Update on Selected HTS Magnet Activities at FBML, Including A New Design Concept for Persistent-Mode HTS Shim Coils & A 1st-Cut Design of a 100-T DC *magnet*

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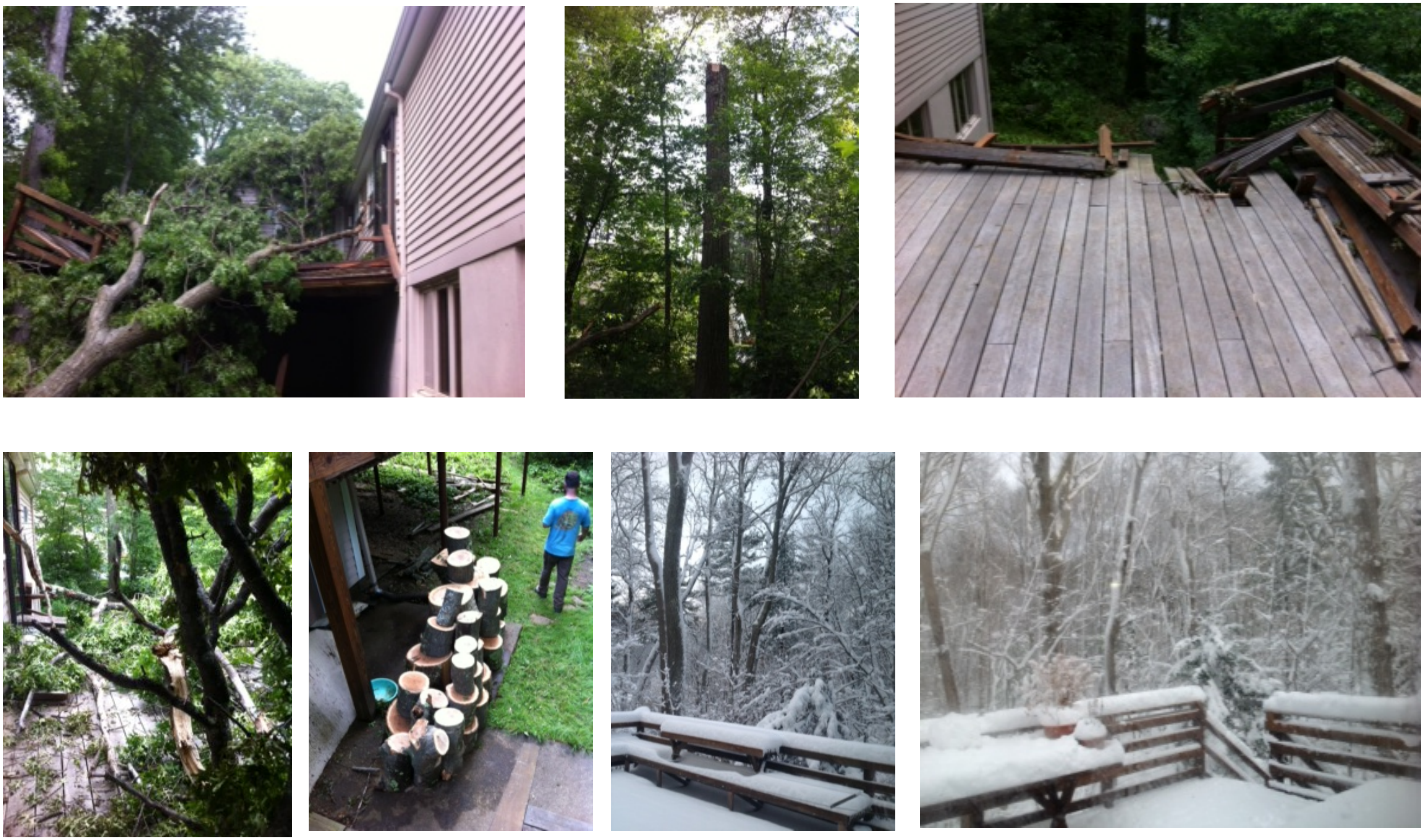
CEA. Saclay

June 26, 2013

A Happening in Weston, MA, during the night of June 2, 2013



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Outline

- Magnet Technology Division
- Research Activities
  - A. On-going (7)
  - B. Being proposed (1)
  - C. Proposed (not expected to be funded)
- Conclusions

Magnet Technology Division (MTD)

Yuki IWASA, Head
Juan BASCUÑÀN, Assistant Head, cryogenics
Seungyong HAHN, magnet (design; analysis; experiment)
John VOCCIO, magnet (design, assembly, experiment)
Jiayin LING, MIT ME grad student (PhD): Tsingua
Roger LO, MIT undergrad research intern (freshman)
Scott McDONALD, MIT undergrad research intern (freshman)
Egor TSIAULOUSKI, MIT undergrad research intern, a Cambridge U exchange student
Julio COLOQUE, Technician
Peter ALLEN, Technician
Nicholas CANDELINO, Technician, Northeastern U. undergrad intern
Youngjae KIM, Postdoc (April 2012—): Yonsei U.
Jungbin SONG, Postdoc (December 2012—): Korea U
Thibaut LÈCREVISSE, Postdoc (Fall 2013—): CEA Saclay
Kazuhiro KAJIKAWA, Visiting Scientist (April 2013—March 2014): Kyushu U.
Yung CHU, VS (May 2013—April 2014): NFRI (Kstar)
Yasuaki TERAO, VS (June 2013—May 2014): JASTEC
Frederic TRILLAUD, VS (July—August 2013): Universidad Nacional Autonom W Mexico,

MIT FBML Magnet Technology Division Activities

A. On-Going

A1. 1.3 GHz LTS/HTS NMR magnet *(NIH)**—To Be Described (TBD)

A2. *SN$_2$-cooled* MgB$_2$ 0.5 T/240 mm MRI magnet *(NIH)*** TBD

A3. Compact YBCO Annulus NMR magnet *(NIH)****

A4. 1.5-T/75-mm slow magic-angle-spinning NMR magnet *(NIH)*^

A5. No-insulation (NI), multi-width (MW) windings for HTS NMR magnet *(NIH)*^^

A6. NI HTS magnet for wind power generator *(KETEP)*^^^

A7. Partial NI winding technique for NbTi MRI magnets *(JASTEC)*

* Bascunan, et al. MT23 (Coils); Kim, et al. MT23 (Overbanding)

** Ling, et al. MT23 (Coil performance); Voccio, et al. MT23 (Joints, unreacted & reacted)

*** Hahn, et al. MT23

^ Voccio, et al. MT23

^^ Hahn, et al. MT23

^^^ Song, et al. MT23

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FBML MTD Activities (cont.)

B. Being proposed

B1. Persistent-mode HTS shim coils *(NIH)** *TBbD*

C. Proposed

C1. A 100-T *DC* magnet *(NIH—Paper Study)*** *TBbD*

* Yukikazu Iwasa, et al., accepted for publication in *Appl. Phys. Lett*. (July 2013)

** Iwasa, et al., MT23

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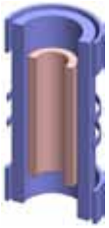
MIT 1.3 GHz LTS/HTS NMR Magnet:

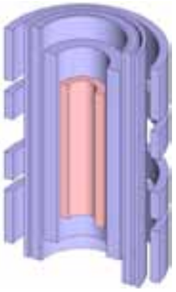
Update Plan 2012

Phase 1
2000-02



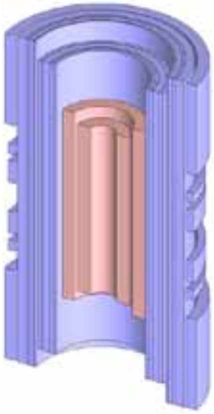
350 MHz
L300/H50

Phase 2
2003-07



700 MHz
L600/H100

Phase 3A
2008-12



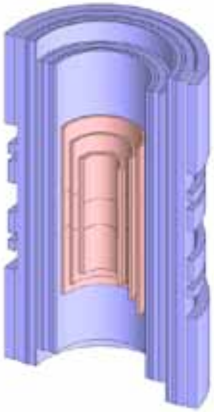
1.1 GHz
L500/H600

H600
Stolen (2012)

Post Theft Phase 3A
2012-15

H800
(H370+H242+H188)

Phase 3B
2015-18



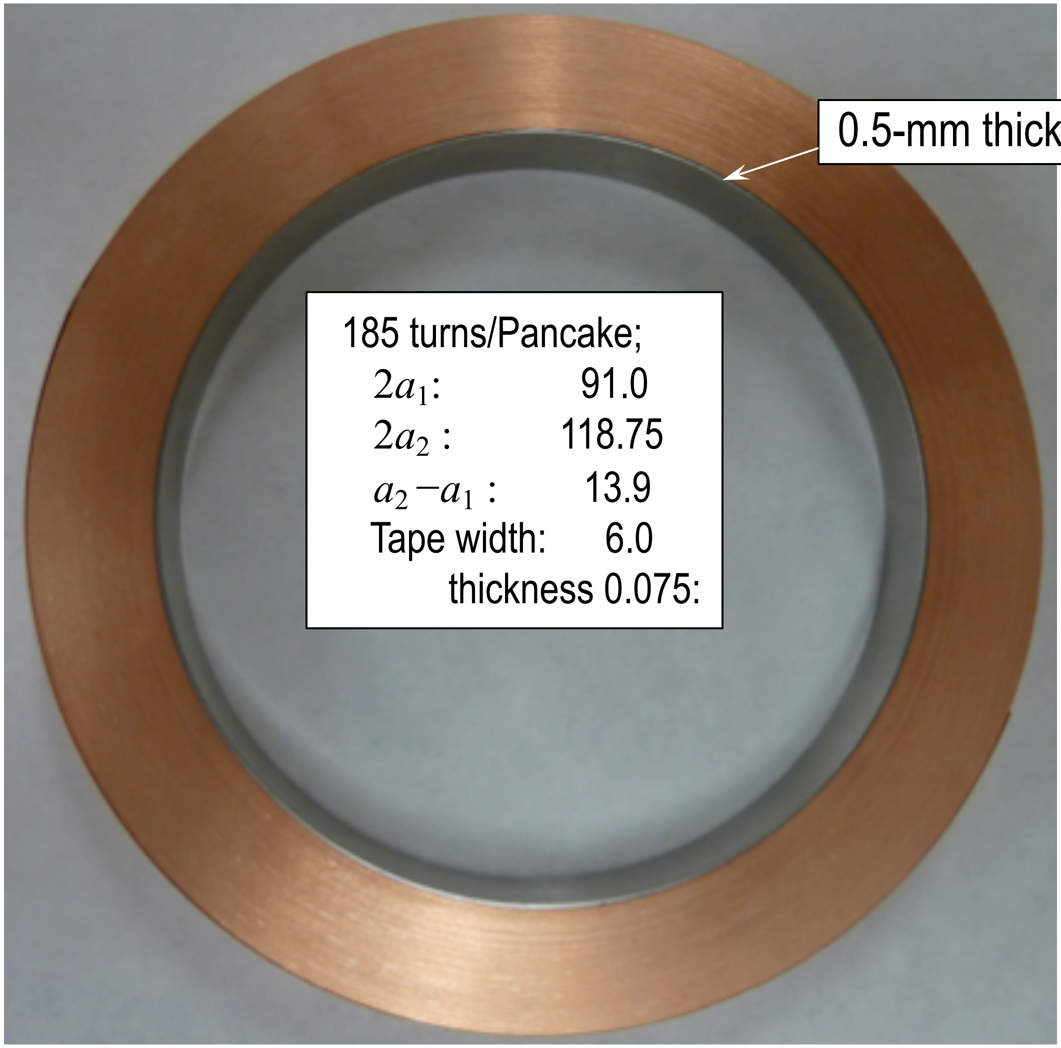
1.3 GHz
L500/H800

H800

- Comprises 3 nested HTS coils
- Each coil, an assembly of GdBCO No-Insulation (NI) DP coils
- Each coil, overbanded
- Unique Features of NI DP coils
  - Mechanically robust—no weak materials* within winding
  - Self-protecting

* LHe or insulation

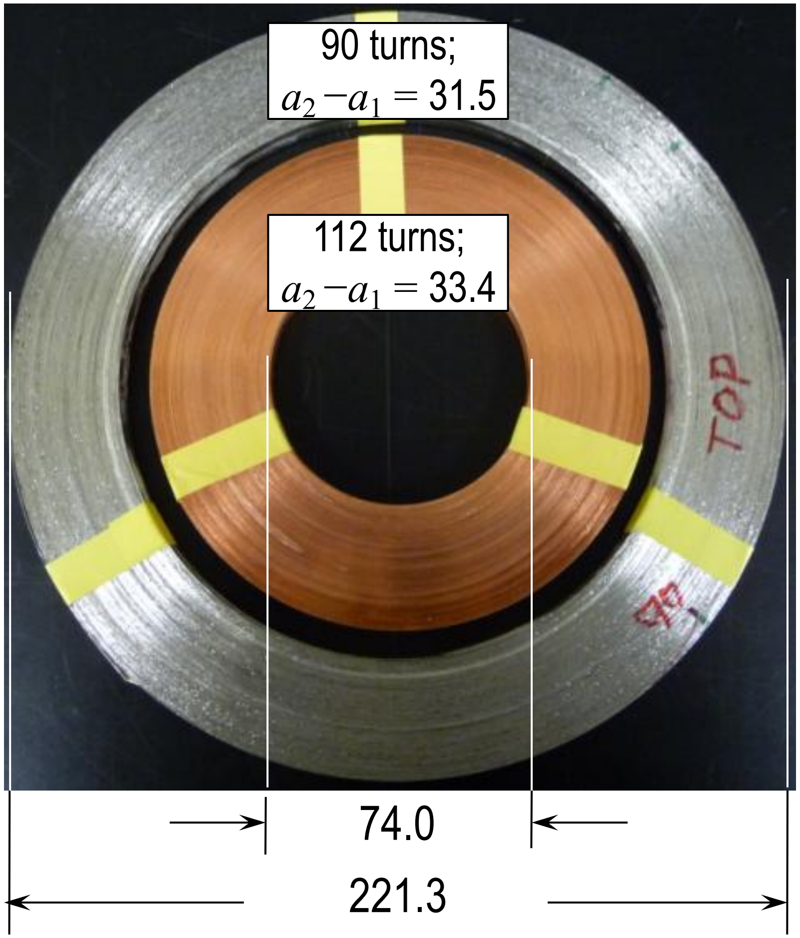
H800: Coil 1 (GdBCO) NI-DP



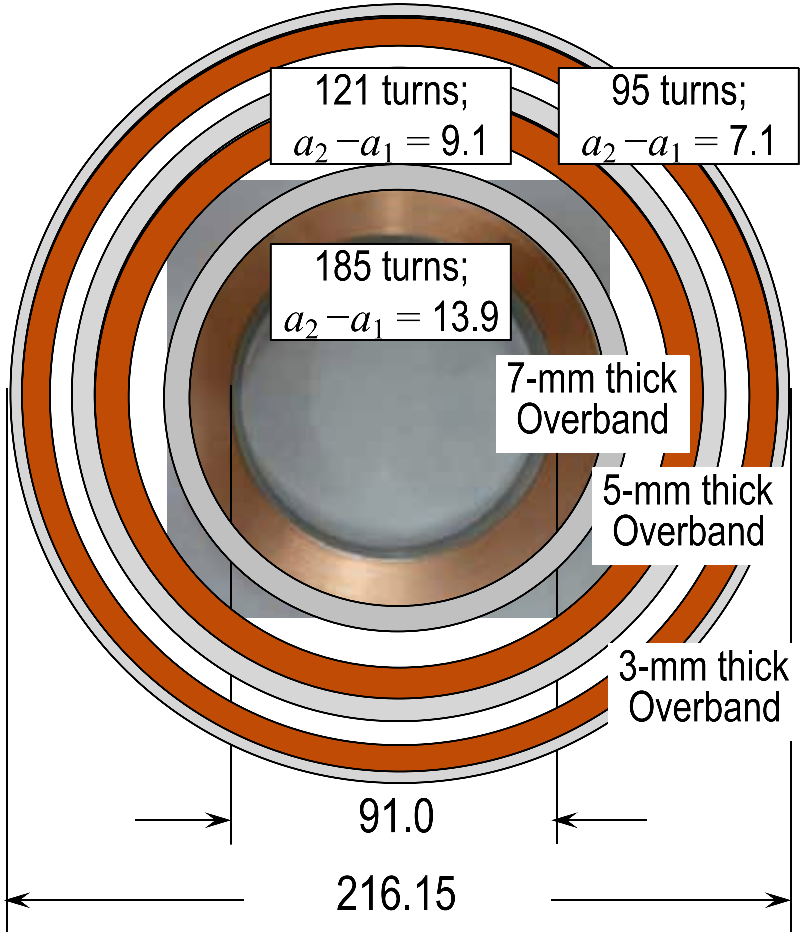
0.5-mm thick ss ring

185 turns/Pancake;
$2a_1$: 91.0
$2a_2$: 118.75
$a_2 - a_1$: 13.9
Tape width: 6.0
thickness 0.075:

H600 (14.09 T): I_{op}=250 A
Coil 1 (4-mm GdBCO: 56 DP)
Coi2 (4.3-mm Bi2223: 56 DP)



H800 (18.79 T): I_{op}=250 A
Coil 1 (6-mm GdBCO: 26 NI-DP)
Coil 2 (6-mm GdBCO: 32 NI-DP)
Coil 3 (6-mm GdBCO: 38 NI-DP)

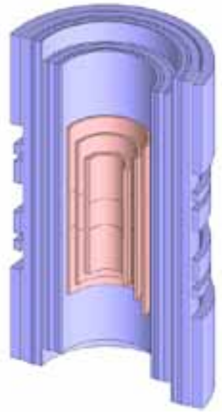


Phase 3B

*New, **competitive** application, i.e., funding not assured:*
Our plan: 6/01/2015 – 5/31/2018

- *H800 and L500 assembled, by 12/31/2015*
- *1.3-GHz field, 30.5 T, by 5/31/2016*
- *Special NbTi shims*
  for SCF of H800 installed, 12/31/2016
- *A high-resolution 1.3 GHz NMR magnet, by 5/31/2018*

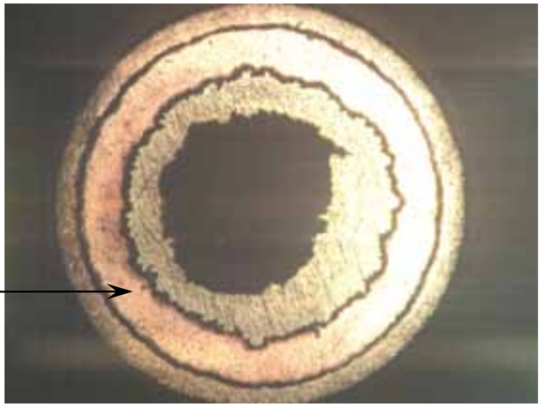
Phase 3B
2015-18

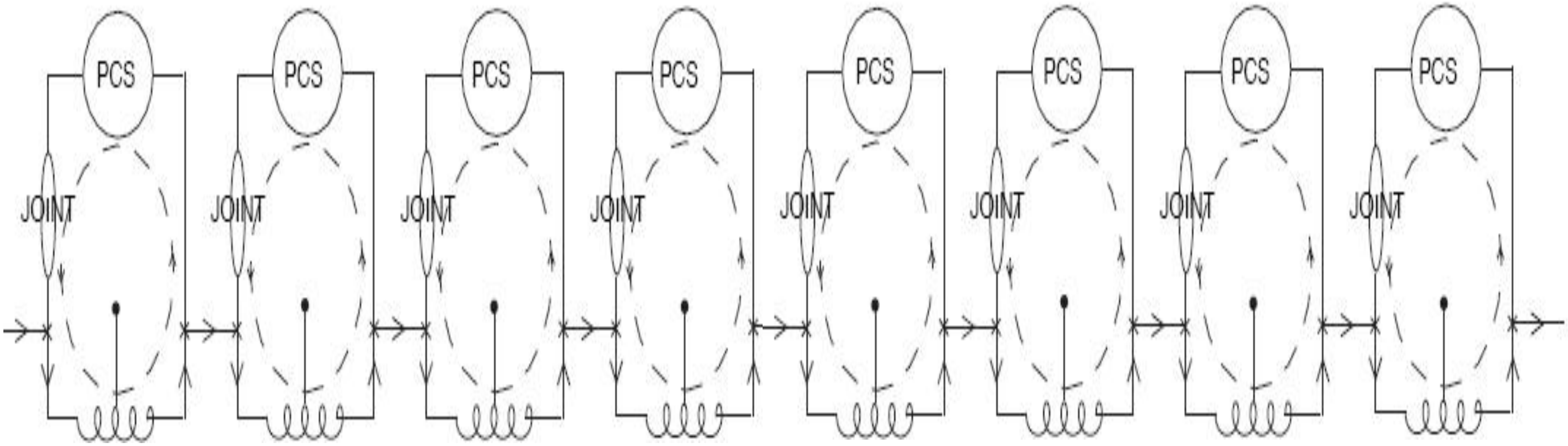


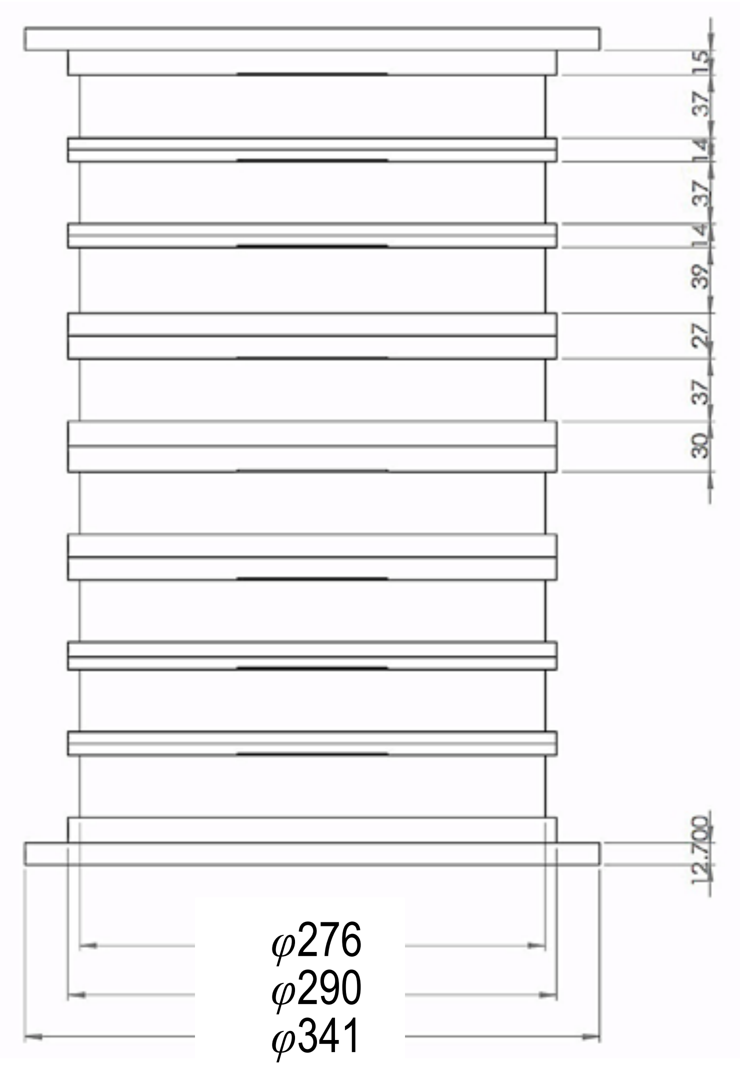
1.3 GHz
L500/H800

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

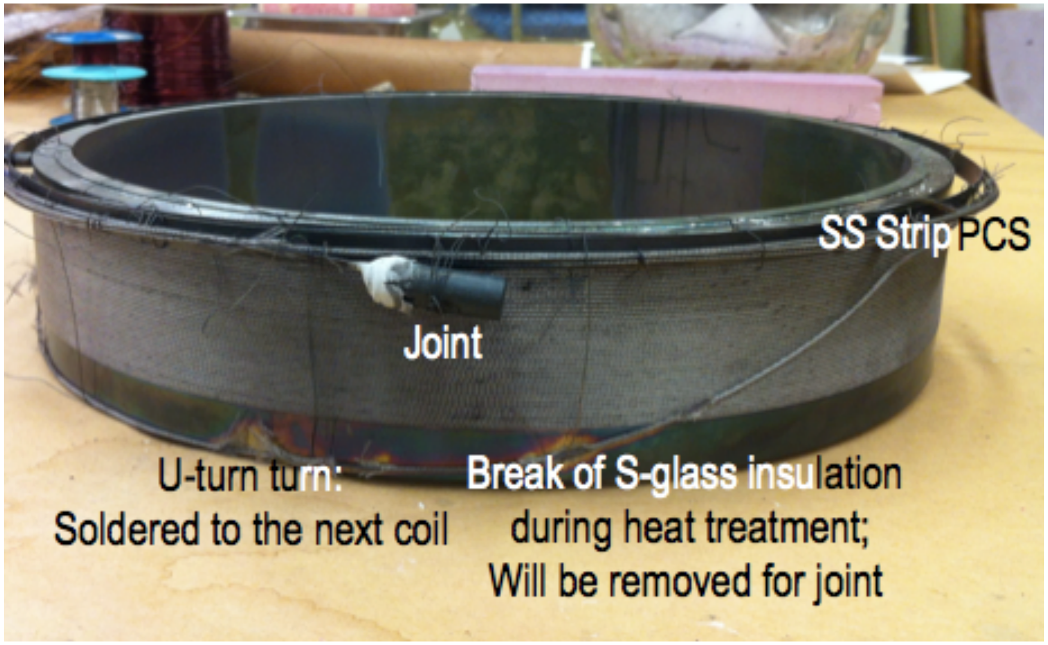
- *Consists of 8 coils (4 Main; 4 Correction), each with PCS and terminated with its superconducting joint*
- *Each coil wound with ~300-m long,* φ0.84 mm *monofilament MgB_2* wire

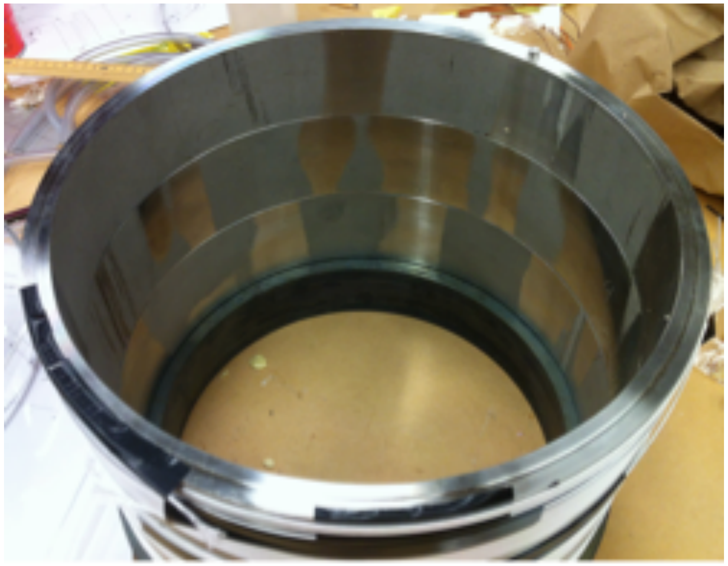

Copper matrix (35%)

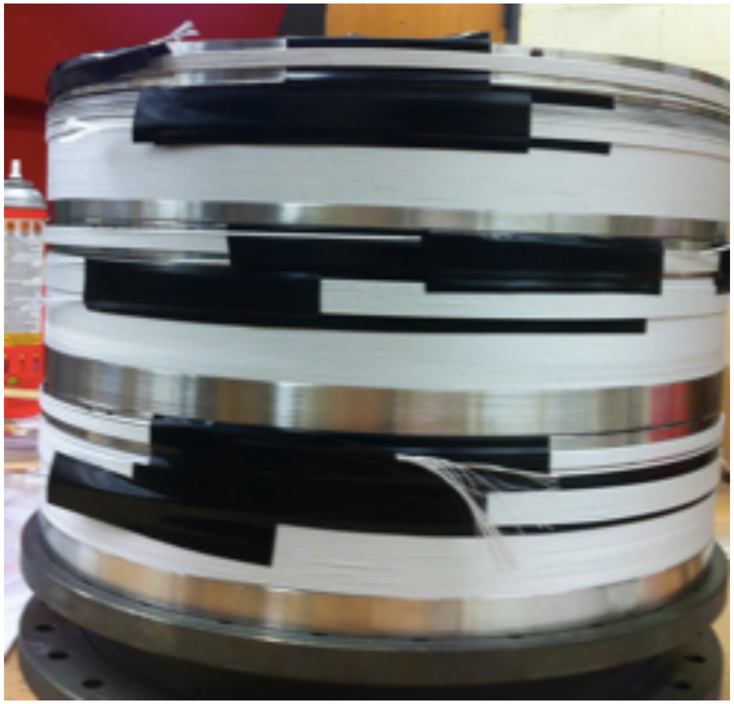



15
37
14
37
14
39
27
37
30
12.700
φ276
φ290
φ341

Reacted Coil (#1) &
3 Wound Coils







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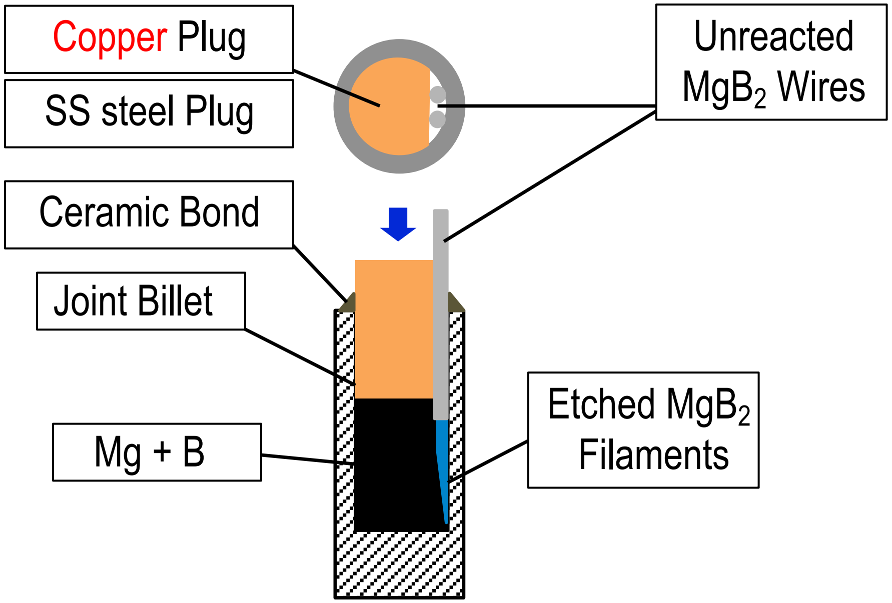
Monofilament MgB_2 Wire Joints

- *Joint technique with unreacted monofilament (ϕ0.4 mm) MgB_2 wires (HyperTech) very reliable, i.e., nearly 100% but still* NOT *100%*



Copper Plug

SS steel Plug

Ceramic Bond

Joint Billet

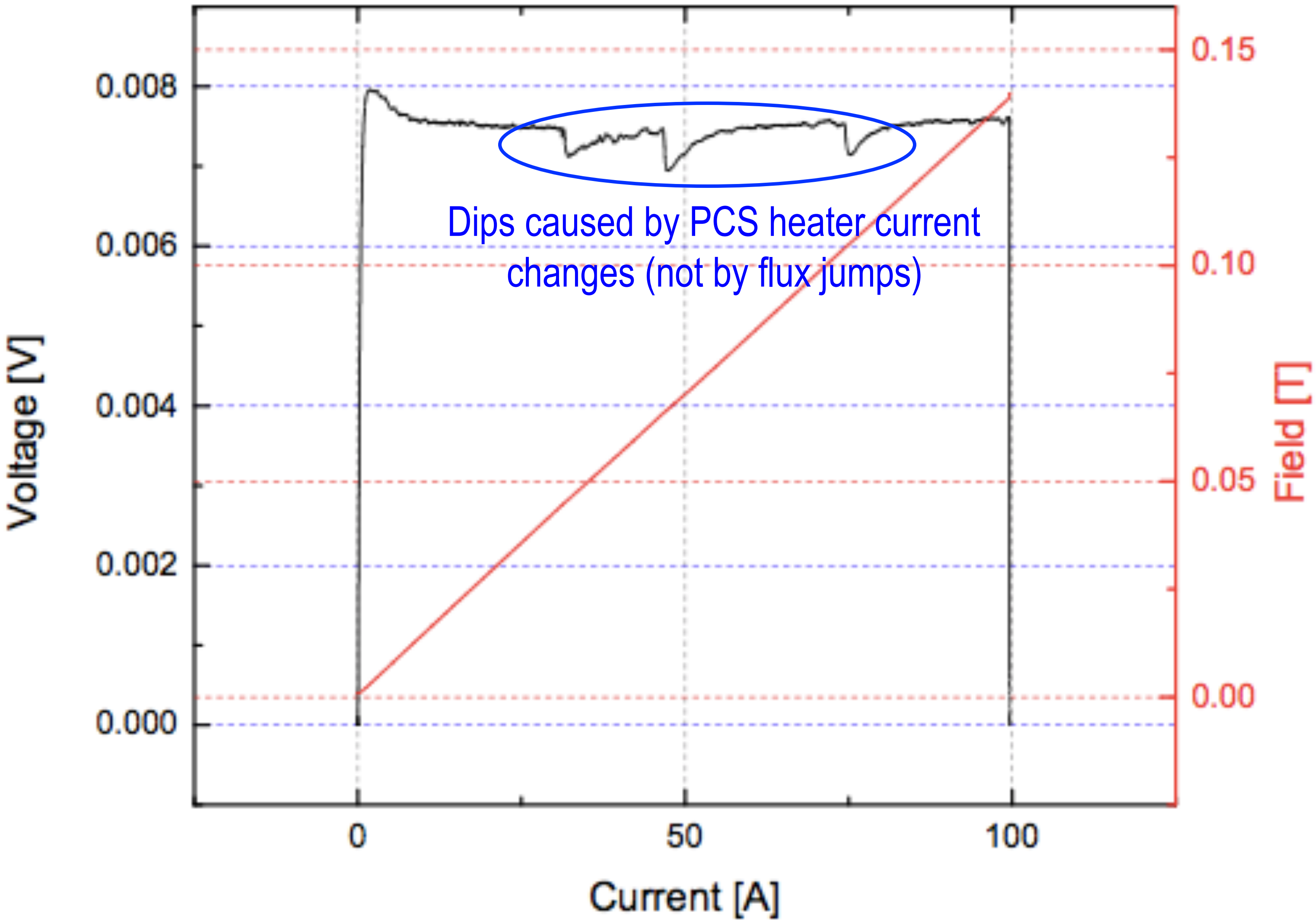
Mg + B

Unreacted MgB_2 Wires

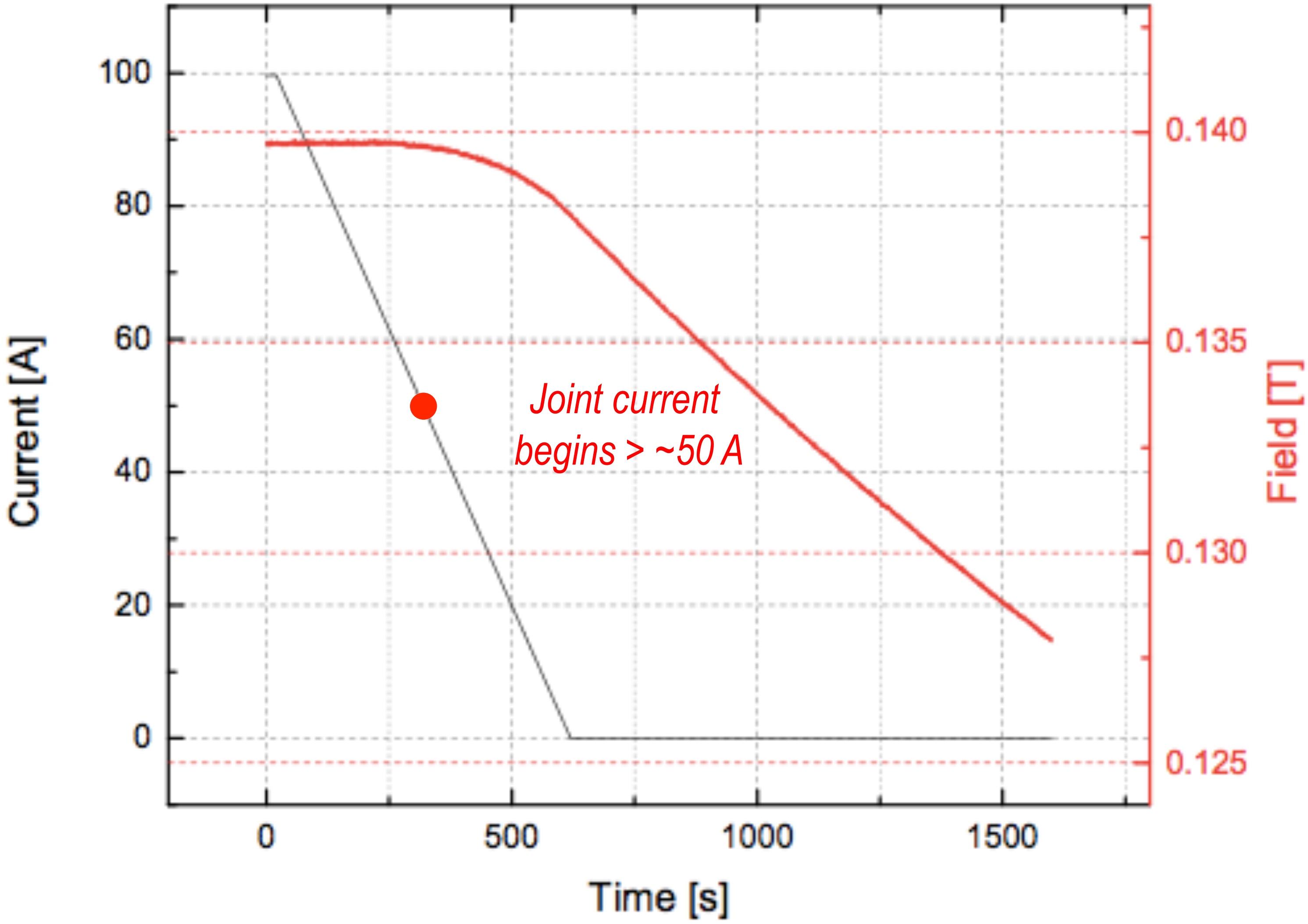
Etched MgB_2 Filaments

- Good joints: >300 A @10 K; >225A @15K, all s.f.

Coil #1 Test: Charging at 12 K—Driven mode

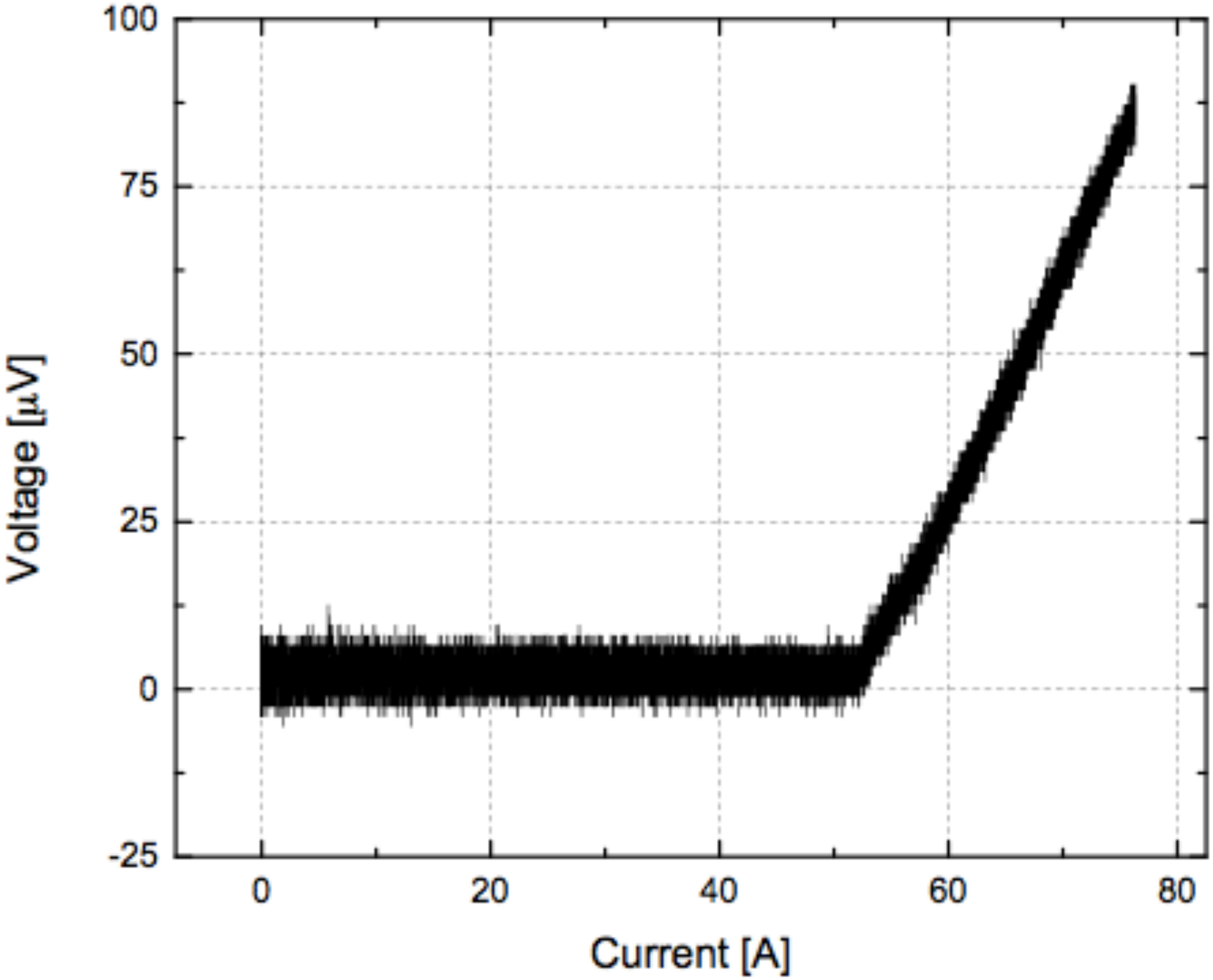

Dips caused by PCS heater current changes (not by flux jumps)

Coil #1 Test: Discharge at 12 K —Joint fails at 50 A



Joint current begins > ~50 A

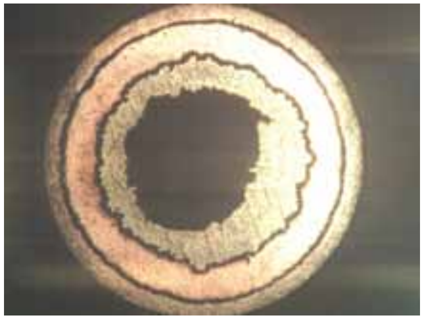
Coil #1 Joint at 15 K: $I_c \approx 60$ A *Expected $I_c > 200$ A, s.f.*



Protection

Adiabatic, *no* NZP Heating

$$Z(T_f, T_i) \equiv \int_{T_i}^{T_f} \frac{C_m(T)}{\rho_m(T)}\, dT = \left(\frac{\gamma_{m/s}}{1+\gamma_{m/s}} \right) J_{m_\circ}^2 \tau_{ah}$$



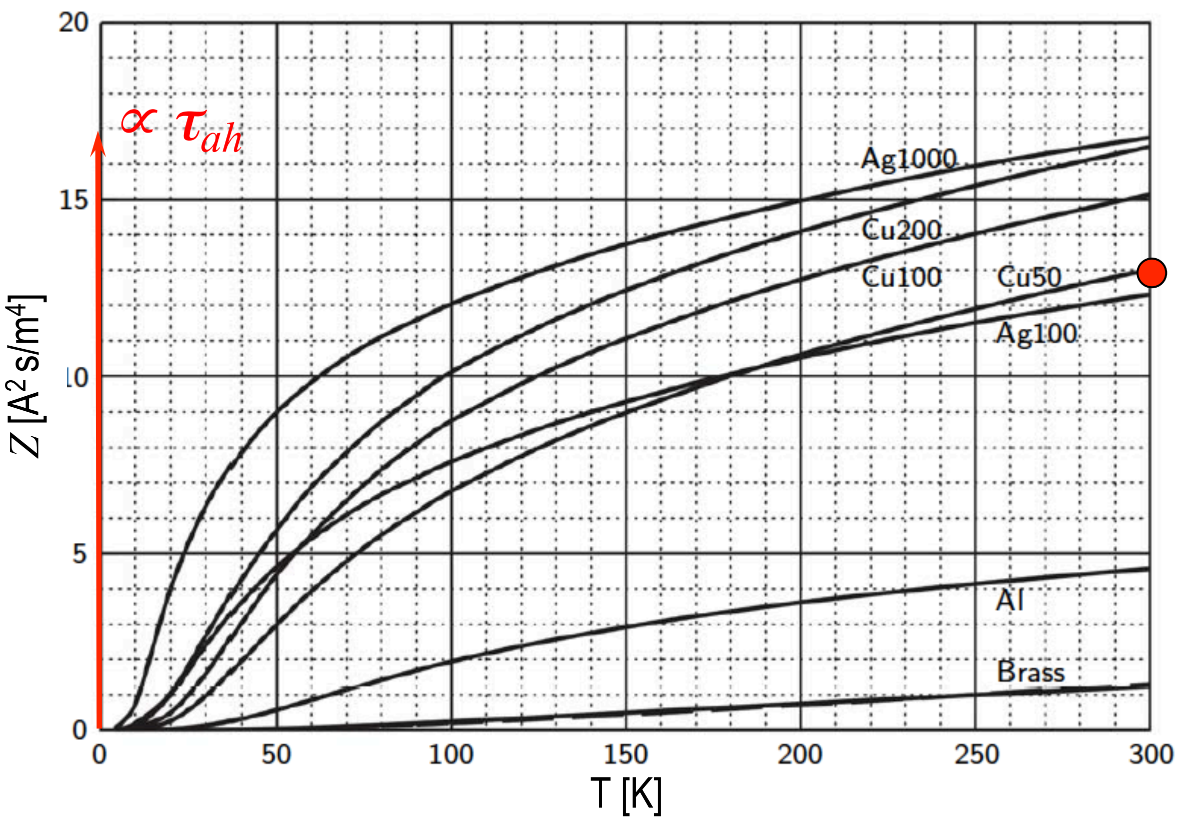
Copper matrix (35%)

I_{op} = 100 A

J_m = 515 A/mm^2

τ_{ah} = 2 s

Actual: > 2 s



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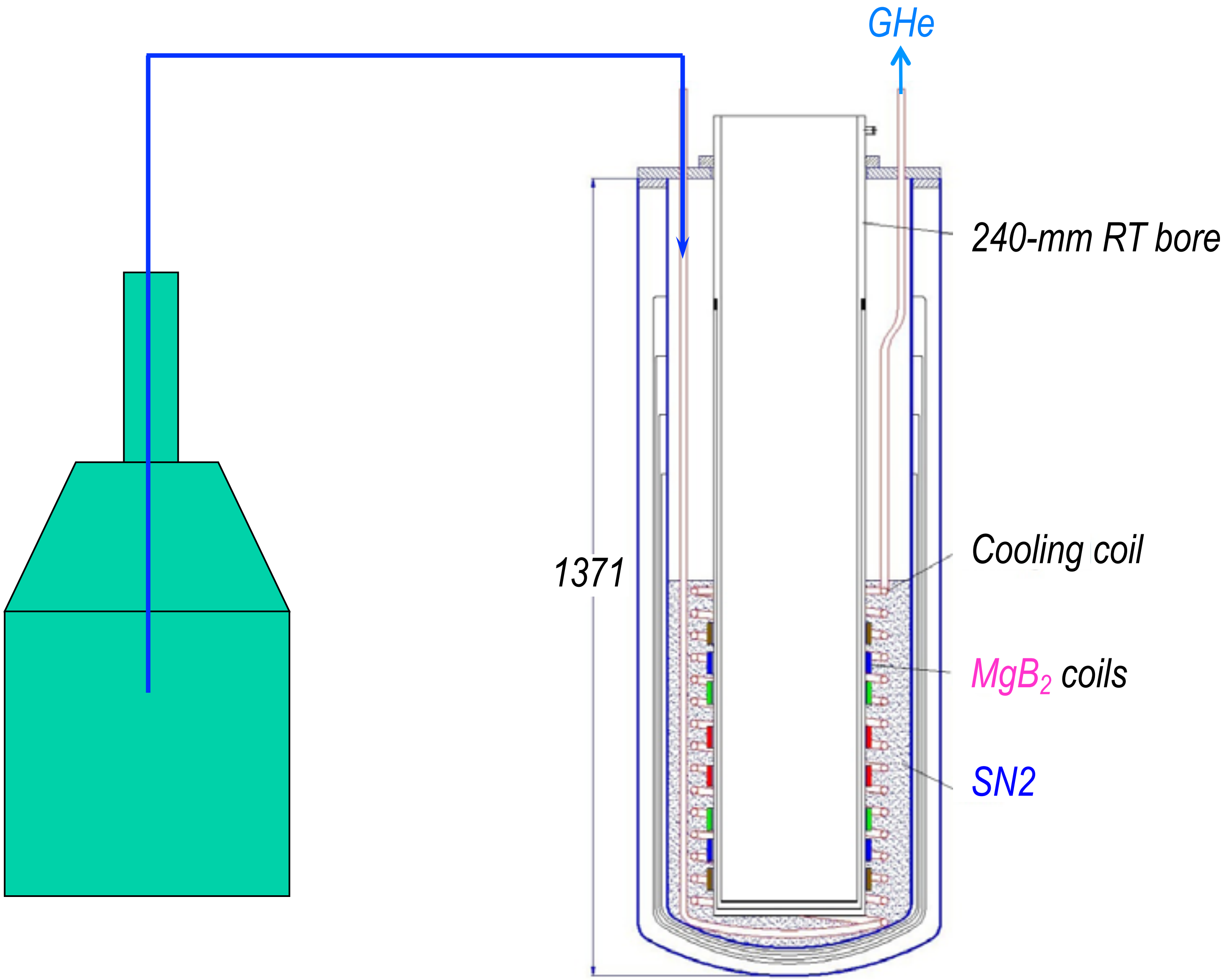
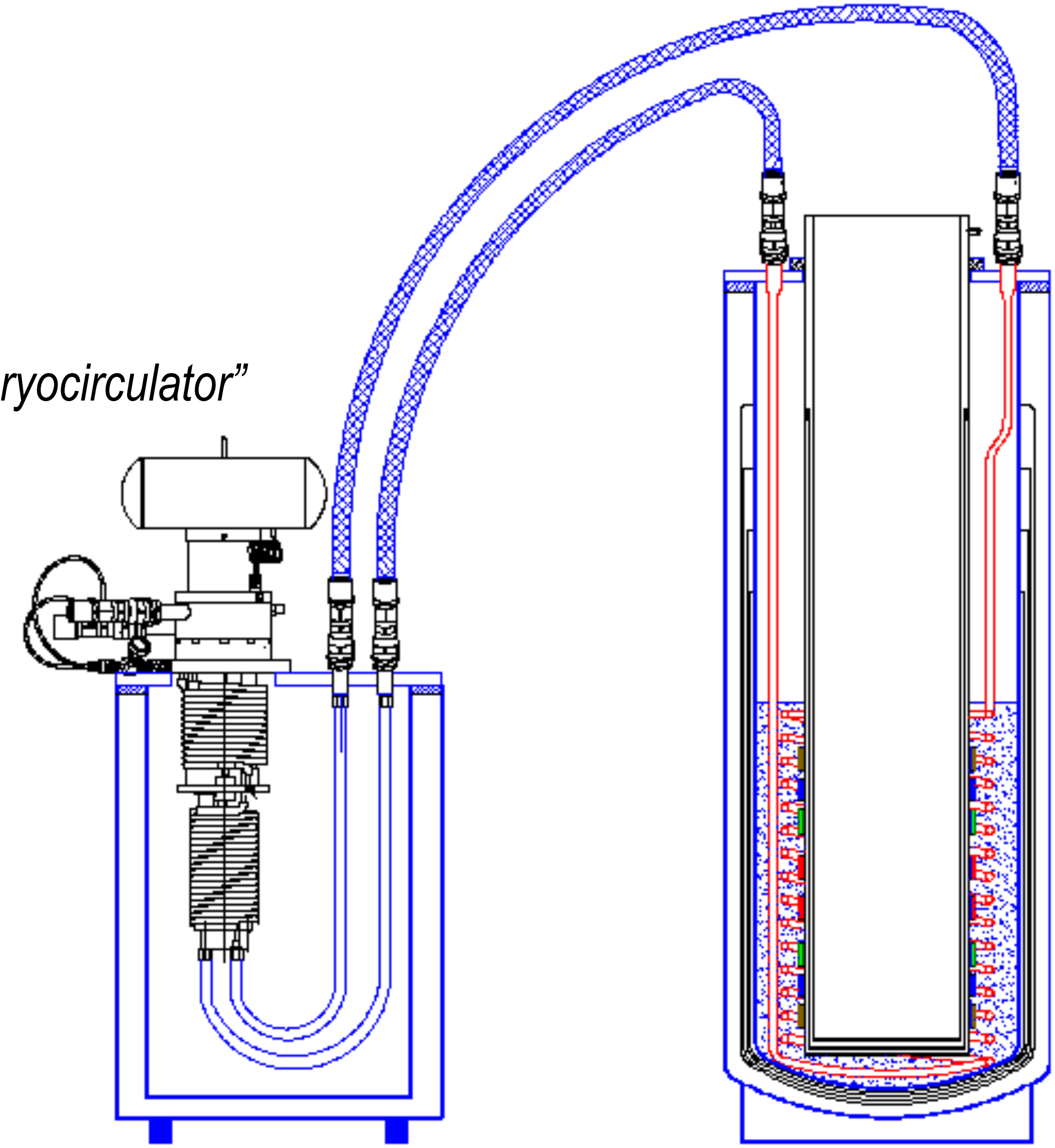
0.5-T/240 mm MgB_2 MRI Magnet

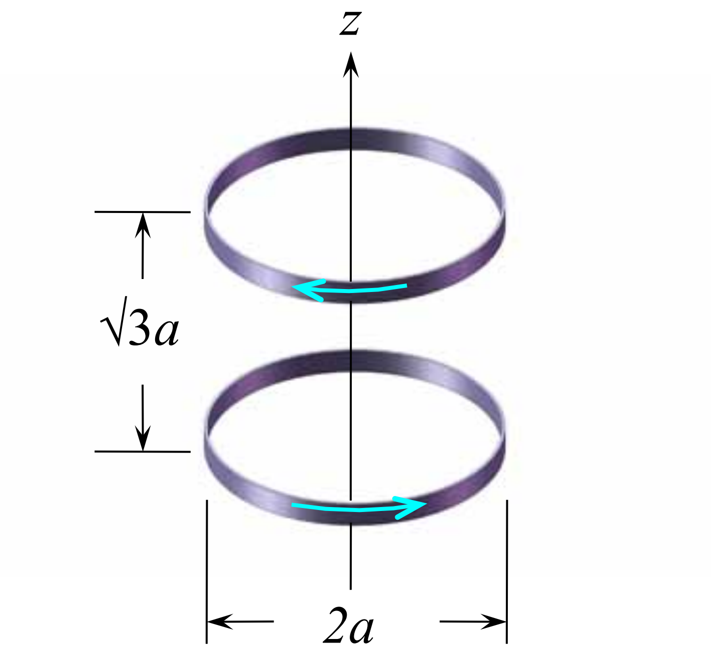


0.5-T/240 mm MgB_2 MRI Magnet with a "Cryocirculator"

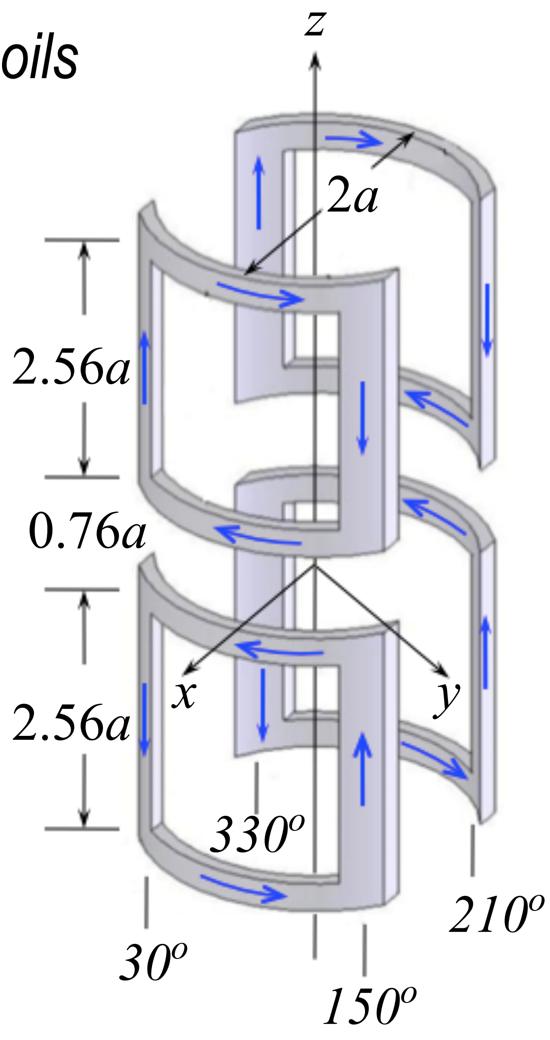


Persistent-Mode HTS Shim Coils

First, *Z1* and *X1* shim coils



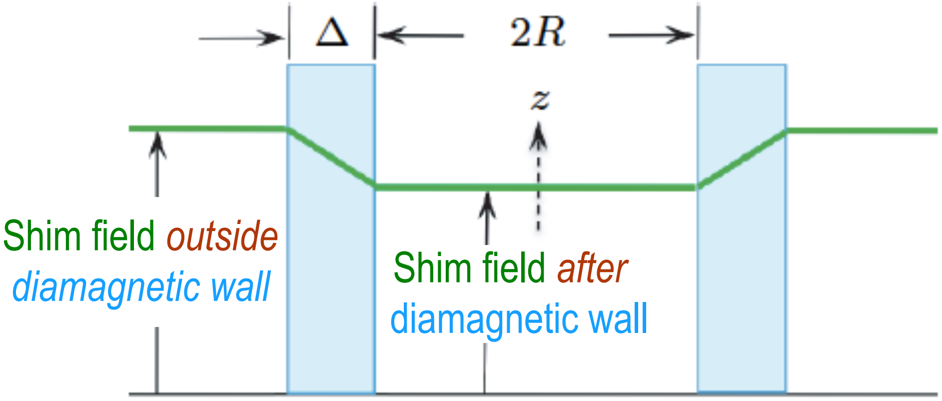
Ideal *Z1* shim coil



X shim coil

Advantages of HTS Shims

- Can operate >12-T field (vs. < 12-T for NbTi)
- Can operate >10-K temperature (vs. near 4.2 K for NbTi)
- Radial build, < 5 mm (vs. >15 mm for NbTi)
- Placeable inside main magnet assembly (vs. outside for NbTi)
  - Immune from "diamagnetic" effects of main magnet assembly



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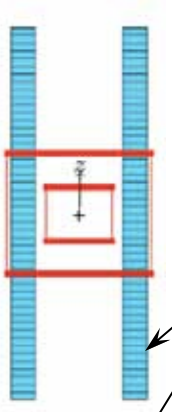
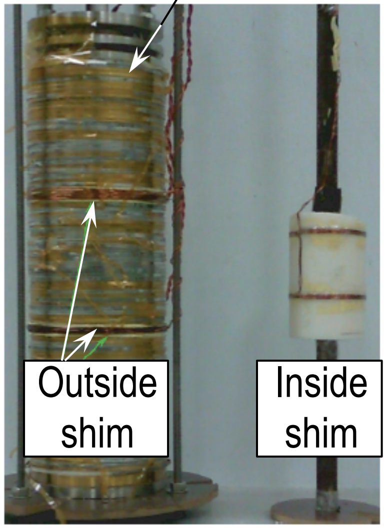
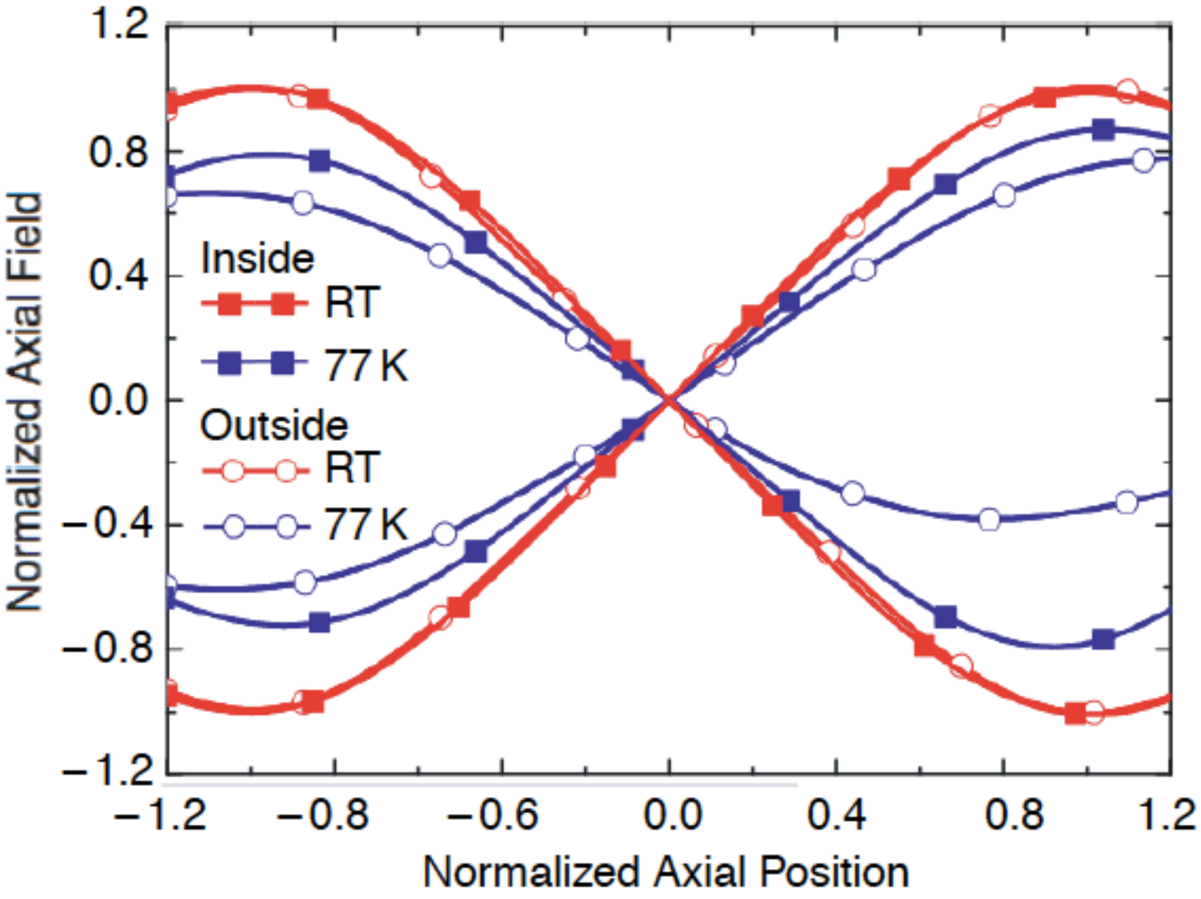
An Example of "Diamagnetic Wall" Effects on Shim Field

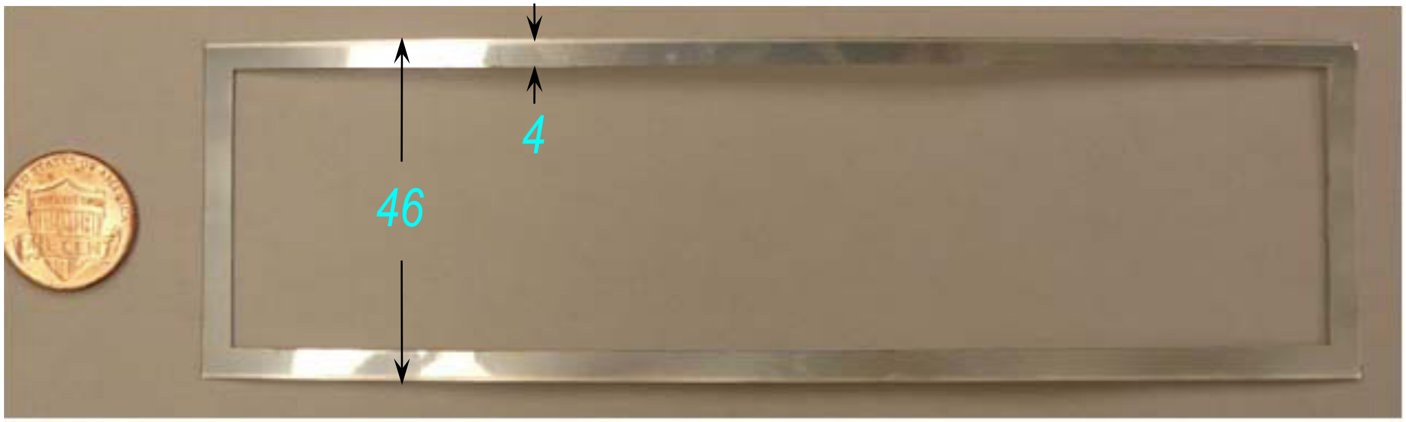


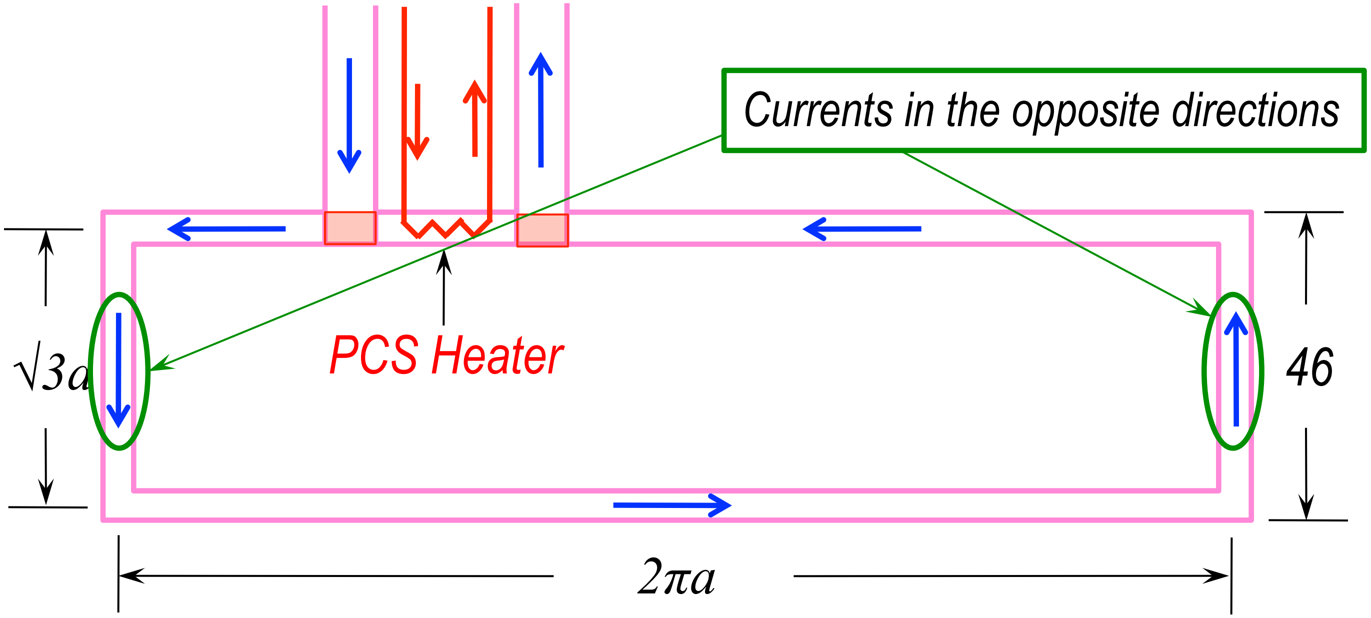
H50—Bi2223 DP
assembly used in
Phase 3A of 1.3G





$Z1$ Shim Coil: Cut from 46-mm Wide YBCO/RABiTS Tape

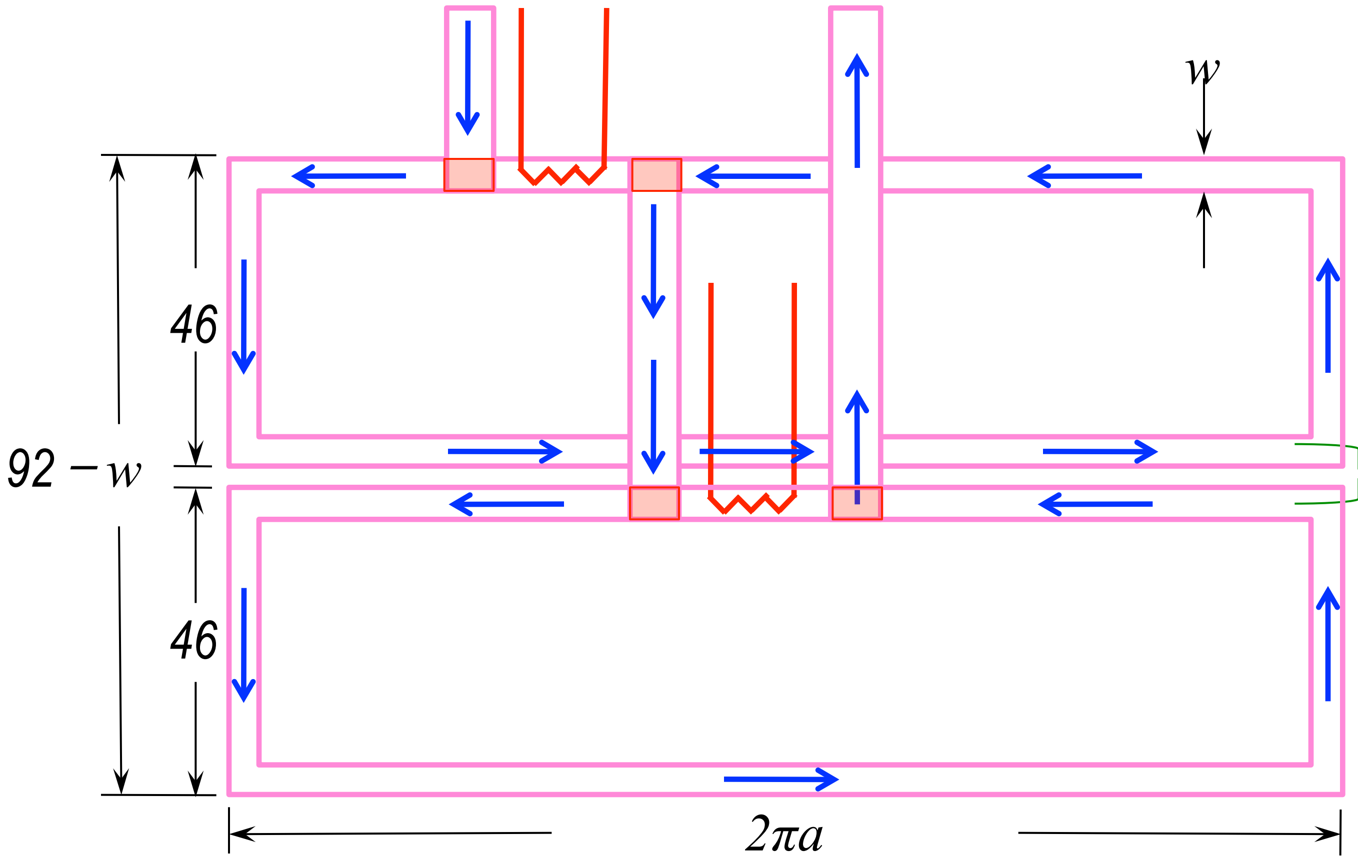




Currents in the opposite directions

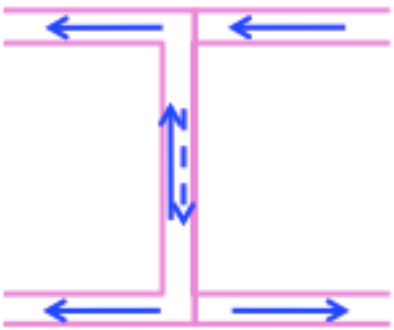
Variations of $Z1$ Shim Coil With 46-mm Wide Tape (cont.)

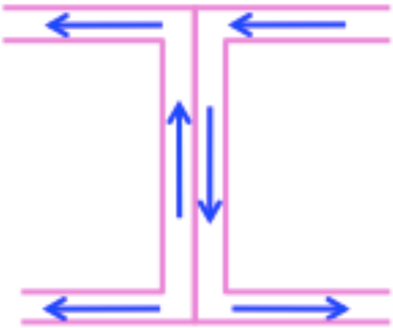
Axially Longer ($\sqrt{3}a > 46$ mm, e.g., 92 mm $- w$)

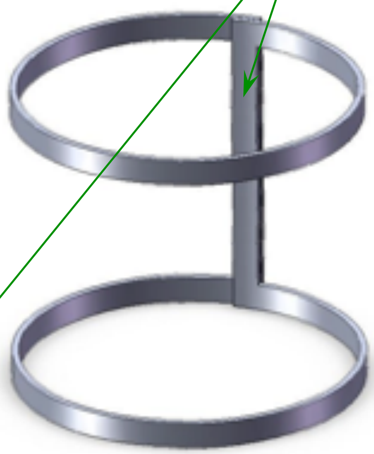


Two horizontal segments ($\pm I$) overlapped

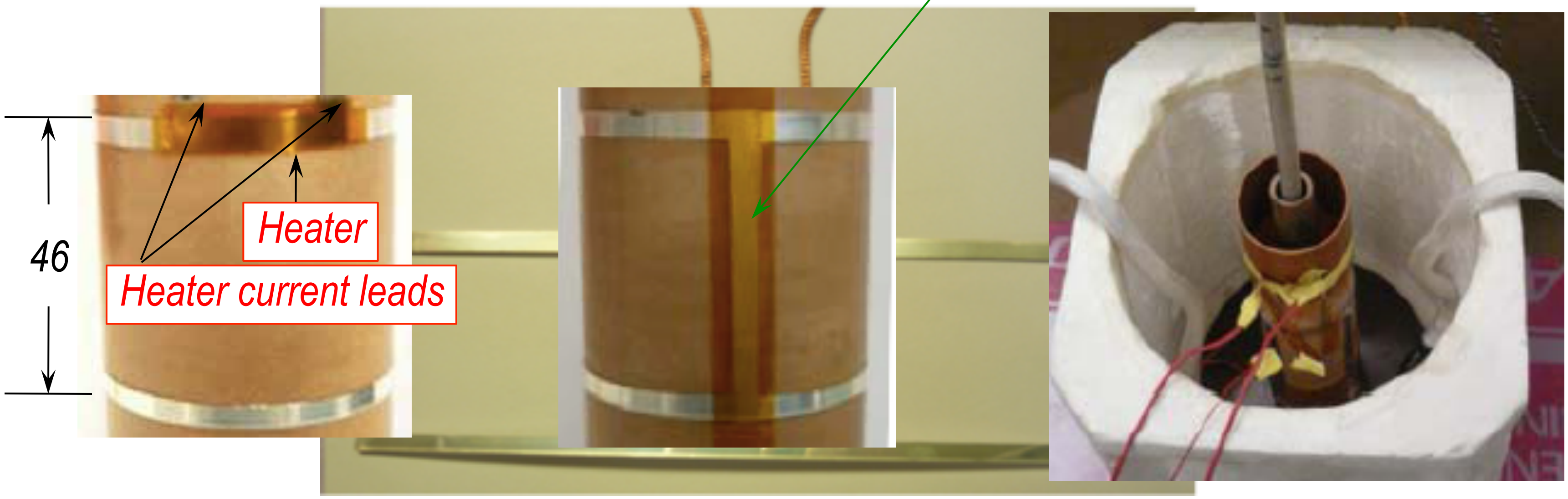
Two Options to Merge Vertical Ends


Overlapping


Side-By-Side

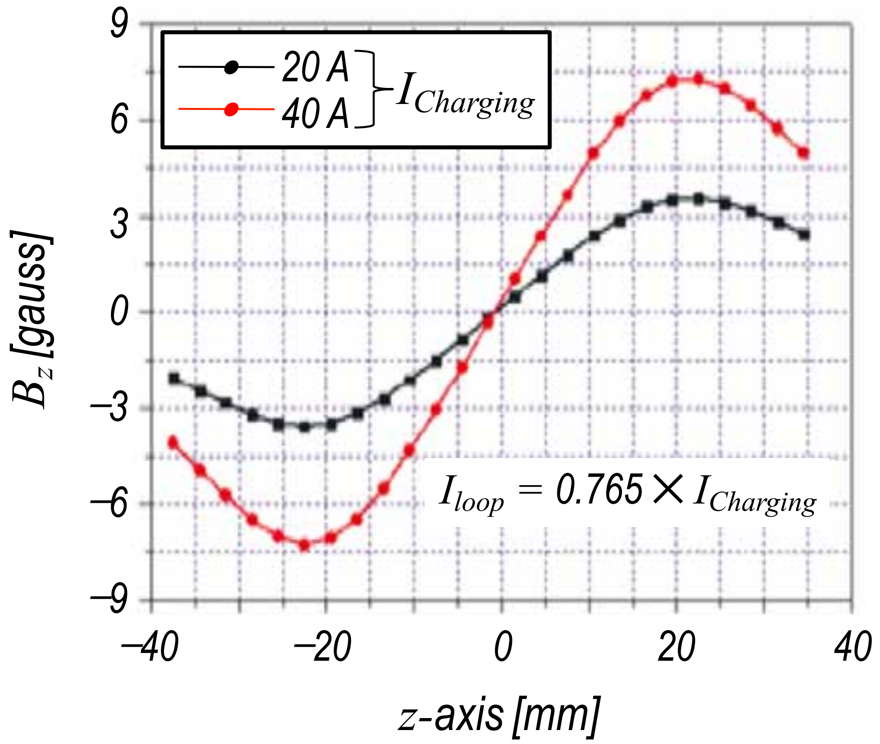


A Small Prototype $Z1$ Shim

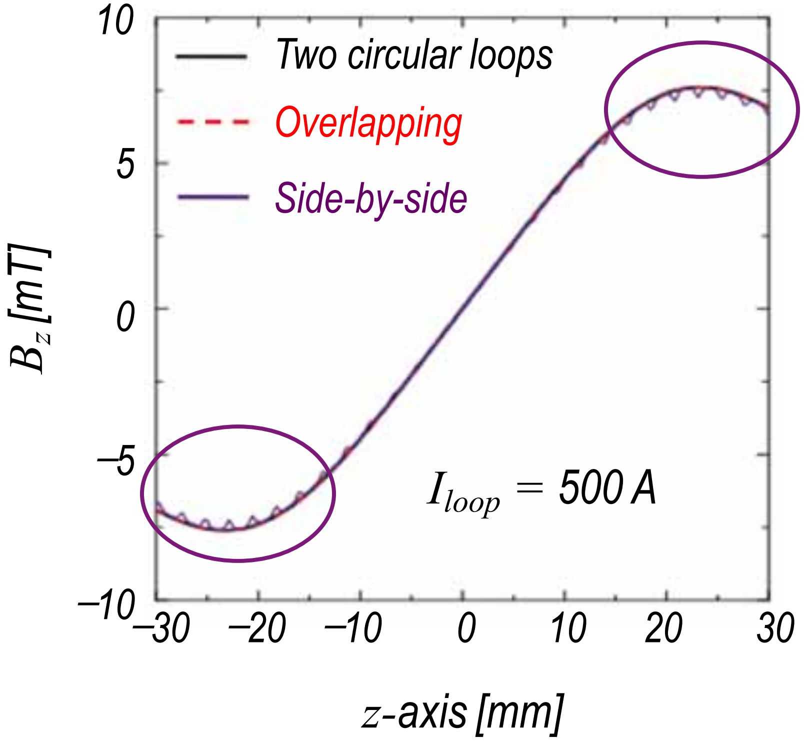


Results

Experiment



Computation



- $I_{loop} / I_{charging} \propto L_{heated} / L_{coil}$

- *Overlapping: Virtually ideal*
- *Side/side: higher harmonics errors*

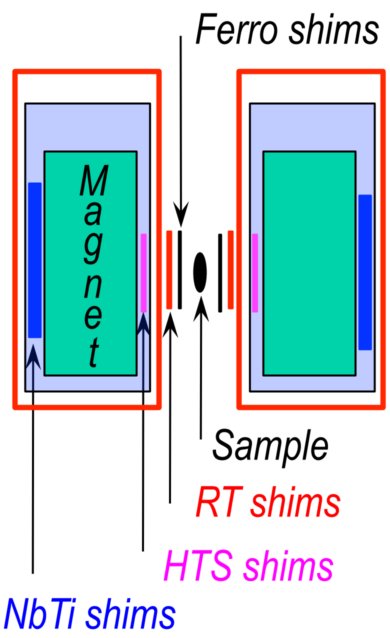
Conclusions

Unique Features of HTS Shim Coils

- Only YBCO coils that can operate in persistent mode
- Placeable, like RT coils, close to the magnet center, i.e., sample location (> 12 T) where NbTi shim cannot operate
- > 10 K operation capability—useful for LHe-free magnets
- More compact than NbTi shims

Market Prospect

- Niche market for NMR magnets:
  - high-field;
  - LHe-free



1st-Cut Design of a 100-T DC HTS Magnet

- Review of high-field magnet techniques
  - DC (Copper) & Pulse (Steel)
  - Pulse (Ag/Steel)
- Why > 40 T ***DC*** magnets feasible only with HTS
- A 100-T ***DC*** HTS magnet: first-cut design
- A Plan to achieve a 100-T ***DC*** HTS magnet
  - Key parameters of 1st – cut 40-T, 50-T, 60-T ***DC*** HTS magnets
- Conclusions

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Why ***DC*** *Field?*

"My own thoughts ran in the direction of producing
constant *magnetic fields.**
There are many experiments that are extremely difficult or impossible
to perform in a hundredth of a second." (c. 1930)

Francis Bitter, *Magnets: The Education of a Physicist* (Doubleday, 1959)

** Unlike pulse (1920s—1930s) fields of Peter Kapitza*

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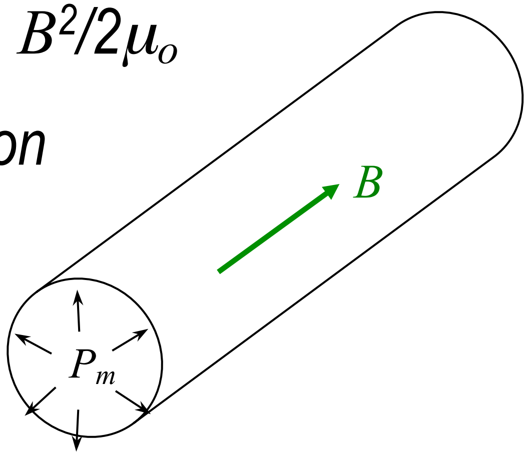
Three Most Important Issues for *High-Field* Superconducting Magnets

- *Superconductor—critical current density,* $J_c(B)$
- *Mechanical integrity—magnetic pressure,* $B^2/2\mu_o$
- *Protection—to ensure repeatable operation*

$$\frac{E_m}{\text{Volume}} = \frac{B^2}{2\mu_\text{o}} = P_m$$



B [T]	P_m [MPa]	σ_y [MPa] of selected metals
10	40	Cu: 70
25	250	"1/2 hard" Cu: 280
50	1000	Austenitic steel: 900
75	2250	Hastelloy 700 316LN: 1400 (@ 77 K)
100	4000	

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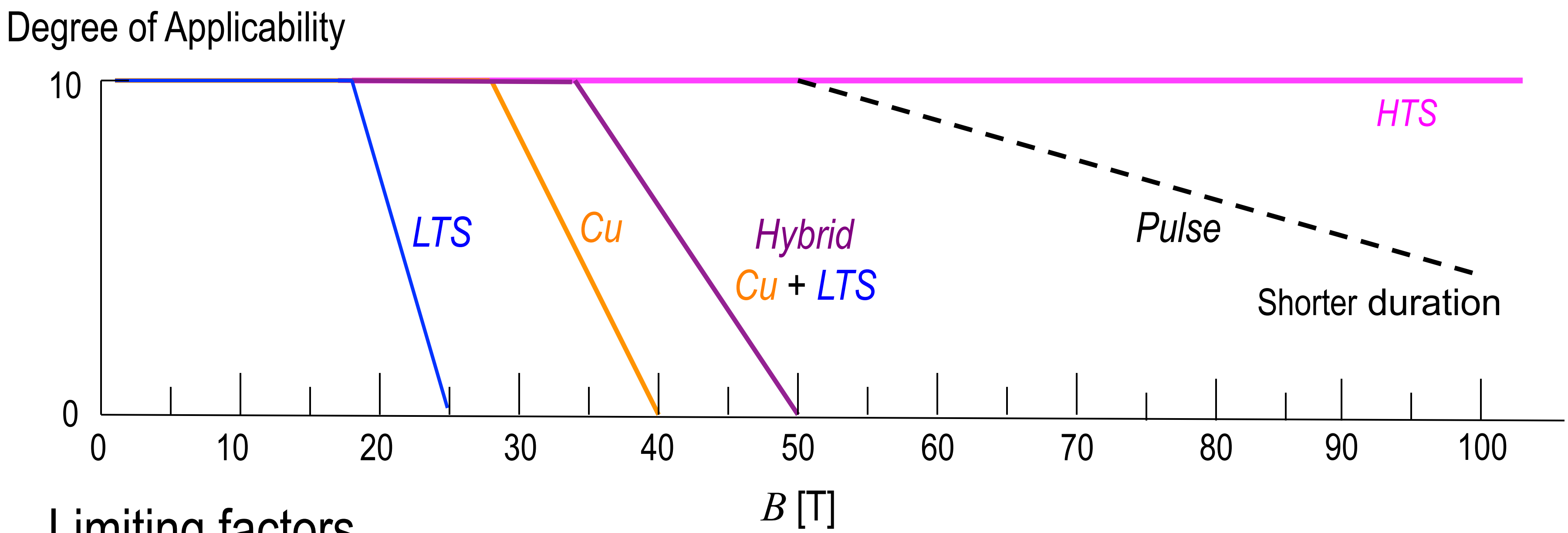
High-Field Magnets



Limiting factors

LTS: $J_c(B)$

Cu: Material strength of copper and copper alloys; Power

Hybrid: Combination of Cu & LTS

Pulse: Material strength of high-strength steel alloys; Power

HTS: $J_c(B)$; material strength of reinforcement steel alloys

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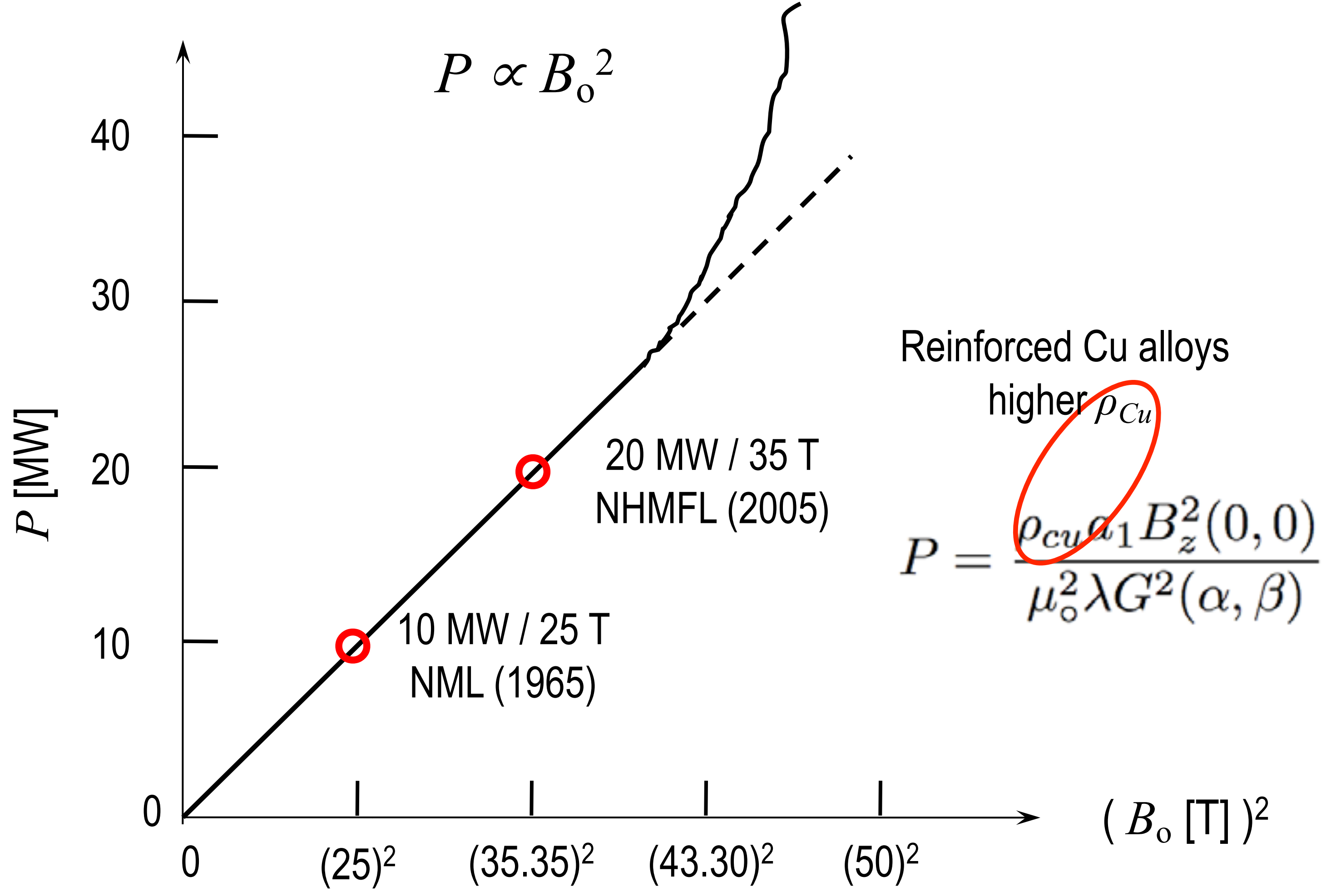
Copper Magnet



Reinforced Cu alloys
higher ρ_{Cu}

$$P = \frac{\rho_{cu}\alpha_1 B_z^2(0,0)}{\mu_o^2 \lambda G^2(\alpha,\beta)}$$

- Cooling power of the same enormous magnitude must match P
- < 40 T likely a limit

Why a Large Steel Magnet must be of a Short Duration?

Power density, p [W/m^3] = $\rho_{cd} J^2$

Field duration Δt to keep conductor temperature rise ΔT, under adiabatic Joule heating density of $\rho_{cd} J^2$:

$$\Delta t \leq \frac{c_p \Delta T}{\rho_{cd} J^2}$$

Illustration

c_p = 4 x 10^6 J/m^3 K;
ΔT = 100 K;
ρ_{cd} = 10^{-6} Ωm;
J = 2 x 10^8 A/m^2:

Δt = 10 ms

Selected Pulse Magnets

Location	B_o [T]	Bore [mm]	Δt [ms]
Tokyo U	200*	5	<0.001
Los Alamos	100	15	< 0.1
Dresden	100	20	10
Toulouse	73	15	10
Leuven	70	10	8
Osaka	70	10	7
FBML (<1990)	65	13	7
Nijmegen	60	23	5

** One-shot—destructive—magnet, i.e. unprotected*

Why a Silver/Steel 1-s High-Field Magnet Impractical?

Power density, p [W/m^3] $= \rho_{cd} J^2$

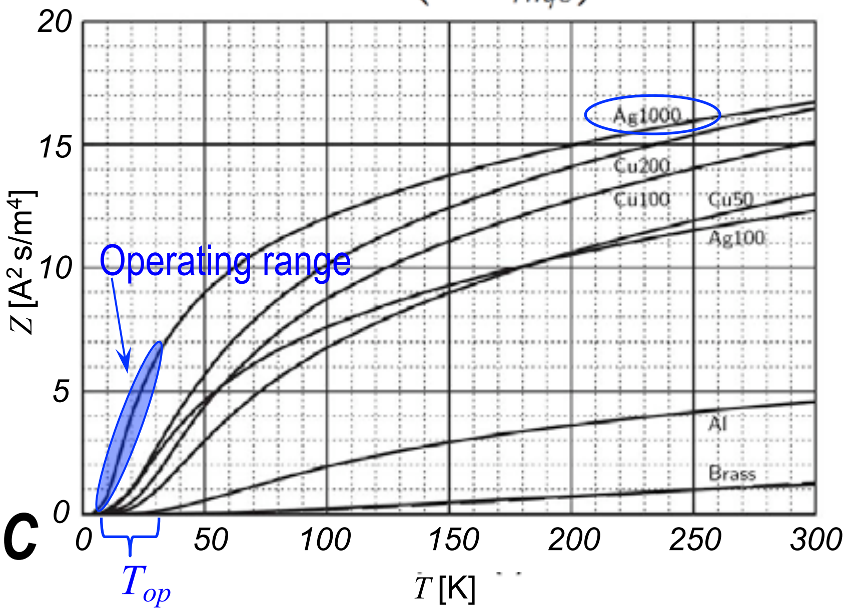
To limit T_{op} of a silver/steel magnet in the range 4.2-30 K (*to keep silver resistance constant*) over a period of ~1 s (τ_{ah}), under adiabatic heating, $J_{m_\circ} = 250 \times 10^6$ A/m^2, or $\lambda J \leq 200 \times 10^6$ A/m^2

Silver

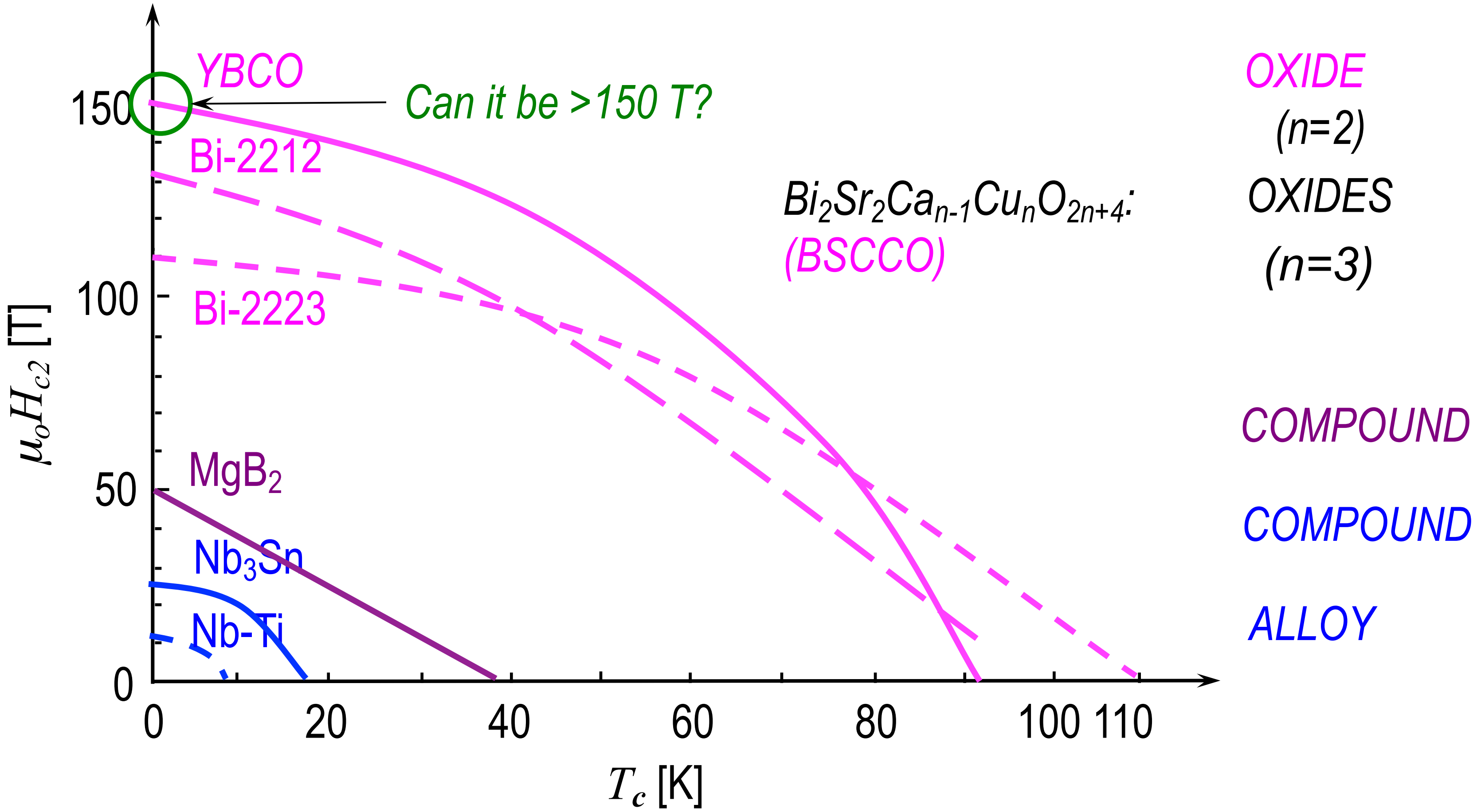
$$Z(T_f, T_i) \equiv \int_{T_i}^{T_f} \frac{C_m(T)}{\rho_m(T)}\, dT = \left(\frac{\gamma_{m/s}}{1+\gamma_{m/s}}\right) J_{m_\circ}^2 \tau_{ah}$$

With $(\lambda J)_{\max} = 200 \times 10^6$ A/m^2, a ballpark design shows that a 50-T/***10 mm*** cold bore 1-s silver/steel magnet will require a power of ***>>10 MW***, and ***the same*** **cooling power at 4.2 K**: ***Impractical!***

$(\lambda J)_{\max} > 200 \times 10^6$ A/m^2,
feasible with an HTS magnet:
Size "*practical*" and, most importantly, in ***DC***



$\mu_o H_{c2}$ vs. T_c Plots for LTS & HTS



- With YBCO, a 100-T HTS magnet *not inconceivable*

Field Generation

$$B_\circ = \mu_\circ \lambda J a_1 F(\alpha,\beta) \qquad F(\alpha,\beta) = \beta \ln\left(\frac{\alpha + \sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}}\right)$$

Illustration

$B_\mathrm{o} = 100$ T

$\mu_\mathrm{o} = 4\pi \times 10^{-7}$ H/m

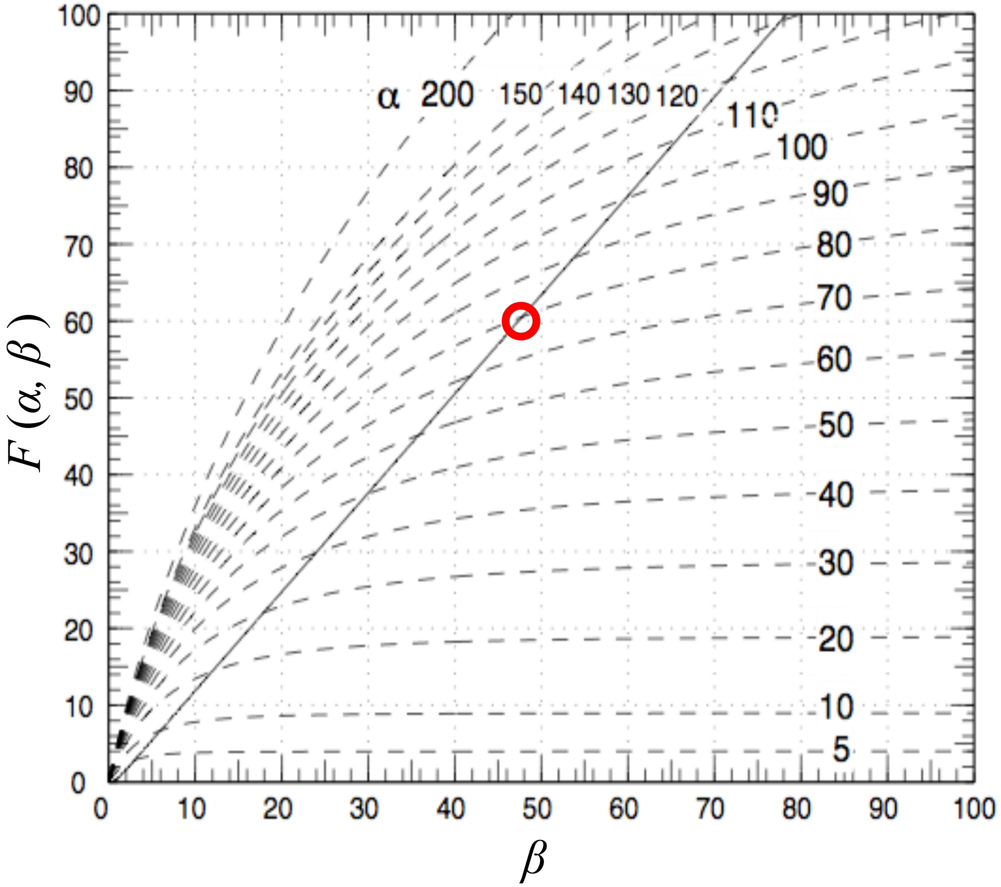
$2a_1 = 10$ mm (winding i.d.)

$\lambda J = 270 \times 10^6$ A/m^2 (overall current density)

$F(\alpha, \beta) \sim 60$

$\alpha = 80$; $\beta = 47$ (minimum volume)

$2a_2 = 800$ mm; $2b = 470$ mm



- Even for a 10-mm bore, a 100-T magnet is “large”

- Because $\lambda J = 270 \times 10^6$ A/m^2 unsustainable (because of stresses) over the entire winding *without reinforcement*, a real 100-T magnet *much* bigger

Why a Large Magnet must be of a Nested-Coil Assembly?

- Conductor grading—standard procedure for LTS magnets
- Hoop stress, σ_θ, particularly for high-field magnets

$$\sigma_\theta = \frac{\lambda J B_1 a_1}{\alpha - 1}\left\{(\alpha-\kappa)\left[\frac{2+\nu}{3}\left(\frac{\alpha^2+\alpha+1+\alpha^2/\rho^2}{\alpha+1}\right)-\frac{1+2\nu}{3}\rho\right] - (1-\kappa)\left[\frac{3+\nu}{8}\left(\alpha^2+1+\frac{\alpha^2}{\rho^2}\right)-\frac{1+3\nu}{8}\rho^2\right]\right\}$$

- $\sigma_{\theta max}$ occurs at $\rho = 1$ $(r = a_1)$
- For most nested coils, $\kappa \sim 0.9$,

  $\sigma_{\theta max} >> \lambda J B_1 a_1$ for $\alpha > 3$

  $\sigma_{\theta max} > \lambda J B_1 a_1$ for $\alpha > 1.2$

  $\sigma_{\theta max} \approx \lambda J B_1 a_1$ for $\alpha \approx 1$

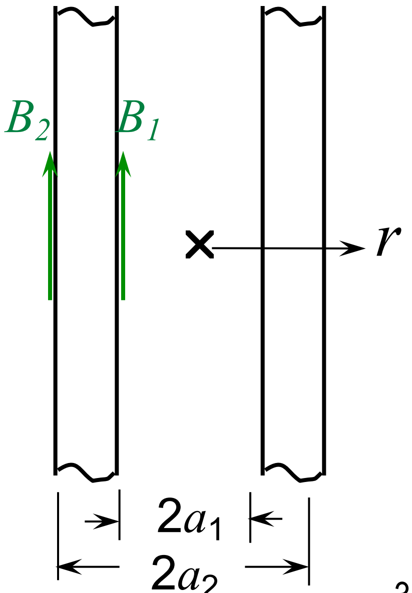
  $\sigma_{\theta max} \approx 51\, \lambda J B_1 a_1$ for $\alpha \approx 80$ $(\kappa \approx -0.1)$

$\alpha = 2a_2/2a_1$

$\rho = r/a_1$

$\kappa = B_2/B_1$

$\nu =$ Poisson's ratio
~ 0.3

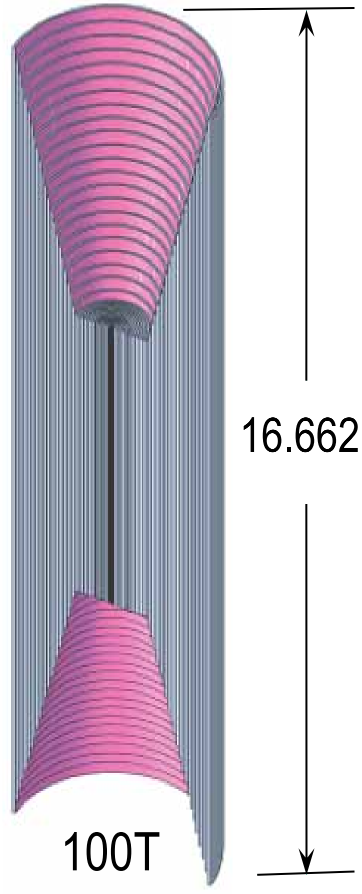


Basic Design Approach

- Nested-coil formation, each coil (mostly $\alpha \cong 1$) of HTS tape and high β (to reduce its $B_{// c\text{-}axis}$ field), i.e., minimum-volume approach unsuitable
  - SuperPower 12-mm wide, 0.095-mm thick (0.050-mm thick Hastelloy) GdBCO tape used in a 39-double-pancake (DP) coil assembly
  - *Overbands* of high-strength SS tape of "large" thicknesses, to limit conductor strains (<0.6%) and keep radial strains against large magnetic stresses
- No-insulation winding technique, now being developed at MIT
  A promising technique to make GdBCO DP coils: 1) mechanically robust; 2) high λJ (efficient); 3 self-protecting—proven, with small GdBCO DP coils
  - Further R&D: 1) with larger NI DP coils; 2) under fault-mode conditions

A 100-T ***DC*** GdBCO (12 mm × 95 μm) Magnet: 1st - Cut Design

— Cold bore: 20 mm; 4.2 K (close-loop) —



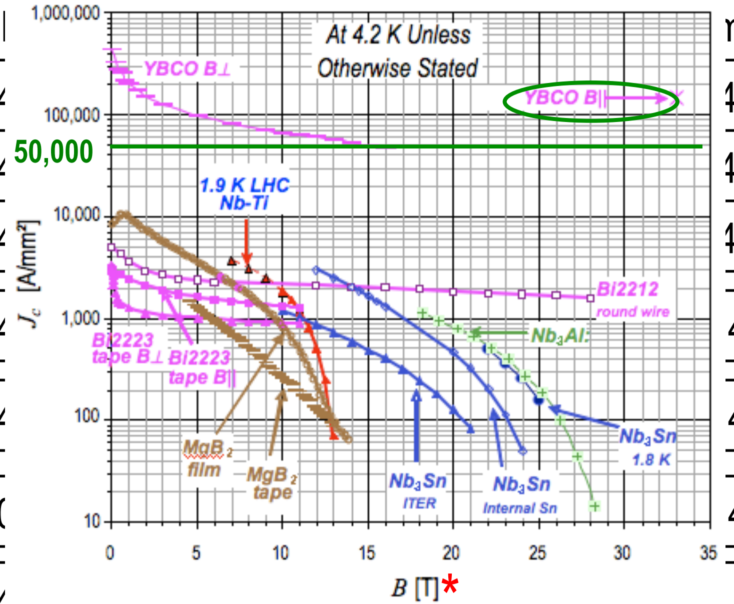
Center field [T]	100
Outer diameter / height [m]	5.6 / 16.7
# Nested Coils	39
# DP Coils	14,589
# Joints	14,588
Maximum tape length/DP [m]	2,973
Total 12-mm wide tape length [km]	12,367
I_{op} [A] / # Parallel tapes (@600 A)	2400 / 4
$[\lambda J]_{overalwinding}$ [A/mm^2]	30.9
Inductance [kH]	42.4
E_{mag} @I_{op} [GJ]	122
Charging time @400 V [day]	2

- Each coil requires "thick" overbands of high-strength stainless steel
- No Insulation winding technique: make 100T self-protecting

Table 1A: 100-T ***DC*** GdBCO Magnet—1st-Cut Design

— I_{op}= 2400 A (4 × 600 A); T_{op}= 4.2 K; L= 42.4 kH; E_{mag}= 122 GJ —

Coil	$2a_1$ (a_2-a_1) [mm]	α / β	λJ [A/mm^2]	B_{max} [T]	# Turns/ DP (#	# Total	Length (12-mm)	Total (12-mm) n]
1	20 (5.3)	1.53000 / 301	520.8	100.0	28 (24			4
2	60.6 (5.3)	1.17492 / 99.3	520.8	96.5	28 (24			4
3	101.2 (6.4)	1.12648 / 59.4	520.8	93.0	34 (24			4
10	833.4 (4.9)	1.011876/ 7.22	520.8	67.0	26 (24			4
15	1634.0 (3.4)	1.00416 / 3.68	520.8	53.5	18 (24			4
20	2430.8 (2.6)	1.00214 / 3.00	520.8	44.0	14 (30			4
37	5199.2 (5.3)	1.00204 / 3.00	520.8	13.1	28 (64		*	4
38	5371.0 (8.3)	1.00309 / 3.00	520.8	9.8	44 (665)	29260	743.6*	494.475 × 4
39	5549.0 (7.6)	1.00274 / 3.00	520.8	4.6	40 (687)	27480	698.3*	479.700 × 4



$2a$ = 5.6 m; $2b$ = 16.7 m

Total length (12 mm): 10,100 km

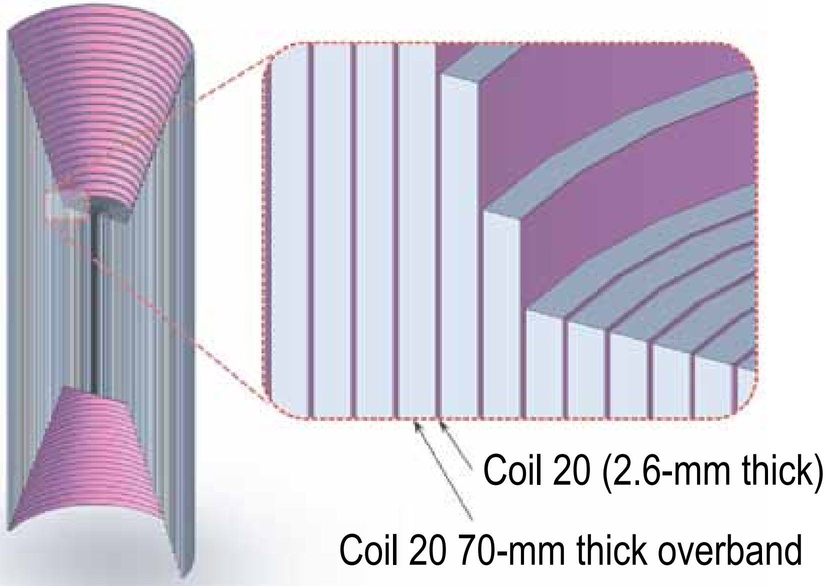
- J_c = 50,000 A/mm^2 I_{op} = 600 A @4. 2 K and 100 T (Coil 1) for GdBCO layer thickness 1-μm, i.e., GdBCO layer area: 12 mm × 0.001 mm—If needed, GdBCO layer to 2-μm thick

* Longer than longest GdBCO tape readily available now: a *challenge*

Table 1B: 100-T ***DC*** GdBCO Magnet—1st-Cut Design

— I_{op}= 2400 A (4 × 600 A); T_{op}= 4.2 K; L= 42.4 kH; E_{mag}= 122 GJ —

Coil	$2a_1$ / $(a_2$-$a_1)$ [mm]	Radial Gap [mm]	SS Overband Thickness [mm]	B_1 @ a_1 [T]	κ	$\sigma_{\theta max}$ [Mpa]	Overband σ_θ [MPa]
1	20.0 / 5.3	15.0	10	100.0	0.97	398 *	270
2	60.6 / 5.3	15.0	10				
3	101.2 / 6.4		20				
19	2272.2 / 2.6	76.7	Coils 11-39 70				
20	2430.8 / 2.6	77.0					
21	2590.0 / 2.7						
37	5199.2 / 5.3	80.6					
38	5371.0 / 8.3	80.7					
39	5549.0 / 7.6						

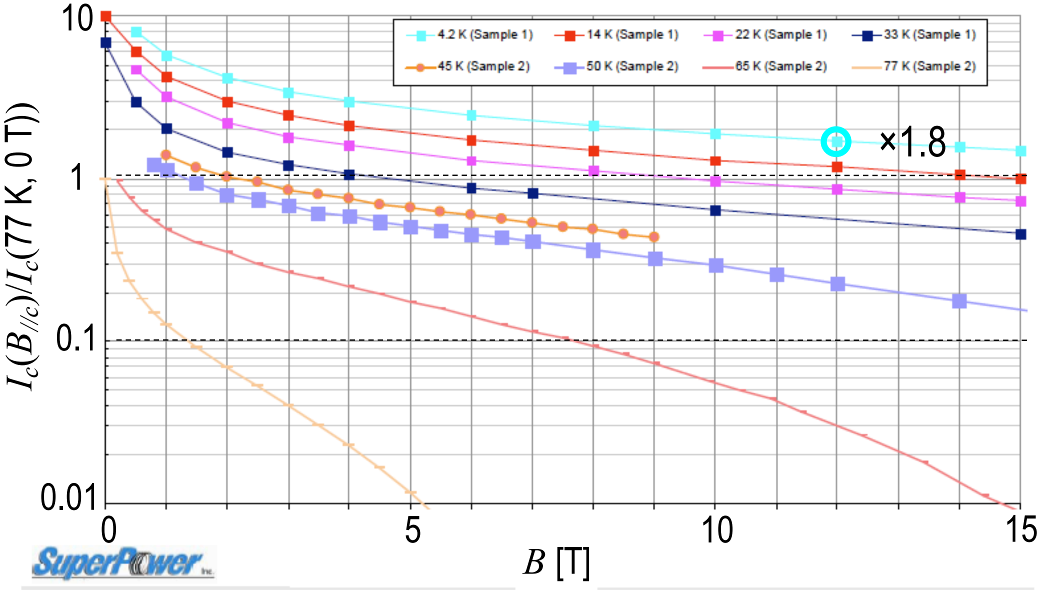


* To compensate for the maximum winding strain of 0.27%;
Total strain at 398 MPa: 0.60% (=0.27% + 0.33%)
Young's modulus: GdBCO (12 mm × 0.095 mm): 120 GPa;
Young's modulus: stainless steel: 200 GPa

Table 1C: 100-T ***DC*** GdBCO Magnet—1st-Cut Design

— I_{op}= 2400 A (4 × 600 A); T_{op}= 4.2 K; L= 42.4 kH; E_{mag}= 122 GJ —

Coil	$2a_1$ / β [m]	$B_{r\,max}$ / B_z @$B_{r\,max}$ [T]
1	0.0200 / *300*	1.9 / 80.4
2	0.0606 / *99.3*	3.5 / 77.5
37	5.19 / *3.0*	9.7 / 13.1
38	5.37 / *3.0*	11.4 / 9.8
39	5.55 / *3.0*	9.9 / 4.6

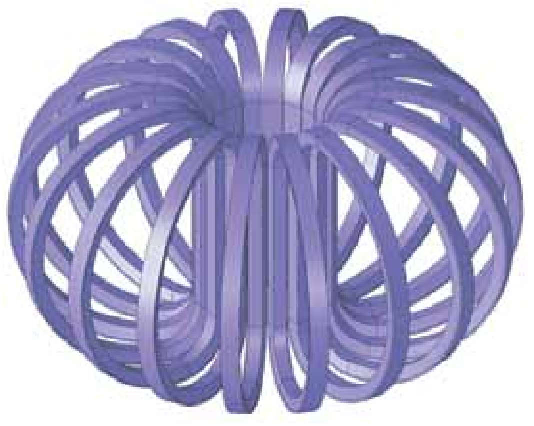


- $B_{r\,max}$ = 11.1 T (Coil 38) I_c down to ×1.8 I_c (77 K); probably OK
- For β = 100 (Coil 1), $B_{r\,max}$ = 1.9 T
  - $B_{r\,max}$ always reducible ➔ $B_{r\,max}/B_{center} = 0$ for $\beta = \infty$
  - Penalty: Taller magnet & more conductor
- 100-T: β = 3 (outer coils) ➔ a huge magnet; tons of conductor: but ***feasible***

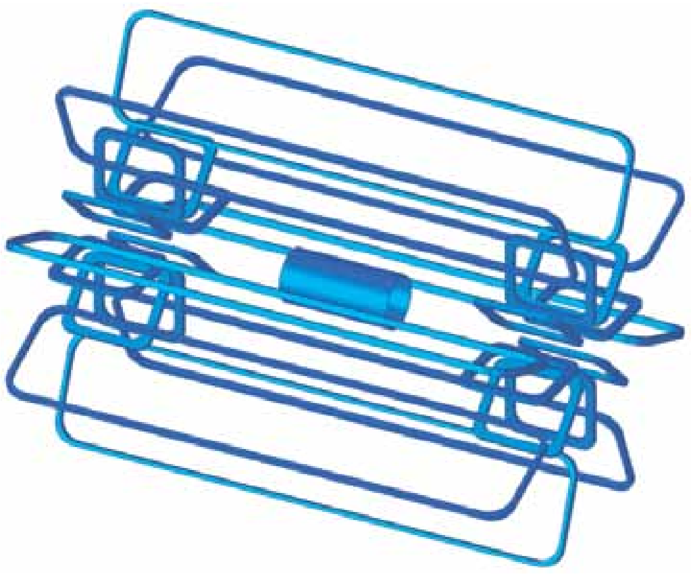
Comparison

Magnet	Superconductor	Conductor Tonnage	Magnetic Energy [GJ]
100T	GdBCO	125	122
ITER TF	Nb_3Sn	410	41
LHC ATLAS	NbTi	360	10

100T



ITER TF



LHC ATLAS

A Plan

Proceed in steps: 40-T; 50-T; 60-T, 70-T; 80-T; 90-T; finally 100-T

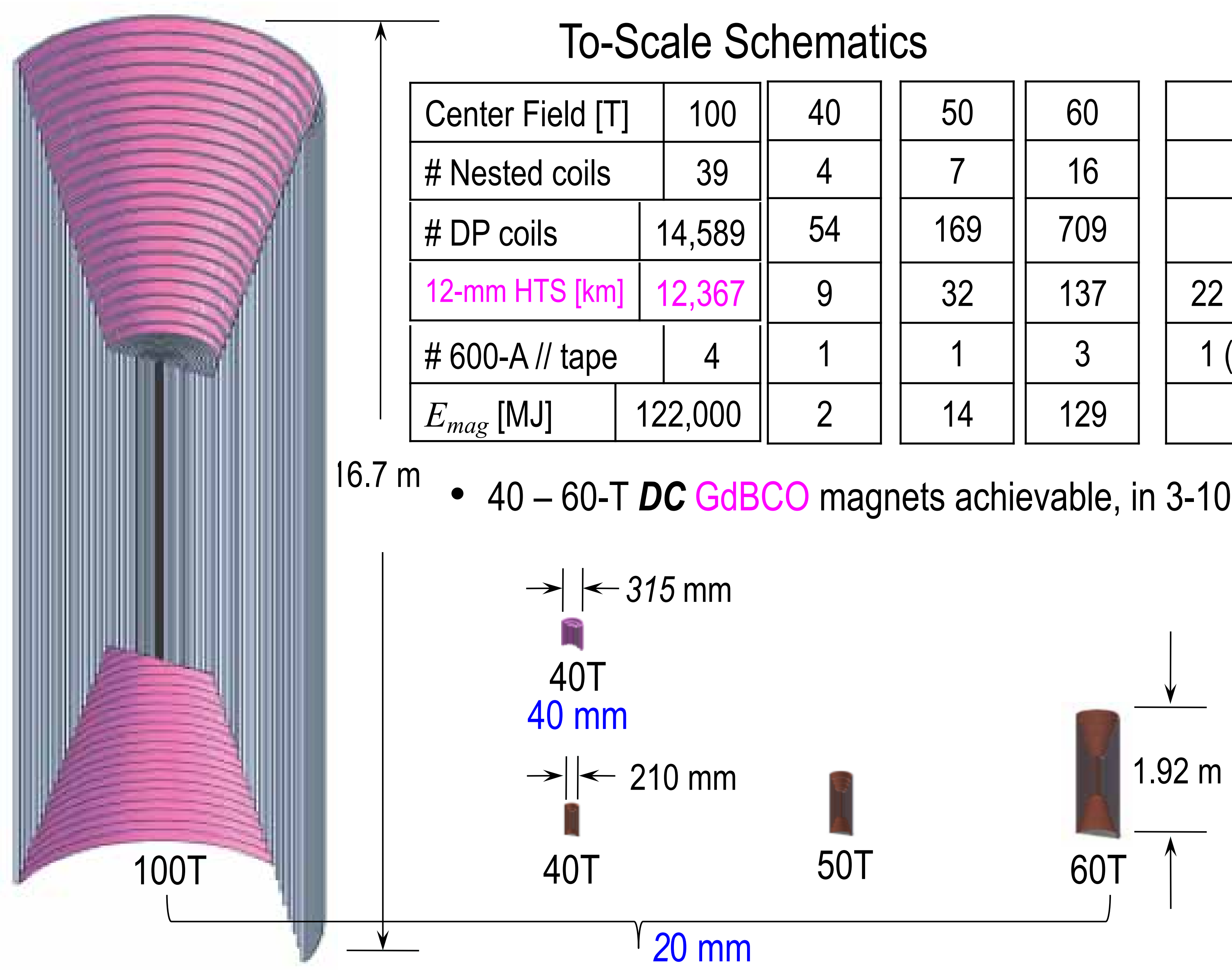
In each step:

- Nested-coils are stressed ~equal to those expected in a 100-T magnet
- Test (& further develop) overbands reinforcement technique
- Test (& further develop) NI winding technique
- Measure GdBCO performance
- If required, modify basic design approach

To-Scale Schematics

Center Field [T]	100	40	50	60	40
# Nested coils	39	4	7	16	6
# DP coils	14,589	54	169	709	168
12-mm HTS [km]	12,367	9	32	137	22 (6-mm)
# 600-A // tape	4	1	1	3	1 (302 A)
E_{mag} [MJ]	122,000	2	14	129	3

- 40 – 60-T ***DC*** GdBCO magnets achievable, in 3-10 years



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Conclusions

- A 100-T ***DC*** GdBCO magnet, at least technically, achievable
  - 1st –cut design is what it is: a 1st-cut;
    it obviously requires further design iterations and optimization
- 40 – 60-T ***DC*** GdBCO magnets achievable, in 3-10 years
- Our > 40-T ***DC*** GdBCO magnets, though each only of a 20-mm cold bore (RT bore ~10 mm) offer:
  - Incredibly exciting opportunities in high-field areas in superconducting magnet technology, physics, materials sciences, medical sciences; perhaps even entirely new areas of research
  - Ultimate hallmark of the enabling technology of superconductivity
  - Will have a sweeping impact on superconductivity and most decisively challenge superconducting magnet technology to its utmost limit

Thank you

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