High Magnetic Field Science and the Magnetic Resonance Industry

Presentation to the Committee to Assess the Current Status and Future Direction of High Magnetic Field Science in the United States

Jim Hollenhorst
Senior Director of Technology, CTO Staff
Agilent Technologies
May 17, 2012

Outline

Measurements fuel the advance of science and technology

Nuclear magnetic resonance

Biomolecules *in flagrante delicto*

Progress in magnetic field strength

Superconducting wire

Challenges

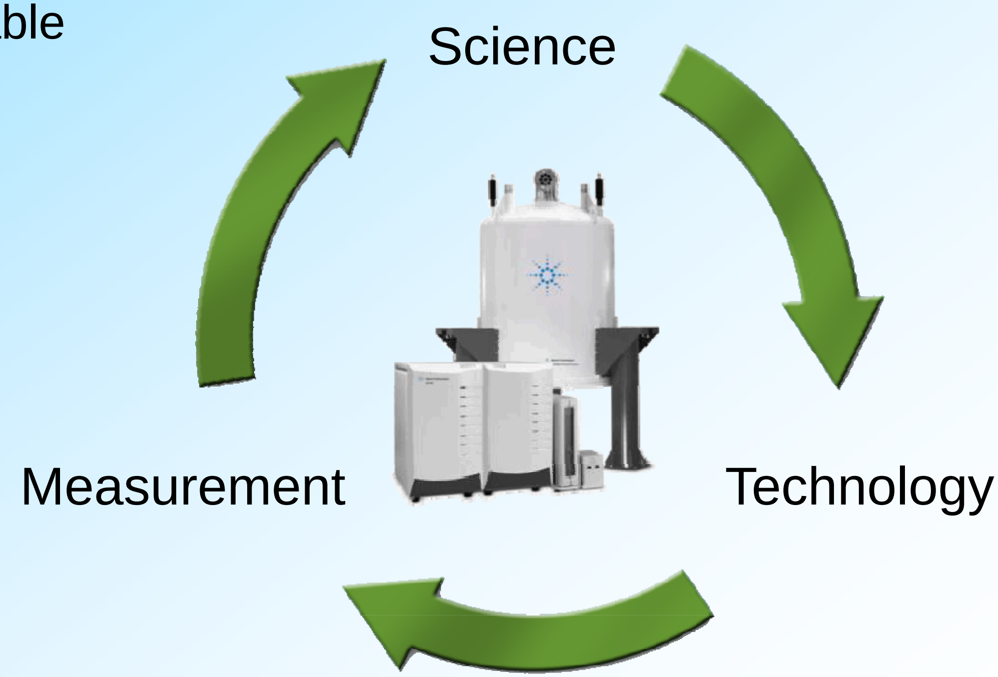
US competitiveness

Summary

Magnetic measurements

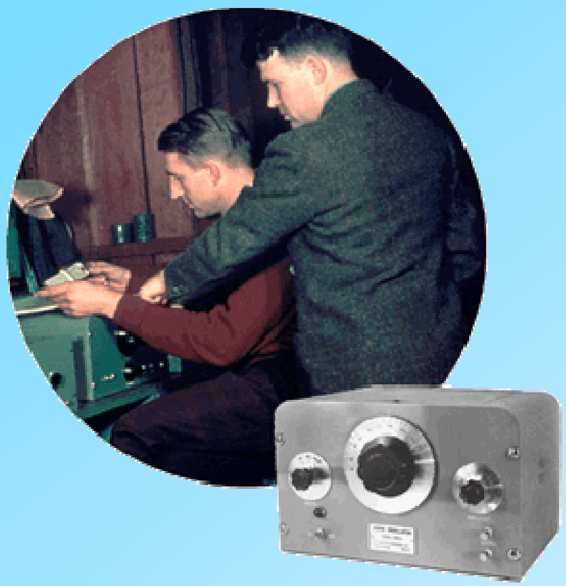
Progress in science is fueled by new measurement technologies

- Extreme conditions create new measurement challenges
- New measurement capabilities enable new science
- New science leads to advances in technology
- New technology enables new measurements

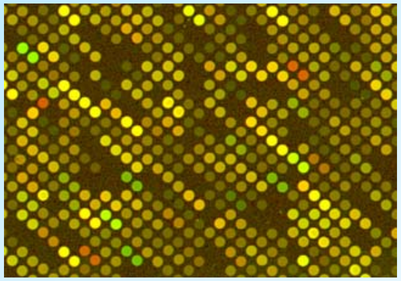


Two Revolutions

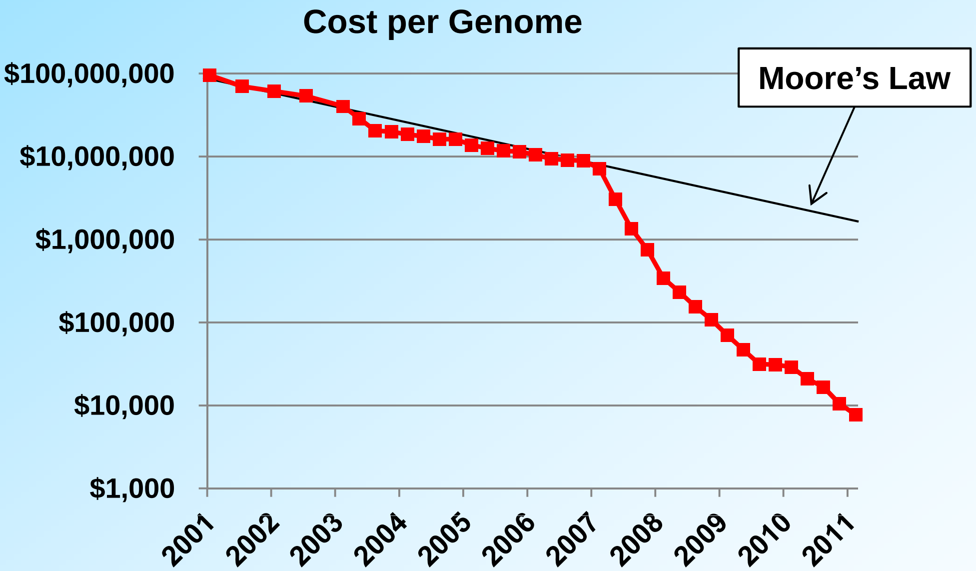
We are just beginning the life science revolution



Revolution in Electronics



Revolution in the Life Sciences



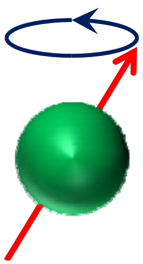
Source: National Human Genome Research Institute

Nuclear Magnetic Resonance

Measuring nuclear magnetism for structure elucidation, dynamics and imaging

Nuclear Magnetic Resonance

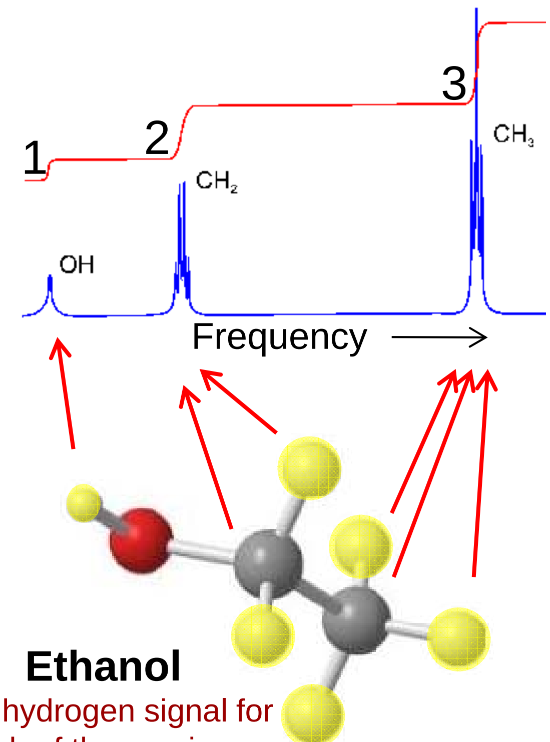
Frequency depends on atom and its neighbors



^{1}H 600 MHz
^{13}C 151 MHz

NMR Spectroscopy

Identification and determination of molecular structure



Ethanol

One hydrogen signal for each of three unique chemical environments

Magnetic Resonance Imaging

Imaging atoms in three dimensions

Magnetic Resonance Imaging

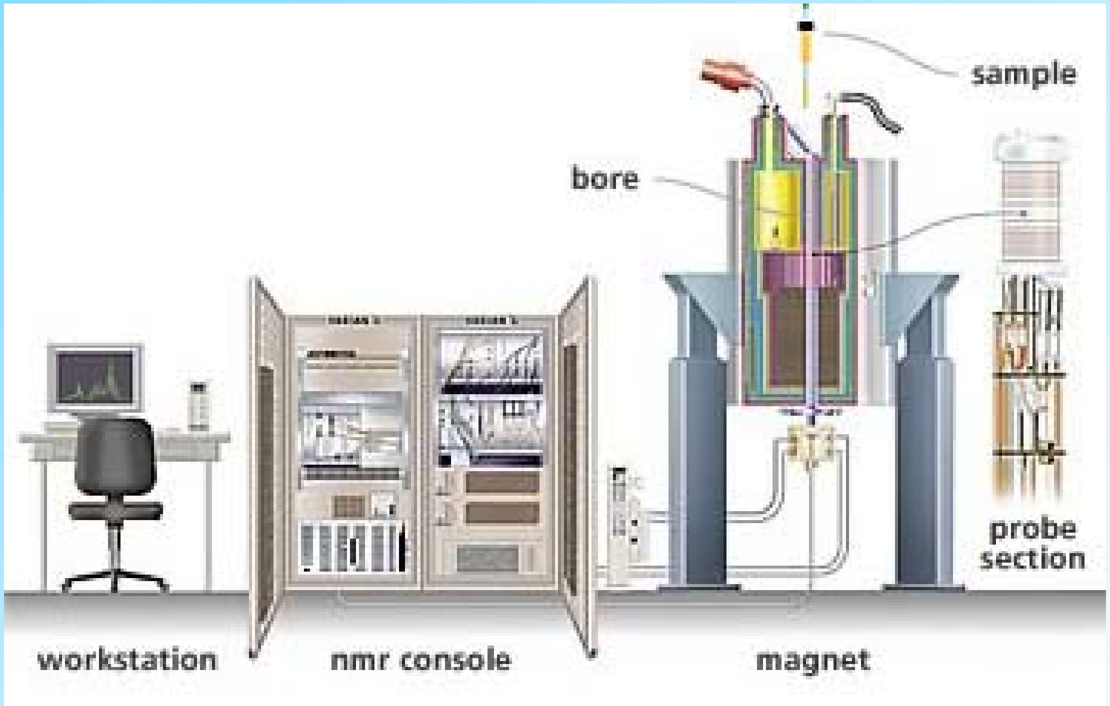
Higher fields for functional MRI and higher resolution

Clinical:
- 1.5 T → 3 T

Research:
- Human → 11 T
- Animal → 17 T

NMR Spectroscopy

Quantitative measurements of chemical structure and dynamics

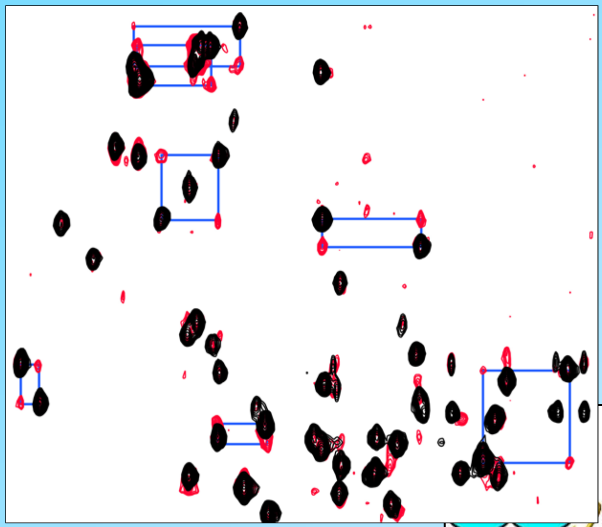


A range of samples types including:

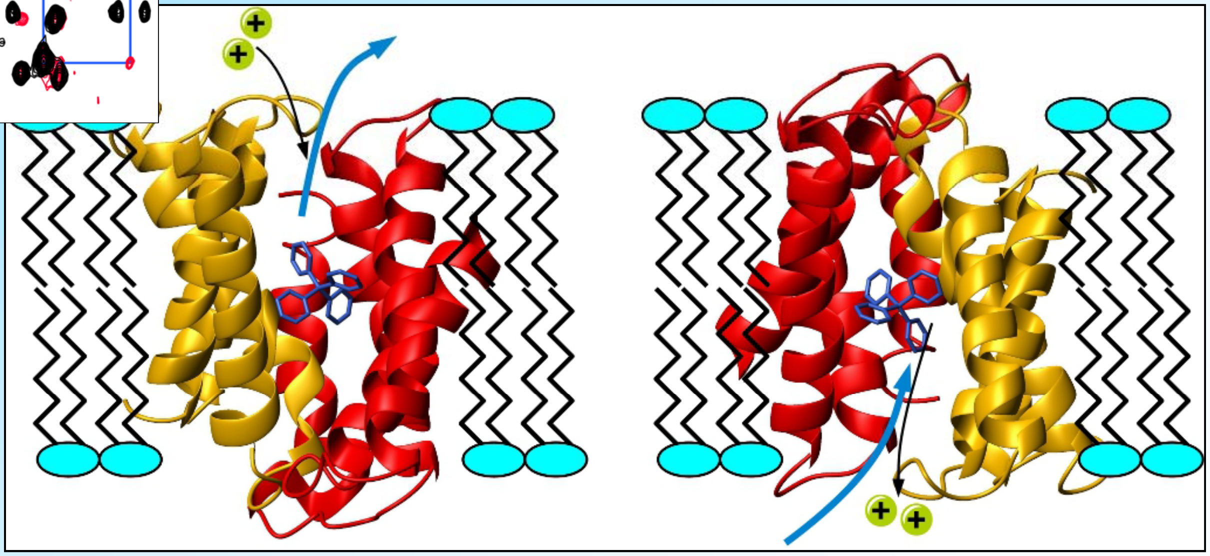
- **Liquids**
- **Solids**
- **'Squishy' materials** including gels, tissue samples, resins, etc.
- **Others** such as liquid crystals and nano materials

NMR Spectroscopy

Biomolecules in flagrante delicto – "Caught in the act" at atomic resolution



Drug transporter caught in the act of conformational change by 2D NMR spectroscopy



Dorothee Kern, *Proteins in Flagrante*, 53rd ENC, April 2012, Miami, FL

Why is high field strength important in NMR?

It is the single biggest factor in determining performance

Magnetic polarization $\propto$ B

Resonance frequency $\propto$ B

Inductive signal $\propto$ B

Signal power $\propto B^4$

Resonator quality factor Q $\propto B^{0.5}$

Noise power $\propto B^{0.5}$

Power signal to noise ratio $\propto B^{3.5}$

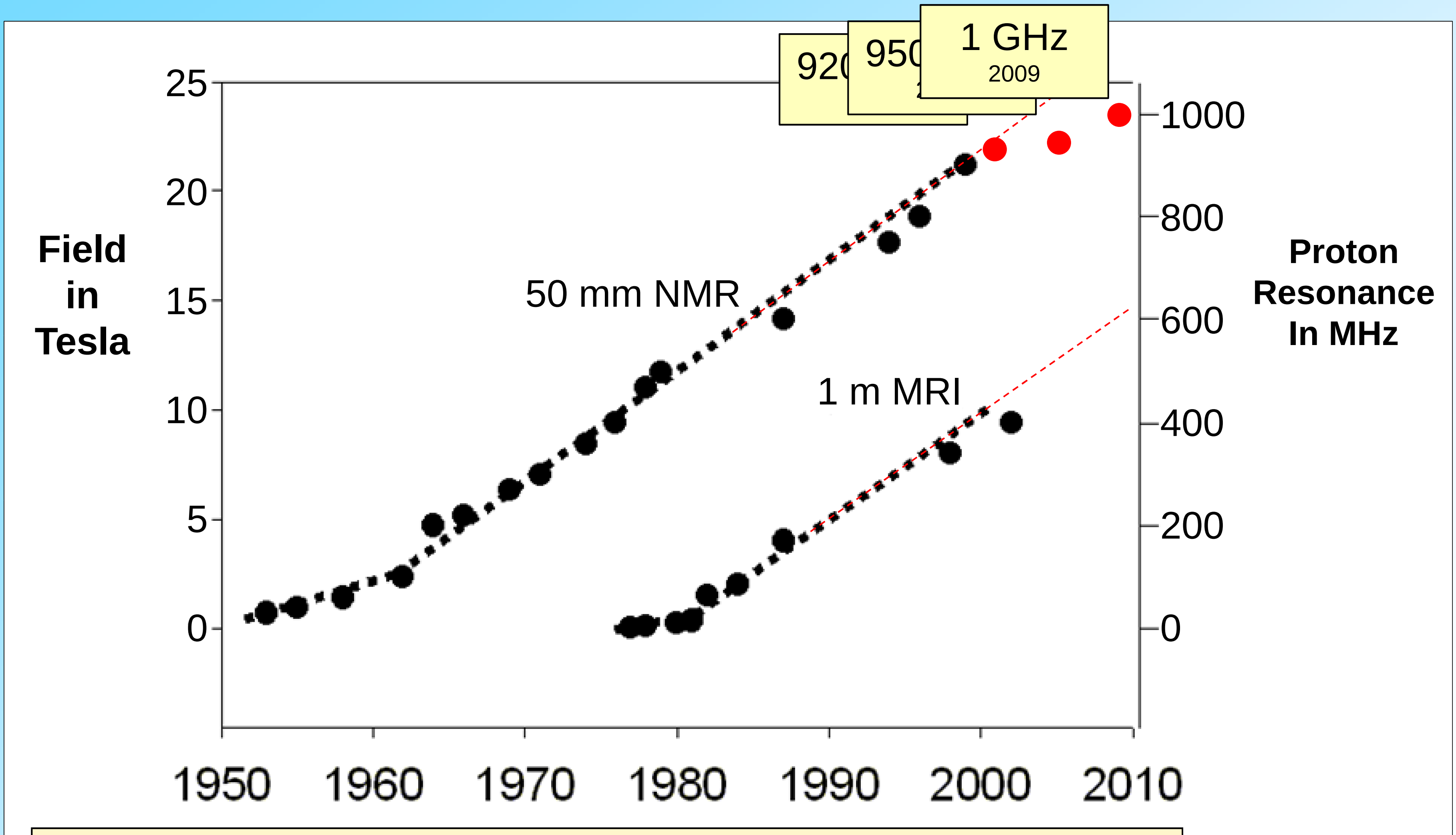
Time to achieve a given SNR $\propto 1/B^{3.5}$

Resolution (Δf/f) $\propto B^{-1}$

It is the practice in the NMR field to report SNR as the square root of the conventional definition, in which case SNR $\propto B^{3/2}$

Progress in Magnetic Field Strength

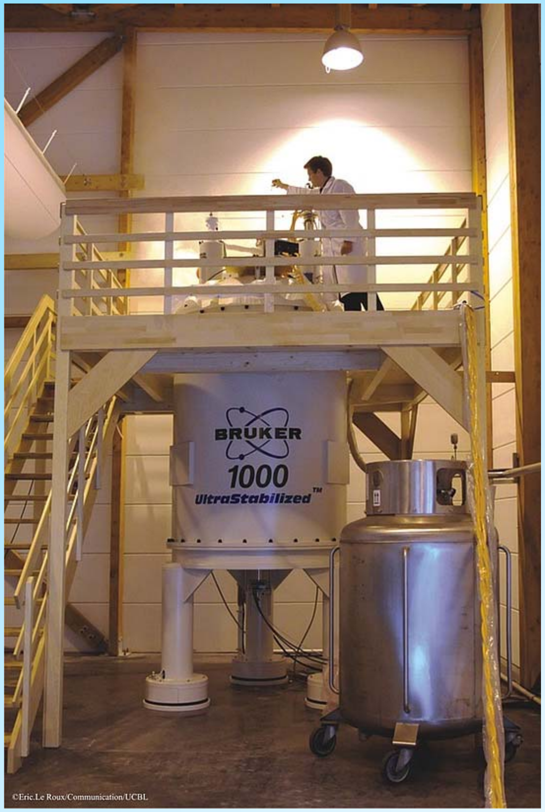
Linear Moore's Law?



W.D. Rooney, G. Johnson, X. Li, E.R. Cohen, S-G. Kim, K. Ugurbil & C.S. Springer, Magn. Reson. Med. 57:308-318 (2007); R. Freeman, Concepts in Magn. Reson., 11: 61-70 (1999)

World records

23.5 T
Highest field all-superconducting magnet
NbTi outer coil
Nb_3Sn inner coil



Bruker Magnet, installed at University Claude Bernard, Lyon, France (2009)
© Eric Le Roux/Communication/UCBL

35.4 T
Highest field superconducting magnet insert
31 T resistive outer coil
4.4 T YBCO inner coil

National High Magnetic Field Laboratory (2011)

NMR's impact on the Life Science Revolution

Tremendous potential yet to be realized

What we can do now

- Structure elucidation of small to medium-sized proteins (~50% of proteome)
- Protein dynamics
- Intermolecular interactions
- Structural analysis of membrane-bound proteins

What higher fields can enable

- Larger proteins (~90% of proteome)
- Shorter time scales
- Smaller perturbations
- Faster results ($\sim B^{3.5}$)
- Higher accuracy
- Qualitative change for solid-state NMR (resolve protons)
- Widened range of applications for membrane-proteins, RNAs, etc.

Magnet Product Range

Narrow bore


400 MHz
Premium Shielded


500 MHz
Premium Shielded


600 MHz
PremiumCOMPACT


700 MHz
Premium Shielded


800, 850MHz
PremiumCOMPACT


900, 950 MHz
Premium Shielded

Wide bore


400 MHz
Premium Shielded


500 MHz
Premium Shielded


600 MHz
Premium Shielded

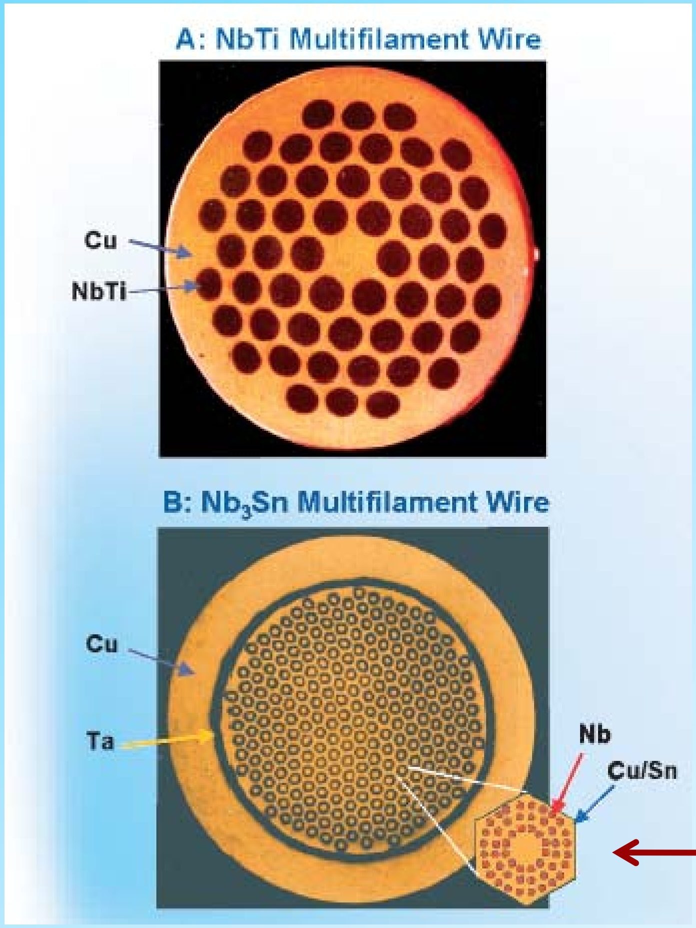

700, 750 MHz
Premium Shielded


800, 850 MHz
Premium Shielded

4.2K Conventional Helium Bath

~2K Dual Reservoir

Low temperature superconductor magnet wire

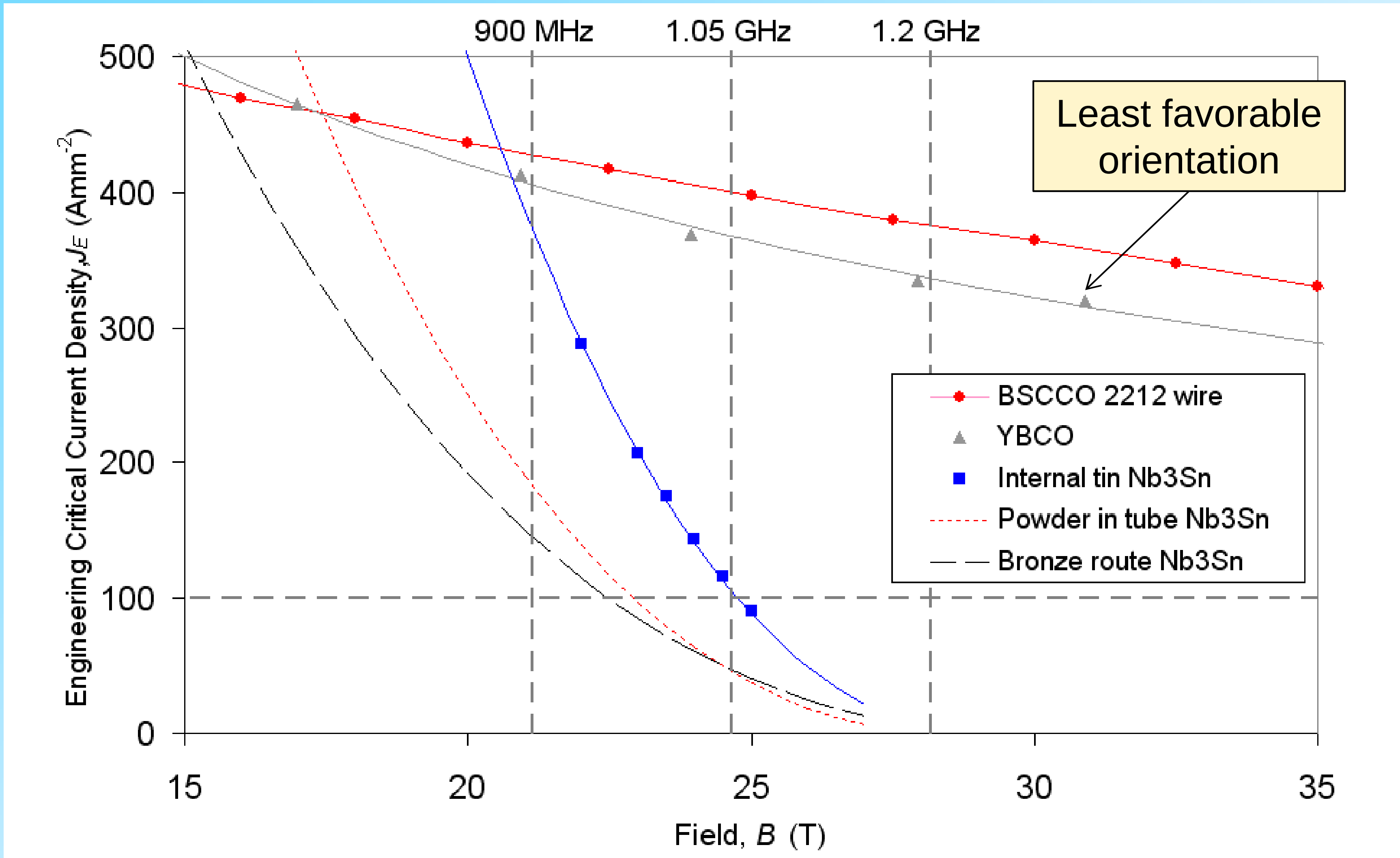


NbTi Used up to 400 MHz
Lowest Cost

Nb_3Sn – Used up to 1000 MHz
Higher Cost

As manufactured, wire does not contain Nb_3Sn, it must be annealed after magnet construction

Superconducting wire for ultra-high fields



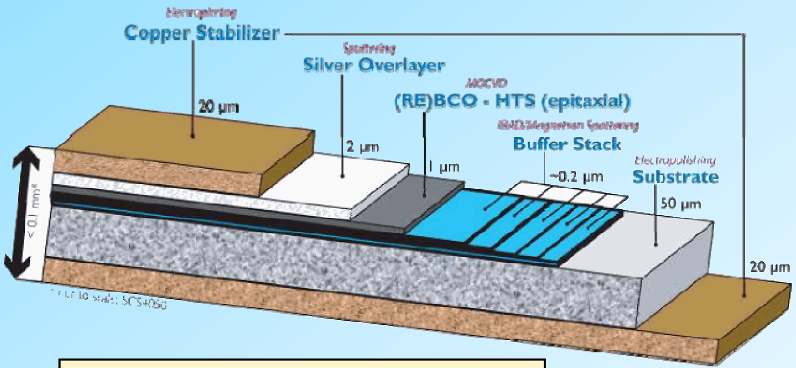
High Temperature Superconductors

Potential turning-point for ultra high-field NMR

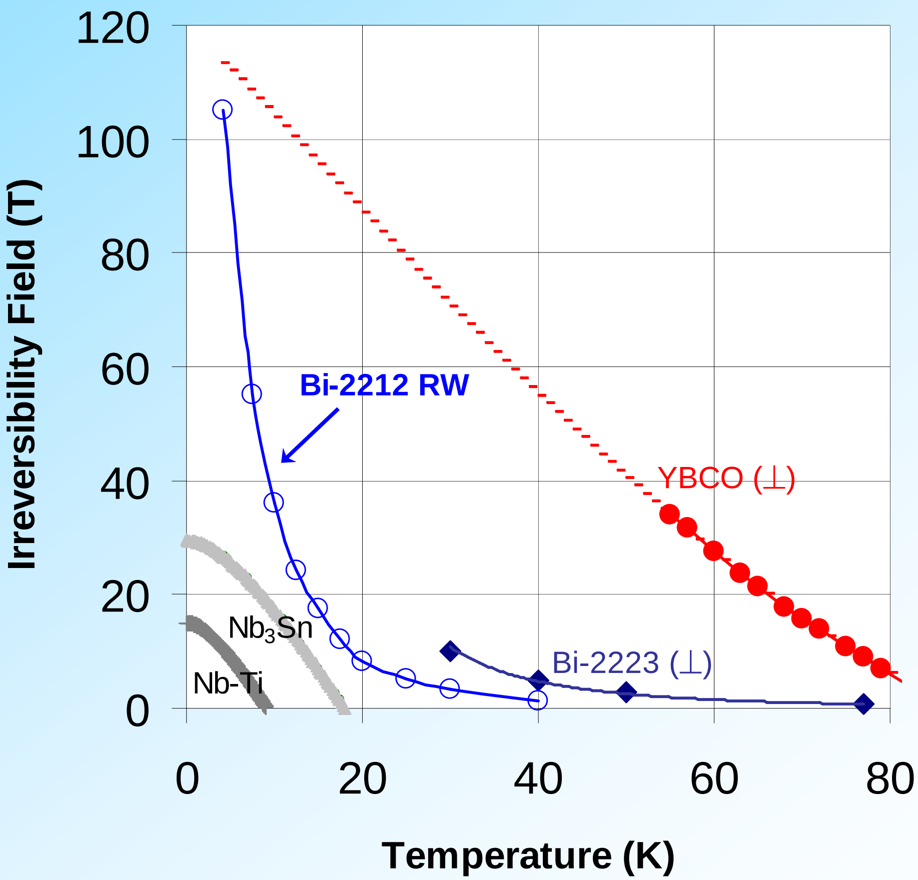
YBCO Critical magnetic field is 4x Nb_3Sn

Potentially:

- > 50 T magnets
- Higher temperature operation at lower fields
- Size reductions



SuperPower – (RE)BCO Tape, 1μm YBCO, 100 μm total



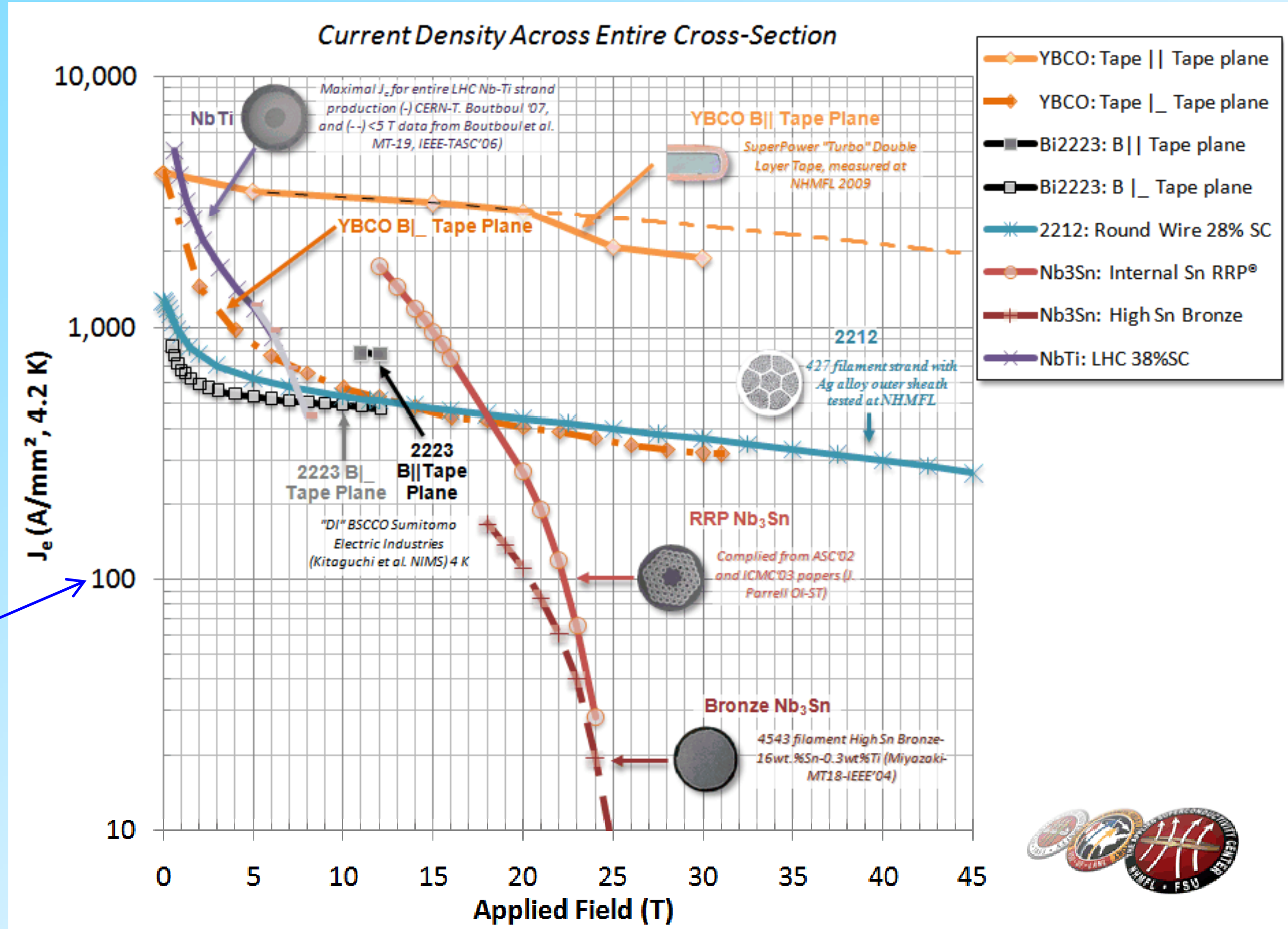
David Larbalestier – SciMag NRC Panel, Washington DC, March, 2012

Many technologies

Nb$_3$Sn is running out of steam at 23.5 T (1 GHz)

But HTS is still immature after 25 years!

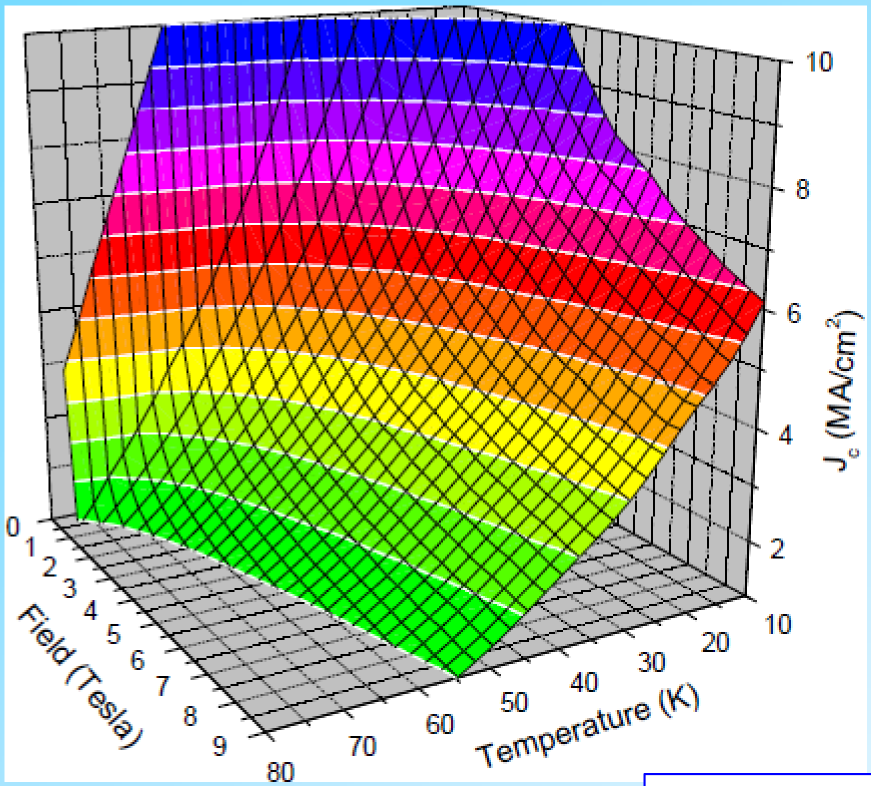
Frequent Design Goal
100 A/mm^2



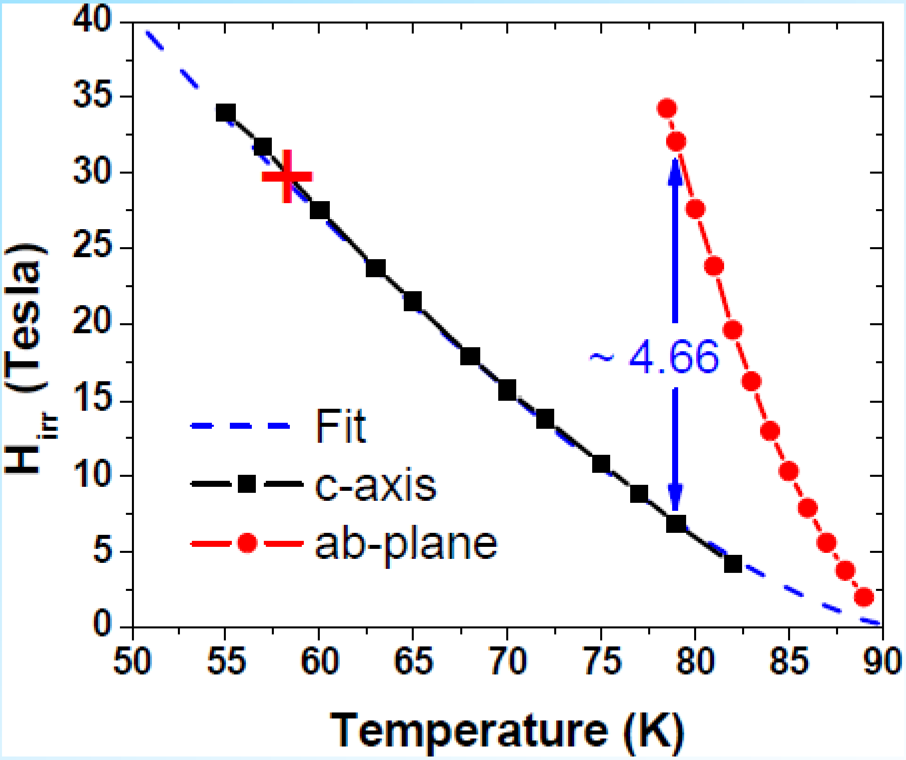
David Larbalestier – SciMag NRC Panel, Washington DC, March, 2012

High Temperature Operation

Performance Like Nb_3Sn at 55 K?



YBCO H_{irr} vs. Temperature



According to David Larbalestier (NHMFL) 9T magnets at 55 K are within reach using YBCO, even with the much lower c-axis critical current

Agilent Technologies

High Magnetic Field Science
National Academies, Washington, DC
May 17, 2012

Challenges for HTS magnets

- Complex, immature conductor technology
- Anisotropic performance
- Uniformity, reproducibility, and stability of conductors
- Long lengths (several kilometers)
- Geometrical constraints with tape conductors
- Limited bend radius
- Zero-resistance joints
- Persistent current operation?
- Field instability due to resistance and flux creep
- Quench protection
- Cost!

US Competitiveness

- European governments are funding infrastructure for life science measurements through programs like INSTRUCT and Bio NMR
- Relative to the United States, Europe has 6-10x the number of 850 MHz wide bore magnets, 2-4x the 900 narrow bore, 6-10x the 950 narrow bore and all of the funded GHz and above magnets (Lyon, Bayreuth, Nijmegen)
- NMR spectroscopy is a $500 M/year business. The majority of these systems are designed and built in Europe

These statements from the 2005 COHMAG report are still valid

Conclusion. *The United States is a leader in many areas of high-field science and technology, but further investment will be required to make it competitive in some critical areas.*

Recommendation. *Government agencies supporting high-field magnetic resonance research should directly support the development of technology and instrumentation for magnetic resonance and magnetic resonance imaging.*

Summary

- Life science is the great frontier of measurement technology
- Progress in magnets has been the most important factor in improving the performance of NMR spectrometers and MRI systems
- The US should put a stronger emphasis on development in high magnetic field science that can improve US industrial competitiveness
- European countries and the EU have emphasized funding of infrastructure for life science measurement, including large magnets for NMR spectroscopy
- NMR has unique requirements for uniformity and stability that are extremely challenging to meet and should be a focus for a portion of the work at NHMFL
- The next breakthrough in ultra-high field NMR systems will require high temperature superconductors
- Major challenges remain for building practical HTS NMR systems, problems that are difficult for any one company to address
- A breakthrough in cost of HTS conductors could also revolutionize lower field magnets, making them cheaper, smaller, and less expensive to operate

Narrow Bore Magnets

Expanding the portfolio to include GHz NMR systems

400MHz 500MHz 600MHz 700MHz 800MHz 850MHz 1GHz