Ultra-High Field Solenoids and Axion Detection

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NATIONAL HIGH MAGNETIC FIELD LABORATORY

Ultra-High Field Solenoids and Axion Detection

- Introduction
- Existing Large-Bore / High Field Systems
- Future Ultra-High-Field / Reduced Cavity Size
  - High Temperature Superconductor (HTS)

National High Magnetic Field Laboratory

Florida State University

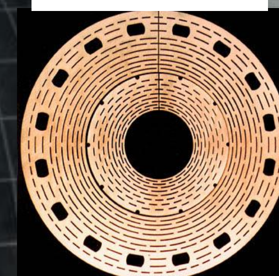
Los Alamos National Laboratory

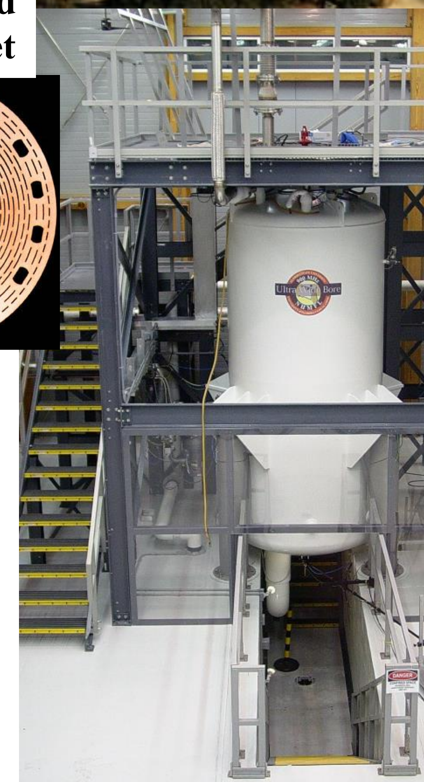
University of Florida

Pulsed Magnetic Field Facility

89 T Pulse Pulsed Magnet
10 msec
15 mm bore

45 T Hybrid DC Magnet



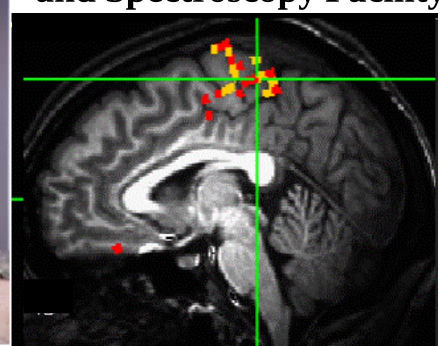


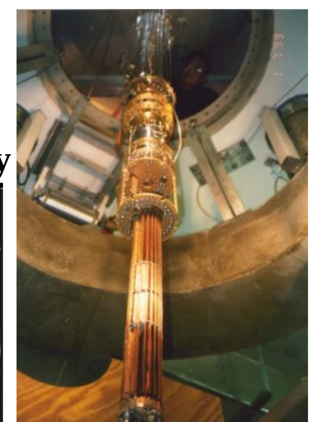
900 MHz, 105 mm bore NMR/MRI Magnet

1.4 GW Motor-Generator

11.1 T MRI Magnet
400 mm warm bore

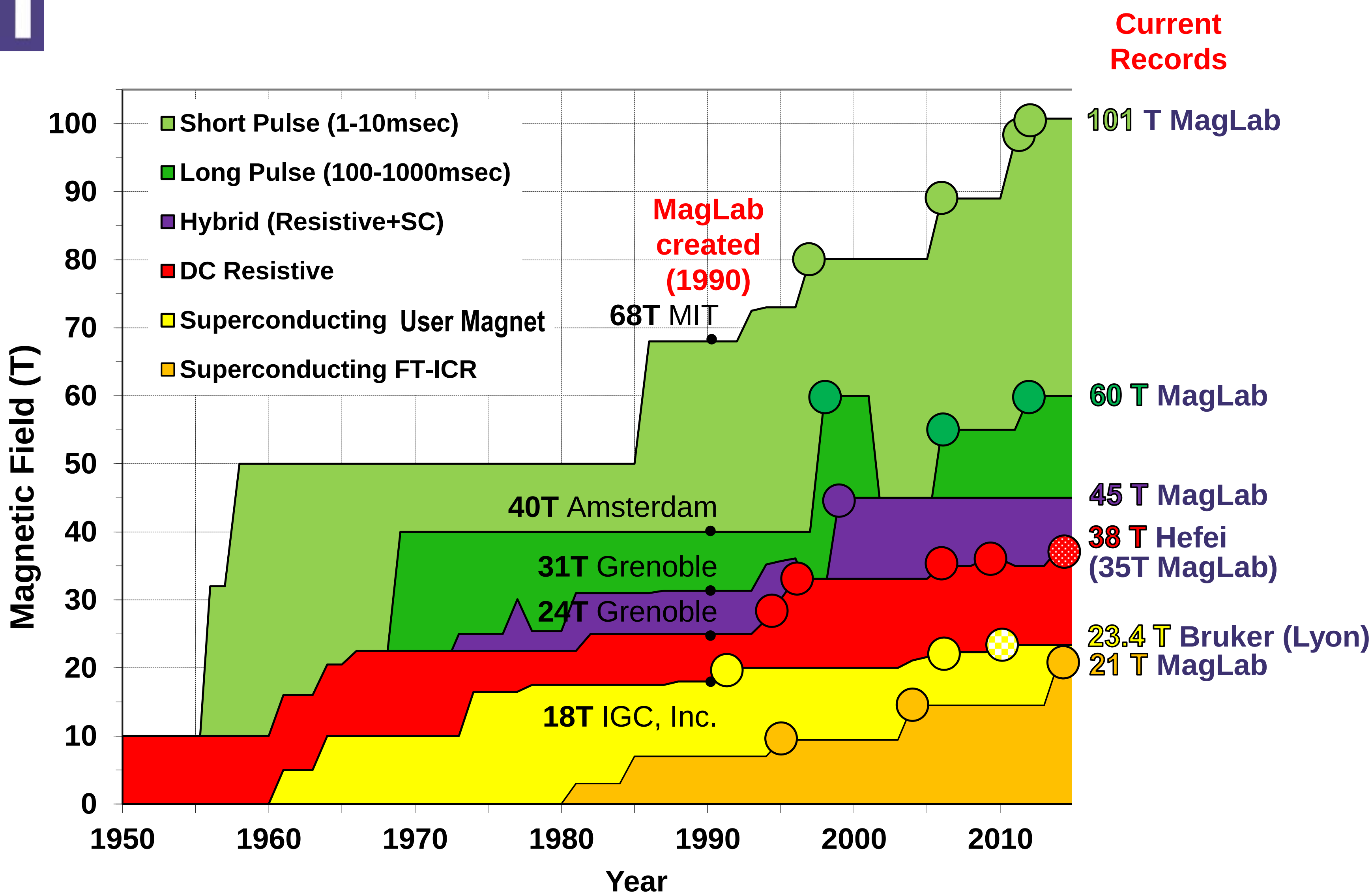
Advanced Magnetic Resonance Imaging and Spectroscopy Facility





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

MagLab Technology in a Worldwide Context



Axion Detection Principles

This discussion focuses on RF cavity techniques in solenoid magnets

Axions within a resonant cavity in a strong magnetic field convert into photons

$$P_a = g_{a\gamma\gamma}^2 V B_0^2 \rho_a C_{lmn} \min(Q_L, Q_a).$$ [1]

Magnet performance is given by

- B^2V

Cavity constrained by

- Field Homogeneity: $B_{z,min}$ is 80 % – 90 % of $B_{z,max}$
- Size limited by frequency, $f \propto 1/R_{cavity}$
- Size limited by cavity technology

[1] Sikivie, *Nuclear Physics B*, 87 (2000)

Solenoids Present & Future

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

B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4
5	900 MHz	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

Optimization Route: Solenoids for Axion DM

High B_0^2V ⟶ Large Bore

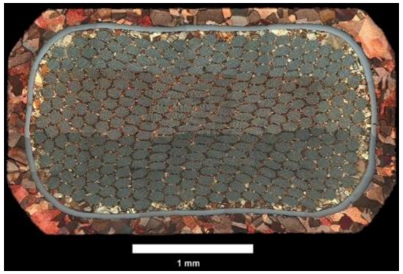
Small Cavities ⟶ Ultra High Fields

1) Determine Maximum diameter of cavity or collection of cavities that is feasible. This sets the bore of the magnet.
2) Determine the maximum length of cavity or collection of cavities that is feasible. This sets the length of the magnet.
3) Increase magnetic field until financial limit is reached.

Today's Solenoids: Monolithic Conductors

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

Italics indicates a magnet not yet operational.



Monolithic, Bronze Route Nb_3Sn (900 MHz)

900 MHz, 21.1 T

ADMX 7 T

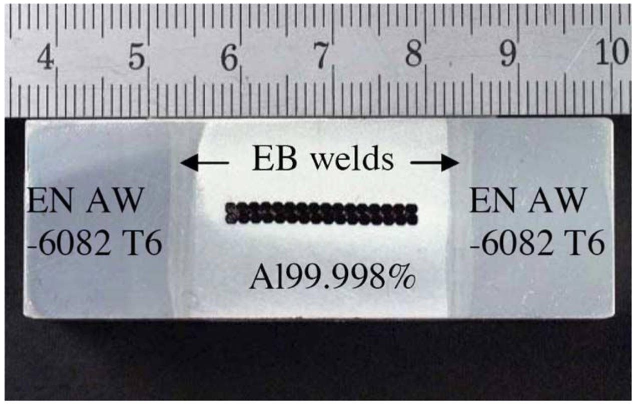
Julich 9.4 T

Today's Solenoids: Stabilized Rutherford-Cable

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

Italics indicates a magnet not yet operational.

[1]Materials only per BBC/CERN.



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

Compact Muon Solenoid

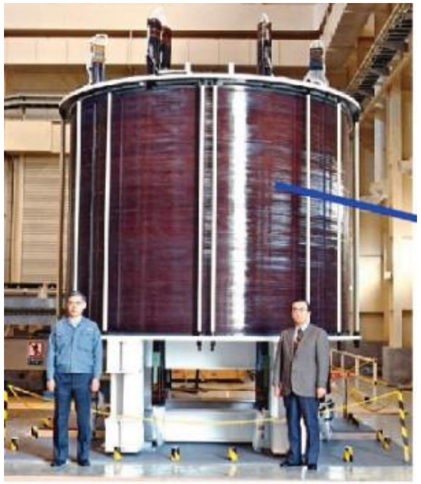
Today's Solenoids: CICC

B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
320	CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4

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

Cable-in-Conduit Conductor (45 T: 10 kA, 14 T Nb_3Sn)

MagLab 45 T Hybrid

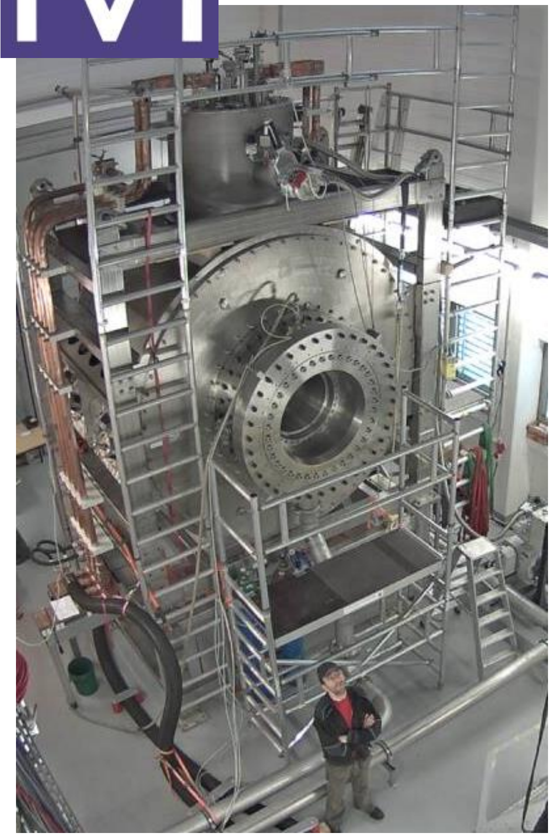


ITER Central Solenoid Module

Recent MagLab Hybrid Magnet Projects: Three CICC Coils with Common Conductors

$B^2V = 36\ T^2m^3$

(Outer Coil Alone)



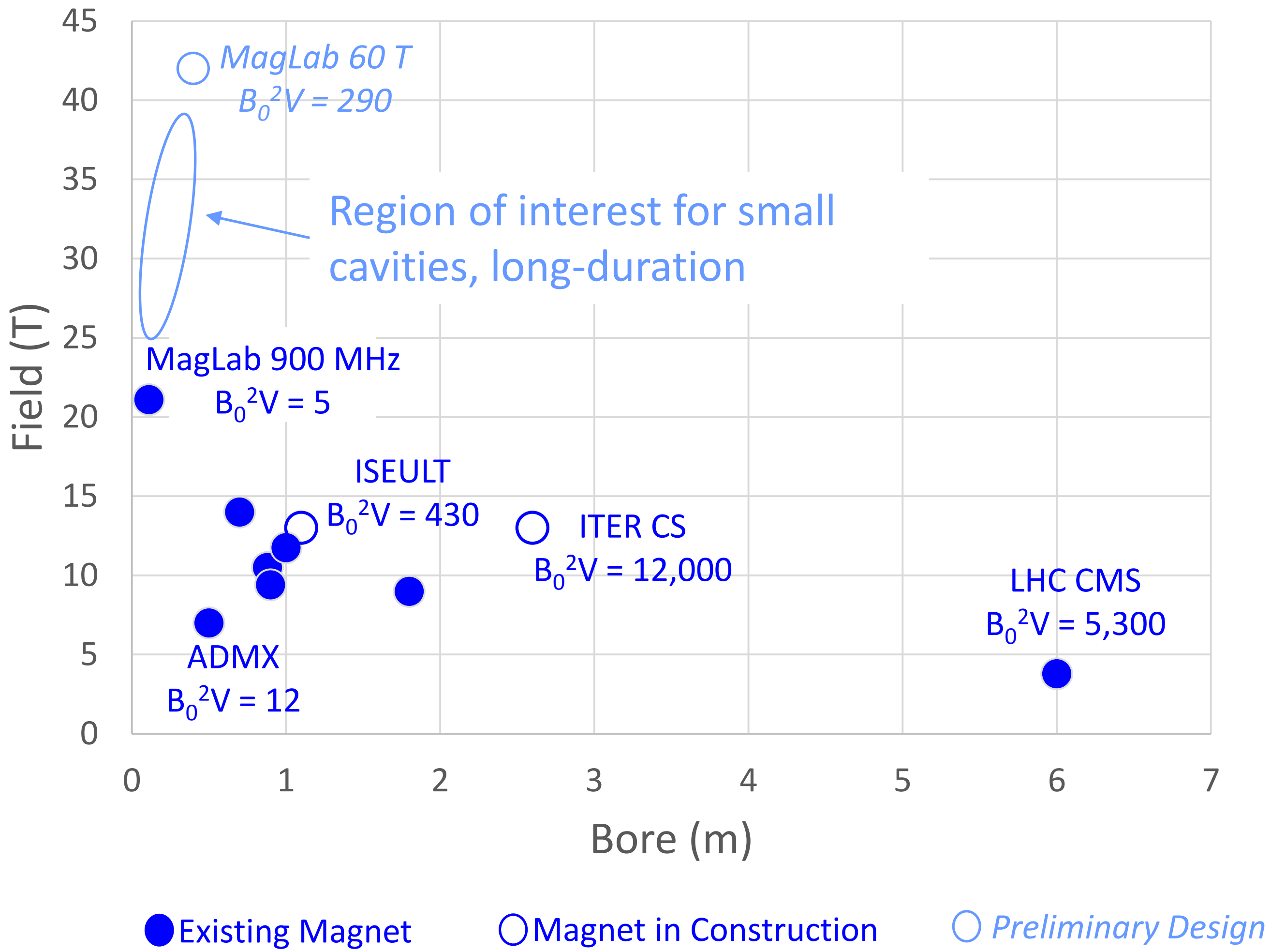
Helmholtz Zentrum Berlin (HZB)	MagLab	Radboud University
Berlin, Germany	Tallahassee, FL	Nijmegen, Netherlands
13 T, 50 cm	13 T, 46 cm	12 T, 52 cm
4 MW	13 MW	24 MW
Neutron Scattering	High-Homogeneity	High-Field
Germany	NSF IMR-MIP, FSU, Germany, Netherlands	Netherlands
2014	2016	2018

Field vs Bore

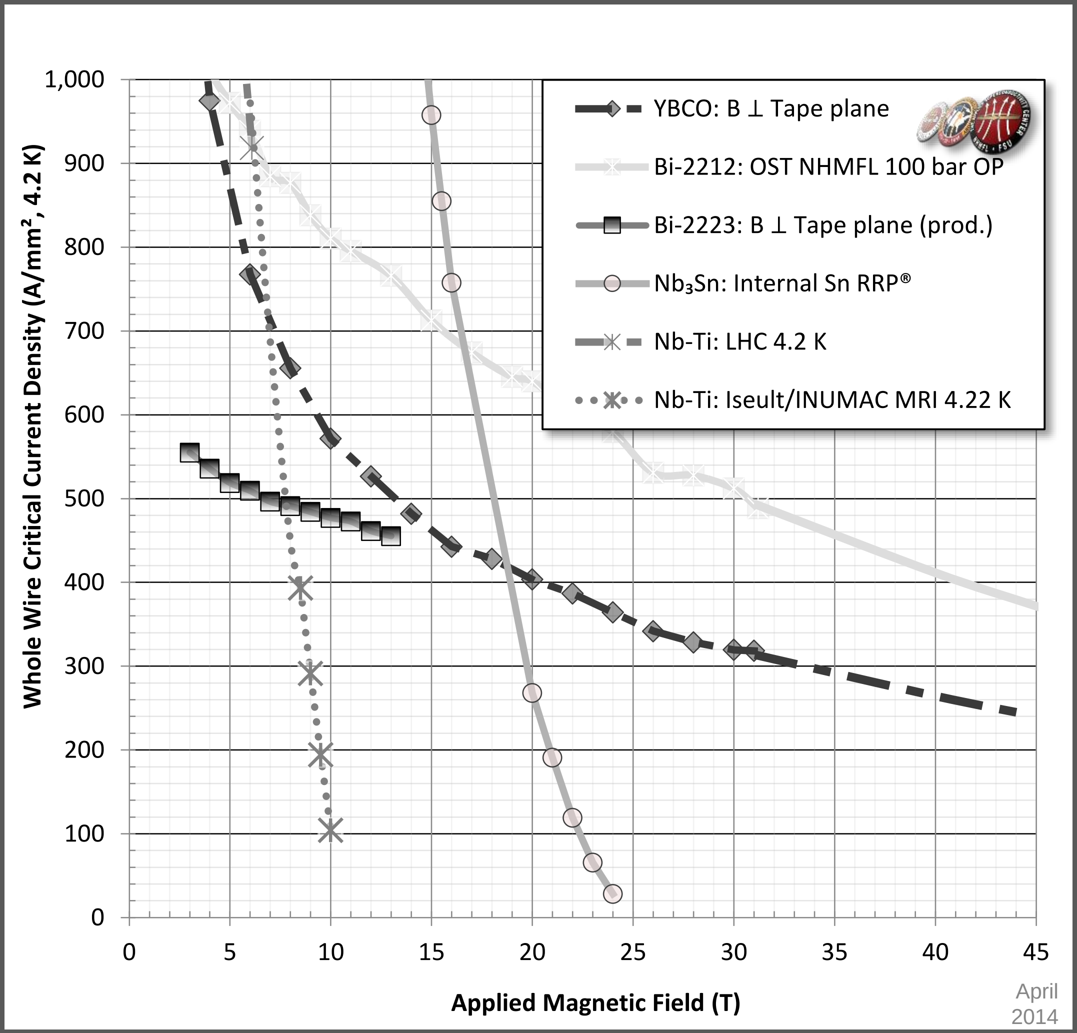
High B_0^2V ➡ Large Bore

Small Cavities ➡ Ultra High Fields

Long Duration ➡ High Temp Superconductors



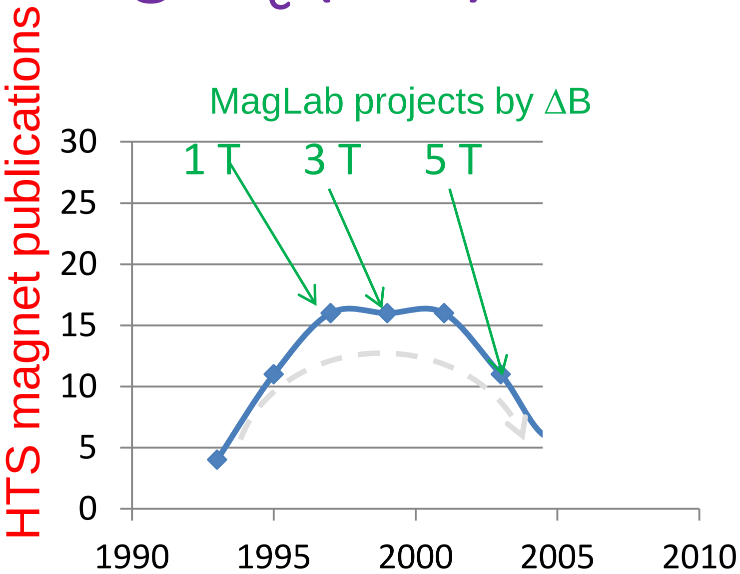
Superconducting Materials for Magnets

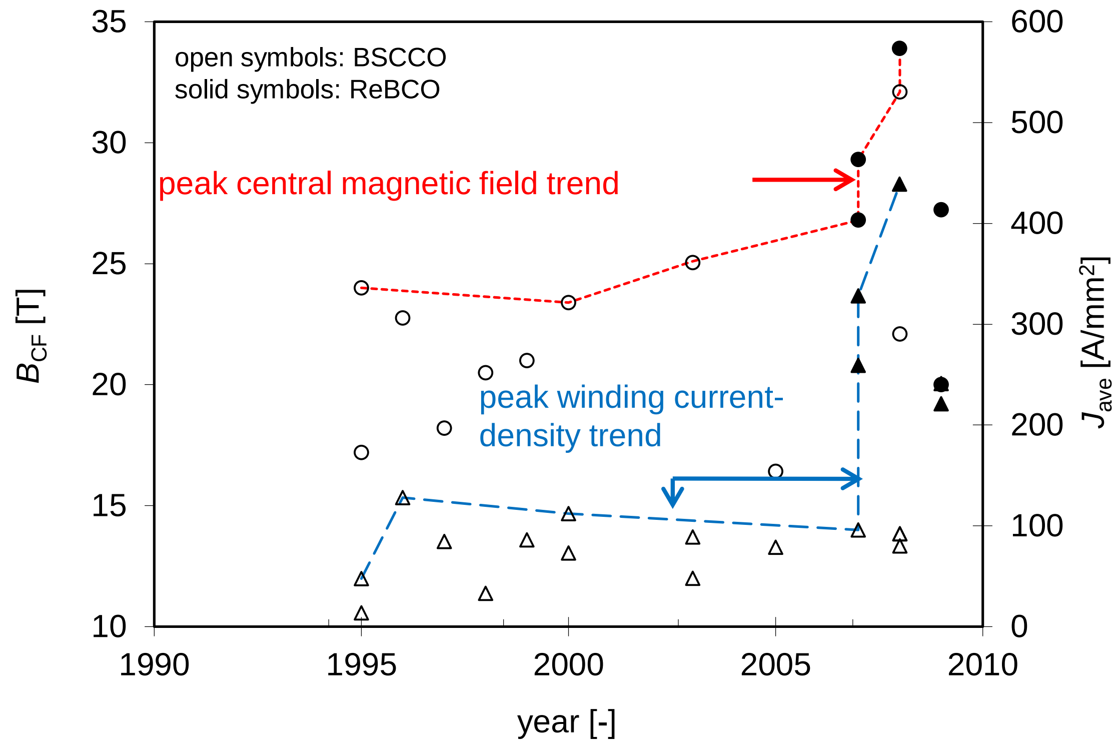


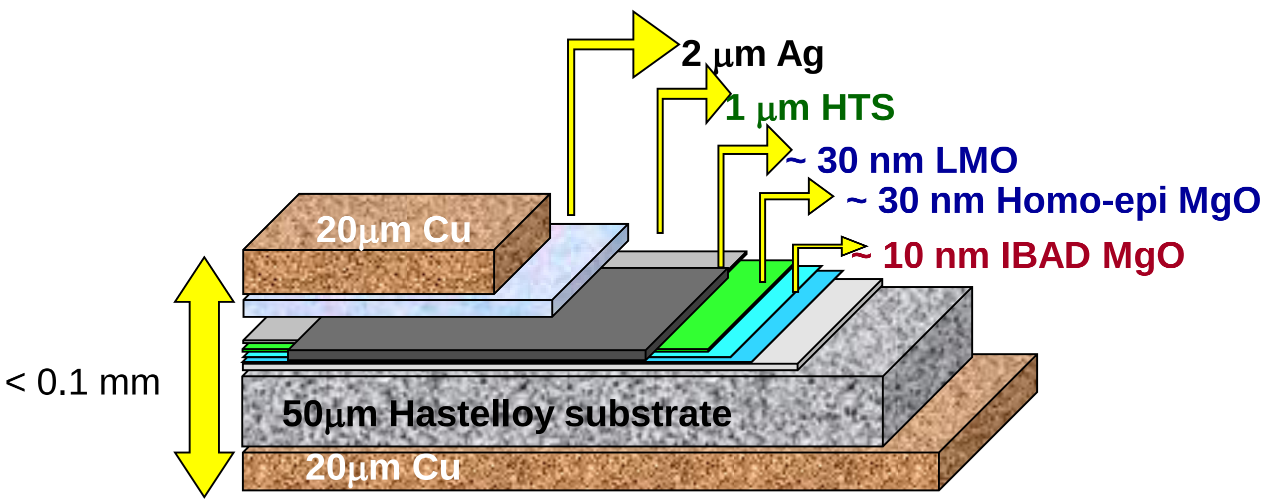
- **The High-Temperature Superconductors (HTS) REBCO, Bi2212, Bi2223 will superconduct at fields >100T.**
- **For >25 T Solenoids, HTS is required.**
- **At 4 K, extremely high combinations of field and current-density attained!**
- **(BI2212, Bi2223, & REBCO superconduct at > 100 T!)**

J_e of wire maintained by P. Lee (http://magnet.fsu.edu/~lee/plot/plot.htm)

High T_c (HTS) Coils

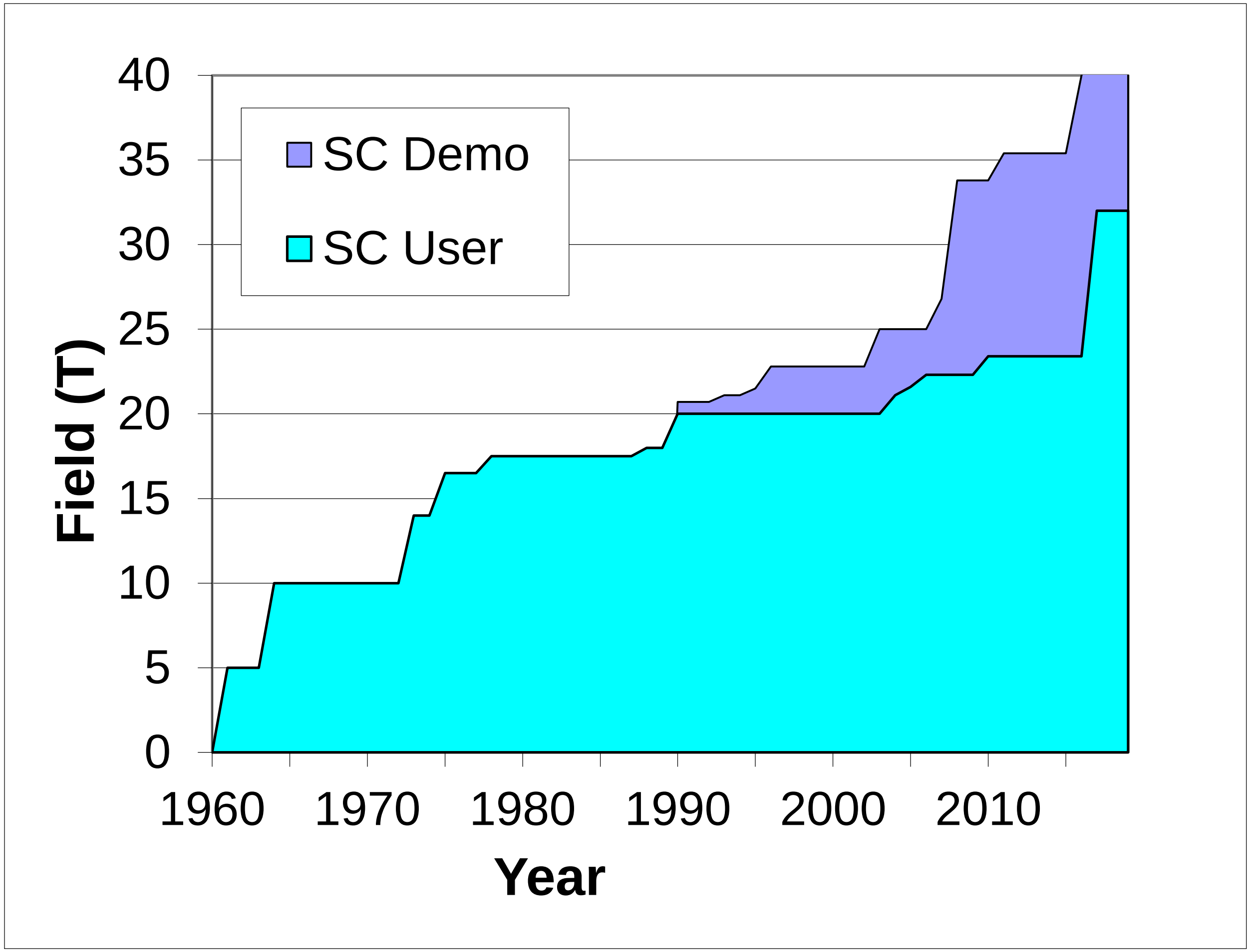






2G YBCO Tape – SuperPower - 2007

Superconducting Magnets Over Time



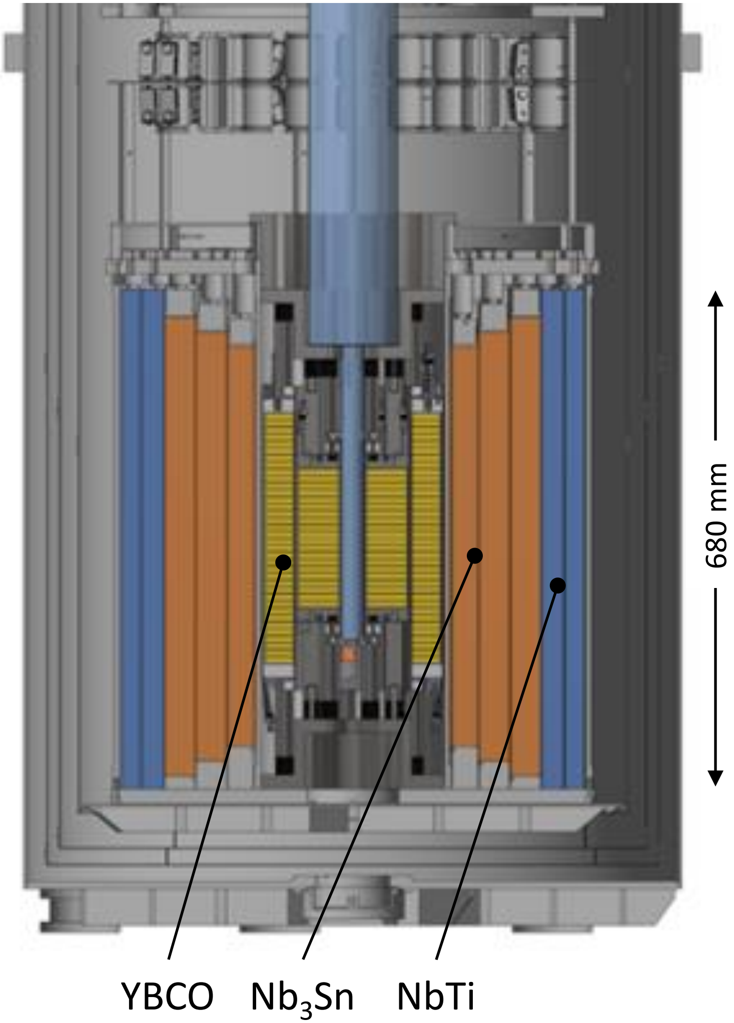
For ~30 years, HTS test coils have been made.

SuperPower's REBCO tape from 2007 enables UHF user magnets.

32 T magnet is assembled at MagLab.

MagLab 32 T SC *USER* MAGNET

2003: 1st 25 T SC test coil
2008: 1st 35 T SC test coil
2015: 1st 27 T all-SC test



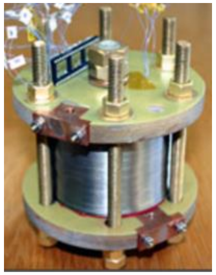
Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ
Uniformity	5×10^{-4} 1 cm DSV

- Commercial Supply:
  - 15 T, 250 mm bore LTS coils – Delivered!
  - Cryostat – Delivered!
  - (Dilution Refrigerator)
- In-House development:
  - 17 T, 34 mm bore YBCO coils – Assembled!

NHMFL - 32 T Technology Development

- YBCO tape characterization & QA
- Insulation technology
  - Ceramic on co-wound SS tape
- Coil winding technology
- Joint technology
- Quench analysis & protection
- Fatigue testing of components

2007

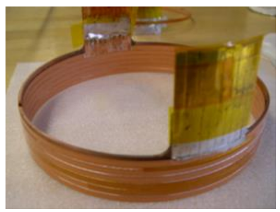


2008

High-B coils
31 T + ΔB

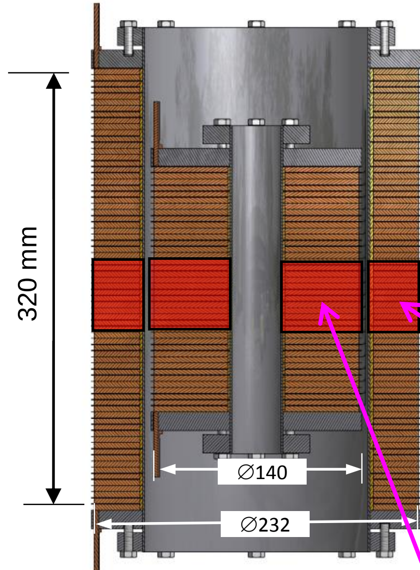
2008

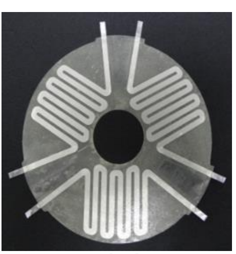
2009



Demonstration inserts
20 T+ ΔB

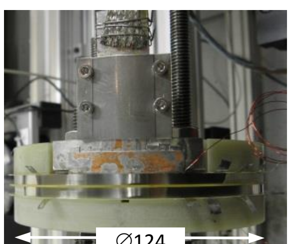
High Hoop-stress coils
>760 MPa





Quench heater

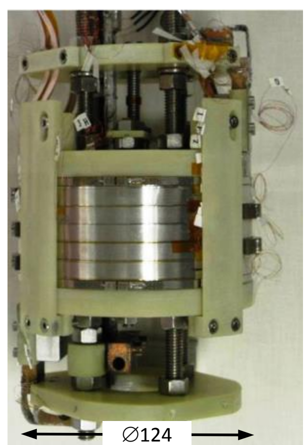
2011



First Quench Heaters

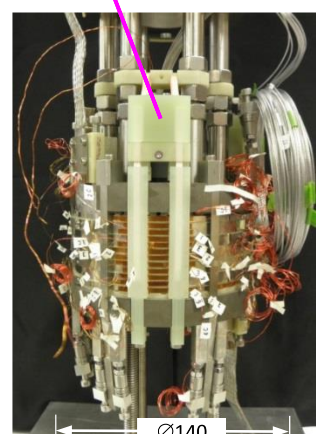
42-62 Mark 1:
1st test coil

2012



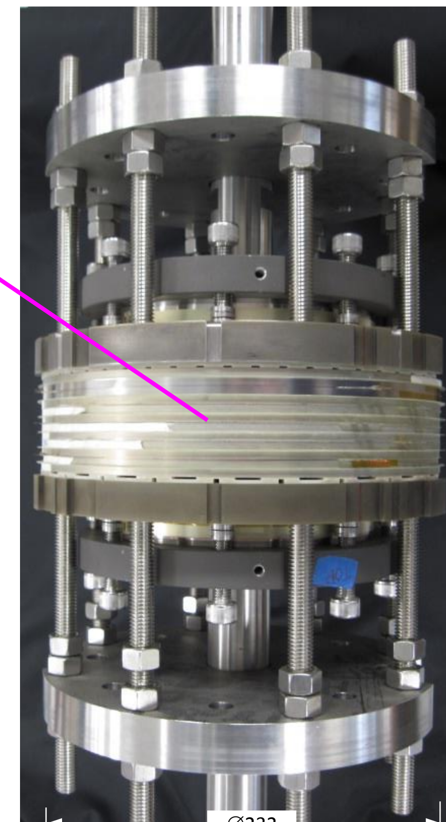
42-62 Mark 2:
2nd test coil

2013



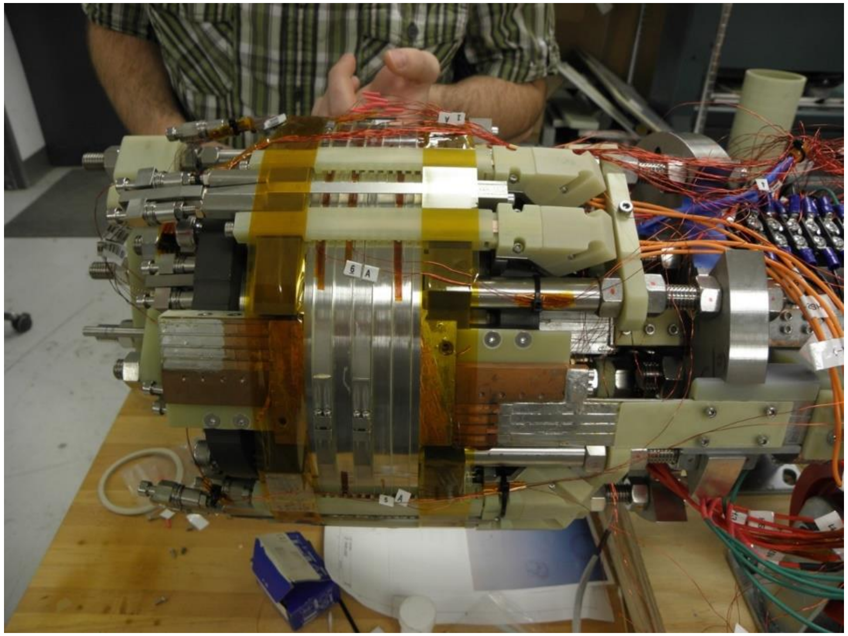
20 - 70:
1st Full-featured Prototype

2014



82 - 116:
2nd Full-featured Prototype

NHMFL - 32 T All Superconducting User Magnet



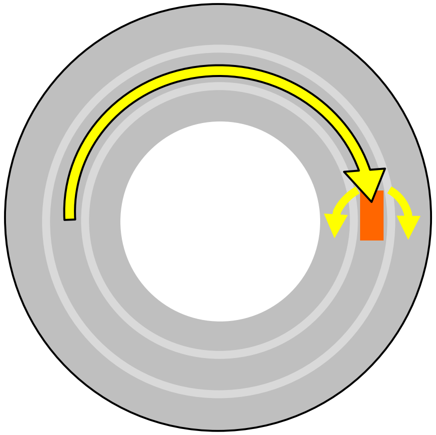
- 2nd Prototype was tested in Aug. 2014 and June 2015.
- Included all features of real coils for 32 T except length.
- Intentionally Quenched >80 times without degradation.

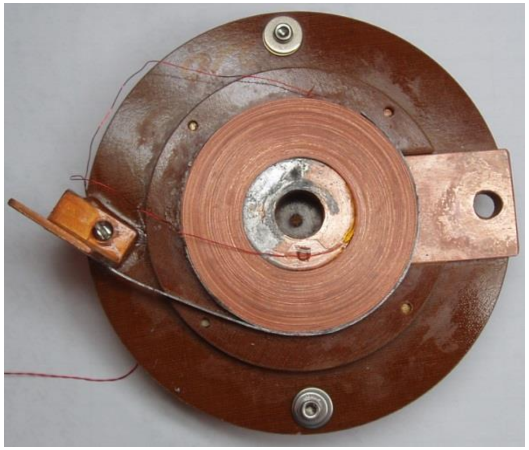
- Cycled to high stress without ill effect:
  - 32 cycles 100% design stress
  - 106 cycles 110% design stress
  - 4 cycles 120% design stress
  - 1 cycle 135% design stress

NHMFL - 32 T All Superconducting User Magnet

- System is now fully assembled.
- Testing of protection system underway.
- Full Field April?

No-Insulation YBCO Coil Technology





- No-Insulation YBCO:
  - By winding coils without insulation, coils can short during a fault mode.
  - This requires less Copper in the winding pack which results in:
    - higher average current density which results in
    - more compact magnets which results in
    - lower stresses

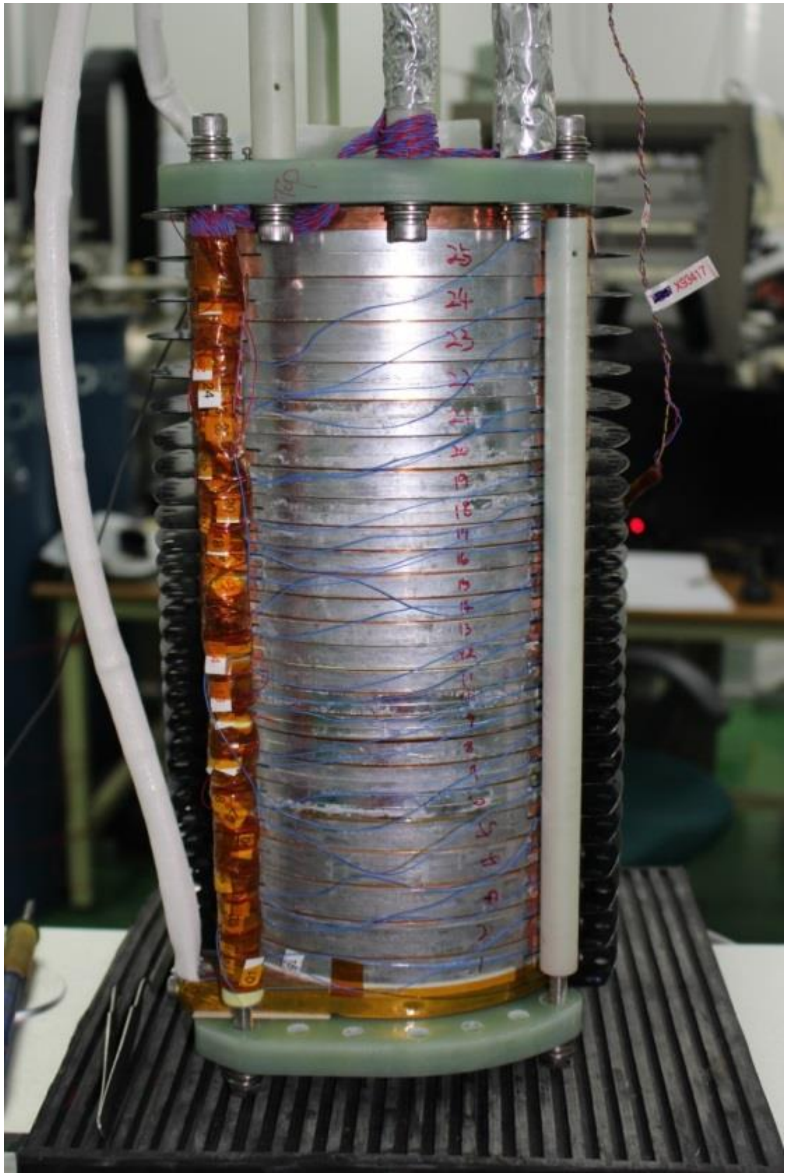
- Coil quench at I_{op}=412 A (1580 A/mm^2)
- 32 T ~ 200 A/mm^2
- No coil damage in 20-s "over-current" operation

Similar concepts:
Partial-Insulation REBCO,
Metal-Insulation REBCO,
Low-Resistance REBCO, etc.

Assoc. Prof.
Seungyong Hahn
Florida State Univ.

NI-YBCO Test Coils

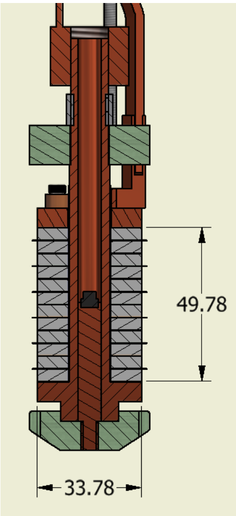
26-T/35-mm MW REBCO
(2015, SuNAM/MIT/FSU)

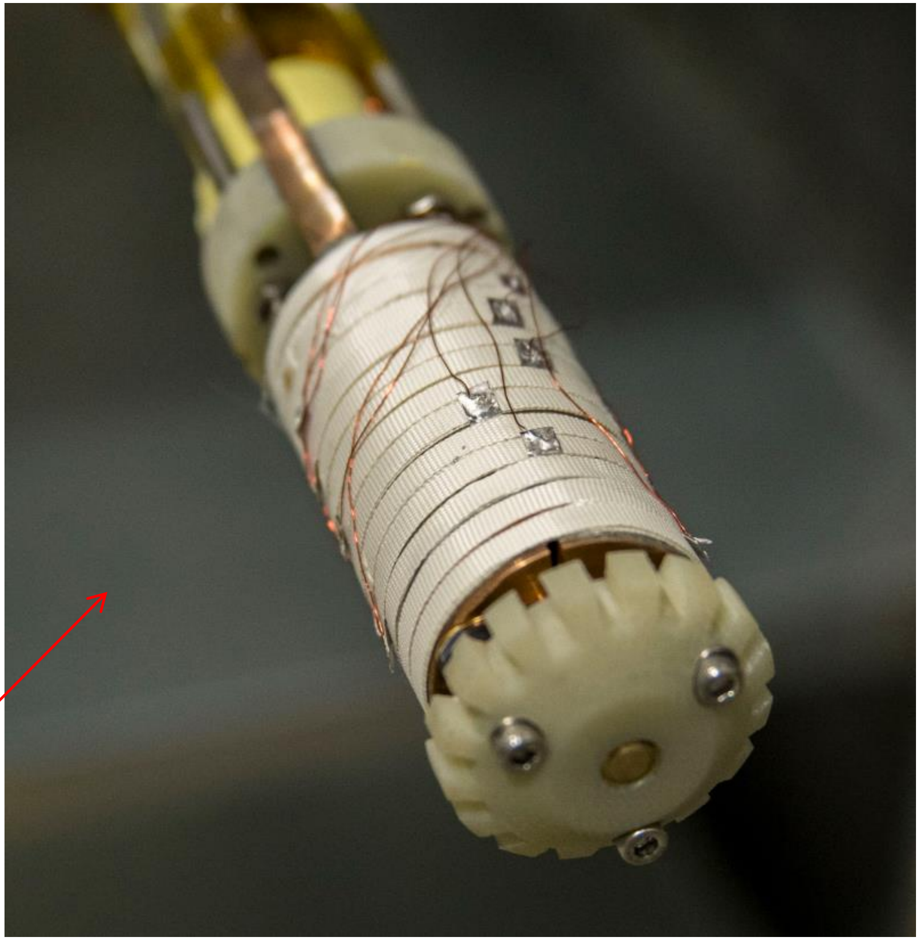


- Coil OD: 172 mm
- *Self-protecting* at J_e of 392 A/mm^2

World Record Field Produced by a Superconducting Magnet (April 2016)

- Total central field = 42.5 T
  - No-insulation coil = 11.5 T
  - Resistive magnet = 31.0 T
- Reached an astounding 1131 A/mm^2
- HTS tape thickness = 42 μm (5 μm Cu)





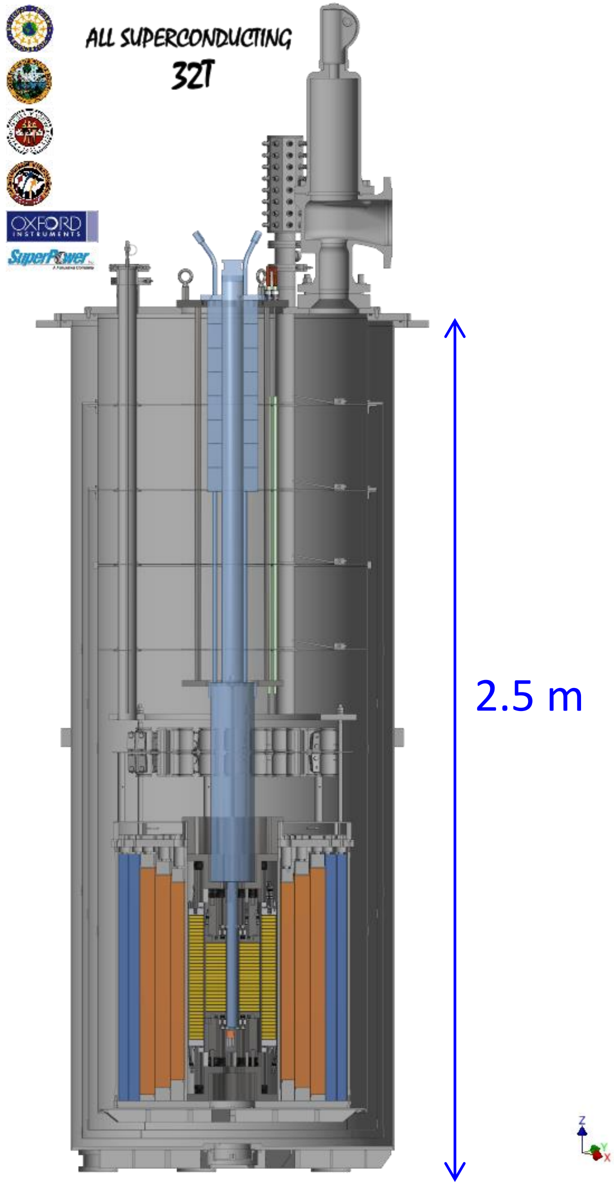
Superconducting Magnets for Axion Detection

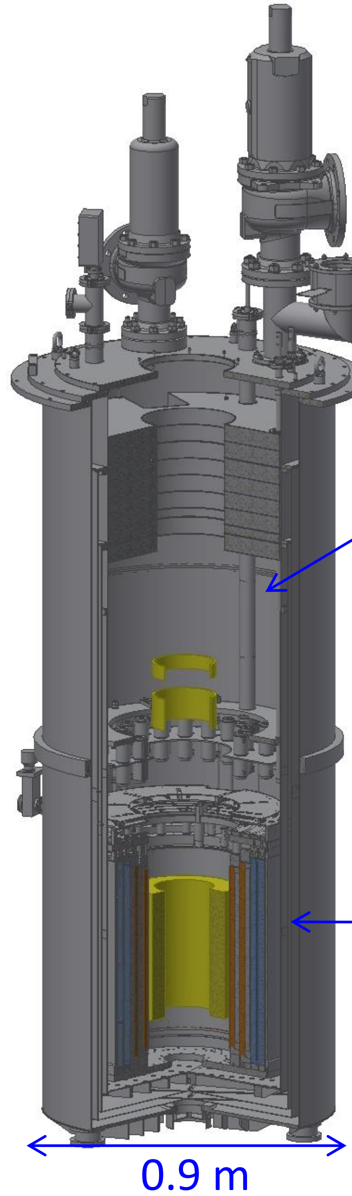
- Two example magnet designs are presented that utilize REBCO superconductors for magnet applications applied to axions
- Design Process
  1. Determine Maximum diameter of cavity or collection of cavities that is feasible.
     - Targeted relatively high frequency ~ 1.4 GHz
     - f = 23 GHz/cm (diameter of resonant cylinder, TM010 mode)
     - Starting point: **16 cm chamber diameter**
  2. Determine the maximum length of cavity or collection of cavities that is feasible.
     - Chamber height = 2.2 × diameter
     - Homogeneity within chamber: $\boldsymbol{B_{z,min} \geq 82\,\%}$ of $B_{z,max}$
  3. Increase magnetic field until financial limit is reached.
     - Starting point of **25 T**
  4. Squid amplifiers need shielded region 0.6 m (preferred) to 1 m (acceptable) above magnet
     - Same bore as magnet
     - B < 1 mT over 0.2 m axially at R=0.00 m
     - B < 4 mT over 0.2 m axially at R=0.04 m

Magnet Design Using HTS

$B_z^2 \times V = 4.8\ T^2m^3$

32 T: 20+36 HTS DP modules
Axion: 50 HTS DP modules

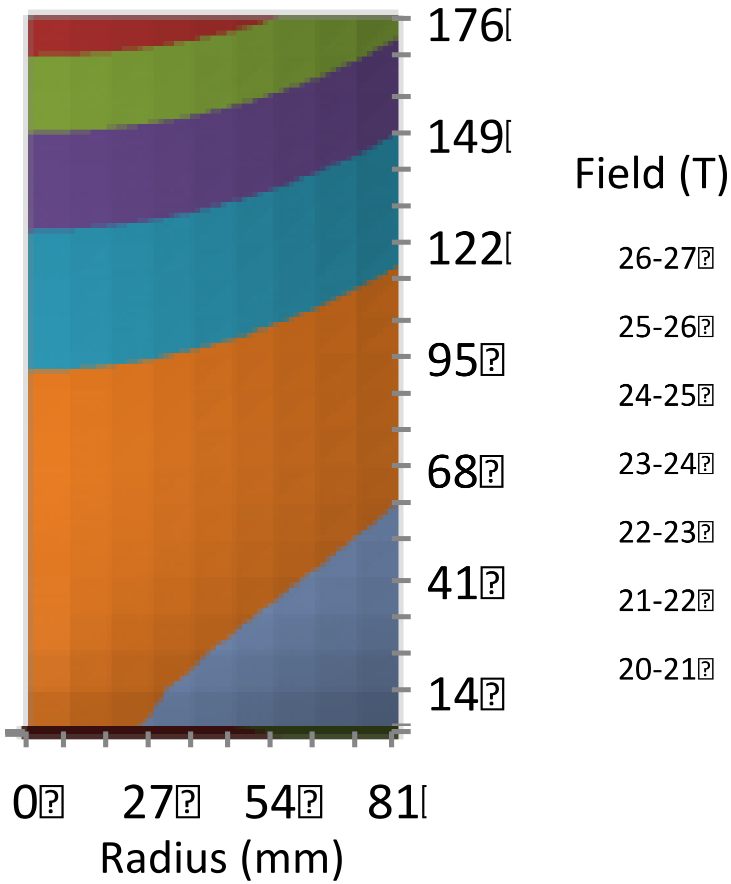




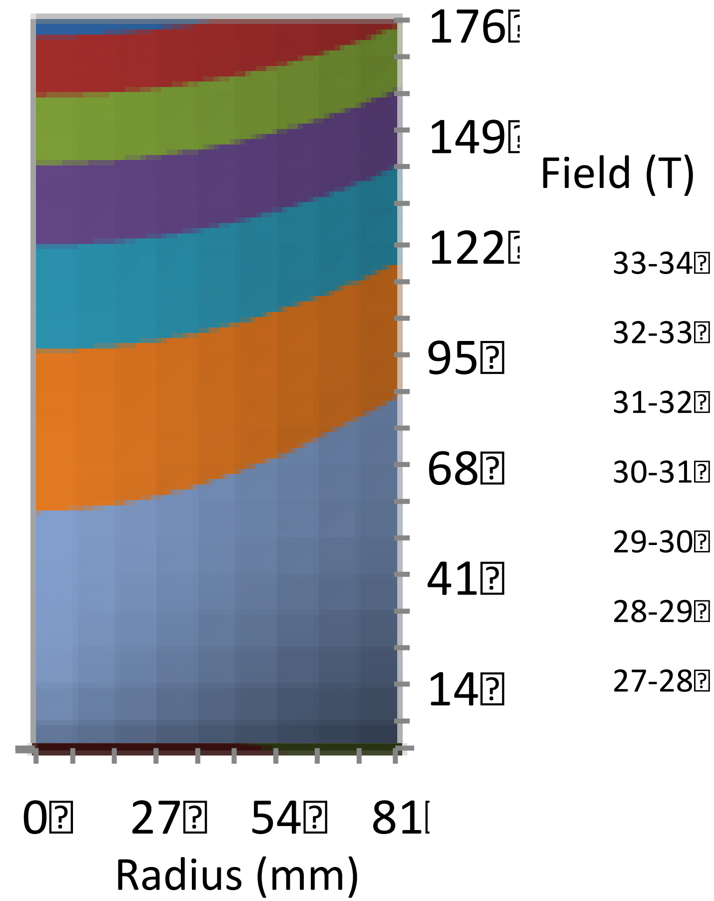
Shield coils 0.6 m above magnet (this version ±5 mT over 100 mm axially-center line only)

Yellow: HTS coil
Red: Nb_3Sn coils
Blue NbTi coils

Magnet Design Using HTS



32 T style LTS outsert



CICC style LTS outsert, $B_z^2 \times V = 8\ T^2m^3$

Axion Detector Magnet Comparisons

	Cavity			
Style	**Diameter (cm)**	**Height (cm)**	**Volume (m^3)**	**f (GHz)**
ADMX	50	100	0.196	0.46
LTS Only	16	35.2	0.007	1.44
HTS / 32 T Outsert	16	35.2	0.007	1.44
HTS / CICC Outsert	16	35.2	0.007	1.44

Style	**B_0 (T)**	**$B^2 \times V$ ($T^2 m^3$)**	**HTS J_{AVE} (A/mm^2)**
ADMX	7.6	11.34	
LTS Only	19	2.5	
HTS / 32 T Outsert	26	4.78	207
HTS / CICC Outsert	33.5	7.94	149/138/137

HTS Magnet Technology Development

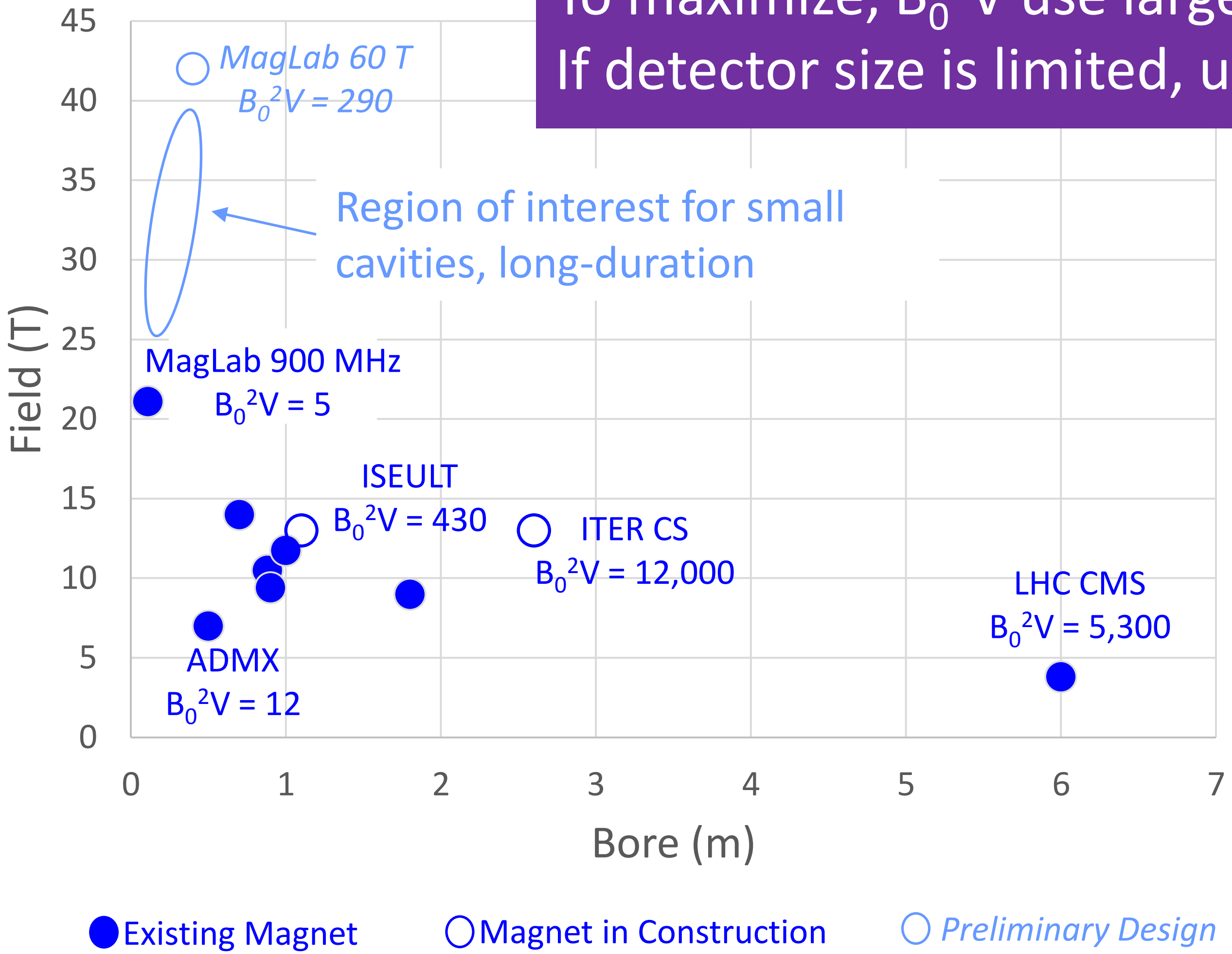
- 1986 – 2006: early development of a variety of HTS materials and test-coils.
- 2007 – 2016: development of magnet-grade HTS conductors and first user-magnets (condensed-matter physics).

Materials		High-Field User Magnets	
2007	High-Strength REBCO	2017	*MagLab 32 T Ins-REBCO*
2013	High-Strength Bi2223	2017	*Sendai 24.5 T Bi2223*
2016	High-Strength Bi2212	2017	*MagLab 20 T NI-REBCO*

- 2017 – 2026: propagation of HTS magnets into various applications (axion detection, neutron-scattering, pre-clinical MRI, NMR, human-MRI, 60 T hybrids, etc.)

Conclusion

To maximize, B_0^2V use large bore.
If detector size is limited, use HTS > 25 T.



On Behalf of the People Who Make the Magnets

32 T SC Magnet Project

H. W. Weijers, W. D. Markiewicz

<u>Analysis</u>

W.D. Markiewicz
A.V. Gavrilin
H.W. Weijers
D. Hilton
P. Noyes

<u>Design</u>

A. Voran
S. Gundlach
Y. Viouchkov
S. Bole

<u>Materials</u>

D. Abraimov
J. Lu
D. McGuire
B. Walsh

<u>Fabrication</u>

T. Painter
Z. Johnson
B. Sheppard
B. Jarvis
G. Sheppard

36 T SCH Magnet Project

M.D Bird, I. R Dixon

<u>Analysis</u>

I.R. Dixon
A.V. Gavrilin
H. Bai
T. Painter
S. Marshall
J. Toth
Y. Zhai
T. Xu

<u>Science</u>

T. Cross
W. Brey
I . Litvak

<u>Design</u>

S. Bole
T. Adkins
K. Cantrell
S. Napier
A. Trowell
S. Gundlach
M. White
G. Miller

<u>Materials</u>

K. Han
J. Lu
B. Walsh
B. Goddard
V. Toplosky

<u>Instrument.</u>

S. Hannahs
A. Powell
P. Noyes
Bonninghausen

<u>Fabrication</u>

L. Marks
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Thank You!

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