Ultra-High Field Magnets for Neutron Scattering

Mark D. Bird, Ph.D.,
Director of Magnet Science & Technology
Outline

• Introduction to the National High Magnetic Field Laboratory
• State of the Art DC Magnets for Neutron Scattering
• Status of REBCO Solenoid Development
• Status of Solenoid Development with other HTS Materials
• Some Comments on Vertical Split HTS magnets for Neutron Scattering
• Some Comments on Pulsed Magnets for Neutron Scattering
National High Magnetic Field Laboratory

Florida State University

1.4 GW Generator

Los Alamos National Laboratory

101T Pulse Magnet
10mm bore

11.4T MRI Magnet
400mm warm bore

University of Florida

Advanced Magnetic Resonance Imaging and Spectroscopy Facility

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

High B/T Facility
900MHz, 105mm bore
21T NMR/MRI Magnet

17T, 6 weeks at 1mK

900MHz, 105mm bore
21T NMR/MRI Magnet
The MagLab Mission: 1990–present

- Operate a world-leading high-magnetic-field user program
- Carry out in-house research in support of the user program
- Maintain facilities and develop new magnets/instrumentation
- Conduct education and outreach activities

The Latest Greatest Hits:

- 2017: 36 T series connected hybrid (1.5 GHz NMR, 1.0THz EMR)
- 2017: 41.5 T resistive magnet
- 2017: 32 T HTS magnet
- 2018: 45.5 T HTS test coil
- 2020: 77 T duplex pulsed magnet (capacitor-bank-driven)
Three Major MagLab Research Themes

MATERIALS  ENERGY  LIFE

Mass in Dalton (a.m.u.)

Oxygen doping $\delta$

Underdoped  Optimal $T_c$  Overdoped

Superconductivity

Hole doping $\rho$

Temperature $T$
In 2019, the MagLab User Program helped to train ~300 postdocs and ~730 graduate students and published ~440 refereed papers, including...

In 2019, the MagLab hosted experiments by more than 2,050 users from 162 institutions across the United States....

...and a total of 298 institutions from throughout the world.

Every year, more than 20% of the experiments’ Principal Investigators are first-time-ever PI’s at the MagLab

7 Proc. of National Academy of Sciences
39 Nature Journals
11 Physical Review Letters
41 Physical Review B
6 Journal of American Chemical Society
MagLab Users by Discipline for each Facility

Traditional High Field Facilities

- ≤ 45 T
- ≤ 100 T (~10 ms)
- ≤ (20 T/0.1 mK)

Magnetic Resonance Facilities

- ≤ 21.1 T, 10 ppb
- ≤ 17 T
- ≤ 21.1 T, 40 cm
- ≤ 11 T, 40 cm
- ≤ 21.1 T, 1 ppm

- DC Field
- Pulsed Field
- High B/T
- EMR
- NMR
- AMRIS
- ICR

- Biology, Biochemistry, Biophysics
- Chemistry, Geochemistry
- Magnets, Materials, Testing, Instrumentation
- Engineering
- Condensed Matter Physics
Purpose: Deliver State-of-the-Art (dc) Magnets to the MagLab’s User Facilities.

Develop Necessary Technologies
   (In collaboration with Applied Superconductivity Center)

Design
   (To meet the requirements of the User Facilities)

Construct
   (In-house, at commercial shops, with other government labs)

Commission
   (In collaboration with the user Facility at MagLab or elsewhere)

The MagLab has developed numerous enabling technologies that have been adopted by ~20 labs worldwide

- MagLab Records
  - 101T/10msec, 2012
  - 60T/0.1 sec, 1998
  - 45T Hybrid, 2000
  - 41.5T Resistive, 2017
  - 32T Supercon, 2017

- 36T/1ppm Series Connected Hybrid, 2017
- 26T Neutron Scattering Magnet (Berlin), 2015
- 25T Split Resistive Magnet, 2011
- 21T/105mm Small Animal MRI, 2004
The high-luminosity upgrade of the LHC (approved/ongoing)

x10 more data in 2037 than at the end of nominal LHC (2023)

MagLab personnel led the development of Hf-doped Nb$_3$Sn wire in the LHC Accelerator Research Program (LARP) that developed the world-record quadrupole magnet design, several of which are now being built in the US and sent to CERN:

This will help increase the brightness of the collider by a factor of 10!

1.2 km of new technologies, in particular new-generation superconducting magnets (strong contribution from the US)

$\rightarrow$ fundamental milestone also for future, more powerful colliders
State of The Art for Scattering Magnets

Field (T) vs. Solid Angle (steradians)

- Grenoble
- MIT
- HZB VM-1
- Tallahassee
- HZB Hybrid
- Birmingham

MagLab Res/LTS Magnets
Commercial Low-Tc Magnets
Hybrid Magnet

13 T, 50 cm Bore Superconducting outer magnet with low electric power consumption.

30° conical space for neutron scattering.

12 T Removable Conical Resistive inner magnet where the field is too high for superconductors.

The capital costs are dominated by the superconducting outsert, power & cooling equipment. The operating costs are dominated by the electricity for the resistive insert.
State of The Art for Scattering Magnets

WHAT SCATTERING MAGNETS SHOULD BE DEVELOPED IN THE FUTURE?
State of The Art for Scattering Magnets

WHAT SCATTERING MAGNETS SHOULD BE DEVELOPED IN THE FUTURE?
The Age of Hi-\(T_c\) Magnets is Arriving!

These magnets are all “simple” solenoids. Split magnets not shown.

![Graph showing the timeline of Hi-\(T_c\) discoveries and achievements](image-url)

- **Discovery of Hi-\(T_c\) materials**
- **Hi-\(T_c\) Test Coils**
- **Availability of High-Strength, Stabilized, Reacted Hi-\(T_c\) Conductors**

- **SC User Magnets**
- **NI-REBCO**
- **32 T**
32 T magnet: User Service

User Service starting now!

The 32 T will provide a unique combination of high field and low noise to the MagLab’s user community!

Major Milestone in road to 40 T!

Liz Green, a Research Faculty member at the MagLab, leads the 1st User Experiment in the 32 T magnet performing NMR measurements of a frustrated magnet system.

The 32 T magnet is unique worldwide. The combination of intense stable field enables experiments not possible elsewhere worldwide.
32 T Test Data

Current bore
Uniformity 1 cm DSV  34 mm
Operating temperature  4.2 K
Helium Consumption  32 liters for this run
Projected He Consump. 40 liter/day at steady field

+32 T central field

2 x 1 hour charging time

-32 T central field

Peak field (32.1 T) later confirmed with $^{63}$Cu NMR measurement

Weijers, et al., Arneil Reyes, et al.,
**Conductor**  
Worked closely with SuperPower and DOE labs to improve quality of REBCO tape supply.

**Joints**  
168 @ <40 nOhms.  
>20,000 cycles at 0.4% strain.

**Insulation**  
Developed ceramic insulation 8 μm thick.

**Analysis**  
Most extensive quench analysis of coupled HTS & LTS magnets.

**Protection System**  
Monitors 56 double-pancakes including 168 joints.  
Delivers 180 kW for 1.0 sec to 54 heaters with redundancy.

**3 Clamping System**  
Provide clamping to both coils throughout the assembly process & operations while allowing relative motion during operations.

**Prototypes**  
1/5 length prototypes tested to > 100 quenches and up to 135% of operating strain.
### HTS Magnets for Science @ >23.5 T Worldwide

<table>
<thead>
<tr>
<th>Field</th>
<th>Conductors</th>
<th>Maker</th>
<th>Location</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.5 T</td>
<td>Bi-2223 + LTS</td>
<td>Toshiba</td>
<td>Sendai</td>
<td>2017</td>
</tr>
<tr>
<td>32.1 T</td>
<td>REBCO + LTS</td>
<td>MagLab</td>
<td>Tallahassee</td>
<td>2017</td>
</tr>
<tr>
<td>26 T</td>
<td>REBCO</td>
<td>Hahn</td>
<td>Daejeon</td>
<td>2018</td>
</tr>
<tr>
<td>25.8 T (1.1 GHz)</td>
<td>REBCO + LTS</td>
<td>Bruker</td>
<td>Nashville</td>
<td>2019</td>
</tr>
<tr>
<td>28.2 T (1.2 GHz)</td>
<td>REBCO + LTS</td>
<td>Bruker</td>
<td>Florence</td>
<td>2020</td>
</tr>
<tr>
<td>28.2 T (1.2 GHz)</td>
<td>REBCO + LTS</td>
<td>Bruker</td>
<td>Zurich</td>
<td>2020</td>
</tr>
</tbody>
</table>

There have been many test coils >23.5 T, but there are only 6 magnets in service.
The MagLab is leading the way in both User Magnets and test coils.
The Age of Hi-\(T_c\) Magnets is Arriving!

These magnets are all “simple” solenoids. Split magnets not shown.

- **Discovery of Hi-\(T_c\) materials**
- **Hi-\(T_c\) Test Coils**
- **Availability of High-Strength, Stabilized, Reacted Hi-\(T_c\) Conductors**

**SC User Magnets**

- **MagLab Records**

**Year**
- 1961
- 1971
- 1981
- 1991
- 2001
- 2011

**Magnetic Field (T)**
- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
- 40
- 45
- 50

**Magnetic Field Levels**
- 32 T
- 40 T

NI-REBCO
MagLab’s I-REBCO Magnets – World Leaders

Project Leader Hongyu Bai & Pit for 40 T SC Magnet

MagLab 32 T Highest Field SC Magnet WorldWide

Project Leader Hongyu Bai & Pit for 40 T SC Magnet

Stage | Duration
---|---
Year 1 R&D | Oct 2018 – Dec 2019
Year 2 Conceptual Design | Dec 2019 – Mar 2021


Screening Currents: Tape Conductors

- $J_t$ = transport current in $\theta$ direction. It creates $B_z$. At top of magnet $B_r$ is positive.
- During charging of the magnet, $B_r$ creates screening currents, $J_s$, in the tape.
- The Screening Current changes the field distribution.

Screening currents also interact with the axial field to produce a “Diamagnetic Torque” on the tape.

The FLOrida Screening-current Strain Software (FLOSSS) computes the screening currents, the field due to them, the strain, and the ac losses. It is the product of a collaboration of researchers at the MagLab, the Karlsruhe Institute of Technology, and Universidad Nacional Autónoma de México.

The Screening Current Induced Field (SCIF) is the difference between the actual field (including screening currents) and what the field would be without screening currents.

For 8 years people have used the “V1” algorithm to compute SCIF for low-field magnets [1-3].

For highly stressed magnets, the “V2” algorithm includes the effect of rotation of the tape on the induced currents and agrees better with measured data [4].

The MagLab has demonstrated 4,800 cycles in a REBCO coil (~10x more than others). Screening-current induced effects were measured:

- Strain (strain gauges)
- Field (Hall probe)

A test coil consisting of 6 double-pancakes

Measurements agree very well with calculations using the “V2” algorithm.
Development for Split Magnets

- Subject solenoids and splits to axial compression.
- Install in existing 12 T split LTS magnet at MagLab.
- Apply cyclic axial compression with MTS machine.

Test will demonstrate:
1) Fatigue under axial compression similar to mid-plane of real 25 – 35 T split magnet
2) Sliding fatigue at the interface between the mid-plane spacer and the coils of 25 – 35 T split magnet.

Total Field > 15 T

One split coil funded in late 2020 by US Department of Energy (DOE) Office of Basic Energy Science (BES) Small Business Technology Transfer (STTR)

One solenoid funded by 40 T early 2021.
MagLab/OI Split Magnet & Mechanical Test System

Existing 12 T split magnet & MTS machine at MagLab.

Used extensively to test Cable-In-Conduit-Conductor at 20 kA, in 12 T at 4 to 20 K with up to 250 kN of tension/compression.
Axial Pressure Test

• Small double pancakes have been fabricated for testing the 500 kN MTS system
• The critical current as a function of axial pressure and cycles will be measured
• Two coils have been fabricated, one coil with co-wind wider than the REBCO and one more narrow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 (mm)</td>
<td>15</td>
</tr>
<tr>
<td>A2 (mm)</td>
<td>25</td>
</tr>
<tr>
<td>L (mm)</td>
<td>8.4</td>
</tr>
<tr>
<td># Pancakes</td>
<td>2</td>
</tr>
<tr>
<td>Tape Width (mm)</td>
<td>4.05</td>
</tr>
<tr>
<td>Spacer thickness (mm)</td>
<td>0.3</td>
</tr>
<tr>
<td>HTS Δt (mm)</td>
<td>0.095</td>
</tr>
<tr>
<td>HTS Turns per pancake</td>
<td>68</td>
</tr>
</tbody>
</table>
Why do we need Development for REBCO magnets?

<table>
<thead>
<tr>
<th>Concern</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue Testing</td>
<td>MagLab is leading the way in fatigue testing of HTS conductor &amp; coils.</td>
</tr>
<tr>
<td>Axial Compression</td>
<td>MagLab has performed some axial pressure tests.</td>
</tr>
<tr>
<td>Novel features of Splits</td>
<td>MagLab has performed some fatigue testing of split REBCO coils. More work Required</td>
</tr>
<tr>
<td>Operation at higher current density</td>
<td>MagLab will be testing a coil at record current density in June.</td>
</tr>
</tbody>
</table>
Split Field vs Mid-Plane for magnets based on MagLab 32 T

<table>
<thead>
<tr>
<th>Location</th>
<th>Gap</th>
<th>Angle</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZB/ESS 2012</td>
<td>20 mm</td>
<td>+/− 10°</td>
<td>25 T</td>
</tr>
<tr>
<td>APS 2016</td>
<td>5 mm</td>
<td>+/− 4°</td>
<td>25 T</td>
</tr>
<tr>
<td>SNS 2019</td>
<td>17 mm</td>
<td>+/− 5°</td>
<td>25 T &amp; 35 T</td>
</tr>
</tbody>
</table>

Attainable field for fixed magnet size depends heavily on mid-plane configuration.

MagLab Response

21 T

MagLab Response

25 T

MagLab Response

Will Require Larger Magnet
Bi-2223 is multifilamentary.
Made by Sumitomo.
Is available with high strength laminations.

Bi-2212 is multifilamentary round wire.
Made by Bruker-OST.
Development of high-strength versions is underway.

REBCO tape w/ single-filament ~1 um film on a substrate (frequently Hastelloy or SS), Ag, Cu.
High mechanical strength.
1st UHF coil by SuperPower, now made by several suppliers.

(Used for both NI- & I-REBCO)
Superconducting Materials used for Magnets

**NbTi**
- The most commonly used SC material (<12 T).

**Nb<sub>3</sub>Sn**
- Most SC magnets > 12 T.
- High field condensed matter physics.
- High Field NMR.
- Fusion confinement.

**High Temperature Superconductors (HTS)**
- >23.5 T requires HTS.
- Bi<sub>2</sub>Cr<sub>2</sub>Ca<sub>2</sub>Cu<sub>3</sub>O<sub>x</sub> Bi2223
- Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>y</sub> (Bi2212),
- REBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-x</sub> (ReBCO),

For magnets >20 T, higher current density (smaller coil-pack) is attained w/ HTS.

The MagLab also is leading the development of ultra-high field coils using Bi-2212.

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J<sub>e</sub> data provided by P. Lee, NHMFL
Pulsed Magnets

Standard pulsed Solenoids:
1 Pulse per 30 Minutes: 60T for 10msec

Existing Conical Scattering:
“Mini-Coils” 1 Pulse per 5 Minutes: 30T for 1 – 4 msec
“Macro-Coils” 1 Pulse per 7 Minute: 40T for 20 msec

Developmental Split Scattering:
“Next-Gen” 1 Pulse per Minute: 25 – 40T for 1 – 5msec
“Rapidly-Pulsed” 1 Pulse per Second: 20 – 30 T for ~ 1 msec
Existing Pulsed Magnets for Scattering

Various combinations of:

- field intensity,
- pulse length,
- bore,
- repetition rate,
- & magnet size

are available.

“Mini-coil”
~6 mm bore, 1 kJ, <$10k.
Magnet & sample at similar temperatures.

“Traditional”
~18 mm bore, 100 kJ, >$10k.
Magnet pre-cooled to 77 K.
LHe cryostat in bore of magnet.

IMR, Tohoku Univ

Nojiri has delivered pulsed min-coils to numerous neutron & x-ray scattering facilities.
40 T from LNCMI to ILL

It is a nitrogen-cooled large angle pulsed magnet, 1 MJ, rise time 20 ms, 40 T, with 7 minutes repetition time.

- Geert Rikken, 2/28/2014 e-mail
Design summary:
Magnet Bore = 16.0 mm
Split Gap = 8.0 mm

Conductor stresses are low enough for 50k cycles

1 pulse per minute
1 – 5 msec pulses

© 2014 NHMFL: Proprietary
Prototype Rapidly-Pulsed Magnet

Proposed for Neutron Scattering at LANSCE
Desired Specs: 30T, 1 Hz Repetition Rate

Hole for incoming & outgoing neutrons. For x-rays, multiple such holes would be used to allow scattering through vacuum instead of aluminum.
# Pulsed Magnet Fatigue Cycles vs. Repetition Rate & Lifetime

## Repetition Interval vs. Fatigue Cycles

<table>
<thead>
<tr>
<th>Repetition Interval</th>
<th>Fatigue Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 day</td>
</tr>
<tr>
<td>minutes seconds</td>
<td></td>
</tr>
<tr>
<td>30 1800</td>
<td>48</td>
</tr>
<tr>
<td>15 900</td>
<td>96</td>
</tr>
<tr>
<td>5 300</td>
<td>288</td>
</tr>
<tr>
<td>10</td>
<td>8,640</td>
</tr>
<tr>
<td>2 43,200</td>
<td>302,400</td>
</tr>
<tr>
<td>1 86,400</td>
<td>604,800</td>
</tr>
<tr>
<td>0.5 172,800</td>
<td>1,209,600</td>
</tr>
</tbody>
</table>

Fatigue Cycles Assuming 24-hr/day, 7 day/week operation

Introducing Cooling Channels into a magnet:
- Accelerates Cool-Down
- Reduces Average Current Density
- Increases Size (for fixed field)
- Increases Stress \((j \times B \times r)\)
- Shortens Lifetime (for fixed field)
Conclusions

- **Hi-T\textsubscript{c}** magnets are now becoming a reality at fields greater than available from Low-T\textsubscript{c} materials!
- There are only a few **solenoids** worldwide using Hi-T\textsubscript{c} materials operating at higher field than Low-T\textsubscript{c} magnets.
  - 24.5 T for condensed matter physics in Sendai
  - 25.8 T for NMR in Memphis
  - 26 T for axion detection in Daejon
  - 28.2 T for NMR in Florence & Zurich
  - 32 T for condensed matter physics in Tallahassee
- The field available from a split magnet of a particular size (cost) depends greatly on the details of the **split geometry**
  - Vertical gap
  - Vertical take-off angle
  - Number of ports
- Development is needed to enable reliable **split magnets** for neutron scattering.
  - Fatigue of HTS coils
  - Effects of axial compression
- A new design study is being funded by SNS to update the report we created in 2012 for ESS and HZB.