Superconducting Magnet Activities at MIT Francis Bitter Magnet Laboratory: Current — Next — Future

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CEA. Saclay

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Contributors

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Outline

Current

- 1.3 GHz LTS (500)/HTS(800) NMR magnet
- MgB2 magnet operated in temperatures up to 20 K
- 7-T MW (multi-width)-NI (no-insulation) GdBCO magnet

Next *(July 2015)*

- LHe-free persistent-mode GdBCO coils

Pending *(After April 2016)*

- A tabletop LHe-free persistent-mode MgB2 magnet for osteoporosis MRI

Epic Winter of 2015—Boston & Suburbs, Weston


February 15, 2015


Noon, February 28, 201


4 pm, February 22, 2015


2 pm July 14, 20

Over 2-m snow (> twice one year's) in ~4 weeks

A Brief History of MIT 1.3G
(1.3-GHz LTS/HTS NMR Magnet)

1999 • A 3-phase program to NIH for a 1G LTS/HTS NMR magnet
Phase 1 Review score: 3.0 percentile

2000 • Phase 1: 300MHz LTS/50MHz HTS magnet

2002 • Phase 1 completed

- To NIH for Phase 2: 600-MHz LTS/100-MHz HTS magnet
- Review score: 20 percentile; Funded because at that time NIH had money & NIH program manager very much liked the project

2007 • Phase 2 completed

- 1G upgraded to 1.3G; Phase 3 split into 3A and 3B (NIH manager)
- Phase 3A: 500MHz LTS (**L500**)/600-MHz HTS (**H600**) magnet
- Phase 3B: 700MHz LTS (**L700**)/**H600** magnet; **L700**~$5M-6M
- 3A review: 11 percentile > 16 percentile pay line

2008 • 3A begins on 6/1/08 with End Date of 5/31/12

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A Brief History of MIT 1.3G

2011
- **H600**, ~complete, stolen during Christmas—New Year vacation

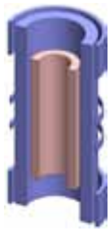
2012
- NIH extends Phase 3A End Date to 5/31/15
  Project receives ~$0.9M from MIT & ~$0.4M from NIH, *not enough*
- Entire 2012 to come up with an **L500**/800-MHz HTS (**H800**) magnet
  L500: available at FBML; **L700** not required, saving NIH ~$5M-6M
  H800, all-GdBCO No-Insulation DP coils: a high-risk, big-pay insert;
  NIH likes it because H800 ➔ >1.3G NMR magnets

2014
- Applied for Phase 3B, before 3A End Date (5/31/15)
- Review score: 45 percentile; ***zero*** funding chance ***1st setback***
  One reviewer very angry: Coil 2 of **H800** won't be finished by 5/15
  Recommended to split Phase 3B to Phase 3B1 and Phase 3B2,
  and complete **H800** in Phase 3B1
  3 other principal reviewers happy with our Phase 3B application,
  except one also not too happy with our slow progress

A Brief History of MIT 1.3G

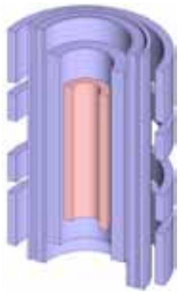
2015
- Submitted (March) Phase 3B1 application to complete H800
- Completely new review panel assigned, a very unusual practice
- Last week received review result: 31 percentile,
  2nd, *could be a fatal,* setback to the 1.3 program
- PSFC Director not ready to give up
- 1.3G users (MIT & Harvard Medical School) not ready to give up
- NIH program manager not ready to terminate the project
- Next move: after a 10-page review report by NIH in mid July

Phase 1 (00-02)



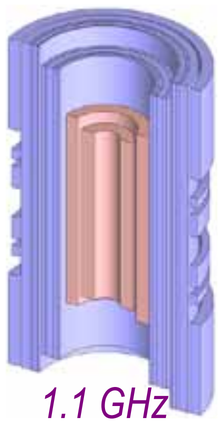
350 MHz
L300/H50

Phase 2 03-07)



700 MHz
L600/H100

Phase 3A 908-12)

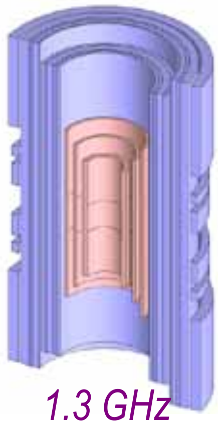


1.1 GHz
L500/H600

Post Theft Phase 3A &
Phase 3B1 2012-2019

H800
(H370+H242+H188)

Phase 3B2 (19-21)



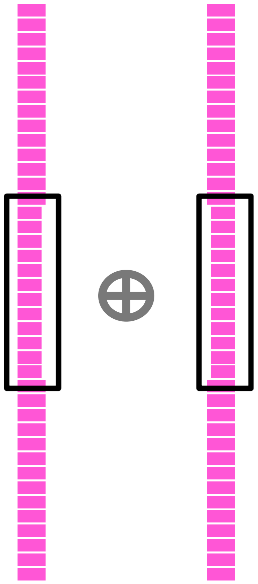
1.3 GHz
L500/H800

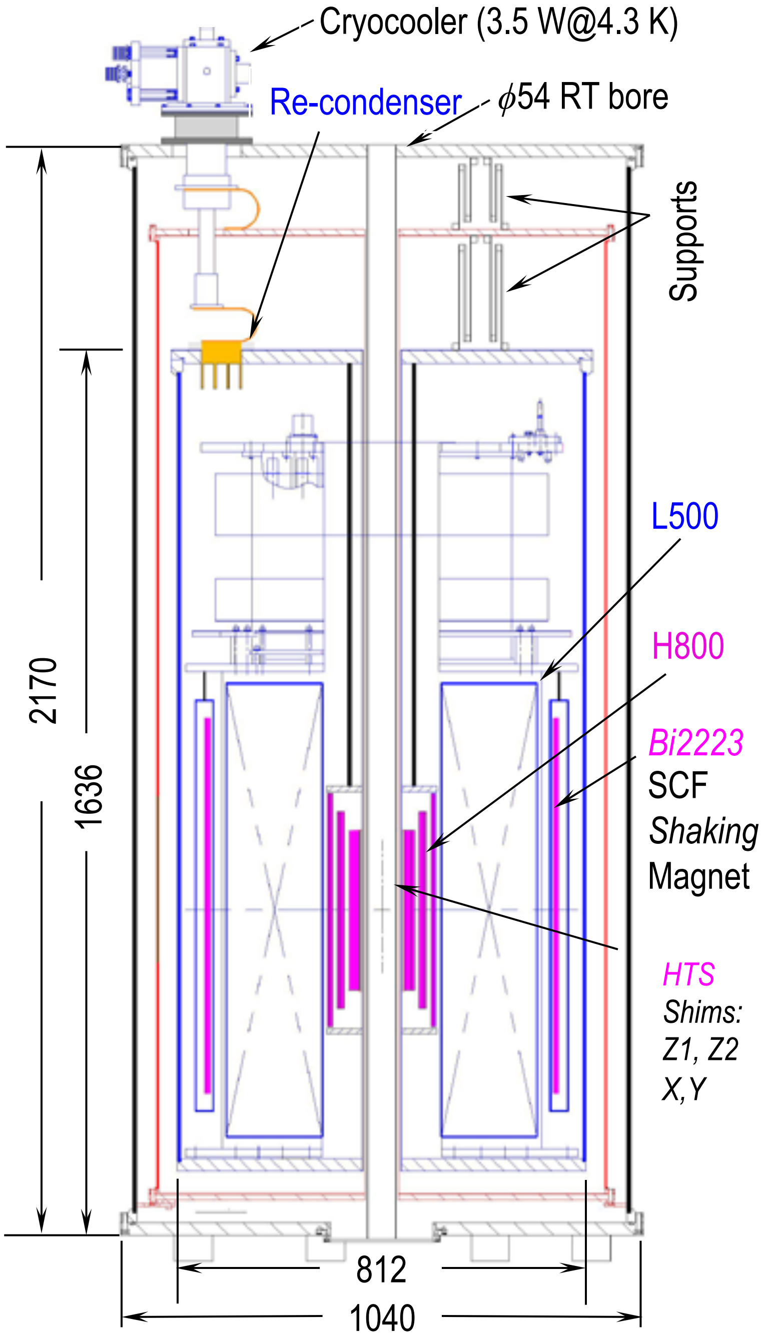
Noteworthy Features of 1.3G

- 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





H800

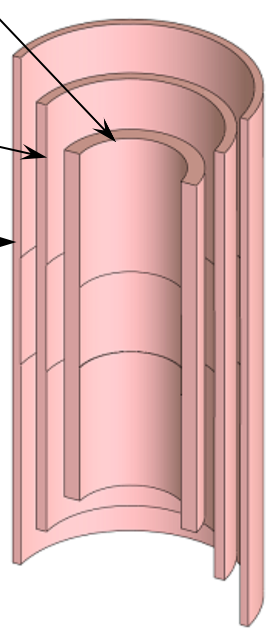
[T_{op} = 4.2 K; I_{op} = 251 A]

- 3-nested-coil formation
- Each coil an assembly of NI DP coils, wound with SuperPower GdBCO tape, 6-mm wide, 75-µm thick (10-µm thick copper) overall

  Coil 1: 26 DP (6 inside-notch); 369 MHz (8.66 T); 90-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



- Total hoop strains [%]: 0.47; 0.39; 0.35
- H800 contribution: 61.5% of 30.5 T

Coil 1 successfully generated 8.66 T

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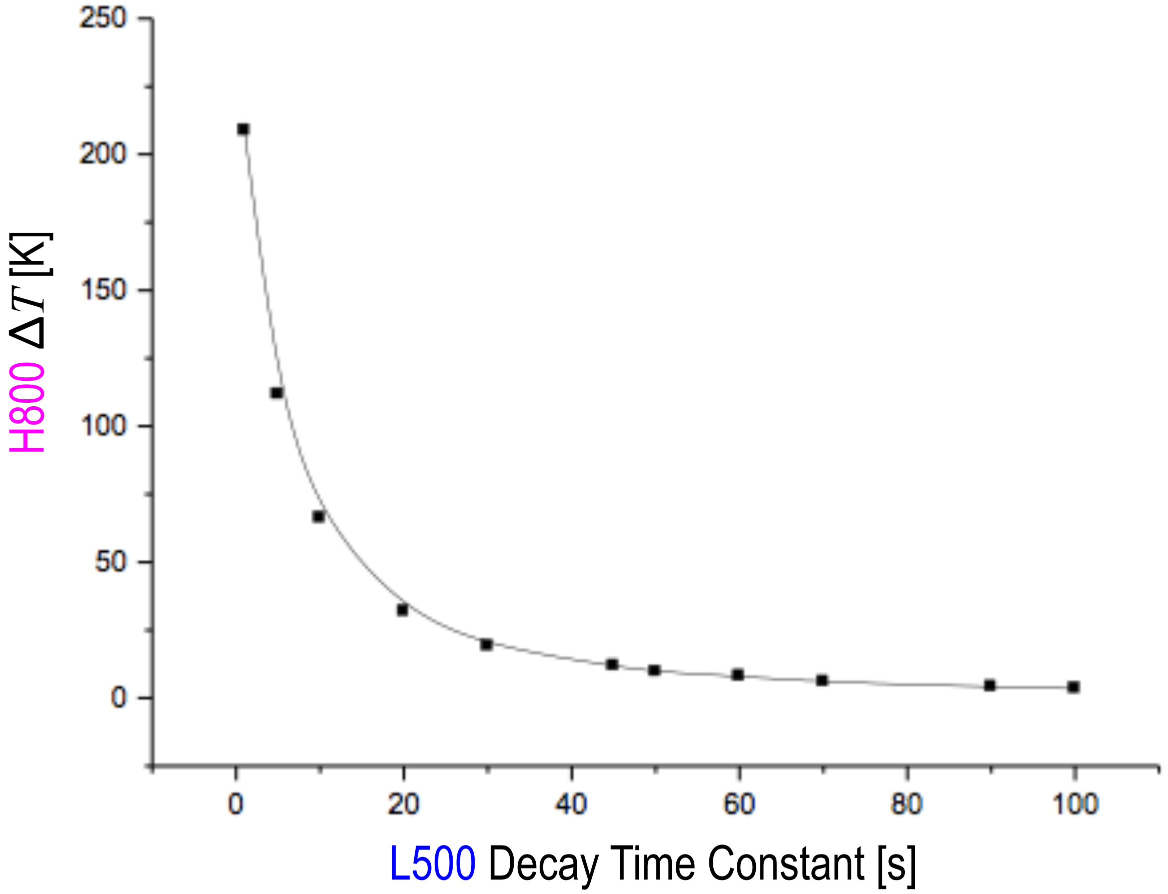
Protection of H800

- H800 itself, self-protecting
- With L500 quenching, H800 overheating depends on L500 decay time

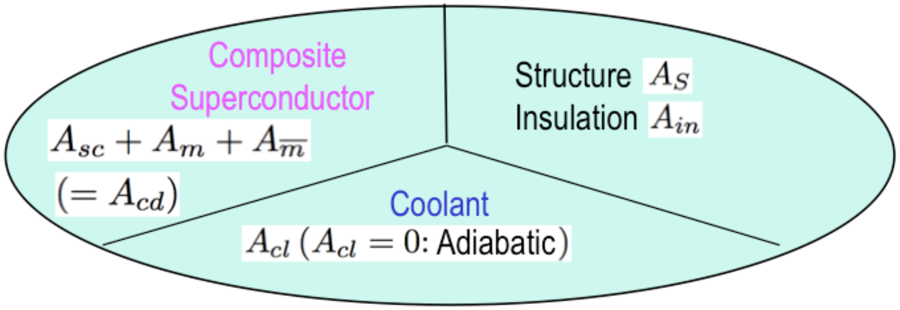


Design Options for Efficient (High-Performance) Magnet

1. Adiabatic Magnet ($A_{cl} = 0$)

$$\frac{I_{op}}{A_{wd}} = \frac{I_{op}}{A_{cd} + A_S + A_{in} + \cancel{A_{cl}}}$$

↑



Composite Superconductor

$A_{sc} + A_m + A_{\overline{m}}$

$(= A_{cd})$

Structure A_S

Insulation A_{in}

Coolant

A_{cl} ($A_{cl} = 0$: Adiabatic)

Why fusion magnets “cryostable,” i.e., $A_{cl} \neq 0$?

Huge mechanical reinforcement within the winding, $A_S >> A_{cl}$:
A_{cl} *little impact* on λJ, i.e., a negligible sacrifice on magnet efficiency

Let’s guarantee *stability* by making the winding *cryostable*, i.e., $A_{cl} \neq 0$

For “small” magnets like NMR, MRI, HEP,
$A_{cl} = 0$ enhances λJ enough to permit “reduced” stability

2. Adiabatic-NI (No-Insulation) —Applied to DP Coils of HTS Tape

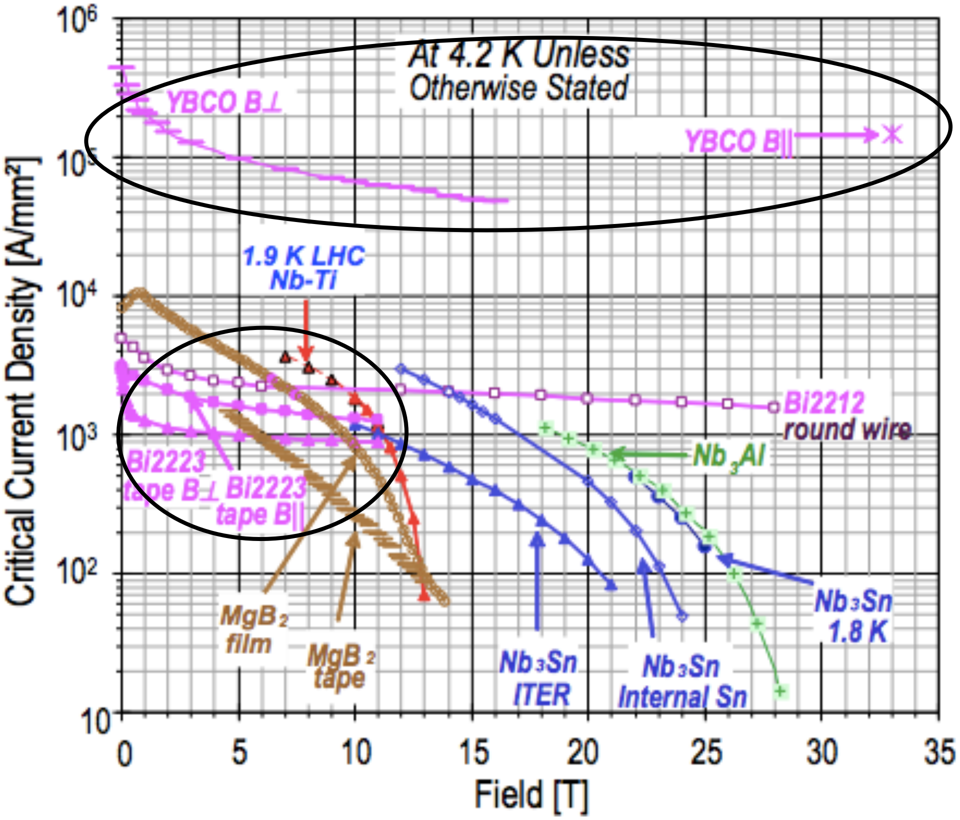
$$\frac{I_{op}}{A_{wd}} = \frac{I_{op}}{A_{cd} + A_S + \cancel{A_{in}} + \cancel{A_{cl}}}$$

Design Options for Efficient (High-Performance) Magnet

3. Adiabatic-NI-MW (Multi-Width)*

MW Winding Formation

- Akin to conductor-grading used in LTS nested coils: *lesser* $I_c(B)$-*performance* conductors for *radially* farther layer-wound coils
- To ameliorate anisotropic $I_c(B)$-performance of HTS tape, *wider* tapes in axially farther DP coils



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* Seungyong Hahn, Youngjae Kim, Dong Keun Park, Kwanglok Kim, John Voccio, Juan Bascuñán, and Yukikazu Iwasa, "No-Insulation Multi-Width winding technique for high temperature superconducting magnet", *Appl. Phys. Lett.*, **103**, 173511 (3pp) (2013).

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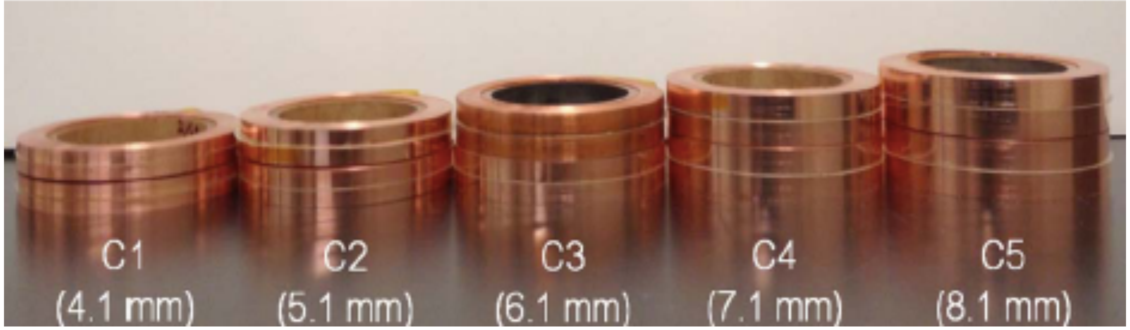
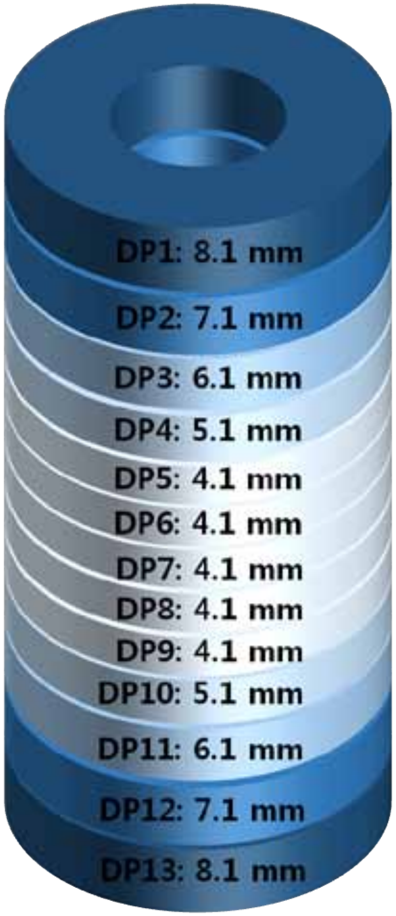
*A 7-T/68-mm Cold Bore MW-NI GdBCO Magnet**

- Composed of 13 *MW-NI GdBCO DP coils*
- Overall height: 150 mm, shorter than all 8-mm wide 13 NI coils of overall height ~208 mm (= 13 × 2 × 8 mm)

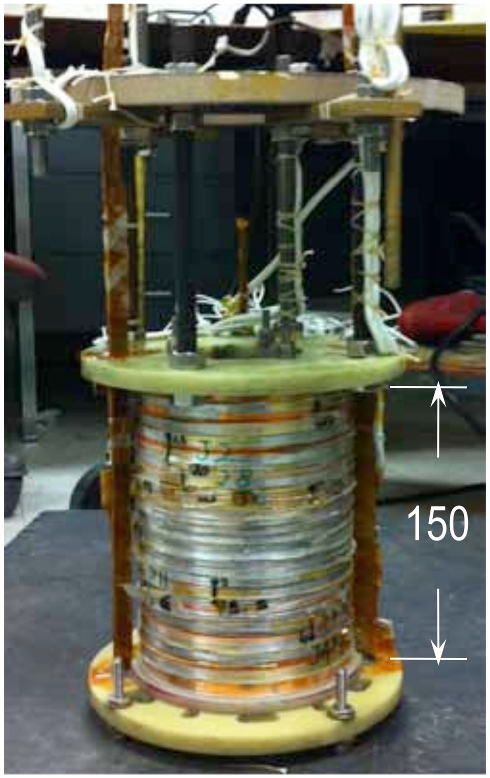




* Seungyong Hahn, Jungbin Song, Youngjae Kim, Thibault Lècrevisse, Young Chu, John Voccio, Juan Bascuñàn, and Yukikazu Iwasa, “Construction and test of 7-T/68-mm cold bore multi-width, no-insulation GdBCO magnet,” *IEEE Trans*. Appl. Supercond. **25**, 4600406 (5pp) (2015)

A 7-T (300-MHz)/68-mm Cold Bore GdBCO Magnet

(I_{op} = 250 A; T_{op} = 4.2 K; $2a_1$ = 78 mm; $2a_2$ = 101 mm; L = 0.592 H)



Selected *Averaged* Parameter Values

DP #	w [mm]	I_c (tape) [A]	I_c (coil) [A]	R_C [$\mu\Omega$]	τ_d [s]
1	8.1	300	76.5	197	46
2	7.1	270	70.4	251	37
3	6.1	236	64.1	177	55
4	5.1	271	57.3	288	35
5	4.1	171	51.7	102	103
6	4.1	171	49.4	95	110
7	4.1	171	48.6	549	19
8--13	Bottom half (13—8) similar to top half (1—6)				

R_m	3.84 mΩ

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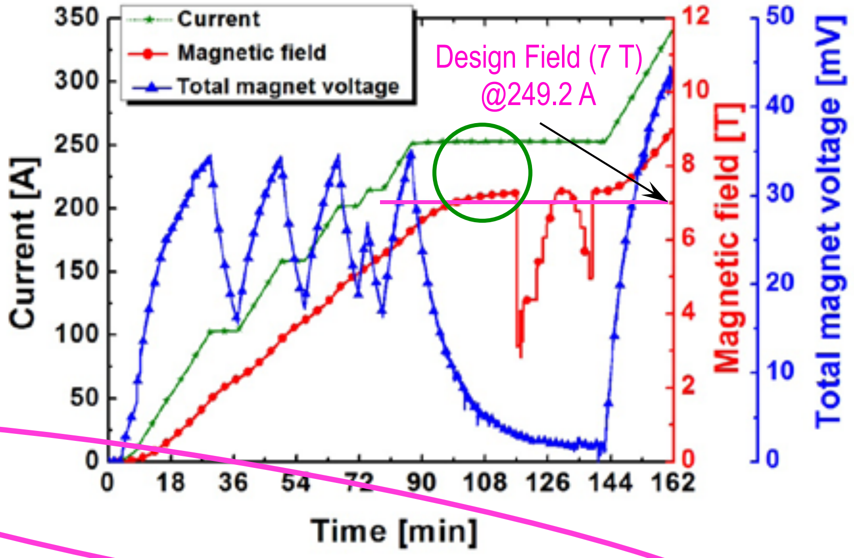
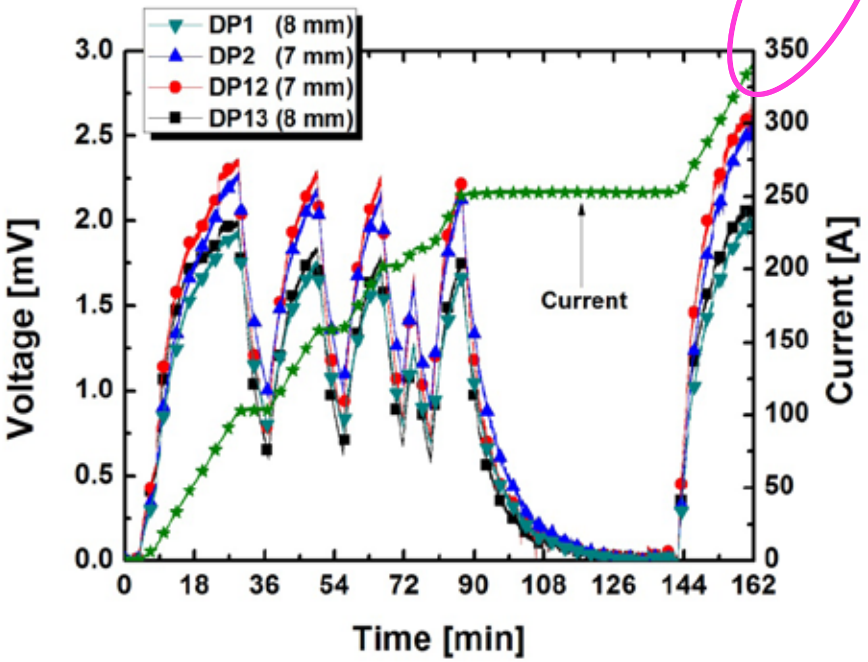
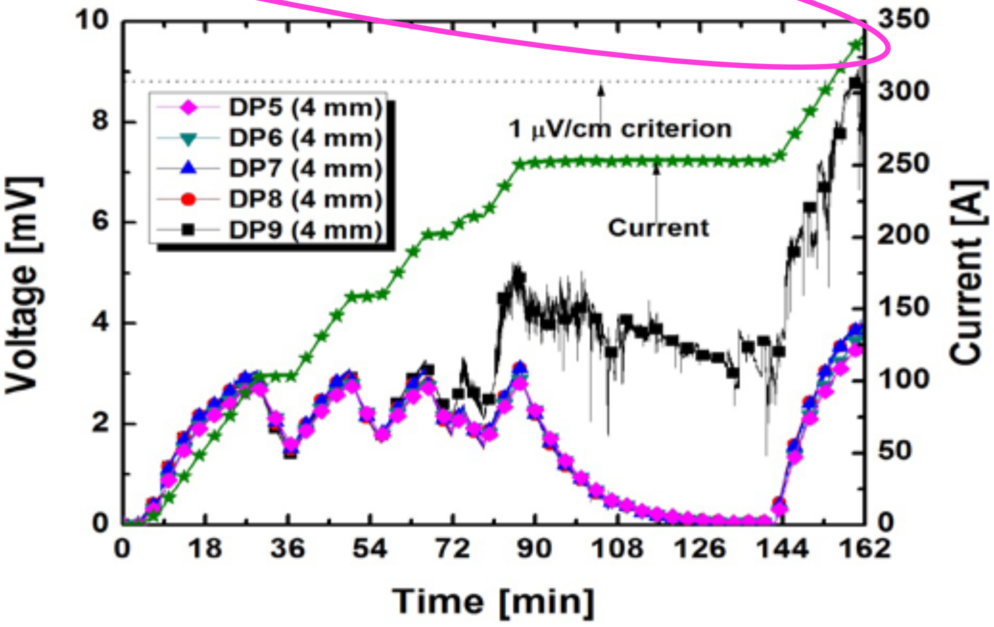
Selected Results @4.2 K

- Achieved 7.31 T (311 MHz) @253.1 A
- Measured charging delay $\tau_d \sim$ 3 min., close to $L/R_m \sim$ 154 s
- Magnet undamaged, even after pushed to an over-current of 343 A







Development of MgB_2 MRI Magnets at MIT

Background

MRI critical for quality health care for:

- Early detection and efficient treatment of disease/injury.
- ~30,000 MRI units now in service worldwide benefit only ~10% of the total humanity, chiefly in the developed nations

NIH (National Institutes of Health) Goal:

- Develop low-cost, easy-to-operate* MRI units to the rest (~90%) of the humanity

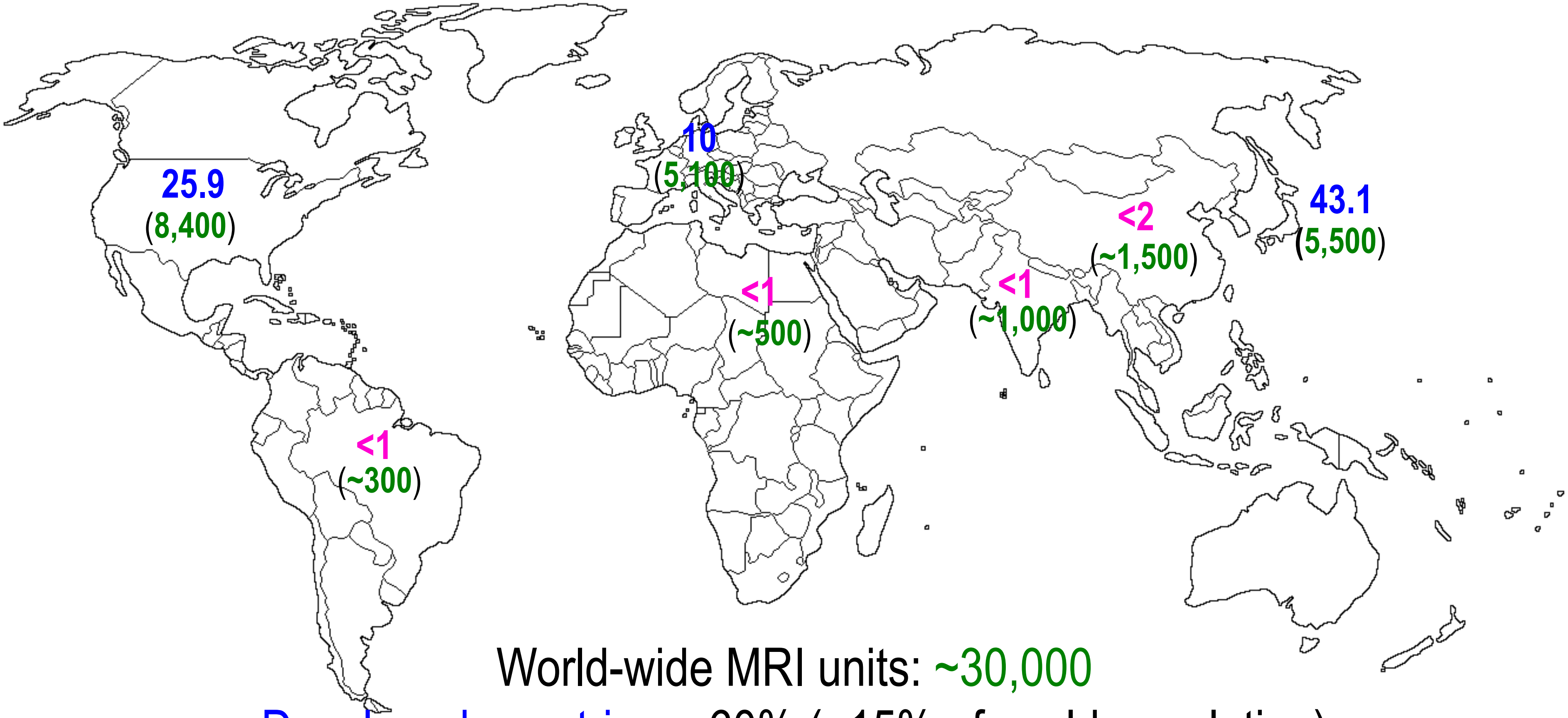
* Preferably LHe-free; Operatable under unreliable power source

MIT's choice: Persistent-mode, actively-protected MgB_2 magnet operating in the range 10 K (nominal) → 15 K

MRI World-Wide Distribution

*MRI units per million population**

(Total Units)



World-wide MRI units: ~30,000

Developed countries: ~60% (~15% of world population)

Huge Market Potentials especially for LHe-free MRI magnets

* Multiple data sources

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MgB_2 Magnet Project: Original Goals (September 2009 – 2015)

MgB_2 0.5-T/80-cm Whole-Body MRI Magnet

Phase 1 (9/01/2009-8/31/2013): Mail Coils (4 inner coils)

Phase 2 (9/01/2013-8/31/2016): Correction Coils (4 inner coils)

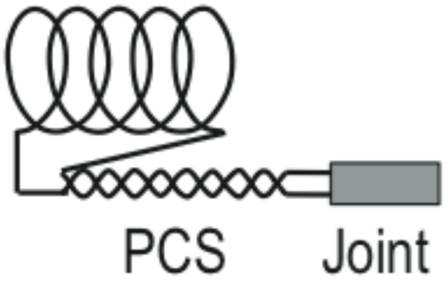
Modified (June 1, 2012)

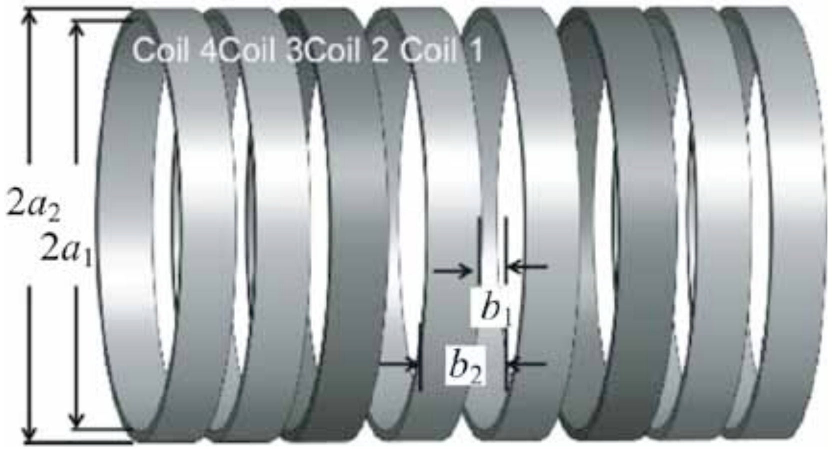
Complete 0.5-T/24-cm RT bore MRI Magnet, by 8/31/2015

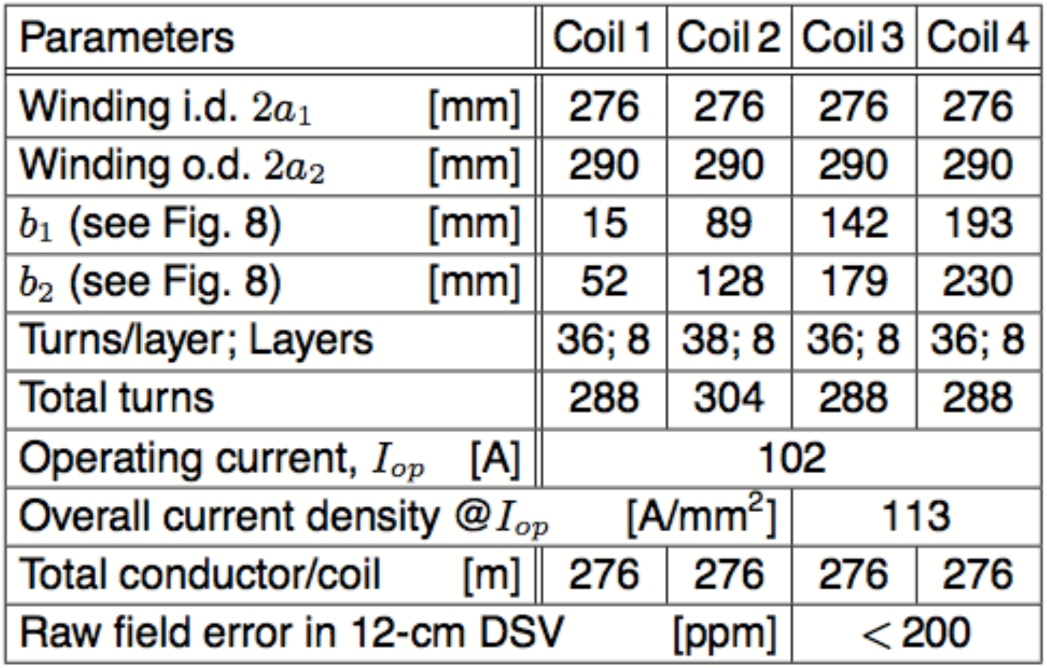
- *Because Hyper Tech's inability to deliver 3-3.5 km long MgB_2 wire by July 2012, decided to build a ~1/3 (24-cm RT) complete MRI magnet*
  - *This magnet will consist of 8 coils (4 Main; 4 Correction), each with PCS and terminated with its superconducting joint*
  - *Each coil wound with ~300-m long, monofilament MgB_2 (HyperTech can deliver mono MgB_2 wire up to 300 m)*

A 0.5-T/24-cm RT Bore MgB2 MRI Magnet

- 8-Module coils, each with a PCS and joint
- Wound with MgB2 monofilament wire
- Wind-and-react
- Persistent operation in the range 10-15 K



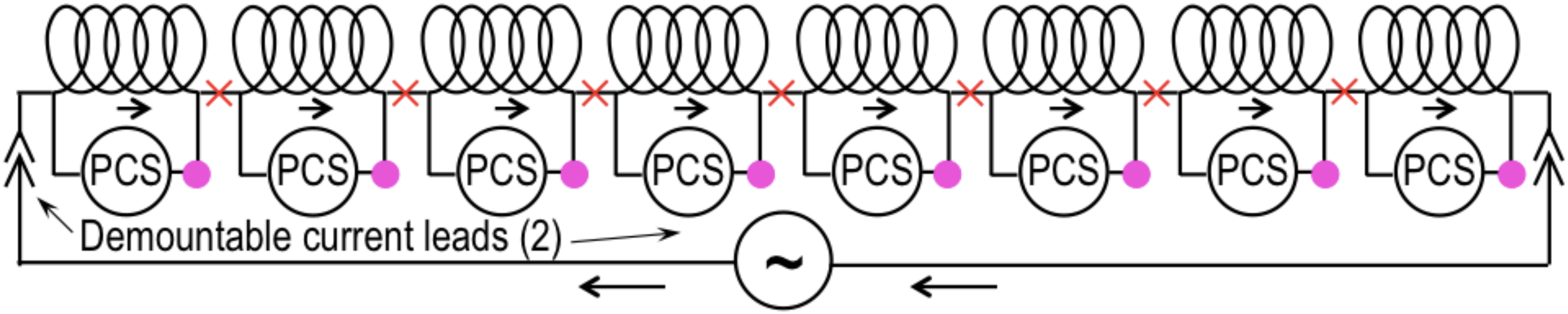




Parameters	Coil 1	Coil 2	Coil 3	Coil 4
Winding i.d. $2a_1$ [mm]	276	276	276	276
Winding o.d. $2a_2$ [mm]	290	290	290	290
b_1 (see Fig. 8) [mm]	15	89	142	193
b_2 (see Fig. 8) [mm]	52	128	179	230
Turns/layer; Layers	36; 8	38; 8	36; 8	36; 8
Total turns	288	304	288	288
Operating current, I_{op} [A]	102			
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	

A 0.5-T/24-cm RT Bore MgB2 MRI Magnet

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



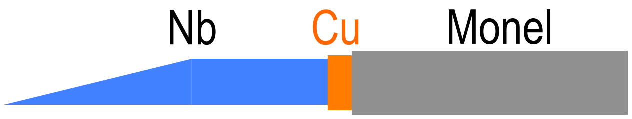
● Superconducting joint

× Superconducting joint

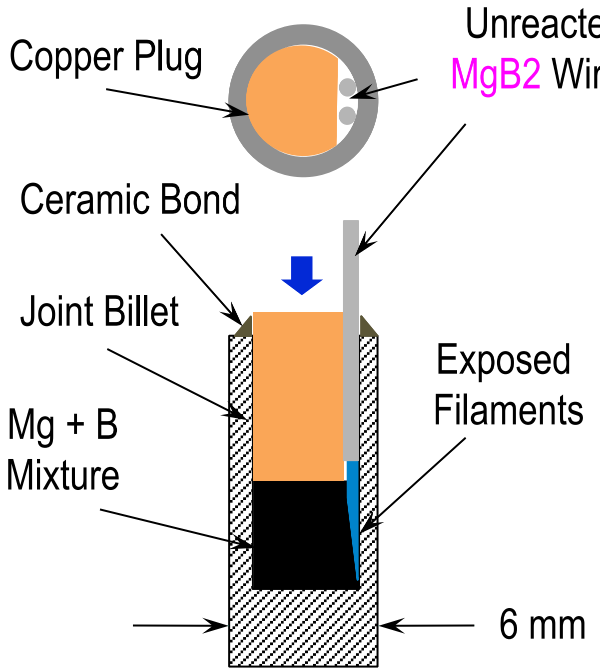
Wind-and-React

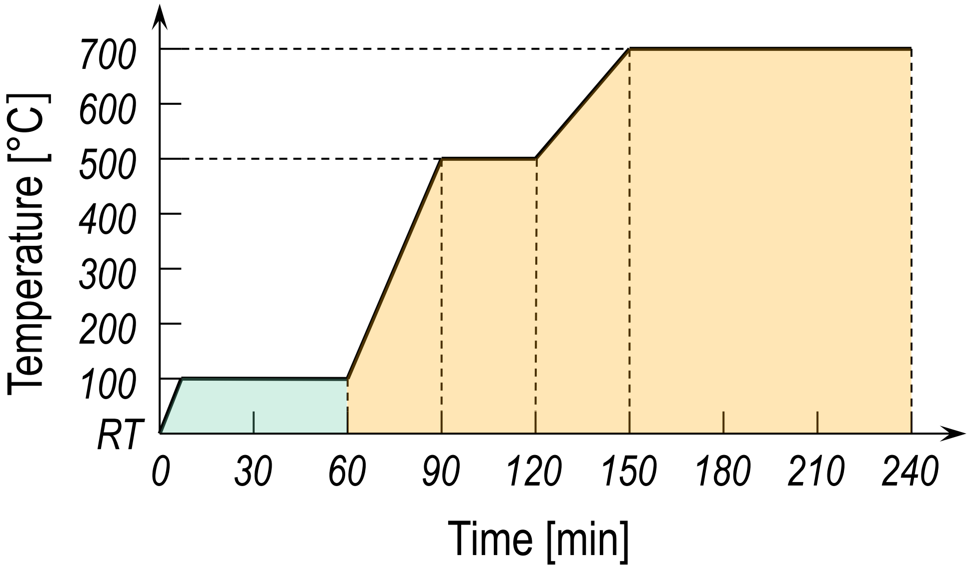
- Not difficult making superconducting joints
- No limit to bending diameter
- Coil-module approach:
  - Relatively easier manufacturing
  - Manageable risk
  - Flexible design

MgB2 Monofilament Unreacted Joint

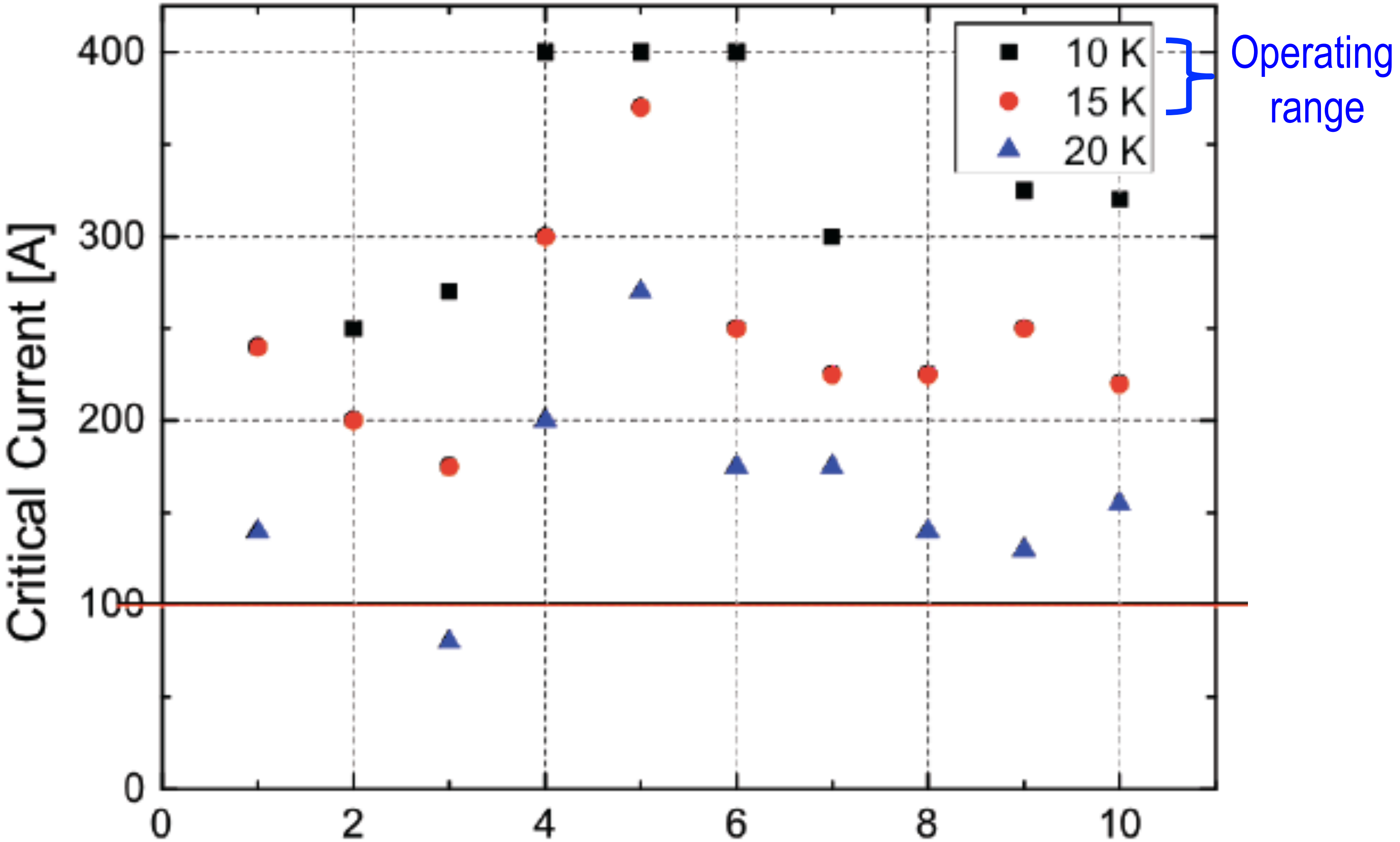


- Acute angle-cut both wires
  - Align fragile filament in the power-pressing direction
  - Enlarge surface area to Mg + B mixture
- Argon environment (35 kPa), no moisture; some contaminants allowable





10 MgB2 Monofilament Unreacted Joints I_c @sf Data



Operating range

Sample #

- 9 joints $I_c \geq 200$ A ($I_{op} = 102$ A), one $I_c = 180$ A

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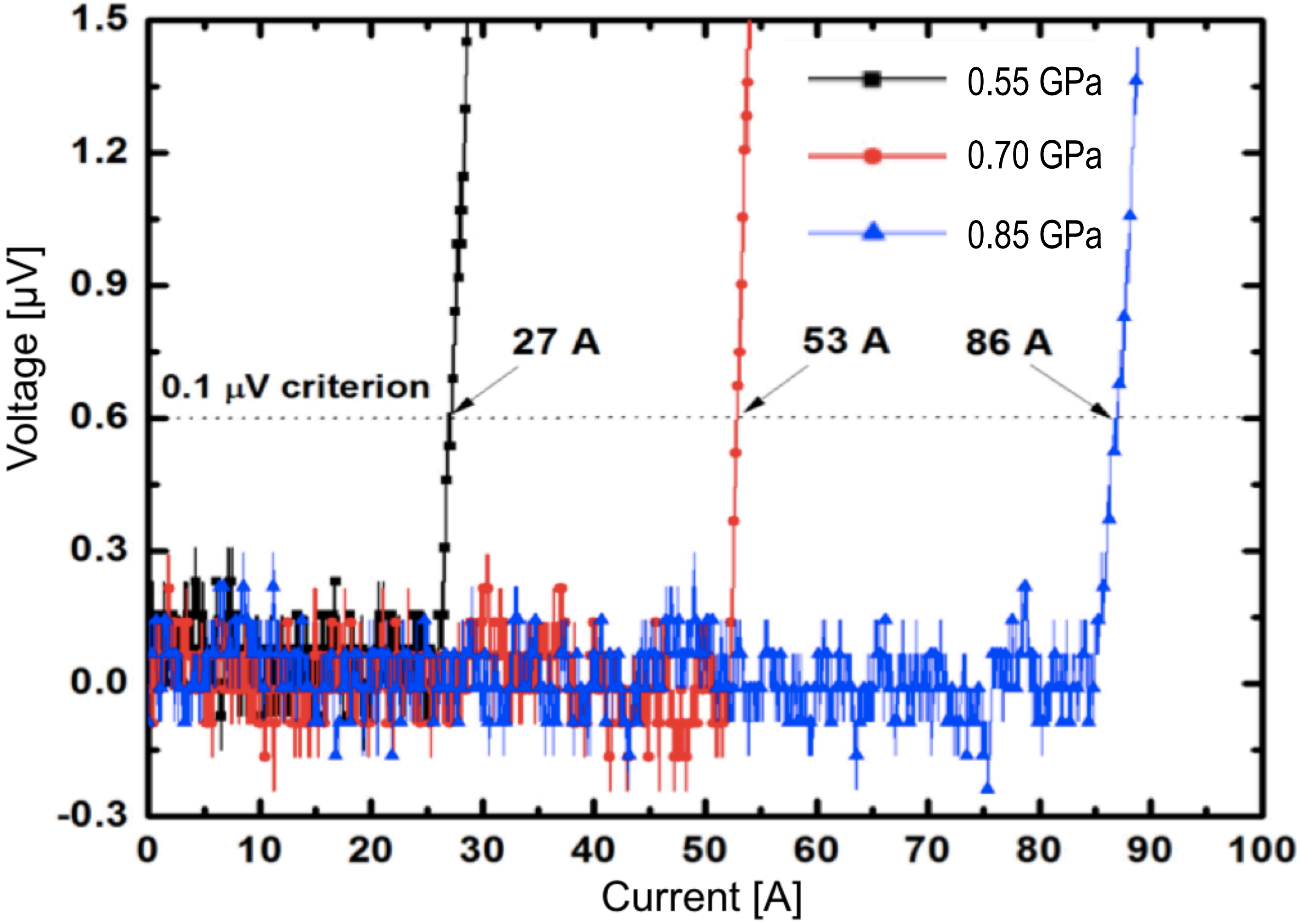
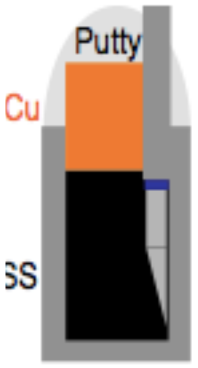
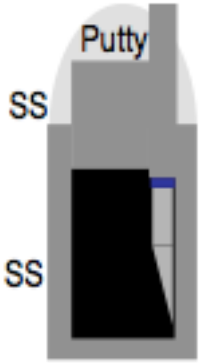
MgB2 Monofilament ***Reacted*** Joints I_c @sf Data

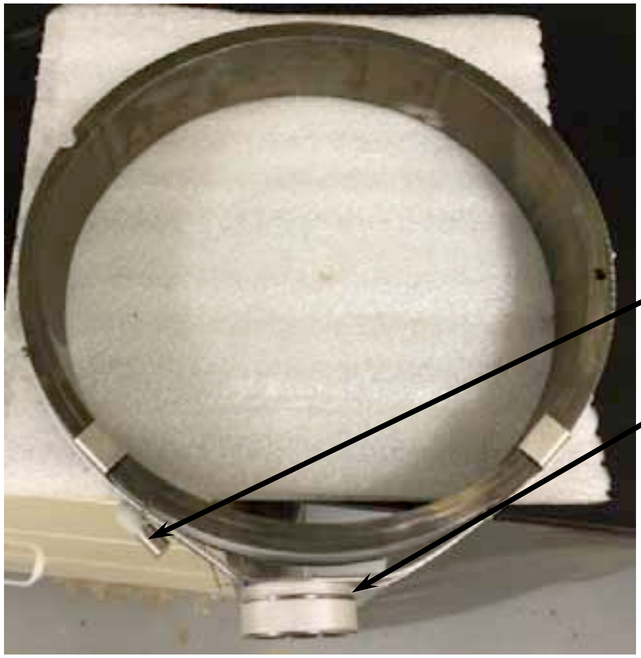


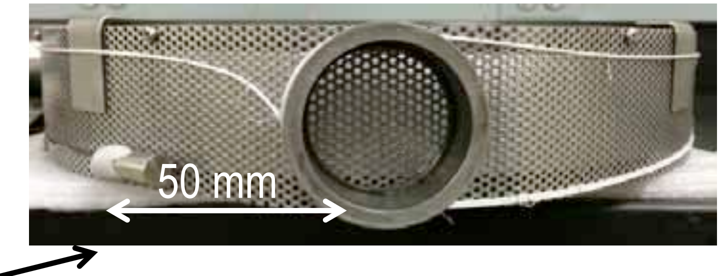


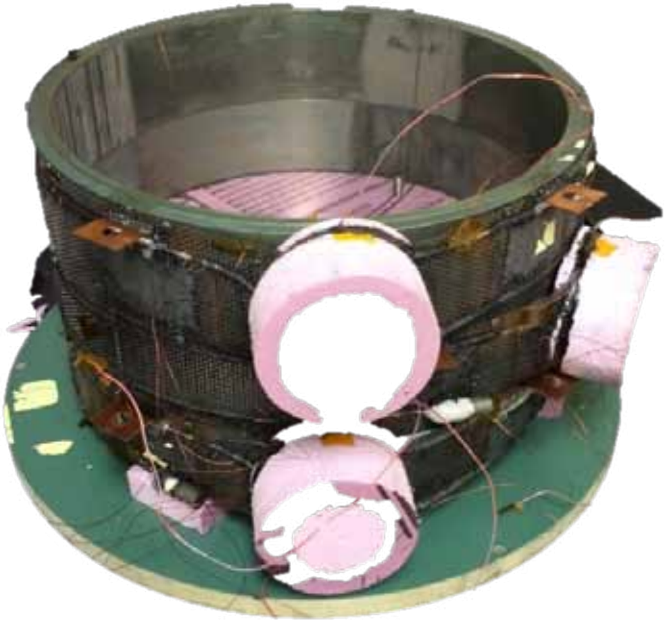


- Instead of copper plug, stainless steel plug used
- Further development required

Coil Design

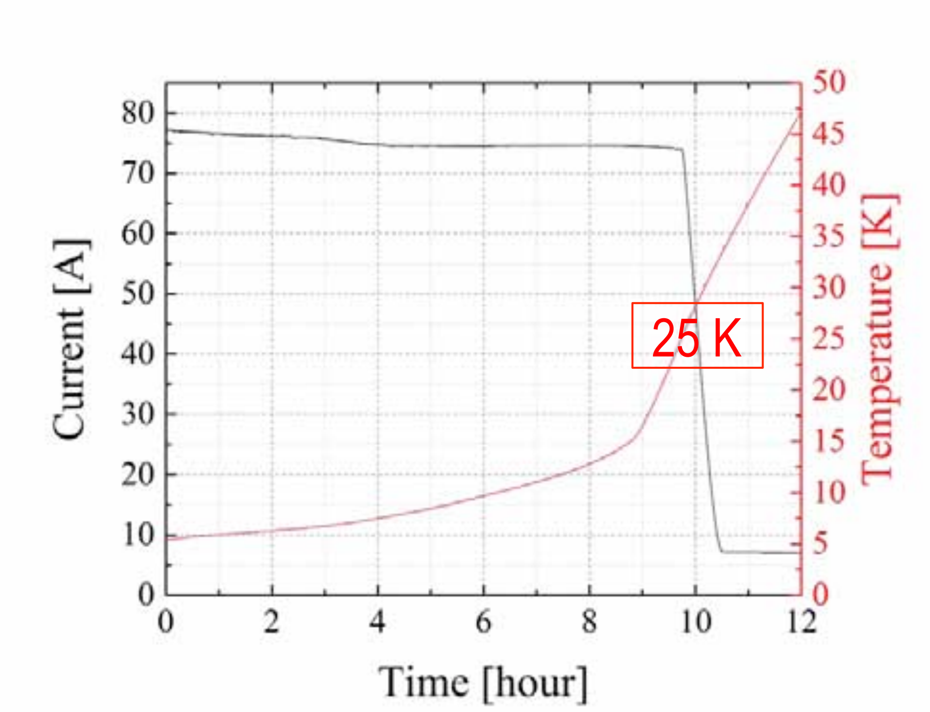




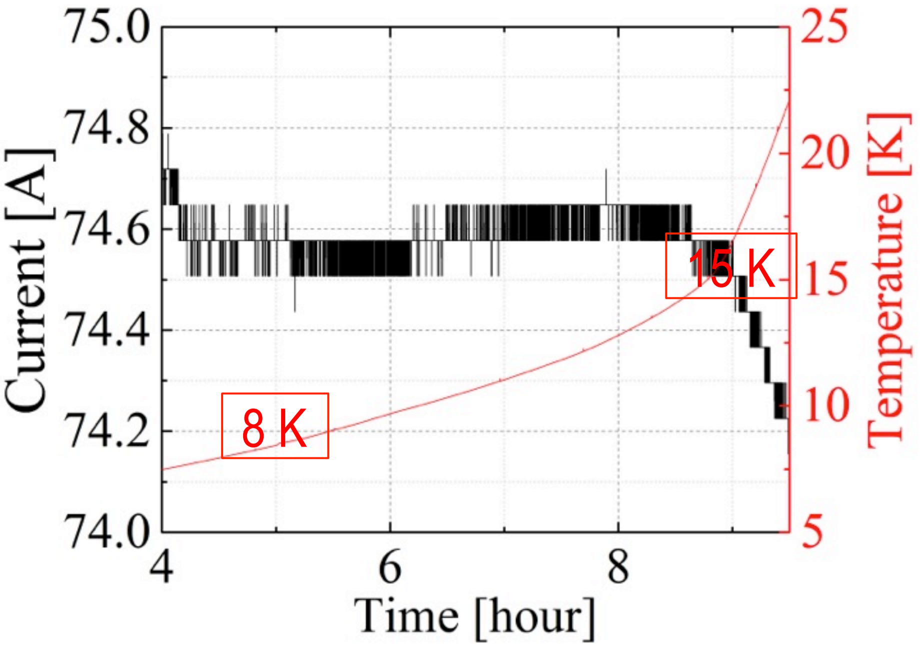


- Perforated sheet for securing PCS and joint
- Copper connectors
- Stycast after heat treatment
- Styrofoam to insulate PCS
- Staggered PCS position to avoid interference

Small-Loop Test at 75 A



25 K

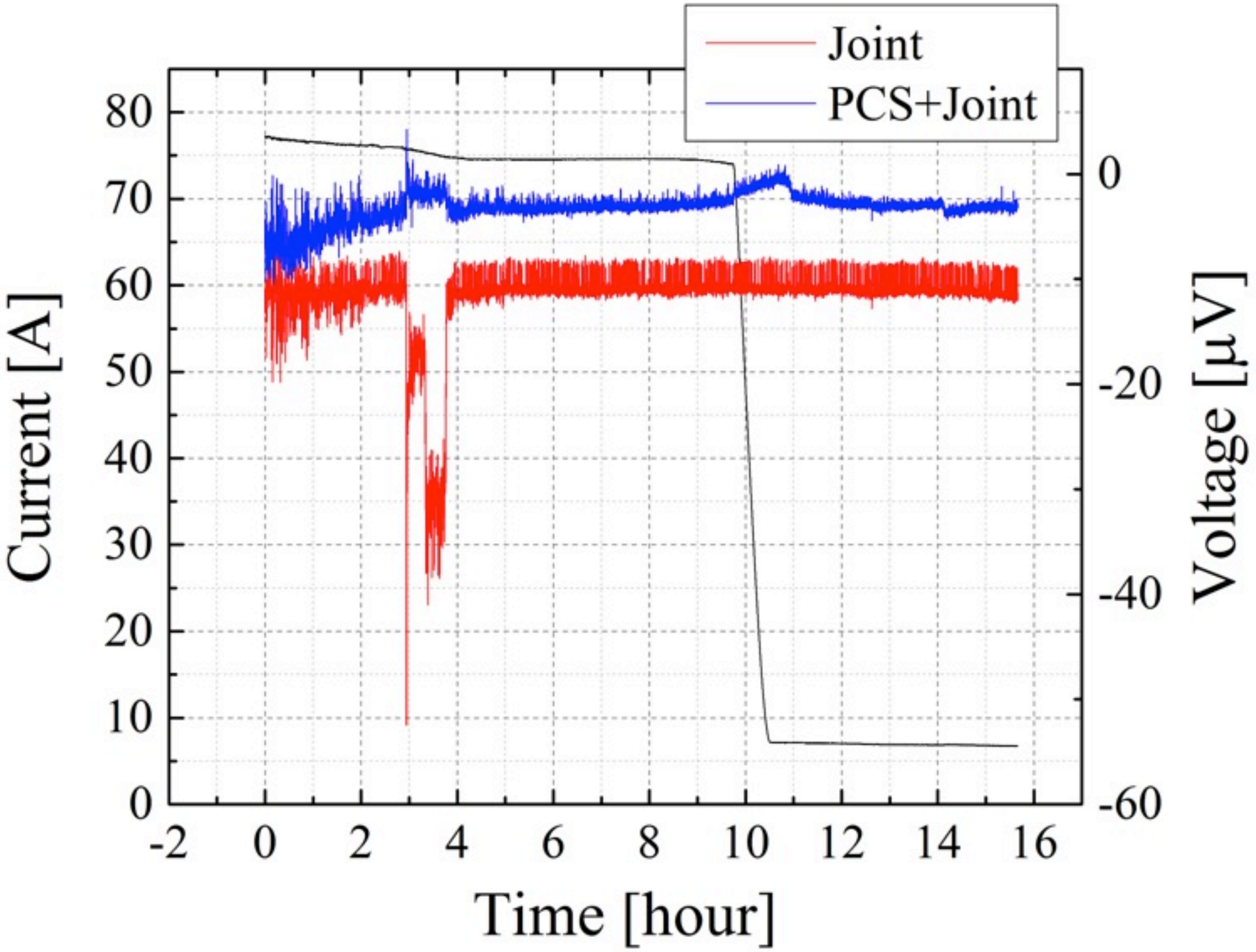


15 K

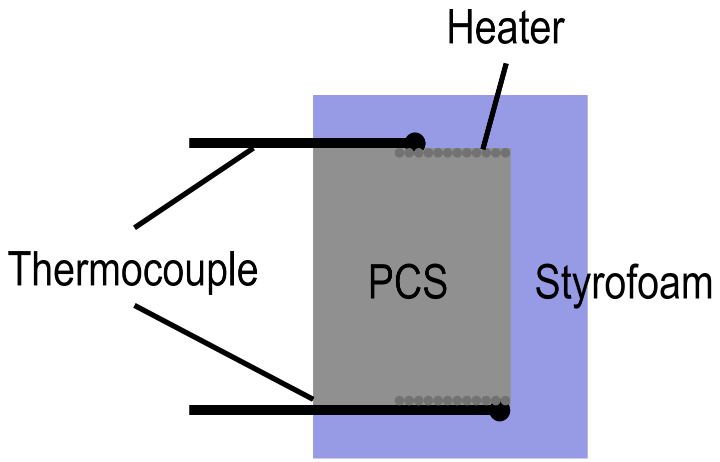
8 K

- Initial decay likely transient effect
- No observable decay 8-15 K for 4.5 hours
- Loop inductance ≈ 3×10^{-5} H
- Loop resistance < 3×10^{-12} Ω

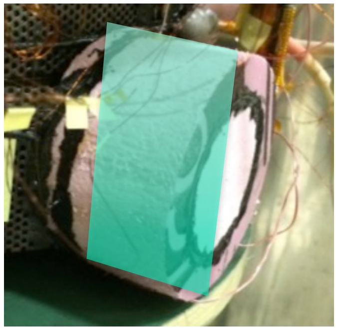
Small-Loop Test at 75 A



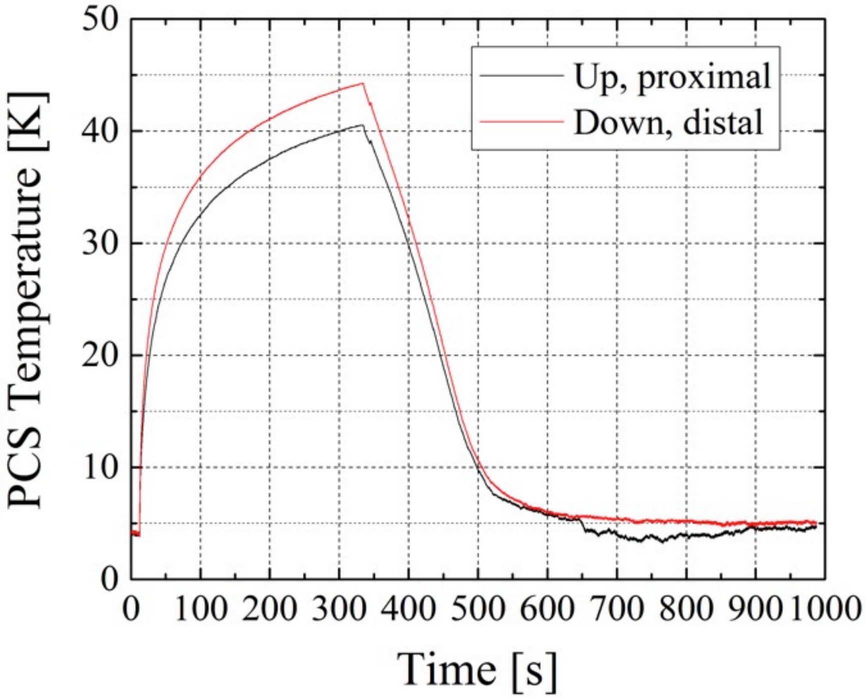
PCS Open/Close



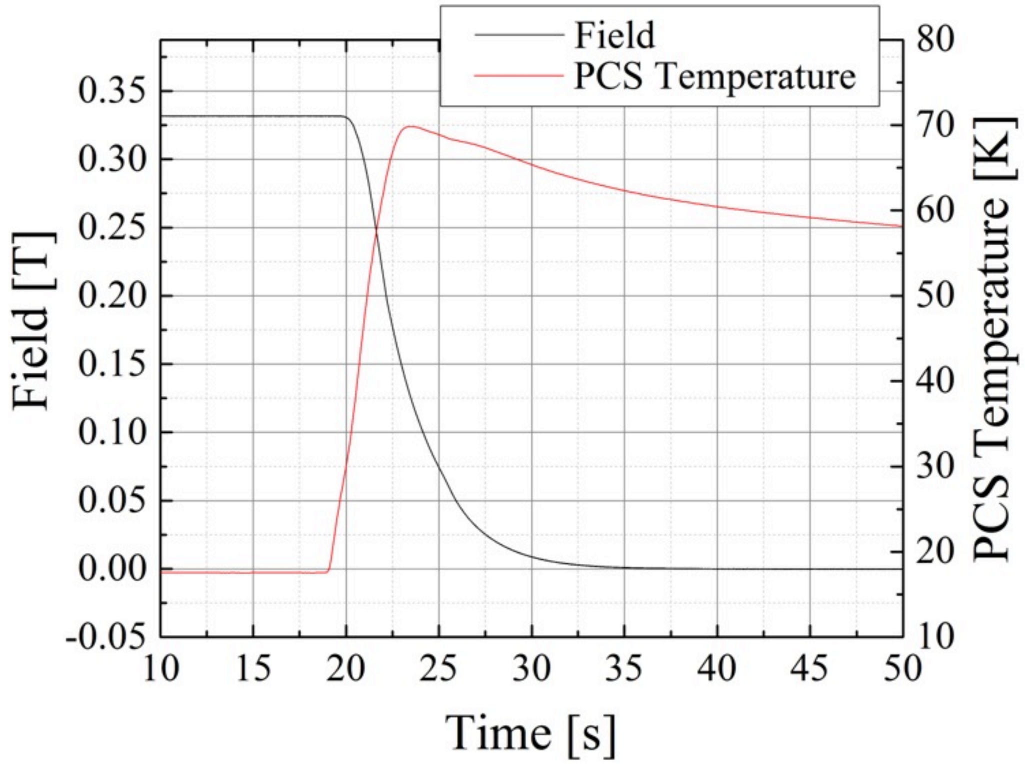
Side view of an insulated PCS

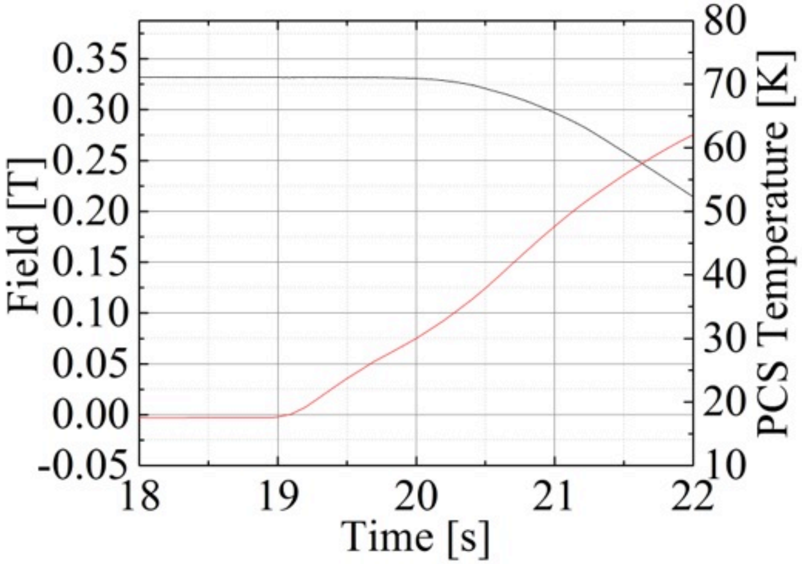


- Opens in 3 min. with 1 W
- Closes in 3 min. in gas helium
- Less than 1 W to maintain 40 K in gas helium at 5 K



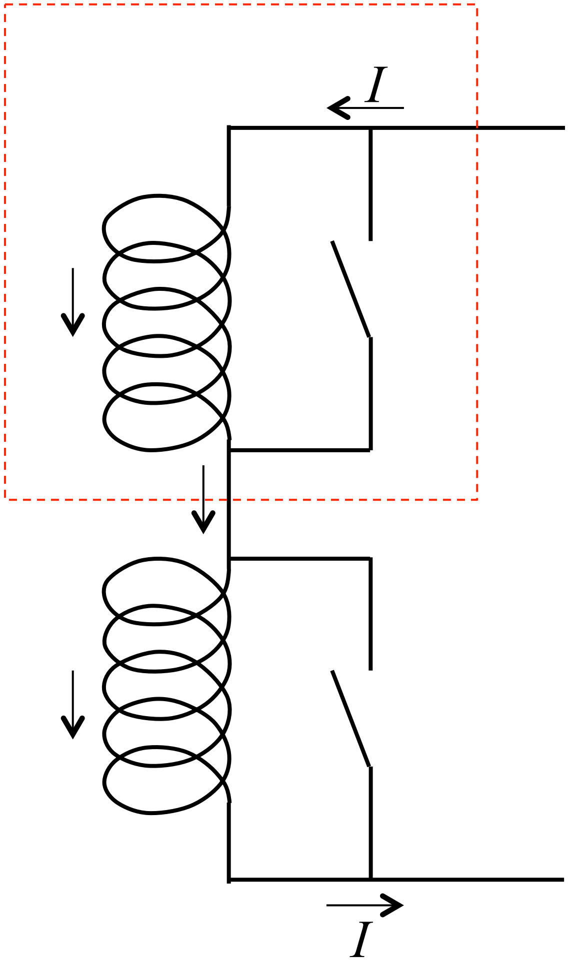
PCS Dump Test

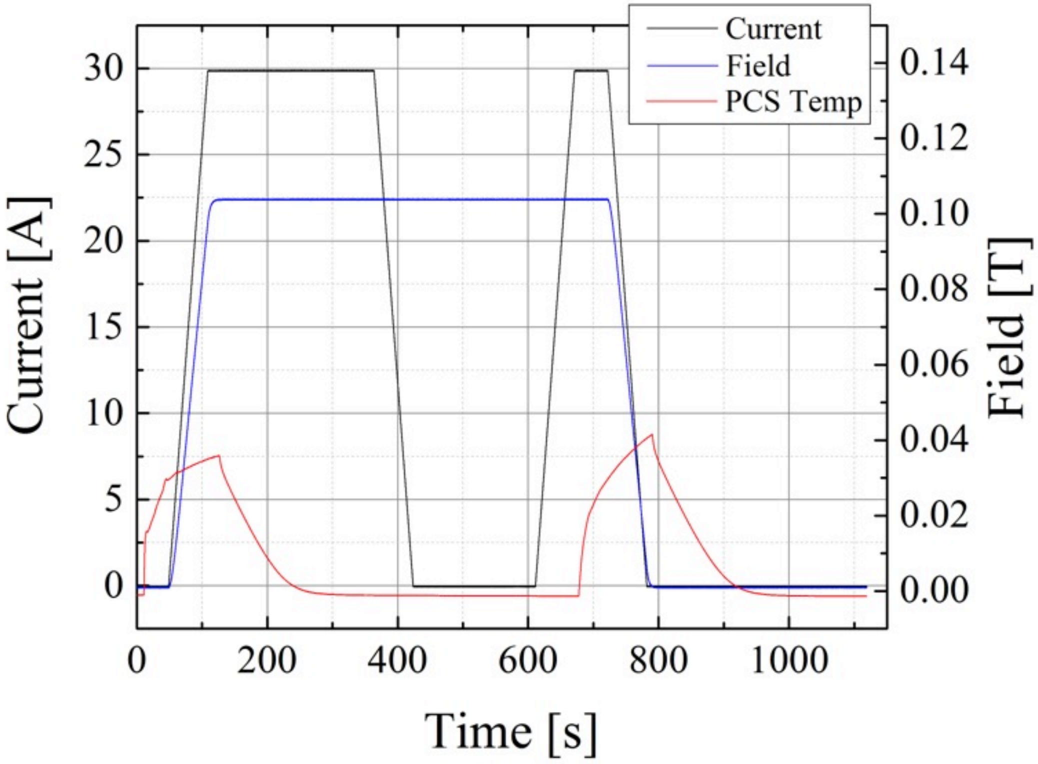




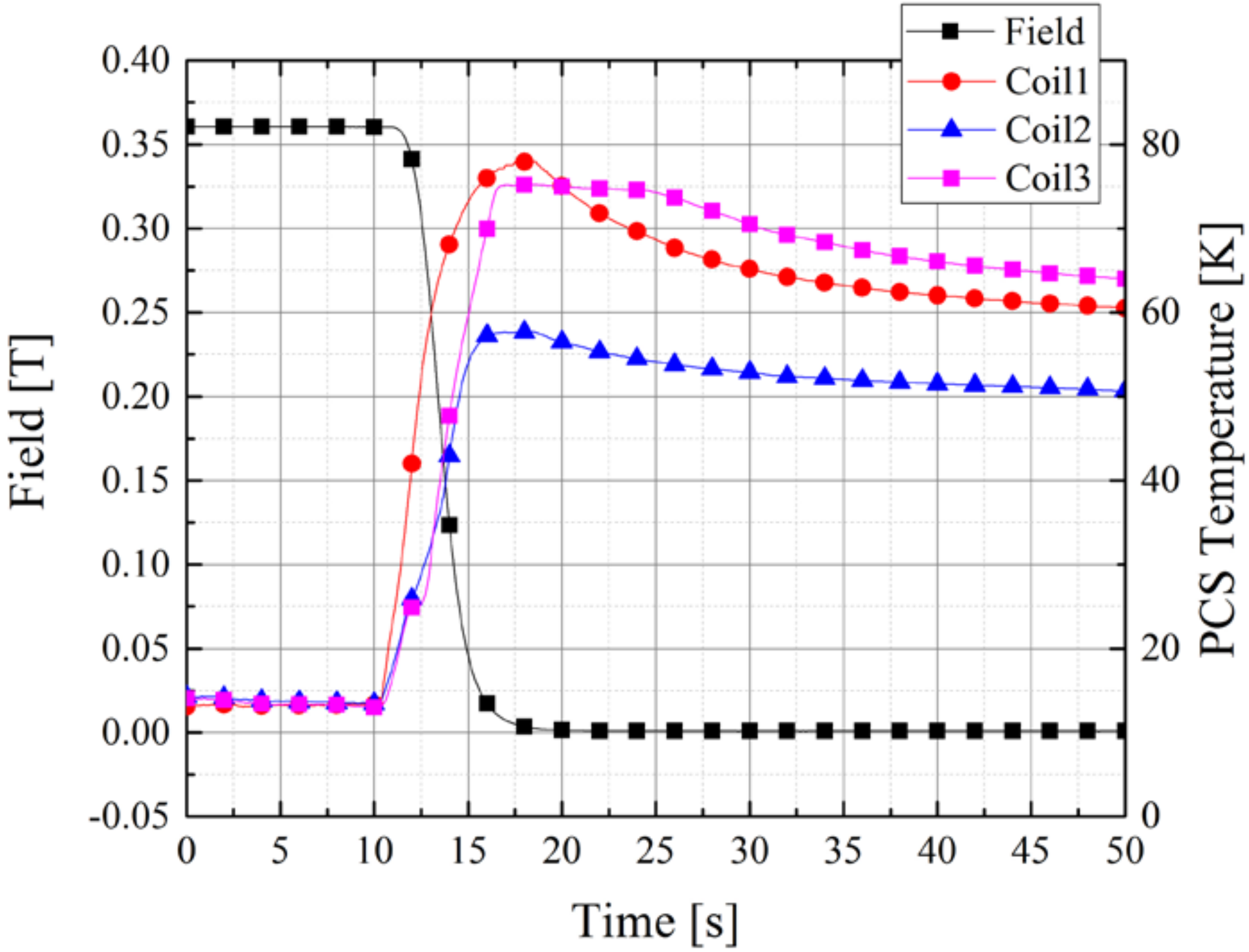
- Dump initiated in 1 s with 0.4-A current; faster with a capacitor
- Dump time constant ~ 3 s
- Highest temperature in PCS < 70 K

Charge/Discharge 3-Coil Assembly in Persistent Mode





3-Coil Assembly Dumping



Timeline

8/31/2014 • NIH program ended

9/01/2014 • Continues as PhD thesis project (Jiayin Ling)

12/31/2014 • 3-coil in persistent mode at 100 A to 10 K and 98 A to 12 K

2/28/2015 • Coil #8 operate at 100 A in persistent mode, 6—16 K

- All 8 coils ready for assembly

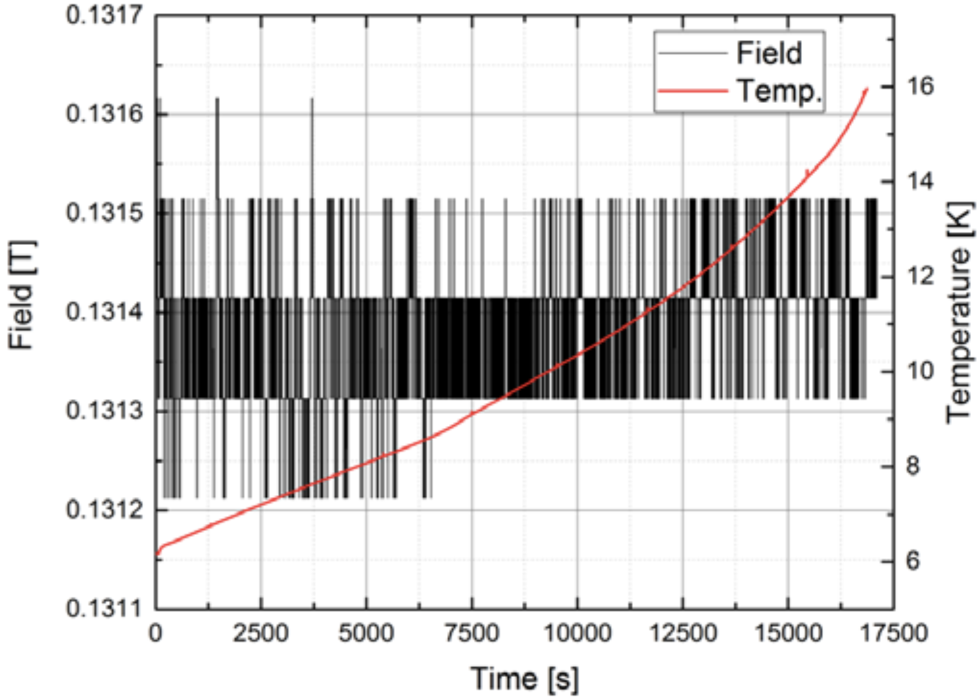
Ling Thesis

By 8/31/15

- Complete the magnet; operate it in persistent-mode in SN2 at 10-15 K
- Measure the field homogeneity

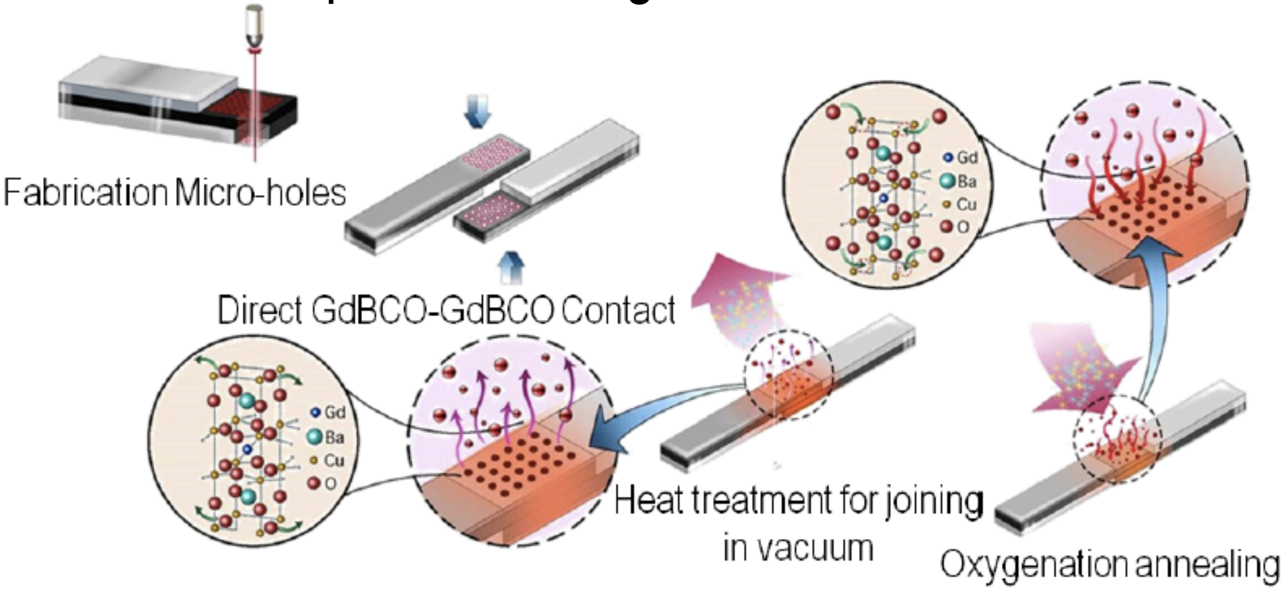
By 1/15/16

- Complete writing thesis & defend



Next (July 1, 2015)
LHe-Free Persistent-Mode GdBCO Coils

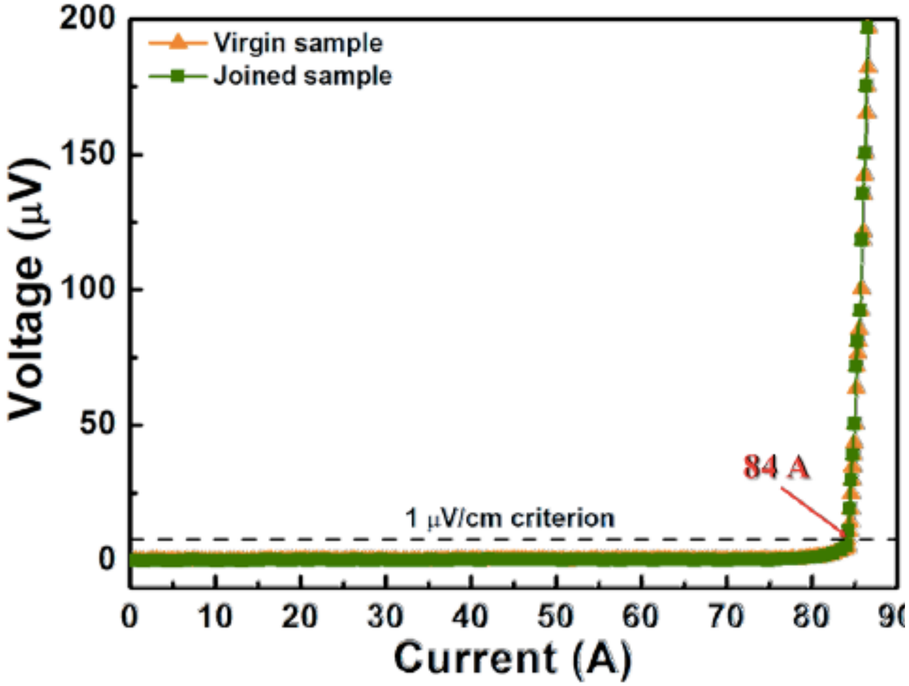
GdBCO-GdBCO Superconducting Joint



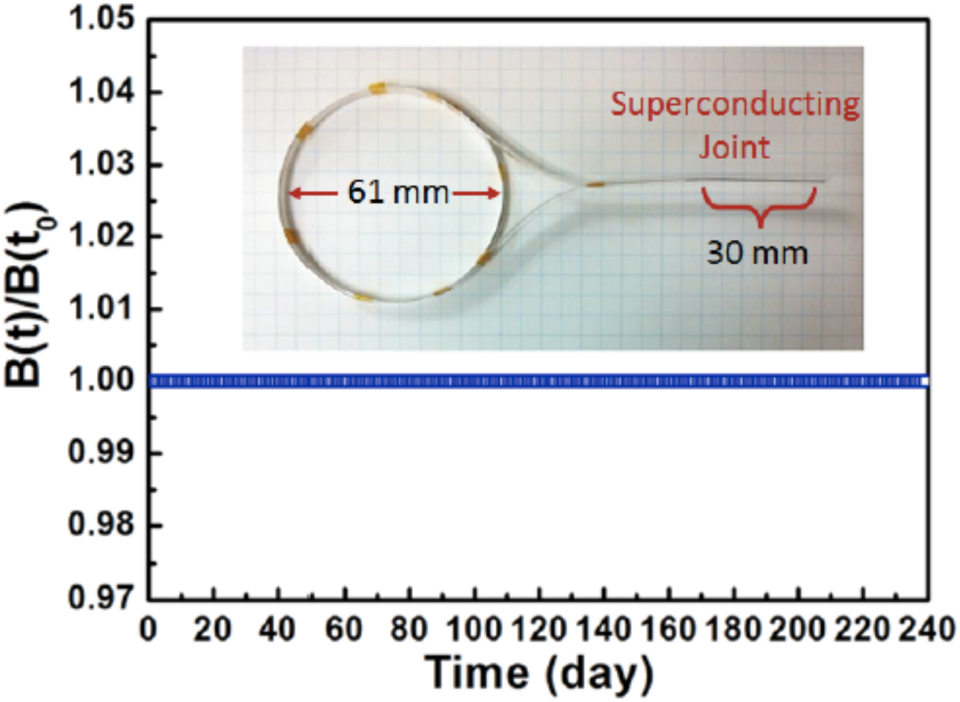
- Yeonjoo Park, Myungwhon Lee, Hessung Ann, Yoon Hyuck Choi, and Haigun Lee, "A superconducting joint for $GdBa_2Cu_3O_{7-\delta}$ coated conductors," NPG Asia Materials **6**, e98 (5pp) (2014)

Superconducting Results at 77 K

V vs. I Traces



Field-Decay Trace



[Haigun Lee, Korea University (2013)]

Two Persistent-Mode GdBCO Magnets

- 2-NI DP coils (i.d.: 83 mm)
- 1-NI DP coil (i.d.: 500 mm)
- Nominal $T_{op} =$ 10 K

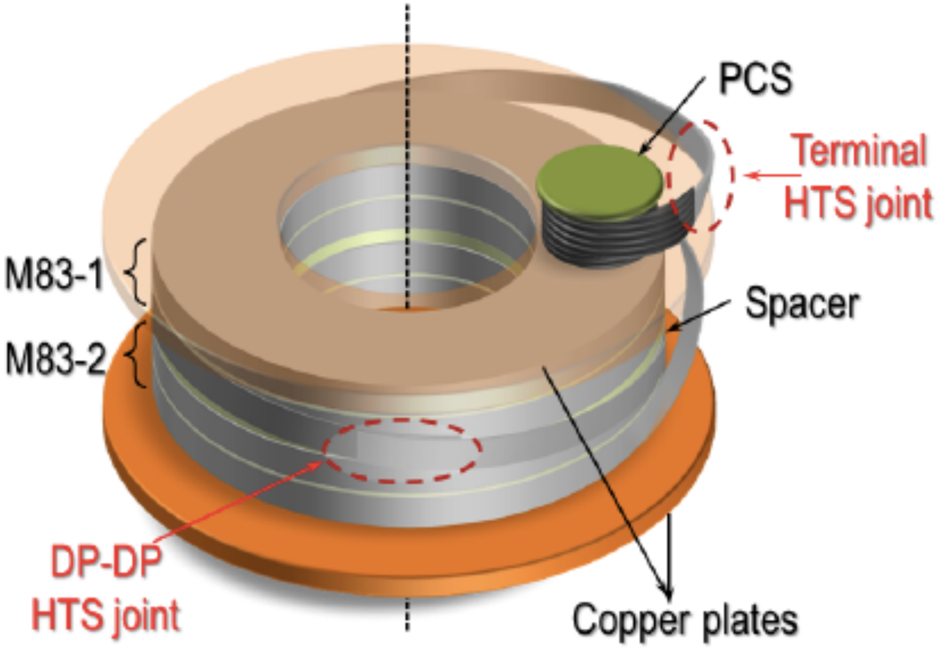
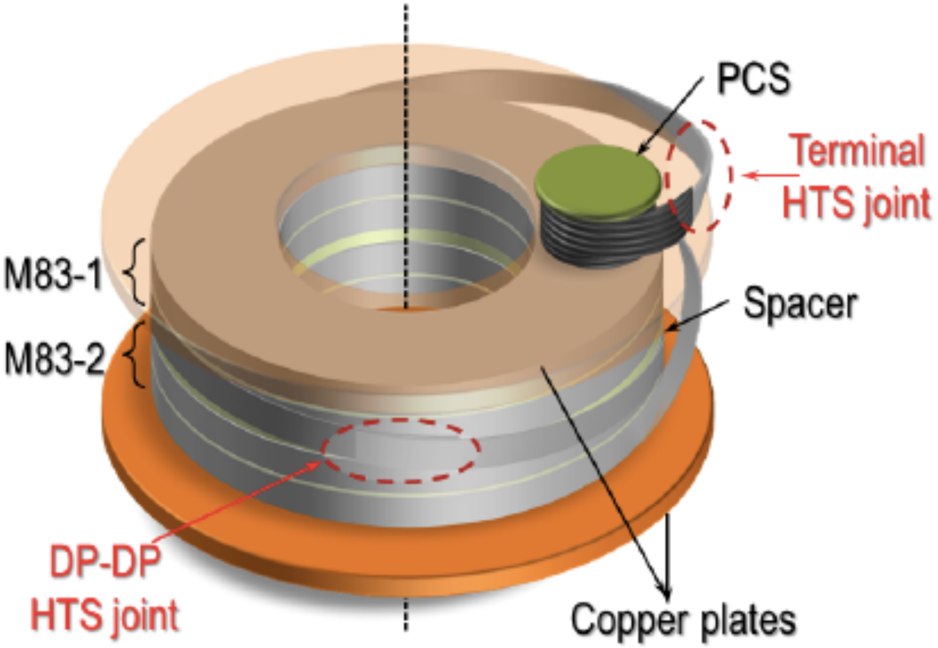


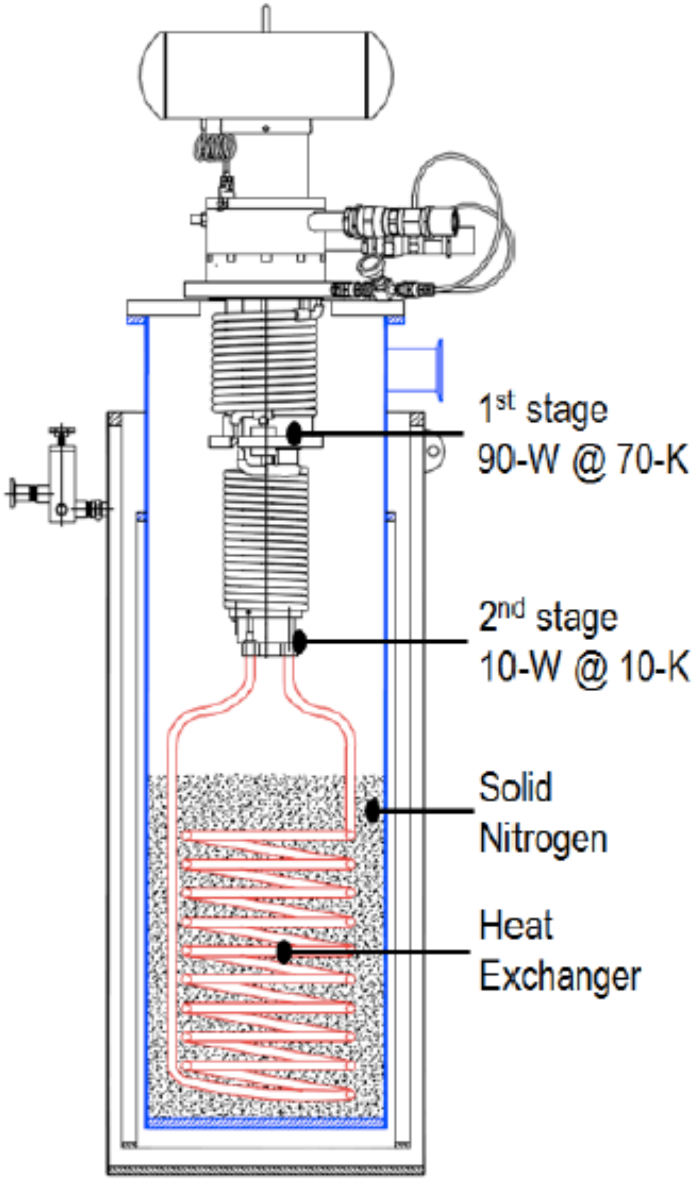
Table 1: Key Design Parameters

Parameters	M83	M500
REBCO Conductor		
Width; thickness [mm]	4.0; 0.1 (0.04 for Cu)	
I_c (77-K, self-field) [A]	$>$ 100 A	
Winding Parameters		
i.d.; o.d. [mm]	83; 120.6	500.0; 510.2
height [mm]	16.5	8.2
Turn per pancake	188	51
Total DP	2	1
Conductor per DP [m]	120.3	161.9
Characteristic Resist. [mΩ]	4.1	0.11
Operation		
I_{op} at 10 K [A]	253.5	394.1
B_c at I_{op} [T]	2.35	0.1
Current density at I_{op} [A/mm^2]	615.3	956.7
Peak $B_\perp$ at 250 A of I_{op} [T]	0.86	0.89
Inductance [mH]	71.2	14.9
Charging time constant [sec]	17.4	135
Stored energy [kJ]	2.29	1.16
Peak hoop stress [MPa]	49	22.3
Persistent-Current-Switch (PCS)		
i.d.; o.d. [mm]	30; 34.8	30;31
height [mm]	5.0	5.0
Turns	24	5
Conductor [m]	2.44	8
R_{pcs} at 10 K [$m\Omega$]	2.4	0.48
t_c at 10 K [sec]	47	166

Y Iwasa (MIT)
Iwasa@jokaku.mit.edu

Two Persistent-Mode GdBCO Magnets





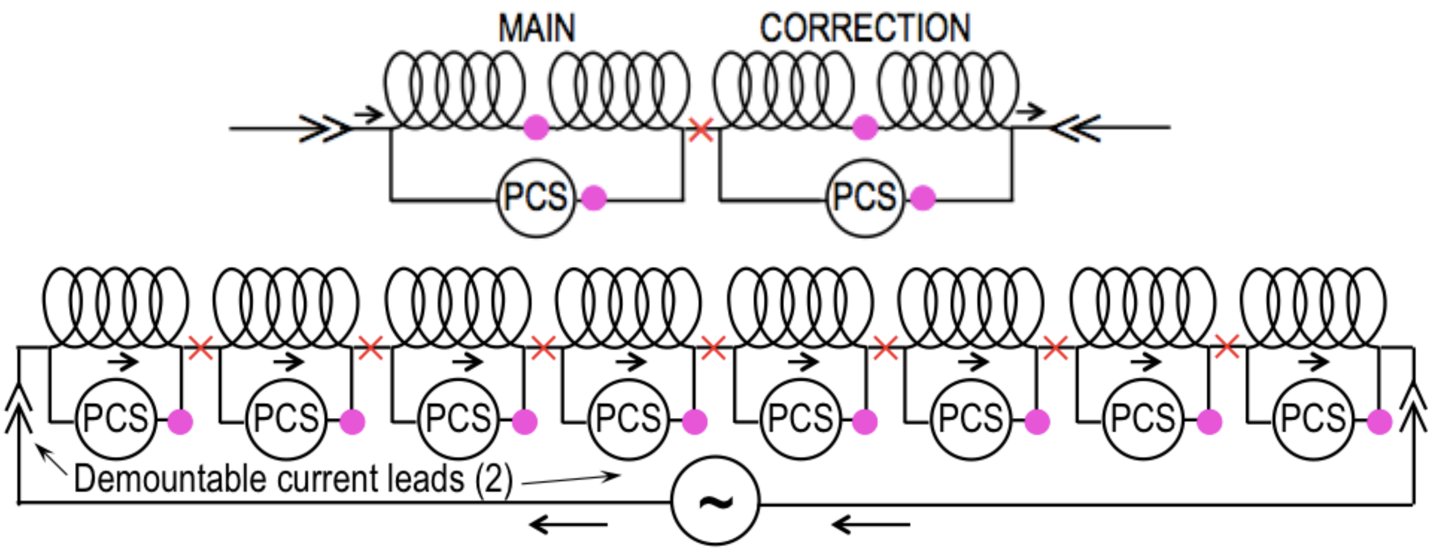
Future (April 2016)
A Tabletop, LHe-Free, Persistent-Mode
1.5-T/9-mm MgB2 Magnet for Osteoporosis MRI*

- First steps in the development of novel bone densitometry technology for low-cost, universal metabolic bone disease screening
- Bone density screening a critically important and effective tool for detecting individuals at risk for osteoporotic fracture
  - Yet less than half of those at risk (over 55 million Americans) screened
- DXA (dual-energy X-ray absorptiometry): gold standard for osteoporosis screening
- If the capital and operating costs of MRI further reduced, MRI can fully characterize bone in a screening test

* For MGH (Mass General Hospital), Dr. Jerome Ackerman Co-Investigator

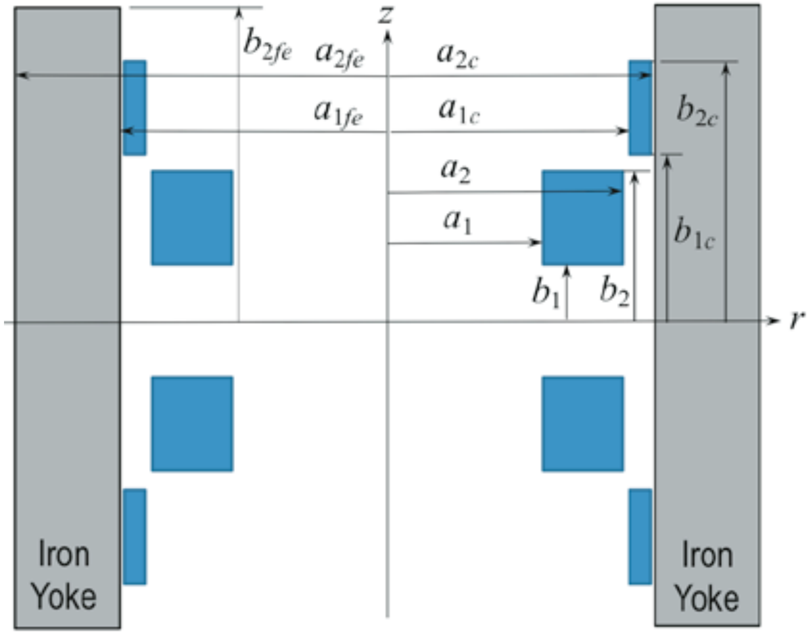
Proposed 1.5-T/9-mm MgB2 Magnet

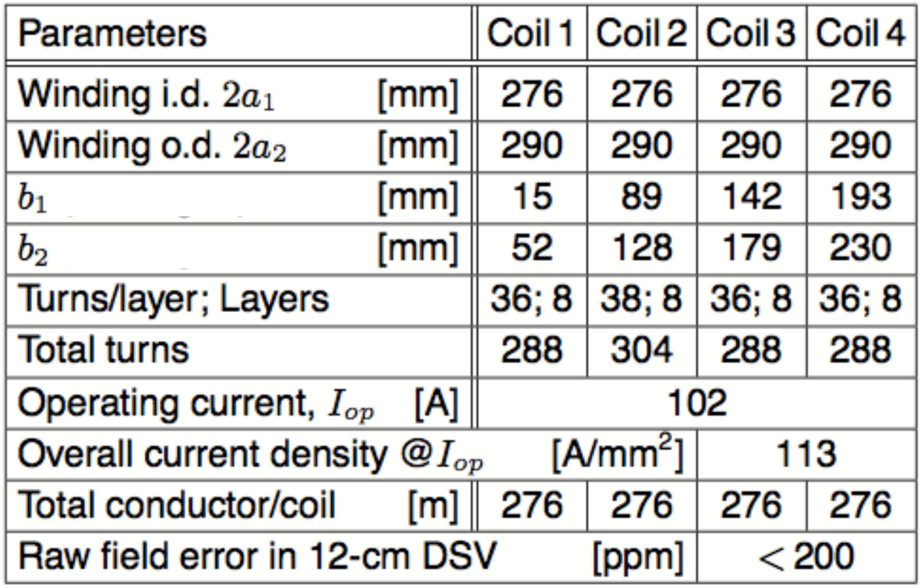
- Same our 8-coil MgB2 magnet design concepts
  - 2-Module coils, each module with a PCS and **2** joints
  - MgB2 monofilament; wind-and-react; 10K➔15 K
- Iron yoke for field shielding:
  - Fringe field <5 gauss in magnet vicinity
  - *Protects center field from extraneous fields*



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

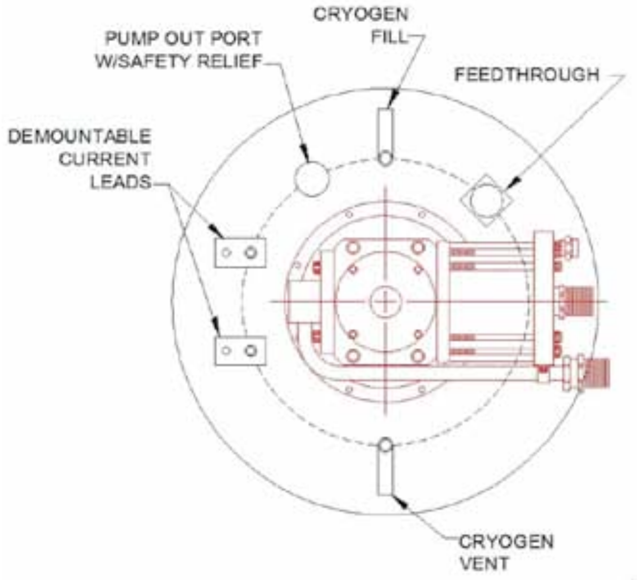


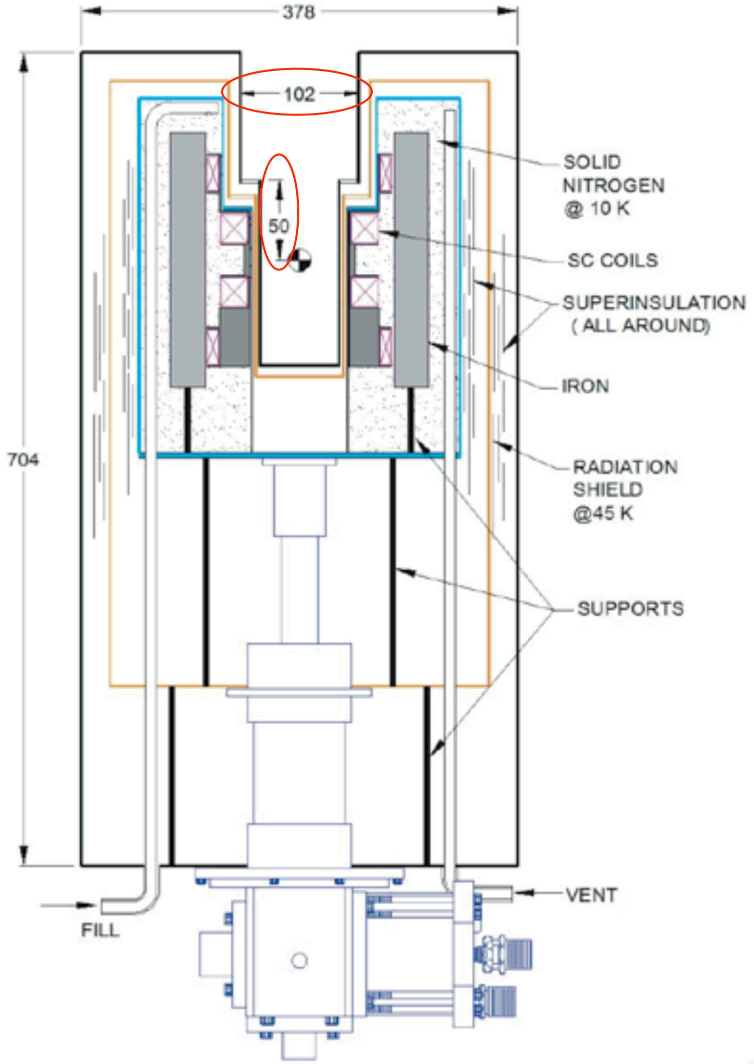


Parameters	Coil 1	Coil 2	Coil 3	Coil 4
Winding i.d. $2a_1$ [mm]	276	276	276	276
Winding o.d. $2a_2$ [mm]	290	290	290	290
b_1 [mm]	15	89	142	193
b_2 [mm]	52	128	179	230
Turns/layer; Layers	36; 8	38; 8	36; 8	36; 8
Total turns	288	304	288	288
Operating current, I_{op} [A]	102			
Overall current density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

Proposed 1.5-T/9-mm MgB2 Magnet

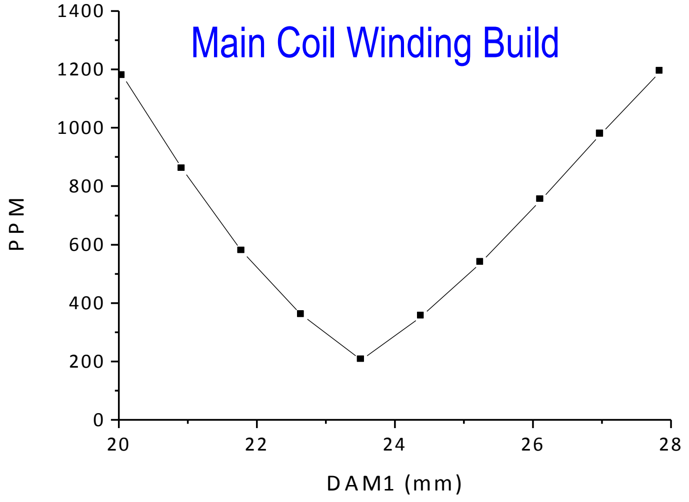
- Cryocooler off, 0.3 W into cold chamber (manufacturer specs)
- Total input to cold chamber ~0.55 W
- ~10-liter SN2: ~15 kJ (10 K➔15 K) (35-kg iron yoke: < 1 kJ)

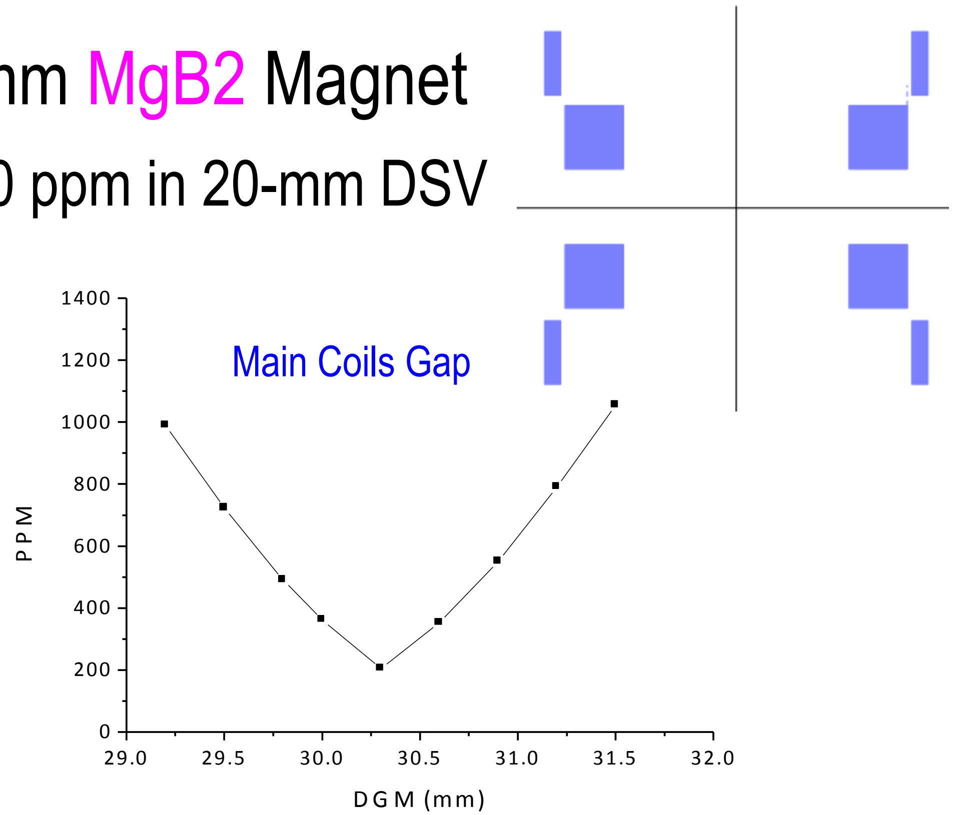


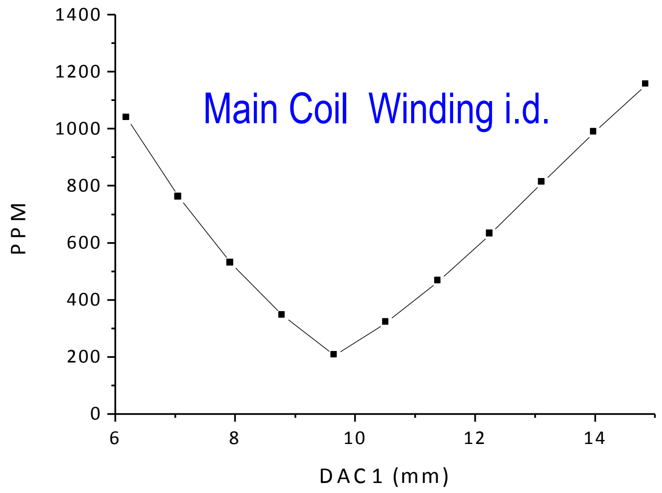


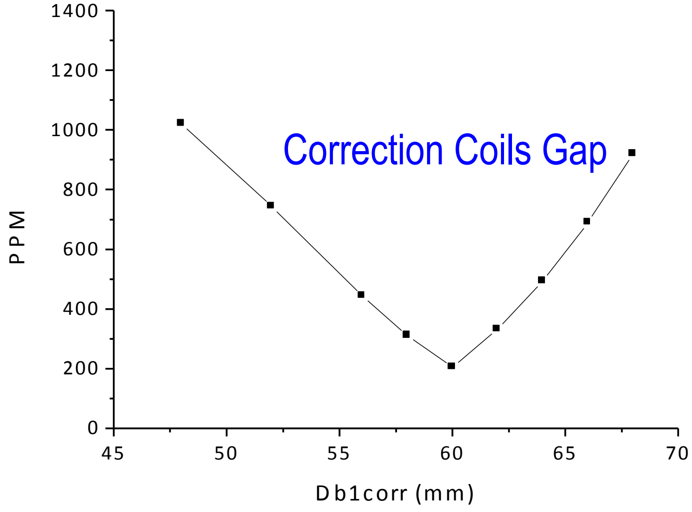
Proposed 1.5-T/9-mm MgB2 Magnet

- As-wound-and-assembled magnet: 200 ppm in 20-mm DSV



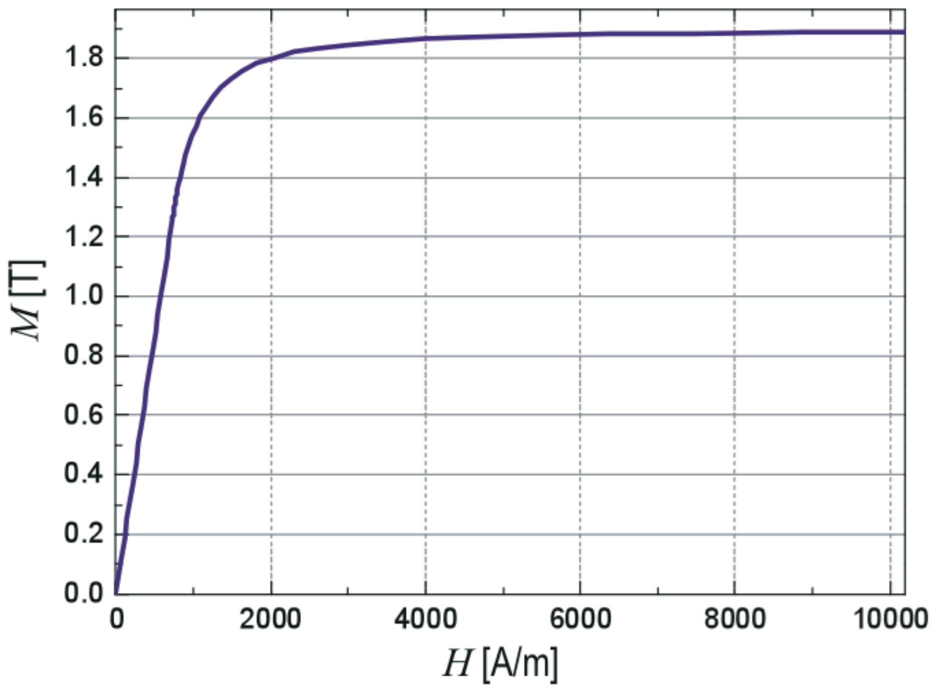


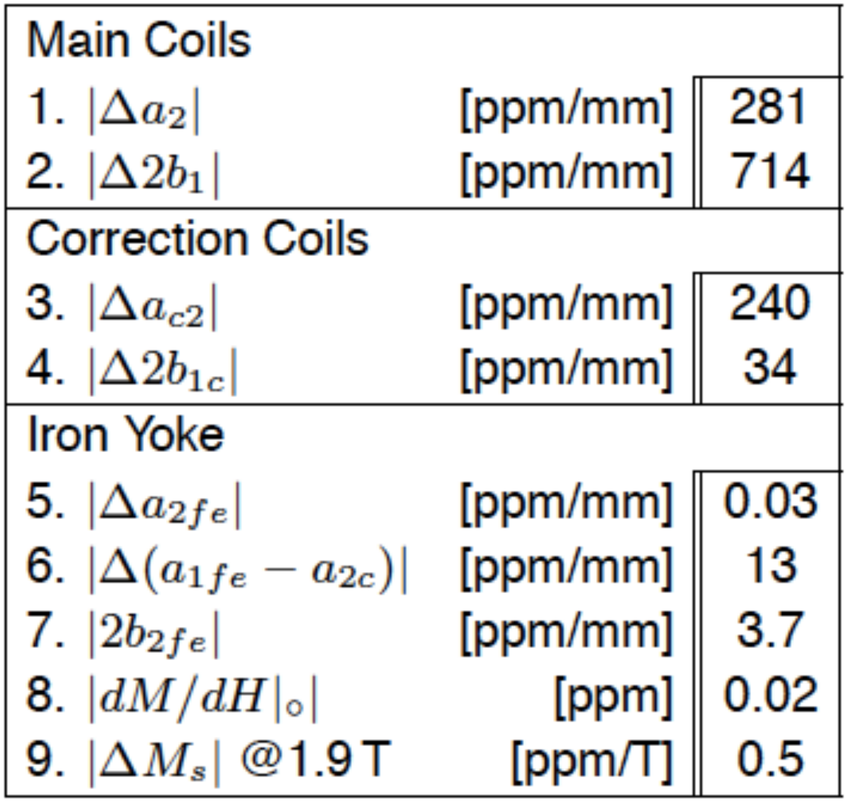




Proposed 1.5-T/9-mm MgB2 Magnet

- As-wound-and-assembled magnet: 200 ppm in 20-mm DSV





Main Coils		
1. $\lvert\Delta a_2\rvert$	[ppm/mm]	281
2. $\lvert\Delta 2b_1\rvert$	[ppm/mm]	714
Correction Coils		
3. $\lvert\Delta a_{c2}\rvert$	[ppm/mm]	240
4. $\lvert\Delta 2b_{1c}\rvert$	[ppm/mm]	34
Iron Yoke		
5. $\lvert\Delta a_{2fe}\rvert$	[ppm/mm]	0.03
6. $\lvert\Delta(a_{1fe} - a_{2c})\rvert$	[ppm/mm]	13
7. $\lvert 2b_{2fe}\rvert$	[ppm/mm]	3.7
8. $\lvert dM/dH\rvert_{\circ}\rvert$	[ppm]	0.02
9. $\lvert\Delta M_s\rvert$ @1.9 T	[ppm/T]	0.5

- From 200 ppm to 5 ppm to be achieved with ferroshimming
- Of 90-mm RT bore, the outermost 10-mm annular space for ferro-tiles

CONCLUSIONS

- We hope to find a way to salvage the 1.3G project.

  Since 2000:
  - We have been working on this project
  - NIH has been supporting this project
  - Our users (MIT, Harvard, others) have been supporting this project

- MgB2 magnet technology approaching viable option
  - Particularly for LHe-free, low-field (<3 T) magnets
  - Further improvement in J_c ($B >$ 3 T. $T \geq$ 10 K) desirable/needed

Thank you!