The Global High Magnetic Field Forum (High Field Forum, or HiFF) was founded in 2014 by the leadership of high magnetic field laboratories in China, France, Germany, Japan, The Netherlands and the United States.

Together, these laboratories represent the increasingly international nature of research using the highest magnetic fields available worldwide.
Global HiFF Members

North America

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Magnet Technologies for User Programs

Status as of January, 2017 ... What new progress?

- **100.7T, 10 msec pulse**
- **60T, 0.1 sec pulse**
- **45.2T DC hybrid**
- **38.5T DC resistive**
- **23.4 T High-Resolution NMR (1.0GHz Superconducting Magnet)**
- **21T ICR**

Legend:
- Short Pulse (1-10 msec)
- Long Pulse (100-1000 msec)
- Hybrid (Resistive+SC)
- DC Resistive
- Superconducting NMR
- Superconducting FT-ICR

Year:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020

Magnetic Field (T):
- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100
36T / 1ppm Series-Connected Hybrid Magnet

- Short Pulse (1-10msec)
- Long Pulse (100-1000msec)
- Hybrid (Resistive+SC)
- DC Resistive
- Superconducting NMR (1.5GHz Hybrid Magnet)

35.2T T NMR (1.5GHz Hybrid Magnet)
Series Connected Hybrid: High-Homogeneity for NMR / MRI

36T in 40mm bore using 20kA and 13MW DC Power

1ppm Homogeneity over 10mm DSV

Series-Connected Cable-in-Conduit Magnet with Florida-Bitter Resistive Magnet

7.4 ton cold mass

Required 20kA HTS Current Leads
Required 20kA Superconducting Magnet
Required Multiple Field Stabilization Techniques
Sensitivity greatly limits the application of nuclear magnetic resonance (NMR) in condensed matter physics, materials research, chemistry and biology.

NMR probes the structure and function of materials, molecules and macromolecules at the atomic level, by signaling the local magnetic field or electric field gradient at all locations of a specific element.

NMR’s sensitivity increases with field strength: For usually-targeted spin-1/2 nuclei like $^1\text{H}$, $^{13}\text{C}$ or $^{29}\text{Si}$, NMR sensitivity increases as $B_0^{3/2}$.

Yet half-integer quadrupolar nuclei of chemically important atoms such as $^{17}\text{O}$ benefit much more dramatically, increasing as $B^{5/2}$ in the solid state, and as $B^{7/2}$ for slow tumbling macromolecules. Oxygen atoms define the sites of many chemical reactions in materials.

Moreover, signal averaging times are reduced by the square of these sensitivity enhancements.
The 36T SCH will be key to studying the local structure of materials containing atoms that span the entire periodic table, materials ranging from industrial glasses to membrane proteins.

NMR researchers can exploit these sensitivity gains to isolate atoms on the surface from those in the bulk to focus on surface catalytic reactions.

The increased ability to resolve NMR lines for quadrupolar nuclei opens the door to study metal atoms that are present in a third of all proteins, metals that often govern their function.

It also will allow users to study the chemistry of materials which have never been probed by NMR before. In particular, it should give access to spin > $\frac{1}{2}$ nuclides like $^{197}$Au, $^{33}$S, $^{25}$Mg or $^{17}$O, which although studied before in amenable systems, could not be analyzed in an overwhelming majority of materials of interest.
Variable field $^{17}$O central-transition NMR spectra of oxalate (70% $^{17}$O-enriched) bound to chicken ovotransferrin (OTf), a protein found in egg white.

Note that 21T is required to resolve three of the four inequivalent oxygen sites.

36T will enable still higher resolution, increasing as $B^{5/2}$ in the solid state, and as $B^{7/2}$ for slow tumbling macromolecules to probe more complex molecular interactions and, ultimately, their functionality.
NMR and MRI Applications Enabled by Increasing Magnetic Field Homogeneity and Stability

- Most Superconducting NMR Magnets: 1 – 10 ppb
- Series Connected Hybrid Magnet < 1 ppm
- High-Res Resistive Magnets: 2 – 50 ppm
- Standard-Resolution Resistive Magnets > 200 ppm

Bo Homogeneity & Stability

- 1 ppb
- 10 ppb
- 100 ppb
- 1 ppm
- 10 ppm
- 100 ppm
- 1 ppt
Replacing flammable liquid electrolytes with solid electrolytes in rechargeable Li-ion batteries will increase both performance and safety. Yet a fundamental understanding of Li transport pathways is necessary to develop solid electrolytes with fast Li ion conduction.

Employ Lithium-6 → Lithium-7 isotope replacement NMR to track Lithium transport pathways in complex solid electrolytes designed for use in solid-state rechargeable batteries. These measurements determine that the preferred Li pathways through experimental solid electrolytes depend on the compositions and structures of the electrolytes.

As the content of ceramic particles in polymer-ceramic composite electrolytes increases, Li transport pathways switch from the modified polymer phase to percolated networks made of ceramic particles. Small molecule additives further enhance Li ion conductivity by creating a new phase with high Li ion mobility.

Yang, Zheng, Chen & Hu, Composite Polymer Electrolytes with Li$_7$La$_3$Zr$_2$O$_{12}$ Garnet-Type Nanowires as Ceramic Fillers: Mechanism of Conductivity Enhancement and Role of Doping and Morphology, ACS Appl. Mater. Interfaces., 9(26), 21773-21780 (2017).
NMR and MRI Applications Enabled by Increasing Magnetic Field Homogeneity and Stability

Most Superconducting NMR Magnets: 1 – 10 ppb
Series Connected Hybrid Magnet < 1 ppm
High-Res Resistive Magnets: 2 – 50 ppm
Standard-Resolution Resistive Magnets > 200 ppm

**B₀** Homogeneity & Stability
The GB1 protein is a good test, because it gives the sharpest NMR lines... which the 36T resolves!

Membrane proteins give broader lines due to their dynamics...they are not amenable to X-ray crystallography or cryogenic electron microscopy.

**Fig. 1:** 35.2 T SCH $^{13}$C spectra. The adamantane spectrum was obtained with a single acquisition resulting in 0.18 ppm linewidths and unfortunately 60Hz noise in the baseline. The uniformly $^{15}$N and $^{13}$C labeled GB1 spectrum represents just 64 acquisitions and the narrowest resonances are 0.4 ppm.

**Fig. 2:** Two-dimensional $^{13}$C-$^{13}$C correlation spectrum for GB1 – In Red is the spectrum from the SCH and in black is the spectrum from an 800 MHz superconducting magnet. In this contoured spectrum the diagonal resonances represents the $^{13}$C spectrum in Fig. 1, the off-diagonal resonances identifies carbons sites that are within ~5Å of each other providing structural information.
ChiZ is a protein from the cell-division apparatus of the tuberculosis bacteria.

**Fig. 3:** Two-dimensional $^{13}$C-$^{13}$C correlation spectrum for ChiZ from *M. tuberculosis* – Red is the SCH spectrum; Black is the supercon spectrum. There is no evidence of t1 noise and as seen in the insert expansion the SCH resonances are much narrower than the black resonances.

The enhanced spectral dispersion of the resonances, improved linewidths, and lack of t1 noise already makes the SCH the world’s best NMR instrument for obtaining NMR spectra from membrane proteins.

Membrane proteins represent a third of the proteins in your body...and 90% of the targets for pharmaceutical developments.
“Project 11”: Amping Up Resistive Magnets

- Short Pulse (1-10msec)
- Long Pulse (100-1000msec)
- Hybrid (Resistive+SC)
- DC Resistive
- Superconducting or Hybrid NMR
- Superconducting FT-ICR

41.4T DC resistive
41.4T in 32mm bore using 32MW DC Power

Six-Coil Florida-Bitter Design: Copper-Silver Alloy Plates and Copper Plates

Six tons

“Project 11”: Amping Up Resistive Magnets

Spinal Tap lead guitarist, Nigel Tufnel, explains the importance of “11”
Reached peak field on August 21, 2017

41.4T (+/-0.2T) using 31.9 MW
Introducing HTS to Hybrid Magnets

Magnetic Field (T)

Year

- Short Pulse (1-10msec)
- Long Pulse (100-1000msec)
- Hybrid (Resistive+SC)
- DC Resistive
- Superconducting or Hybrid NMR
- Superconducting FT-ICR

45.5T DC hybrid using HTS test coil
A VERY SMALL COIL
12 pancakes of REBCO tape
220-234 turns / pancake
• 14 mm ID
• 34 mm OD
• 51 mm tall

HTS test coil generates 14.38T in a 31.08T background field

Yielding 45.46T total field in a proof-of-principal hybrid magnet configuration

Overall winding current density was **1262 A/mm^2**.

Which is...
more than an order of magnitude larger current density than LTS magnets.

three times the current density carried in water-cooled resistive magnets.

sixty times the current density in the filament of a 100W incandescent light bulb.
Little Big Coil 3 (LBC3) Main Test: Overall Signal Profiles

- Charging of LBC3 NI REBCO insert under 31.08 T Background Field
- LBC3 ramp rate: 10 A/min → 5 A/min → 4 A/min
- Actual coil current: 245.3 A (245.5 – 0.2) → Insert magnetic field: 14.38T → Total magnetic field: 45.46T

![Graph showing voltage, field, temperature, and current over time]

- $J_e$: 1419 A/mm$^2$
- $J_w$: 1262 A/mm$^2$
HTS Test Coils in Resistive Magnet Background

Materials enable Magnets

HTS Materials are revolutionary...and are enabling a Magnet Revolution
Why is there a Universal Phase Diagram for Superconductivity?

CeIn₃
a Heavy Fermion Compound with Superconducting Tc ~ 0.2K

\begin{center}
\begin{tikzpicture}
    \begin{axis}[
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        ylabel=Temperature (K),
        xmin=0, xmax=30,
        ymin=0, ymax=10,
        xtick={0,10,20,30},
        ytick={0,5,10},
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        legend style={at={(0.5,0.9)},anchor=north}
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    \addplot[only marks, mark size=2pt, mark options={solid}] coordinates {
        (0,10) (10,5) (20,0.5) (30,0)
    } node[above] {$T_N$}
    \addplot[only marks, mark size=2pt, mark options={solid}] coordinates {
        (0,10) (10,5) (20,0.5) (30,0)
    } node[below] {$T_s$}
    \addplot[domain=0:30, samples=50, color=blue] {10 - 0.5*x} node[below] {Superconductor}
    \addplot[domain=0:30, samples=50, color=black] {5 - 0.05*x} node[below] {Anti-ferromagnet}
    \addplot[domain=0:30, samples=50, color=black] {0 - 0.05*x} node[below] {Ordinary Metal}
    \legend{Superconductor, Anti-ferromagnet, Ordinary Metal}
\end{axis}
\end{tikzpicture}
\end{center}


Electron-doped High-Temperature Iron-Based High-Tc Superconductor
Maximum Tc ~ 10-55K

Ba(Fe₁₋ₓCoₓ)₂As₂

SDW (Metallic Magnet)

METAL

Determination of the phase diagram of the electron doped superconductor Ba(Fe₁₋ₓCoₓ)₂As₂

Hole-doped High-Temperature Copper-Based High-Tc Superconductor

Maximum Tc ~ 40-150K

Is Superconductivity Stabilized by a Quantum Critical Point?

Non-Fermi liquid

$\rho (\mu \Omega \cdot \text{cm})$

$T$ (K)

$\sigma = 1.02 (+/- 0.01) \mu \Omega \cdot \text{cm/K}$
What is a Quantum Critical Point?
Diverging Electron Mass is Evidence of a QCP at Optimum Doping in YBCO

DOI: 10.1126/science.aaa4990
Diverging Effective Mass: Evidence of a Quantum Critical Point at Optimum Doping in YBCO

CLEARLY: We Need Bigger Magnets!

S.E. Sebastian et al. PNAS 107, 6175 (2010)

A Future All-Superconducting Magnet

Magnetic Field (T)

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

32T HTS All-Superconducting Project
(plotted in the (very near) future)
(knock on wood)
Bringing HTS and LTS together to break through the 23.4T barrier for superconducting magnets

32T All-Superconducting Magnet Project
Electronic density of states shows enhancement as $x$ approaches optimum doping, $x = 0.3$. 

**BaFe$_2$(As$_{0.54}$P$_{0.46}$)$_2$**

$T = 1.5 \text{ K}$

$\rho = 13.8 \text{ mJ/mol$_\text{fuc}$K}^2$

Mass Enhancement Diverges at Optimum Doping: Evidence of a Quantum Critical Point in Another Class of High-Tc Superconductors

Electronic density of states shows enhancement as x approaches optimum doping, x = 0.3.
Comprehensive Studies that Require Large Amounts of Magnet Time will Benefit from the 24/7 Operation of the 32T All-Superconducting Magnet.
Magnet Technologies for User Programs

Great Progress!

- 100.7T, 10 msec pulse
- 60T, 0.1 sec pulse
- 45.5T DC hybrid using HTS test coil
- 45.2T DC hybrid
- 41.4T DC resistive
- 35.2T T NMR (1.5GHz Hybrid Magnet)
- 32T HTS All-Superconducting Project
- 23.4 T High-Resolution NMR (1.0GHz Superconducting Magnet)
- 21T ICR
Unlocking the Periodic Table

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**Global High Magnetic Field Forum**

**Why is there a Universal Phase Diagram for Superconductivity?**

**Thank You!**

**CLEARLY:** We Need Bigger Magnets!

**Unlocking the Periodic Table**

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