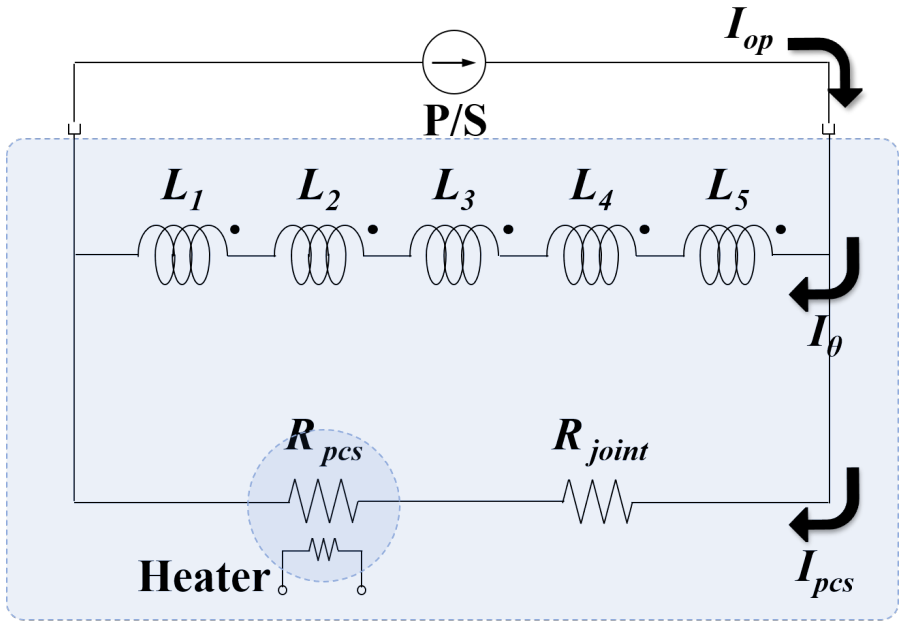
Persistent-Mode

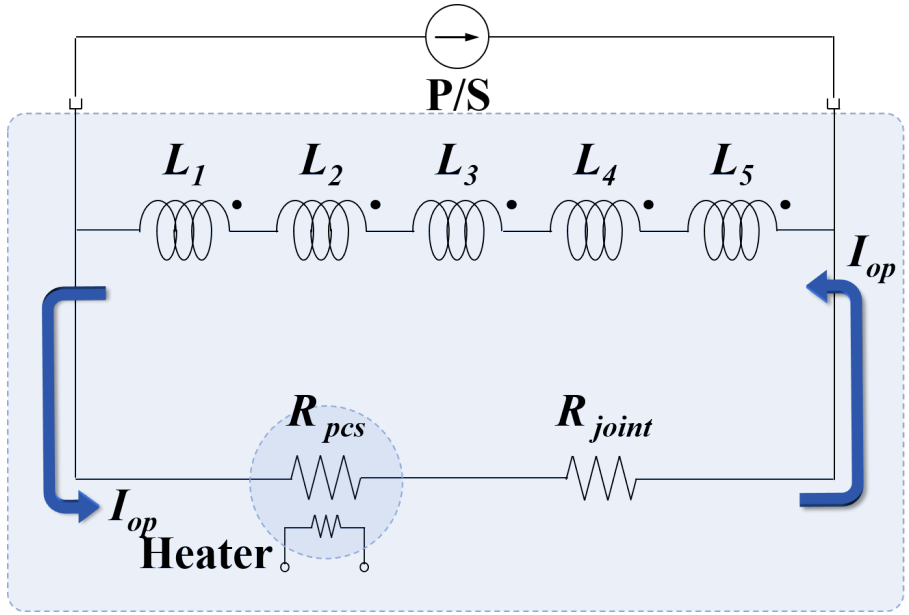
PCS & Circuit Representation

- I_{pcs} as 0.5% = I_{op} (0.56 A)
- With 10 *A/min* ramp, $R_{pcs} = V_{pcs}/I_{pcs} = 0.05\ \Omega$
- $E_{pcs,\ jouleheating}$ =0.02 *W* (charging loss)





< Driven-mode >



< Persistent-mode >

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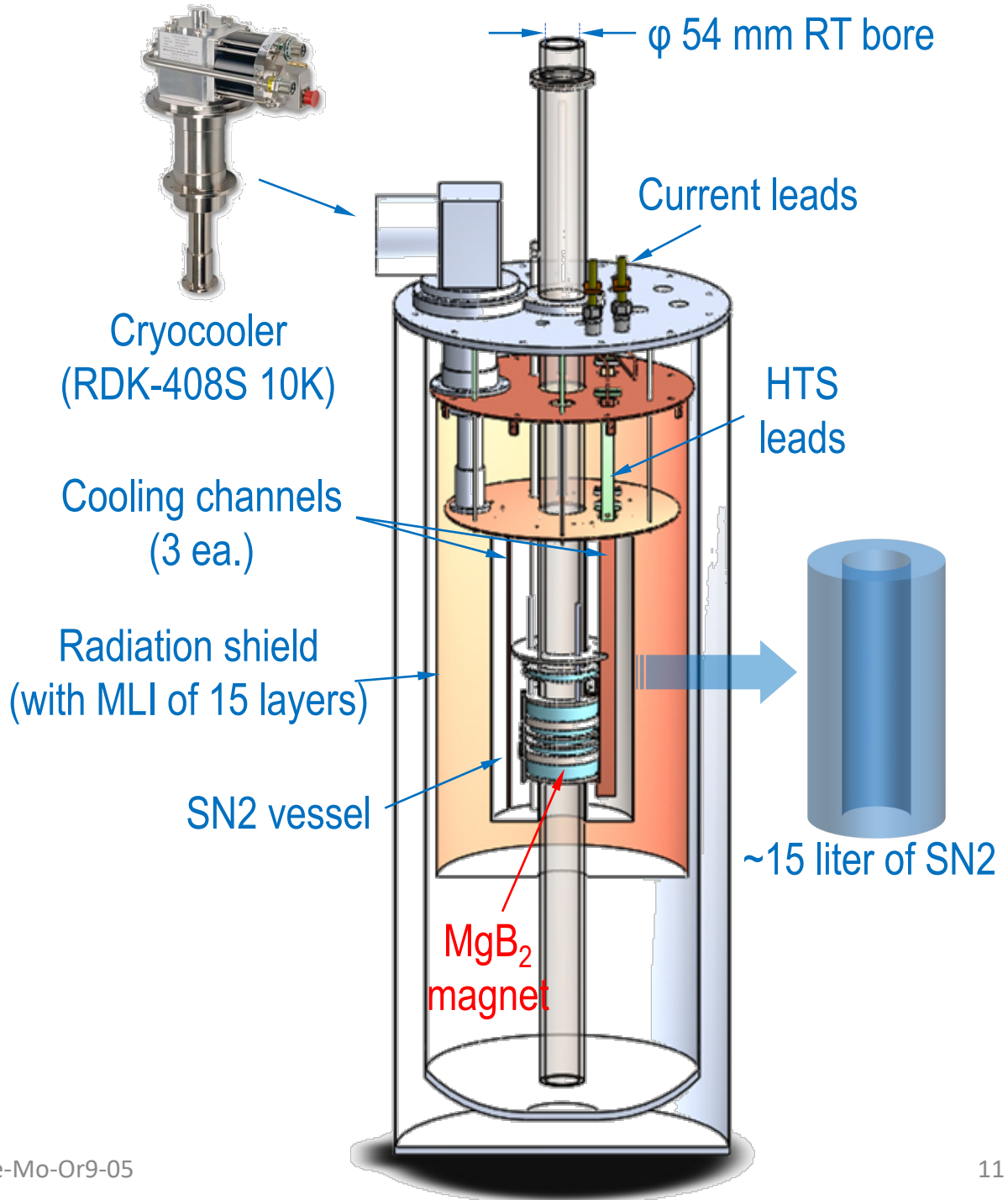
Cryostat for SN2 Cooling

Heat input & SN2 Sustainability

Parameter		Specification	
		1st stage	2nd stage
T_{op}	[K]	45	10
$Q_{conduction}$	[W]	8.113	0.063
$Q_{radiation}$	[W]	3.741	0.556
E_{joule}	[W]	2.212	0.001
Q_{total}	[W]	14.066	0.62
Cooling Power	[W]	(-) 47	(-) 6
ΔT_{SN2} (10 $\longrightarrow$ 20 K)	[hour]	1.25 (with 15 liter of SN2)	



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Construction of Test Magnet and Cryostat

Wind & Joint

Heat-treatment

Assembly

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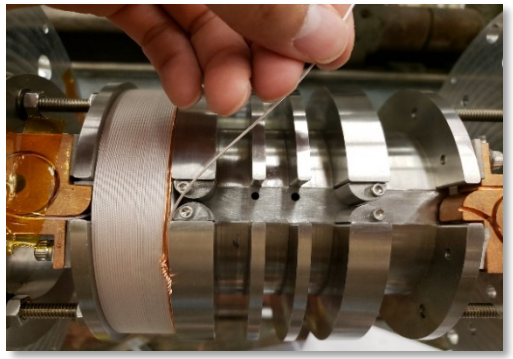
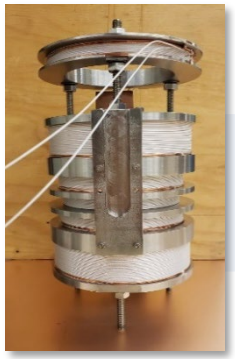
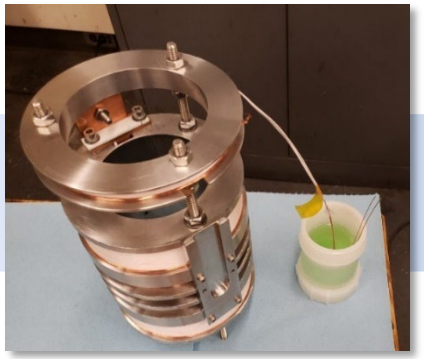
Winding & Superconducting Joint

1. Winding
2. Etching
3. Cutting
4. Wire+Powder
5. Pressing
6. Positioning

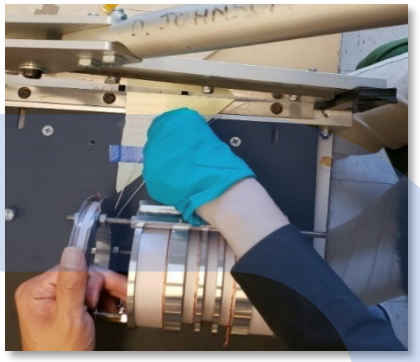




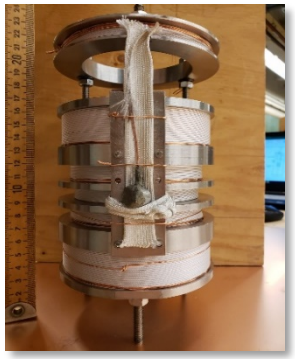
< Winding>



< Etching >



< Cutting with angles >



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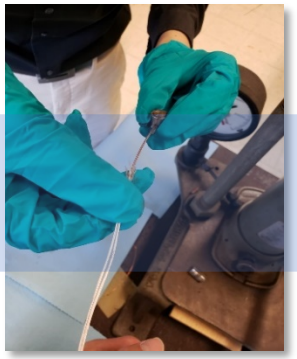
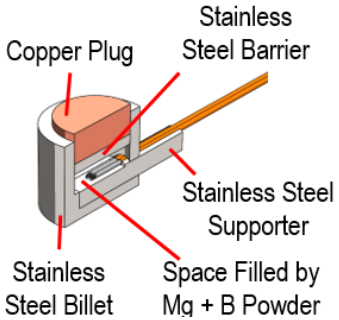
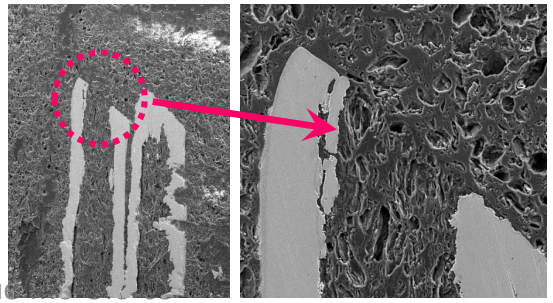
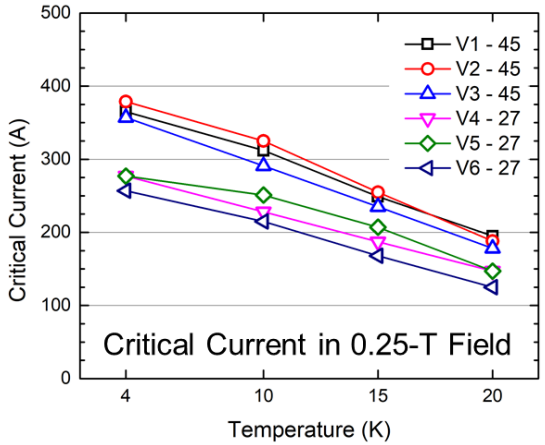


< Joint>







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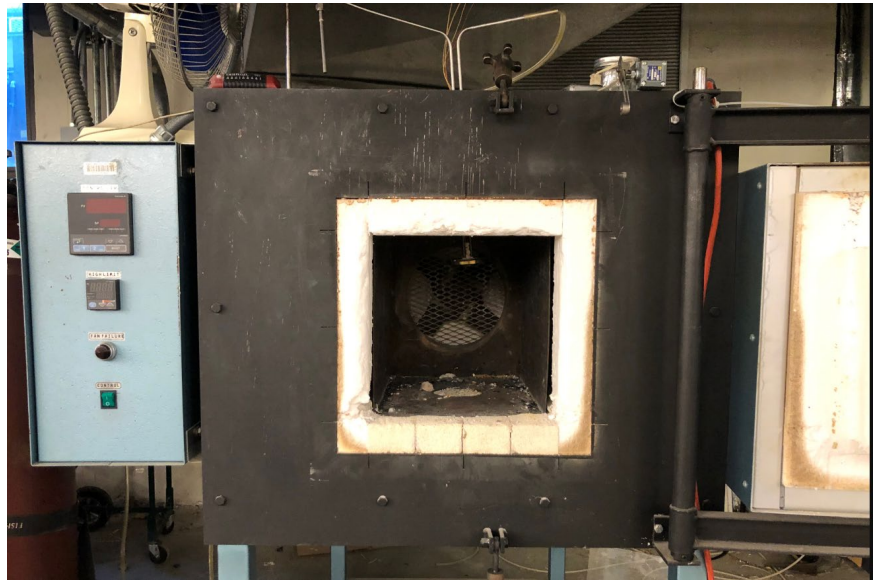
Heat-Treatment

Sintering condition and procedure

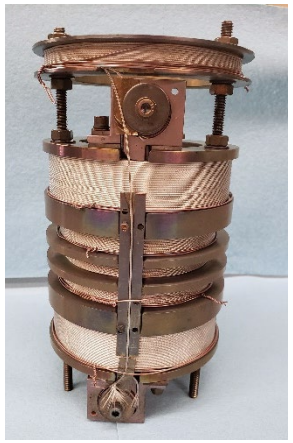
- 605 °C for 12 hours in Argon gas at 1 atm
- Extra stainless steel chamber used to keep maintaining Ar gas environment



< Furnace for heat-treatment >

< Stainless steel chamber + loading frame >

< Pressing with sealing Cu plate >



< Positioning and Ar pipe connection >

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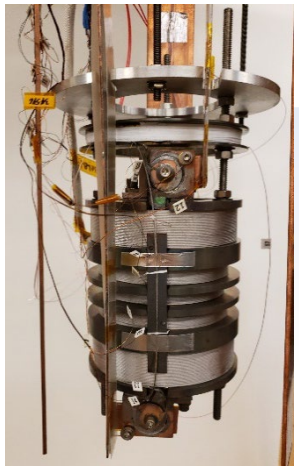
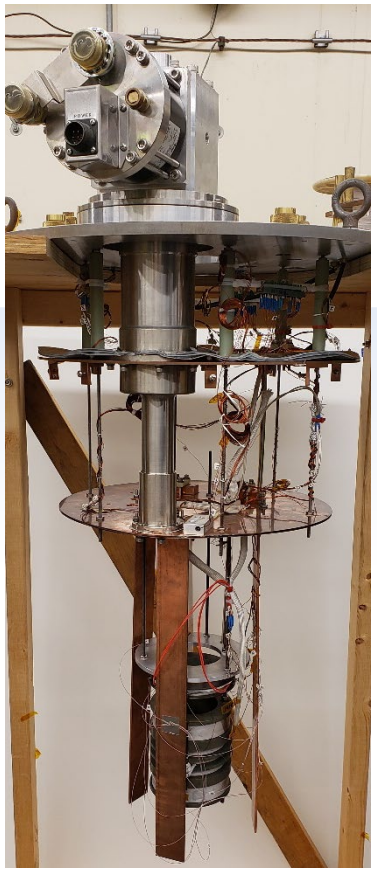
Assembly

Installation of test magnet with cryostat



< Magnet >



< Cooling channel >

< SN2 vessel >

< Radiation shield >

< MLI >

< Cryostat >

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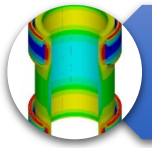
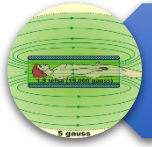
Test of ½-scale MgB_2 Magnet

Cooling



Energization



Field Performance

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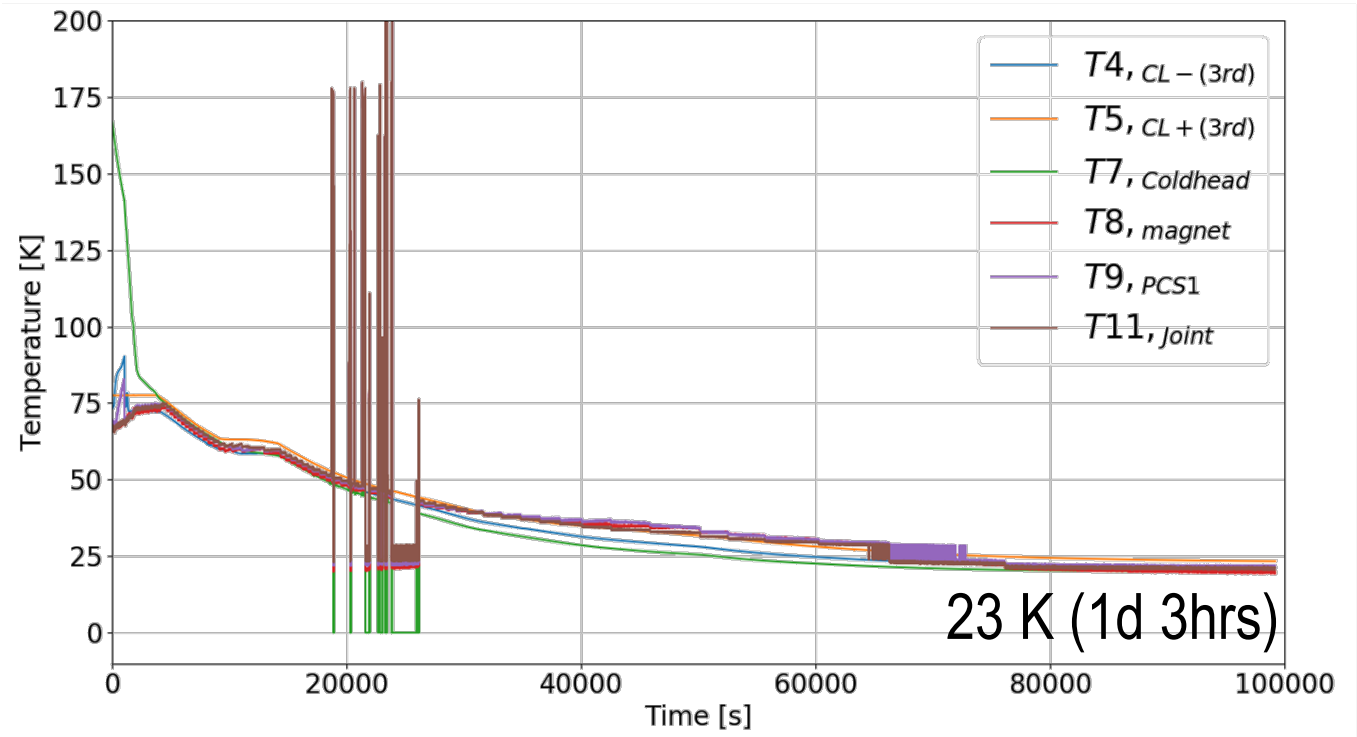
Cooling

MgB2 magnet cooled by SN2

< LN2 injection and solidification by cryocooler >



< Time vs. temperatures during cool-down >

- Temperature of the magnet doesn't go down below 23 K.
- Unexpected heat input is accompanied due to the vacuum leak of RT bore

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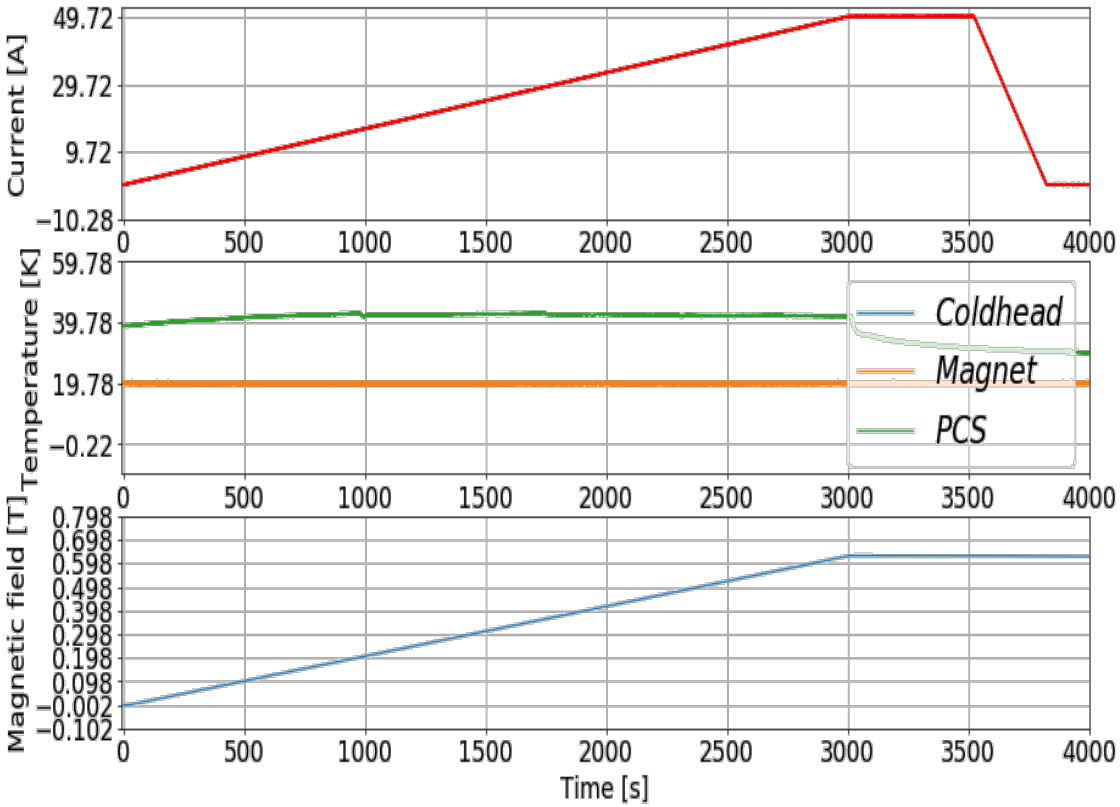
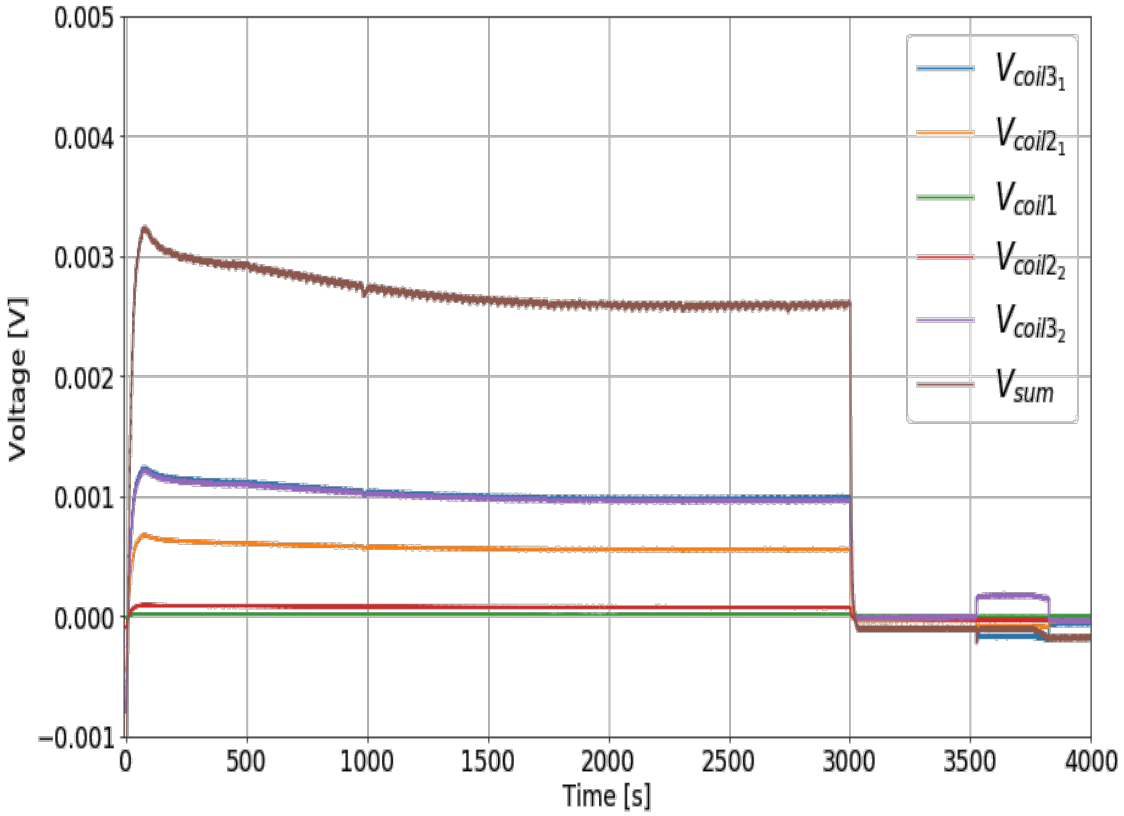
Energization

Charging up to 50 A at ~ 23 K

- Target current was decided with consideration of wire performance in terms of *B*(*T*)
- The magnet successfully charged up to 50 A (0.63 T) and is currently being operated in persistent-mode.



< Time vs. current, temperatures, field plots >

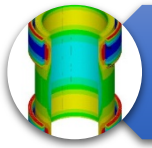


< Time vs. voltages plots >

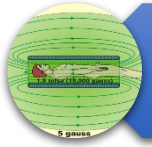
Full-Scale Magnet Design

*Tue-Mo-Po2.07-01

Magnet



Gradient Coil



Overall System

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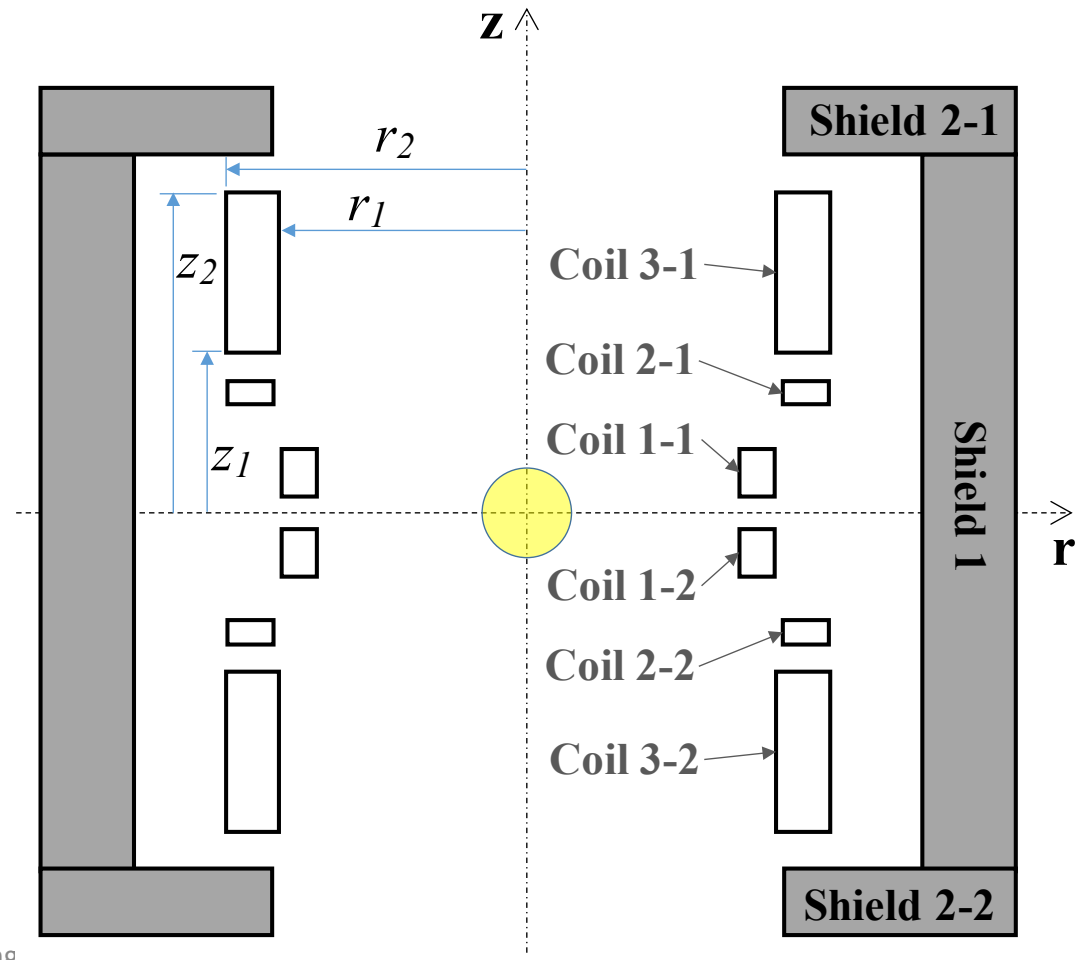
Magnet Design

- Linear Program ➔ Genetic Algorithms with Simulated Annealing ➔ 2D, 3D-FEM



Mid-plane symmetry	Coil 1-1	Coil 2-1	Coil 3-1
Wire (insulated) dimension	0.86 mm × 0.73 mm		
$2r_1$; $2r_2$ [mm]	120.00; 138.98	144.00; 168.82	140.00; 169.20
z_1; z_2 [mm]	4.62; 17.52	30.46; 37.34	45.28; 90.00
# turns/layer; # layers	15; 13	8; 17	52; 20
Total length [m]	1,303		
I_{op} [A]	105		
Center field [T]	1.5		
Max field [T]	1.73	1.45	2.21
σ_{hoop} (EM only) [MPa]	17.4	17	26
Total inductance [mH]	720 (Stored energy: 3.97 kJ)		
Homogeneity @ 25-mm DSV [ppm]	6.4		
5-gauss line [m]	(Radial) 0.48; (Axial) 0.69		

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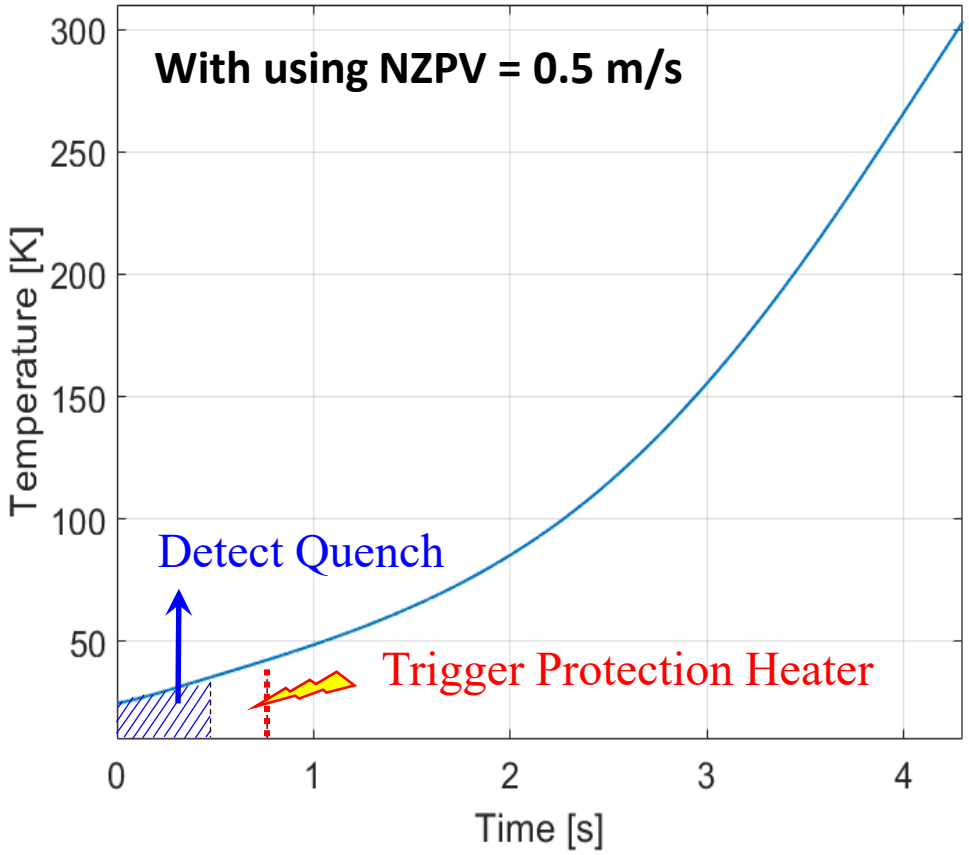
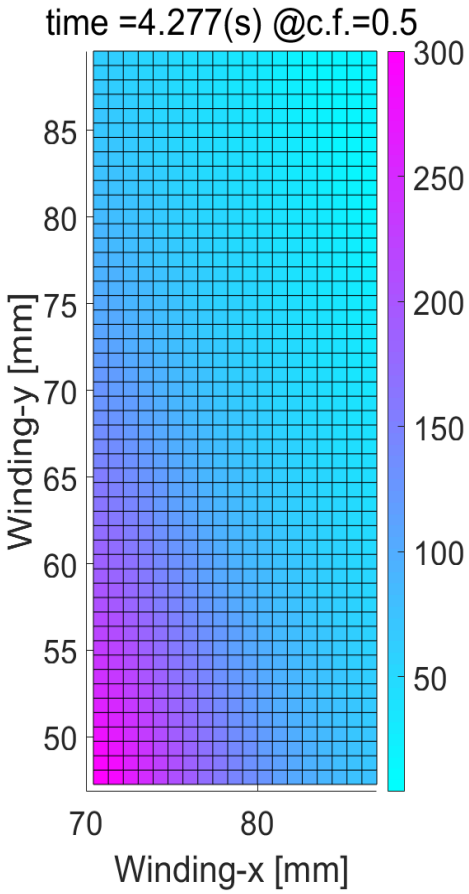
Quench and Protection





- **Active protection** required.
  - Detect in ***0.5 s***.
  - Trigger the quench heater in ***0.3 s*** to suppress the maximum temperature rise below **200 K**.

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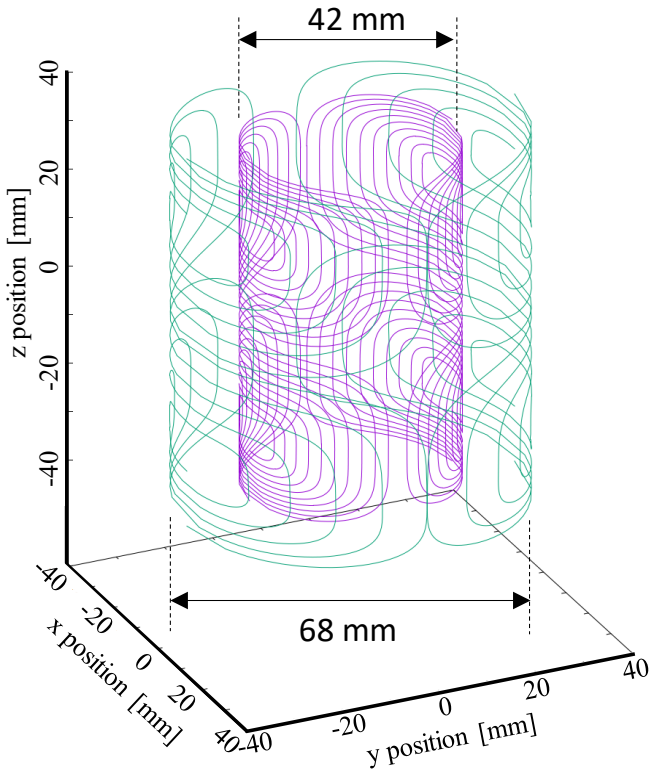
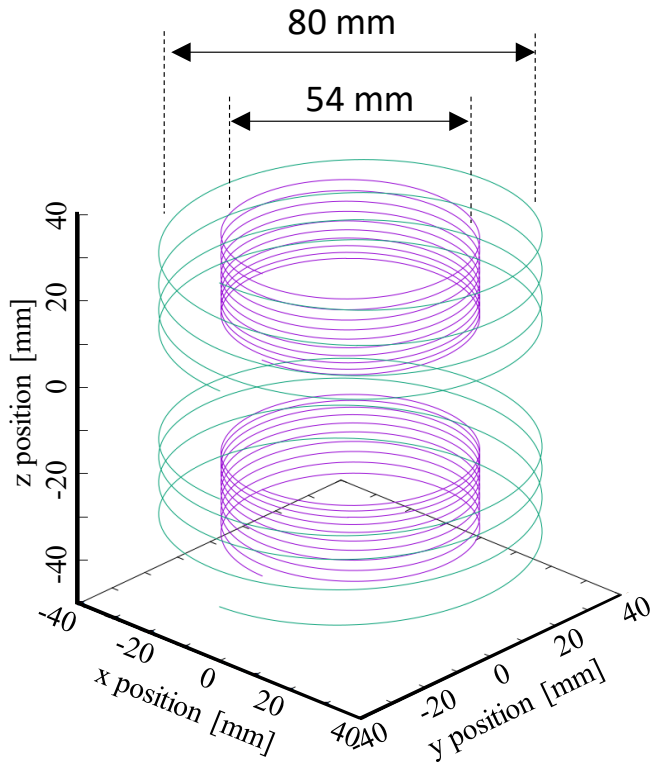
Gradient Coils & Overall System

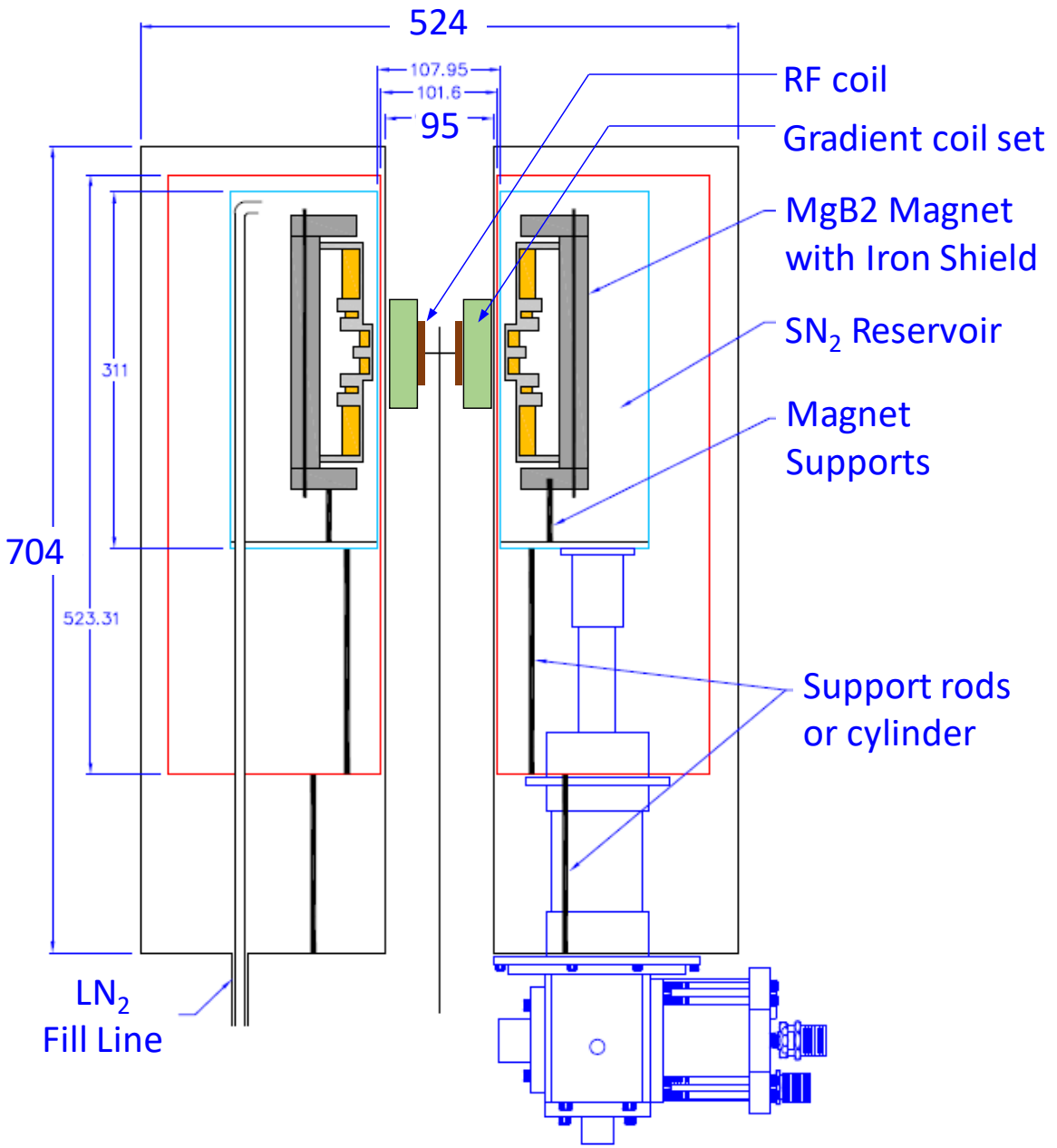
- 1st-Cut Wire path optimization: *Levenberg-Marquardt Algorithm* (LMA) with conformity weighting.



Gradient Strength 13.2 mT/m/A
Wire length 7.25 meters



Gradient Strength 8.22 mT/m/A
Wire length 5.40 m



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Conclusion

- ½-scale MgB_2 Magnet with SN_2 Cooling Constructed.

  ➔ Now 50-A Persistent Mode Operation @ 23 K.

  ➔ Re-test with a Repaired Cryogenic System.
- Full-Scale Magnet Designed Completed.
- SN_2-Cooled Persistent 1.5-T/90-mm MgB2 MRI Magnet Construction in 2019 and Operation in 2020.
- With own-made G-coil, Tabletop Osteoporosis MRI Demonstration in 2020.

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