High Magnetic Field Science and Technology

Greg Boebinger, Director, National High Magnetic Field Laboratory (U.S.)
Professor of Physics, Florida State University and University of Florida
Chair, Global High Magnetic Field Forum

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.

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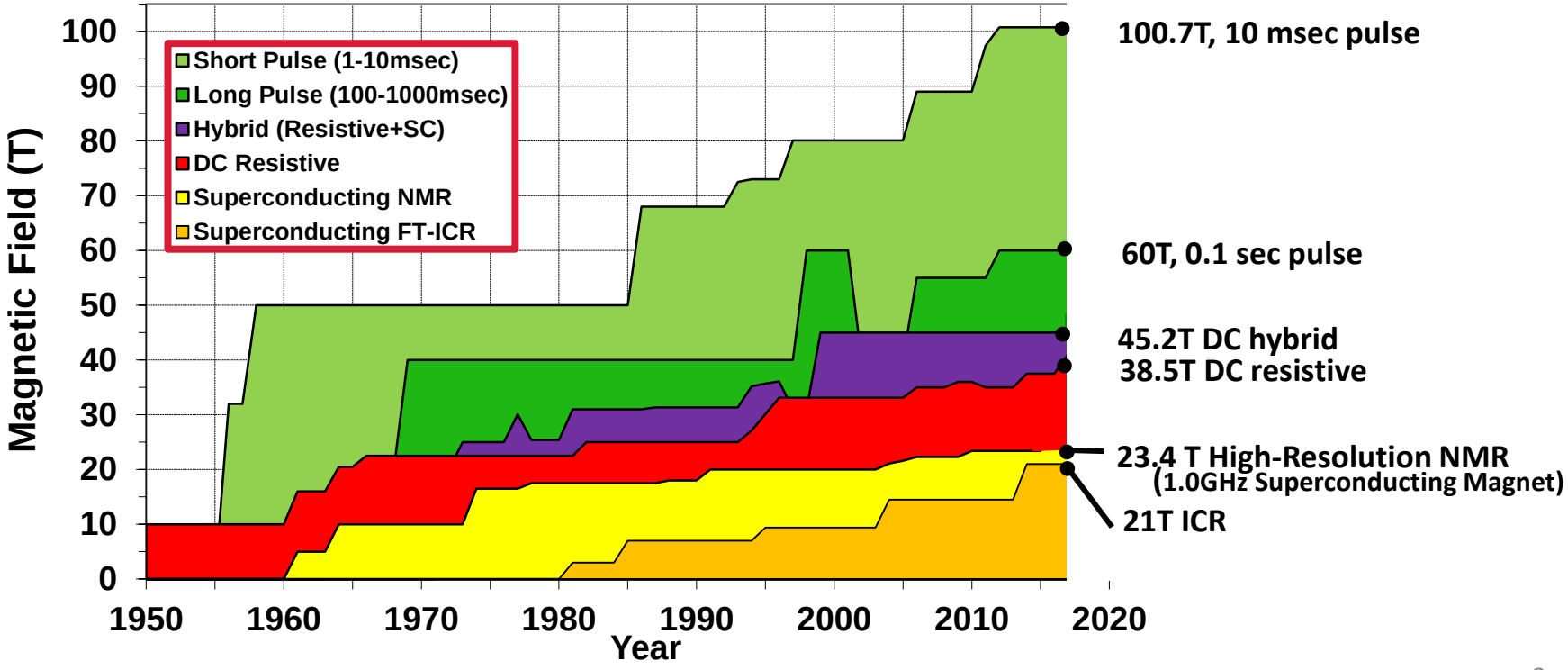
Oliver PORTUGALL (Laboratoire National Champs Magnetiques Intense, Toulouse, FRANCE)

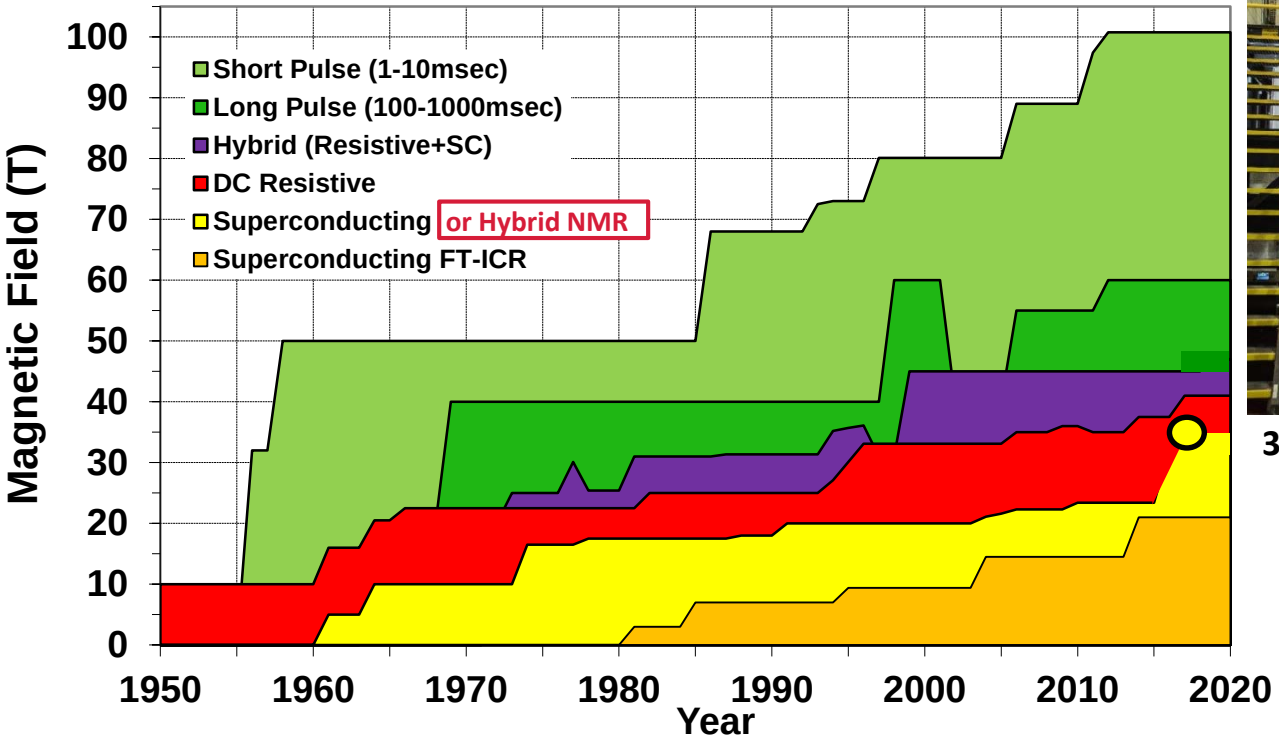
Jochen WOSNITZA (Director, Hochfeld-Magnetlabor Dresden, GERMANY and Director, EMFL-D)

Magnet Technologies for User Programs

Status as of January, 2017…What new progress?

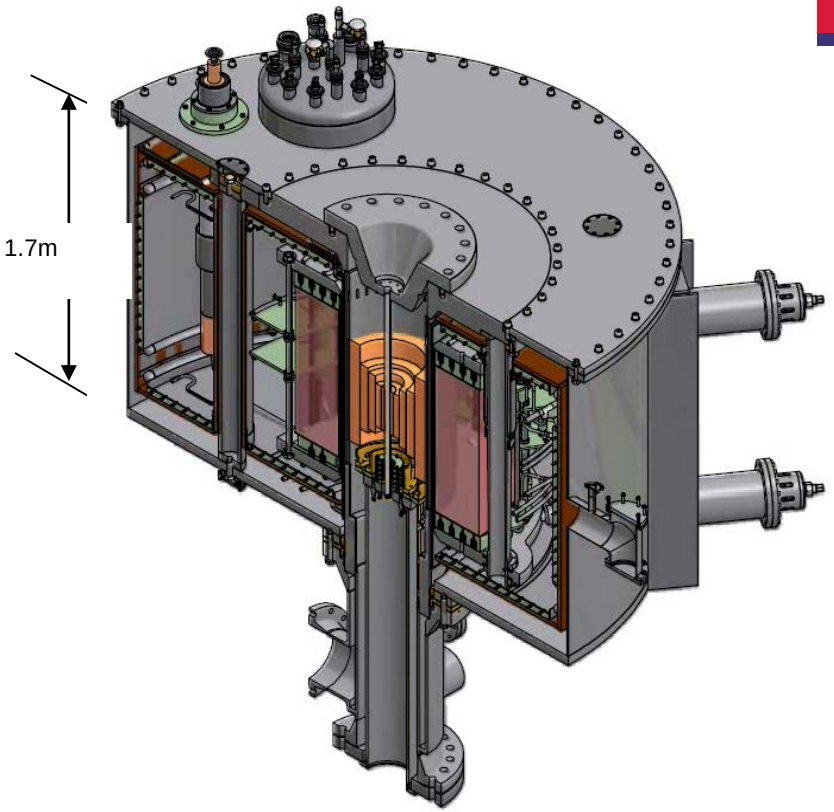


36T / 1ppm Series-Connected Hybrid Magnet



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

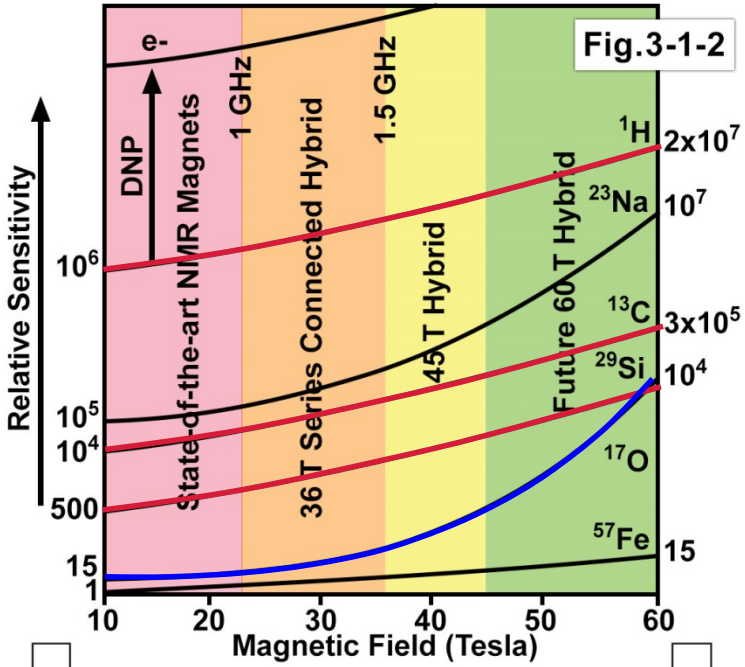
1ppm Homogeneity over 10mm DSV

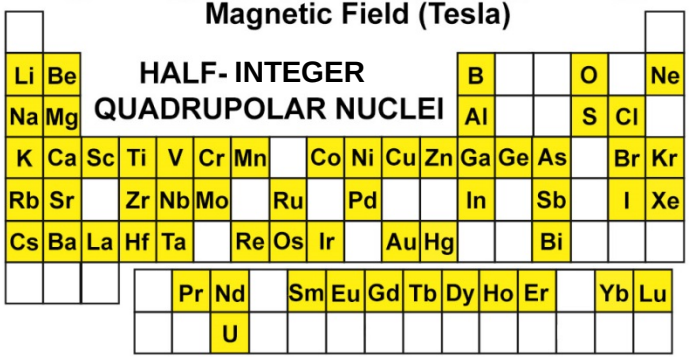
Series-Connected Cable-in-Conduit Magnet with Florida-Bitter Resistive Magnet

7.4 ton cold mass

Required 20kA HTS Current Leads
Required 20kA Superconducting Magnet
Required Multiple Field Stabilization Techniques

Unlocking the Periodic Table





Sensitivity greatly limits the application of nuclear magnetic resonance (NMR) in condensed matter physics, materials research, chemistry and biology.

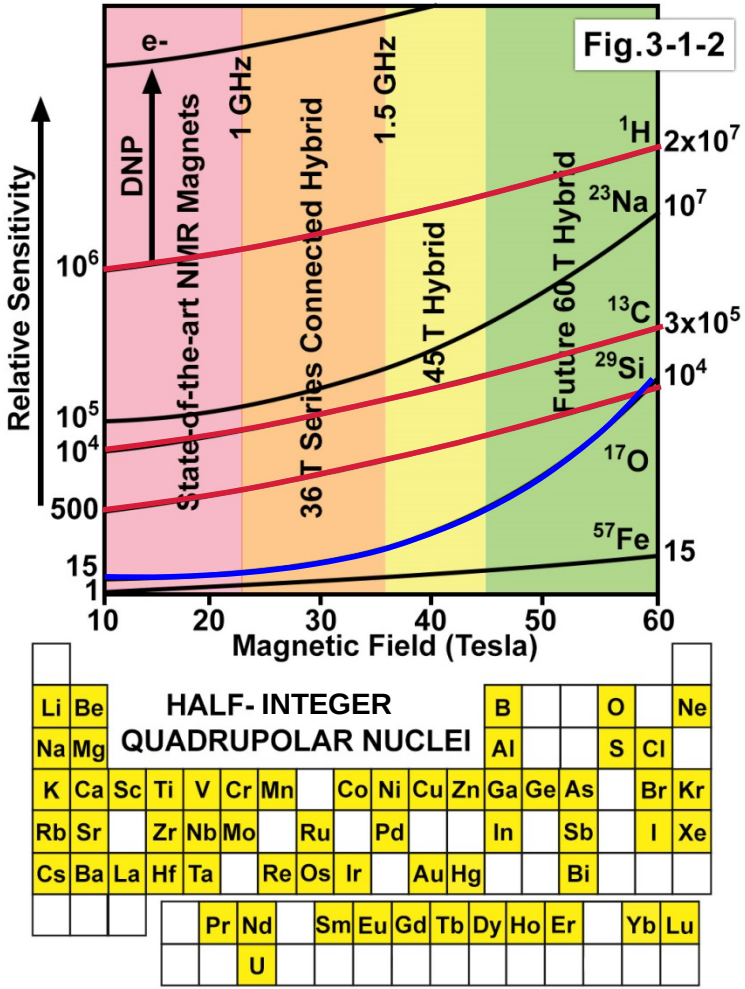
NMR probes the structure and function of materials, molecules and macromolecules at the atomic level, by signaling the local magnetic field or electric field gradient at all locations of a specific element.

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

Yet half-integer quadrupolar nuclei of chemically important atoms such as ^{17}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.

Unlocking the Periodic Table



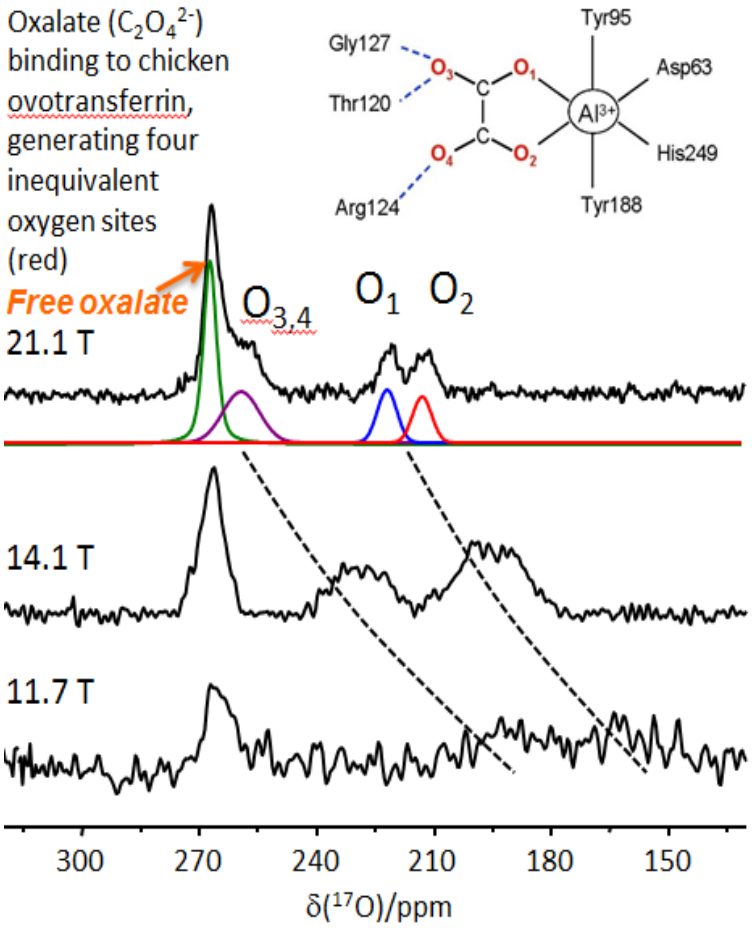
The 36T SCH will be key to studying the local structure of materials containing atoms that span the entire periodic table, materials ranging from industrial glasses to membrane proteins.

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.

<u>It also will allow users to study the chemistry of materials which have never been probed by NMR before</u>. In particular, it should give access to spin > ½ 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.

Resolving ^{17}O, the reactive site

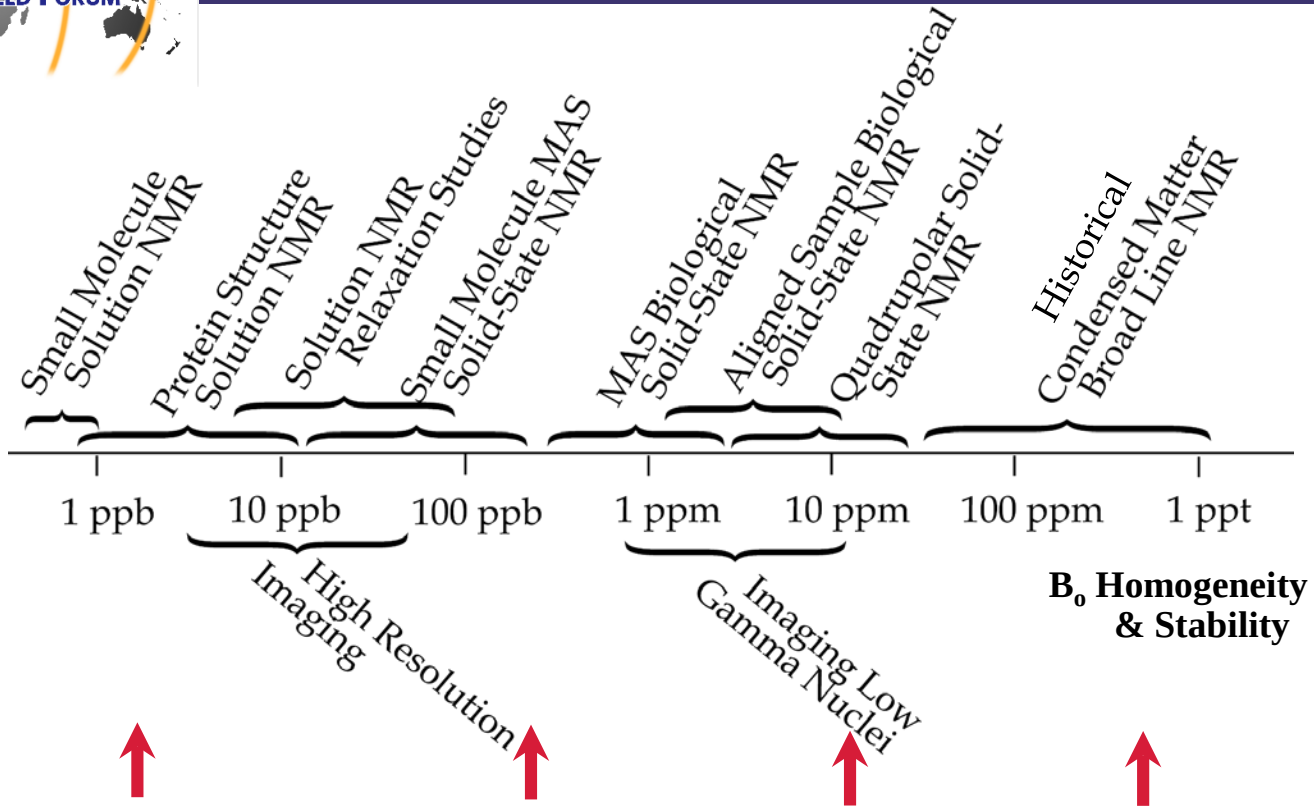


Variable field ^{17}O central-transition NMR spectra of oxalate (70%^{17}O-enriched) bound to chicken ovotransferrin (OTf), a protein found in egg white.

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

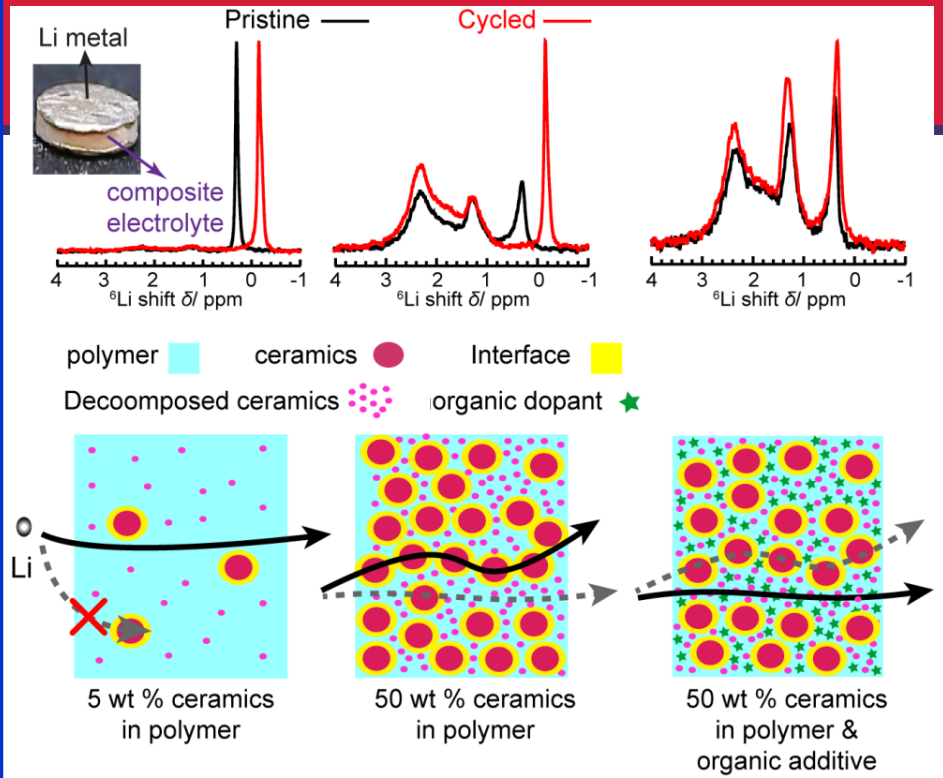
Standard-Resolution Resistive Magnets > 200 ppm

Tracking Lithium Transport Pathways in Solid Electrolyes for Batteries

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.

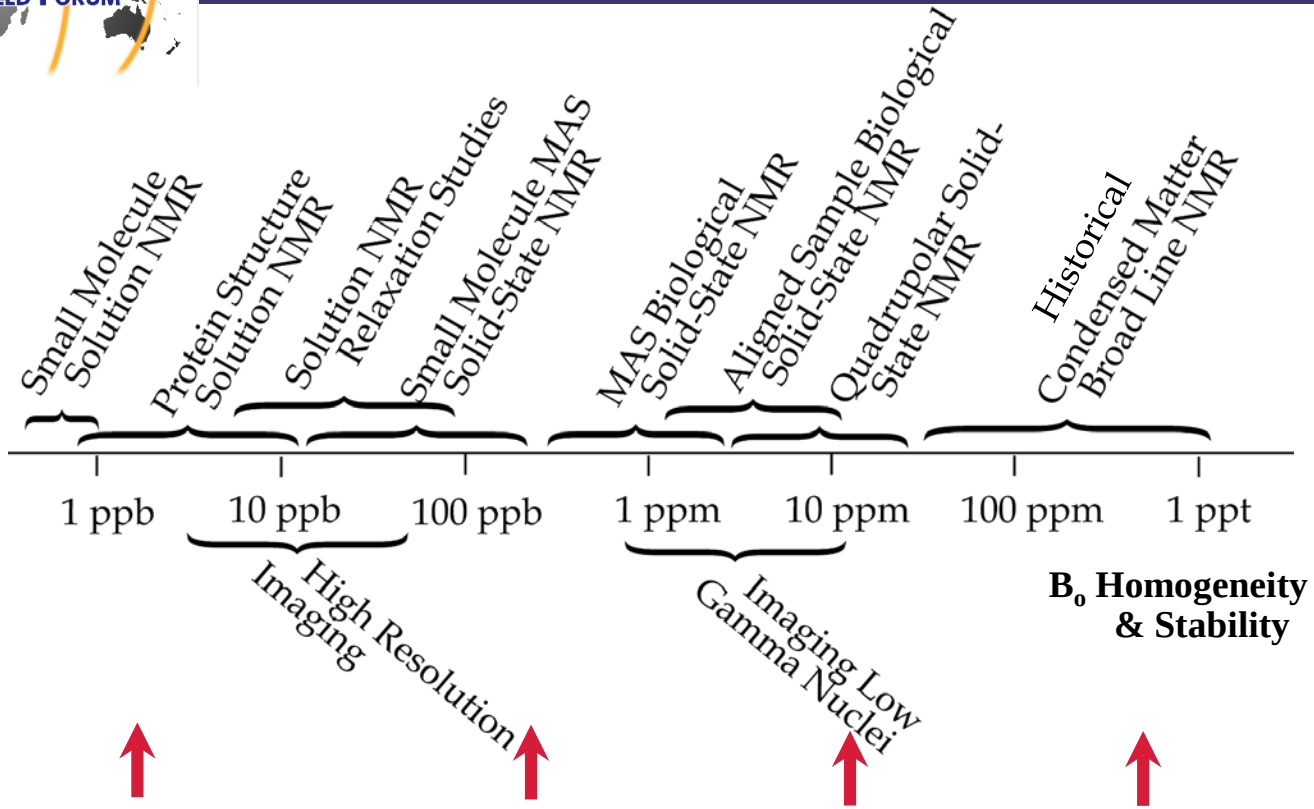
Employ Lithium-6 → Lithium-7 isotope replacement NMR to track Lithium transport pathways in complex solid electrolytes designed for use in solid-state rechargeable batteries. *These measurements determine that the preferred Li pathways through experimental solid electrolytes depend on the compositions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

Yang, Zheng, Chen & Hu, *Composite Polymer Electrolytes with $Li_7La_3Zr_2O_{12}$ 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).



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.

NMR and MRI Applications Enabled by Increasing Magnetic Field Homogeneity and Stability



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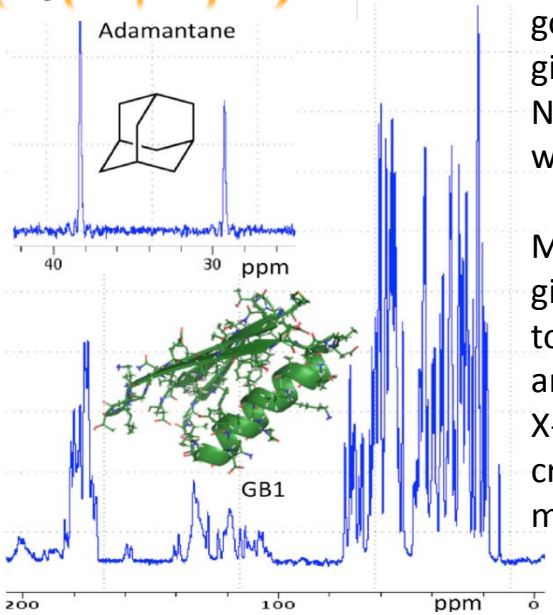
Solving Protein Structures with the SCH Magnet



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

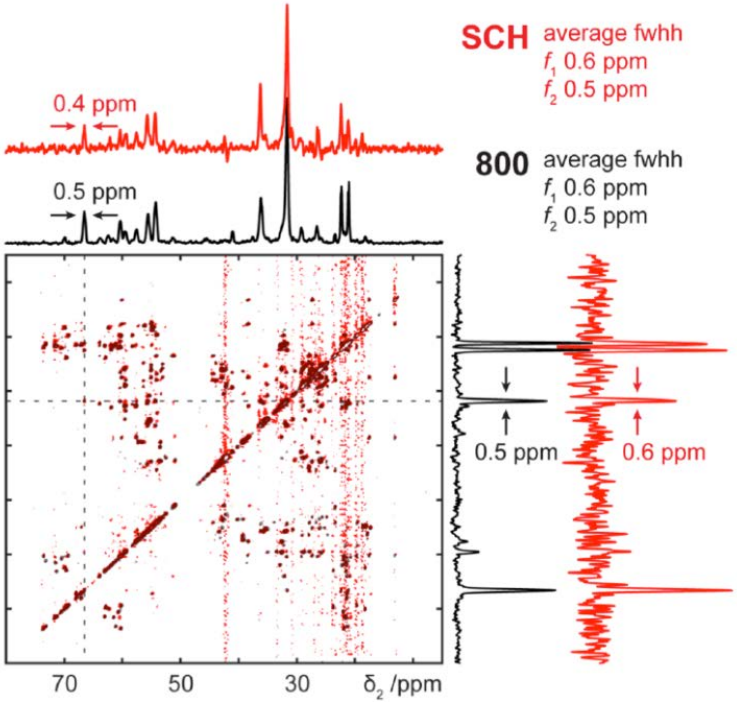
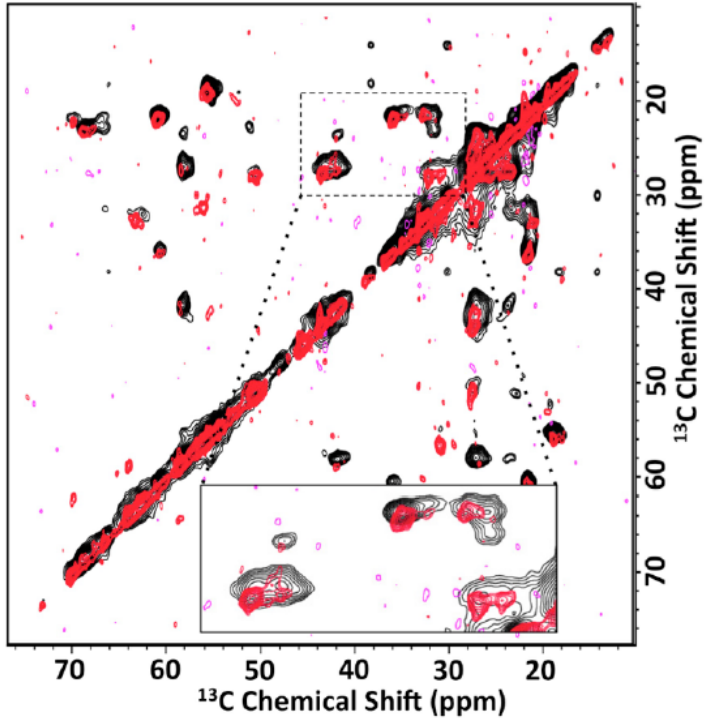


Fig. 1: 35.2 T SCH ^{13}C spectra. The adamantane spectrum was obtained with a single acquisition resulting in 0.18 ppm linewidths and unfortunately 60Hz noise in the baseline. The uniformly ^{15}N and ^{13}C labeled GB1 spectrum represents just 64 acquisitions and the narrowest resonances are 0.4 ppm.

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.

Solving Protein Structures with the SCH Magnet



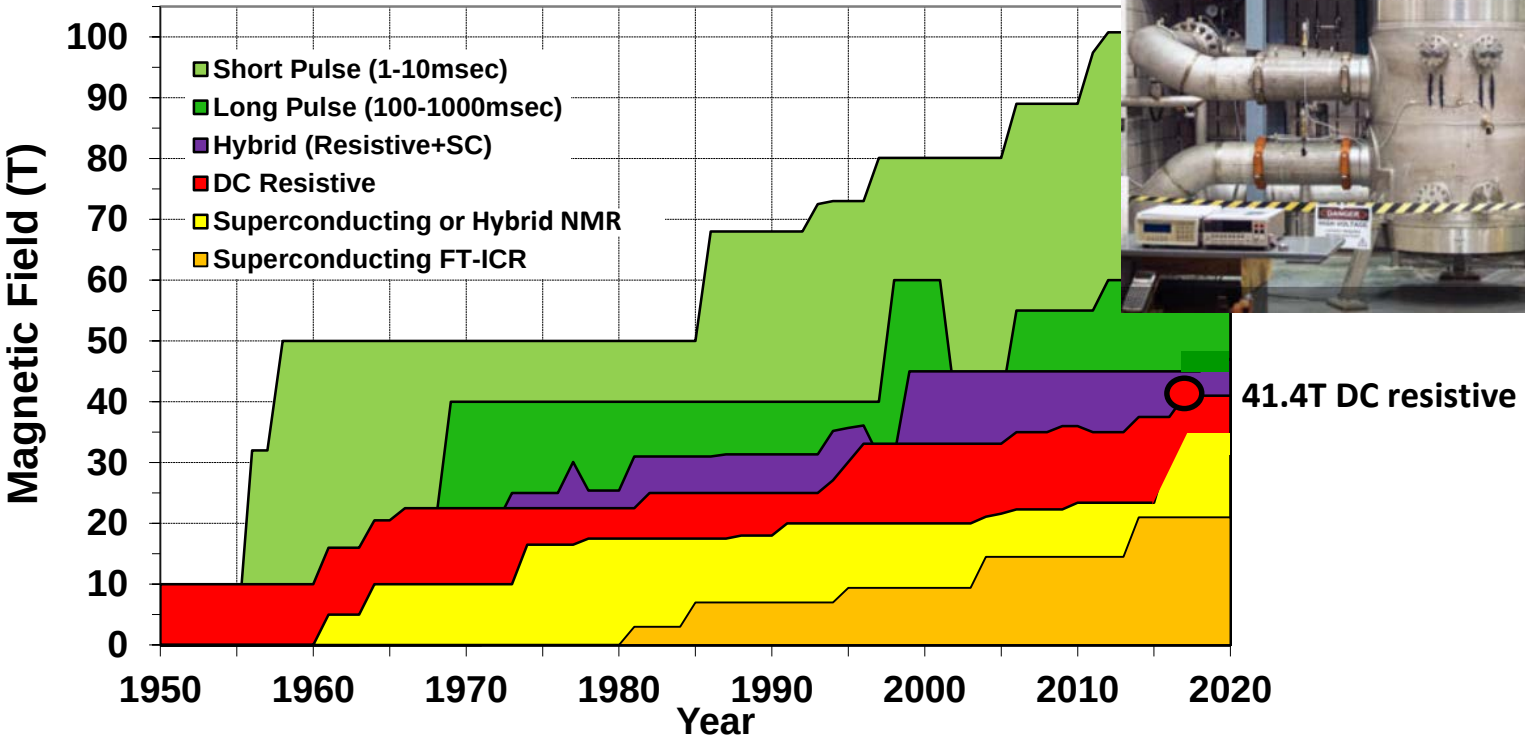
ChiZ is a protein from the cell-division apparatus of the tuberculosis bacteria.

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.

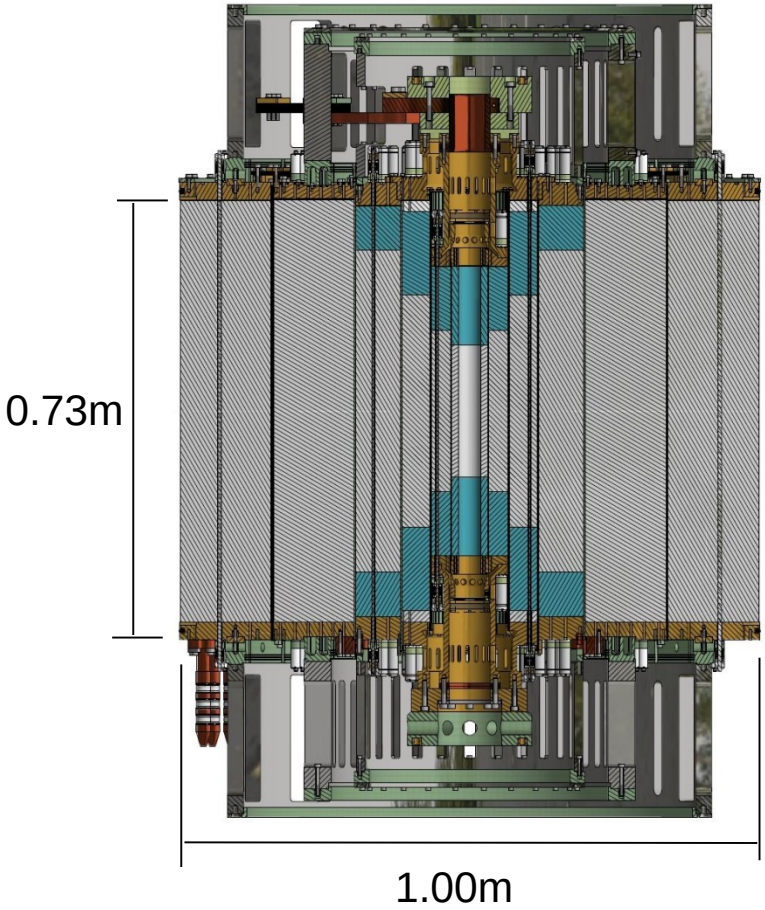
The enhanced spectral dispersion of the resonances, improved linewidths, and lack of t1 noise already makes the SCH the world's best NMR instrument for obtaining NMR spectra from membrane proteins.

Membrane proteins represent a third of the proteins in your body…and 90% of the targets for pharmaceutical developments.

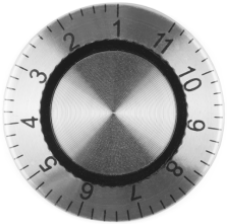
“Project 11”: Amping Up Resistive Magnets



“Project 11”:
Amping Up Resistive Magnets



41.4T in 32mm bore
using 32MW DC Power



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

Six tons

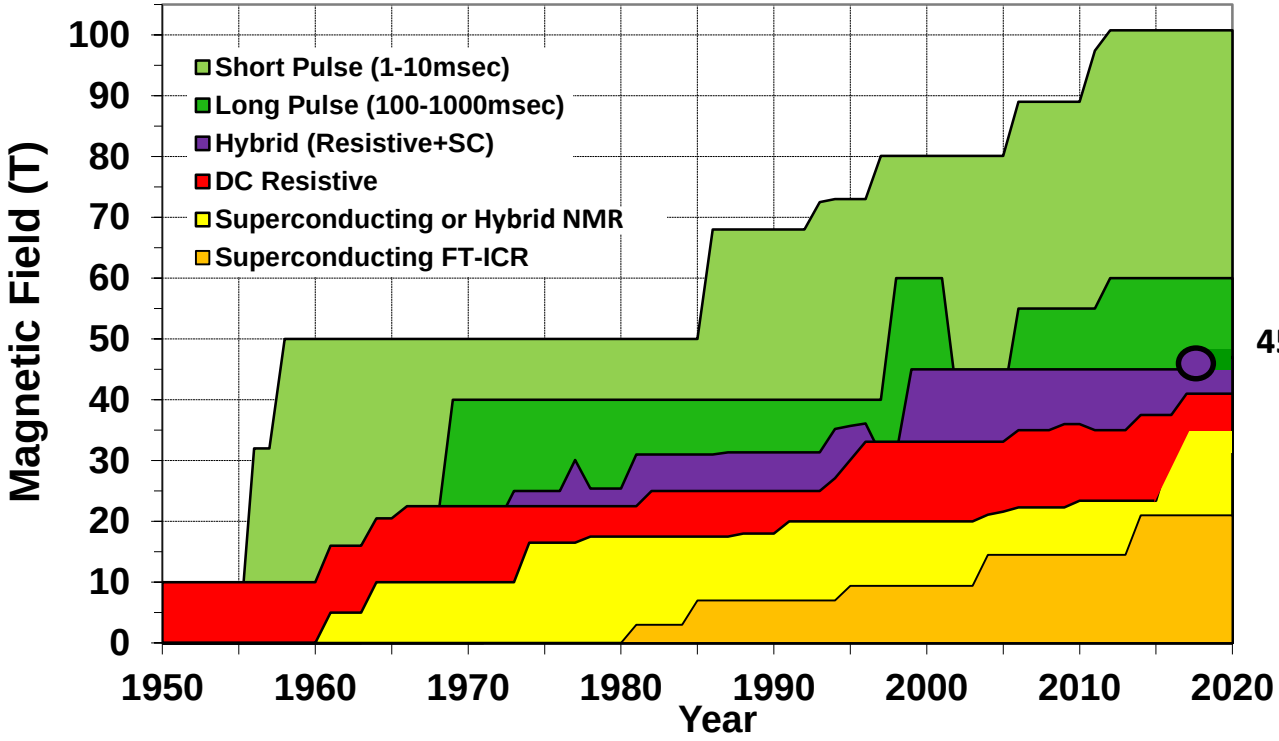
Spinal Tap lead guitarist, Nigel Tufnel, explains the importance of “11”

The new world-record magnet connected to cooling water pipes. Some 4,275 gallons of cold water flush through it per minute to keep it cool.

Reached peak field on August 21, 2017

41.4T (+/-0.2T) using 31.9 MW

Introducing HTS to Hybrid Magnets



45.5T DC hybrid using HTS test coil

HTS Test Coils in 31T Resistive Magnet Background

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…

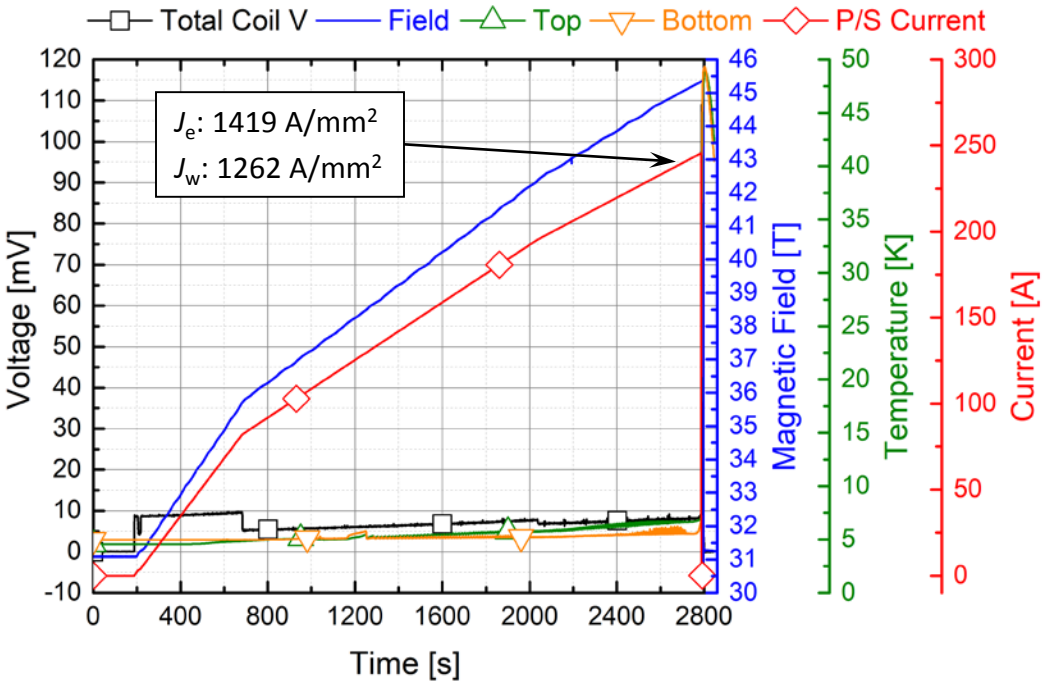
more than an order of magnitude larger current density than LTS magnets.

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

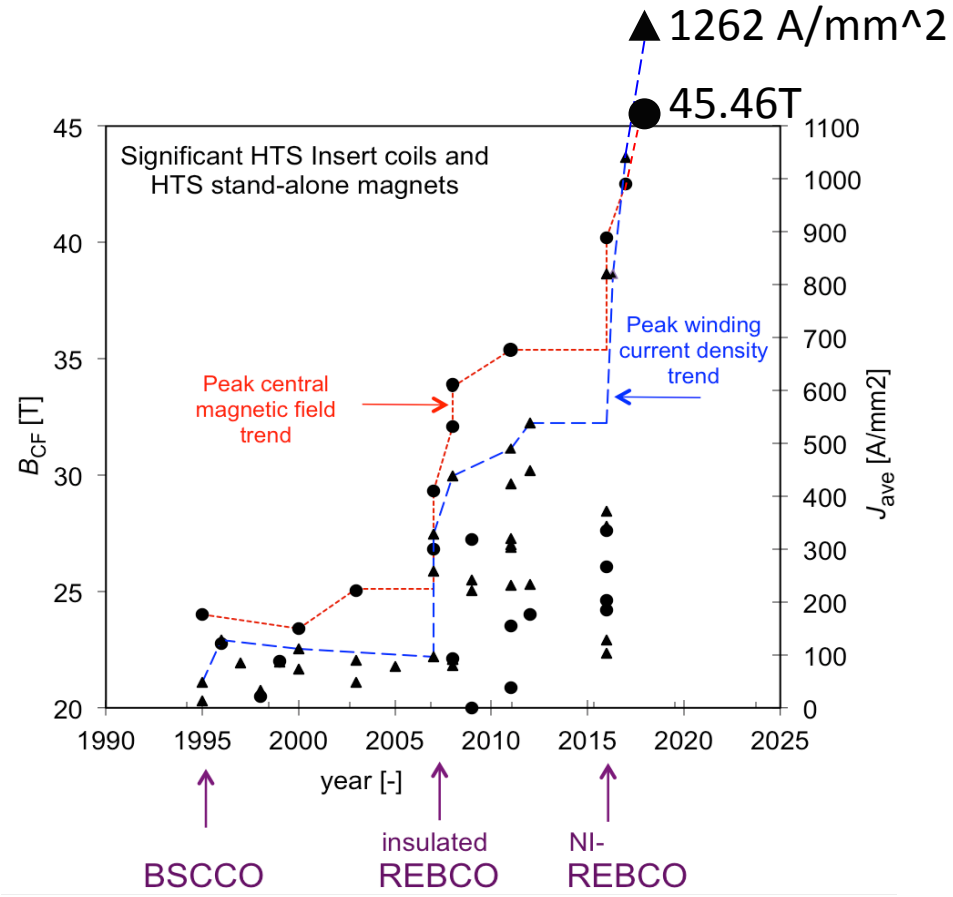
sixty times the current density in the filament of a 100W incandescent light bulb.

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**



HTS Test Coils in Resistive Magnet Background

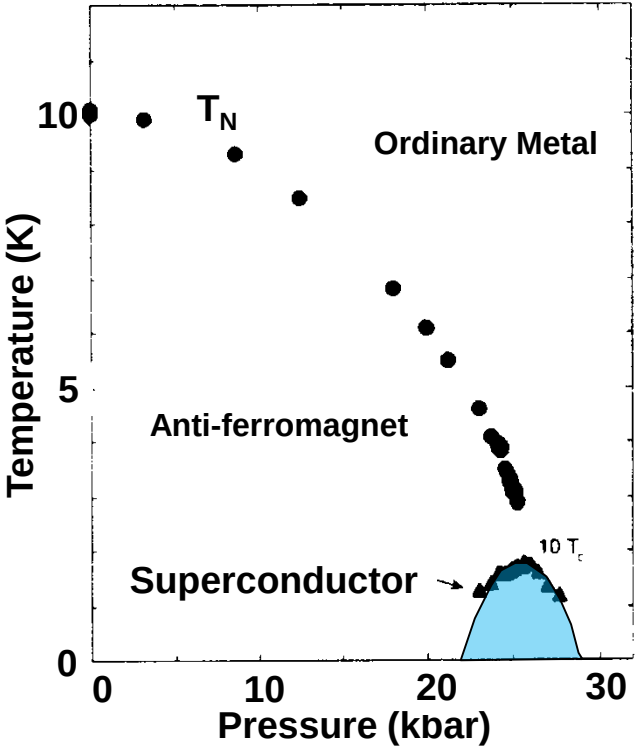


Materials enable Magnets

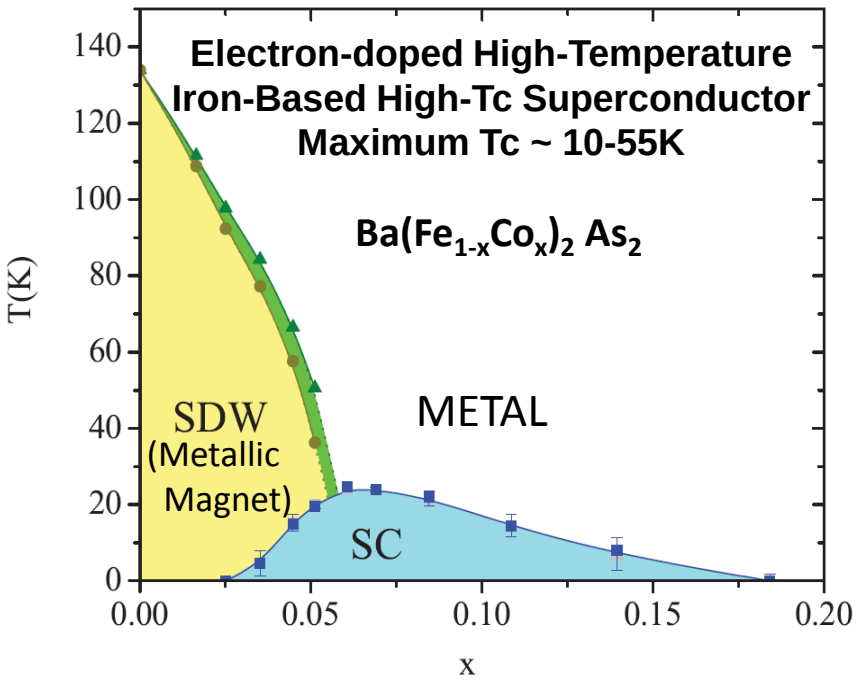
HTS Materials
are revolutionary…
and are enabling
a Magnet Revolution

Why is there a Universal Phase Diagram for Superconductivity?

$CeIn_3$
a Heavy Fermion Compound
with Superconducting Tc ~ 0.2K



N.D. Mathur et al., Nature **394**, 39 (1998)

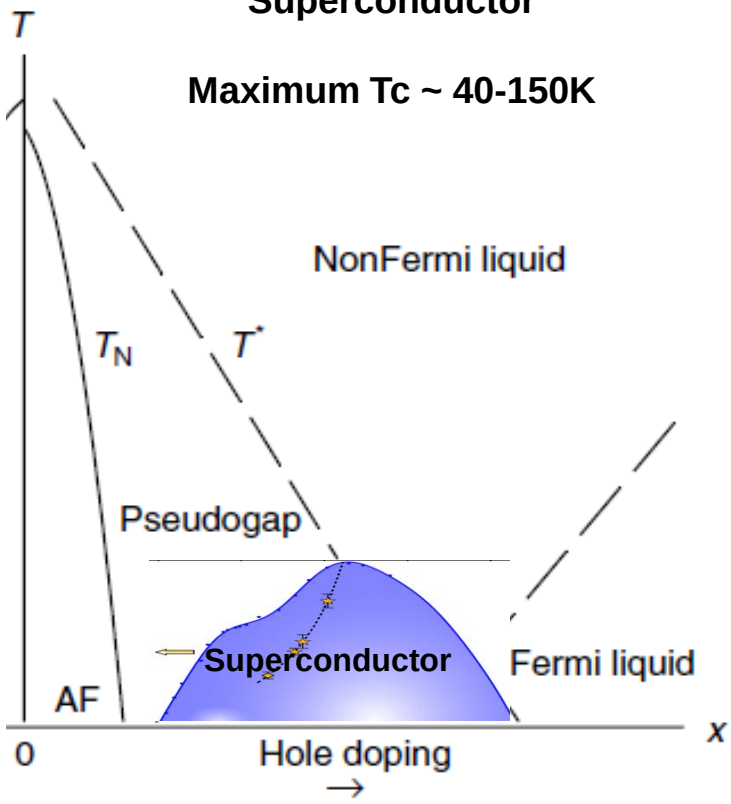


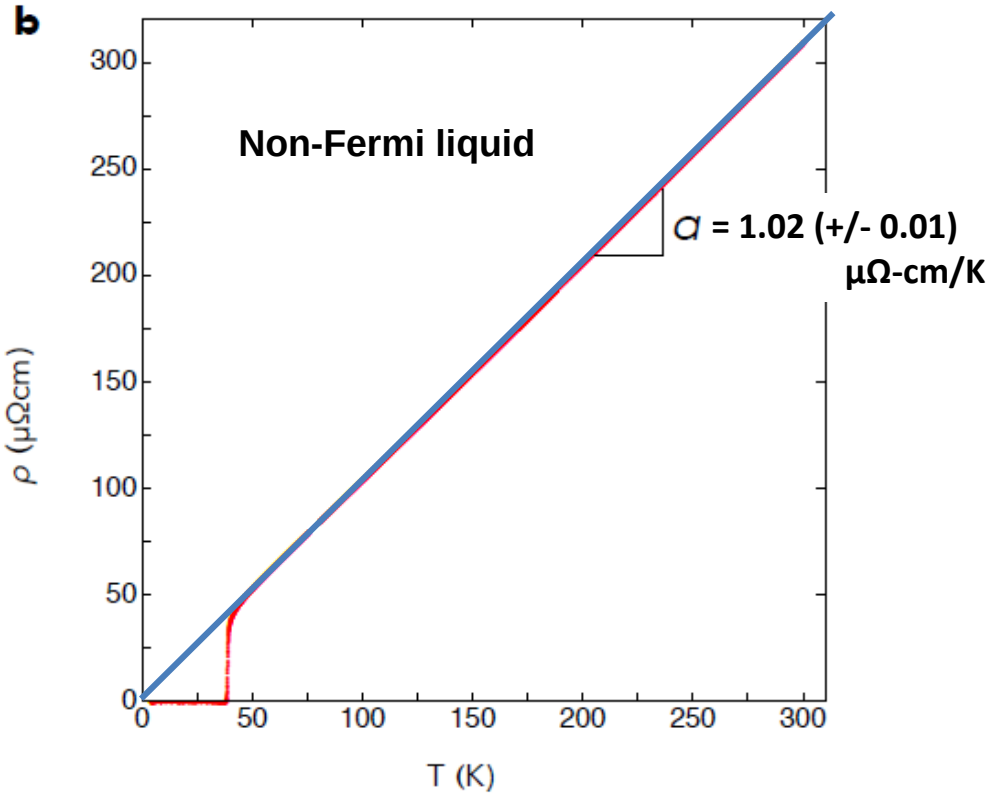
Jiun-Haw Chu, James G. Analytis, Chris Kucharczyk, Ian R. Fisher, Phys. Rev. **B 79**, 014506 (2009)
Determination of the phase diagram of the electron doped superconductor $Ba(Fe_{1-x}Co_x)_2 As_2$

Is Superconductivity Stabilized by a Quantum Critical Point?

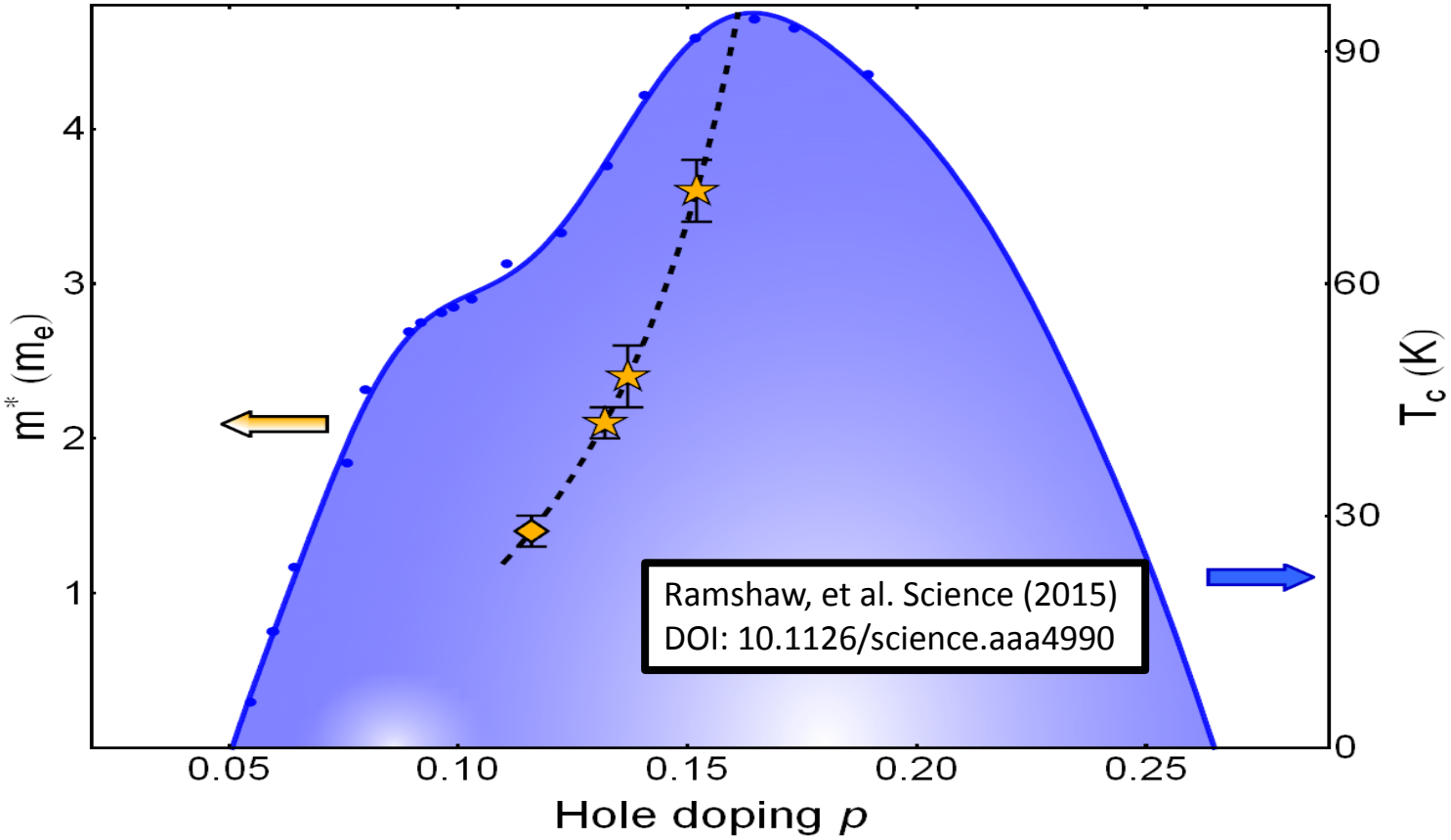
Hole-doped High-Temperature Copper-Based High-Tc Superconductor

Maximum Tc ~ 40-150K



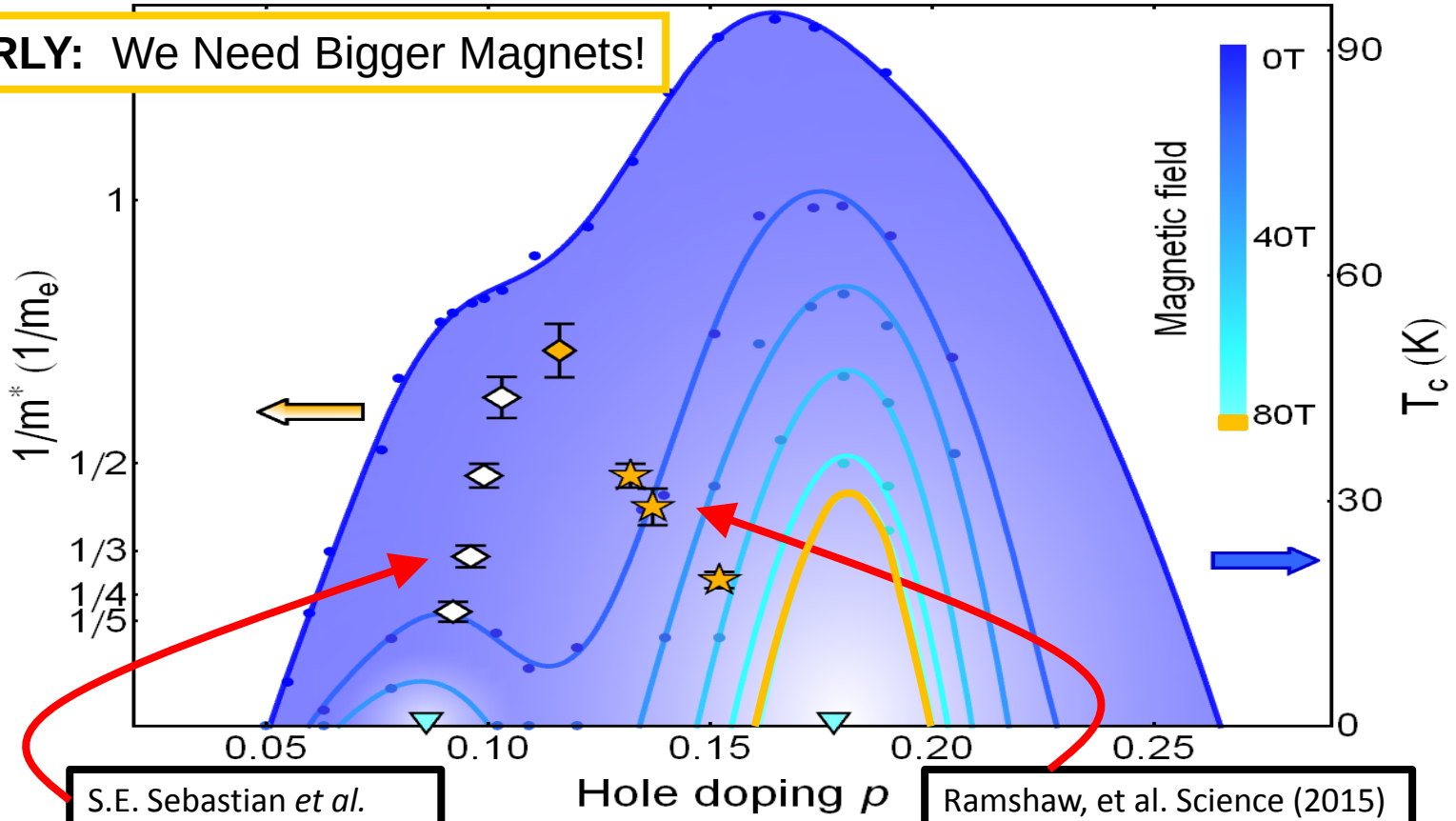


What is a Quantum Critical Point?
Diverging Electron Mass is Evidence of a QCP at Optimum Doping in YBCO



Diverging Effective Mass: Evidence of a Quantum Critical Point at Optimum Doping in YBCO

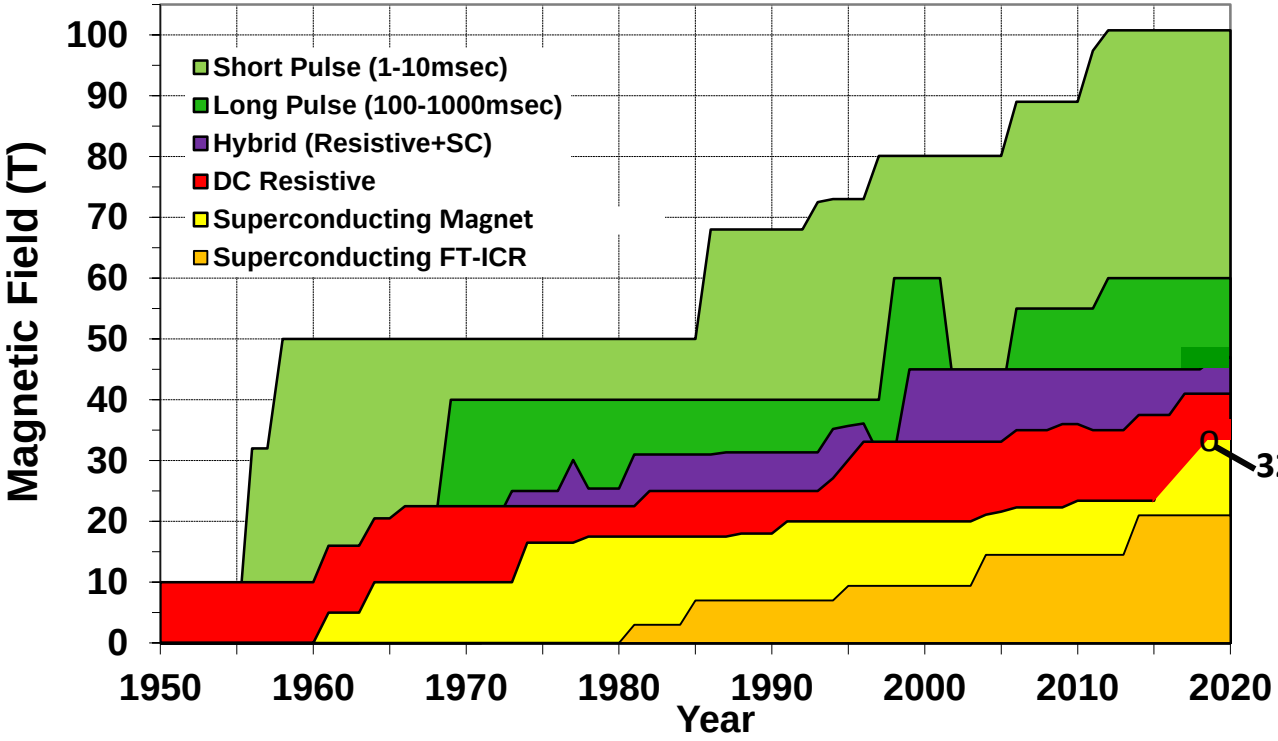
CLEARLY: We Need Bigger Magnets!



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

Ramshaw, et al. Science (2015)
DOI: 10.1126/science.aaa4990

A Future All-Superconducting Magnet



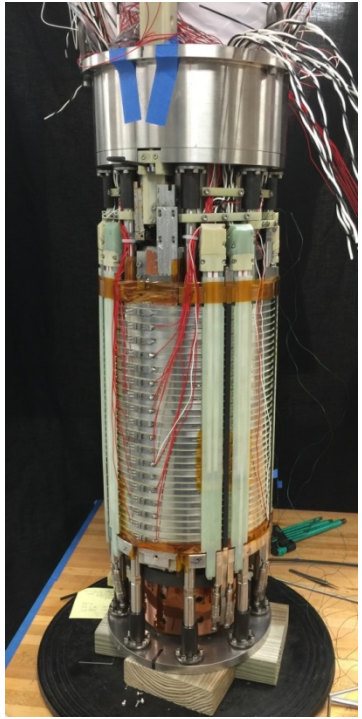
32T HTS All-Superconducting Project

(plotted in the (very near) future)

(knock on wood)

32T All-Superconducting Magnet Project

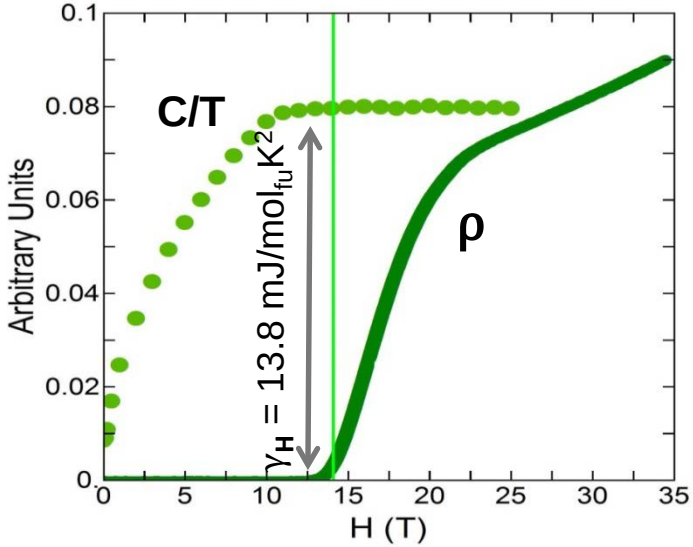
Bringing HTS and LTS together to break through the 23.4T barrier for superconducting magnets



Thermodynamically Probing Quantum Criticality once Magnetic Fields have Suppressed Superconductivity

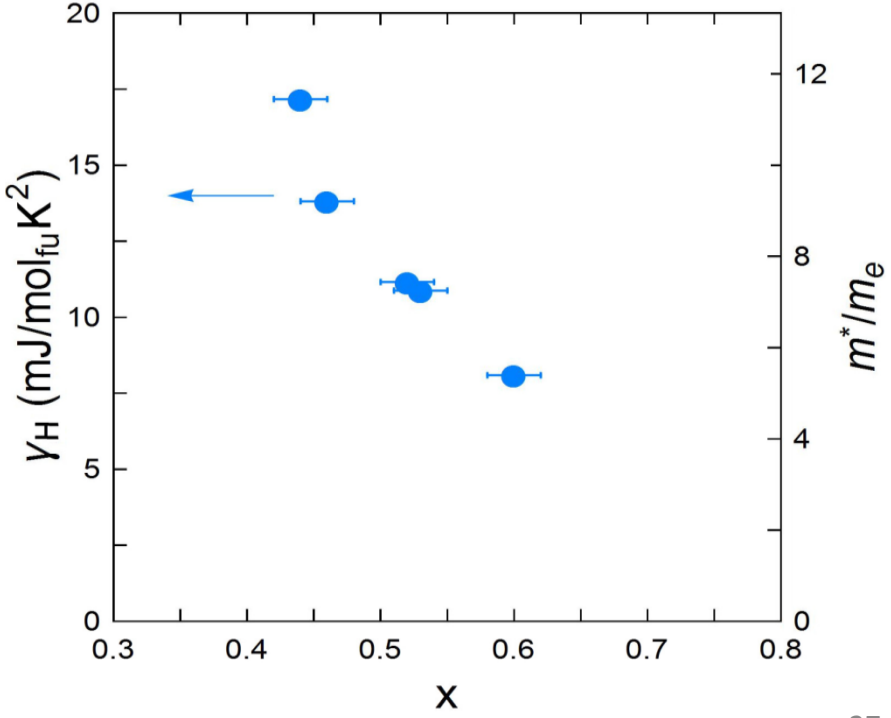
$BaFe_2(As_{0.54}P_{0.46})_2$

T = 1.5 K



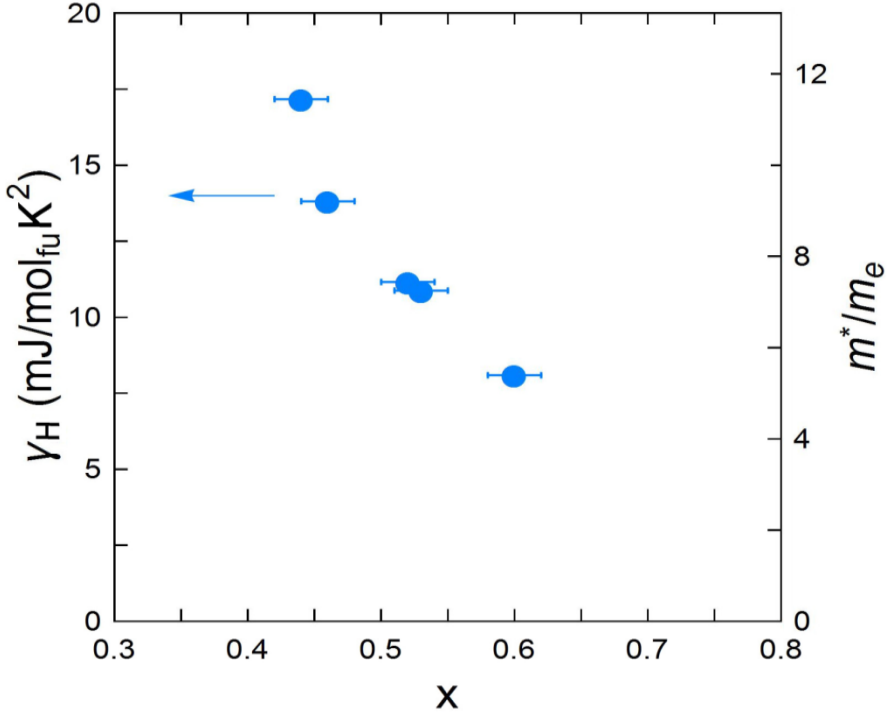
Moir, C.M. *et. al. arXiv:1608.07510* (2016).

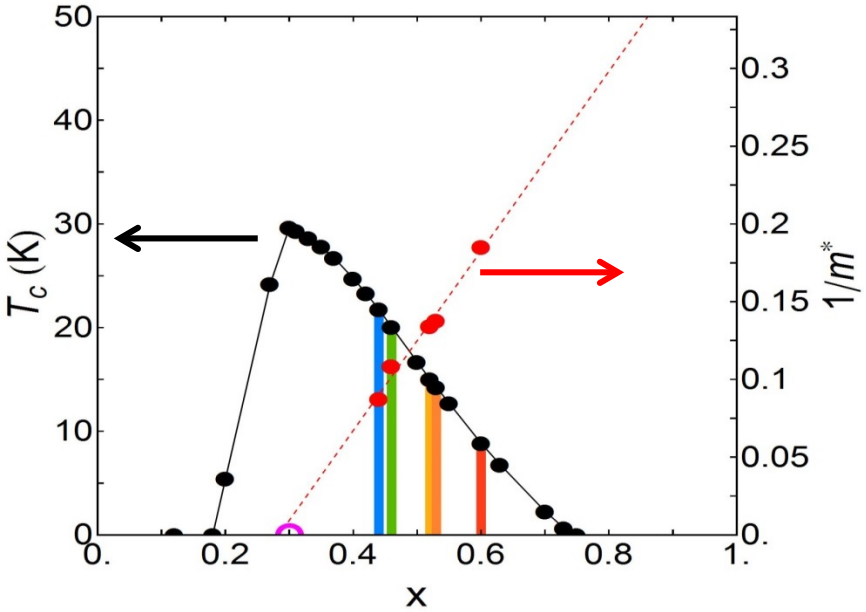
Electronic density of states shows enhancement as x approaches optimum doping, x = 0.3.



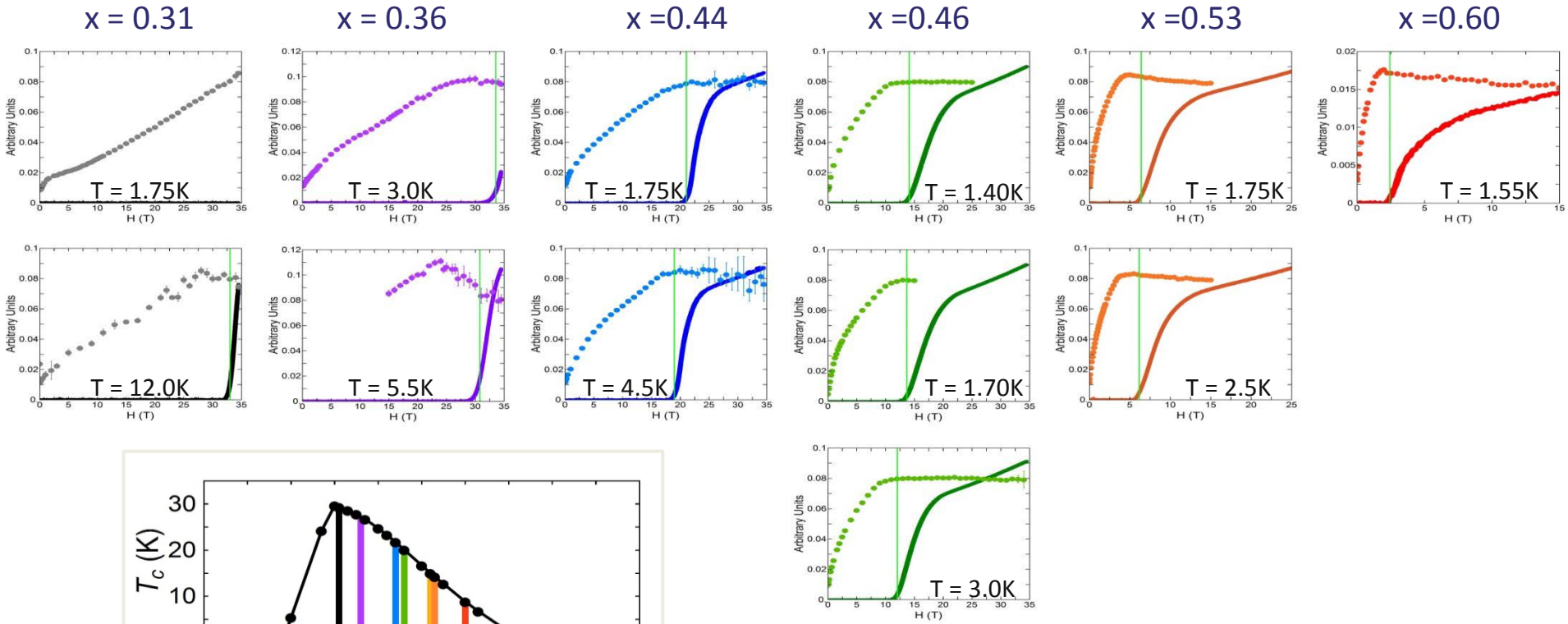
Mass Enhancement Diverges at Optimum Doping: Evidence of a Quantum Critical Point in Another Class of High-Tc Superconductors

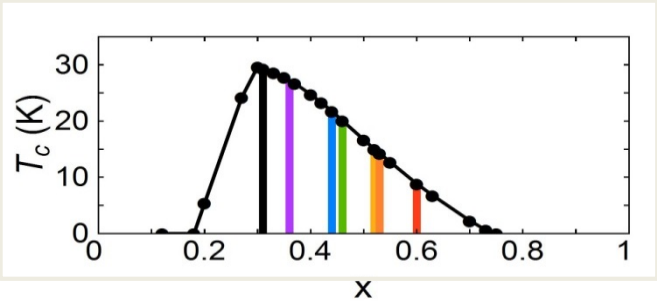
Electronic density of states shows enhancement as x approaches optimum doping, x = 0.3.





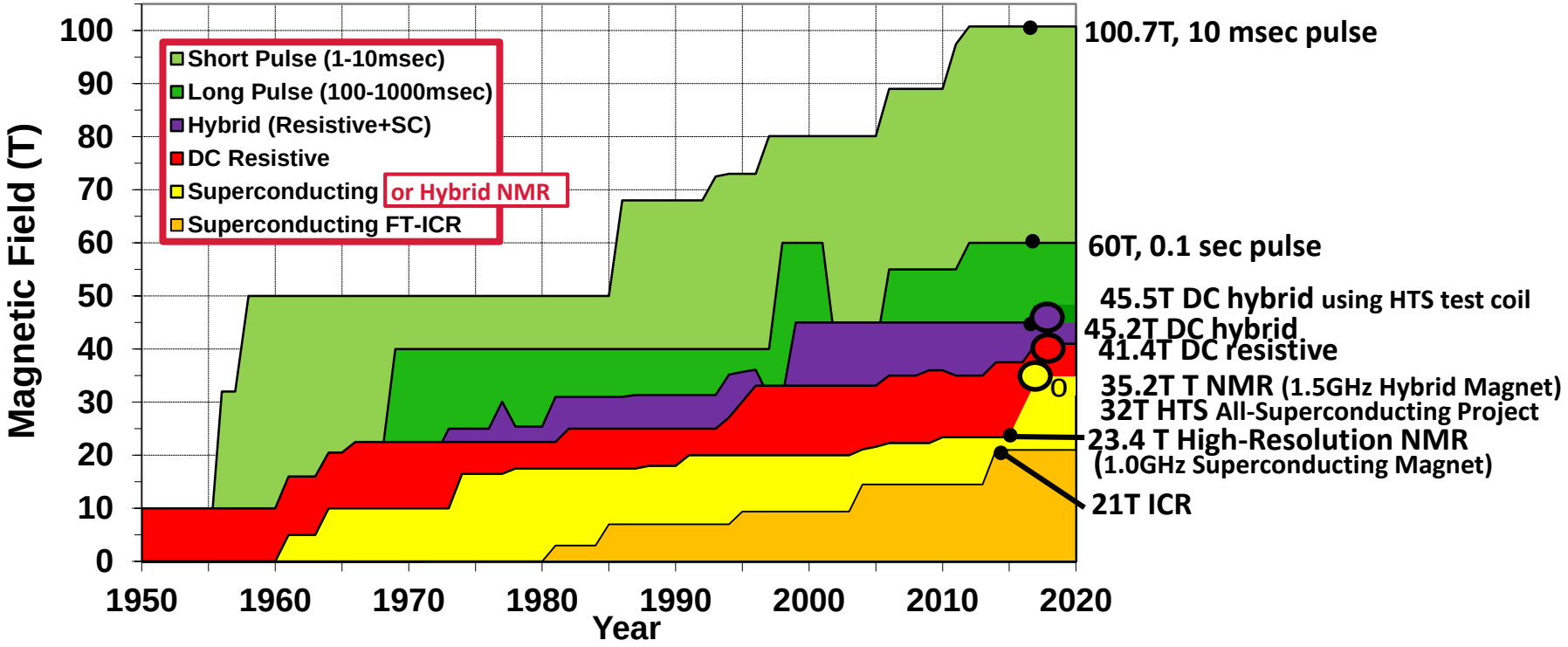
Comprehensive Studies that Require Large Amounts of Magnet Time will Benefit from the 24/7 Operation of the 32T All-Superconducting Magnet





Magnet Technologies for User Programs

Great Progress !



Why is there a Universal Phase Diagram for Superconductivity?

GLOBAL HIGH MAGNETIC FIELD FORUM

Thank You !

CLEARLY: We Need Bigger Magnets!

Unlocking the Periodic Table