UHF DC Magnets at the NHMFL

Mark D. Bird, Ph.D.
Director, Magnet Science and Technology
National High Magnetic Field Laboratory

Florida-Bitter Magnets 1995

Supported by:
NSF National Science Foundation
National High Magnetic Field Laboratory

Florida State University
- 45T Hybrid DC Magnet
- Advanced Magnetic Resonance Imaging and Spectroscopy Facility

Los Alamos National Laboratory
- 1.4 GW Generator
- 101T Pulse Magnet 10mm bore
- 11.4T MRI Magnet 400mm warm bore

University of Florida
- 900MHz, 105mm bore 21T NMR/MRI Magnet
- High B/T Facility 17T, 6 weeks at 1mK

Los Alamos National Laboratory
- 1.4 GW Generator

University of Florida
- 900MHz, 105mm bore 21T NMR/MRI Magnet
MagLab technology has been adopted by ~20 labs worldwide.

~1500 scientists per year use the MagLab’s high-field magnets.

MagLab Records:
- 100T/1msec, 2012
- 60T/0.1 sec, 1998
- 45T Hybrid, 2000
- 35T=31T+4T HTS (HTS Test Coil, 2011)

Hefei, Resistive 38.5 T, 2014

Bruker, NMR 23.4 T, 2009

Records in 1990:
- 68T/10msec MIT
- 40T/1 sec Amsterdam
- 31T Hybrid Grenoble
- 25T/50mm Grenoble
- 20 T IGC

~100 Years of Non-Destructive Magnets
## MagLab Steps

<table>
<thead>
<tr>
<th>Magnet Class</th>
<th>Record at Project Start</th>
<th>MagLab Record or Target</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive</td>
<td>25 T</td>
<td>35 T</td>
<td>40%</td>
</tr>
<tr>
<td>Resistive/Supercon Hybrid</td>
<td>31 T</td>
<td>45 T</td>
<td>45%</td>
</tr>
<tr>
<td>Pulsed</td>
<td>60 T</td>
<td>93 T</td>
<td>55%</td>
</tr>
<tr>
<td>Split</td>
<td>18 T</td>
<td>25 T</td>
<td>39%</td>
</tr>
<tr>
<td>Neutron Scattering</td>
<td>15 T</td>
<td>26 T</td>
<td>73%</td>
</tr>
<tr>
<td>Superconducting Test</td>
<td>20 T</td>
<td>35 T</td>
<td>75%</td>
</tr>
<tr>
<td>Superconducting User</td>
<td>23.5 T</td>
<td>32 T (2016)</td>
<td>36%</td>
</tr>
<tr>
<td>Past High Resolution NMR</td>
<td>14.1 T</td>
<td>21.1 T</td>
<td>50%</td>
</tr>
<tr>
<td>Future High Resolution NMR 1</td>
<td>23.4 T</td>
<td>32.8 T</td>
<td>40%</td>
</tr>
<tr>
<td>Future High Resolution NMR 2</td>
<td>23.4 T</td>
<td>37.5 T</td>
<td>60%</td>
</tr>
<tr>
<td>Future Human Head MRI</td>
<td>10.5 T</td>
<td>20 T</td>
<td>90%</td>
</tr>
</tbody>
</table>
Superconducting Materials for Magnets

- **NbTi**: Used for existing human MRI magnets as well as accelerator and detector magnets for High-Energy Physics. Its peak field is ~10 T at 4.2 K & ~12 T at 2 K.

- **Nb<sub>3</sub>Sn**: Used for most superconducting magnets >12 T (NMR, preclinical MRI, record dc magnets, etc). Its peak field is ~22 T at 4.2 K & ~23 T at 2 K.

The emergence of High-Temperature Superconductors (HTS) in 1986 moved superconducting (SC) magnets from the $J_c$-limited regime to the stress-limited regime like pulsed & dc resistive & hybrid magnets have been in for decades. The Hastelloy-reinforced YBCO tape from SuperPower in 2007 was the first high-strength HTS material and is the core of the MagLab’s 32 T magnet.
### MagLab 32 T SC USER MAGNET

2003: 1\textsuperscript{st} 25 T SC test coil  
2008: 1\textsuperscript{st} 35 T SC test coil  
2015: 1\textsuperscript{st} 27 T all-SC test

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total field</td>
<td>32 T</td>
</tr>
<tr>
<td>Field inner YBCO coils</td>
<td>17 T</td>
</tr>
<tr>
<td>Field outer LTS coils</td>
<td>15 T</td>
</tr>
<tr>
<td>Cold inner bore</td>
<td>32 mm</td>
</tr>
<tr>
<td>Current</td>
<td>172 A</td>
</tr>
<tr>
<td>Inductance</td>
<td>619 H</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>9.15 MJ</td>
</tr>
<tr>
<td>Uniformity</td>
<td>$5 \times 10^{-4}$ 1 cm DSV</td>
</tr>
</tbody>
</table>

**Commercial Supply:**
- 15 T, 250 mm bore LTS coils — Delivered!
- Cryostat — Delivered!
- (Dilution Refrigerator)

**In-House development:**
- 17 T, 34 mm bore YBCO coils
32 T YBCO Technology Development

**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

**Prototype coils** represent 20% of 32 T REBCO coils

**2007**
- High-B coils
  - 31 T + ΔB

**2008**
- Demonstration inserts
  - 20 T+ ΔB
- High Hoop-stress coils
  - >760 MPa

**2009**
- Quench heater
- 1st Full-featured Prototype

**2011**
- First Quench Heaters
- 42-62 Mark 1: 1st test coil

**2012**
- 42-62 Mark 2: 2nd test coil

**2013**
- Heater-only quench protection
- 20 - 70:

**2014**
- 82 - 116:
- 2nd Full-featured Prototype

© 2014 NHMFL: Proprietary

Prototype coils represent 20% of 32 T REBCO coils

© 2014 NHMFL: Proprietary
YBCO Coil Technology

Development Completed:
- Improve YBCO tape.
- Develop Insulation.
- High-Strength Joints.
- Pancake Winding Technology.
- Quench Protection.

2\textsuperscript{nd} Prototype was tested in Aug. 2014.
- Included all features of real coils for 32 T except length.
- Intentionally Quenched >80 times without degradation.
- Was tested again w/ Outsert in June 2015

Cycled to high stress without ill effect:
- 20 cycles 100\% design stress
- 40 cycles 110\% design stress
- 2 cycles 120\% design stress

World’s First 27 T SC Test!

Quench Modelling of No-Insulation YBCO Solenoid

REBCO Pancake Test Coil

- A quench is initiated at one end of a coil in a section of conductor having low critical current
- After quench initiation, the quench propagates by a dynamic, inductive process
- A rapid quench propagation is observed over a wide range of resistance between turns

30 pancake disks
20 radial sections
Several HTS magnets developed elsewhere have been damaged due to insufficient understanding of behavior during quench.

The MagLab has performed extensive modelling & testing (>100 times) of quench in HTS coils.

W.D. Markiewicz
The MagLab is pursuing multiple conductor and coil technologies in pursuit of 30 T NMR.

Operating current, winding current density, copper current density, fraction of $I_c$ are all essentially the same as in 32 T design. Stress level is ~20% higher, ~23 km of HTS conductor versus 10 km in 32 T.

<table>
<thead>
<tr>
<th>Previously developed</th>
<th>Under development</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.1 T/900 MHz UWB</td>
<td>32 T Physics</td>
<td>30 T / 1.3 GHz NMR</td>
</tr>
<tr>
<td>21 T LTS</td>
<td>15 T LTS + 17 T HTS</td>
<td>15 T LTS, 15 T HTS</td>
</tr>
<tr>
<td>Homogeneity: ppb level</td>
<td>Homogeneity: $10^{-4}$ level</td>
<td>Homogeneity: Bio-NMR</td>
</tr>
</tbody>
</table>

HTS section shares many design parameters with 32 T design. Field homogeneity and stability are the major new challenges.

W.D. Markiewicz
36 T, 1ppm Resistive/Superconducting Magnet

- Provide a unique combination of performance parameters:
  - High field (36T)
  - High field quality (1ppm)
  - Larger bore (40 mm)
  - 1 Power Supply (13 MW)

- Enable
  - NMR experiments not possible elsewhere.
  - Demonstration of value of building high-resolution NMR magnets >30 T (where FSU is also a world leader).
  - Development of 60 T hybrid proposed by COHMAG.
# MagLab 36 T, 1 ppm Hybrid Magnet Status

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Arrived</td>
<td>Sept. 2014</td>
</tr>
<tr>
<td>Cold-Test including cold-box, cryostat, controls</td>
<td>Dec. 2014</td>
</tr>
<tr>
<td>Assembly of Cold-Mass and Current-Leads complete</td>
<td>Apr. 2015</td>
</tr>
<tr>
<td>Paschen Test Complete</td>
<td>June 2015</td>
</tr>
<tr>
<td>Cryostat Closed</td>
<td>Oct. 2015</td>
</tr>
<tr>
<td>Insert Plumbing Complete</td>
<td>Dec. 2015</td>
</tr>
<tr>
<td>Insert Coils installed</td>
<td>Jan 2015</td>
</tr>
<tr>
<td>Cool-down Complete</td>
<td>April 2016</td>
</tr>
<tr>
<td>Insert-Only</td>
<td>May 2016</td>
</tr>
<tr>
<td>36 T</td>
<td>June 2016</td>
</tr>
</tbody>
</table>
Basic cell-layout was developed in collaboration w/ user committee. Layout & schedule meetings occur every 2 weeks.
Cascade Field Regulation for 20 MW, 25 T magnet

This work can be readily extended to high-resolution HTS NMR magnets without persistent joints.

Jeff Schiano, et al., Penn State Univ.
Mapping and Shimming a 20 MW Magnet

Passive shims on probe cap

Active shims on insert tube

This work can be readily extended to HTS magnets with screening-current-based inhomogeneity.
CP MAS Low-E probe ($^1$H–X–Y)

2.0 mm $^1$H–X–Y MAS probe, 38 kHz speed

Probe is nearly complete; currently tuning RF circuit

X and Y isotopes frequencies are set by sliding TUNE CARDS

Initially for 2D experiments like $^{13}$C/$^{13}$C correlation etc.

Sealed LiCl capillary for 4$^{th}$ external freq. lock channel is located above spinner

Y-channel can double as internal $^2$H lock channel if external $^7$Li lock fails to work

Adaptations for “remote” sideways tuning (Magnet safety regulation)

Thin Cu-plated rf shield minimizes eddy current distortions in $B_0$ sensor

Sealed external lock capillary above spinner

Actual probe

Development of State-of-the-Art probes must go hand-in-hand with magnets.

Bill Brey & Peter Gorkov
DC Inter-Lab Collaboration, Tech Support and Tech Transfer

SupCon Magnets
Michigan State: We delivered Unique Nuclear Physics Magnet
Brookhaven: We developed conceptual design of Magnets for Muon-Collider.
LBL, MIT, JLab, Wellington, NIST: We test LTS & HTS Cables.

Hybrid Magnets
Lund: We performed design study of 25 – 30 T HTS mag. for neutrons.
Argonne: We developed Nb₃Sn Undulator Compts.
BNL, Twente: HTS Coil Collaboration.

Resistive Magnets
Nijmegen: We delivered 45T outsert coil & 20 kA HTS Leads.
Tsukuba: We delivered 30T
Grenoble: We delivered coils & housings for 30–35T

HZ Berlin: We are developing 25 T for neutrons.
Oak Ridge: We designed 35T for neutrons.

ITER: We characterized SC Strand, Conduit & CICCs. Contributed to resolution of Nb₃Sn problems.
Hefei: Developing 40 T w/ CICC.

Five of six largest resistive magnet labs worldwide have adopted the Florida-Bitter technology. MagLab plays the leading role in international hybrid magnet development effort.
Former MagLab personnel: Soren Prestemon, Deputy Division Dir., Lawrence Berkeley Lab; Kathleen Amm, MRI Technologies & Systems Leader, GE Global R&D; Ting Xu, Cryogenic Operations Leader at FRIB.
3 Recent Hybrid Magnets by MagLab
(Same Nb$_3$Sn Cable-In-Conduit Conductors)

Chinese & Italian as well as numerous domestic projects were rejected due to insufficient personnel.

<table>
<thead>
<tr>
<th>Helmholtz Zentrum Berlin (HZB)</th>
<th>MagLab</th>
<th>Radboud University</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berlin, <strong>Germany</strong></td>
<td>Tallahassee, FL</td>
<td>Nijmegen, <strong>Netherlands</strong></td>
<td></td>
</tr>
<tr>
<td>26 T</td>
<td>36 T</td>
<td>45 T</td>
<td>Location</td>
</tr>
<tr>
<td>13 T</td>
<td>13 T</td>
<td>12 T</td>
<td>Tot Field</td>
</tr>
<tr>
<td>50 cm</td>
<td>46 cm</td>
<td>52 cm</td>
<td>SC Field</td>
</tr>
<tr>
<td>Neutron Scattering</td>
<td>Condensed-Matter Physics</td>
<td>Condensed-Matter Physics</td>
<td>SC Bore</td>
</tr>
<tr>
<td>2015</td>
<td>2016</td>
<td>2018</td>
<td>Purpose</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operational</td>
</tr>
</tbody>
</table>
In 2014 The MagLab delivered a 26 T magnet for neutrons scattering to the Helmholtz Zentrum Berlin.

The superconducting part of this magnet provides 13 T in a 50 cm horizontal bore.
MRI Magnet Field vs Bore

Field (T) vs Bore (m)

- Existing
- Underway
- Targets

MagLab
Neurospin
NIH
Minnesota
Juelich
Iseult
HTS
Nb3Sn
NbTi

NbTi only
Nb3Sn Required
High Temperature Superconductors
The National High Magnetic Field Lab in Tallahassee, Florida presently operates a 21.1 T, 105 mm bore NMR magnet for small animal MRI! Image quality improves dramatically with field!

In-Vivo proton MRI of rat-head @ 21.1 T (A) and 9.4 T (B). Both MRI images were acquired using spin echo pulse sequence and the same imaging parameters. The resolution of images was 0.137 x 0.137 x 0.41 mm³ [1].

20 T MRI magnets with various bores (up to 90 cm) can be built using traditional Low-Temperature Superconductors (LTS, NbTi & Nb₃Sn). This has not been done due to cost and safety concerns.

## Perspective on 20 T MRI Magnet

**11.75 T, 90 cm Whole-Body**  
Under Construction, due 2014 (Iseult)

**20 T, 68 cm Head-Only**  
Preliminary Concept

---

### Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Iseult</th>
<th>MagLab 20 T Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Mass (Ton)</td>
<td>65</td>
<td>~35</td>
</tr>
<tr>
<td>Stored Energy (MJ)</td>
<td>338</td>
<td>~350</td>
</tr>
<tr>
<td>Current Density (A/mm²)</td>
<td>26.4</td>
<td>~40</td>
</tr>
<tr>
<td>Magnet Design</td>
<td>CEA</td>
<td>MagLab</td>
</tr>
</tbody>
</table>

---

**HTS & High-Strength materials at 4 K operate at high field and current-density resulting in compact magnets.**
## 32 T SC Magnet Project
- **H.W. Weijers**
- **W.D. Markiewicz**

### Analysis
- **W.D. Markiewicz**
- **A.V. Gavrilin**
- **H.W. Weijers**
- **D. Hilton**
- **P. Noyes**

### Design
- **A. Voran**
- **S. Gundlach**
- **Y. Viouchkov**
- **S. Bole**

### Materials
- **D. Larbalestier**
- **D. Abraimov**
- **J. Lu**
- **D. McGuire**
- **B. Walsh**

### Fabrication
- **T. Painter**
- **T. Xu**

## 36 T SCH Magnet Project
- **M.D. Bird**
- **I.R. Dixon**

### Analysis
- **I.R. Dixon**
- **H. Bai**
- **T. Painter**
- **S. Marshall**
- **J. Toth**
- **Y. Zhai**
- **T. Xu**

### Design
- **S. Bole**
- **T. Adkins**
- **K. Cantrell**
- **S. Napier**
- **A. Trowell**
- **S. Gundlach**
- **M. White**
- **G. Miller**

### Materials
- **K. Han**
- **J. Lu**
- **B. Walsh**
- **B. Goddard**
- **V. Toplosky**
- **J. McRae**

### Fabrication
- **L. Marks**
- **R. Stanton**
- **D. Richardson**
- **M. Leuthold**
- **N. Walsh**
- **N. Adams**
- **L. English**
- **J. Lucia**
- **J. Deterding**
SUMMARY

• HTS Materials enable a revolution in UHF NMR (> 30 T).
  – The MagLab will deliver a 32 T superconducting user magnet in 2016.
  – We are pursuing 1.4 GHz (32.8 T) high-resolution NMR.

• Large-Scale Nb$_3$Sn magnet technology can be applied to human MRI magnets >14 T.
  – The MagLab has built 13 – 14 T SC magnets with 50 – 60 cm room-temperature bores.
  – Higher fields in larger bores with High-Homogeneity is feasible.

• 20 T human-head MRI will likely require HTS materials on a large scale.