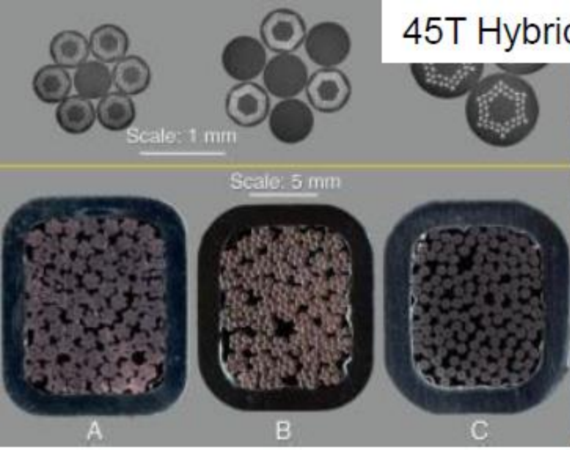
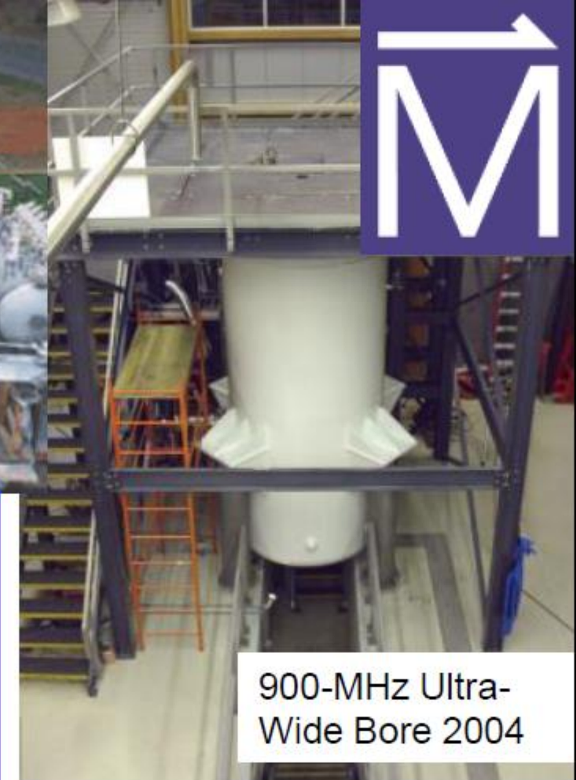


45T Hybrid 1999



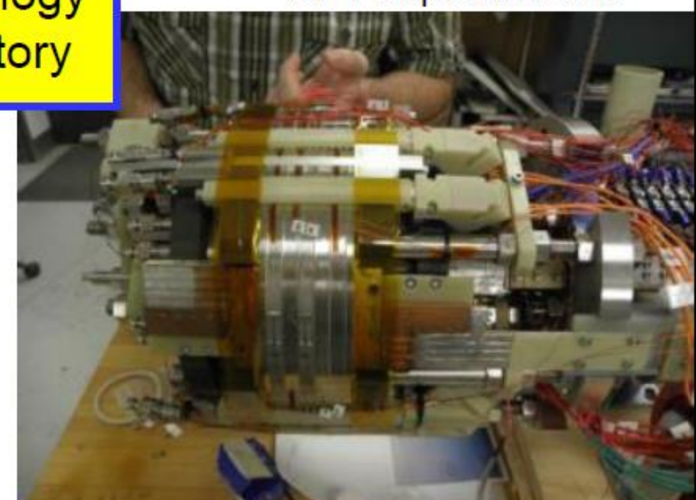
900-MHz Ultra-Wide Bore 2004

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

27 T Supercon 2015



Supported by:
National Science Foundation

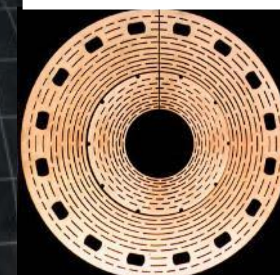
National High Magnetic Field Laboratory

1.4 GW Generator

Florida State University

Los Alamos National Laboratory

45T Hybrid
DC Magnet

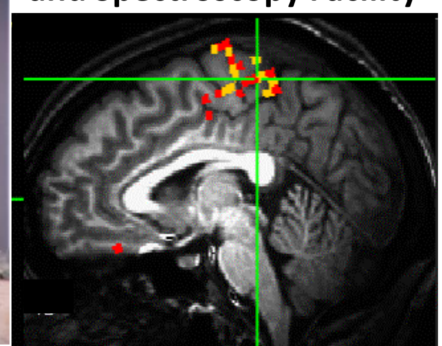


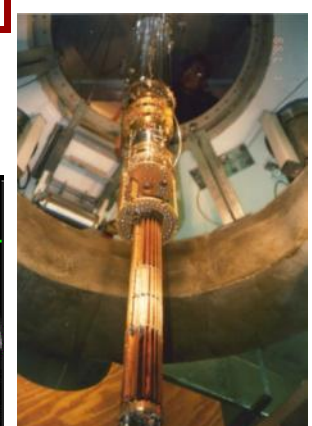
101T Pulse Magnet
10mm bore

University of Florida

Advanced Magnetic
Resonance Imaging
and Spectroscopy Facility

11.4T MRI Magnet
400mm warm bore

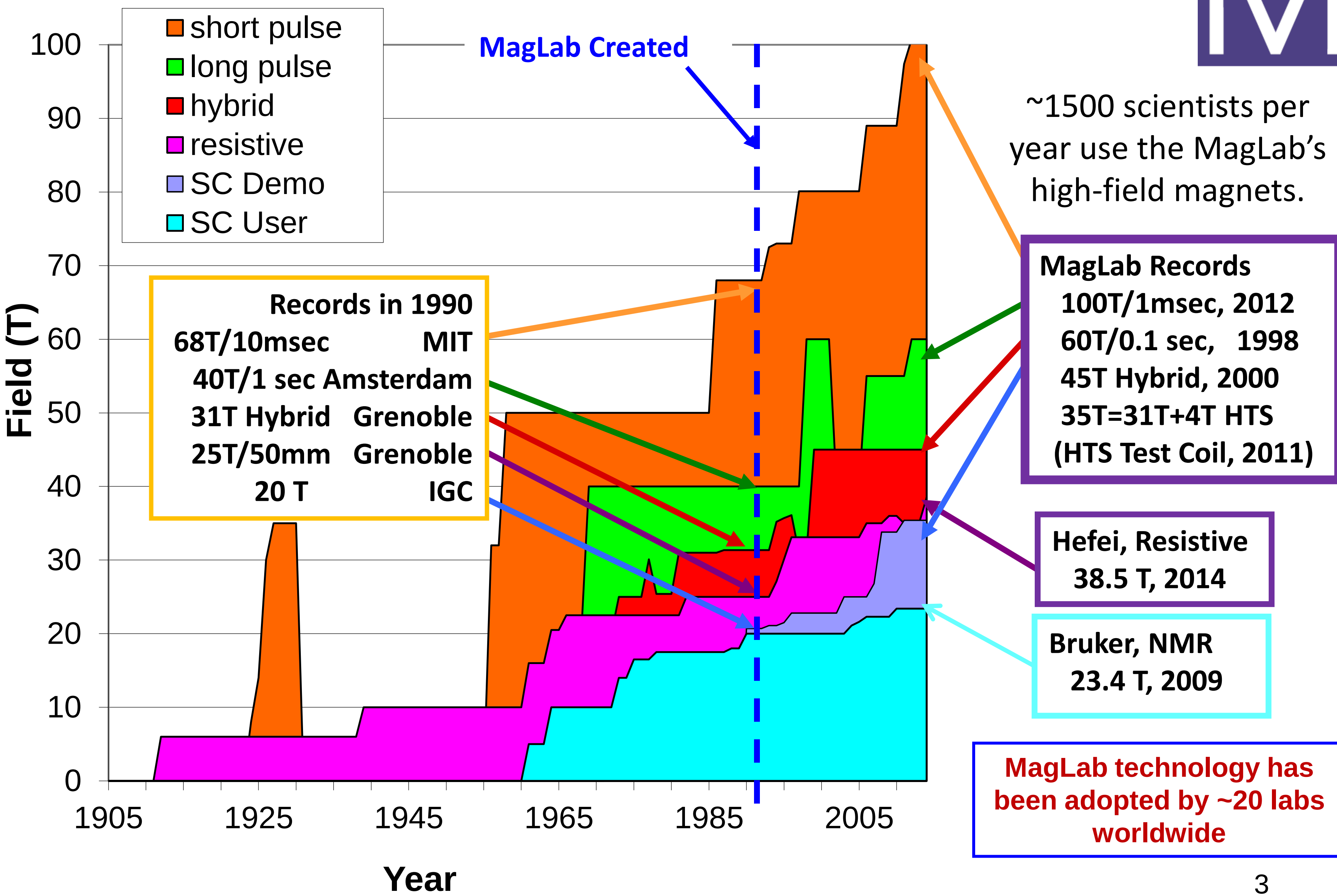




High B/T Facility
17T, 6weeks at 1mK

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

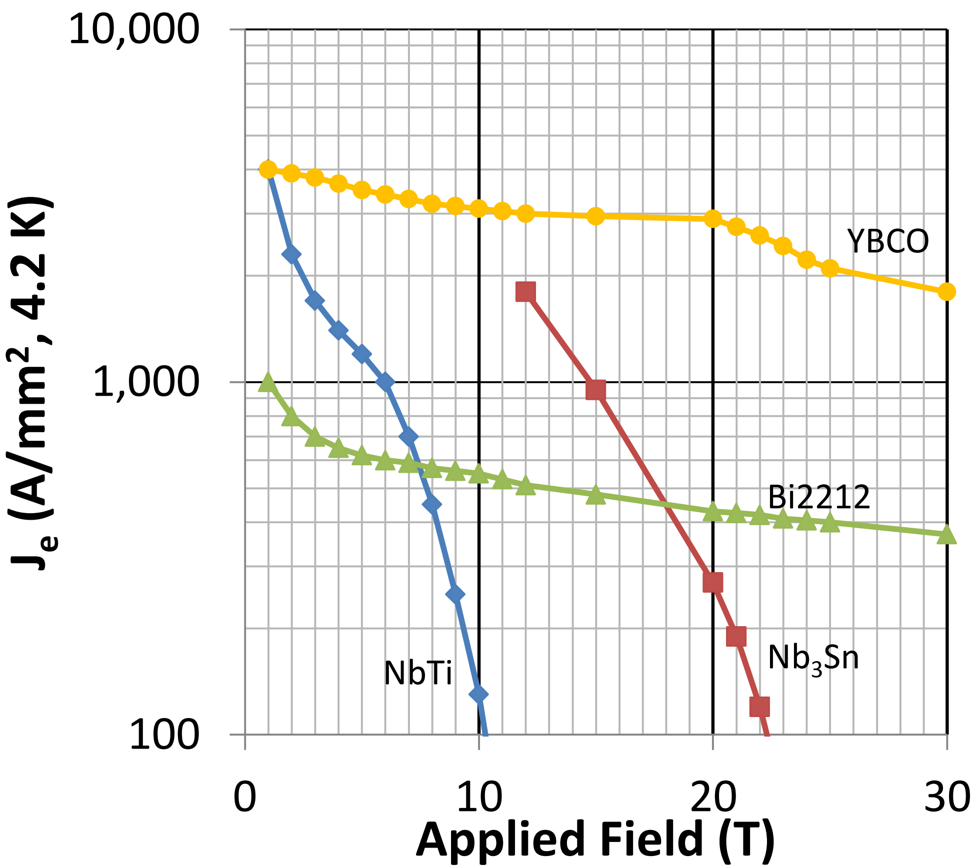
~100 Years of Non-Destructive Magnets



MagLab Steps

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

Superconducting Materials for Magnets



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.

NbTi is used for existing human MRI magnets as well as accelerator and detector magnets for High-Energy Physics.

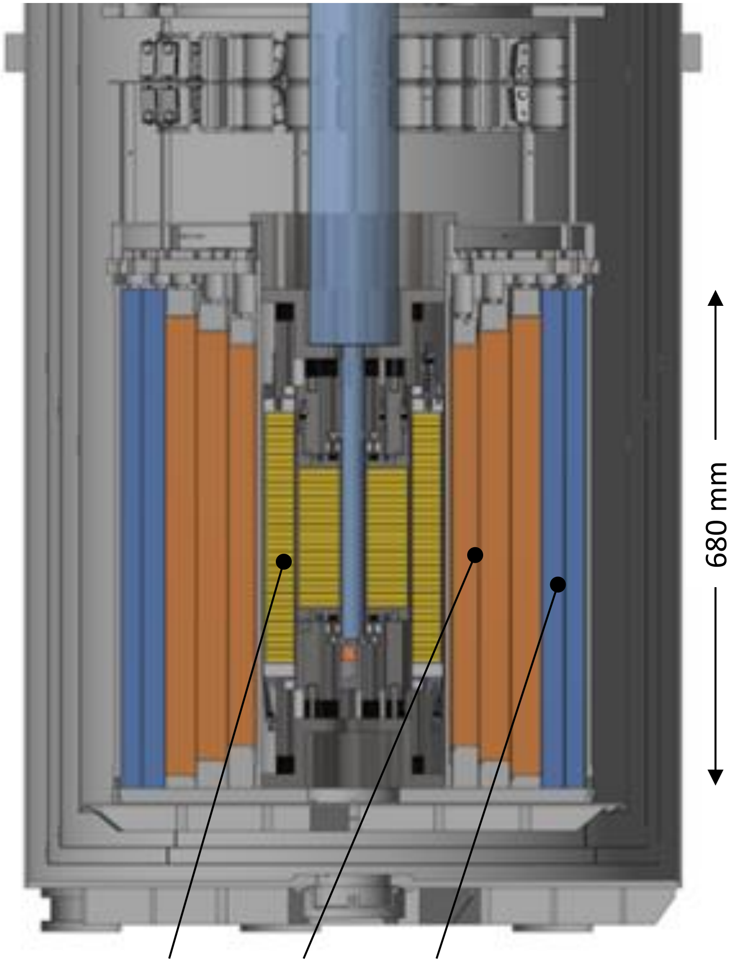
Its peak field is ~10 T at 4.2 K & ~12 T at 2 K.

Nb_3Sn is 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.

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	$5\text{x}10^{-4}$ 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

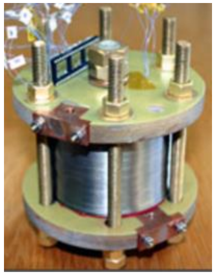
32 T YBCO Technology Development

<u>Development:</u>

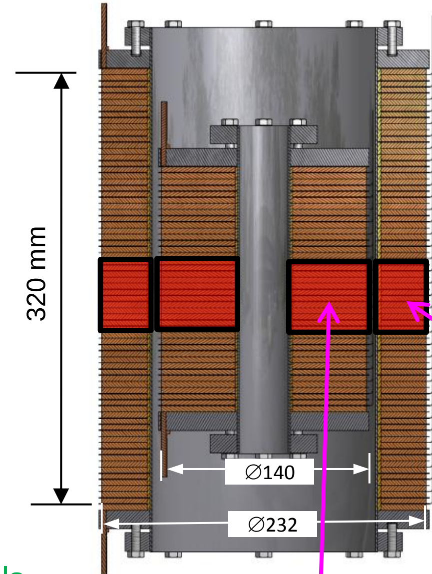
- YBCO tape characterization & QA
- Insulation technology
  - Ceramic on co-wound SS tape
- Coil winding technology
- Joint technology
- Quench analysis & protection
- Fatigue testing of components

Prototype coils represent 20% of 32 T REBCO coils

2007



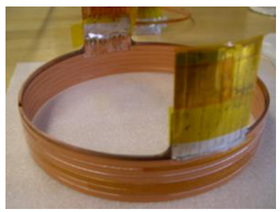
2008

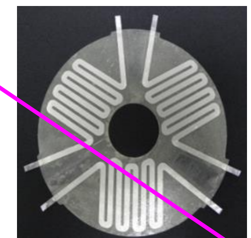


2008

High-B coils
31 T + ΔB

2009



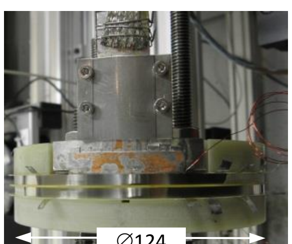


Quench heater

Demonstration inserts
20 T+ ΔB

High Hoop-stress coils
>760 MPa

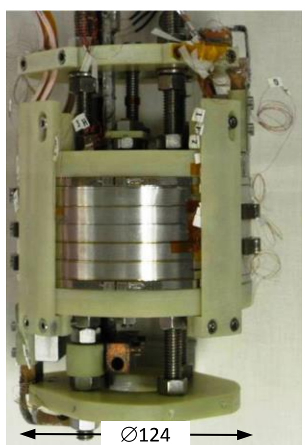
2011



First Quench Heaters

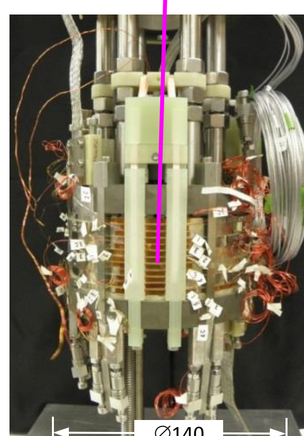
42-62 Mark 1:
1st test coil

2012



42-62 Mark 2:
2nd test coil

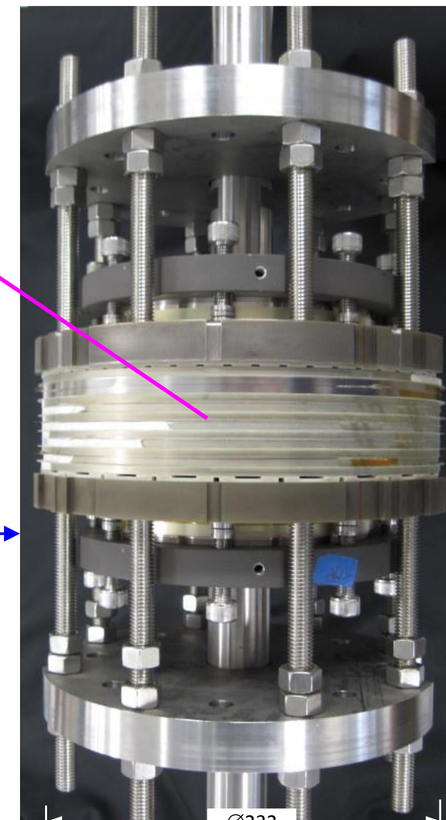
2013



20 - 70:
1st Full-featured Prototype

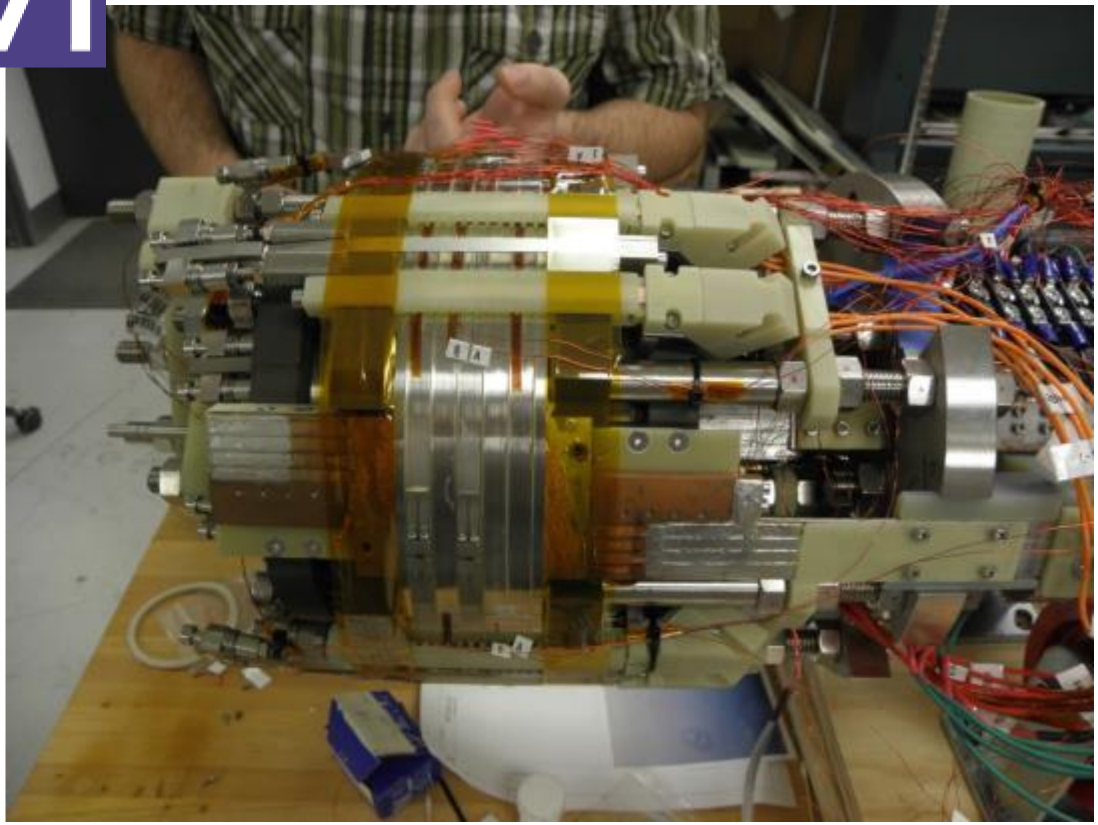
Heater-only quench protection

2014



82 - 116:
2nd Full-featured Prototype

YBCO Coil Technology



- Development Completed:
  - Improve YBCO tape.
  - Develop Insulation.
  - High-Strength Joints.
  - Pancake Winding Technology.
  - *Quench Protection.*
- 2nd 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
- World's First 27 T SC Test!

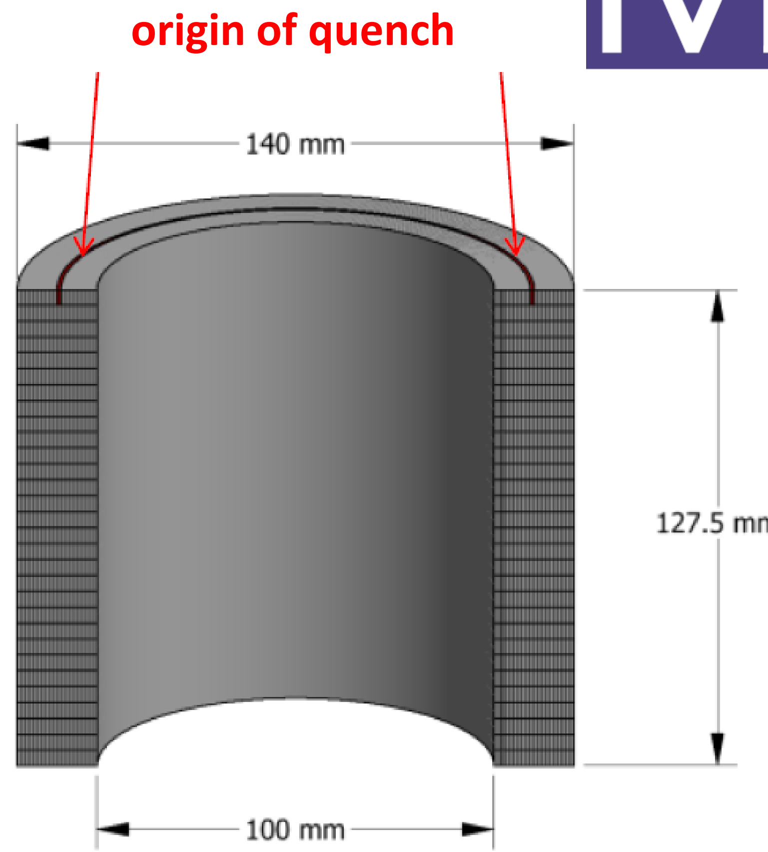
- Cycled to high stress without ill effect:
  - 20 cycles 100% design stress
  - 40 cycles 110% design stress
  - 2 cycles 120% design stress

Weijers, Markiewicz, Voran, Abraimov, Bai, Gavrilin, Gundlach, Hannahs, Hilton, Lu, Noyes, Painter, Viouchkov,, White, et al.

Quench Modelling of No-Insulation YBCO Solenoid

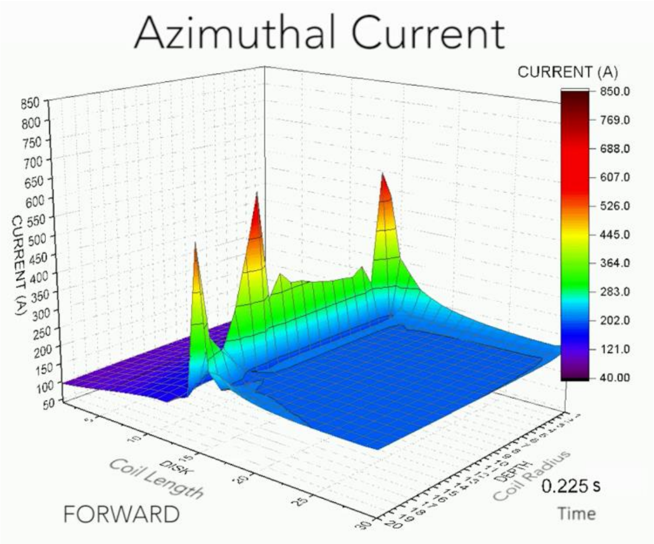
REBCO Pancake Test Coil

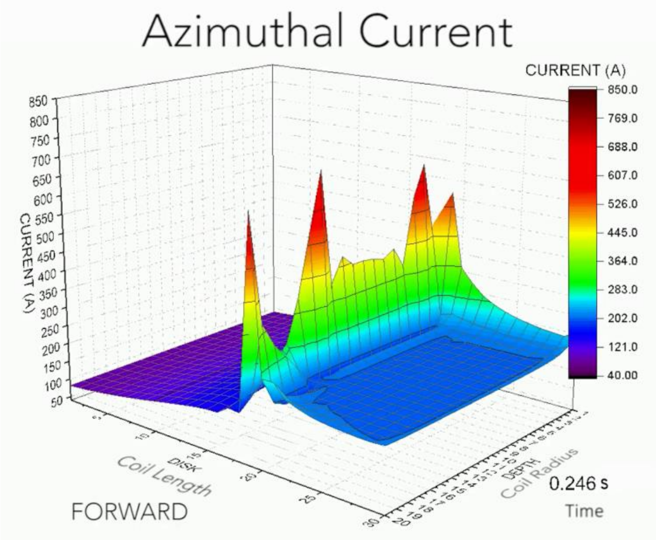
- A quench is initiated at one end of a coil in a section of conductor having low critical current
- After quench initiation, the quench propagates by a dynamic, inductive process
- A rapid quench propagation is observed over a wide range of resistance between turns

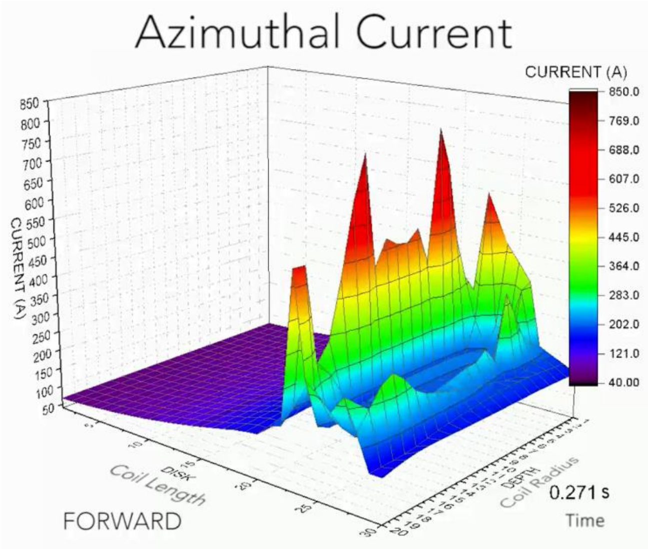


30 pancake disks
20 radial sections

Quench Modelling in NI-YBCO







Several HTS magnets developed elsewhere have been damaged due to insufficient understanding of behavior during quench.

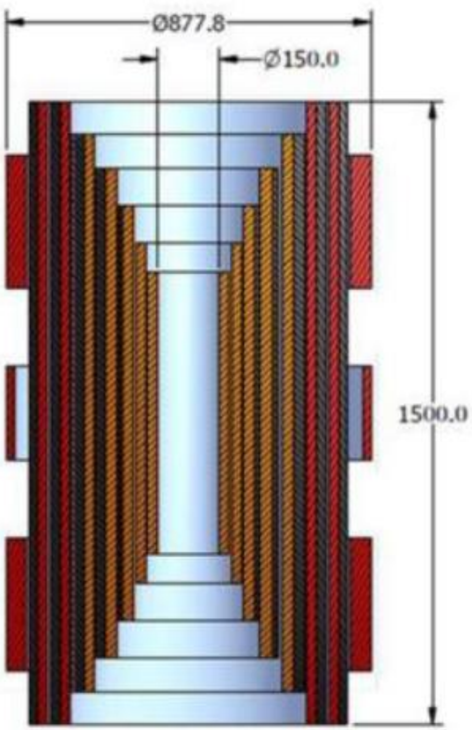
The MagLab has performed extensive modelling & testing (>100 times) of quench in HTS coils.

W.D. Markiewicz

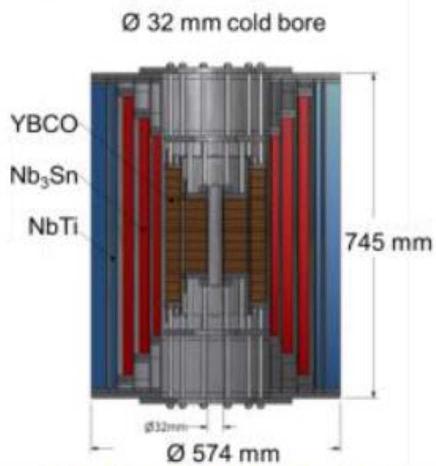
Perspective on 30 T NMR

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

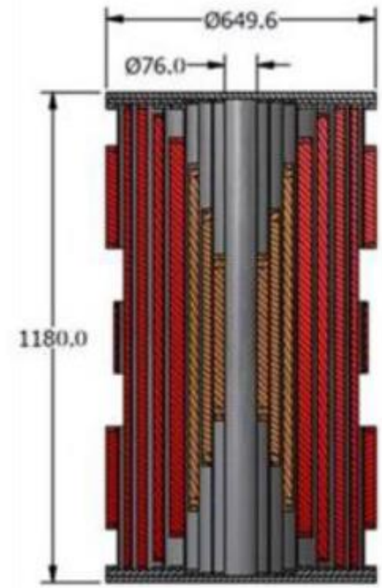
Schematics are to scale



Previously developed
21.1 T/900 MHz UWB
21 T LTS
Homogeneity: ppb level



Under development
32 T Physics
15 T LTS + 17 T HTS
Homogeneity: 10^{-4} level



Concept
30 T / 1.3 GHz NMR
15 T LTS, 15 T HTS
Homogeneity: Bio-NMR

Operating current, winding current density, copper current density, fraction of I_c are all essentially the same as in 32 T design

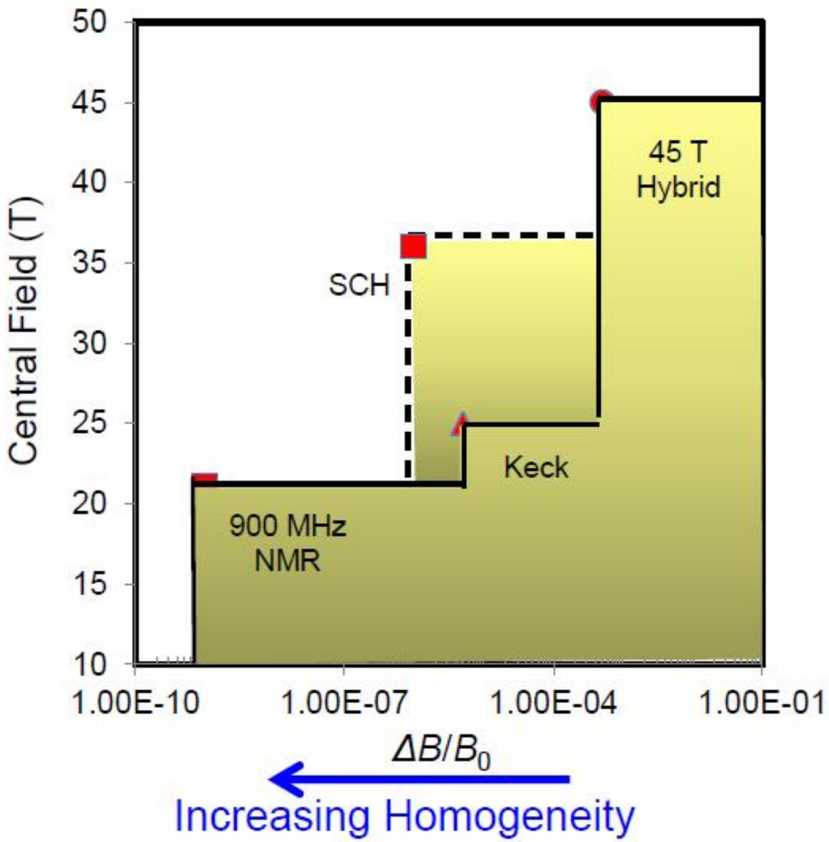
Stress level is ~ 20% higher,

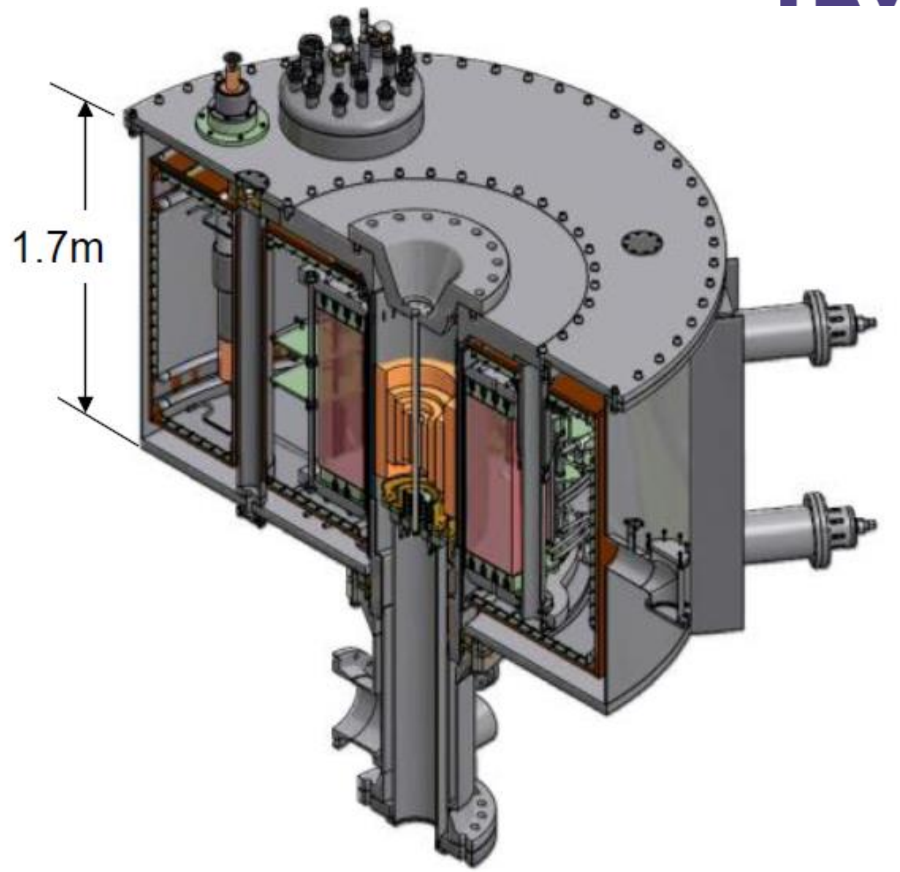
~23 km of HTS conductor versus 10 km in 32 T

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





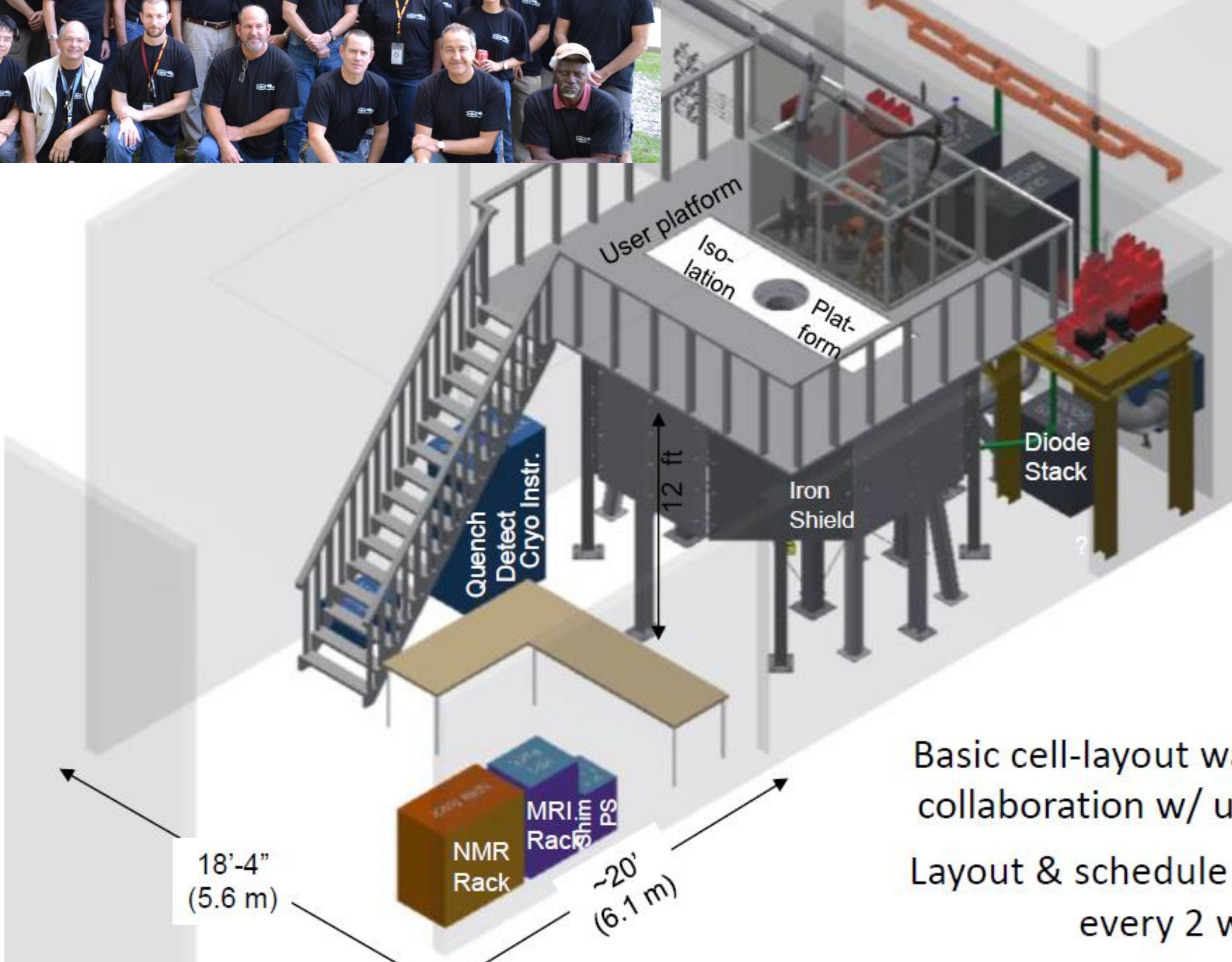
- Provide a unique combination of performance parameters:
  - High field (36T)
  - High field quality (1ppm)
  - Larger bore (40 mm)
  - 1 Power Supply (13 MW)

- 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

Milestone	Date
Cryostat Arrived	Sept. 2014
Cold-Test including cold-box, cryostat, controls	Dec. 2014
Assembly of Cold-Mass and Current-Leads complete	Apr. 2015
Paschen Test Complete	June 2015
Cryostat Closed	Oct. 2015
Insert Plumbing Complete	Dec. 2015
Insert Coils installed	Jan 2015
Transfer Line installation complete	Mar. 2016
Cool-down Complete	April 2016
Insert-Only	May 2016
36 T	June 2016

MagLab 36 T, 1-ppm Hybrid Magnet Cell Isometric

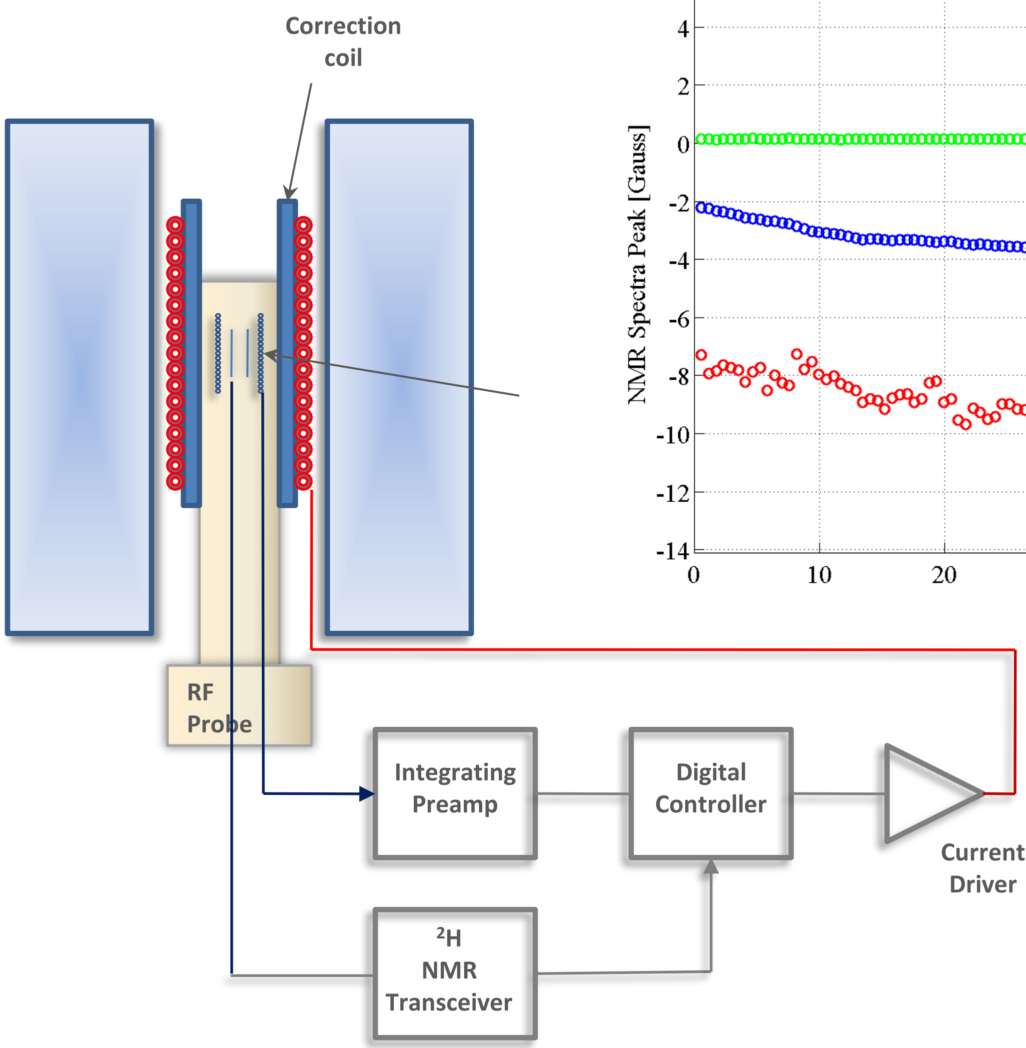


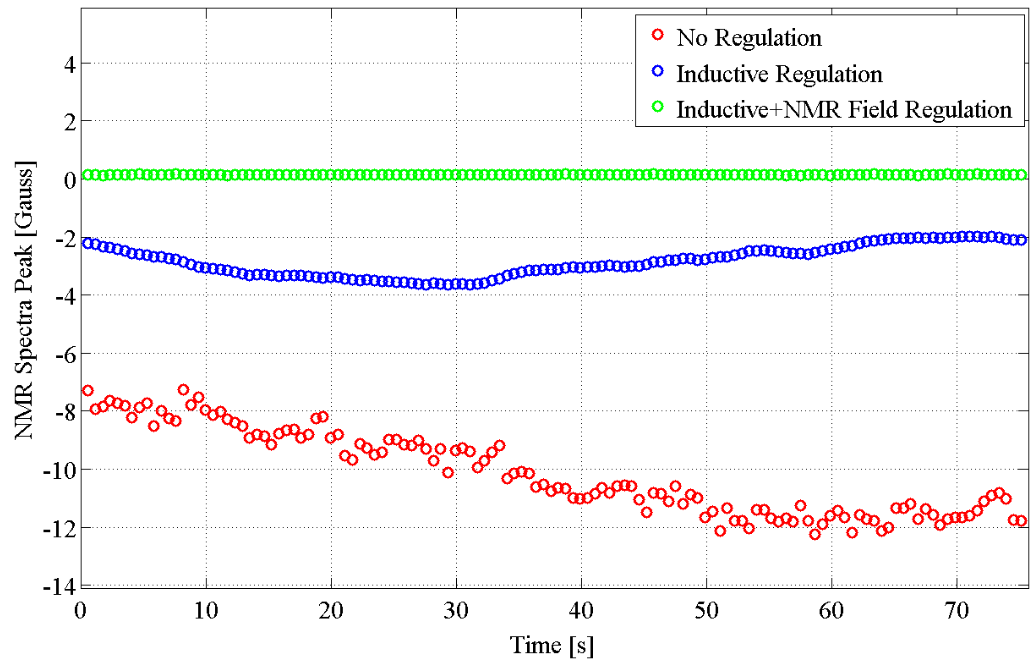
Bird, Dixon, Toth, Bole, Adkins, Bai, Cantrell, Gavrilin, Han, Li, Lu, Marks, Marshall, Noyes, Painter, Walsh, White, Cherisol, Deterding, English, Helms, Lucia, Maddox, O'Reilly, Ray, Richardson, Stanton, Windham, Zavion, et al.,

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

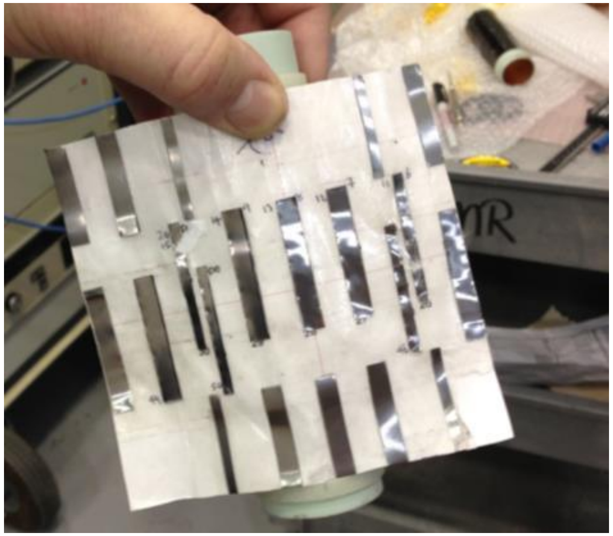




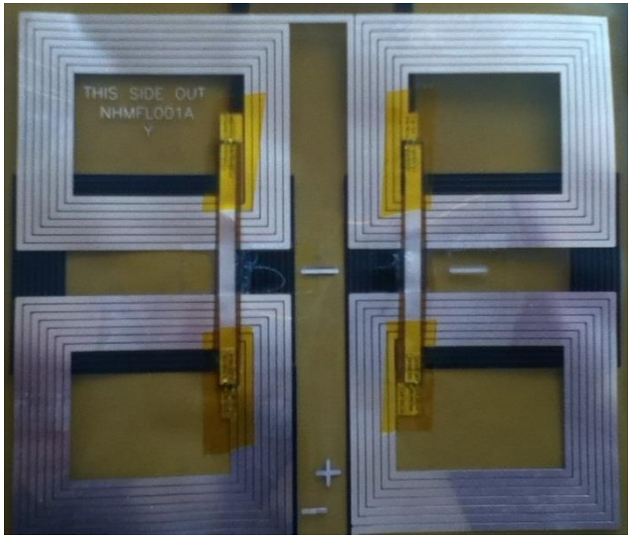
This work can be readily extended to high-resolution HTS NMR magnets without persistent joints.

Jeff Schiano, et al., Penn State Univ.

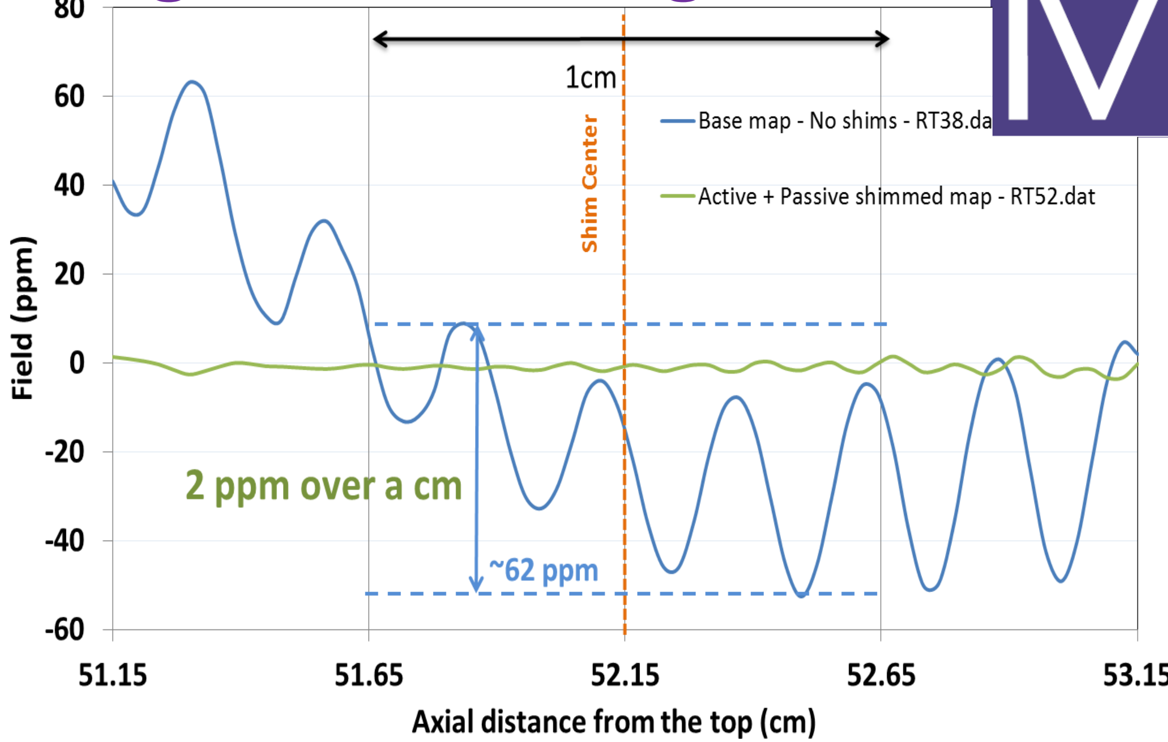
Mapping and Shimming a 20 MW Magnet

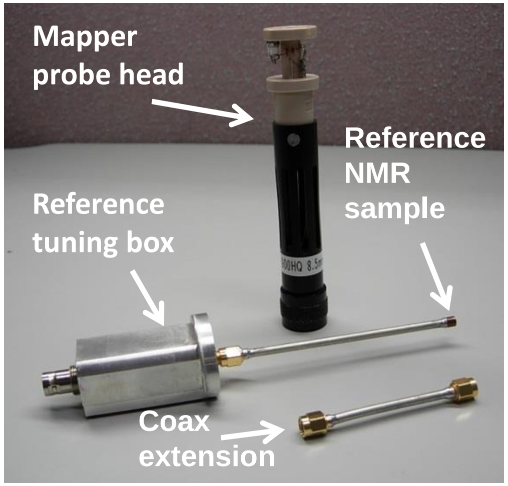


Passive shims on probe cap



Active shims on insert tube





Oxford NMR

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

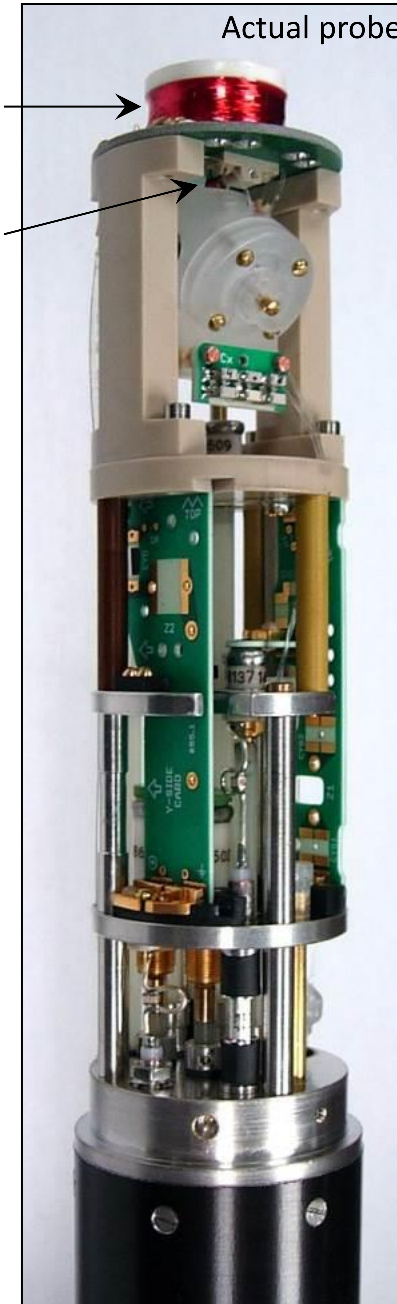
Initially for 2D experiments like ^{13}C/^{13}C correlation etc.

Sealed LiCl capillary for 4th external freq. lock channel is located above spinner

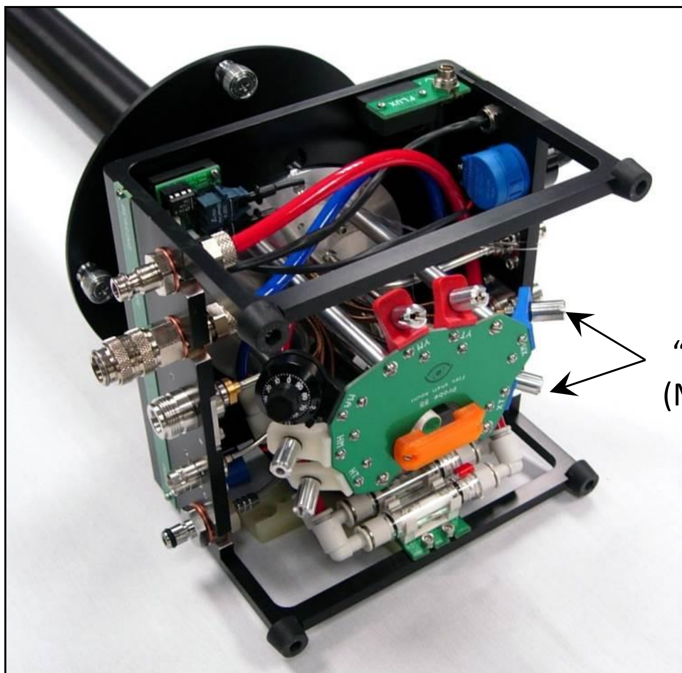
Y-channel can double as internal ^{2}H lock channel if external ^{7}Li lock fails to work

B_0 sensor

Sealed external lock capillary above spinner



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



Adaptations for "remote" sideways tuning (Magnet safety regulation)

Bill Brey & Peter Gorkov

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

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.

Lund: We performed design study of 25 – 30 T HTS mag. for neutrons.

Argonne: We developed Nb_3Sn Undulator Compts.

BNL, Twente: HTS Coil Collaboration.

Hybrid Magnets

Nijmegen: We are building 45T outsert coil & 20 kA HTS Leads.

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 Nb_3Sn problems.

Hefei: Developing 40 T w/ CICC.

Resistive Magnets

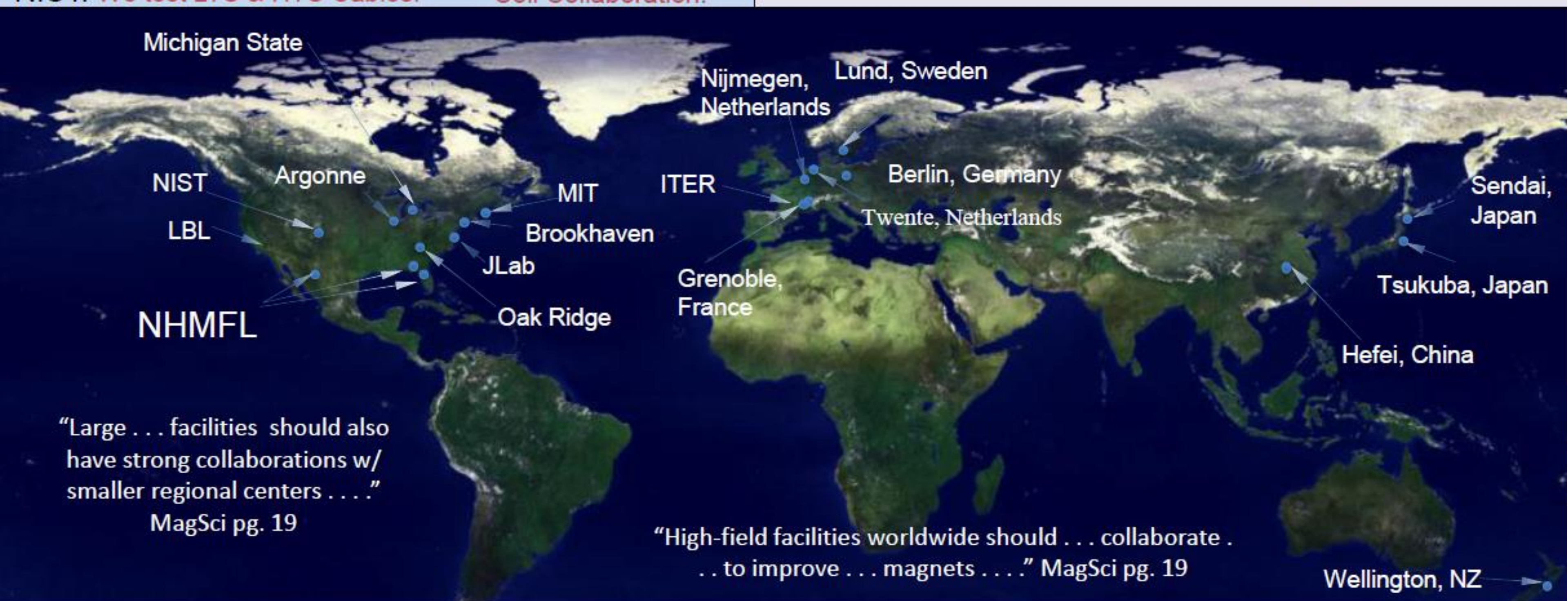
Nijmegen: We delivered 33T

Tsukuba: We delivered 30T

Grenoble: We delivered coils & housings for 30–35T

Hefei: Developing Florida-Bitter.

Sendai: Operates Florida-Bitter.



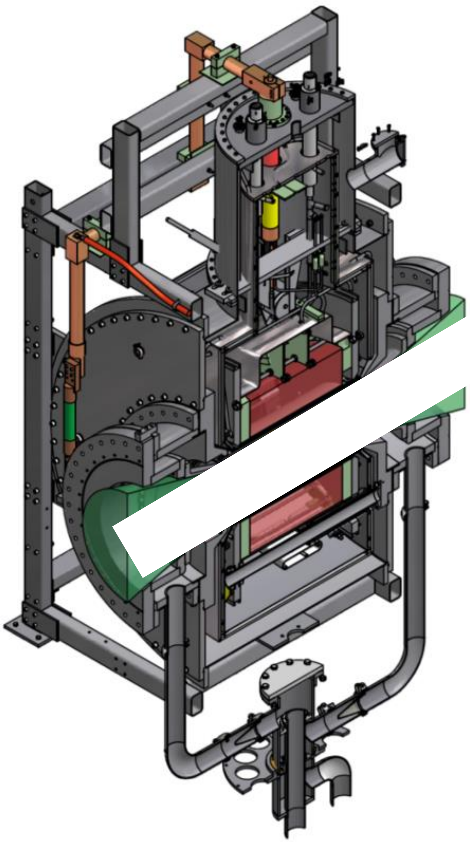
Five of six largest resistive magnet labs worldwide have adopted the Florida-Bitter technology.

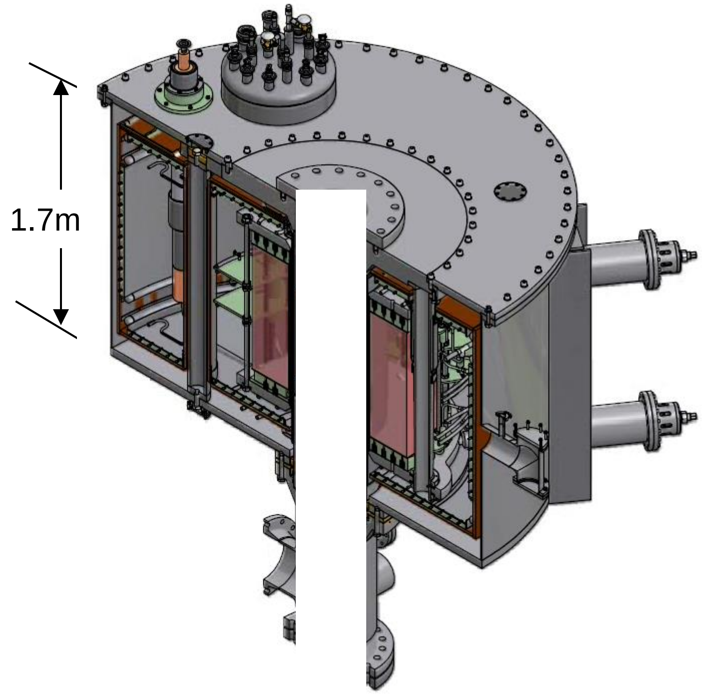
MagLab plays the leading role in international hybrid magnet development effort.

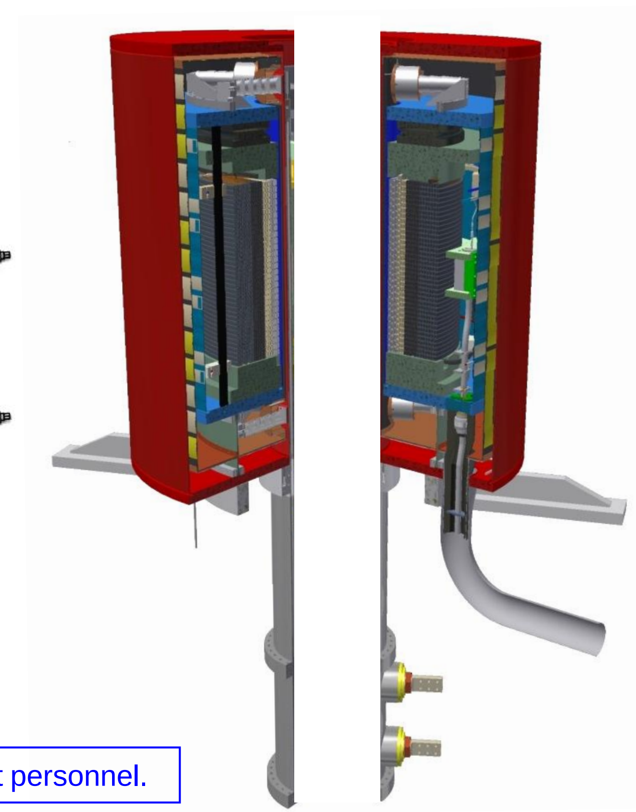
Former MagLab personnel: Soren Prestemon, Deputy Division Dir., Lawrence Berkeley Lab; Kathleen Amm, MRI Technologies & Systems Leader, GE Global R&D; Ting Xu, Cryogenic Operations Leader at FRIB.

3 Recent Hybrid Magnets by MagLab

(Same Nb_3Sn Cable-In-Conduit Conductors)







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

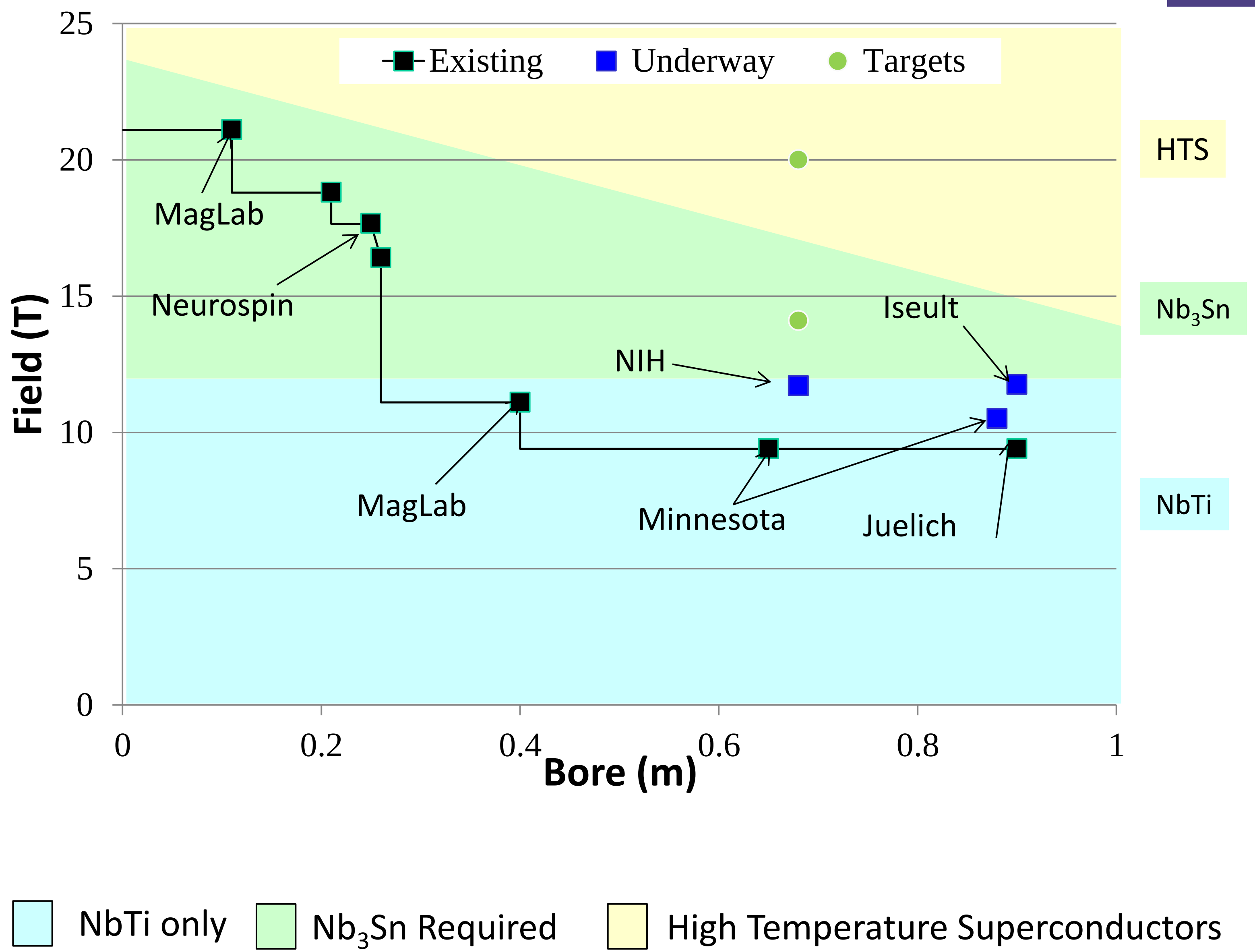
Helmholtz Zentrum Berlin (HZB)	MagLab	Radboud University	Lab
Berlin, Germany	Tallahassee, FL	Nijmegen, Netherlands	Location
26 T	36 T	45 T	Tot Field
13 T	13 T	12 T	SC Field
50 cm	46 cm	52 cm	SC Bore
Neutron Scattering	Condensed-Matter Physics	Condensed-Matter Physics	Purpose
2015	2016	2018	Operational

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.

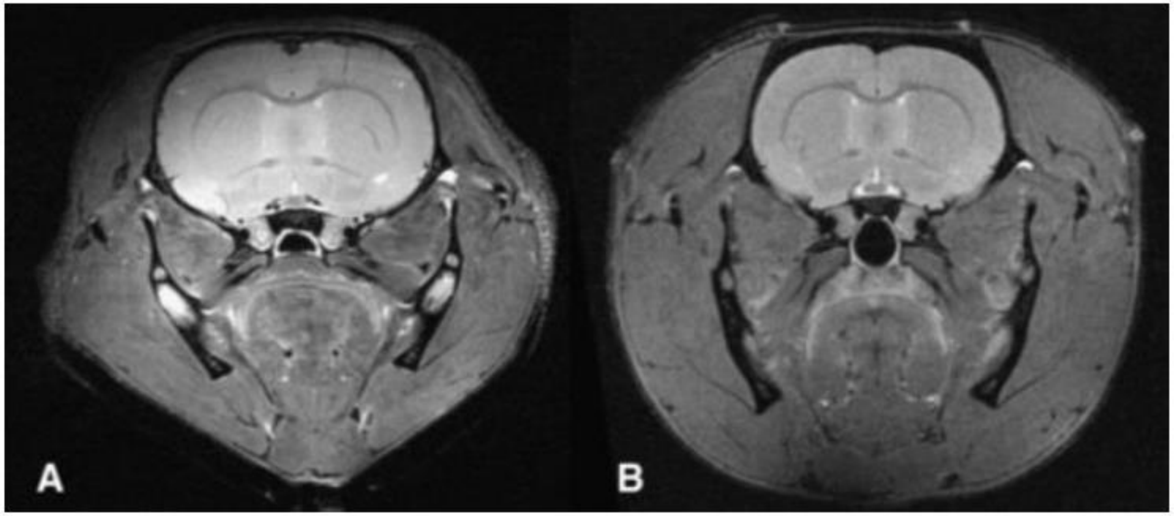
NATIONAL HIGH MAGNETIC FIELD LABORATORY

MRI Magnet Field vs Bore



20 T MRI

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 mm^3 [1].

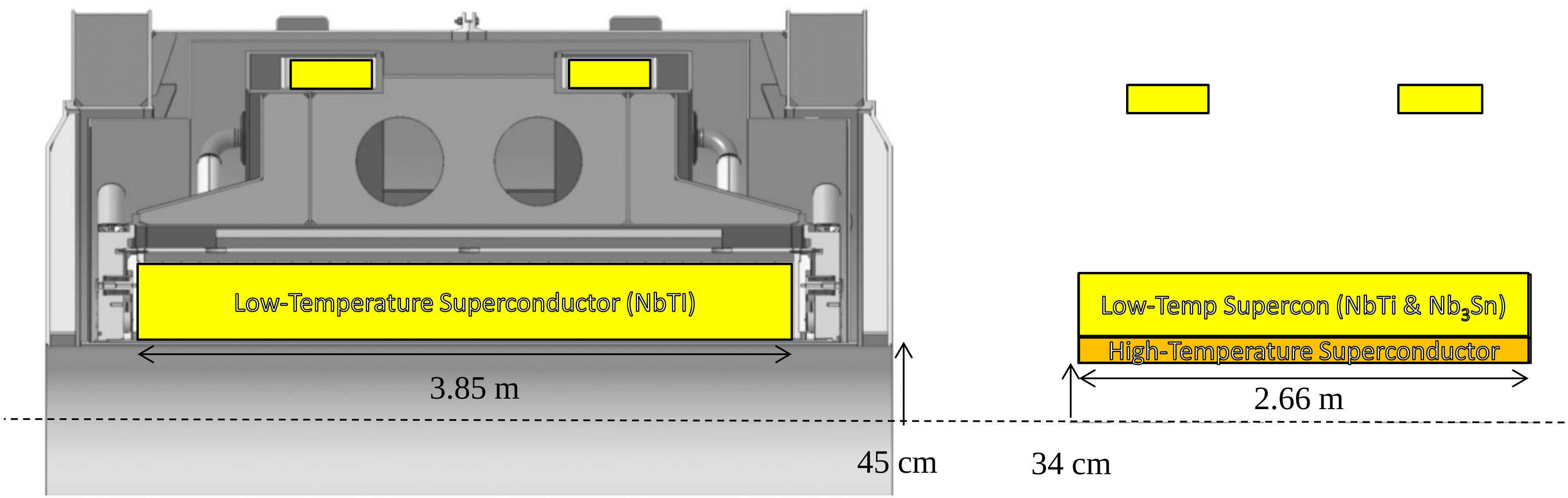
20 T MRI magnets with various bores (up to 90 cm) can be built using traditional Low-Temperature Superconductors (LTS, NbTi & Nb_3Sn).
This has not been done due to cost and safety concerns.

[1] Schepkin, et al., MRI, 28 (2010) 400 - 407

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	Iseult	MagLab 20 T Concept
Conductor Mass (Ton)	65	~35
Stored Energy (MJ)	338	~350
Current Density (A/mm^2)	26.4	~40
Magnet Design	CEA	MagLab

HTS & High-Strength materials at 4 K operate at high field and current-density resulting in compact magnets.

On Behalf of The MagLab's SC Magnet Teams

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

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

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

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

36 T SCH Magnet Project

M.D. Bird
I.R. Dixon

Analysis
I.R. Dixon
A.V. Gavrilin
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

Science
T. Cross
B. Brey
I. Litvak

Controls
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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_3Sn 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.