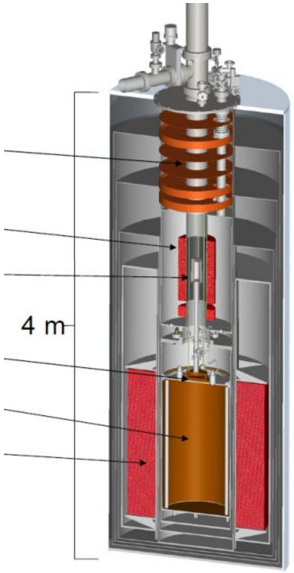
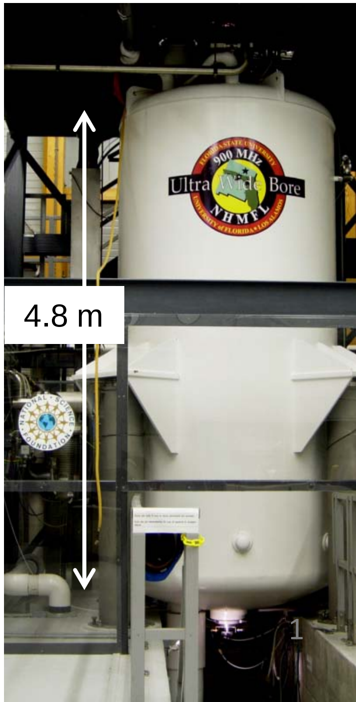


B_0^2V for Solenoids

Mark D. Bird
Director of Magnet Science &
Technology at the National High
Magnetic Field Lab, Tallahassee, FL



B_0^2V for Solenoids

INTRODUCTION TO MAGLAB

TODAY'S SOLENOIDS

THE POTENTIAL OF HTS

SUMMARY

National High Magnetic Field Laboratory

Pulsed Magnetic Field Facility

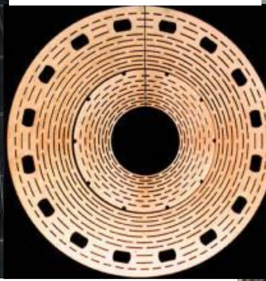
89T Pulse Pulsed Magnet
10msec
15mm bore

Florida State University

Los Alamos National Laboratory

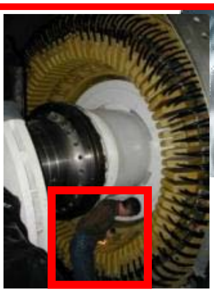
University of Florida

45T Hybrid DC Magnet



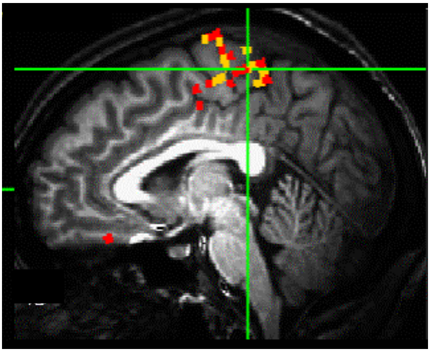
900MHz, 105mm bore NMR/MRI Magnet

1.4GW Motor-Generator



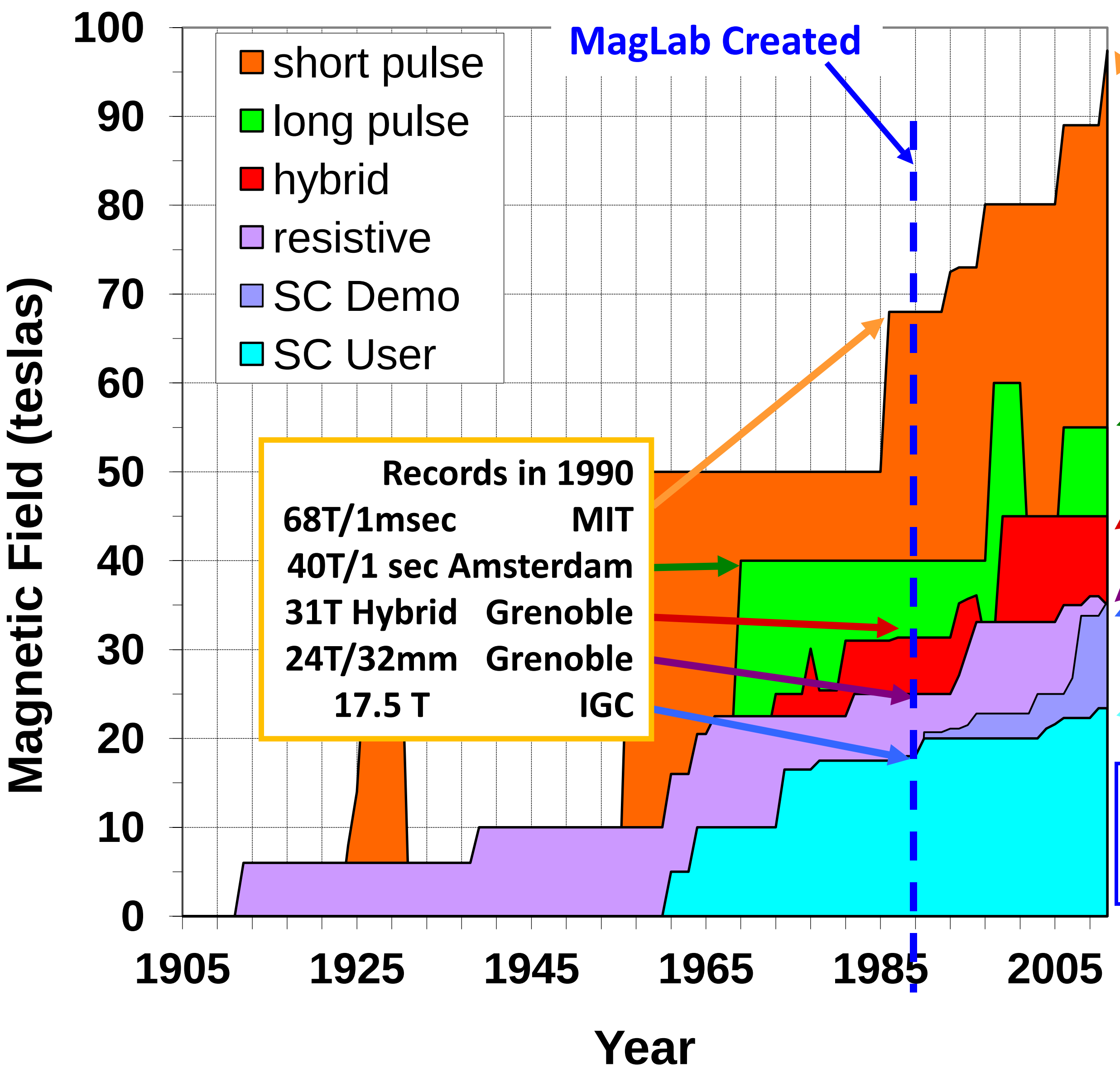
11.4T MRI Magnet
400mm warm bore

Advanced Magnetic Resonance Imaging and Spectroscopy Facility



High B/T Facility
17T, 6weeks at 1mK

MagLab User Program Technology Leads the World



Records in 1990

68T/1msec	MIT
40T/1 sec	Amsterdam
31T Hybrid	Grenoble
24T/32mm	Grenoble
17.5 T	IGC

MagLab Records
100T/1msec, 2012
60T/1 sec, 1998
45T Hybrid, 2000
36T/32mm, 2009
35T=31T+4T HTS
(HTS Test Coil, 2011)

Bruker, NMR
23.4 T, 2009

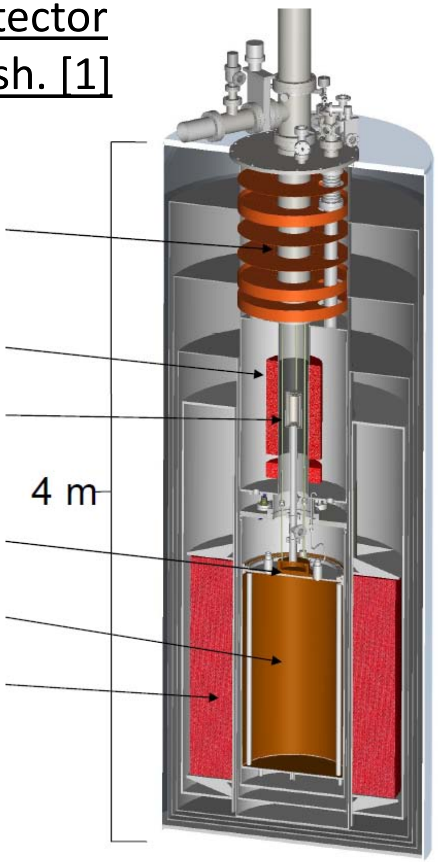
MagLab technology has been adopted by ~20 labs worldwide

Today's Solenoids: ADMX

Axions decay into microwave photons in a strong magnetic field.

MagLab Previous Involvement: Advice on Relocation

Existing Detector
at U. of Wash. [1]



Baffling

Bucking Magnet

SQUID

"1K"Pot

Microwave Cavity

Main Magnet
8 Tesla
600 mm Bore
13 ton

Conversion Microwave photons are detected by one of the world's quietest radio receivers.

$$P_a = g_{a\gamma\gamma}^2 \boxed{V B_0^2} \rho_a C_{lmn} \min(Q_L, Q_a).$$ [2]

Magnet performance is given by:
$\int B^2 dV$

Cavity constrained by
- Field Homogeneity
- Size limited by frequency
- Size limited by cavity technology

[1] Carosi, UCLA Dark Matter, 2/25/2010

[2] Asztalos, et al., PRL, 104 041301 (2010)

Solenoids Present & Future

CICC = Cable-In-Conduit Conductor
SRC = Stabilized Rutherford-Cable
Mono = Monolithic Conductor
Pers = persistent

B_0^2V (T^2m^3)	**B^4 (kT^4)**	**Magnet**	**Application/ Technology**	**Location**	**Field (T)**	**Bore (m)**	**Len (m)**	**Energy (MJ)**	**Cost ($M)**
12000	*29*	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	0.2	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	7	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*19*	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	29	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*3112*	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*12*	*Magnex*	*MRI/Mono Pers*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	8	Magnex	MRI/Mono Pers	Juelich	9.4	0.9	3	190	
70	41	45 T out	HF/Sn CICC	MagLab	14	0.7	1	100	14
12	2	ADMX	Axion/Ti mono/SRC	U Wash	7	0.5	1.1	14	0.4
5	29	900 mod	NMR/Sn mono	MagLab	21.1	0.11	0.6	40	15

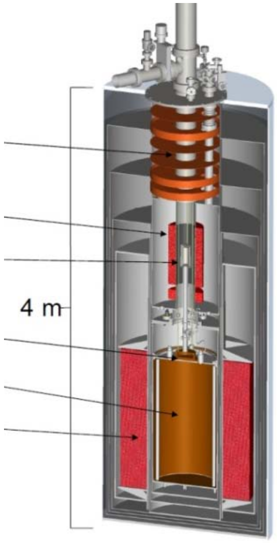
[1] Materials only per BBC/CERN.
[2] US inner module $50M per Minervini

Italics indicates a magnet not yet operational

Today's Solenoids: Monolithic Conductors

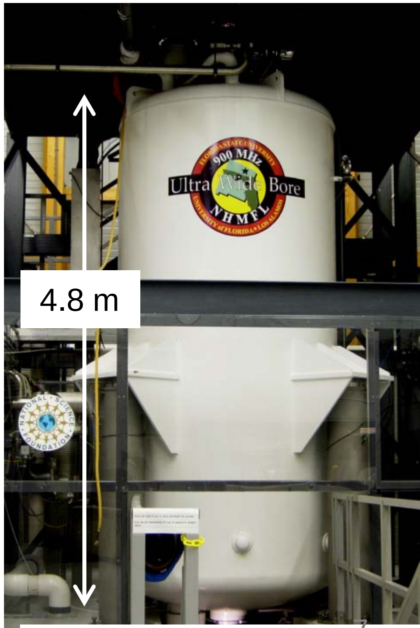
B_0^2V (T^2m^3)	B^4 (kT^4)	Magnet	Application/ Conductor	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
650	7	Tore Supra	Fusion/NbTi	Cadarache	9	1.8	3	600	
250	*12*	*Magnex*	*MRI/NbTi Pers*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	8	Magnex	MRI/NbTi Pers	Juelich	9.4	0.9	3	190	
12	2	ADMX	Axion/NbTi/SRC	U Wash	7	0.5	1.1	14	0.4
5	29	900 mod	NMR/Nb_3Sn	MagLab	21.1	0.11	0.6	40	15

Italics indicates a magnet not yet operational.



ADMX: Axions

Juelich: MRI



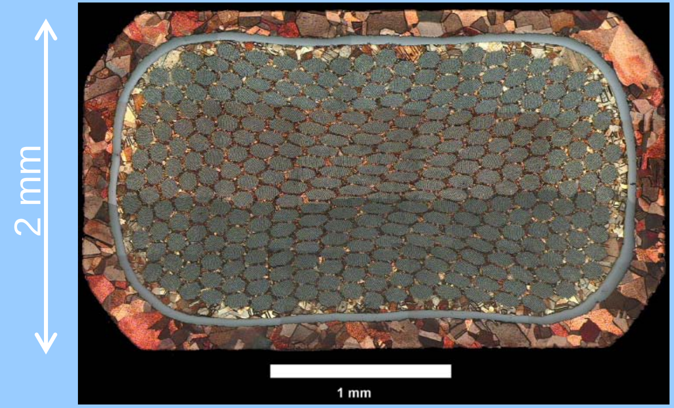
MagLab 900: NMR

Today’s Solenoids: Monolithic Conductors

- Advantages
  - Well-developed Technology.
    - General-purpose “research” magnets.
    - NMR, MRI magnets.
    - ADMX.
    - Commercial suppliers [Magnex (Agilent), Bruker, Oxford, Cryomagnetics, Wang, etc.]
  - NbTi or Nb_3Sn.
  - Persistent Switches Exist.
  - High Homogeneity Possible.

- Dis-advantages
  - Limited to modest currents (<500 A).
  - No Helium, little Cu or Al within coil-pack.
  - Relatively unstable.
  - Quench protection difficult for large systems.

MagLag 900 MHz: 285A, 21.2 T Nb_3Sn rectangular



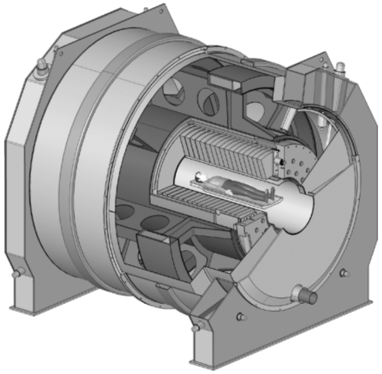
Today's Solenoids: Stabilized Rutherford-Cable

B_0^2V (T^2m^3)	B^4 (kT^4)	Magnet	Application/ Conductor	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
5300	0.2	CMS	Detector/NbTi	CERN	3.8	6	13	2660	>458[1]
430	*19*	*Iseult*	*MRI/NbTi*	*CEA*	*11.75*	*1*	*4*	*338*	
12	2	ADMX	Axion/NbTi/SRC	U Wash	7	0.5	1.1	14	0.4

Italics indicates a magnet not yet operational.

[1] Materials only per BBC/CERN.

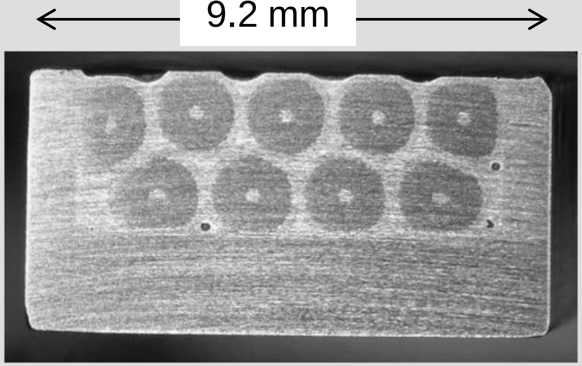
Compact Muon Solenoid



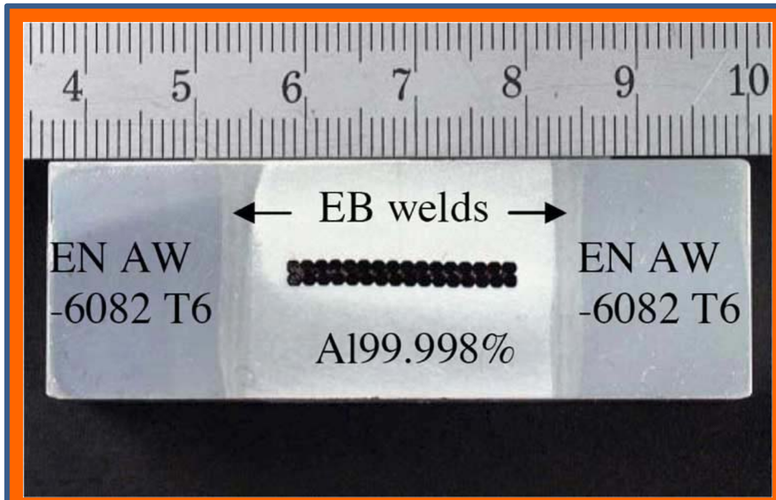
Iseult 11.7 T MRI system (under development)

Stabilized Rutherford Conductor

- Advantages
  - Cable allows higher currents than monolithic.
  - Cu or Al stabilizes & strengthens.
  - Preferred for protection of large magnets (>100 MJ).
  - Used for highest $\sim\int B^2 dV$ magnet completed to-date (CMS).
- Uses
  - Detector Magnets (CMS, ATLAS, etc.)
  - Iseult/Inumac 11.75 T MRI
- Disadvantages
  - Persistent Switches not available (possible?)
  - Used for specialty magnets, one-off fabrication. Limited industrial base. National Labs frequently involved.
  - Al-stabilized only suitable for NbTi.
  - To date: NbTi only. Nb_3Sn Rutherford cables being developed for dipoles and quadrupoles. Not aware that externally stabilized ones exist yet.



Iseult: 1.5 kA, 12 T, NbTi Rutherford cable in Cu stabilizing channel



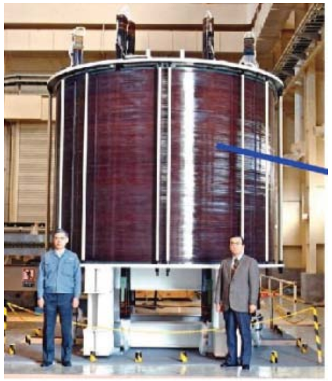
CMS: 19 kA, 4 T, NbTi Rutherford cable in Al co-extruded & welded stabilizing channel

Today’s Solenoids: CICC

B_0^2V (T^2m^3)	B^4 (kT^4)	Magnet	Application/ Conductor	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12,000	*29*	*ITER CS*	*Fusion/Nb_3Sn*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
320	29	ITER CSMC	Fusion/Nb_3Sn	JAEA	13	1.1	2	640	>50[2]
70	41	45 T out	HF/Nb_3Sn	MagLab	14	0.7	1	100	14

Italics indicates a magnet not yet operational. [2]US inner module $50M per Minervini.

MagLab 45 T Hybrid

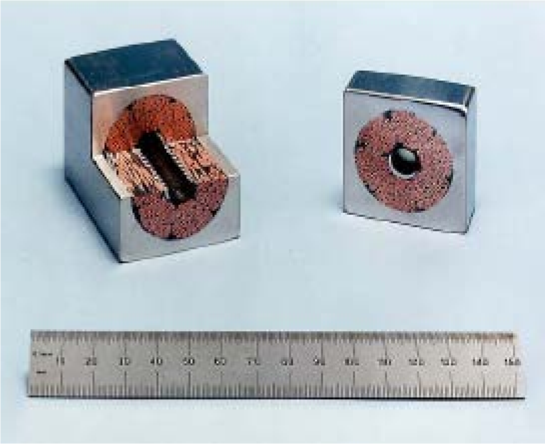


ITER Central Solenoid Model Coil

ITER Central Solenoid

Cable-In-Conduit Conductors

- Advantages
  - Steel conduit provides strength (stress ~jBr).
  - He provides stability (100 W dc possible w/o quench for some designs).
  - Used for highest ~$\int B^2 dV$ magnet attempted to-date (ITER CS).
  - Used w/ NbTi and Nb_3Sn.
- Uses
  - Magnets with disturbances (fusion, hybrid outserts).
- Disadvantages
  - Steel and helium result in relatively low current-density and large coils.
  - Strain-state in Nb_3Sn CICC not well-understood.
  - Limited manufacturing infrastructure, (National Labs).



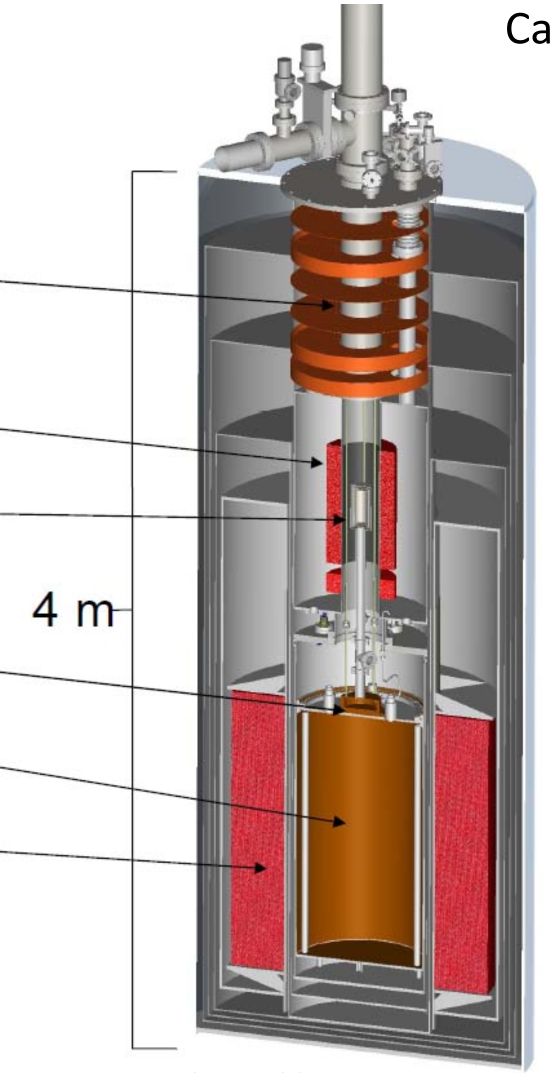
ITER: 50 kA, 13 T, Nb_3Sn CICC

45 T: 10 kA, 15 T, Nb_3Sn CICC

Modify ADMX?

Can we add coils to ADMX to increase $\int B^2 dV$?

Perhaps

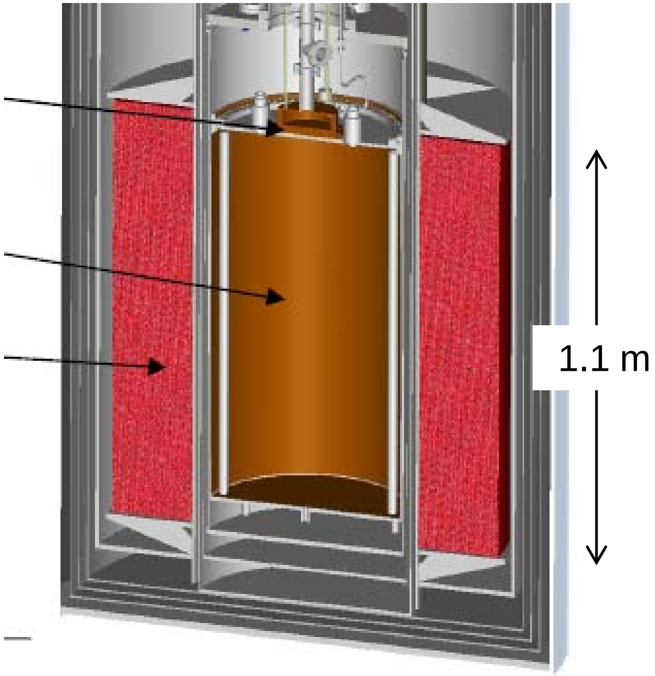


ADMX Magnet
8 Tesla
600 mm Bore
14 MJ

MagLab 900 NMR
21.2 Tesla
110 mm Bore
40 MJ

Modify ADMX?

Can we add coils to ADMX to increase $\int B^2 dV$?

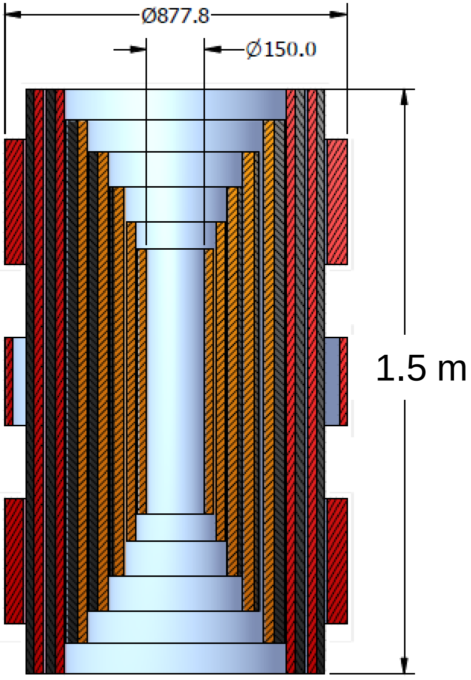


ADMX Magnet

8 Tesla

600 mm Bore

14 MJ



MagLab 900 MHz Ultra-Wide Bore NMR Magnet

21.2 Tesla

110 mm Bore

40 MJ

Coil Dimensions & Field from MagLab 21.2 T NMR

ID (m)	B (T)	L (m)	B_0^2V (T^2m^3)	B^4 (kT^4)
0.64	5.6			
0.56	7.6	1.32	18.8	3
0.47	10.4	1.28	24.5	12
0.40	13.2	1.20	26.3	30
0.33	15.6	1.10	23.5	59
0.26	18	0.95	16.9	105
0.20	20	0.80	9.7	160
0.15	21.1	0.65	5.1	198

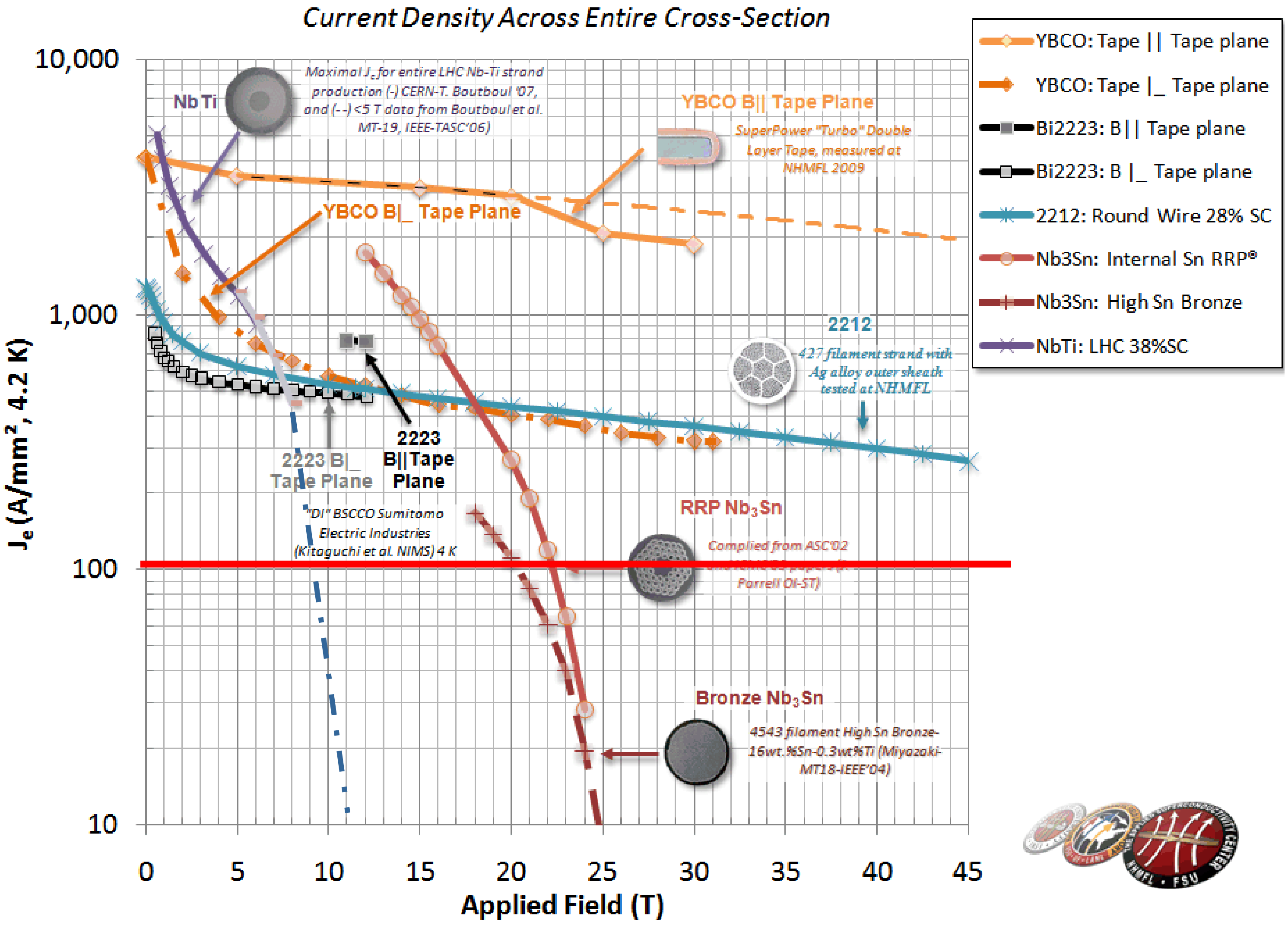
Adding coils might increase performance. Who would do it?

Cavity-Size Constraints

- Cavities longer than a wavelength of the photons are inefficient: 0.3 m length/diameter constraint.
- Present ADMX dimensions: 0.53 m diameter, 1 m length.
- Can cavities be slaved together?
- If not, pursue higher field in the same volume as ADMX.

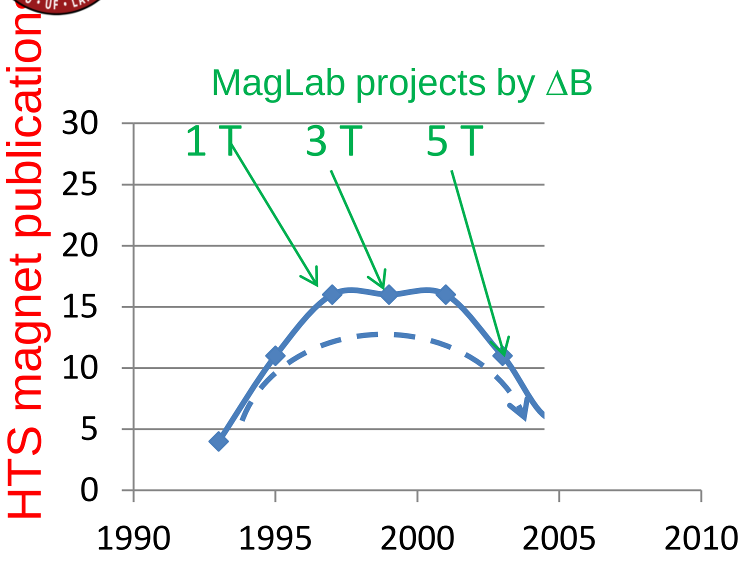
Future Solenoids:

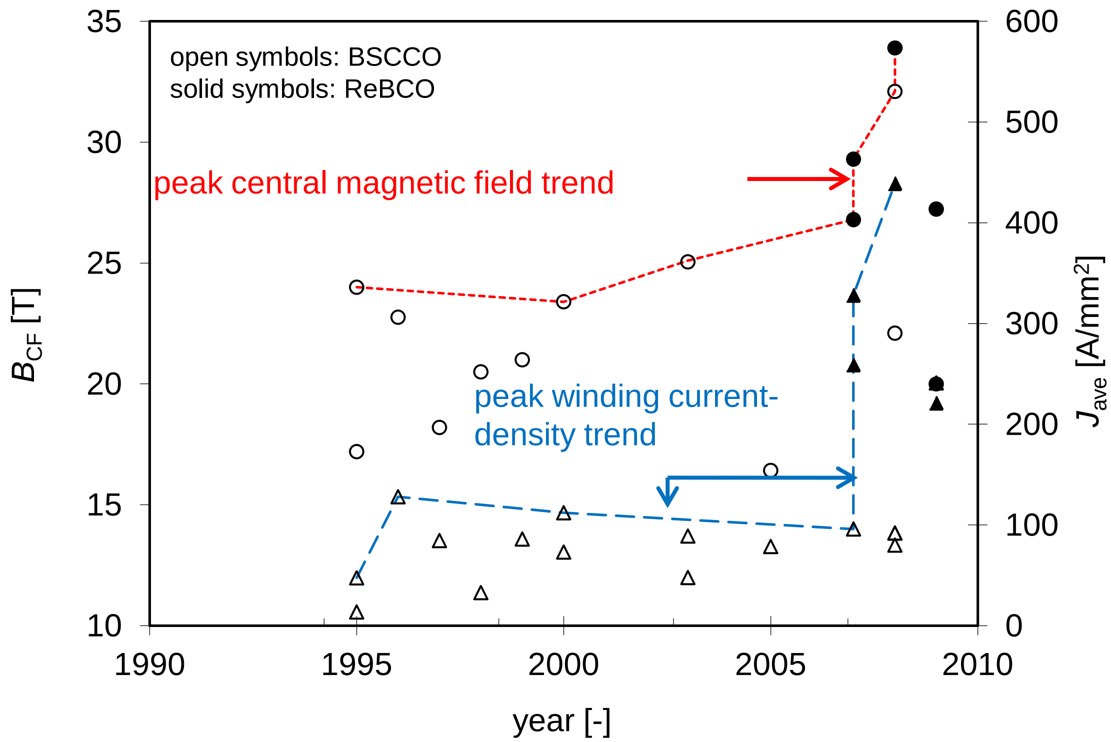
High-Temperature Superconductors

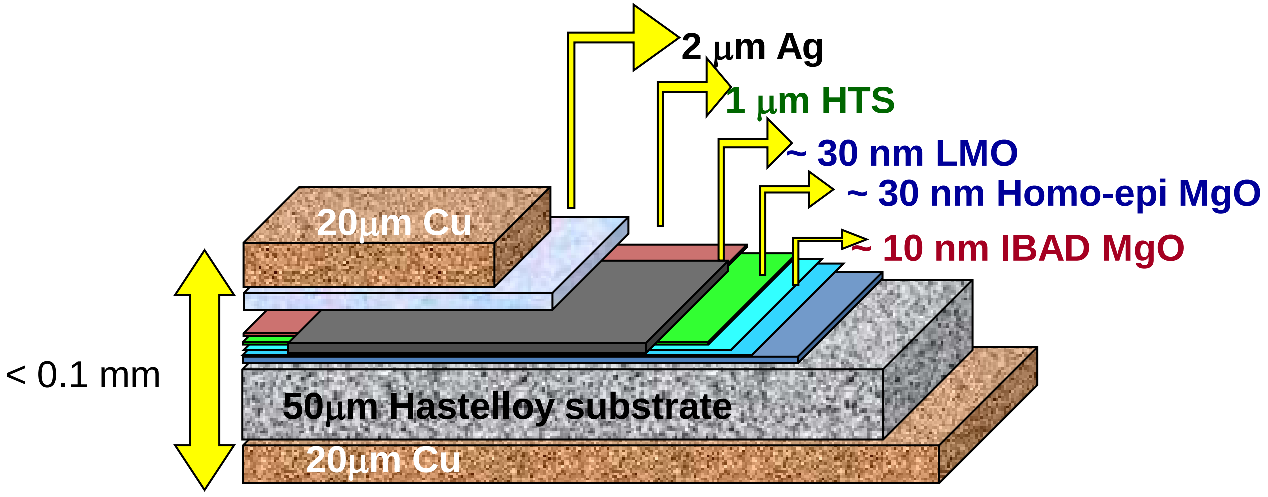


Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

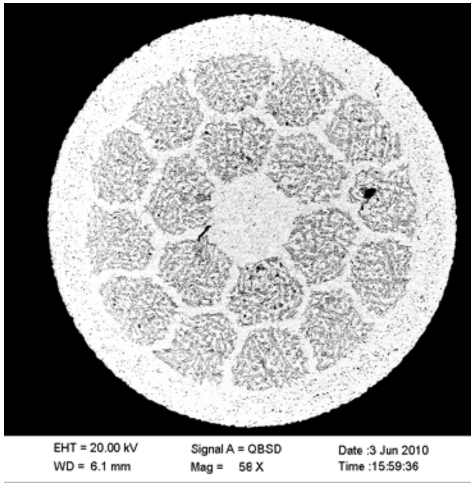
High T_c Coils







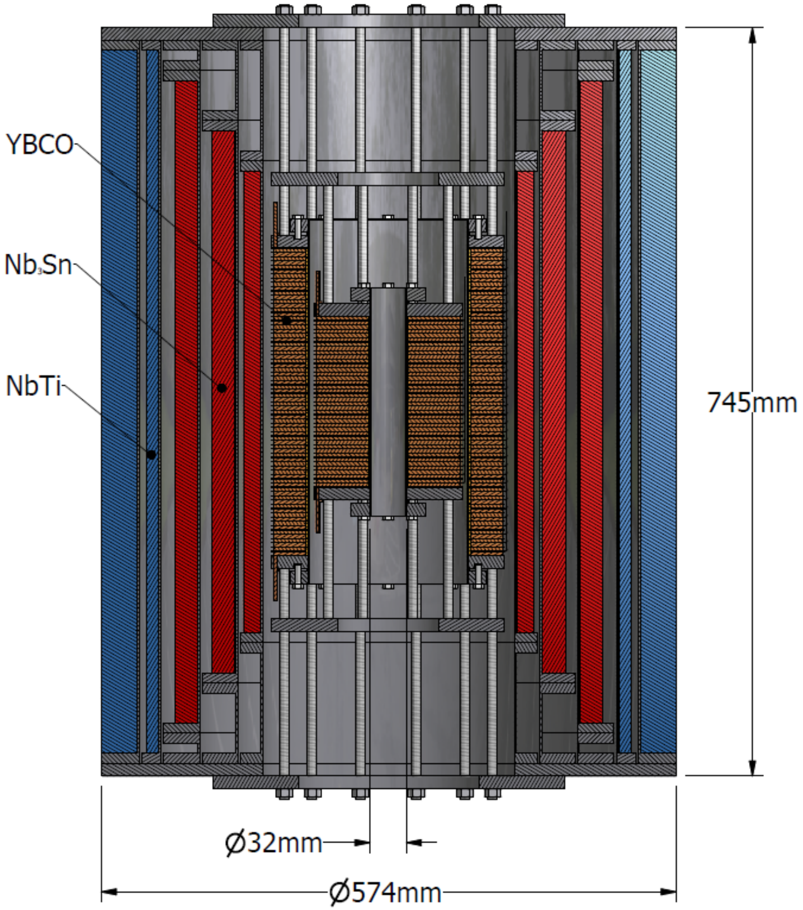
2G YBCO Tape - SuperPower



Bi2212 Round Wire - OST

1st HTS User Magnet

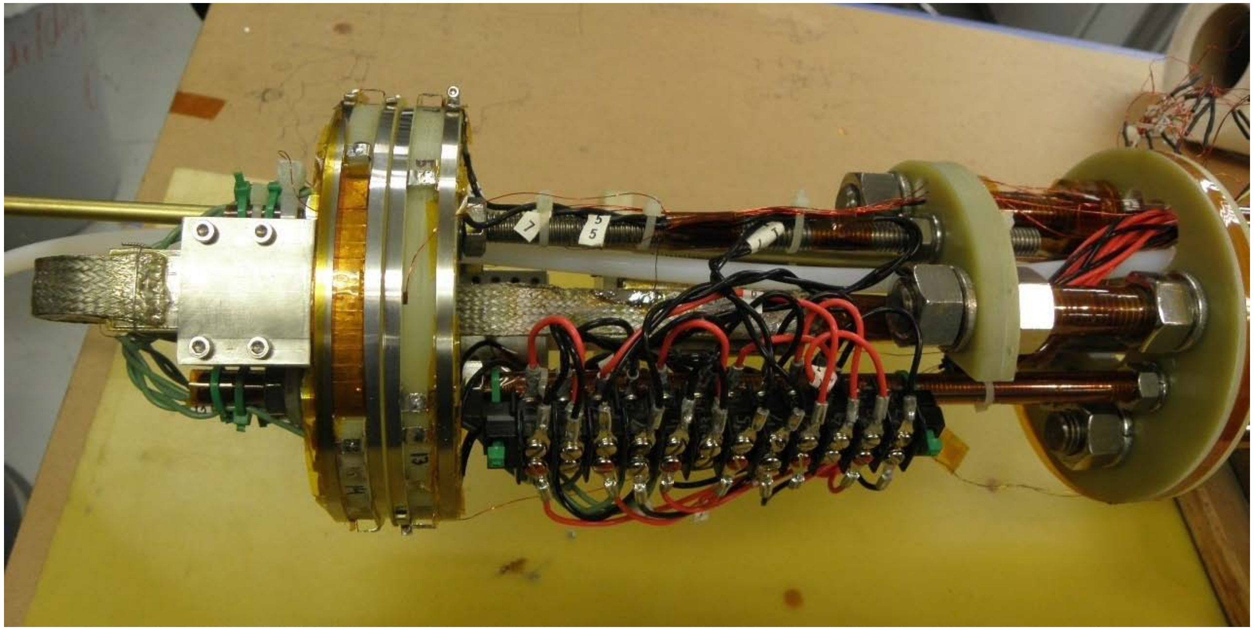
32 TESLA SUPERCONDUCTING MAGNET



Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ
Uniformity	5×10^{-4} 1 cm DSV

Principal Investigator: Denis Markiewicz

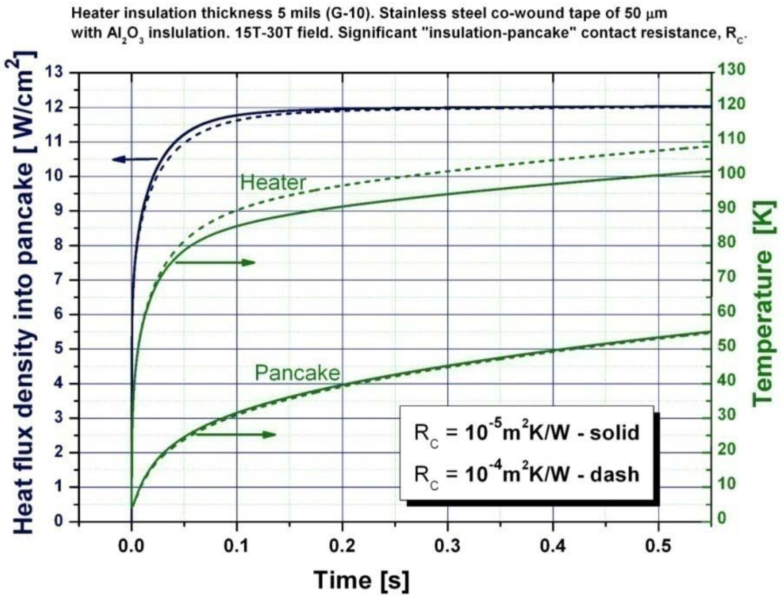
Co-PI’s: David Larbalestier, Steven Julian

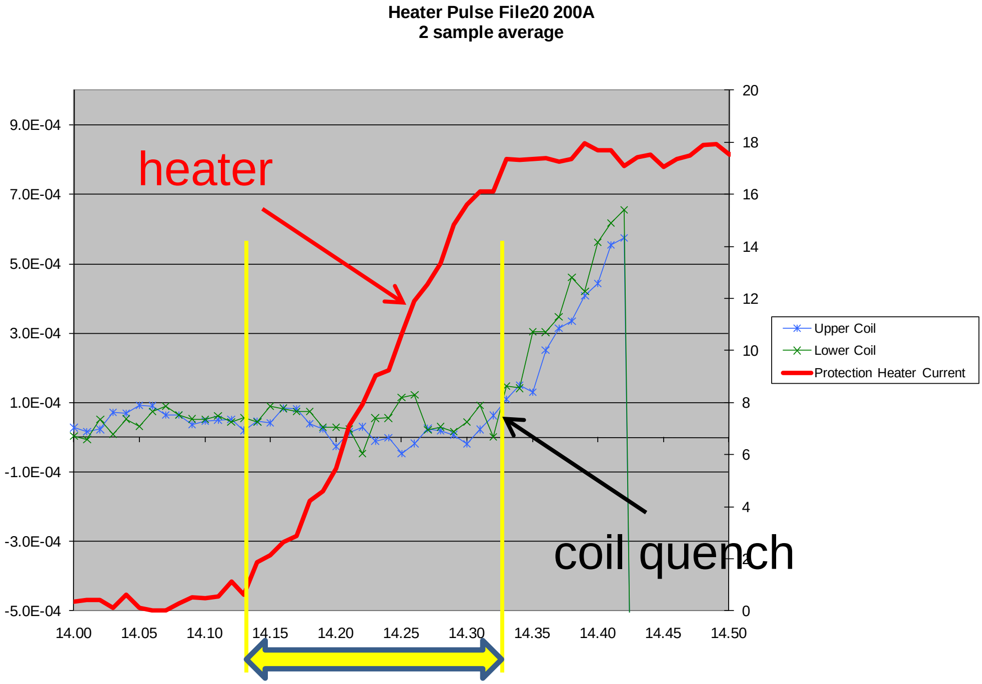


YBCO test coil on support structure

The technology development phase will continue with the fabrication of a series of test coils that will demonstrate conductor and coil performance prior to fabrication of the 32 T magnet YBCO coils.

Quench Protection of YBCO Coils





Performance of quench protection heaters is studied by analysis and measurements on test coils.

Proof of principle of heater performance verified by coil measurements.

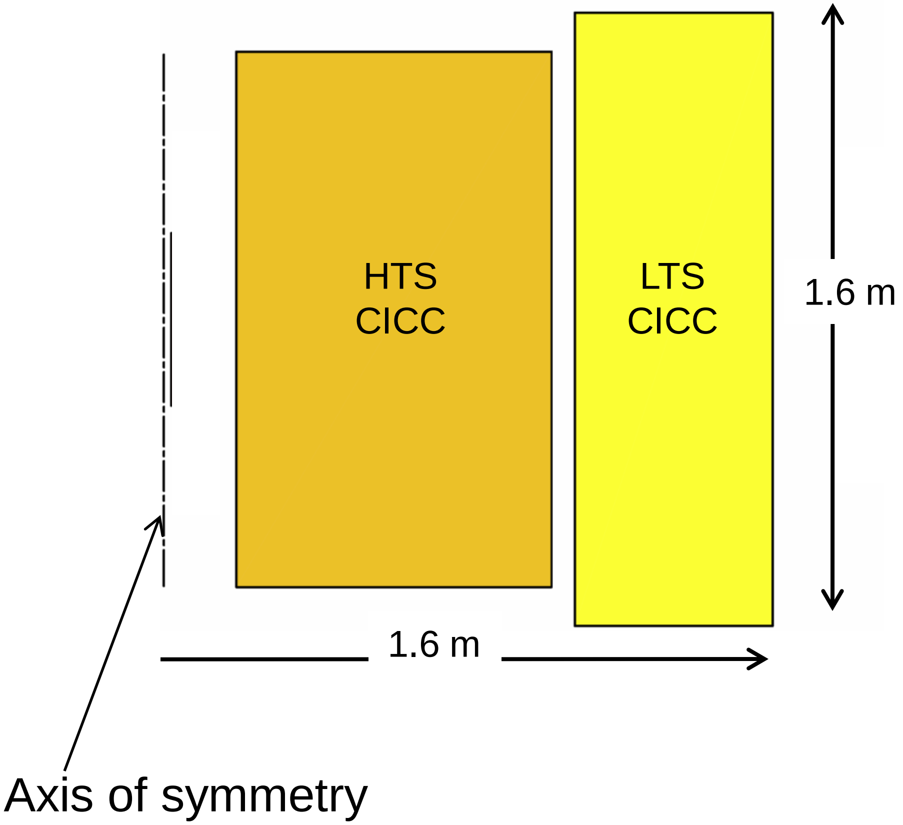
Full heater performance characterization tests to be made at high field.

Potential HTS Solenoids

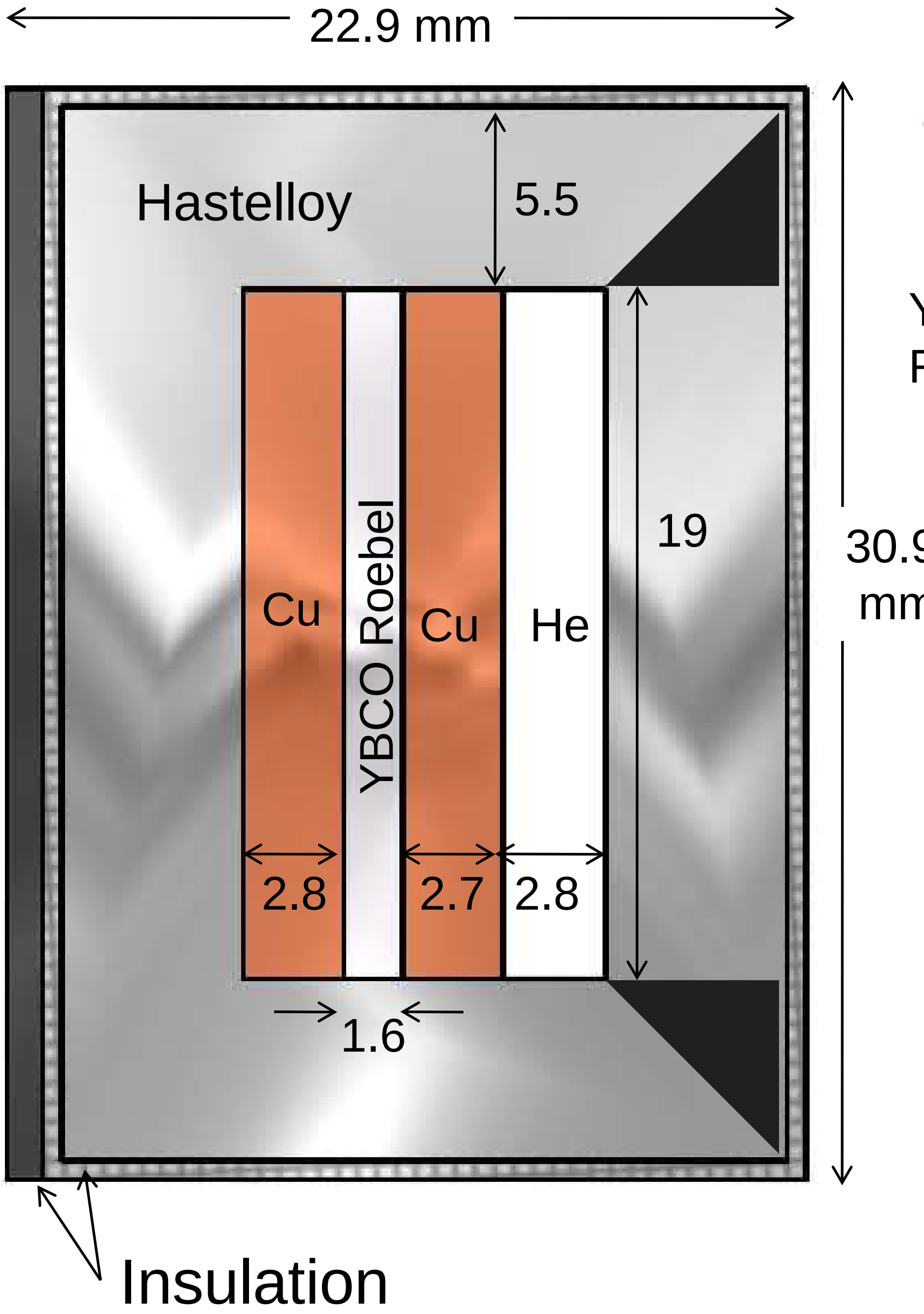
B_0^2V (T^2m^3)	B^4 (kT^4)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
290	*3112*	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	

Italics indicates a magnet not yet operational (and, in this case, yet not funded).

- HTS Cable Concept
  - 42 T
  - 370 mm bore
  - 1.5 m long
  - 1.1 GJ
  - $B_0^2 V = 290\ T^2m^3$



42 T, 30 kA
YBCO CICC concept



Assume

I/I_c	50%
J_{Cu}	250 A/mm2
Stress	500 MPa
He void	40%

- Advantages
    - YBCO superconducts > 100 T
    - Hastelloy provides strength
    - He provides stability
    - Cu provides protection
- Disadvantages
    - Unproven Technology

HTS cable testing @ MagLab

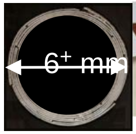
Sample shape and field angle?

Loop/spiral or U-shape or hairpin?

Twisted stack, 4 mm wide

ROEBEL ~5- 12 mm

CORC



Existing test setup for 20 T LBRM

Nominally 7 kA

141 mm cold-bore cryostat

Under development for LBRM

Nominally 16 kA (IRL)

Nominally 2 kA (LBL)

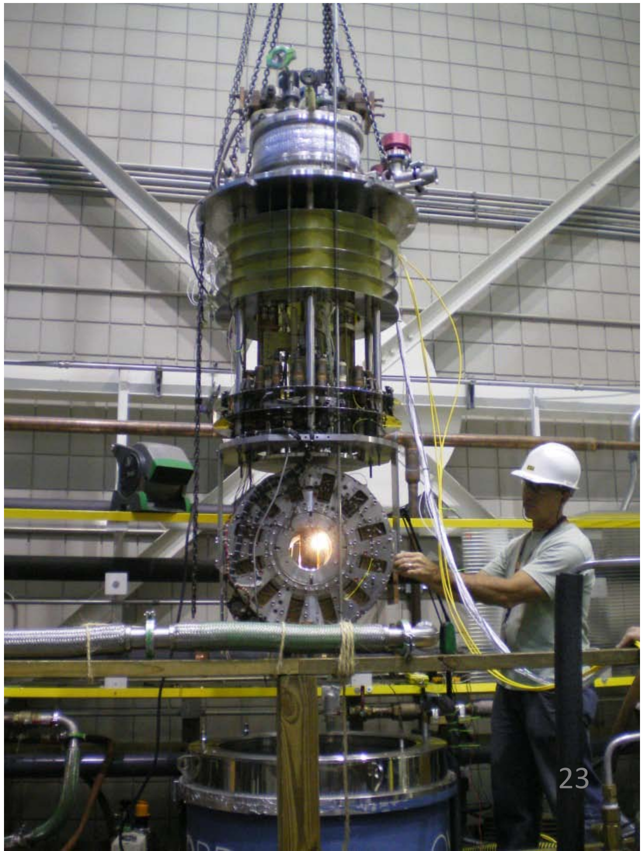
168 mm cold-bore cryostat

Option: 12 T split magnet

Nominally 16 kA

150 mm cold-bore,

30x70 mm radial access



Summary

Estimates of performance and cost of potential approaches to next-generation magnets for rf Axion search

Objective	Approach	Cavity Size D * L (m * m)	B_0^2V (T^2m^3)	B^4 (kT^4)	Cost
Maximize $\int B^2dV$	Very Large Magnet, 4-15 T, cabled conductor (CICC or SRC).	Ø2 – 10 m * 15 – 20 m	2,000 – 10,000	0.2 - 3000	$30M - $1B
Size ~ 1 m	High Field Magnet (20 – 40T): High-Temperature Superconductor	Ø0.5 m * 1.5 m	30 - 300	1000 - 3000	$10M - $200M
Persistent	Monolithic conductor, large-bore MRI magnet (<10 T), commercial	Ø0.9 m * 3 m	250	7 - 12	$5M - $10M
Min cost Upgrade	Use ADMX, Add inner coils (~13 T)	Ø0.4 m * 1 m	20	15 - 25	<$1M
Present System	ADMX	Ø0.5 m * 1 m	12	2	0 ($0.4M)

Seeking Postdoctoral Scholars to Develop Magnet Technology!