HTS Magnet Technology Activities
at MIT FBML

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At
CEA Saclay

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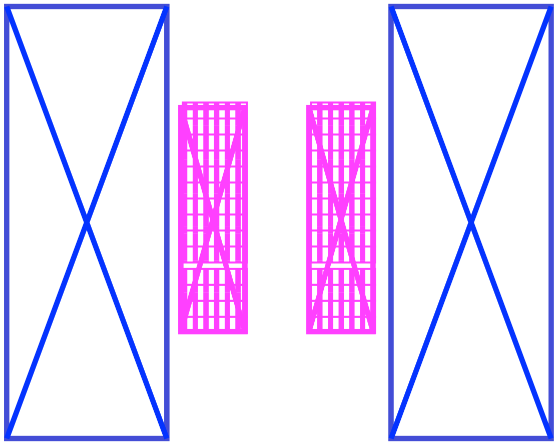
Outline

- MIT 1.3-GHz LTS/HTS high-resolution NMR magnet
- LHe-free, persistent-mode REBCO NI DP coils
- A 0.5-T/280-mm MgB_2 magnet-SN2 system (completed, January 2016)
- A tabletop LHe-free, persistent-mode MgB_2 "finger" magnet-SN2 system for osteoporosis screening (scheduled to begin late 2016)

*MIT 1.3-GHz LTS/HTS NMR Magnet**

- [1999] A 3-phase program application to NIH to complete a *1-GHz* NMR magnet with a *combination of LTS magnet and HTS insert*, specifically of DP coils: an LTS/HTS magnet
- Magnet: LTS background magnet + *HTS insert*
  - LTS background magnet: to be purchased
  - HTS insert: stack of DP coils, to be built at FBML



- Supported by the National Center for Research Resources; National Institute of Bioimedical Imaging and Bioengineering; and National Institute of General Medical Sciences (NIGMS), NIH. Currently supported by NIGMS.

Acknowledgement (Chronological Order)
Juan Bascuñàn; Haigun Lee (now Korea U); Seungyong Hahn (FSU/NHMFL);
Wooseok Kim (Korea Polytechnique U); Min Cheol Ahn (Kunsan U); Tsuyoshi Yagai (Sophia U);
Ryuya Ando (Hitachi); Weijun Yao (ORNL); Dong Keun Park (Samsung Electronics); Youngjae Kim (NHMFL);
Thibault Lècrevisse (CEA); Jungbin Song (Korea U); John Voccio (Wentworth Institute of Technology);
Timing Qu (Tsinghua U); Mingzhi Guan (CAS, Langzhou); Kazuhiro Kajikawa (Kyushu U); Phil Michael (PSFC)

MIT 1.3-GHz LTS/HTS NMR Magnet

- [2000—2002] Phase 1: 350-MHz (300-MHz LTS/50-MHz HTS) magnet
- [2003—2007] Phase 2: 700-MHz (600-MHz LTS/100-MHz HTS) magnet
  - One important result: Screening-current" field (SCF) identified as a large source of error fields, primarily from the 100-MHz HTS insert
- [2007] NCRR & MIT agreed to move up to *1.3-GHz* ➔ Phase 3 into 3A & 3B
- [2008] NIBIB & NIGMS agreed to co-sponsor 1.3G

Phase 2: JASTEC L600

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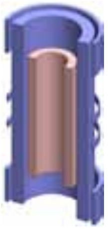
Original 1.3 GHz Project (2008)

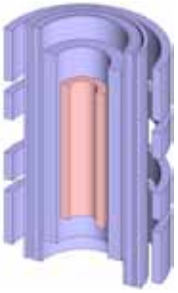
(January 2012)

Phase 1
2000-02



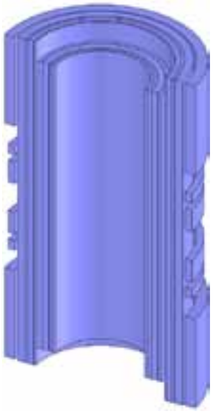
350 MHz
L300/H50

Phase 2
2003-07



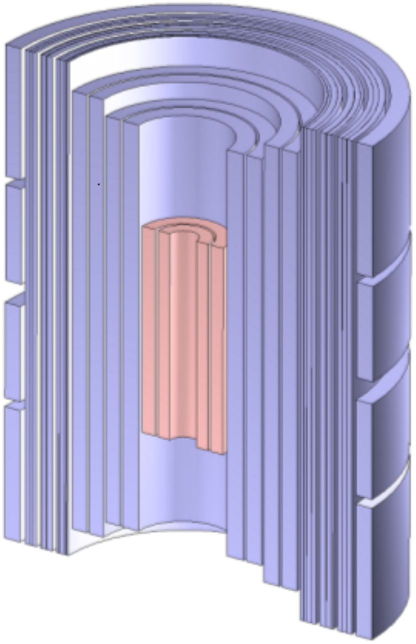
700 MHz
L600/H100

Phase 3A
2008-12



1.1 GHz
L500/H600

Phase 3B
2013-17



1.3 GHz
L700/H600

Theft of H600 discovered on 1/9/2012!

- NIGMS now supports the entire 1.3G (Phases 3B1 and 3B2)

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H800

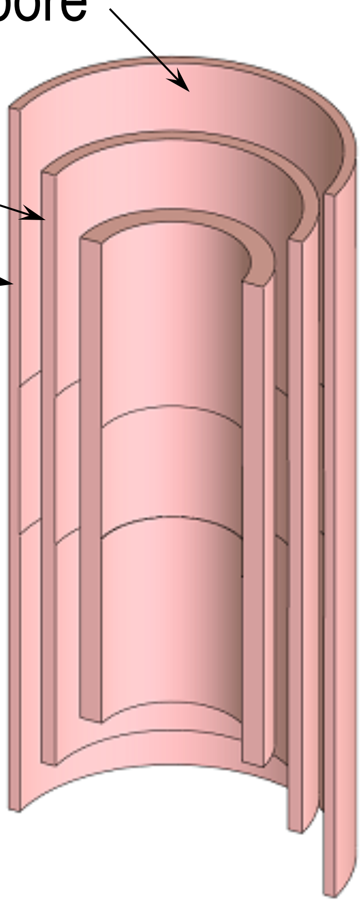
$[T_{op} = 4.2\text{ K}; I_{op} = 251\text{ A}]$

- 3-nested-coil formation
- Each coil an assembly of ***NI*** DP coils, wound with REBCO tape, 6-mm wide, 75-µm thick overall, with 10-µm thick copper/side

Coil 1: 26 DP (6 inside-notch); 369 MHz (8.66 T); 91-mm bore

Coil 2: 32 DP (8 inside-notch); 242 MHz (5.68 T)

Coil 3: 36 DP (8 inside-notch); 189 MHz (4.44 T)
216 mm o.d. (including 3-mm build overband)
L500 cold bore: 237 mm



- H800 contribution: 61.5% of 30.5 T

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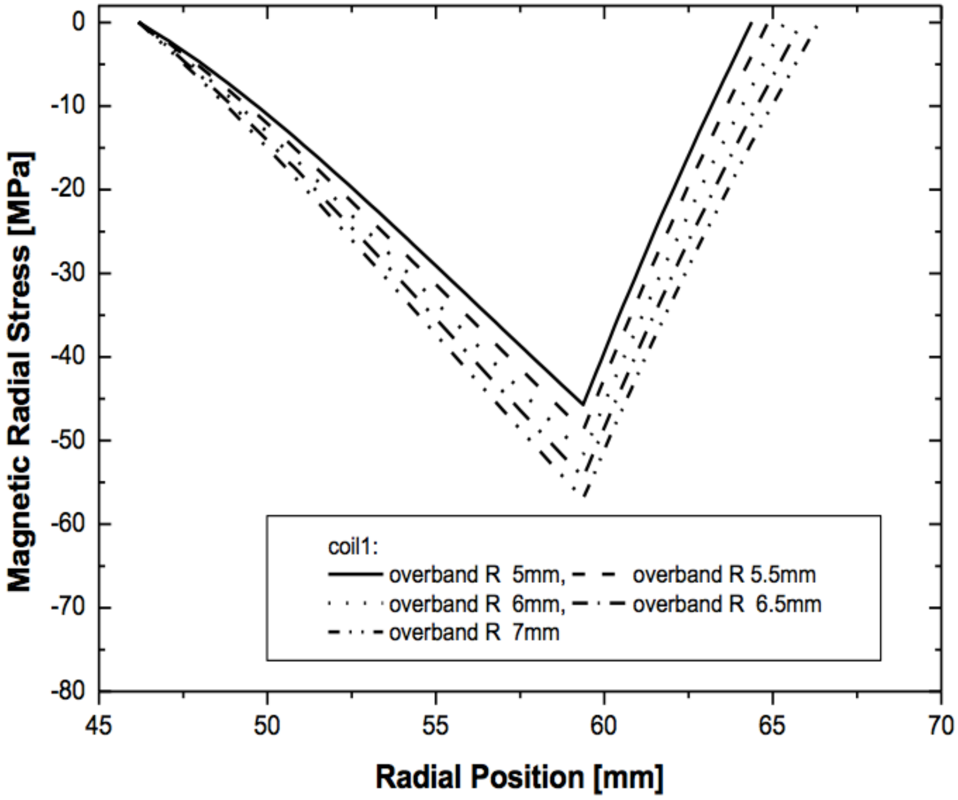
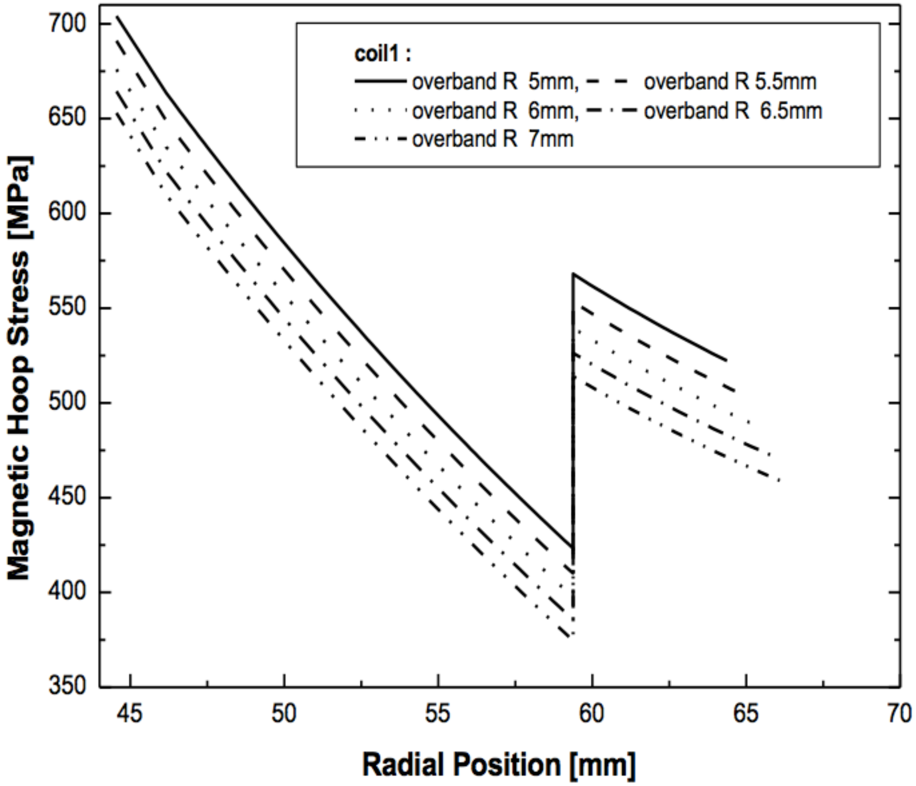
*Overbanding H800 Coils**





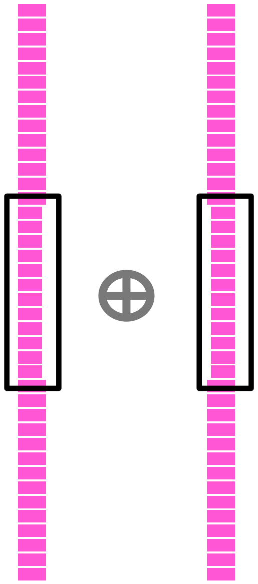
* Mingzhi Guan, Seungyong Hahn, Juan Bascuñán, Timing Qu, Xingzhe Wang, Peifeng Gao, and Yukikazu Iwasa, "A parametric study on overband radial build for a REBCO 800-MHz Insert of a 1.3-GHz LTS/HTS NMR magnet." presented at MT24.

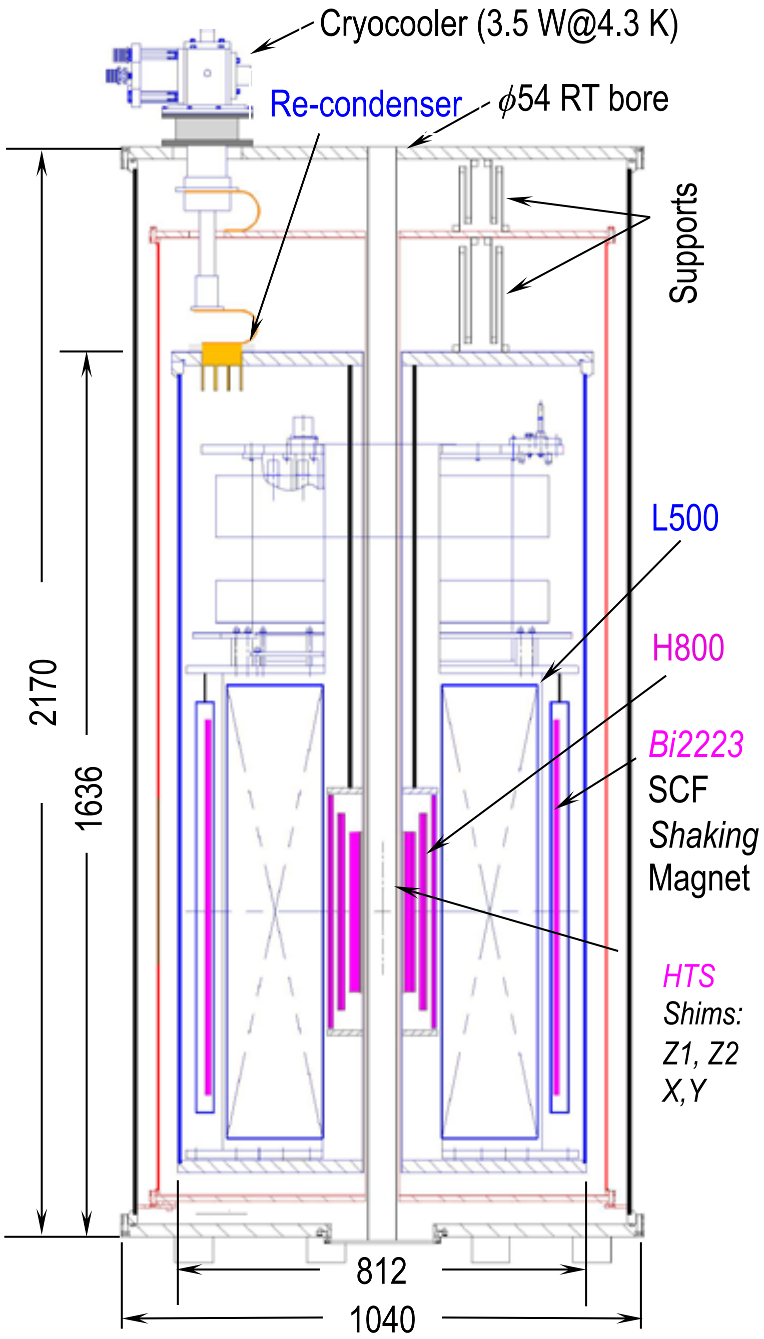
Noteworthy Features of 1.3G

- H800 field contribution: >61%
- NI winding technique for 3 H800 coils
- Inside-notch double-pancake coils

  ➚ *field homogeneity of a "short" magnet*
- Persistent-mode HTS shims:

  Z1, Z2, X, (Y)
- SCF shaking magnet
- LHe re-condensation





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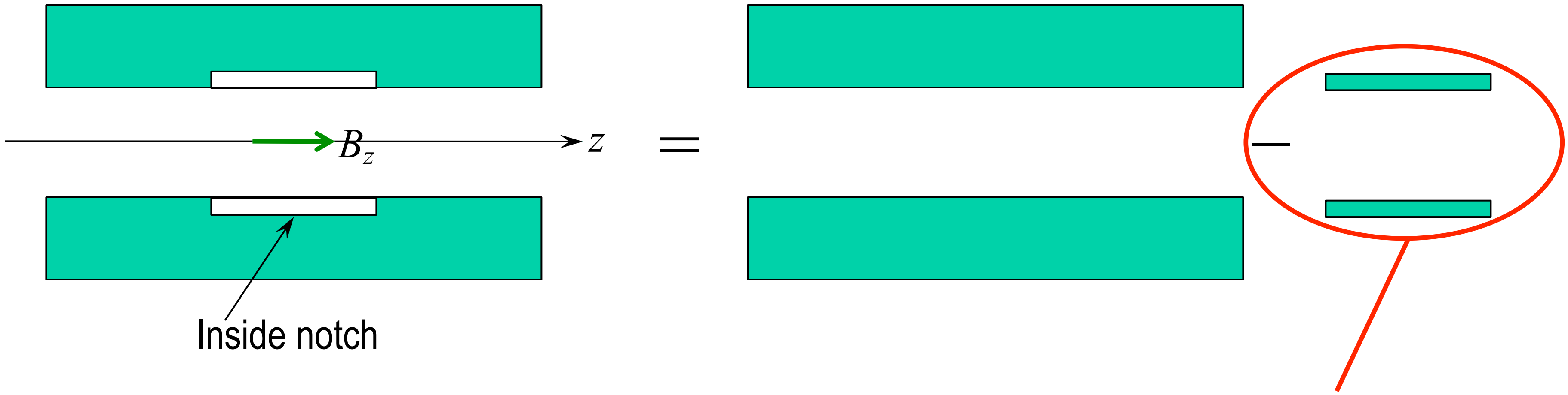
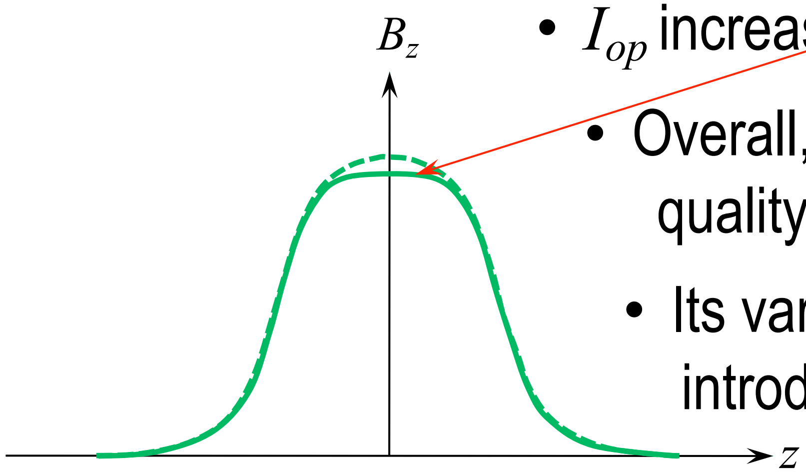
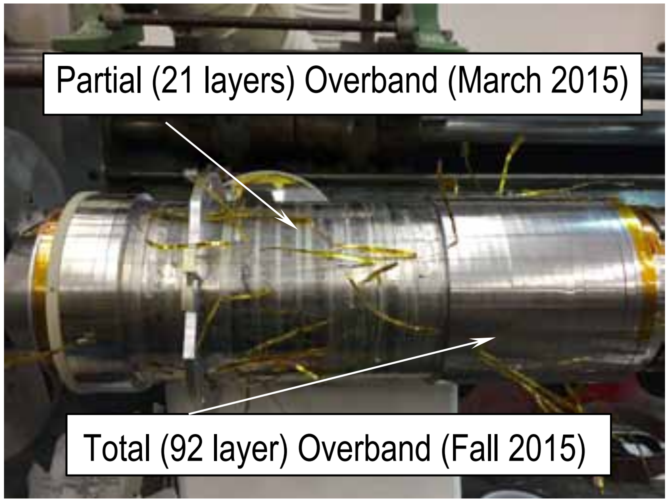
Why a “notch” improves field uniformity?



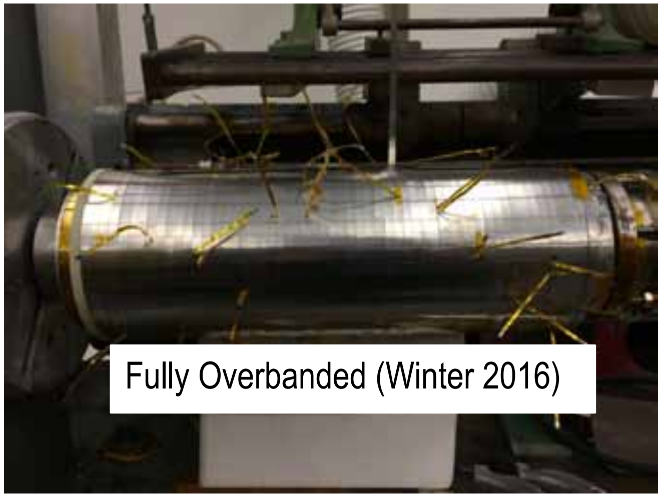
- Improves center field by trimming off field at center region
  - I_{op} increased a bit for a slight loss of ampere-turns
- Overall, an efficient technique to improve the field quality of a “short” magnet, e.g., our H800
  - Its variations used in *all* LTS NMR magnets, introduced, for the first time, in an HTS insert



Overbanding Coil 1 (2015—2016)


Partial (21 layers) Overband (March 2015)

Total (92 layer) Overband (Fall 2015)


Fully Overbanded (Winter 2016)

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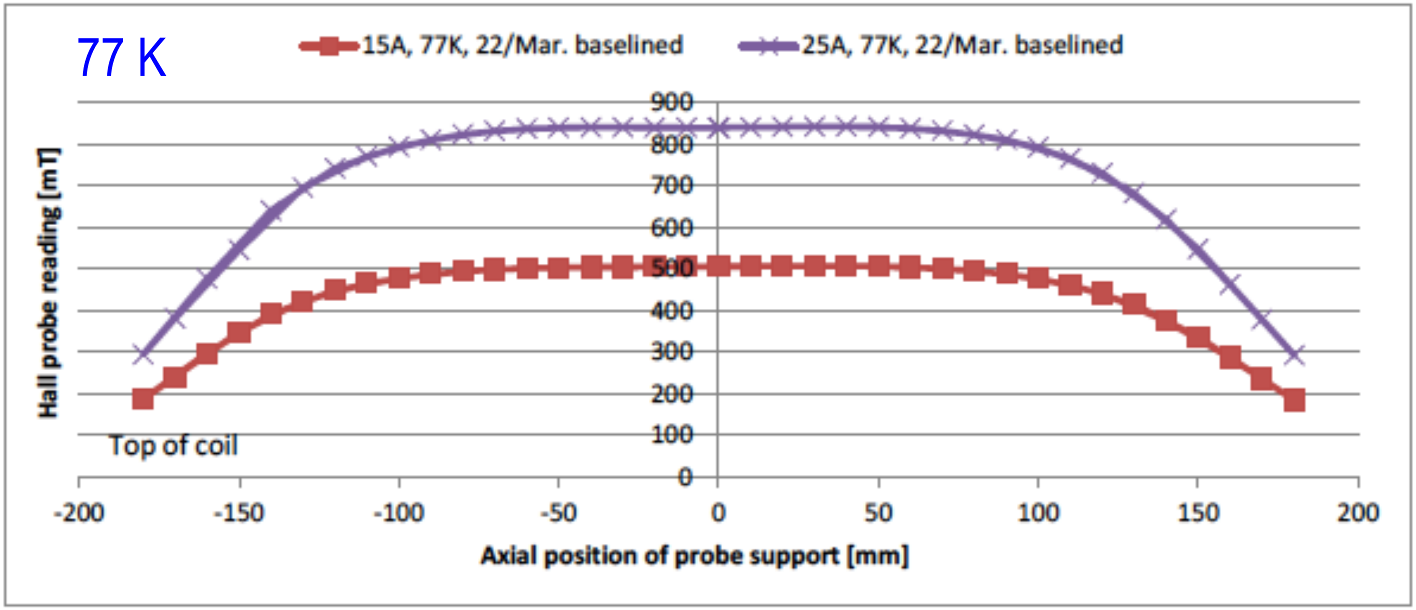
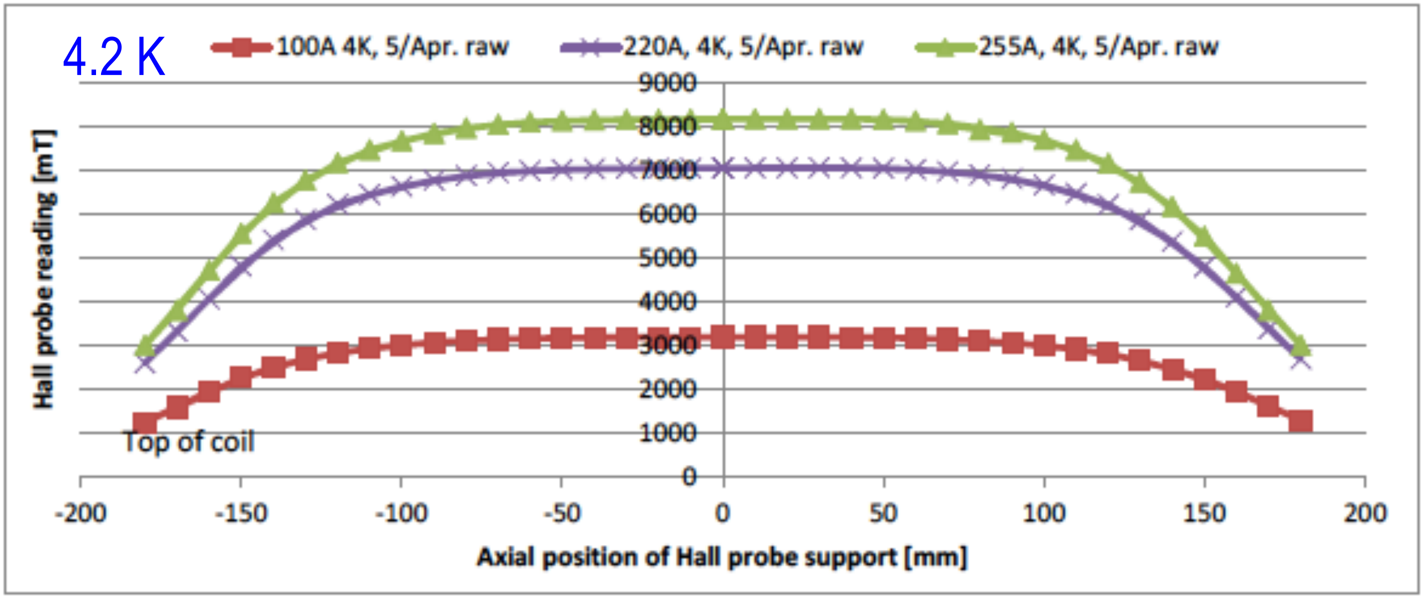
Field Mapping Data





Coil 1 Results

Date	Overband	T [K]	I [A]	B_o / I [mT/A] (Design: 34.46)	τ_m [s]	R_m [mΩ]
Jun 2014	0	77	0 ←→ 30	34.20 ←→ 34.64	Computed: 138	17.6
	0	4.2	15 / 30 253.0	34.47 / 34.7 34.17 (Design: 8.66 @251.3 A)	Measured 140(4.2 K) 170 (77 K)	17.2 14.3
Mar 2015	21	77	20	33.72	190	12.8
Feb 2016	92 (full)	77	10 / 20 / 30 / 40	33.83 / 33.46 / 32.60 / 28.47	245	9.9
Apr 2016	full	77	15 / 25.2	33.7 / 33.4	229 / 230	11.3 / 10.6
		4.2	99.8	31.9	596	4.2
			220.3	31.9	549	4.4
			255.7	31.9	569	4.3

4.2 K Results

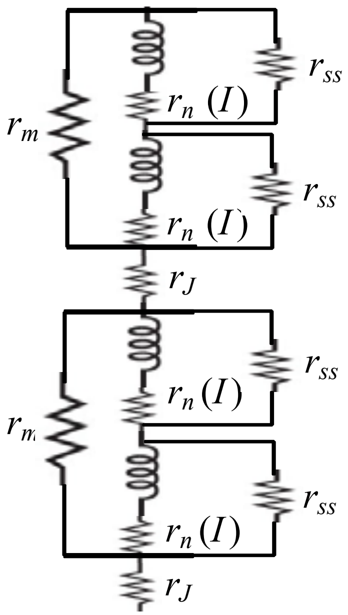
- $B_o/I =$ 34.17 mT/A, 99.15% of design value (06/2014, no overbanding)
- $B_o/I =$ 31.9 mT/A, 92.26% of design value (04/2016, full overbanding)

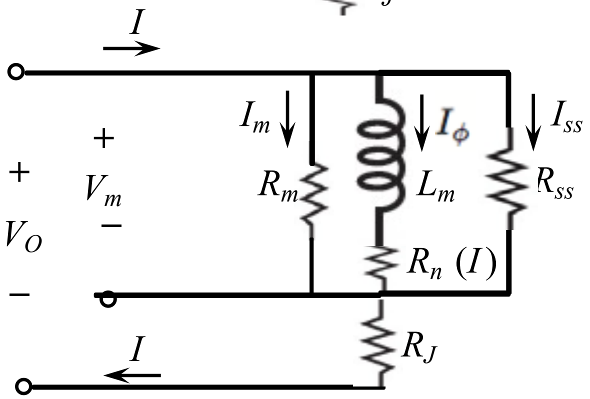
Circuit Model & 1st – Order Analysis

$$R_{ss} = 52 \times \frac{(n_p)^2(\rho_{ss}/\rho_{cu})R_{c_{cu}}}{w_{ss}\, l_{ss}}$$

$$= 52 \times \frac{(52)^2(51\,\mu\Omega\,\text{cm}/0.25\,\mu\Omega\,\text{cm})(30\,\mu\Omega\,\text{cm}^2)}{(6\,\text{mm})(36\,\text{m})} = 70.2\,\Omega$$

Ignore R_{ss}





Center Field B_o Computation

$$B_o = b_o(N - N_m)I_\phi = b_o(N - N_o)(I - I_m)$$

$$= b_o N I \left(1 - \frac{N_m}{N}\right)\left(1 - \frac{I_m}{I}\right)$$

$$\frac{B_o/I}{b_o N} = \left(1 - \frac{N_m}{N}\right)\left(1 - \frac{V_m/R_m}{I}\right)$$

$$N_m = N\left[1 - \left(\frac{B_o/I}{b_o N}\right)\left(\frac{I}{I - V_m R_m}\right)\right]$$

Coil parameters

Measurement

$$R_m = 26 r_m$$

$$R_J = 25 r_j$$

$$R_{ss} = 52 r_{ss}$$

$$R_n(I) = 52\, r_n(I)$$

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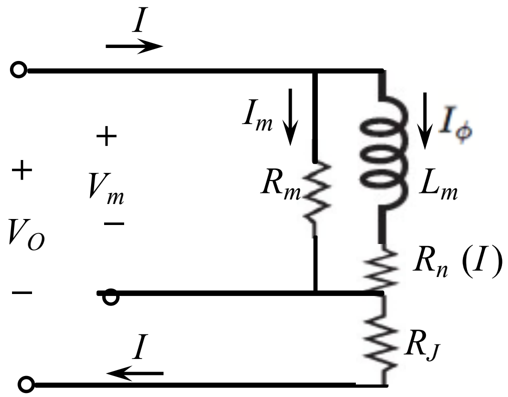
Circuit Model & 1st – Order Analysis

Center Field B_o Computation

$$\frac{B_\circ/I}{b_\circ N} = \left(1 - \frac{N_m}{N}\right)\left(1 - \frac{V_m/R_m}{I}\right)$$

$$N_m = N\left[1 - \left(\frac{B_\circ/I}{b_\circ N}\right)\left(\frac{I}{I - V_m R_m}\right)\right]$$



$b_o N$ = 34.46 mT/A; N = 9512; E_c = 0.1 μV/cm; $2b_2$ = 118 mm

I [A]	B_o/I [mT/A]	V_o [μV]	V_J * [μV]	V_m **= V_m [μV]	I_m [A]	I_φ [A]	N_m
10	33.83	31.8	7.3	24.5	0.003	~10	174
20	33.46	103.0	14.6	88.4	0.009	~20	276
30	32.60	624.0	21.9	6018	0.608	29.4	330
40	28.47	64,400	29.2	64,692	6.5 A	33.5	129

* $V_J = R_J I$, where R_J = 730 nΩ (@77 K after 4.2 K run, Jun 2014)

** $V_m = R_m I_m$, where R_m = 9.8 mΩ (@77 K after full overbanding, Feb 2016)

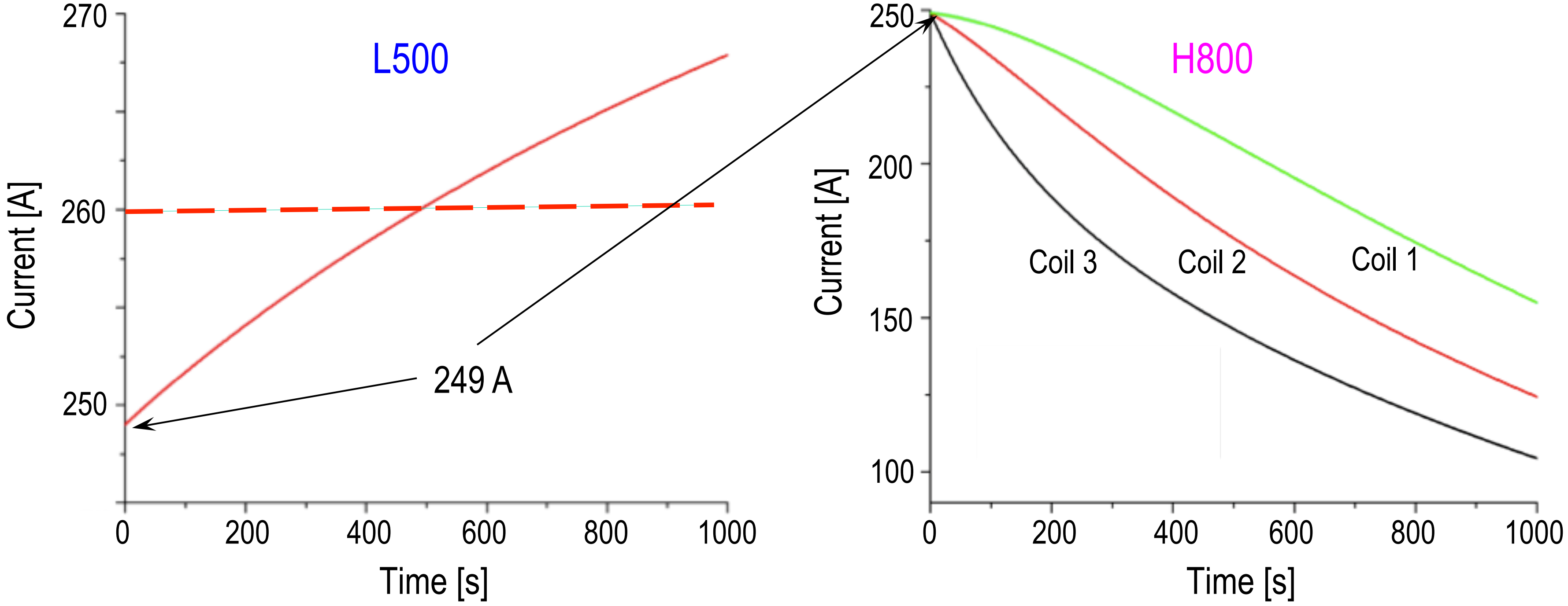
Protection of H800

- Itself, self-protecting
- L500 quench highly unlikely at 4.2 K—designed to operate at 6.2 K—made of all Nb_3Sn; the magnet discharges with a time constant of ~200 s
- Worst scenario: entire 1.3G energy (6.4 MJ) into a 100-kg mass of H800: Final temperature ~280 K
  - Radial current (through contact) acts like a built-in current source for the global heater planted throughout the NI winding

H800 must, and will, be protected against fault-mode events

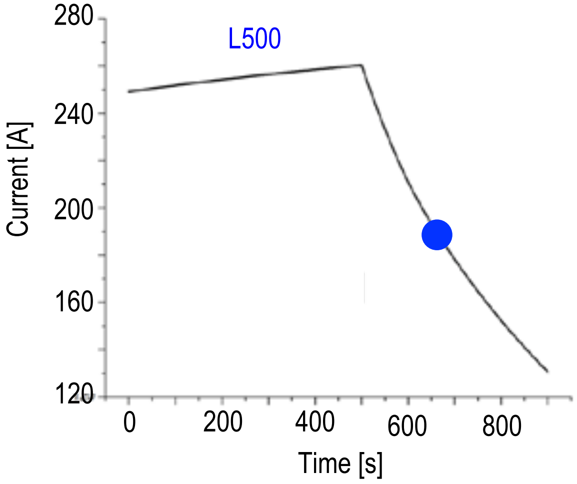
Series-Connected Option (L500-H800)

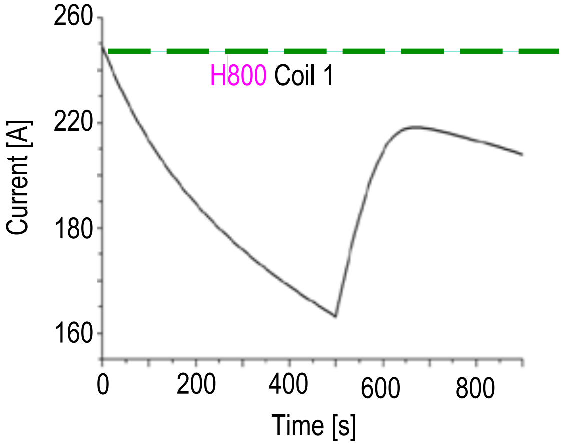
- Series-connected L500 (246 A)-H800 (251A), at $I_{op} = 249$ A a viable option
- L500 shunted by resistors and PCS; each H800 coil shunted by R_m and the entire H800 shunted by a 500-mΩ resistor
- Entire magnet shunted by 10-mΩ dump resistor with a switch
  - ➢ Dump switch opened at $t = 0$
    - ▪ JASTEC (L500 manufacturer) limit: ≤ 260 A

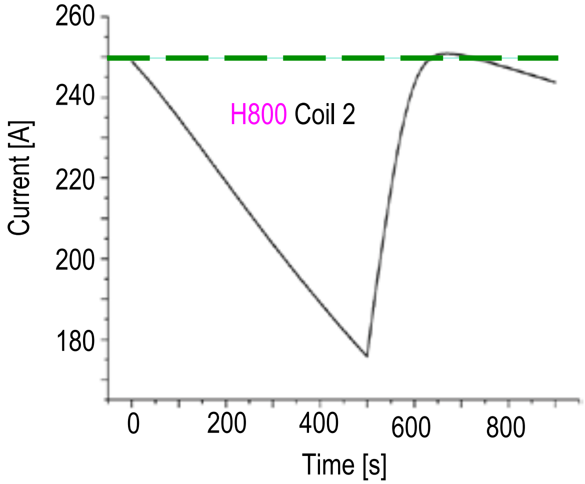


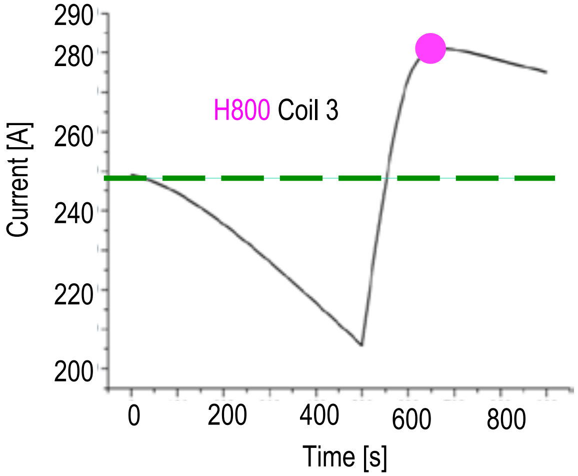
Series-Connected Option (L500-H800)

- ➢ Dump switch opened at $t = 0$
- ➢ Activate L500 PCS at 260 A
- Desirable to keep H800 at ≤ 250 A









- Although H800 peaks at 280 A (>250 A at 30.5 T), because L500 down to 190 A, center field down to 30.0 T, so H800 *might* be safe
- Obviously many combinations of external parameters to be studied, to keep both L500 and H800 from *over-stressed* and *over-heated*

Principal Aims of Phase 3B1 (2015-2018)

- Complete Coil 2: winding & overbanding
- Complete Coil 3: winding & overbanding
- Complete H800 by assembling Coils 1-3
- Operate H800 at 4.2 K
- Assemble L500/H800; operate at 4.2 K and *generate a 30.5-T field*
- Characterize the 30.5-T field—not expected to be of an NMR quality
- *Continue developing HTS shim coils and "shaking-field" shimming technique*

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LHe-Free Persistent-Mode HTS Magnets for NMR & MRI*

Specific Aims

1. Build NI REBCO DP coils, each terminated with a *superconducting* joint

2. Design, build, and operate a persistent-current switch (PCS) viable to NI REBCO DP coils

- Supported by the National Institute of Bioimedical Imaging and Bioengineering of the NIH

Acknowledgement
Seungyong Hahn (Co-Investigator, now FSU/NHMFL);
Timing Qu (Tsinghua U); Phil Michael (PSFC);
John Voccio (Wentworth Institute of Technology); Juan Bascuñàn

LHe-Free Persistent-Mode HTS Magnets for NMR & MRI

Results to Date

Joints

To date no successful results with any of 6 joints tested that meets a ≤10-pΩ resistance criterion required for persistent-mode operation; the 6 joints made by and received from KJOINS, a company that uses a technique successfully developed and reported by Haigun Lee of Korea U during MT23 (2013) and published in *NPG Asia Materials* in 2014

PCS

One PCS designed, built, and successfully operated in LN2 (77—65 K) and in SN2 (60—57 K) with an NI REBCO DP coil. The coil, having a terminal joint resistance of 50 nΩ, operated in "semi-persistent" mode with a field decay time constant of ~100 hours.

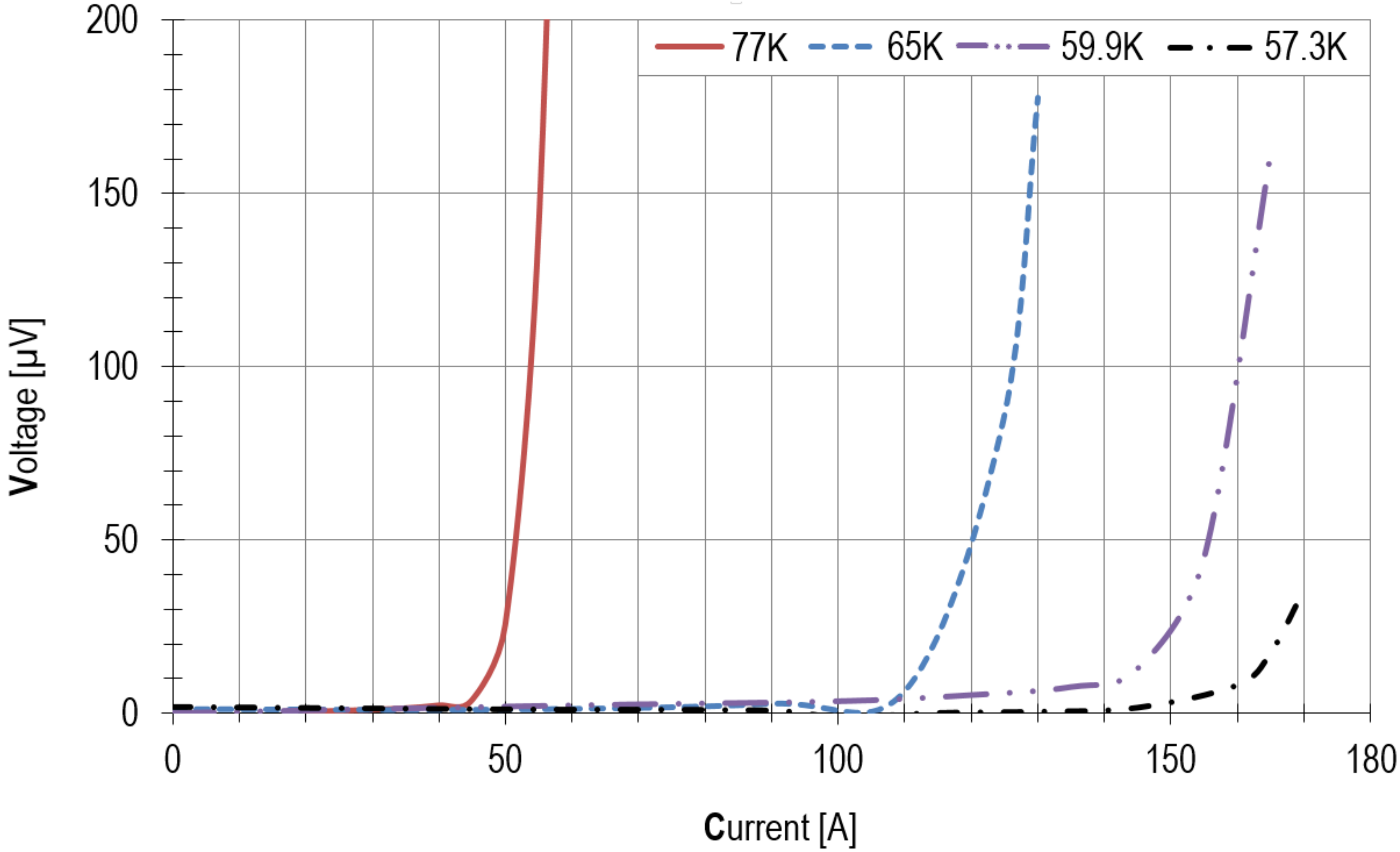
Timing Qu, Phil C. Michael, J. Voccio Juan Bascuñán, Seungyong Hahn, and Yukikazu Iwasa, "Persistent-current switch for high-temperature superconducting pancake coils: design and test results of a coil operated in liquid nitrogen (77 K—65 K) and in solid nitrogen (65 K—57 K)," submitted to *Appl. Phys. Lett* (June, 2016).

REBCO NI DP Coil

$2a_1$ / $2a_2$ / $2b$ [mm]	150.7 / 167.9 / 12.1
SS Ring ID / Wall [mm]	148.7 / 1
Total # turns / 6-mm wide tape length [m]	242 / 125 m
Computed center field [mT/A]	1.91
Computed inductance, L [mH]	17.2
R_m computed [mΩ] measurement [mΩ]	0.25 (R_c = 30 μΩ cm^2) 0.30 (current discharge time constant)

DP Coil V vs. I Traces at 77 K, 65 K, 59.9 K, 57.3 K

($V_c = 1250\ \mu V$ @ $E_c = 0.1\ \mu V/cm$)



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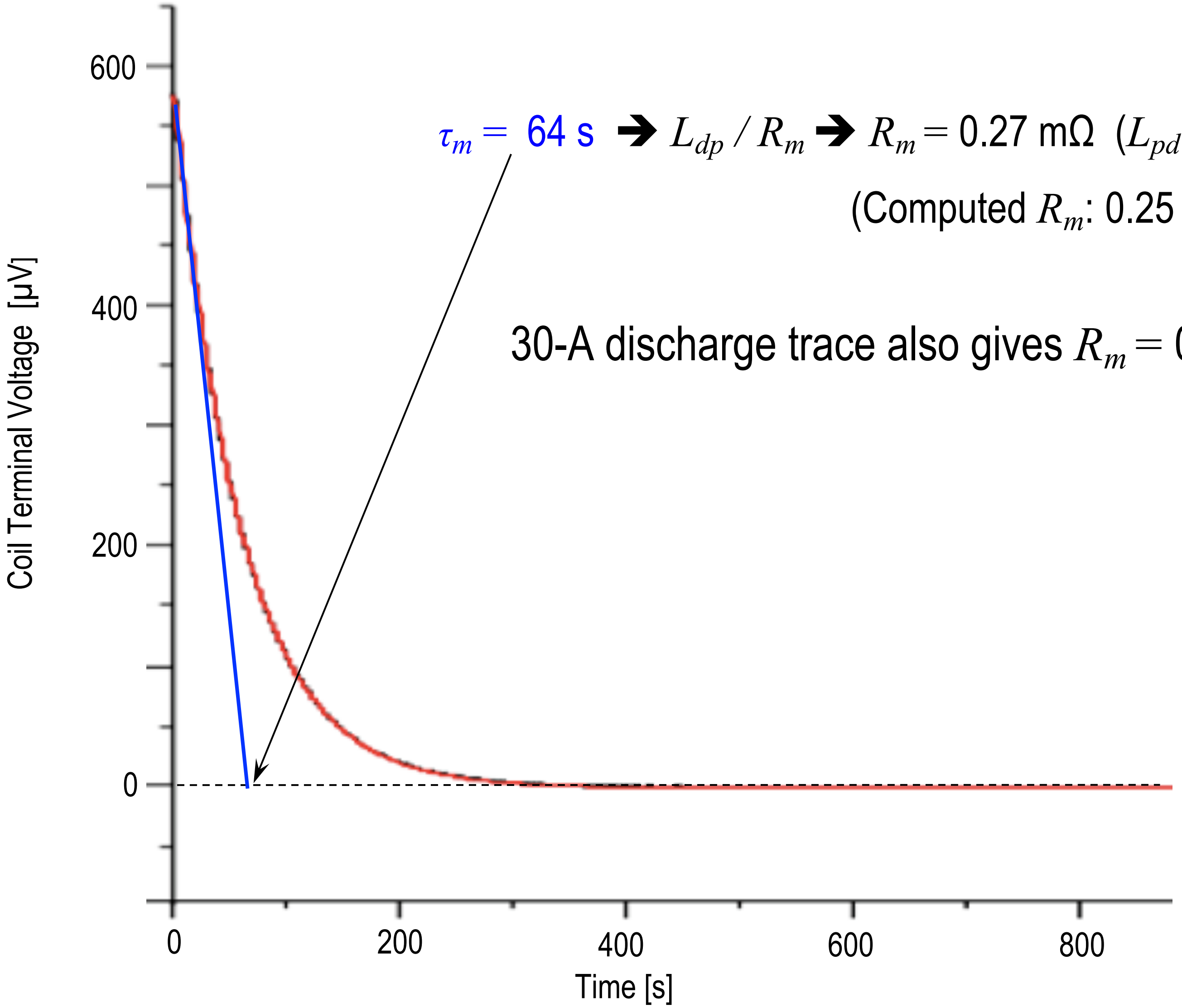
DP Coil $V(t)$ Under Discharge Mode from 20 A



$\tau_m =$ 64 s ➔ L_{dp} / R_m ➔ $R_m = 0.27$ mΩ ($L_{pd} = 17.2$ mH)

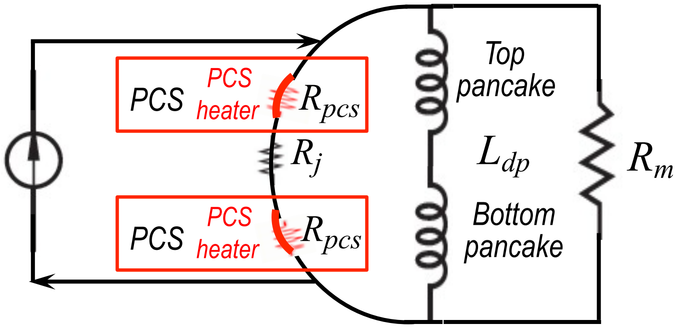
(Computed R_m: 0.25 mΩ)

30-A discharge trace also gives $R_m = 0.27$ μΩ

PCS Design

Circuit

L_{dp} : DP coil inductance
R_m : NI DP coil shunt resistance
R_j : Pancake-Pancake joint resistance
R_{pcs} : Normal-state PCS resistance

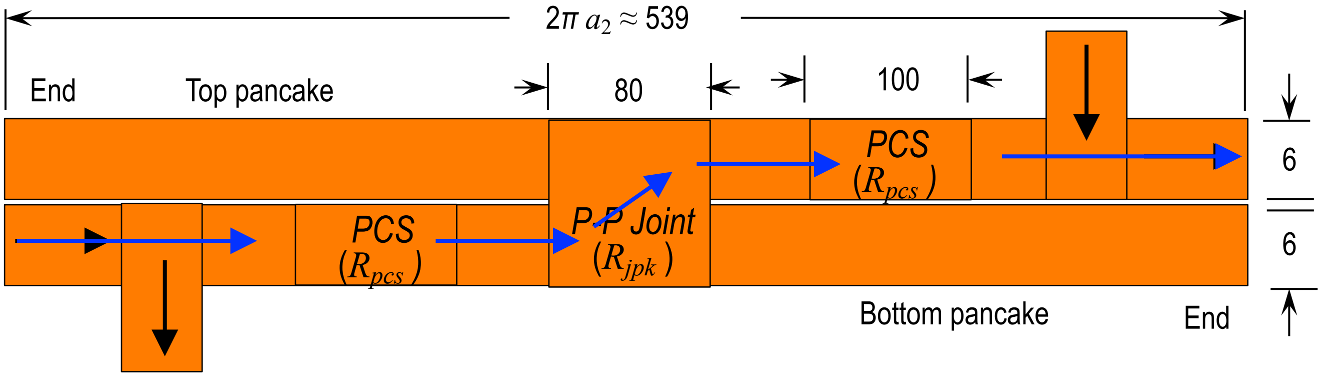


$R_j = 0$ for persistent-mode operation

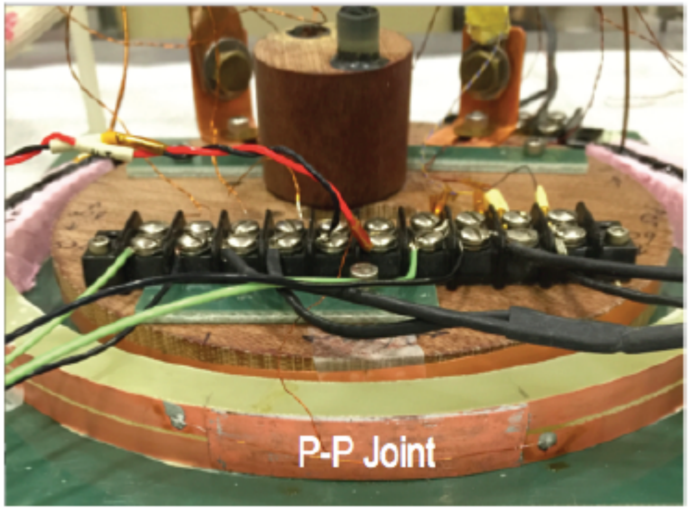
Only one PCS required

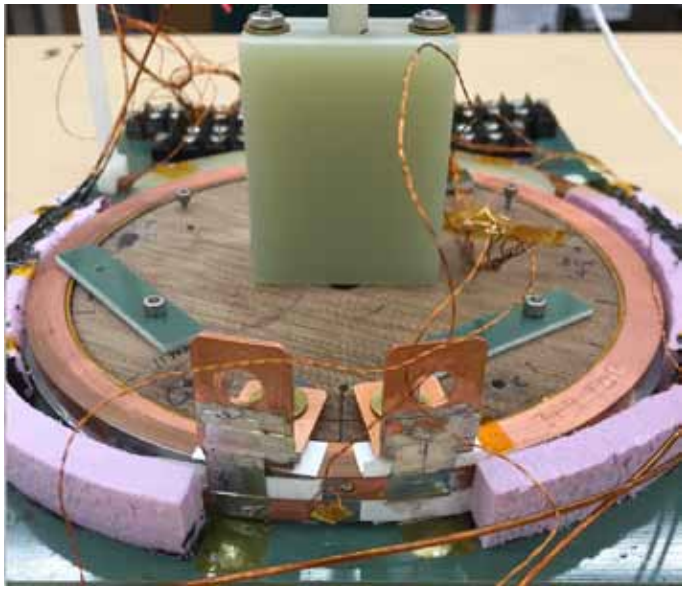
Requirements

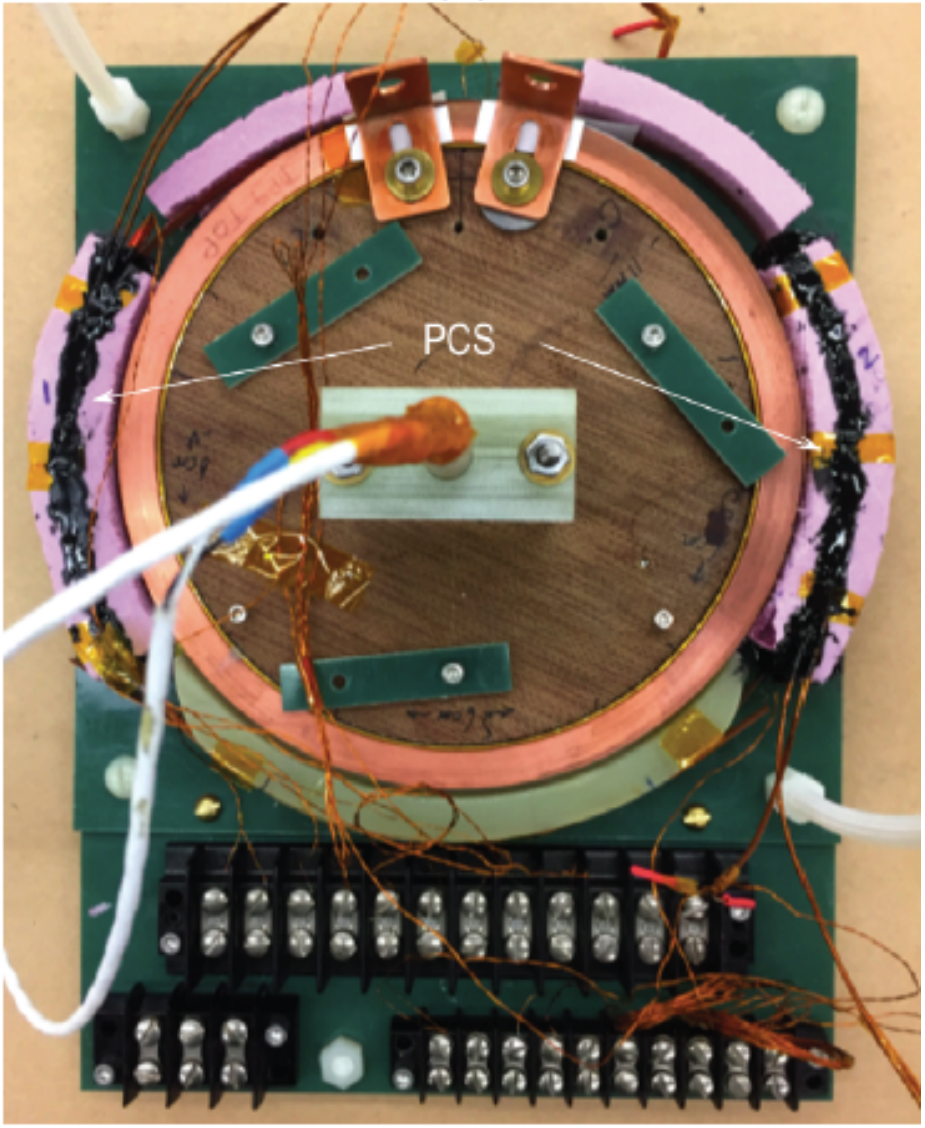
- Simple configuration; easy to install
- When resistive, its resistance, $R_{pcs} > R_m$
- Minimum heater power requirement (In Year 1, this requirement at the bottom priority)



Photos of PCS Test Rig







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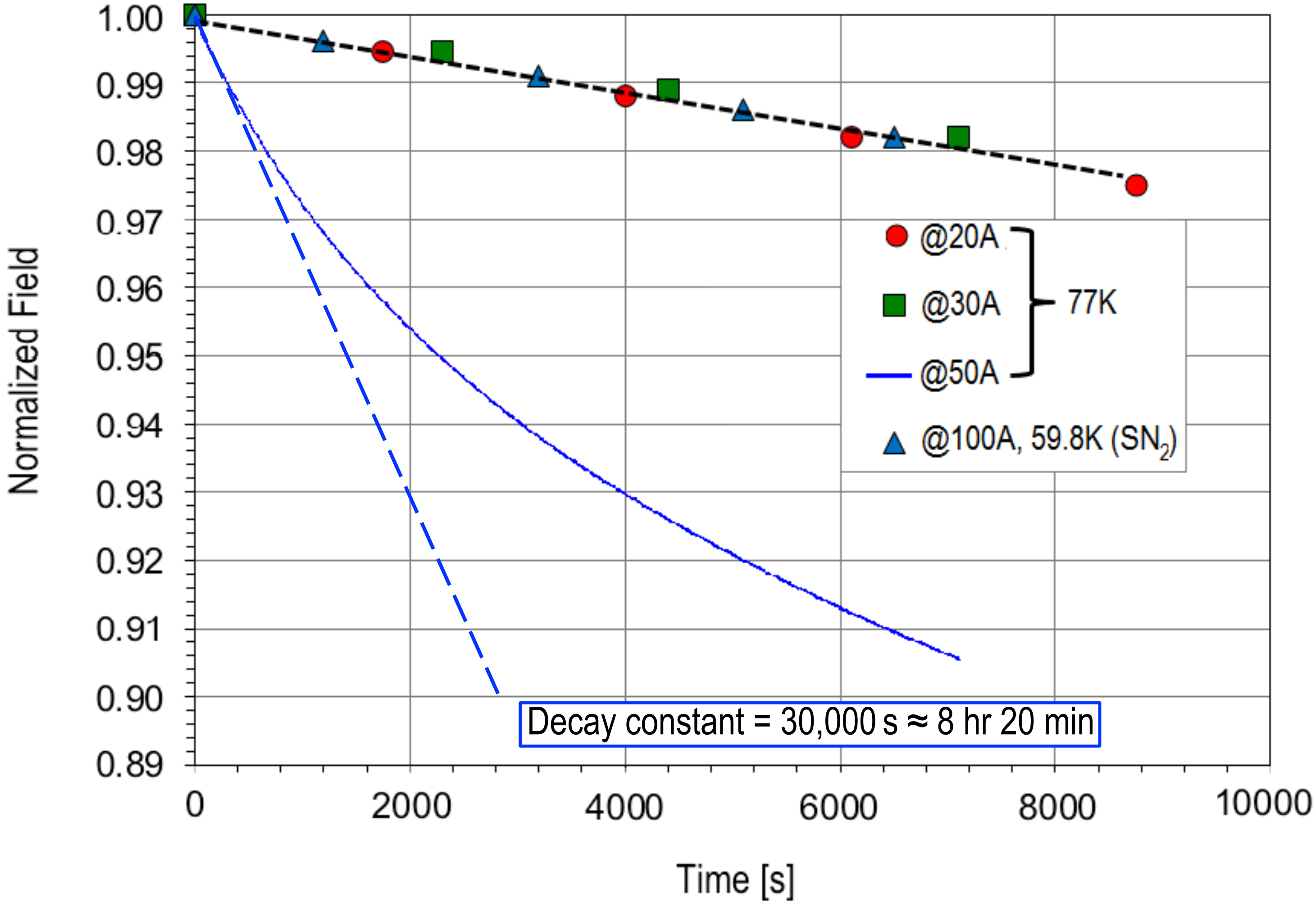
DP Coil in “Semi-Persistent” Mode



Decay constant = 30,000 s ≈ 8 hr 20 min

$\tau_m =$ 3.65 x 10^5 s ➔ L_{dp} / R_j ➔ R_j ≅ 50 nΩ (in the right range)

PCS Summary

Year 1 (07/1/2015—06/30/2016)—Results

- No REBCO-REBCO superconducting joints achieved
- PCS for REBCO NI DP coil designed, built, and operated successfully in the range 77—57 K, though only in "semi-persistent" mode

Year 2 (05/1/2016—04/30/2017)—Major Activities

- Improve PCS heater: now requires ~1 W at 77 K ➔ 20—80 mW target, i.e., ~100—500 mW at 4.2 K (Note that ΔT from ~15 K to ~90 K)
    - Achieve this improvement still keeping the layer thickness < 5 mm
- Operate a new rig at 4.2 K, in SN2, i.e., *LHe-free operation*

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MgB2 Magnet Projects

Recently Completed*

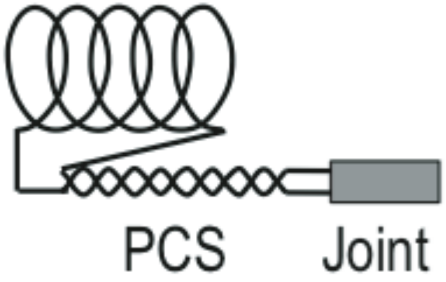
- A persistent-mode MgB_2 0.5-T/240-mm SN2-cooled magnet for MRI

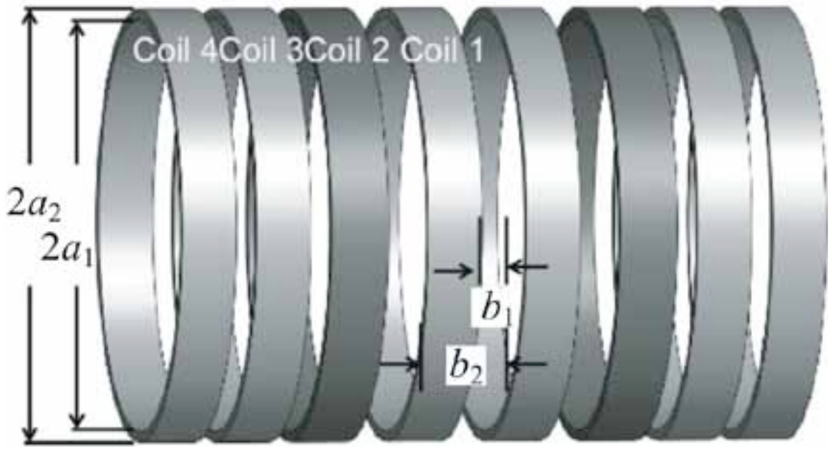
- Supported chiefly by the National Institute of Bioimedical Imaging and Bioengineering, NIH

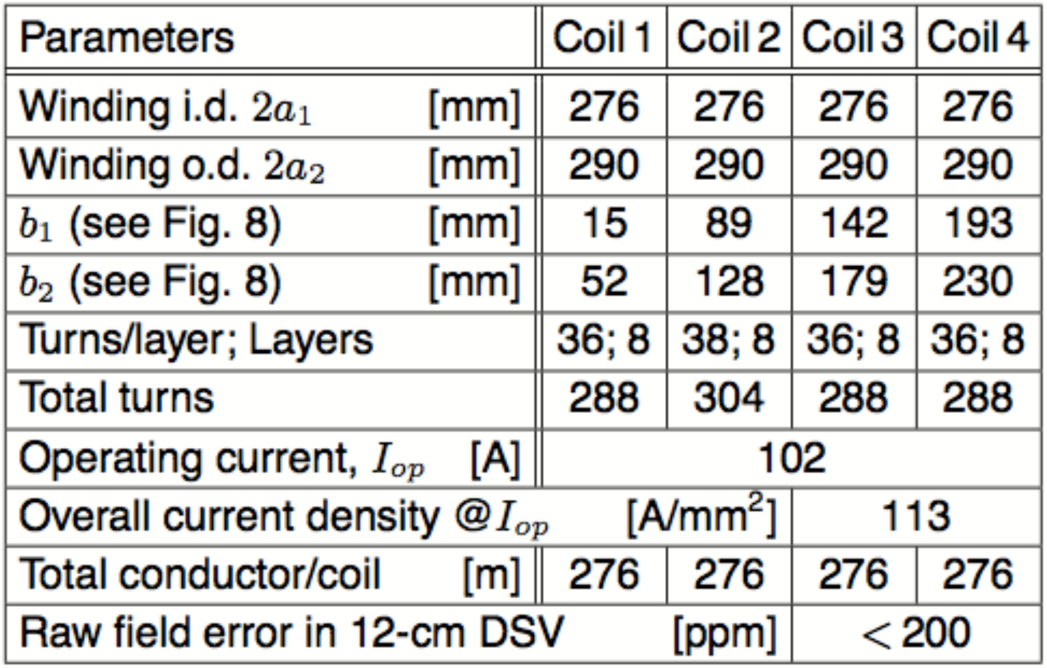
Acknowledgement (Chronological Order)
Juan Bascuñàn; Weijun Yao (now ORNL); Seungyong Hahn (FSU/NHMFL);
Woo-Seok Kim (Korea Polytechnique U); Dong Keun Park (Samsung Electronics); Jiayin Ling (GE Healthcare);
John Voccio (Wentworth Institute of Technology); Youngjae Kim (NHMFL); Jungbin Song (Korea U)
Timing Qu (Tsinghua U); Phil Michael (PSFC)

A Persistent-Mode MgB2 0.5-T/240-mm SN2-Cooled Magnet for MRI

- 8 coil-PCS-joint modules
- Wound with MgB2 monofilament wire
- Wind-and-react
- Persistent operation in the range 10-15 K



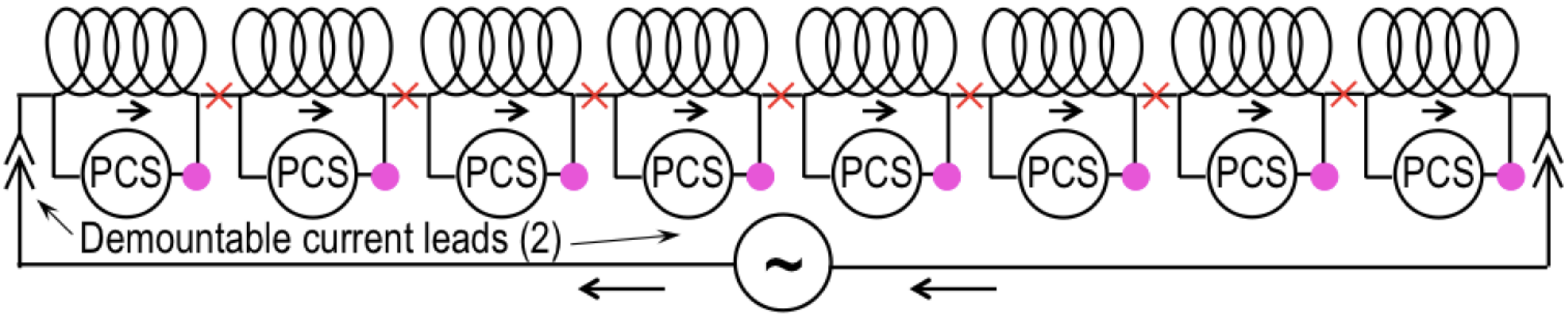




Parameters	Coil 1	Coil 2	Coil 3	Coil 4
Winding i.d. $2a_1$ [mm]	276	276	276	276
Winding o.d. $2a_2$ [mm]	290	290	290	290
b_1 (see Fig. 8) [mm]	15	89	142	193
b_2 (see Fig. 8) [mm]	52	128	179	230
Turns/layer; Layers	36; 8	38; 8	36; 8	36; 8
Total turns	288	304	288	288
Operating current, I_{op} [A]	102			
Overall current density @I_{op} [A/mm^2]			113	
Total conductor/coil [m]	276	276	276	276
Raw field error in 12-cm DSV [ppm]			< 200	

Circuit Model

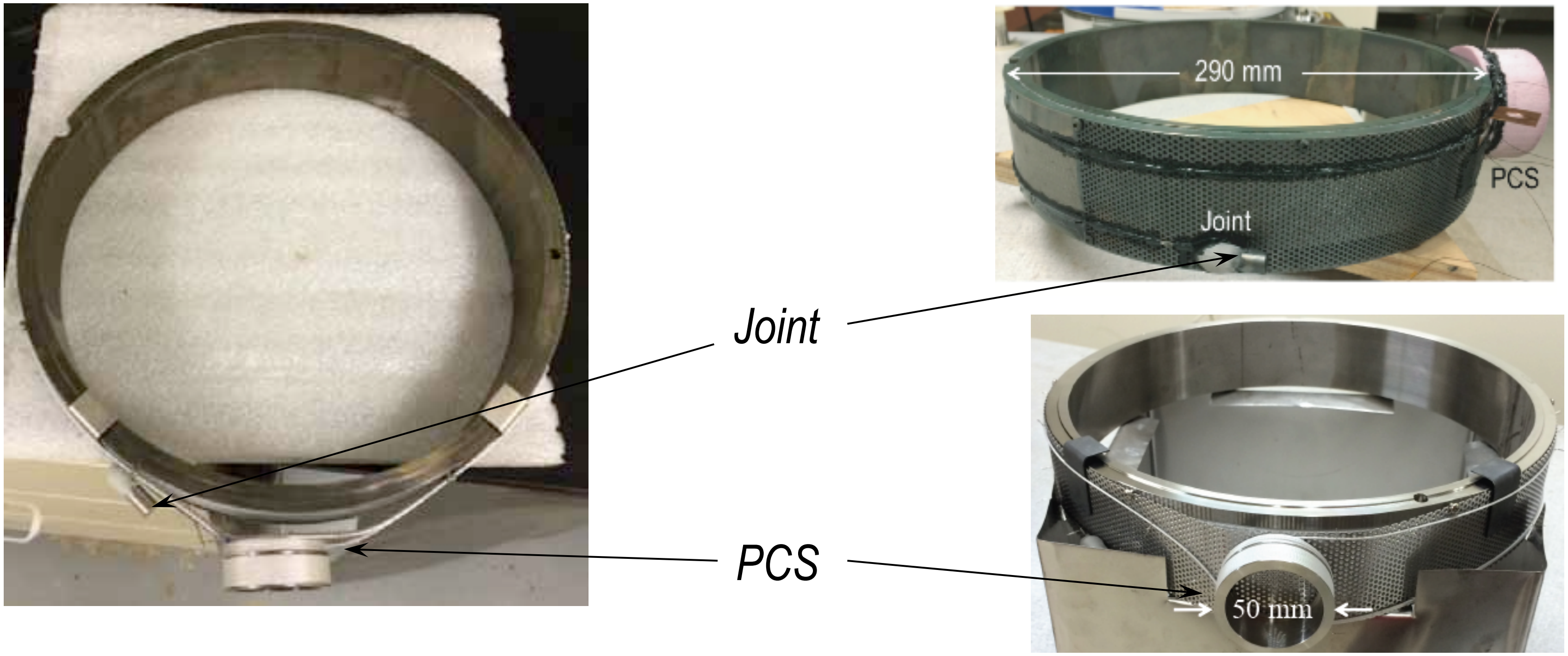
- With each PCS open, energize magnet, all 8 coils series connected
- Close each PCS at $I_{op} =$ 102 A



● Superconducting joint

✕ Superconducting joint

Coil Assembly



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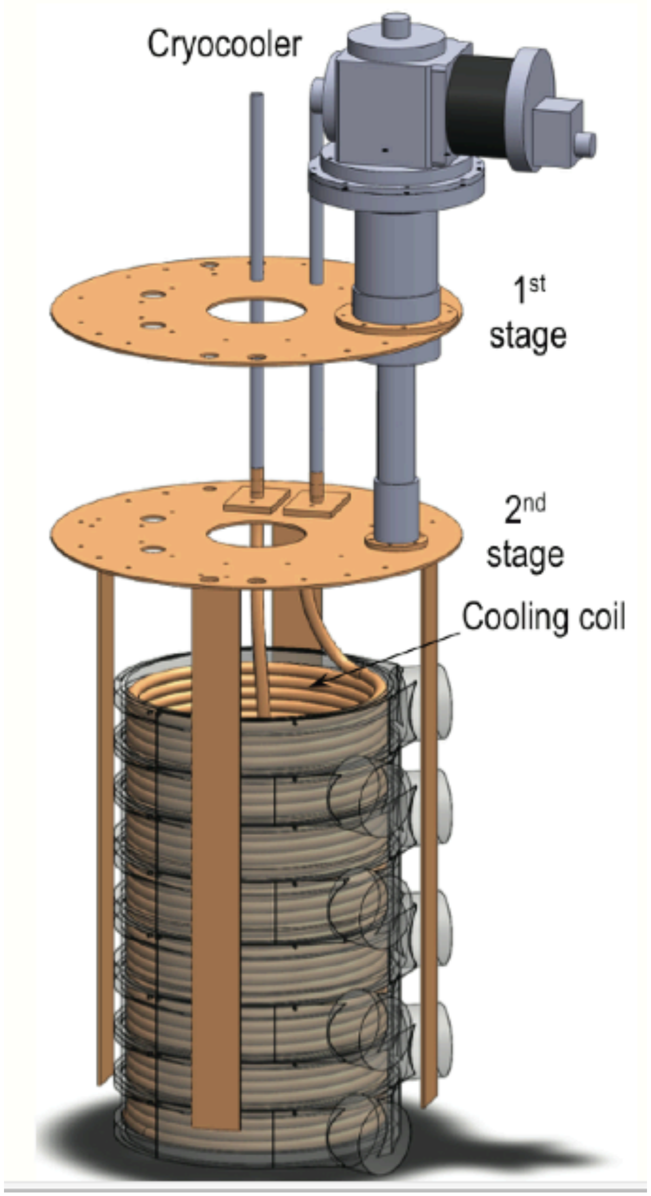
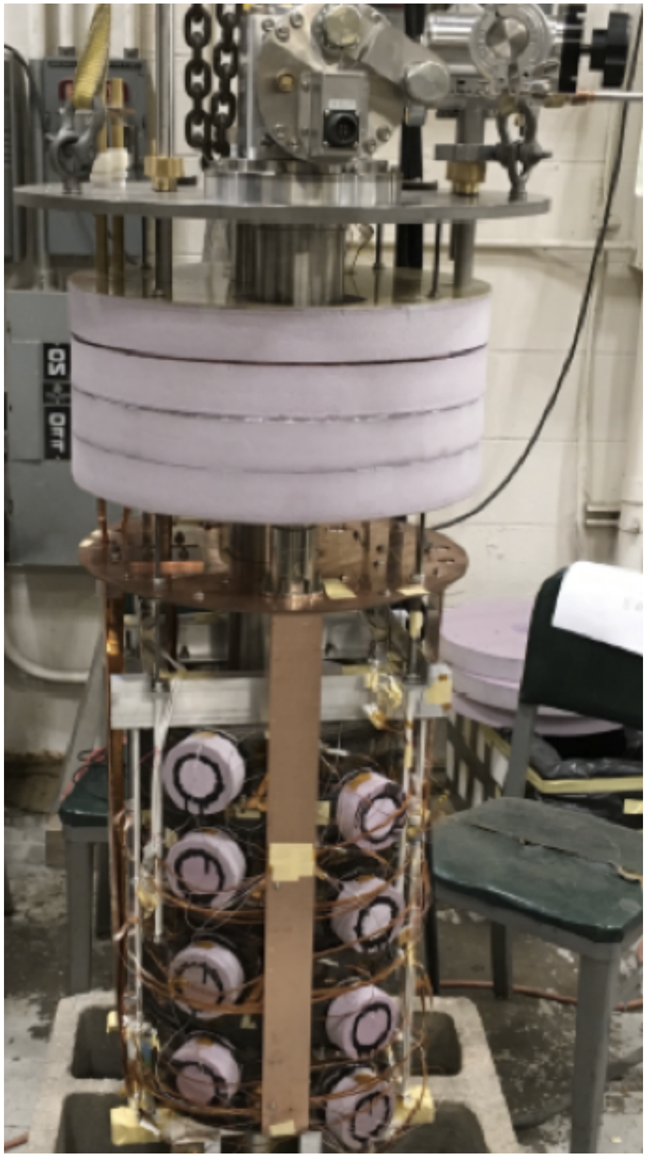
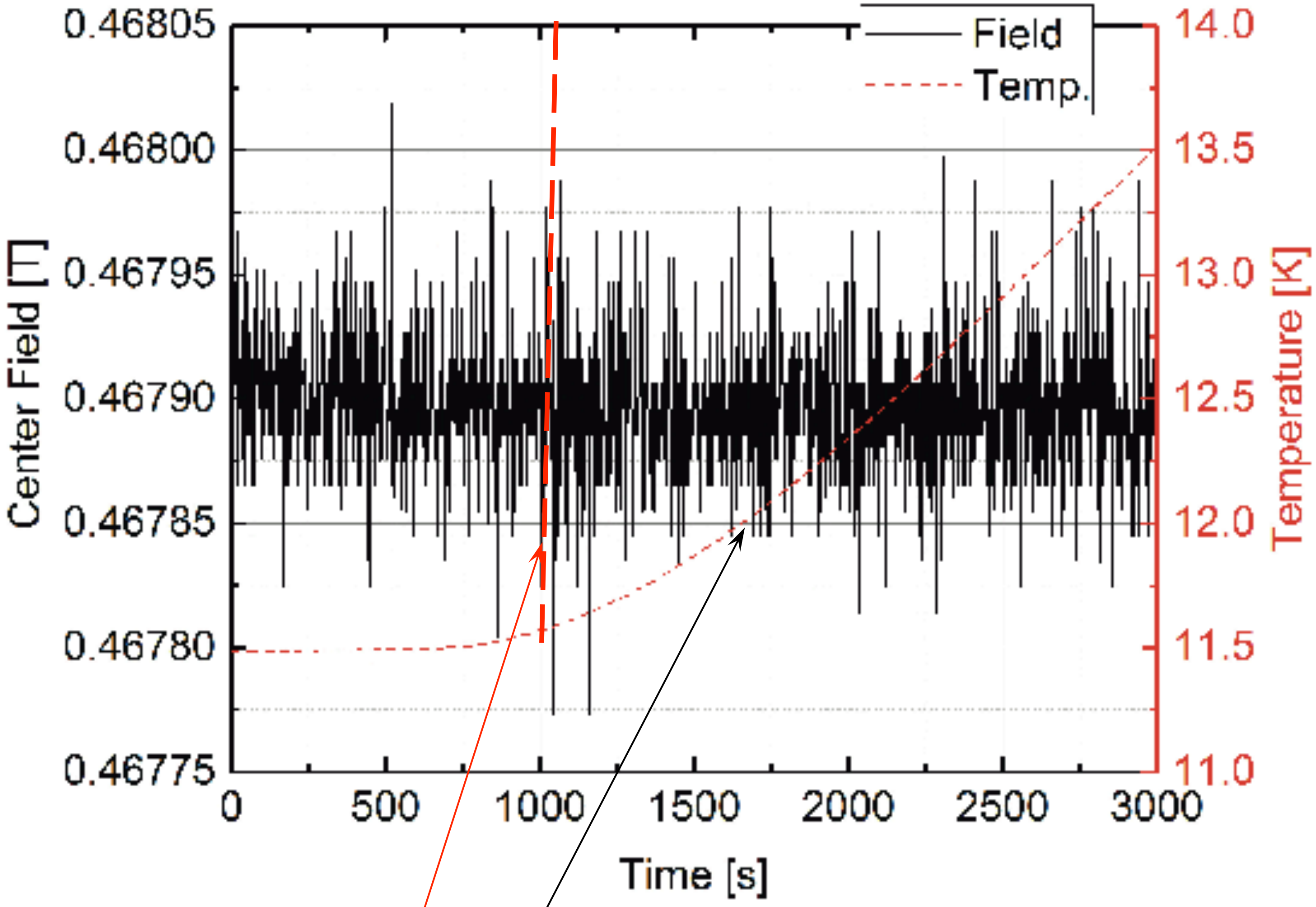
Coil Assembly



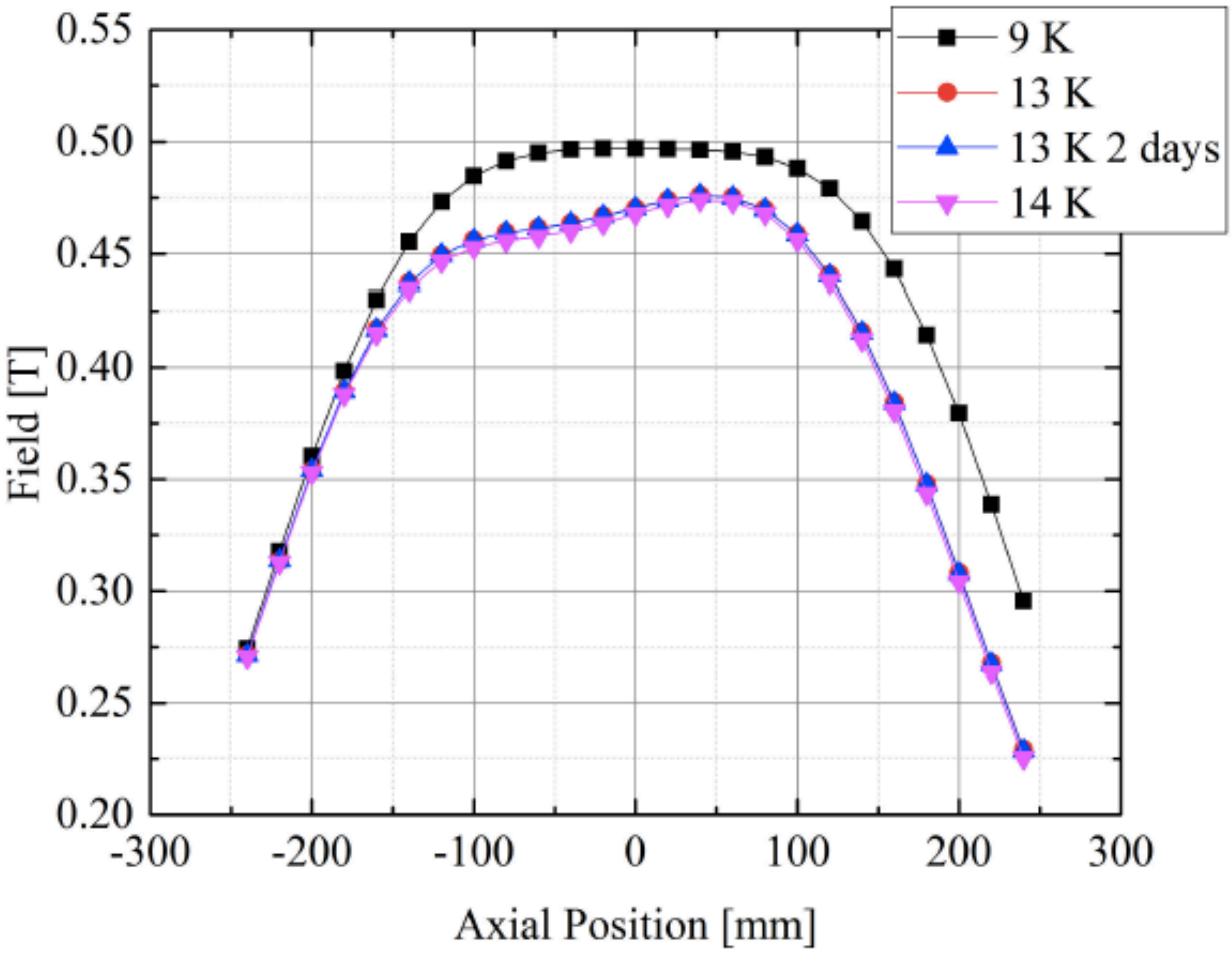


Data

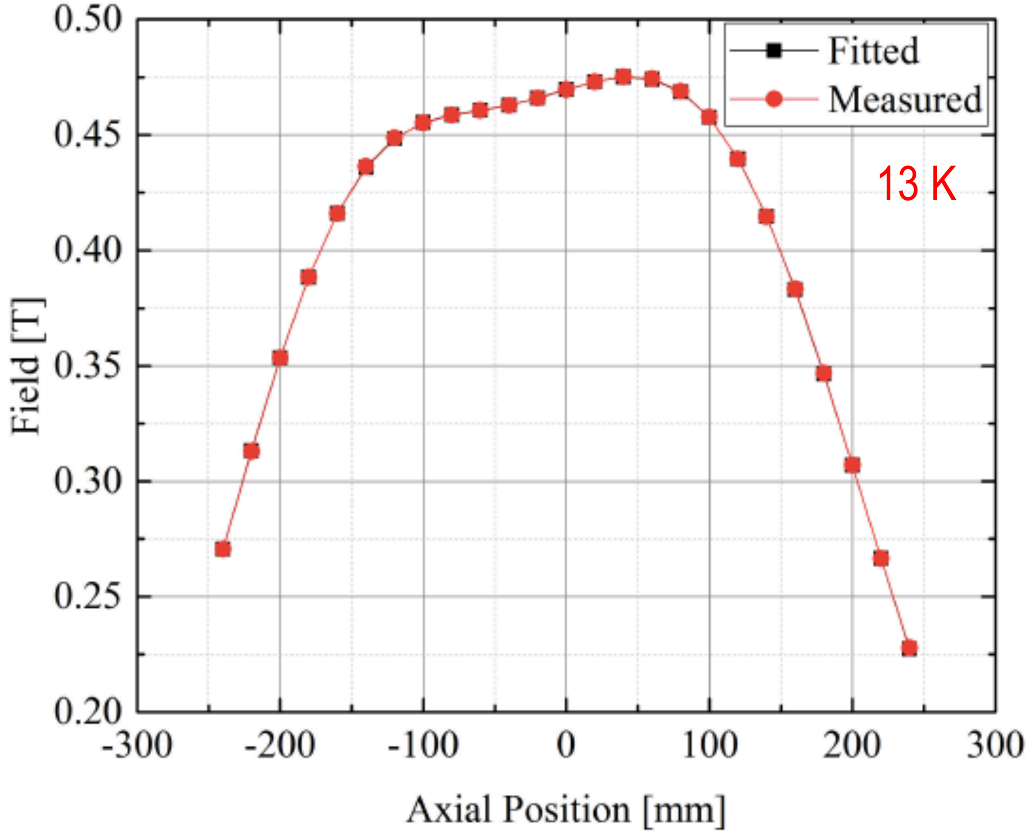


- $dT/dt = $ 0.8 mK/s, with ~60 kg of SN2
- $dT/dt = $ 50 mK/s, *without* ~60 kg of SN2 (magnet cold mass $\approx$ 50 kg)

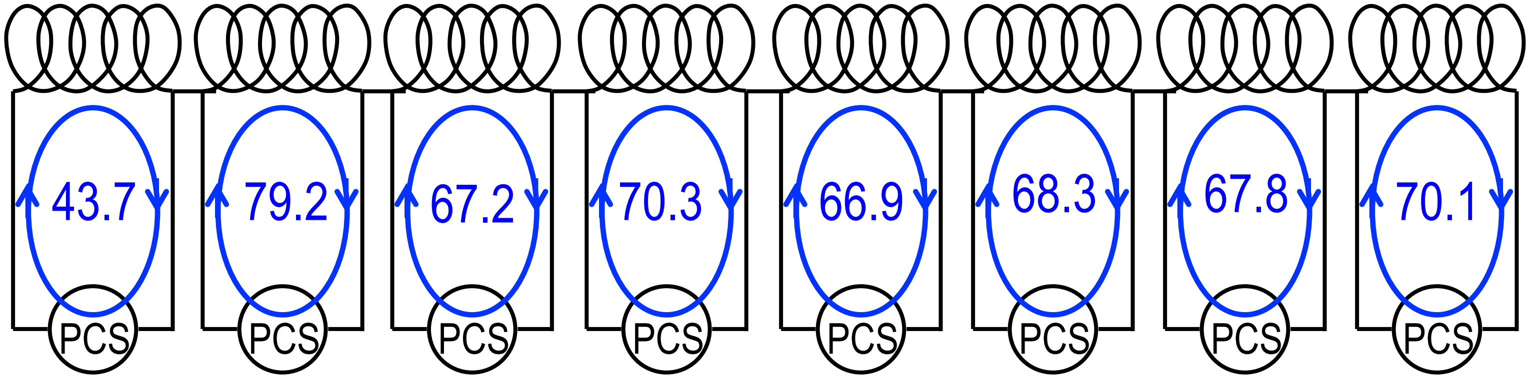
Data


Field [T]
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
-300
-200
-100
0
100
200
300
Axial Position [mm]
9 K
13 K
13 K 2 days
14 K

Data



0.50
0.45
0.40
0.35
0.30
0.25
0.20
Field [T]
-300
-200
-100
0
100
200
300
Axial Position [mm]
Fitted
Measured
13 K



43.7
79.2
67.2
70.3
66.9
68.3
67.8
70.1
PCS
PCS
PCS
PCS
PCS
PCS
PCS
PCS

Conclusions

- Persistent-mode operation successfully achieved with an MgB_2 magnet composed 8 coil-PCS-joint modules
- Modularization particularly useful during development stage; for commercial units may require further refinement
- In LHe-free magnet, SN2 considerably enhances the thermal capacity of a cold mass, providing good thermal stability to the magnet. SN2 also maintains a uniform temperature environment around the magnet.
- This MgB_2 magnet a major milestone in the MgB_2 MRI magnet technology.
  - A promising option for the next generation LHe-free MRI magnet system
  - May promote further R&D work in this technology, and ultimately to proliferation of the MgB_2 MRI magnet in the near future.

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MgB2 Magnet Projects

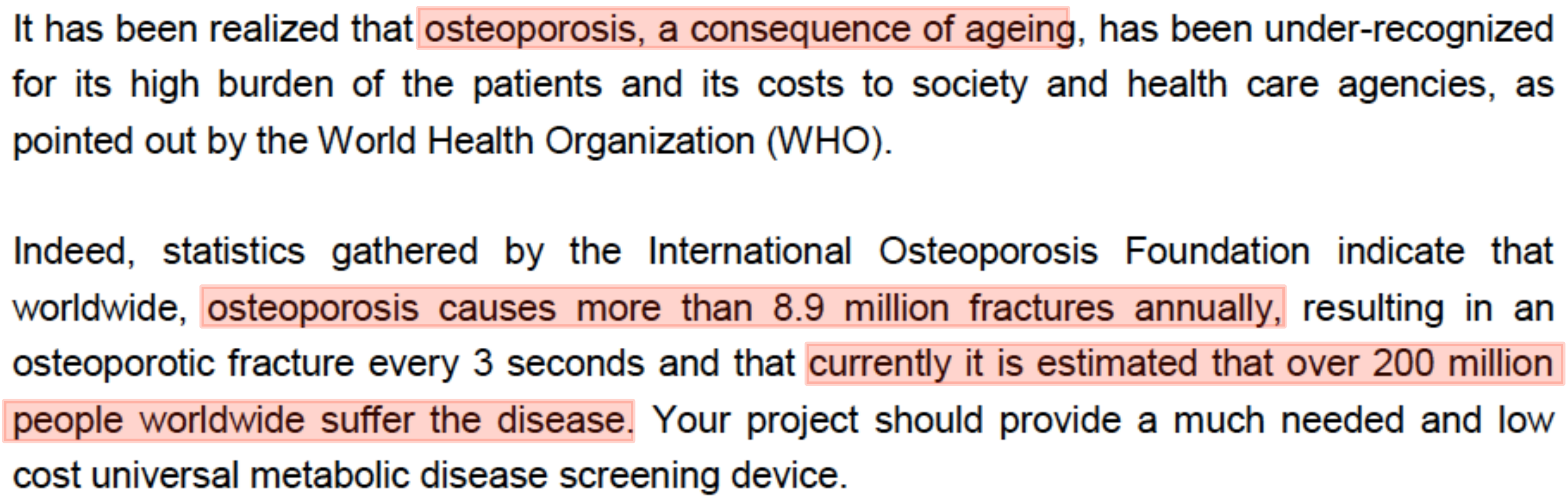
Expected to Begin Late 2016*

- A tabletop liquid-helium-free, persistent-mode MgB_2 0.5-T/50-mm “finger” MRI magnet for osteoporosis screening

* To be supported by the National Institute of Bioimedical Imaging and Bioengineering, NIH

Acknowledgement
Jerome Ackermann (Co-Investigator, Massachusetts General Hospital);
Juan Bascuñàn; Timing Qu (now Tsinghua U)

from Denis Le Bihan’s Support Letter to NIH for Our Application

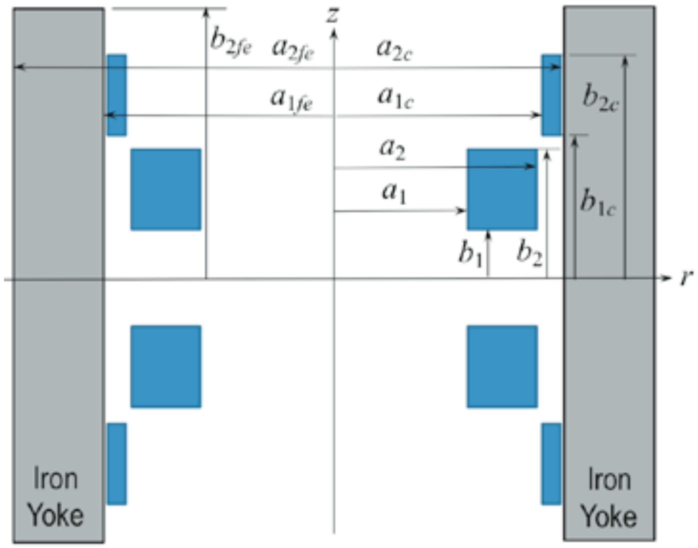


It has been realized that osteoporosis, a consequence of ageing, has been under-recognized for its high burden of the patients and its costs to society and health care agencies, as pointed out by the World Health Organization (WHO).

Indeed, statistics gathered by the International Osteoporosis Foundation indicate that worldwide, osteoporosis causes more than 8.9 million fractures annually, resulting in an osteoporotic fracture every 3 seconds and that currently it is estimated that over 200 million people worldwide suffer the disease. Your project should provide a much needed and low cost universal metabolic disease screening device.

Proposed 1.5-T/9-mm MgB2 Magnet

- Spatial field homogeneity: ≤ 5 ppm within 20-mm DSV
- ϕ50-mm RT bore; 50-mm distance to magnet center for a finger
- With SN2, persistent-mode 1.5 T for ~7 hr with cryocooler off:
    - Quiescent, vibration-free MRI measurement environment
- Iron yoke for field shielding:
    - Fringe field <5 gauss in magnet vicinity
    - *Protects center field from extraneous fields*



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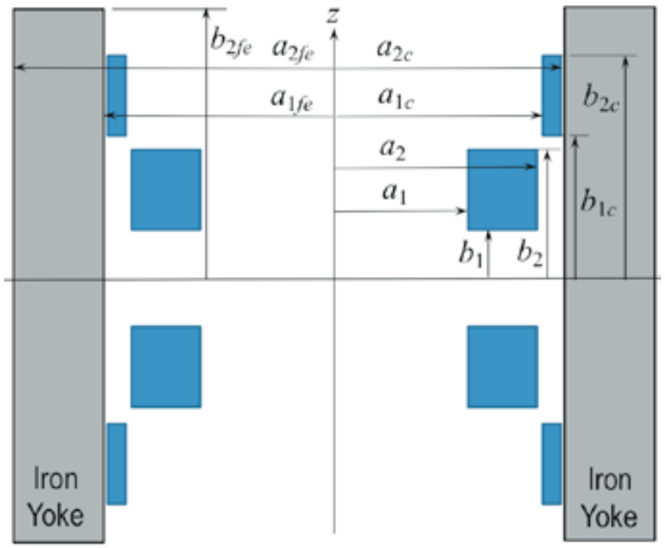
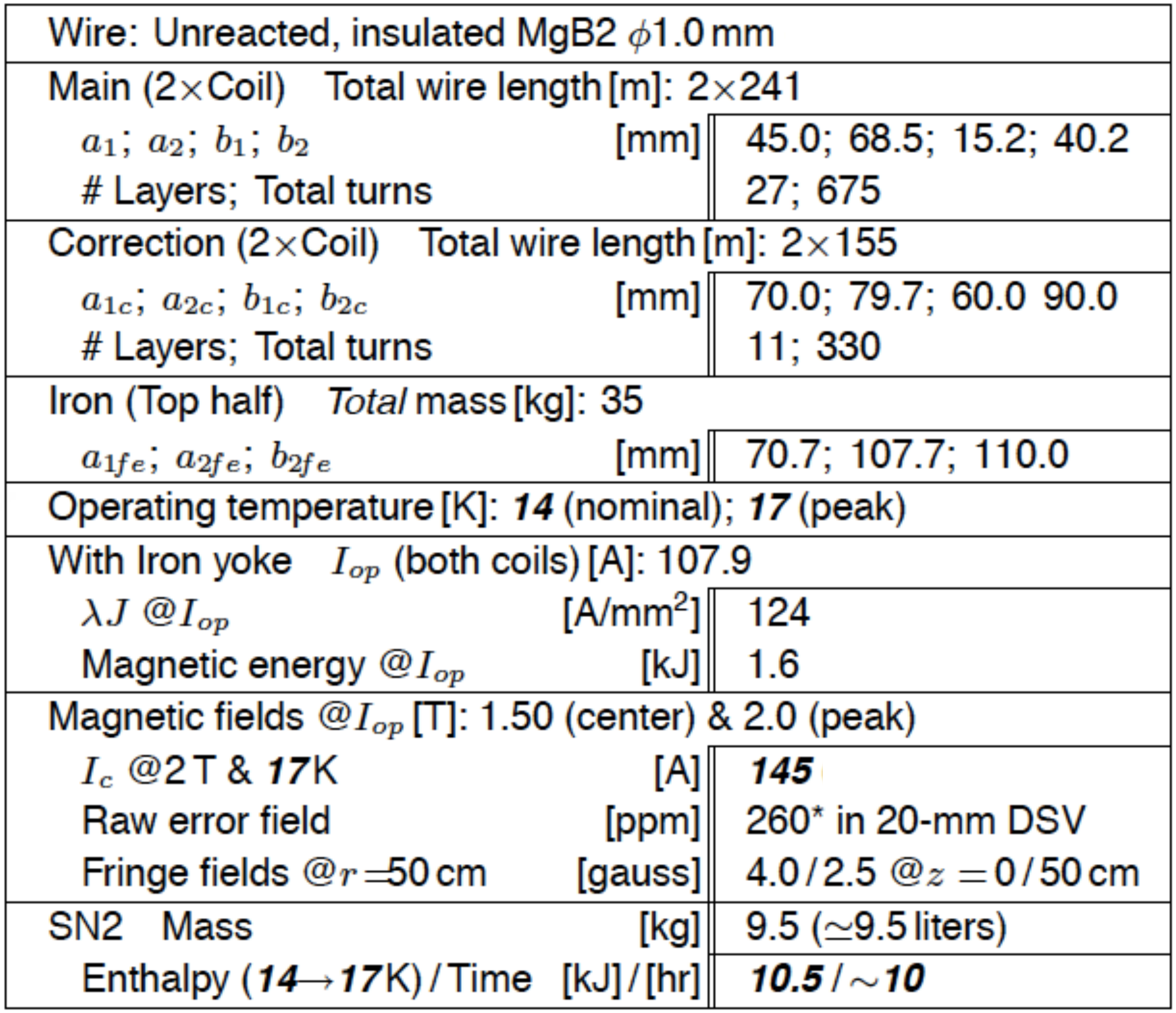
Proposed 1.5-T/9-mm MgB2 Magnet

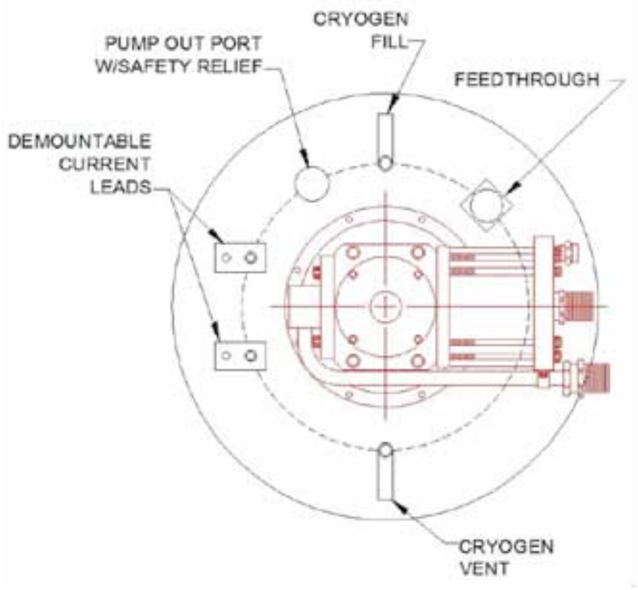


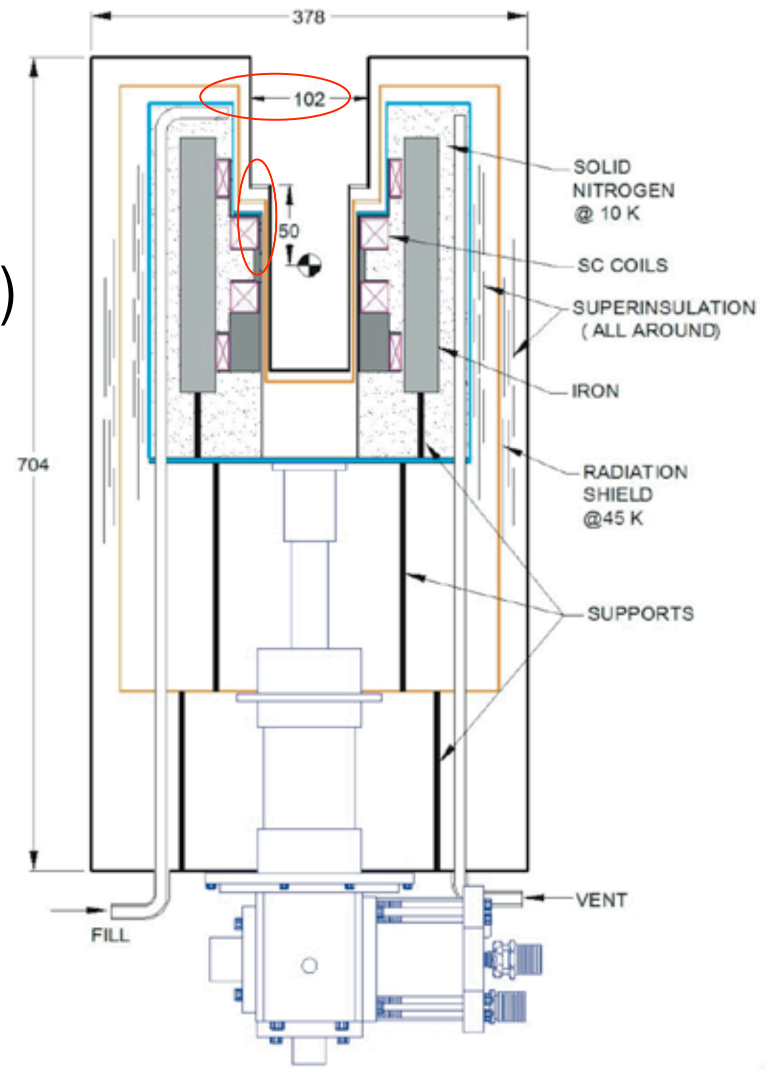


Wire: Unreacted, insulated MgB2 ϕ1.0 mm		
Main (2×Coil) Total wire length [m]: 2×241		
a_1; a_2; b_1; b_2	[mm]	45.0; 68.5; 15.2; 40.2
# Layers; Total turns		27; 675
Correction (2×Coil) Total wire length [m]: 2×155		
a_{1c}; a_{2c}; b_{1c}; b_{2c}	[mm]	70.0; 79.7; 60.0 90.0
# Layers; Total turns		11; 330
Iron (Top half) *Total* mass [kg]: 35		
a_{1fe}; a_{2fe}; b_{2fe}	[mm]	70.7; 107.7; 110.0
Operating temperature [K]: ***14*** (nominal); ***17*** (peak)		
With Iron yoke I_{op} (both coils) [A]: 107.9		
λJ @I_{op}	[A/mm^2]	124
Magnetic energy @I_{op}	[kJ]	1.6
Magnetic fields @I_{op} [T]: 1.50 (center) & 2.0 (peak)		
I_c @2 T & ***17*** K	[A]	***145***
Raw error field	[ppm]	260* in 20-mm DSV
Fringe fields @r = 50 cm	[gauss]	4.0 / 2.5 @z = 0 / 50 cm
SN2 Mass	[kg]	9.5 (≃9.5 liters)
Enthalpy (***14***→***17***K) / Time	[kJ] / [hr]	***10.5*** / ∼***10***

Proposed 1.5-T/9-mm MgB2 Magnet

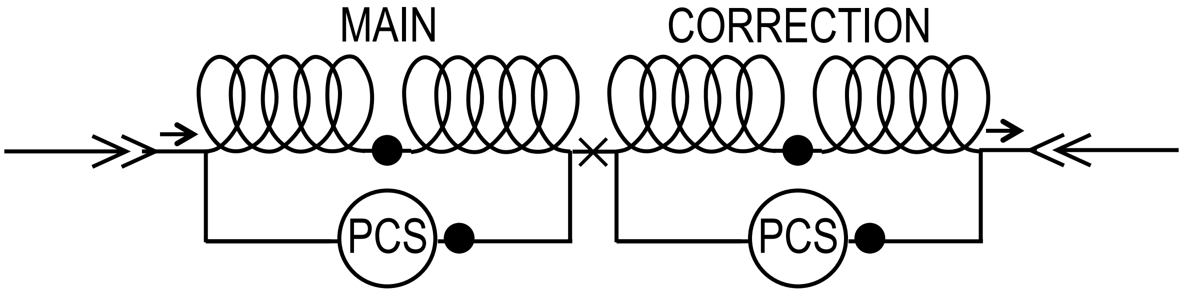
- Cryocooler off, 0.3 W into cold chamber (manufacturer specs)
- Total input to cold chamber ~0.55 W
- ~10-liter SN2: ~11 kJ (14 K➔17 K in ~10 hr) (35-kg iron yoke: < 1 kJ)





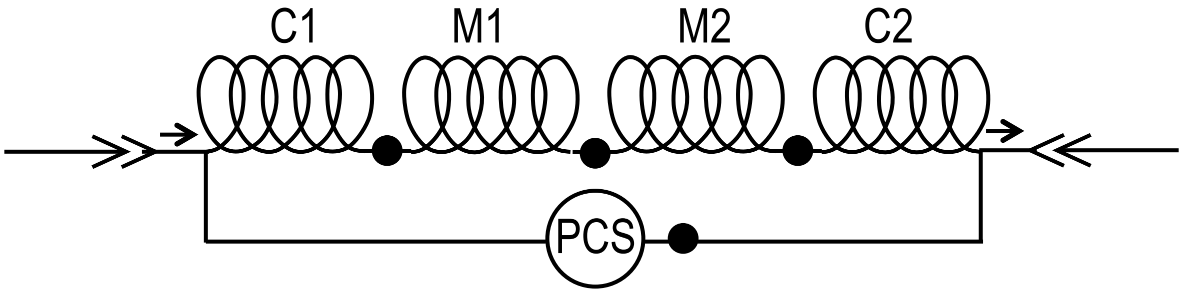
Two Options

Option 1



- \+ Two coil-joint-coil-PCS-joint modules ➔ one module may be saved
- – Different currents in two persistent-mode loops

Option 2



- \+ One persistent-mode loop
- – All four coils discarded even with one mishap (coil, joint, PCS)

Option 2 Adopted

CONCLUSIONS

- MIT completing a 1.3G (500/800) high-resolution NMR magnet
  - HTS share: 61.5% of 30.5 T
  - Critical issues: Protection (over-stressing & over-heating);
SCF error fields:
- PCS designed, built, and operated for persistent-mode REBCO NI DP coils
- Superconducting joints for REBCO still challenging
- A persistent-mode MgB_2 0.5-T/240-mm-SN2 magnet system for MRI successfully completed
  - Coil-PCS-joint module approach viable in development stage; further refinement needed for application to commercial units
- A tabletop, LHe-free, persistent-mode “finger” MgB_2 1.5-T/9-mm MRI magnet for osteoporosis screening, to start in late 2016

Merci Beoucoup!