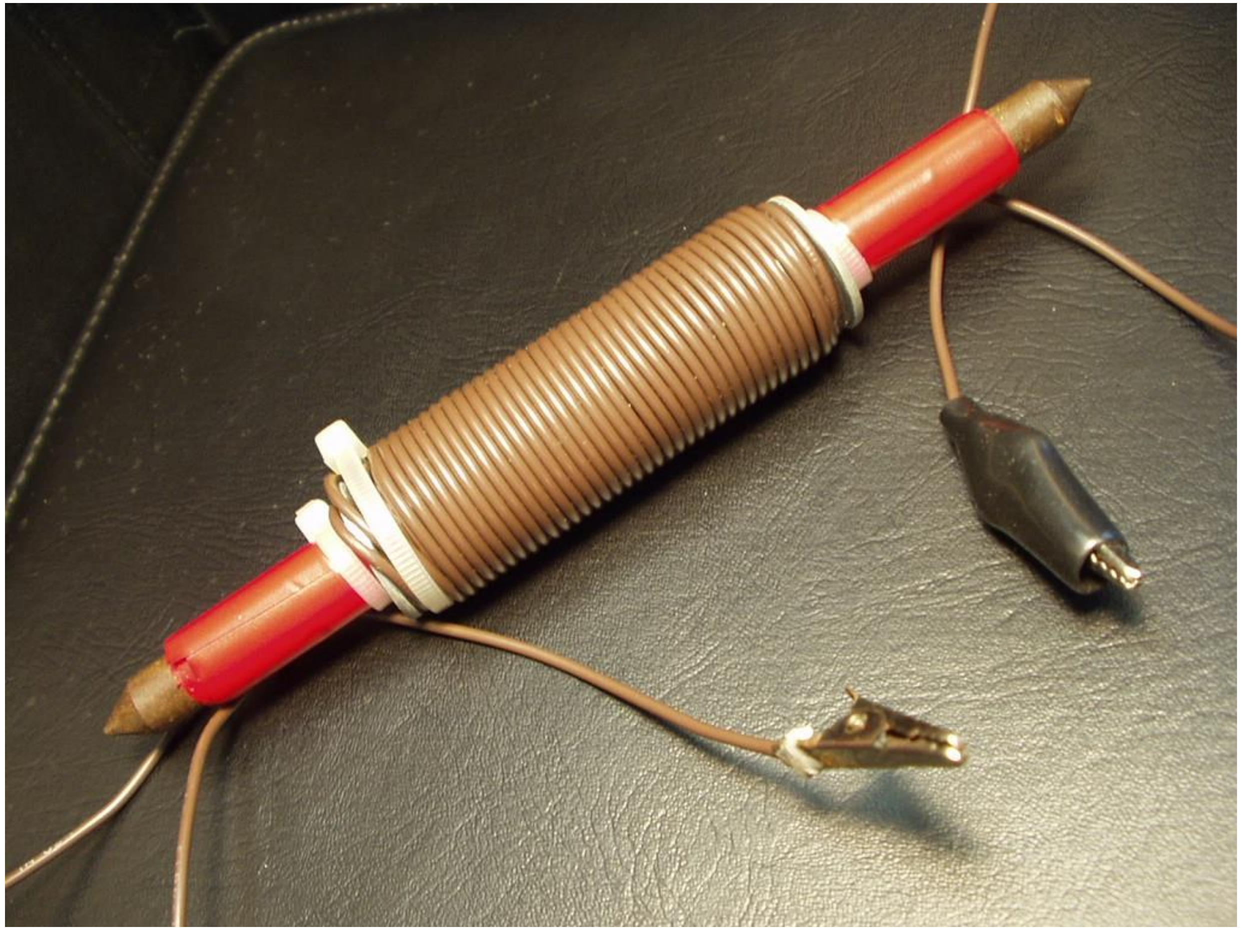
The 1.5 GHz, 1 ppm NMR Magnet at the National High Magnetic Field Lab

Mark D. Bird

Director of Magnet Science and Technology

National High Magnetic Field Lab, Florida State University, 1800 E. Paul Dirac Dr., Tallahassee, FL, USA.

How do you Build an Electromagnet?



Construction
Copper wire
w/ insulation

Steel Bar

Battery

Intensity
0.03 T
Lift ~1 oz steel

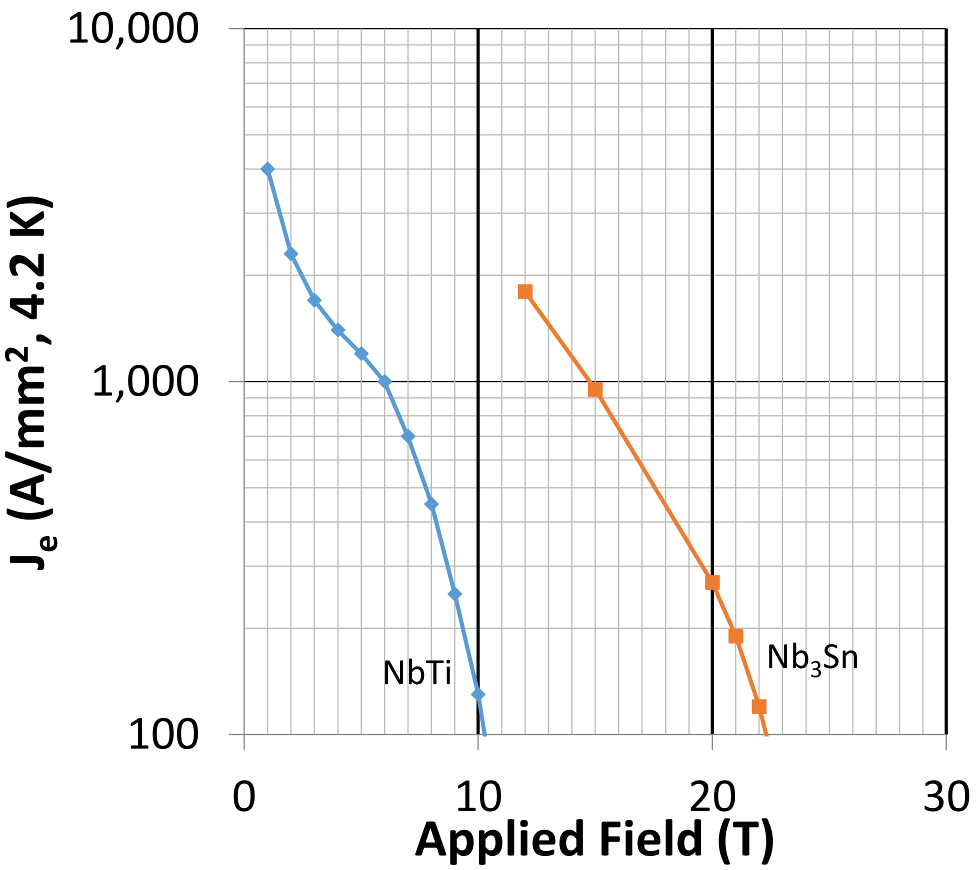
Strength
Lorentz forces!

Cooling
Joule heating for
resistive materials.

Superconductors!

NATIONAL MAGLAB

Have You Used a Superconducting Magnet?



NbTi is used for SC magnets < 12 T.

1. Human MRI magnets,
2. High-Energy Physics:
    a) Accelerators,
    b) Detectors.

B_{max} is ~10 T at 4.2 K & ~12 T at 2 K.

Nb_3Sn is used for SC magnets >12 T.

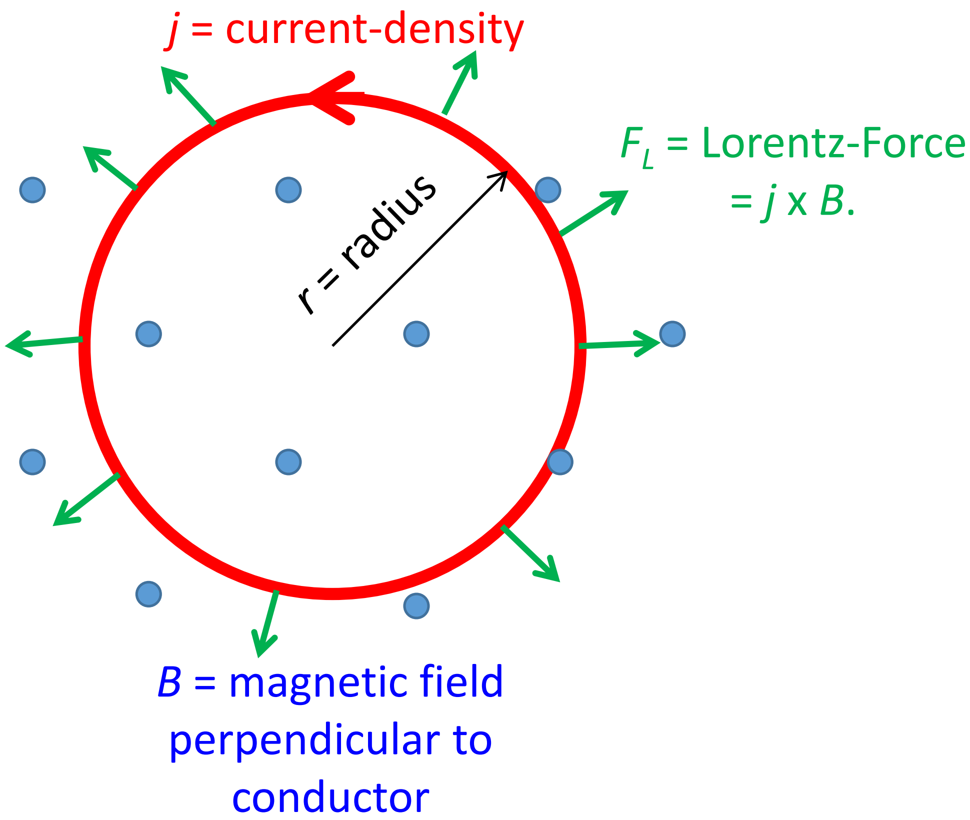
1. NMR (up to 23.5 T),
2. Preclinical MRI (up to 21.1 T),
3. Condensed-matter physics,
4. Fusion.

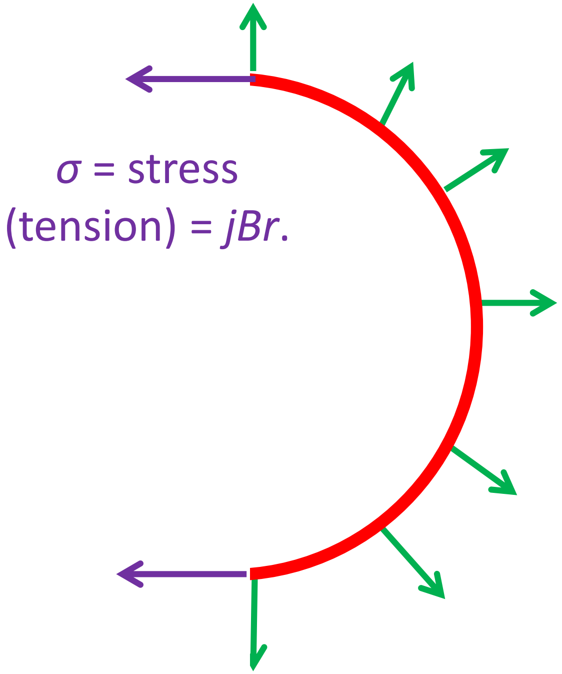
Its peak field is ~22 T at 4.2 K & ~23 T at 2 K.

J_e data provided by P. Lee, NHMFL

NATIONAL MAGLAB

Stress in High-Field Solenoids

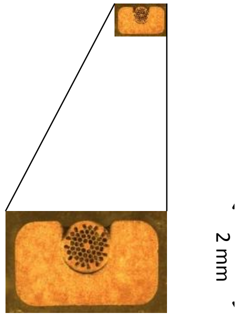




If we double the field of the magnet with fixed inner-diameter and current-density, the stress (tension) in the wire doubles!

MRI Magnet Conductor Design

	3 T, 90 cm
Superconductor	NbTi
# of strands	1
Current (Amps)	~300
Reinforcement	Cu
Strength (MPa)	>250
Stiffness (GPa)	110
Stabilizer	Cu
C_p (mJ/cc/K)	1
Protection	Cu
J_{cu} (A/mm^2)	~280



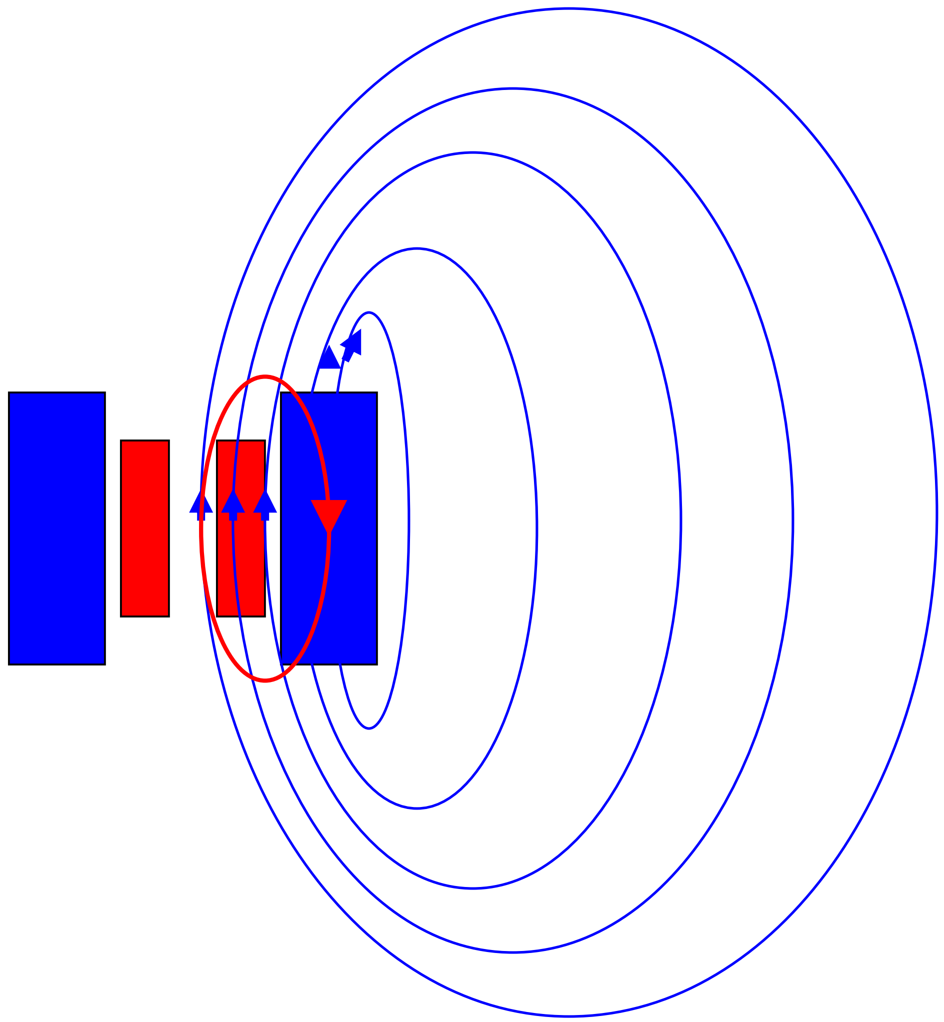
What is a Hybrid Magnet?

A resistive magnet operating inside a superconducting magnet.

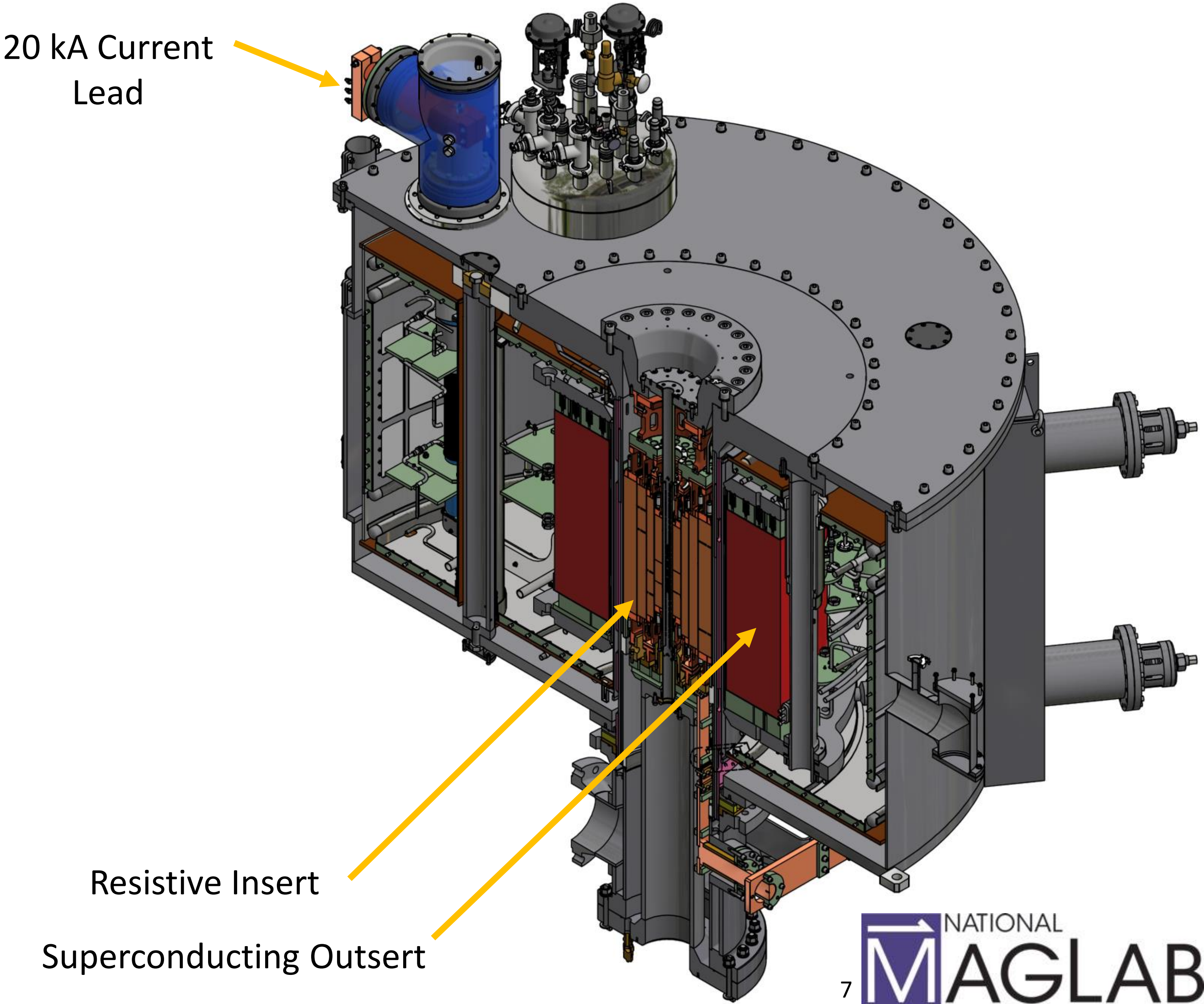
Superconducting magnets are limited by the critical field of the superconductor. (The record field is 24.5 T for a permanent installation).

Resistive magnets have no intrinsic limit. However, the power requirements increase faster than the square of the field.

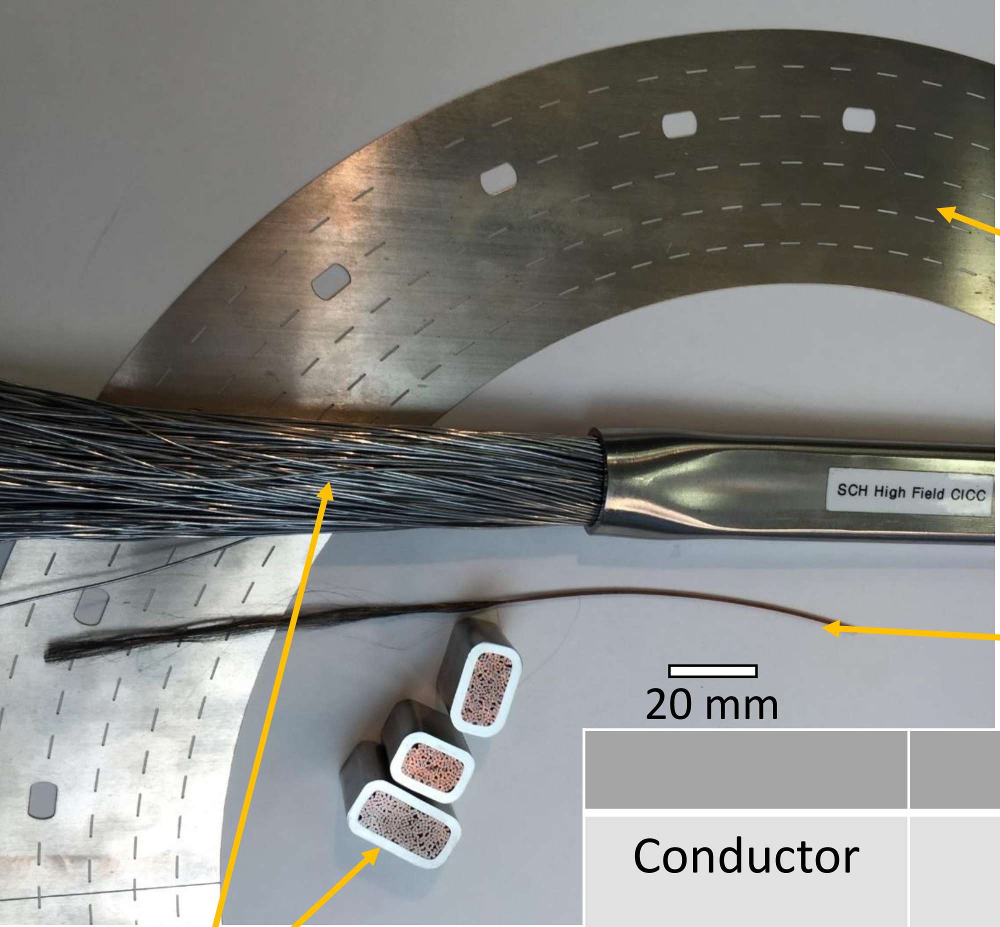
Combining the 2 technologies results in high field with modest operating cost.



36 T, 1 ppm Series-Connected Hybrid Magnet



Technology Comparison



1.5 GHz Insert:
~2,000 A Florida-Bitter Disk

Typical NMR Magnet:
~300 A Superconducting Wire

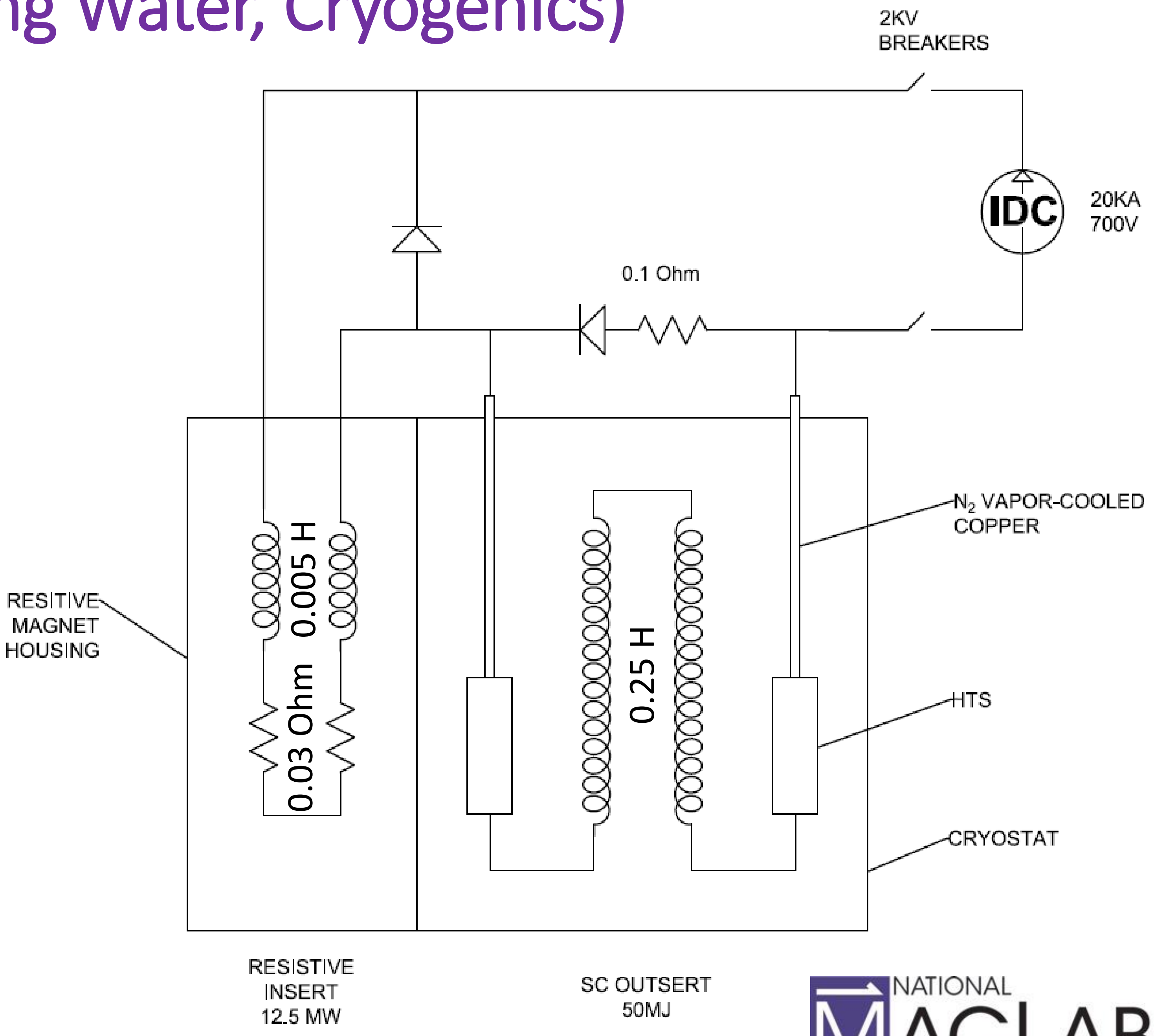
1.5 GHz outsert:
20,000 A Cable-In-Conduit Conductor

	Typical NMR Magnet	1.5 GHz
Conductor	Single strand SC wire.	SC: >100 strands Resistive: Cu-alloy sheet metal
Current	200 A – 400 A	20,000 A
Inductance	Large (~1000 H for 0.9 GHz)	Modest (0.25 H for 1.5 GHz)
Power	~10 nWatts	12.5 MW (625 V in resistive magnet)
Joints	~0.01 nOhm	~1 nOhm
Coolant	LHe at 2 – 4 K to maintain.	SC: SHe at 4.5 K, 10 g/s to maintain. Res: H_2O 10 C enter, 40 C exit.

NATIONAL MAGLAB

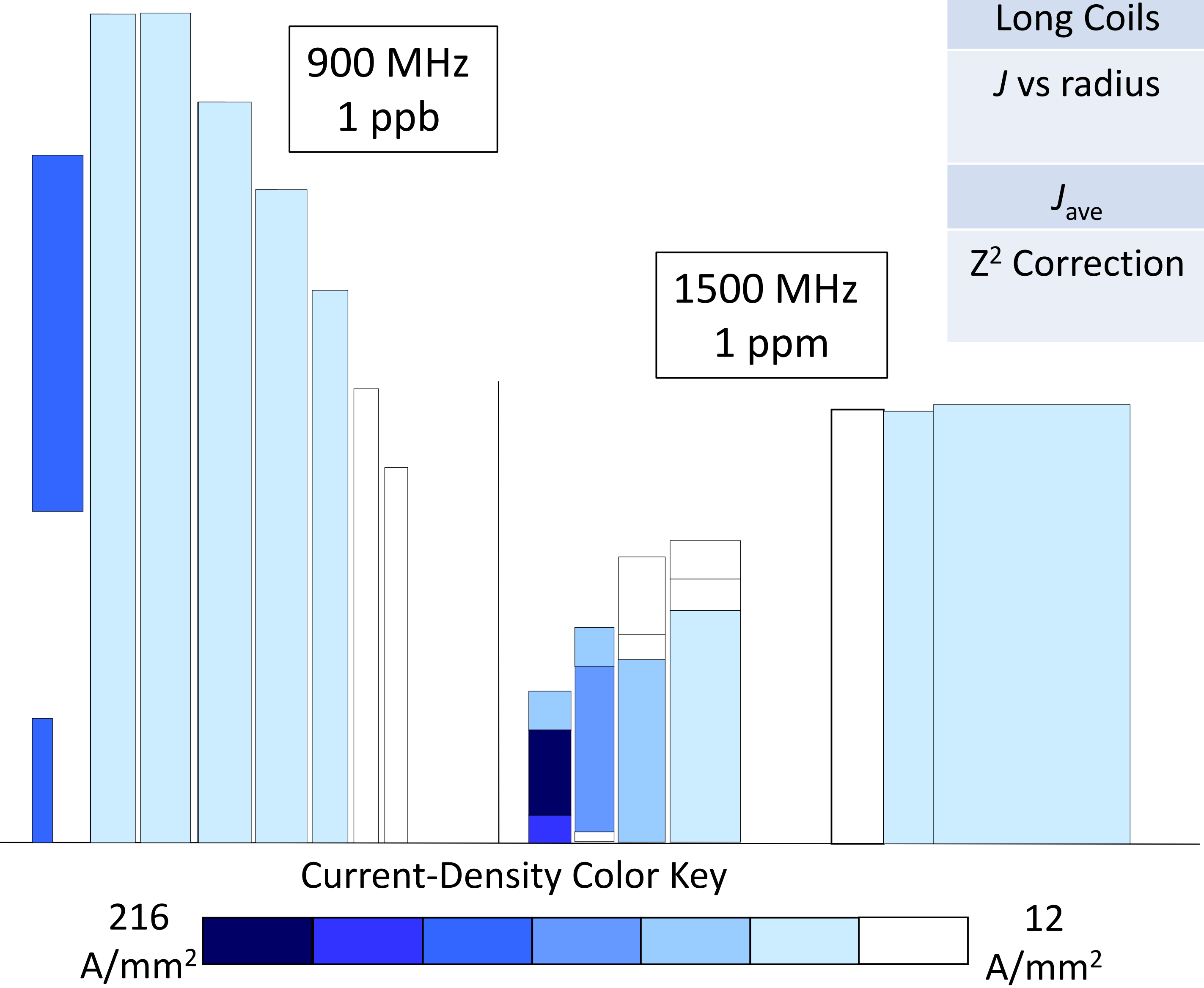
Infrastructure (Power, Cooling Water, Cryogenics)

- During normal operation, breakers are closed and no current flows through the diodes.
- 12.5 MW resistive magnet is in series with 50 MJ superconducting magnet.
- If a quench is detected, breakers open 20 kA circuit (2 kV). (Glitch in incoming power also causes breaker opening.)
- **If quench occurs, loud bang due to breaker opening, roar due to helium venting.**
- Resistive and SC magnets discharge nearly independently.
- Energy of SC magnet dumped in external resistor.
- Energy of resistive magnet dumped internally.
- Cooling water system provides 126 l/s of H_2O 8 C and 26 bar.
- Cryoplant provides 10 g/s of He @ 3.5 bara, 4. K.



NATIONAL MAGLAB

Current Density Distribution



	SC magnets	Resistive magnets
Long Coils	Uniform field	Extreme power
J vs radius	Hi *B* = Lo *J* Outer coils have higher *J*.	Large *R* = Hi Power. Inner coils have higher *J*.
J_{ave}	Large Coils.	Compact Coils.
Z^2 Correction	Notches at OD.	Reduced *J* at mid-plane of ID.

J = current density, *B* = magnetic field, *R* = radius

Coil Mis-Alignment

Inhomogeneity arises from coils being shifted with respect to each other.

$$A = A_0 + A_2 z^2 + \ldots$$

and

$$B = B_0 + B_2(z - b)^2 + \ldots$$

gives

- $A + B = (A_0 + B_0 + B_2\, b^2) - 2bB_2 z + (A_2 + B_2\,)z^2 + \ldots.$

- For the innermost coil of the 35 T magnet, $B_2 = -17.6$ ppm/mm^2.
- For 2-coil system, goal = 10 ppm /10 mm, tolerance = 0.028 mm.
- For 2-coil system, goal = 1 ppm /10 mm, tolerance = 0.0028 μm.

Coil Mis-Alignment

Inhomogeneity arises from coils being shifted with respect to each other.

$$A = A_0 + A_2 z^2 + \ldots$$

and

$$B = B_0 + B_2 (z - b)^2 + \ldots$$

gives

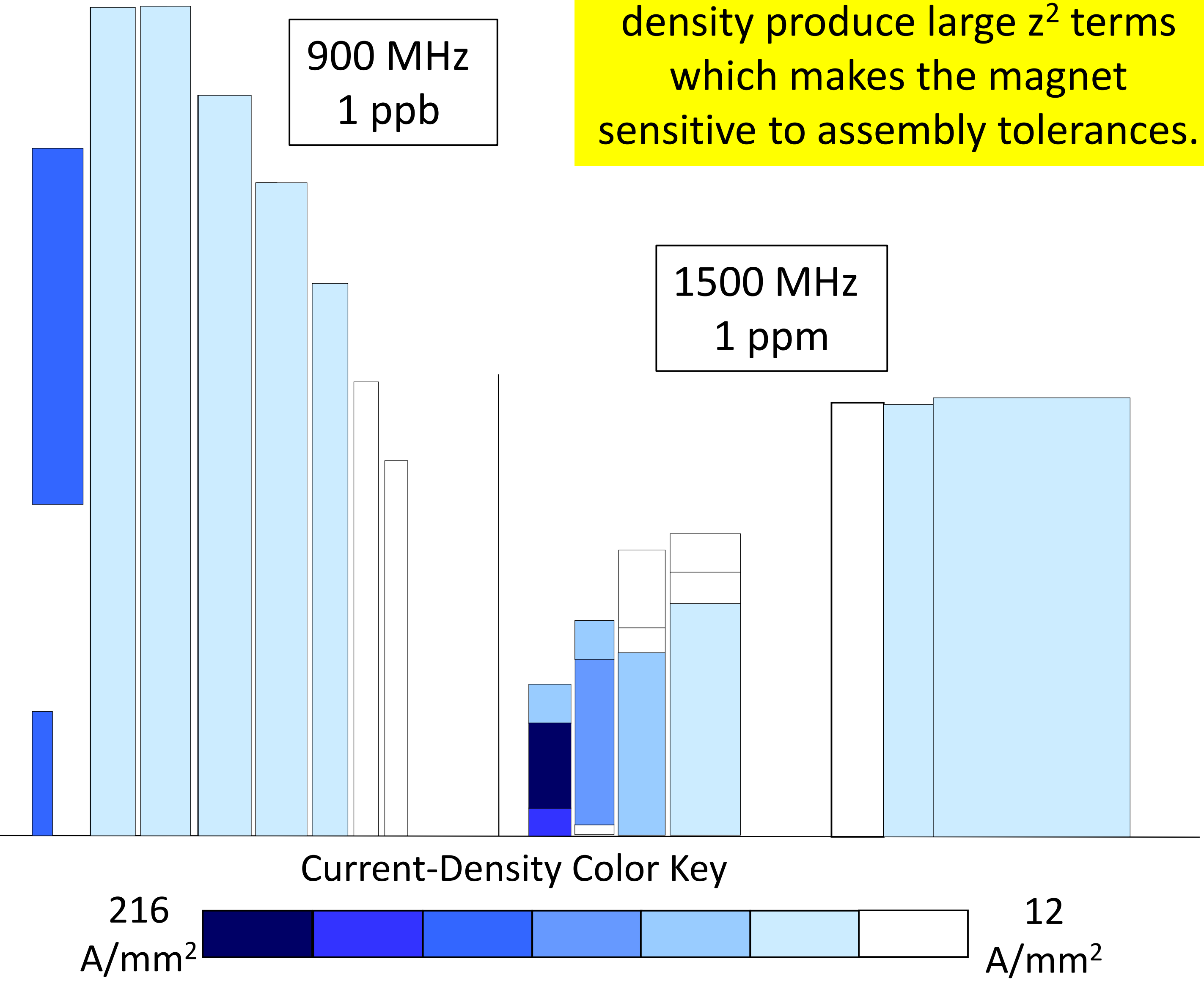
- $A + B = (A_0 + B_0 + B_2 b^2) - 2bB_2 z + (A_2 + B_2) z^2 + \ldots.$

- For the innermost coil of the 35 T magnet, $B_2 = -17.6$ ppm/mm^2.
- For 2-coil system:

Goal	Tolerance
10 ppm/10 mm	0.028 mm
1 ppm/10 mm	0.0028 mm

Current Density Distribution

Short coils with high current density produce large z^2 terms which makes the magnet sensitive to assembly tolerances.



900 MHz Coils	Z^2 term (T/m^2)
1 (innermost)	-0.73
2	-0.80
3	-0.93
4	-1.14
5	-1.20
6	-0.98
7	-1.43
8	-6.03
9(outermost)	13.28
Total	0.04

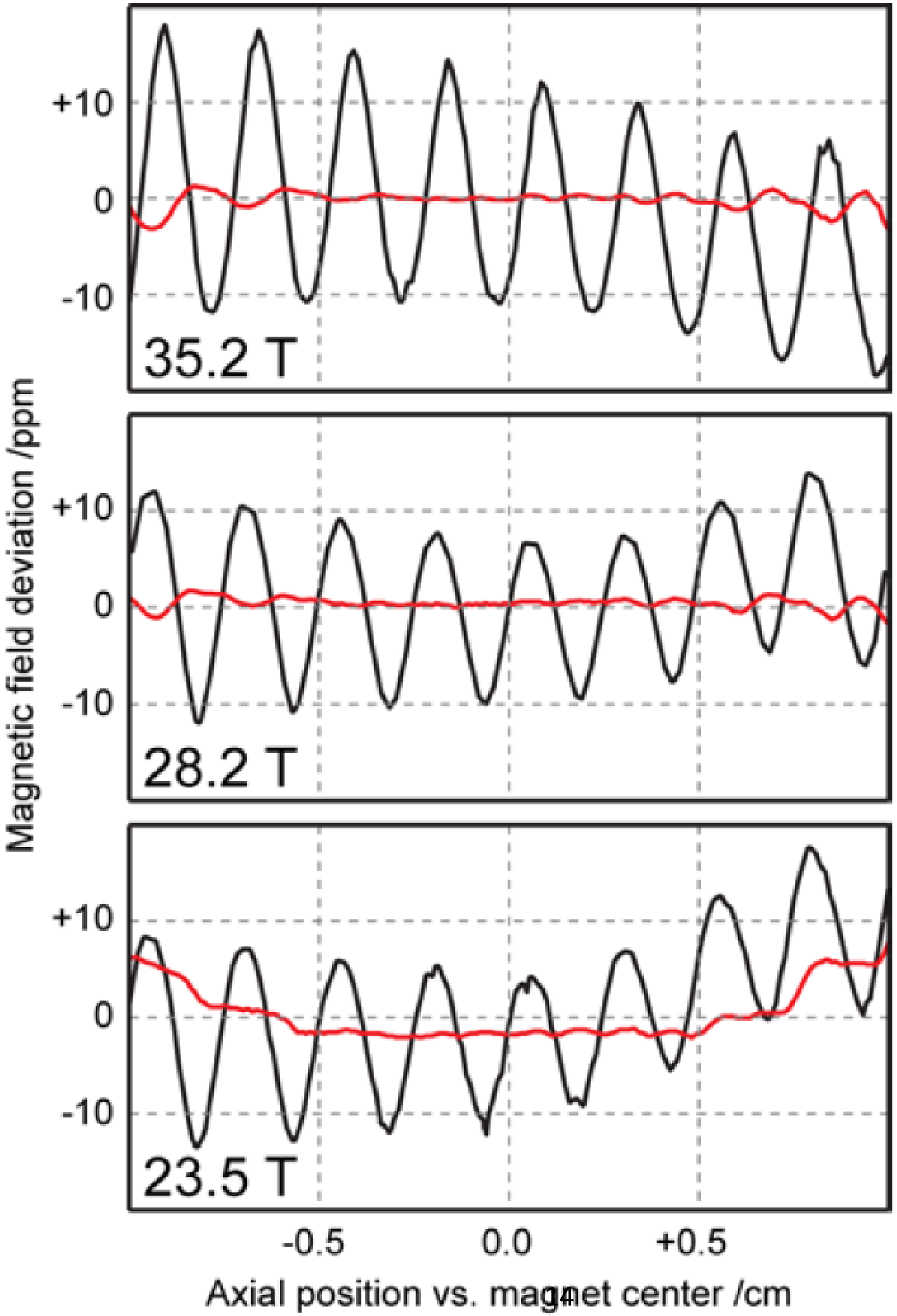
SCH Coils	Z^2 term (T/m^2)
Resistive A	51.9
Resistive B	41.6
Resistive C	-32.9
Resistive D	-28.1
Superconducting	-29.7
Total	2.8

Field Shimming

	SC NMR	1.5 GHz Hybrid
Raw	~10 ppm/cm	>100 ppm/cm, z
Coil Shifting	N/A	~25 ppm/cm, x
x, y, z, z^2 shims	SC coils at OD. < 1 ppm/cm	Ferrous strips ID. ~5 ppm/cm
Higher order shims	Resistive shims @ ID. 28 – 40 channels. ~ 1 ppb	Resistive shims @ ID. 7 channels total. < 1 ppm

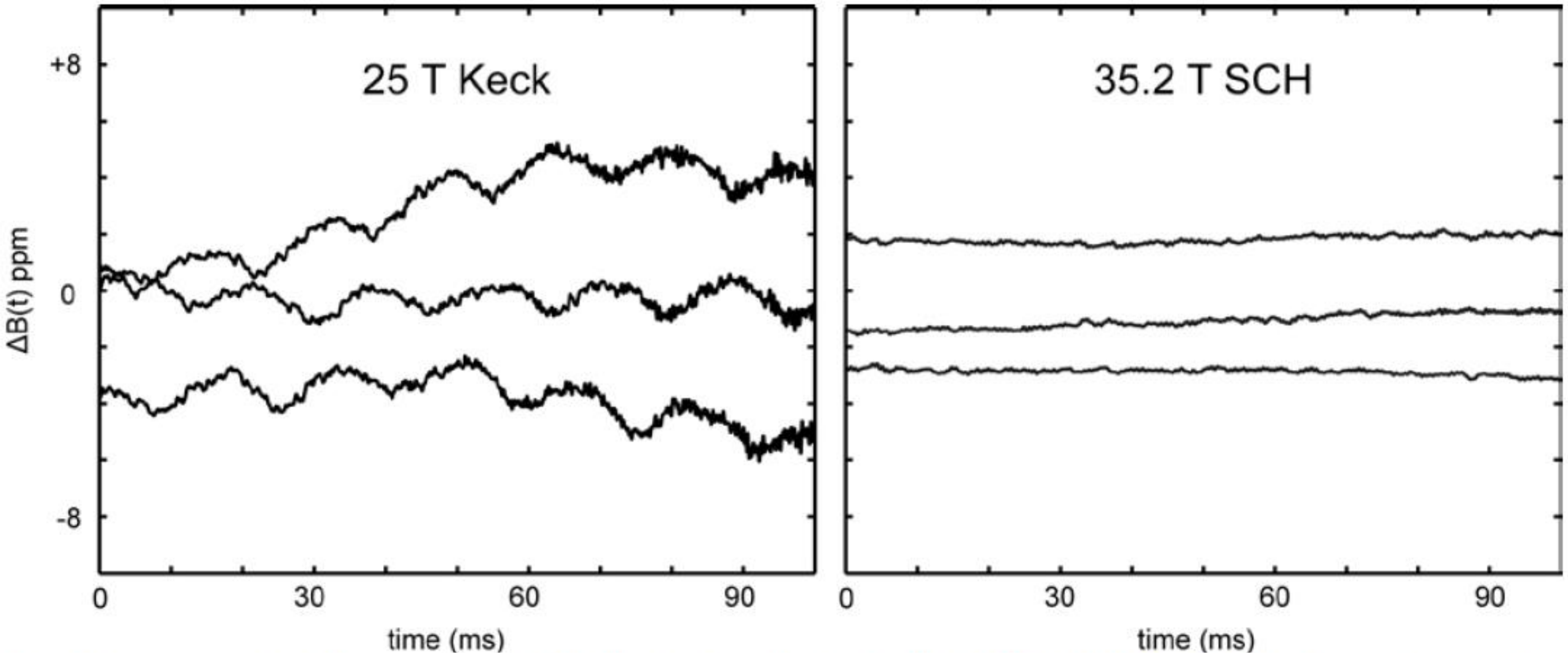
Separate Ferromagnetic shim sets for 1.0, 1.2, & 1.5 GHz.

Ferromagnetic and resistive shims by Oxford NMR



NATIONAL MAGLAB

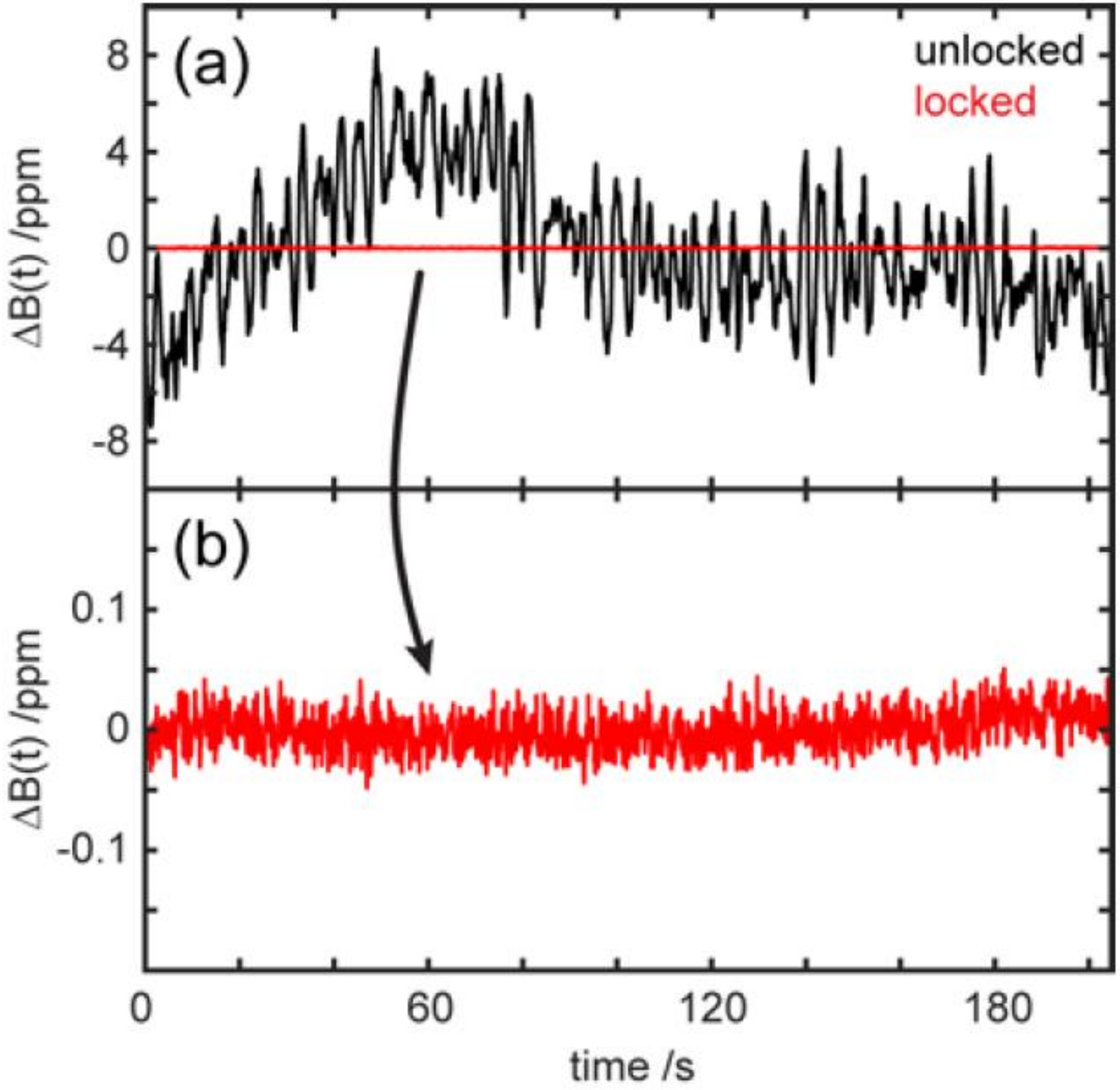
Raw Field Stability: 14 MW Power Supply + Inductance



	25 T	35.2 T
Inductance (mH)	5	250

NATIONAL MAGLAB

Stabilized Field



External Bruker lock yields < 0.1 ppm.

Traditional NMR Magnet:
Persistent, no power supply, ~10 ppb/hr.

1.5 GHz:
20 kA, 700 V power supply, < 0.1 ppm

6.84 M LiCl aqueous solution doped with 750 mM $MnCl_2$ was used to provide a strong and fast responding ^7Li signal. The doping is necessary because a duration of ~$T1$ is necessary for the continuous-wave (CW) NMR magnetization to reach a steady-state, which is essential for the NMR lock to function properly. In this instance, doping of the solution with MnCl2 shortens the 7Li *T*1 and *T*2 to the same approximate value of ~5 ms (measured at B0 = 14.1 T) without severely broadening the line width of the signal.

28 T Mouse MRI Modification

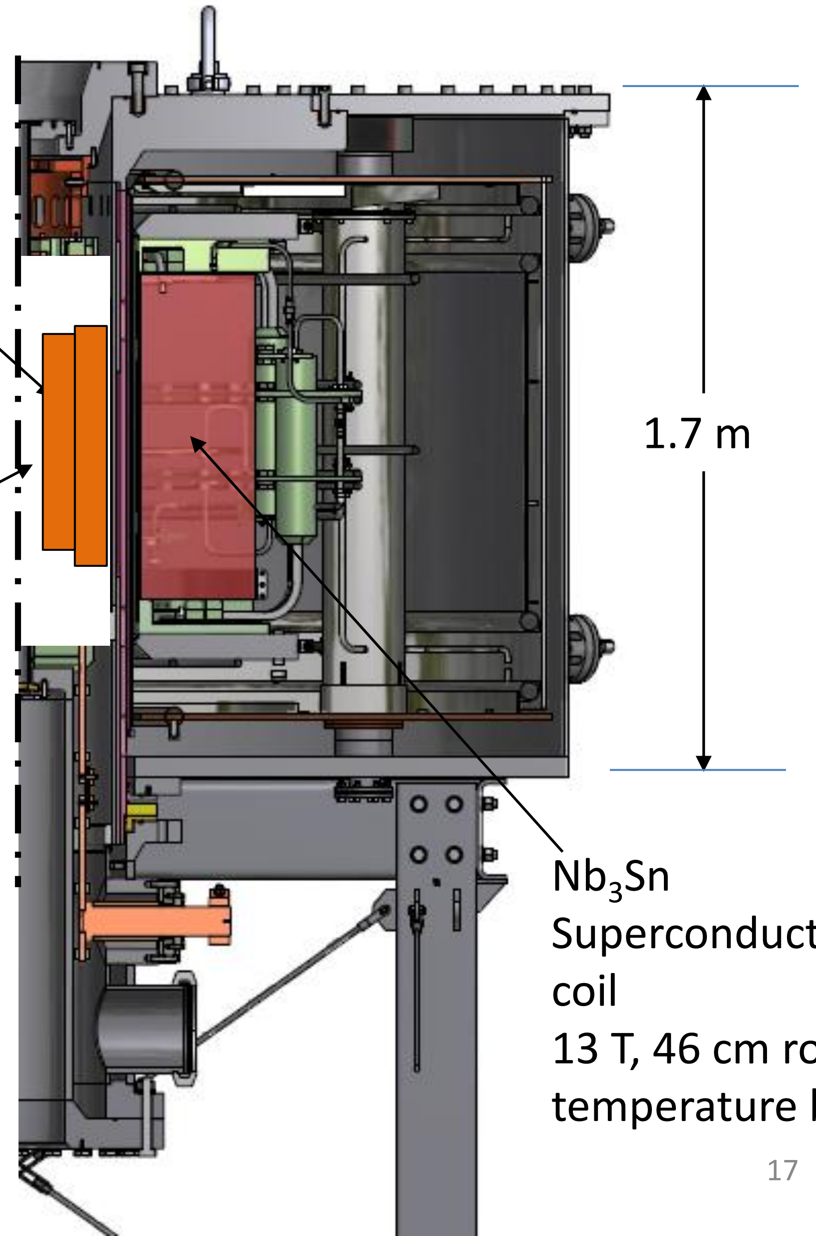
The resistive coils operate at ~90% of yield stress and will wear out ocassinally due to metal fatigue.

It is possible to replace the resistive coils of this magnet with a set that provides lower field in a larger bore.

Configuration	Bore (cm)	FOV (cm)	Field (T)
Initial NMR	4	1	36
Intended MRI	9	3	28

Resistive coils for MRI: 90 mm bore, 2 coils.

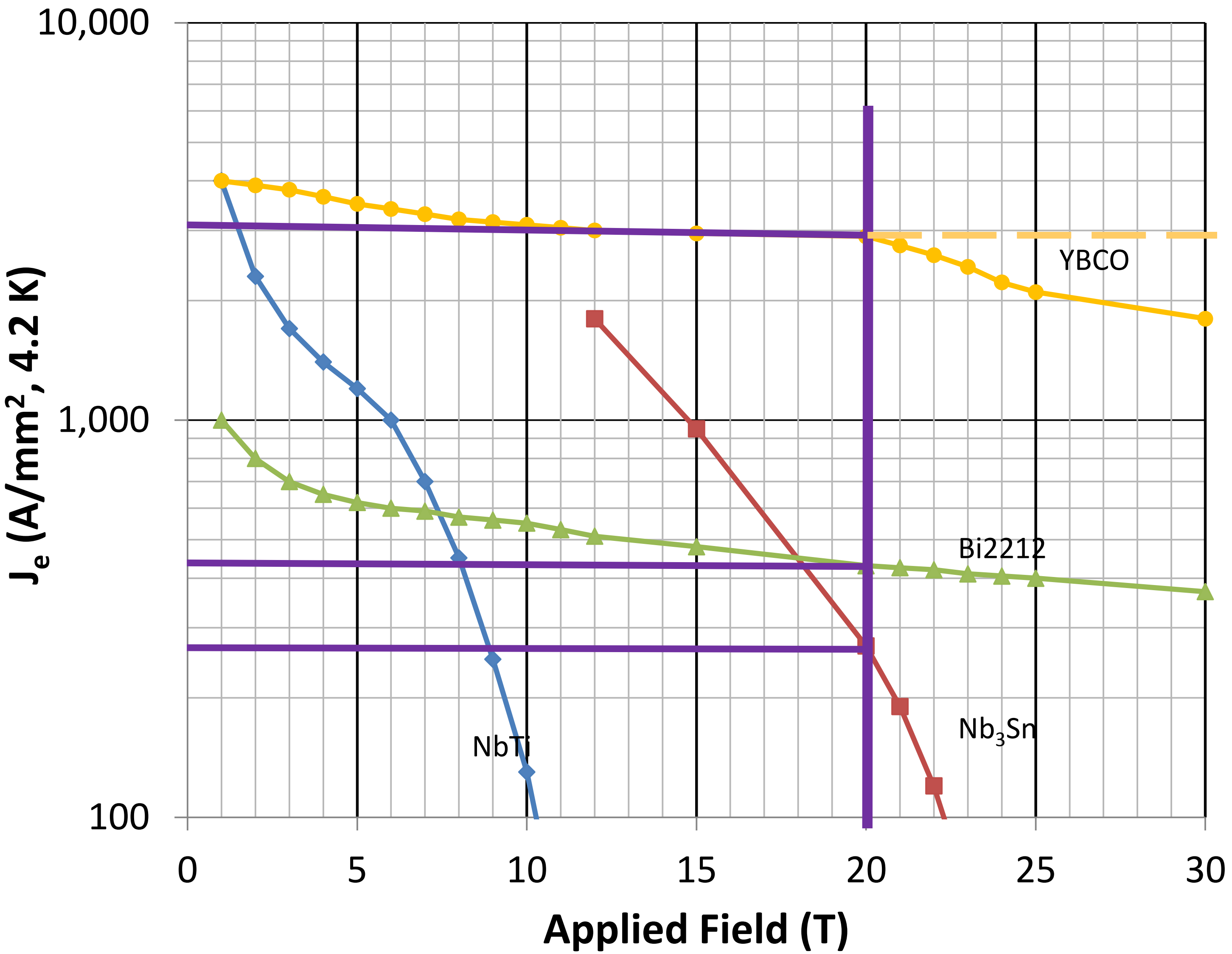
Resistive coils for NMR: 40 mm bore, 4 coils. Operational 2016



Nb_3Sn Superconducting coil
13 T, 46 cm room-temperature bore

NATIONAL MAGLAB

High Temperature (& Field) Superconducting Materials

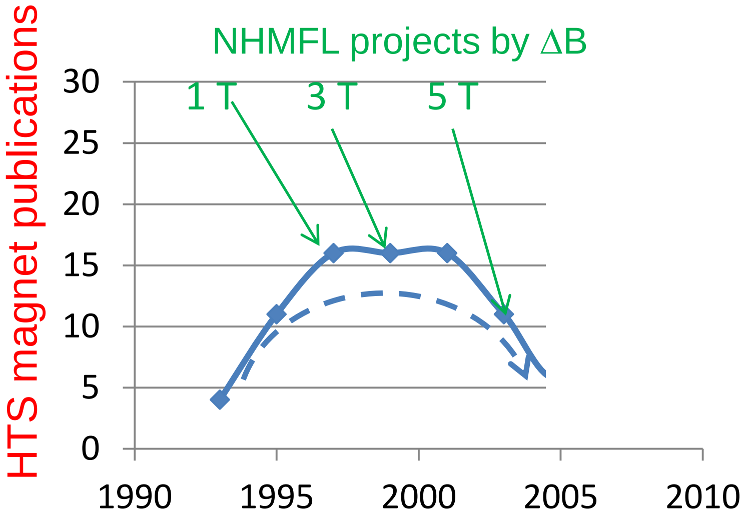


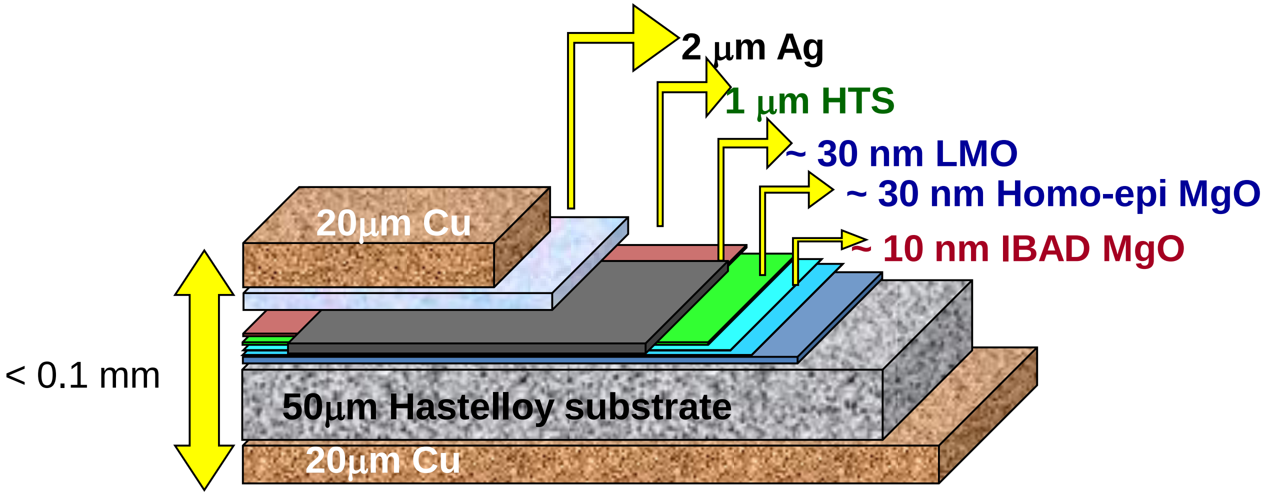
~1 ppb not possible with resistive magnets.

>24 T not possible with LTS magnets.

J_e data provided by P. Lee, NHMFL

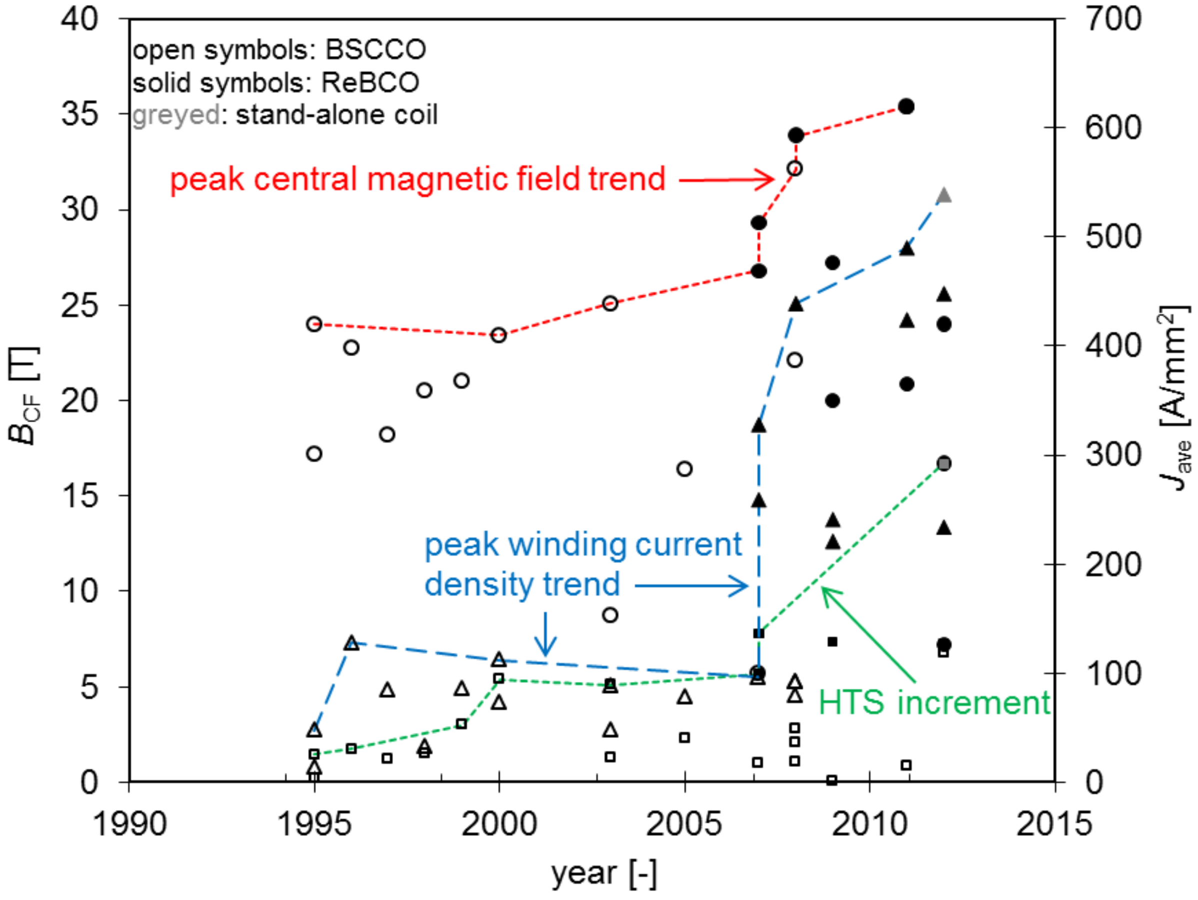
HTS Materials Revolution





2G YBCO Tape – SuperPower - 2007

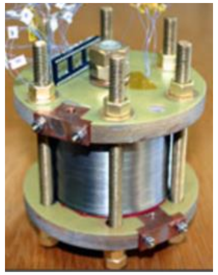
HTS Test Coil Field and Current Density



J_{ave} and B_{CF} data from H. Weijers, NHMFL

32 T TBCO Technology Development

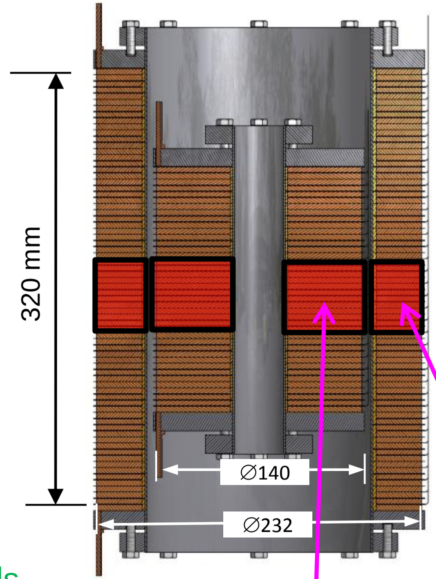
2007

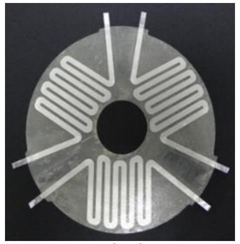


2008

High-B coils
31 T + ΔB

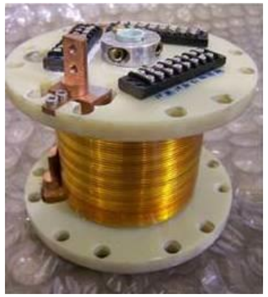
Prototype coils represent 20% of 32 T REBCO coils



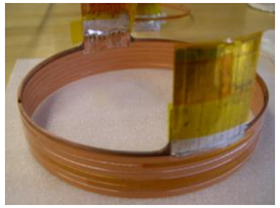


Quench heater

2008



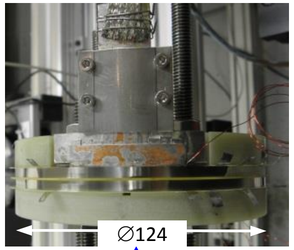
2009



Demonstration inserts
20 T+ ΔB

High Hoop-stress coils
>760 MPa

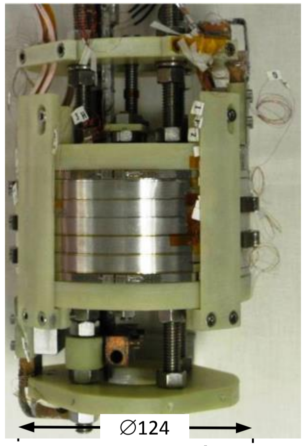
2011



First Quench Heaters

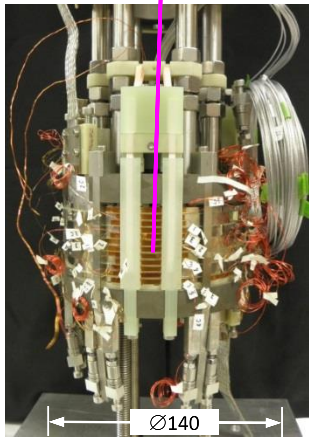
42-62 Mark 1:
1st test coil

2012



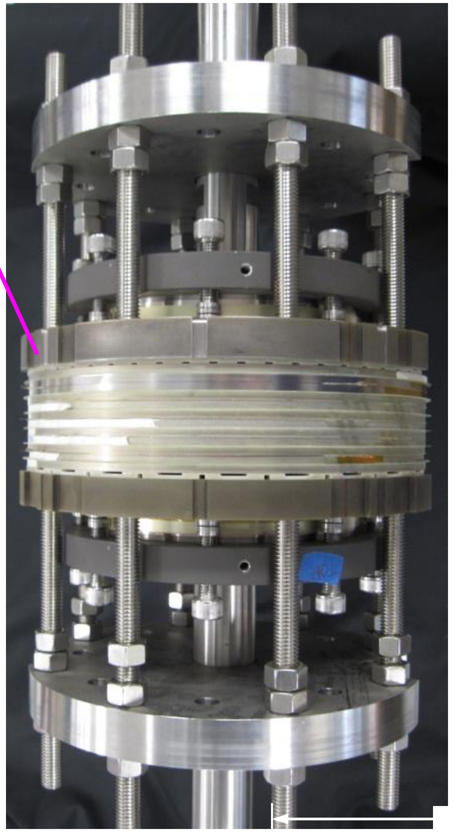
42-62 Mark 2:
2nd test coil

2013



20 - 70:
1st Full-featured Prototype

2014



∅232

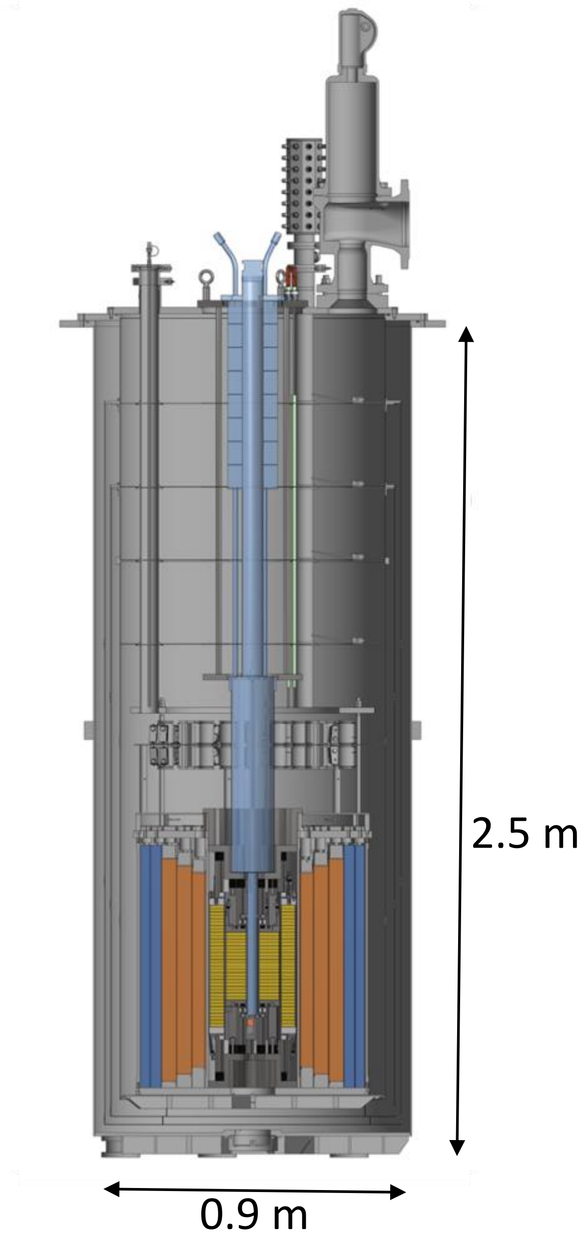
82 - 116:
2nd Full-featured Prototype

7-Year Development:

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

Photos from H. Weijers, NHMFL

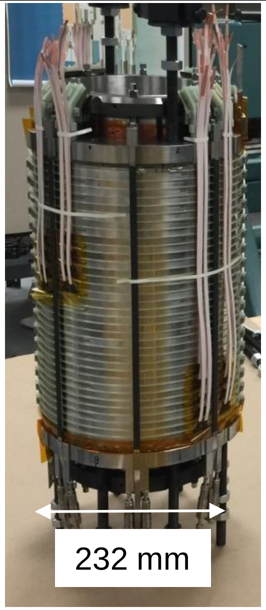
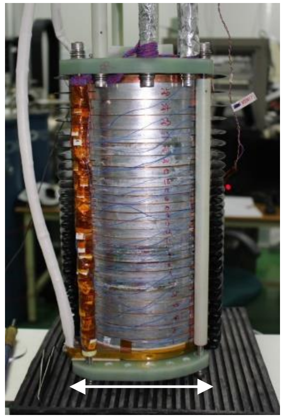
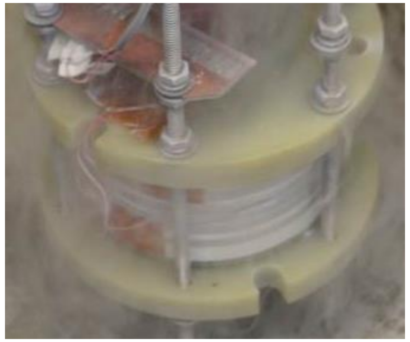
32 T Superconducting Magnet



Development:

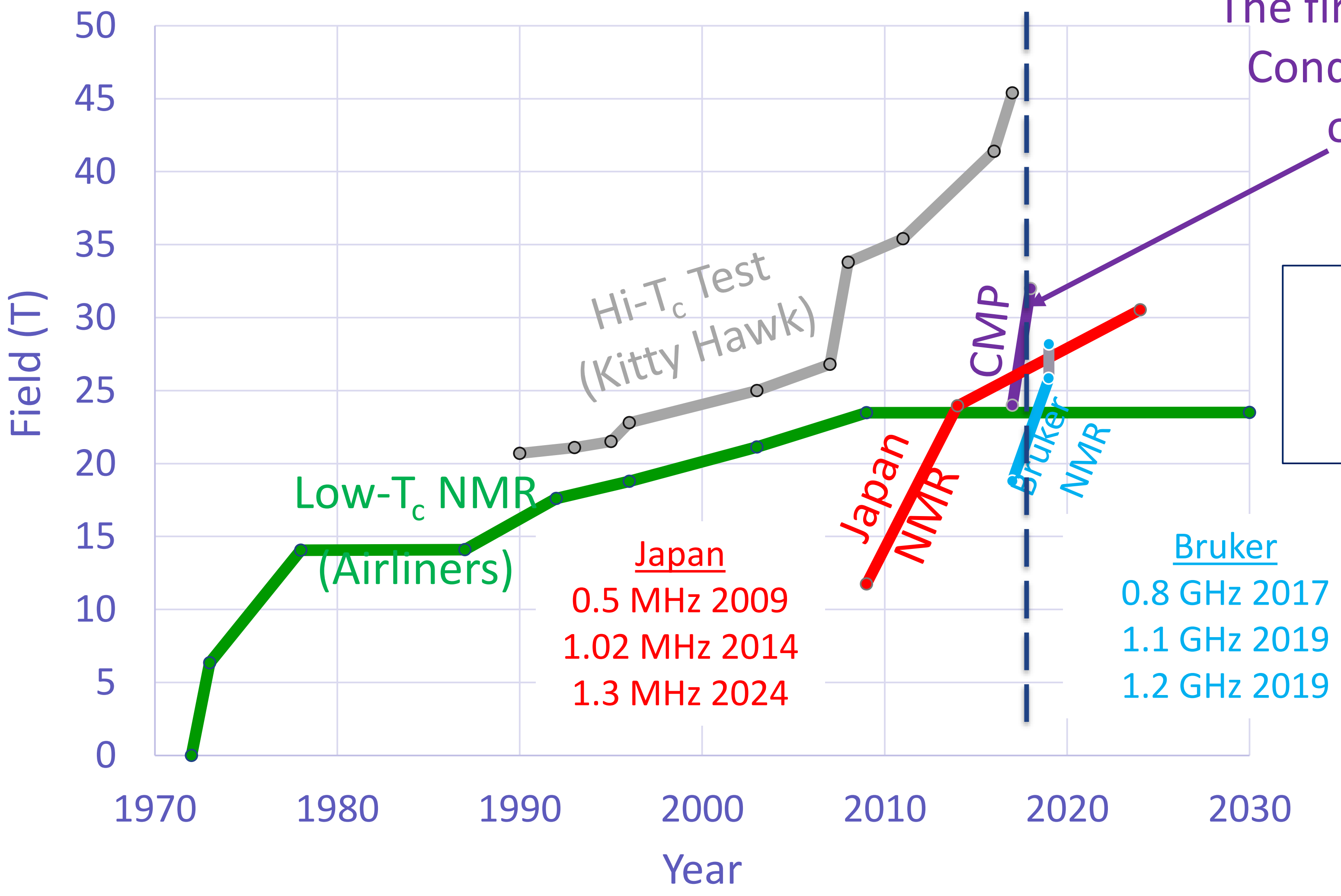
- YBCO tape characterization & QA
- Insulation technology
    - Ceramic on co-wound SS tape
- Coil winding technology
- Joint technology
- Quench analysis & protection
- Extensive testing of components

30 T Superconducting NMR Effort

Insulated REBCO	No-Insulation REBCO	Bi2221	Bi2223
	 172 mm	240 mm 	 240 mm
First Hi-Strength Tape available. Most technology development complete, including quench analysis and testing.	Extremely compact. Sometimes Self-Protecting.	Multi-filamentary is better for NMR.	Multifilamentary. High strength.
Some concern about single-crystal by the mile.	Limited quench modelling and active protection.	Over-Pressure Heat Treat. Few Test Coils. No quench modelling or testing.	Low current density. No quench modelling or testing.

Ultra High Field NMR Magnets

The first UHF HTS user magnets for Condensed Matter Physics were only completed in 2017.



Very rapid progress is being made on HTS magnets for NMR!

NMR (User) Magnet Goal?

	~200 ppm	10 ppm	1 ppm	0.1 ppm	0.01 ppm
0.4 GHz			**RIKEN, I-REBCO, 2014**		**RIKEN, I-REBCO, 2015**
0.7 GHz			**MIT, Bi2223, 2006**		**Bruker, I-REBCO, 2017** *RIKEN, Bi2223, 2018*
1.0 GHz	**Sendai, Bi2223, 2017**		*Riken, Bi2223?, 2022*		**Bruker, LTS, 2009** **NIMS, Bi2223, 2015**
1.1 GHz					*Bruker, 2019*
1.2 GHz					*Bruker, 2019*
1.3 GHz					*MIT, 2019* *RIKEN, 2024*
1.4 GHz	*MagLab, I-REBCO, 2019*				
1.5 GHz			**MagLab, Res, 2017**		
2.0 GHz	**MagLab, Res, 2000**		(MagLab EAC recommendation)		

Key: Complete, *Underway,* (proposed)

We're Doing 1.5 GHz NMR, we hope you are too!

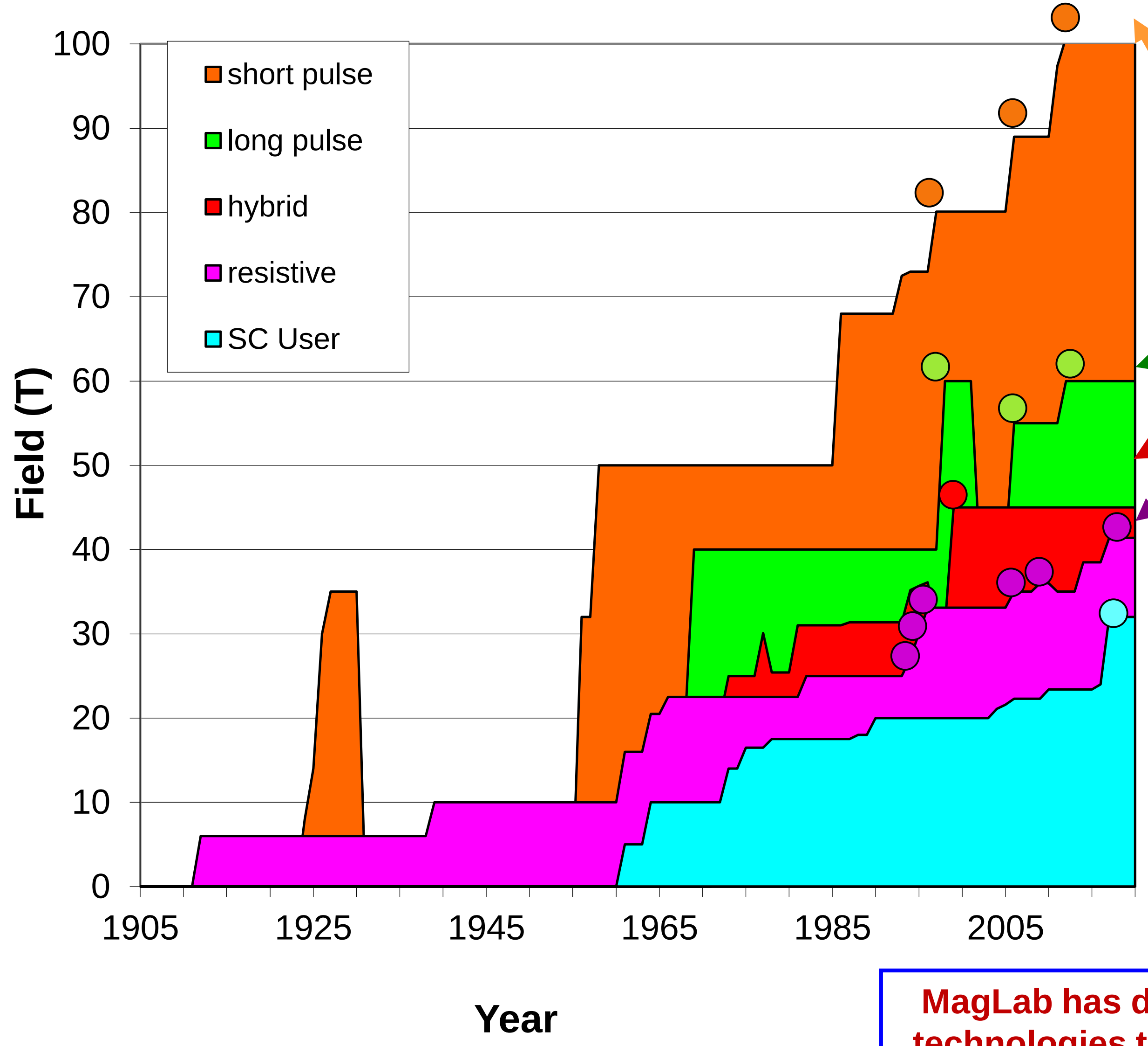
NATIONAL HIGH MAGNETIC FIELD LABORATORY

36 T SCH Magnet Project

M.D Bird, I. R Dixon

Analysis	Design	Materials	Fabrication	Facilities
I.R. Dixon	S. Bole	K. Han	L. Marks	J. Kynoch
A.V. Gavrilin	T. Adkins	J. Lu	R. Stanton	C. Rodman
H. Bai	K. Cantrell	B. Walsh	D. Richardson	V. Williams
T. Painter	S. Napier	B. Goddard	Leuthold	R. Lewis
S. Marshall	A. Trowell	V. Toplosky	N. Walsh	W. Nixon
J. Toth	S. Gundlach	**Instrument.**	N. Adams	G. Nix
Y. Zhai	M. White	S. Hannahs	L. English	J. Maddox
T. Xu	G. Miller	A. Powell	J. Lucia	L. Windham
Science		P. Noyes	J. Deterding	
T. Cross		Bonninghausen	E. Arroyo	
W. Brey				
I . Litvak				

Non-Destructive User Magnets:
Unique Magnets Enabled by Unique R&D



MagLab Records
101T/10msec, 2012
60T/0.1 sec, 1998
45T Hybrid, 2000
41.4T Resistive, 2017
32T Supercon, 2017

+ 21 T Pre-Clinical MRI
+ 25 T Split
+ 26 T Neutron Scattering

+ 45.1 T = 31 + 14 T HTS test coil

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

NATIONAL MAGLAB