Ultra-High Field Solenoids and Axion Detection

Mark D. Bird
Director, Magnet Science & Technology
NHMFL, Tallahassee, FL, USA

Iain Dixon, Seungyong Hahn,
Denis Markiewicz,
Huub Weijers
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)
1.4 GW Motor-Generator

89 T Pulse Pulsed Magnet
10 msec
15 mm bore

Florida State University

45 T Hybrid DC Magnet

Los Alamos National Laboratory

University of Florida

Advanced Magnetic Resonance Imaging and Spectroscopy Facility

National High Magnetic Field Laboratory

11.1 T MRI Magnet
400 mm warm bore

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

900 MHz, 105 mm bore NMR/MRI Magnet
MagLab Technology in a Worldwide Context

- **Short Pulse (1-10msec)**
- **Long Pulse (100-1000msec)**
- **Hybrid (Resistive+SC)**
- **DC Resistive**
- **Superconducting User Magnet**
- **Superconducting FT-ICR**

**Current Records**

- 101 T MagLab
- 60 T MagLab
- 45 T MagLab
- 38 T Hefei (35T MagLab)
- 23.4 T Bruker (Lyon)
- 21 T MagLab

**Yearly Records**

- 68T MIT (1990)
- 40T Amsterdam
- 31T Grenoble
- 24T Grenoble
- 18T IGC, Inc.

**Magnetic Field (T)**

- 1950-2020

**MagLab created (1990)**
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

- \( B^2 V \)

Cavity constrained by

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

## Solenoids Present & Future

<table>
<thead>
<tr>
<th>$B^2_V$ (T$^2$m$^3$)</th>
<th>Magnet</th>
<th>Application/Technology</th>
<th>Location</th>
<th>Field (T)</th>
<th>Bore (m)</th>
<th>Len (m)</th>
<th>Energy (MJ)</th>
<th>Cost ($M)</th>
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<tbody>
<tr>
<td>12000</td>
<td>ITER CS</td>
<td>Fusion/Sn CICC</td>
<td>Cadarache</td>
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<td>2.6</td>
<td>13</td>
<td>6400</td>
<td>&gt;500</td>
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<tr>
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<td>MRI/Mono</td>
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CICC = Cable-In-Conduit Conductor  
SRC = Stabilized Rutherford-Cable  
Mono = Monolithic Conductor

Italics indicates a magnet not yet operational.

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

High $B_0^2V$ $\rightarrow$ Large Bore
Small Cavities $\rightarrow$ Ultra High Fields
# Today’s Solenoids: Monolithic Conductors

<table>
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<tr>
<th>$B_0^2V$ $(T^2m^3)$</th>
<th>Magnet</th>
<th>Application/Conductor</th>
<th>Location</th>
<th>Field (T)</th>
<th>Bore (m)</th>
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</tbody>
</table>

Italics indicates a magnet not yet operational.

- Monolithic, Bronze Route Nb$_3$Sn (900 MHz)
- 900 MHz, 21.1 T
- ADMX 7 T
- Julich 9.4 T
### Today’s Solenoids: Stabilized Rutherford-Cable

<table>
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<th>$B_0^2V$ (T²m³)</th>
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¹Materials 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

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*Italicics indicates a magnet not yet operational.* $^2$US inner module $50M per Minervini.

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Cable-in-Conduit Conductor
(45 T: 10 kA, 14 T Nb$_3$Sn)

MagLab 45 T Hybrid

ITER Central Solenoid Module
Recent MagLab Hybrid Magnet Projects:
Three CICC Coils with Common Conductors

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

$B^2V = 36 \text{T}^2 \text{m}^3$
(Outer Coil Alone)
Field vs Bore

High $B_0^2V$ ➔ Large Bore

Small Cavities ➔ Ultra High Fields

Long Duration ➔ High Temp Superconductors

Region of interest for small cavities, long-duration

Existing Magnet  ○ Magnet in Construction  ○ Preliminary Design

MagLab 60 T
$B_0^2V = 290$

MagLab 900 MHz
$B_0^2V = 5$

ISEULT
$B_0^2V = 430$

ADMX
$B_0^2V = 12$

ITER CS
$B_0^2V = 12,000$

LHC CMS
$B_0^2V = 5,300$
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!
- \((\text{Bi2212, Bi2223, & REBCO superconduct at > 100 T!})\)

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

MagLab projects by ΔB

HTS magnet publications

Peak central magnetic field trend

Peak winding current-density trend

open symbols: BSCCO
solid symbols: ReBCO

1 T 3 T 5 T

year [-]


B_{CM} [T]

J_{ave} [A/mm^2]

10 15 20 25 30 35

0 5 10 15 20 25 30 35

20 µm Cu

< 0.1 mm

50 µm Hastelloy substrate

20 µm Cu

2 µm Ag

1 µm HTS

~ 30 nm LMO

~ 30 nm Homo-epi MgO

~ 10 nm IBAD MgO

2G YBCO Tape – SuperPower - 2007
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: $5 \times 10^{-4}$ 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
- High-B coils
- 31 T + ΔB
- Demonstration inserts
- 20 T + ΔB
- 2008
- High Hoop-stress coils
- >760 MPa
- 2009
- 2010
- First Quench Heaters
- 42-62 Mark 1: 1st test coil
- 2011
- 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
• 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

- No coil damage in 20-s “over-current” operation

- Coil quench at $I_{op} = 412$ A ($1580 \text{ A/mm}^2$)
- $32 \text{ T} \sim 200 \text{ A/mm}^2$

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/mm²
- 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
     • \( f = 23 \text{ GHz/cm} \) (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 \( \times \) diameter
     • Homogeneity within chamber: \( B_{z,\text{min}} \geq 82 \% \) of \( B_{z,\text{max}} \)
  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
     • \( B < 1 \text{ mT} \) over 0.2 m axially at \( R=0.00 \text{ m} \)
     • \( B < 4 \text{ mT} \) over 0.2 m axially at \( R=0.04 \text{ m} \)
Magnet Design Using HTS

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

Yellow: HTS coil
Red: Nb₃Sn coils
Blue NbTi coils

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

\[ B_z^2 \times V = 4.8 \text{T}^2 \text{m}^3 \]
Magnet Design Using HTS

32 T style LTS: outsert

CICC style LTS: outsert, $B_z^2 \times V = 8 \, T^2 m^3$
Axion Detector Magnet Comparisons

<table>
<thead>
<tr>
<th>Style</th>
<th>Diameter (cm)</th>
<th>Height (cm)</th>
<th>Volume (m$^3$)</th>
<th>f (GHz)</th>
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<td>0.196</td>
<td>0.46</td>
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<td>LTS Only</td>
<td>16</td>
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<tr>
<th>Style</th>
<th>$B_0$ (T)</th>
<th>$B^2 \times V$ (T$^2$m$^3$)</th>
<th>HTS $J_{AVE}$ (A/mm$^2$)</th>
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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).
- **2017 – 2026**: propagation of HTS magnets into various applications (axion detection, neutron-scattering, pre-clinical MRI, NMR, human-MRI, 60 T hybrids, etc.)

<table>
<thead>
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<th>Year</th>
<th>Materials</th>
<th>Year</th>
<th>High-Field User Magnets</th>
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<tr>
<td>2007</td>
<td>High-Strength REBCO</td>
<td>2017</td>
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<td>2013</td>
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<td>2016</td>
<td>High-Strength Bi2212</td>
<td>2017</td>
<td>MagLab 20 T Ni-REBCO</td>
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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

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Design</th>
<th>Materials</th>
<th>Fabrication</th>
<th>Facilities</th>
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<td>K. Han</td>
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36 T SCH Magnet Project
M.D Bird, I. R Dixon

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Science
T. Cross
W. Brey
I. Litvak

Materials
K. Han
J. Lu
S. Bole
T. Adkins
K. Cantrell
A. Trowell
S. Gundlach
M. White
S. Hannahs
A. Powell
P. Noyes
Bonninghausen

Facilities
J. Kynoch
C. Rodman
V. Williams
R. Lewis
W. Nixon
G. Nix
J. Maddox
L. Windham
Thank You!

dixon@magnet.fsu.edu