Thanks to…
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Mark Bird, NHMFL, FSU
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Scott Crooker, NHMFL, LANL
Tim Cross, NHMFL, FSU
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Art Edison, NHMFL, Univ. of Florida
Nathanael Fortune, Smith College
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Ke Han, NHMFL, FSU
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Marcelo Jaime, NHMFL, LANL
Kee Hoon Kim, NHMFL, LANL
Alex Lacerda, NHMFL, LANL
Alan Marshall, NHMFL, FSU
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Albert Migliori, NHMFL, LANL
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Justin Schwartz, NHMFL, FSU
Jim Sims, NHMFL, LANL
John Singleton, NHMFL, LANL
Hans Van Tol, NHMFL, FSU
Stan Tozer, NHMFL, FSU
Huub Weijers, NHMFL, FSU
Sergei Zvyagin, NHMFL, FSU
…and many more

High Magnetic Fields: A Physics and Engineering Perspective

Greg Boebinger
National High Magnetic Field Laboratory
Los Alamos National Laboratory

National High Magnetic Field Laboratory
- ***Existing infrastructure***
- ***High-field magnets***

Materials research for high-field magnets

Overview of high-magnetic field research

Scientific opportunities for the future

MAGNET LABORATORIES WORLDWIDE

High Stationary Magnetic Fields Laboratory
Krasnoyarsk, Russia
www.krascience.rssi.ru

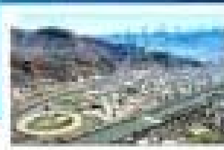
Kurchatov Institute
Moscow, Russia
www.kiae.ru

High Field Laboratory for Superconducting Materials,
Sendai, Japan
vostok.imr.tohoku.ac.jp/index-E

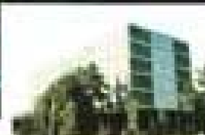
Tsukuba Magnet Laboratory
National Research Institute for Metals, Tsukuba, Japan
www.nrim.go.jp:8080/tml/eng/startmenu

National High Magnetic Field Laboratory
Tallahassee, Florida, USA
www.magnet.fsu.edu

High Field Magnet Laboratory,
University of Nijmegen
www-hfml.sci.kun.nl



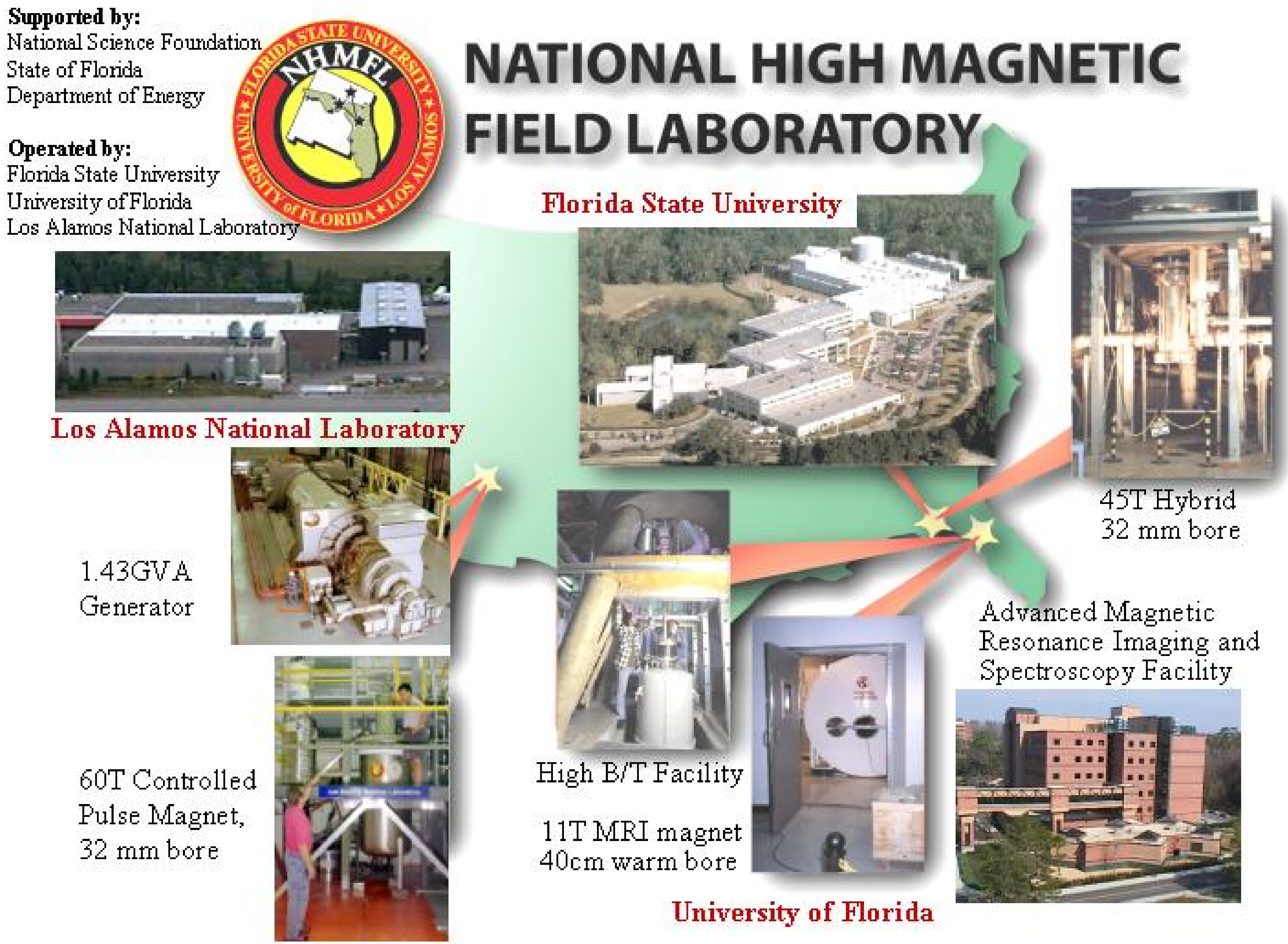
Grenoble High Magnetic Field Laboratory
Grenoble, France
ghmfl.polycnrs-gre.fr



Technische Universität Braunschweig
www.tu-bs.de

International Laboratory of High Magnetic Fields and Low Temperatures
Wroclaw, Poland
alpha.mlspmint.pan.wroc.pl

Hefei, China


Supported by:
National Science Foundation
State of Florida
Department of Energy
Operated by:
Florida State University
University of Florida
Los Alamos National Laboratory
FLORIDA STATE UNIVERSITY
NHMFL
UNIVERSITY of FLORIDA
LOS ALAMOS
NATIONAL HIGH MAGNETIC FIELD LABORATORY
Florida State University
Los Alamos National Laboratory
45T Hybrid
32 mm bore
1.43GVA
Generator
Advanced Magnetic
Resonance Imaging and
Spectroscopy Facility
60T Controlled
Pulse Magnet,
32 mm bore
High B/T Facility
11T MRI magnet
40cm warm bore
University of Florida

ACTIVE MAGNET LAB VISITING SCIENTISTS

NORTHWESTERN U.S.
Colorado State University
Montana State University
Washington State University

MIDWESTERN U.S.
Argonne National Laboratory
Indiana University
Iowa State University
University of Chicago
Univ. of Wisconsin at Milwaukee

ASIA
Japan
- Central Research Institute of Electric Power Industry
- Hiroshima University
- Osaka City University

Korea
- POSTECH
- Seoul National University
- University of Seoul

EUROPE
Czech Republic
- Charles University, Prague
- Czech Academy of Sciences

England
- University of Cambridge
- University of Oxford

France
- CEA-SPEC, Paris
- CRMD-CNRS, Paris
- CRTBT/CNRS, Grenoble
- Institut Laue-Langevin, Grenoble
- Universite de Paris-Sud

Germany
- Dortmund University
- Hahn-Meitner Institute, Berlin
- Max Planck Institute, Dresden
- Universitaet Wuerzburg

Netherlands
- Leiden University
- Universiteit van Amsterdam

Poland
- Polish Academy of Sciences

Russia
- Ioffe Institute

NORTHEASTERN U.S.
Bell Labs, Lucent Technologies
Boston College
Boston University
Clark University
IBM, Watson Research Center
John Hopkins University
Massachusetts Institute of Technology
Northeastern University
Penn State University
Rutgers State University
Tufts University
University of Connecticut

SOUTHWESTERN U.S.
Chemistry Division – LANL
LANSCE Division – LANL
MST Division– LANL
New Mexico State University
Rice University
San Diego State University
UC Irvine
UC Los Angeles
UC Riverside
UC San Diego
UC Santa Barbara
University of Nevada at Las Vegas

SOUTH AMERICA
Argentina
- Centro Atomico Bariloche (CEA)
- Universidad de Buenos Aires

Brazil
- University de Sâo Paulo
- University of Campinas

SOUTHEASTERN U.S.
Clemson University
Florida State University
Georgia Inst. of Technology
Louisiana State University
University of Florida

Educational Outreach at the NHMFL

RESEARCH EXPERIENCES FOR UNDERGRADUATES

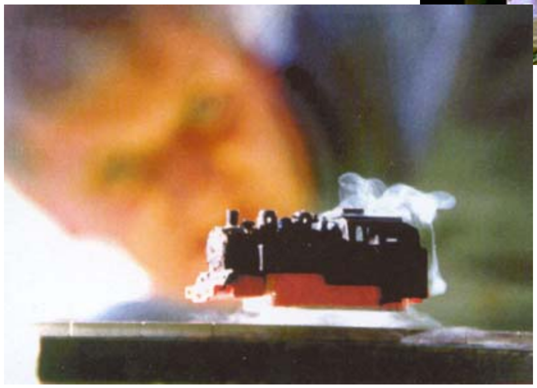
In 2003, 19 undergraduates will be provided experiences that encourage them to pursue graduate study and careers in science.

User Program includes undergraduates from leading undergraduate institutions, including Occidental College and Smith College, and smaller graduate programs, including Clark University and Tufts University

These students benefit enormously from exposure to unique experimental equipment and expertise, as well as exposure to other students from around the world.

RESEARCH EXPERIENCES FOR TEACHERS

In 2003, 16 teachers will extend their understanding of real world science



TOURS & OUTREACH 2003

People touring the NHMFL	=	2,600
K-12 Educational Outreach	=	4,200
Annual NHMFL Open House	=	2,700

Total direct contact hours = 21,000

Curriculum Development

Annually, the NHMFL creates classroom materials for over 4,000 K-12 students.

Science, Tobacco & You continues to provide quality science curriculum materials to teachers nationwide. The 2002-2003 contract with Florida Department of Health provided another 500 teachers with materials. A total of 135 workshops for 6,750 teachers have been conducted.

MagLab: Alpha and *Science, Optics & You* continue to provide structure to teacher workshops and summer institutes. 100 educators participated in NHMFL-led workshops.

Website Development focuses on user-friendly resources for teachers, students and the general public.

Including Electromagnetism Applets…
…developed by Mark Davidson's Team

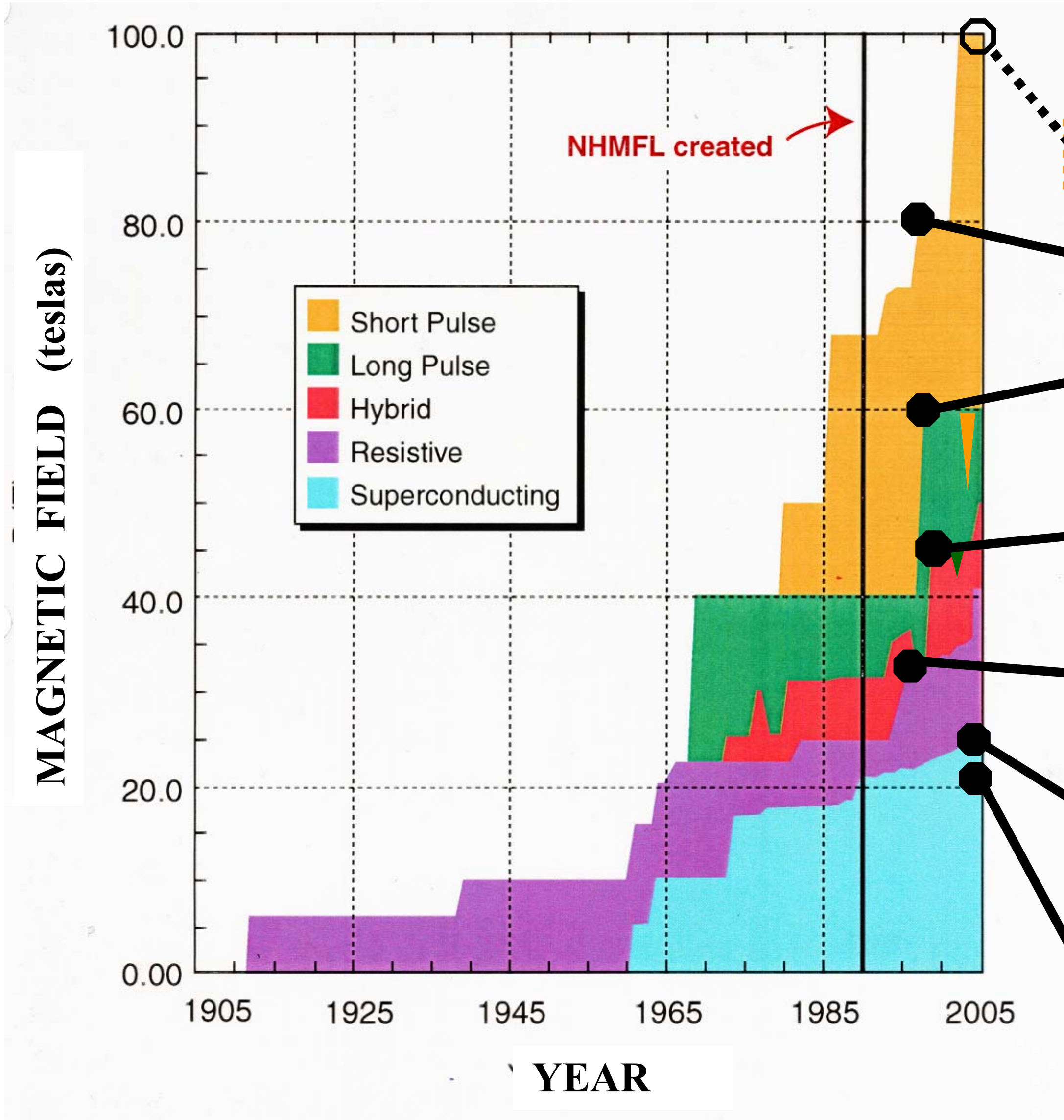
"KAPOW ! SUPERHERO SCIENCE"

High magnetic fields, levitation and electromagnetic pulses told in the context of…

the X-Man villain: Magneto-Man

MAGNETS

100 YEARS OF NON-DESTRUCTIVE MAGNETS



2004 - 100T Multi-shot Pulsed Magnet

1999: 80T Short-Pulse Magnet (tied-world record)

1998: 60T Controlled-Pulse Magnet (world record) (rebuild in 2004)

1999: 45T DC Hybrid Magnet (world record)

1996: 33T DC Resistive Magnet (world record)

2003: 25T in 38mm bore using 5T high-Tc insert (world record)

2003: 900 MHz (21.1T) NMR magnet (competitive in peak field, uniquely large 105mm warm bore)

Resistive Magnets

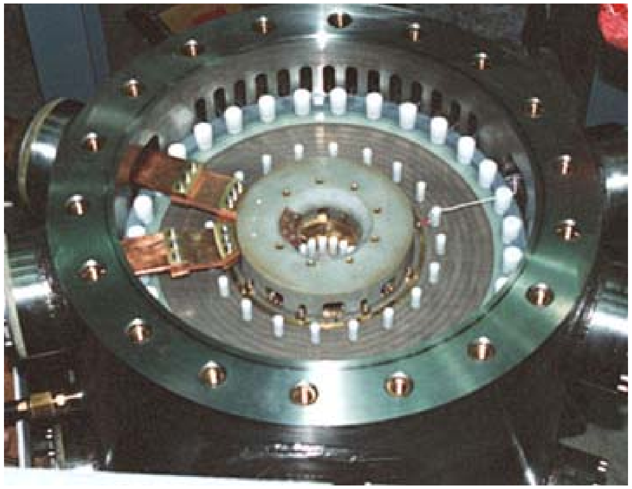
NHMFL Stress and Heat Management Program

Currently available:

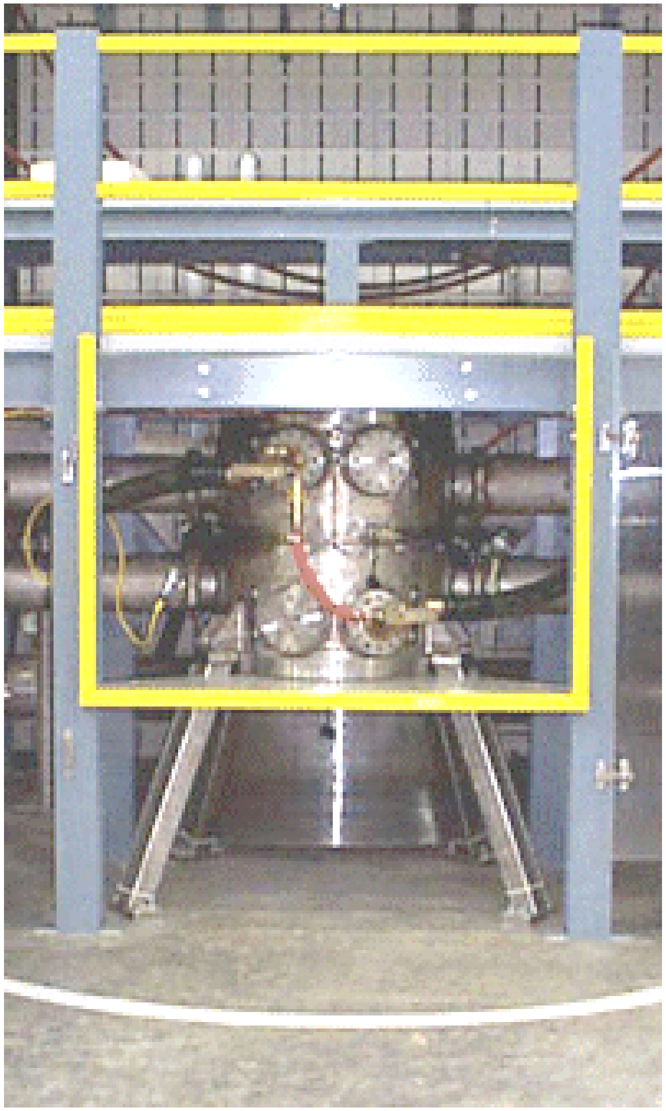
33 T, 32mm bore, 17MW

Proposed Upgrade:

>35 T, 32mm bore, 20MW

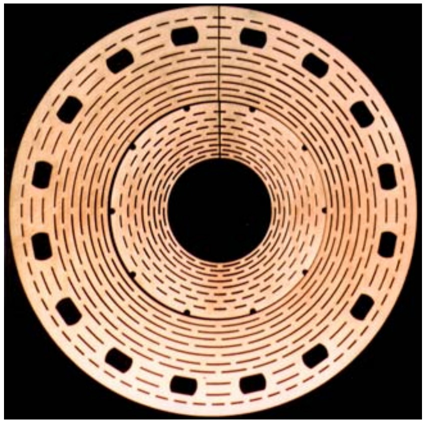


Mechanical stress ~ 665 MPa
(~90% of yield stress)
Current Density = 700 A/mm^2
Power Density = 13 W/mm^3
Heat Flux = 7 W/mm^2



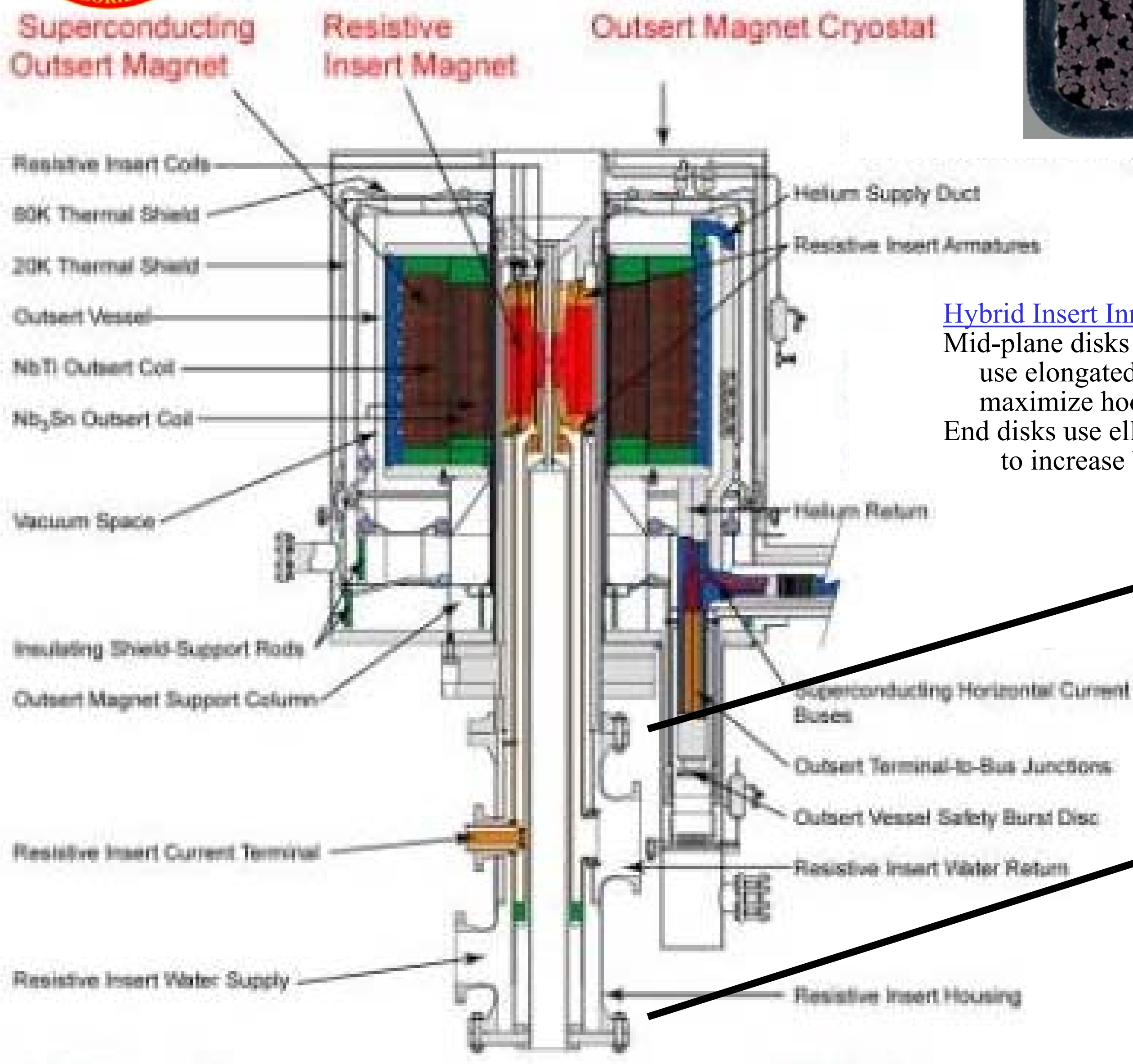
Florida-Bitter Magnet Plates

Heavily elongated holes
Reduce stress concentrations
Staggered azimuthally
Reduce radial force transmission



Perforations reduce
the stress in the plates
Magnet at peak uses
30 - 40% less power
Four of the five largest magnet labs
use Florida-Bitter plates.

45T NHMFL hybrid magnet



Cu/Nb_3Sn composite strands around Cu cores inside 10mm x 12mm steel conduit

Mid-Plane / End Turn
Florida Bitter Plates

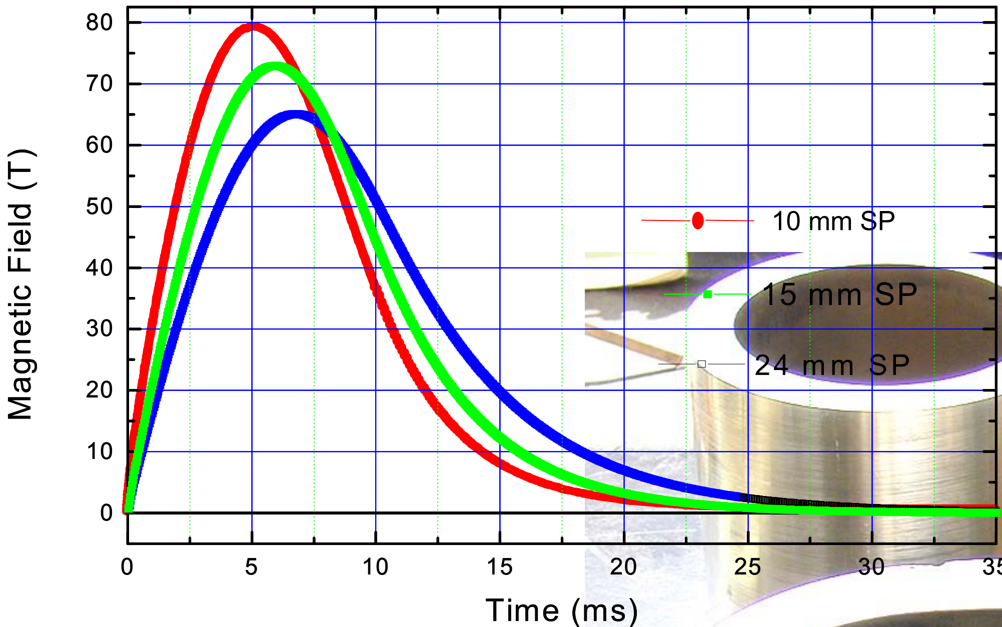
Hybrid Insert Innovations

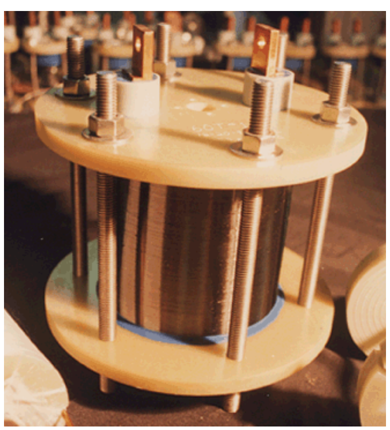
Mid-plane disks use elongated hole to maximize hoop strength.

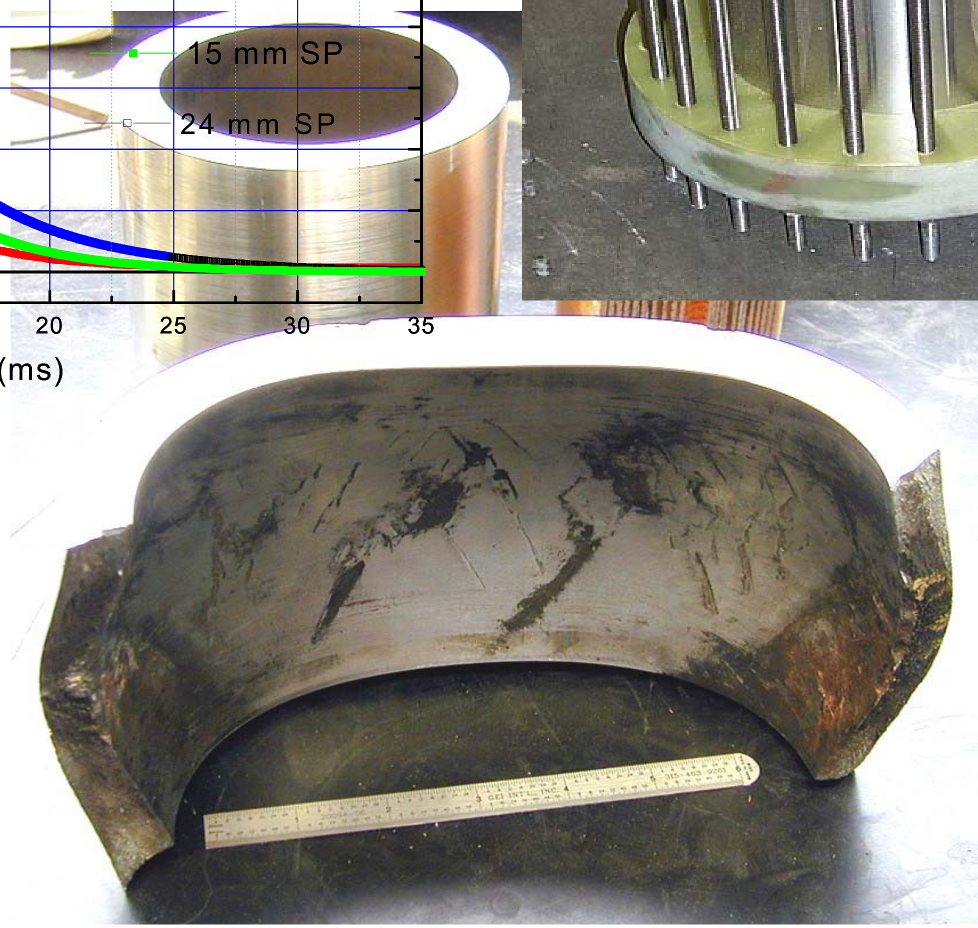
End disks use elliptical holes to increase bending stiffness.

Short-Pulse Magnets

NHMFL Stress and Fatigue Management Program







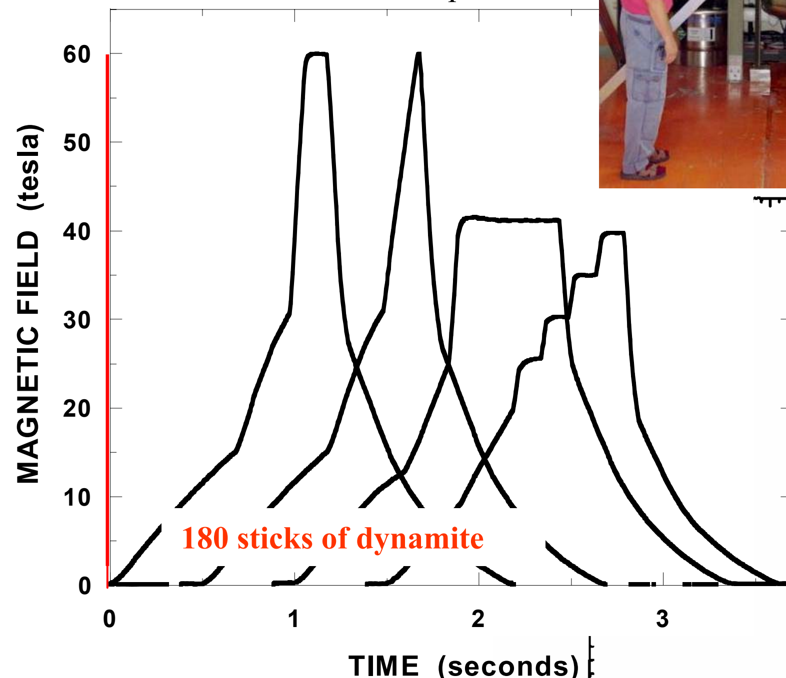
Long-Pulse Magnets

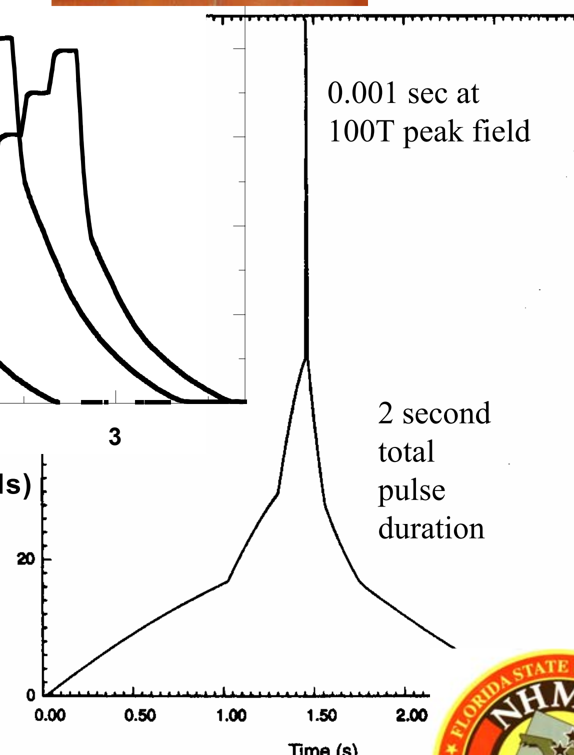
Short-Pulse Magnets on Steroids

The only
research magnet
of its kind
in the world…
…now being
rebuilt…

Controlled
Pulse Profiles

0.100 sec at
60T peak field



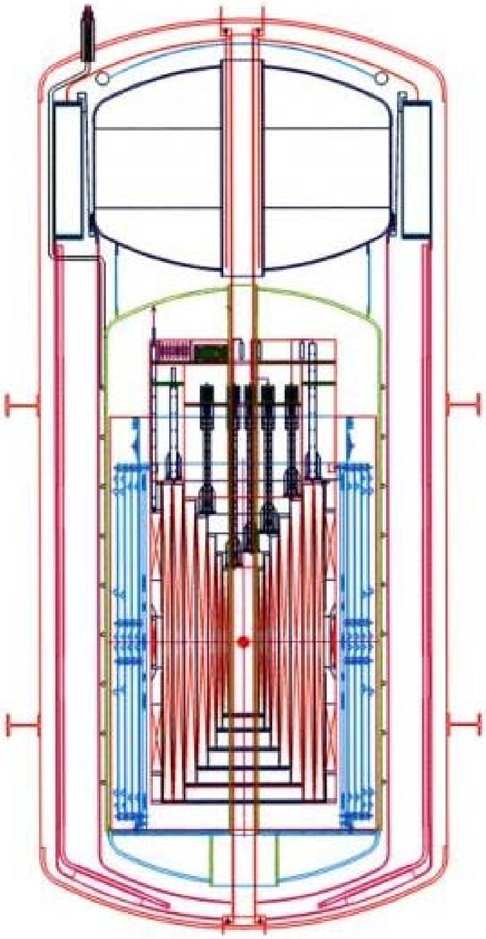


COMING in 2004

1,000,000 gauss magnet

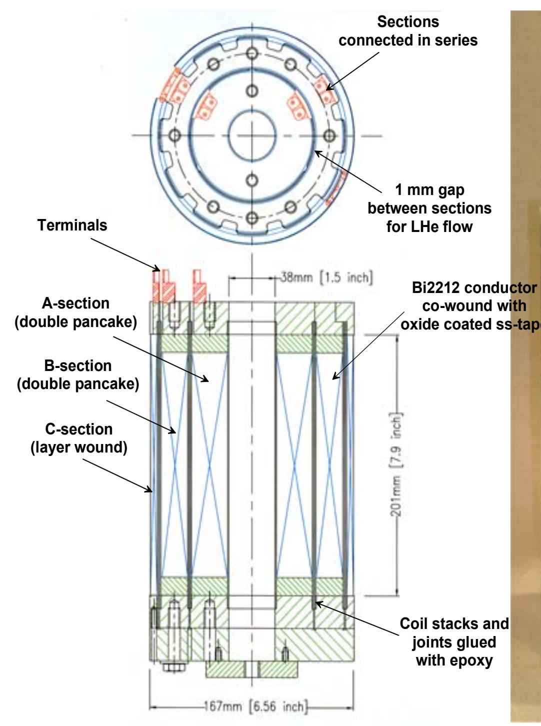
250 sticks of dynamite

Superconducting Magnet Development



900 MHz NMR magnet
- 21.1 teslas
- 105mm warm bore
- 1 ppb homogeneity

High Tc Insert Coil
- 1999…3T…16mm bore
  in 19T background field
- 2003…5T…38mm bore
  in 20T background field



NHMFL: Justin Schwartz, Huub Weijers, Ulf Trociewitz
Industrial Collaborator: Ken Marken, Oxford Instruments

Worldwide 900 MHz NMR Systems

Location	Supplier	Freq. (MHz)	Bore (mm)	Status
NHMFL	NHMFL	900	105	Final Assembly
PNNL	Oxford	900	63	Commissioning
Tsukuba	Kobe	920	54	Operational
Frankfurt	Bruker	900	54	Operational
Munich	Bruker	900	54	Operational
Scripps	Bruker	900	54	Operational
Zurich	Bruker	900	54	Operational
U. Yokohama	Oxford	900	54	Operational
Yokohama (RIKEN)	Oxford	900	54	Operational

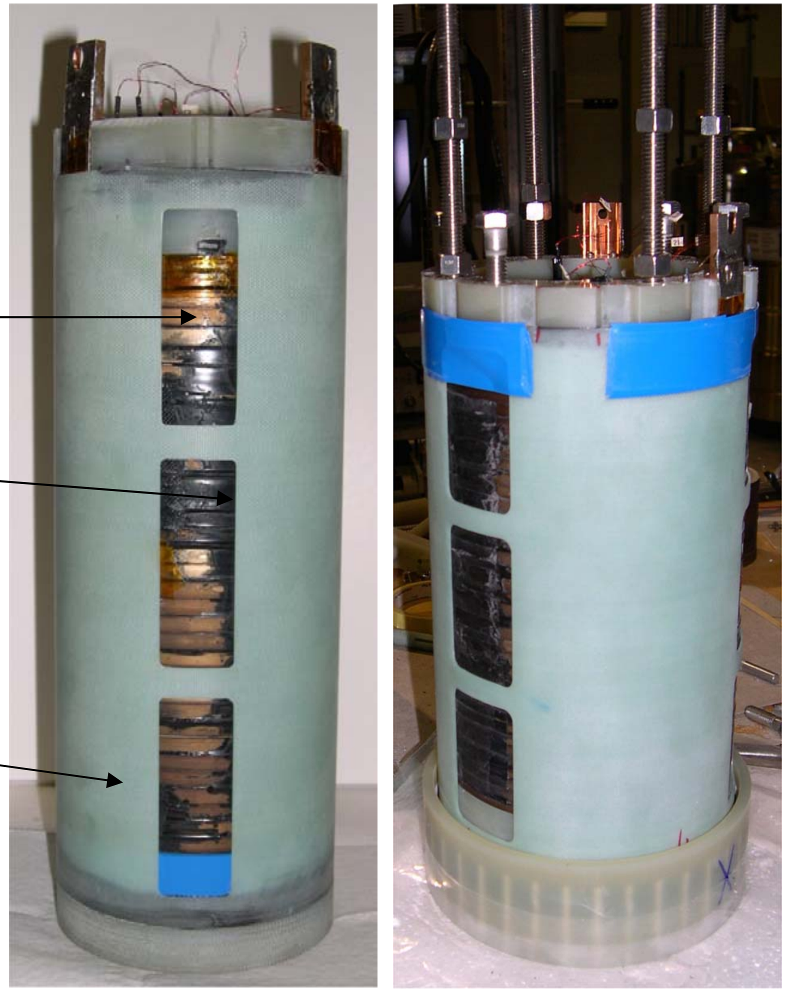
5T High-Tc Superconducting Insert Magnet

Opening the door to general purpose superconducting magnets in the 20T to 25T range…
…an important step on the road to the 25T (1066 MHz) NMR magnet mentioned in the 1988 Seitz-Richardson report

Bi-2212 conductor, reinforced with ZrO_2 - coated stainless steel tape

Current leads glass-fiber epoxy reinforced

Thin-wall G-10 shell with circumferential openings at 120° for LHe cooling



A- and B-units: each a stack of 17 Bi-2212 double pancakes

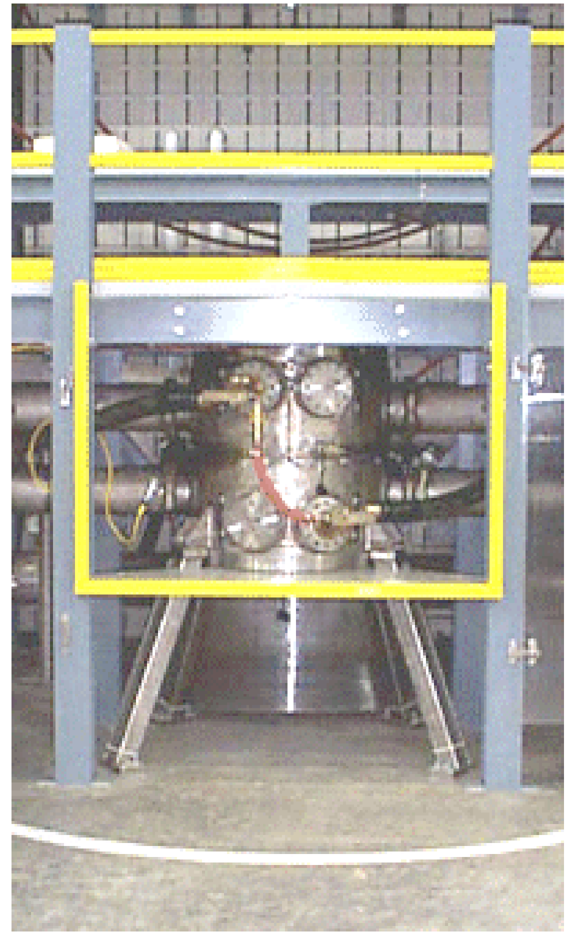
Complete Insert with layer-wound C-unit

H.W. Weijers, U.P. Trociewitz, F. Trillaud, A. Mbaruku, P.V.S.S Sastry, Y.S. Hascicek, J. Schwartz, K. Marken, M. Meinesz, H. Miao,
IEEE Trans. on Appl. Supercond. 13, 1396-1399 (2003) *"Development of a 5 T HTS insert magnet as part of 25 T Class Magnets"*

Other Resonance Magnets

Magnex 500MHz (11.7T)
400mm bore magnet

Bruker 750MHz
89mm bore system



Keck Magnet, 25T
52 mm bore magnet
12 ppm homogeneity

and Ion Cyclotron Resonance Magnets

Challenges in Producing High Magnetic Fields

Permanent Magnets

0.4 gauss **Earth's Magnetic Field**
600 gauss **Iron-Oxide Magnets (refrigerator magnets)**
4,000 gauss **Neodymium-Iron-Boron (rare earth magnets)**

--- limit of permanent magnets

Electromagnets

220,000 gauss **Superconducting Magnets (NHMFL-Tallahassee)**
---must solve the Hc2 problem
(hours at peak field)

450,000 gauss **Hybrid DC Magnet (NHMFL-Tallahassee)**
--- must solve cooling and stress
(hours at peak field)

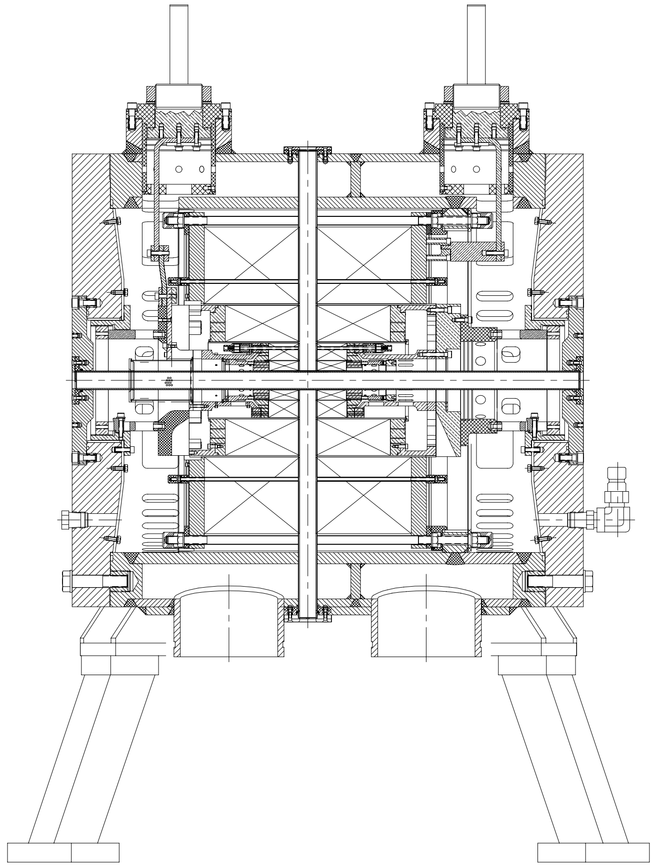
800,000 gauss **Pulsed Magnet (NHMFL-Los Alamos)**
--- ignore the cooling problem
focus on stress and fatigue
(milliseconds to seconds)

....TOO MUCH PRESSURE FOR ANY MATERIAL TO WITHSTAND....

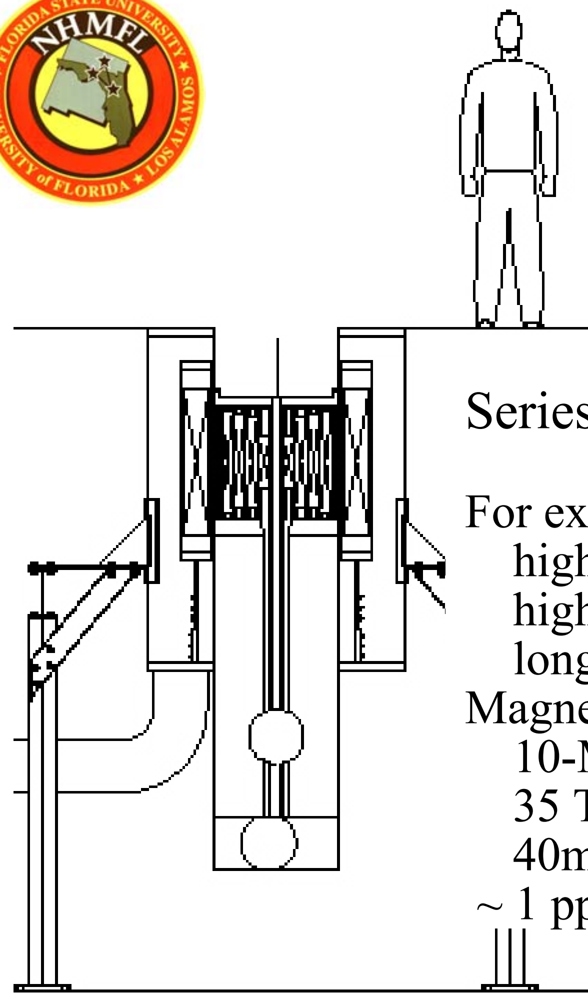
3,000,000 gauss **Single-turn 'Inertial' Magnet**
(ISSP, Japan and Berlin, Germany)
--- ignore the pressure problem
(microseconds)

8,000,000 gauss **Flux Compression Magnet**
(Ancho Canyon-Los Alamos)
(microseconds…
…and sample destruction)

Ideas for Future Magnets



Split-Gap Resistive Magnet
~20T, 20MW or ~30T, 40 MW
32mm split, 50 mm horizontal bore
90 ° access



Series-Connected Hybrid

For experiments requiring
- high homogeneity
- high temporal stability
- long times at peak field

Magnet specs
- 10-MW magnet
- 35 T central field
- 40mm clear bore
- ~ 1 ppm in 10-mm DSV

Less ripple (higher L/R)
Higher uniformity (large, low-current windings)
Reduced engineering for fault protection
- ~ 1/3 power of all-resistive magnet
- fits standard resistive-magnet cell
- opportunity for simultaneous service

Magnets at Neutron Sources

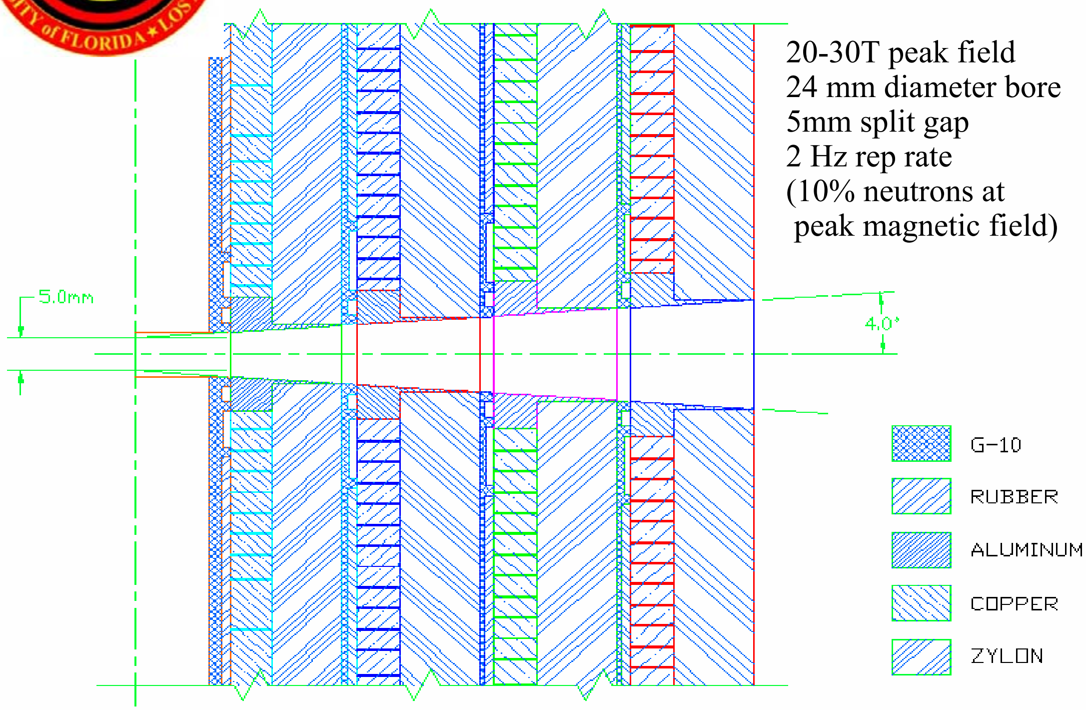
NEUTRONS

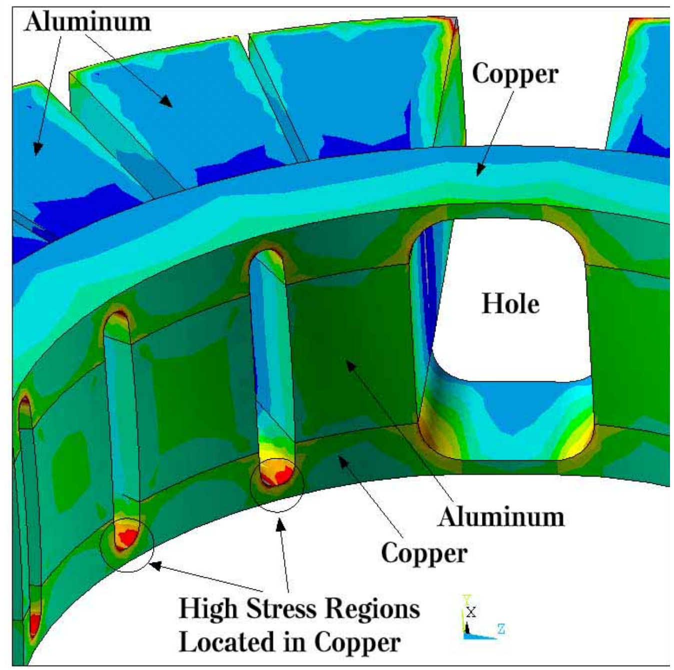
< 1 msec pulse period

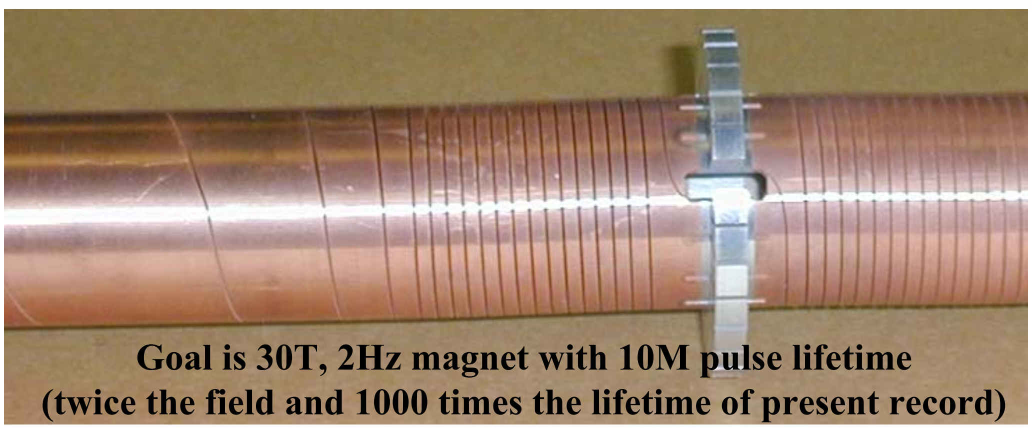
20 Hz rep rate

1–10 mm beam

20-30T peak field
24 mm diameter bore
5mm split gap
2 Hz rep rate
(10% neutrons at
peak magnetic field)







Goal is 30T, 2Hz magnet with 10M pulse lifetime
(twice the field and 1000 times the lifetime of present record)

Showstopper ?

CHALLENGES of Magnets for Neutrons

SPLIT-GAP MAGNETS

15-20 T/0.5 Hz	**symmetric, RPM**	**(KEK, Japan)**
15 T/17.6*T	**symmetric, SC**	**(HMI, Germany)**
14.5 T/17.1*T	**symmetric, SC**	**(HMI, Germany)**
13 T	**asymmetric, SC**	**(ILL/LLB, France)**
11.5 T	**symmetric, SC**	**(NIST, USA)**
11 T	**asymmetric, SC**	**(LANSCE, USA)**
10 T	**asymmetric, SC**	**(JAERI, Japan)**
9 T	**symmetric, SC**	**(NIST, USA)**
7.5 T	**symmetric, SC**	**(ISIS, England)**
7 T	**asymmetric, SC**	**(NIST, USA)**
7 T	**asymmetric, SC**	**(HFIR, USA)**

**increased field at the cost of sample volume, achieved with Nd pole pieces inserted into the gap*

SINGLE-SCATTERING-ANGLE MAGNET

(a conical holes for incoming and scattered neutrons)

20-25 T/0.5 Hz symmetric, RPM (KEK, Japan)

CHALLENGES of Repetitively Pulsed Magnets

ELECTRICAL

Insulator bonding to Cu & Al alloys
- **under water,**
- **under high strain**
- **under repeated cycling ~10 Mcycles**

Insulator breakdown: ~ 320 V turn-to-turn
~5000 V layer-to-layer

MECHANICAL

Weldability of Cu & Al alloys
Fatigue of Cu and Al alloys
Fatigue of O-rings
Fatigue of the Zylon reinforcing fiber

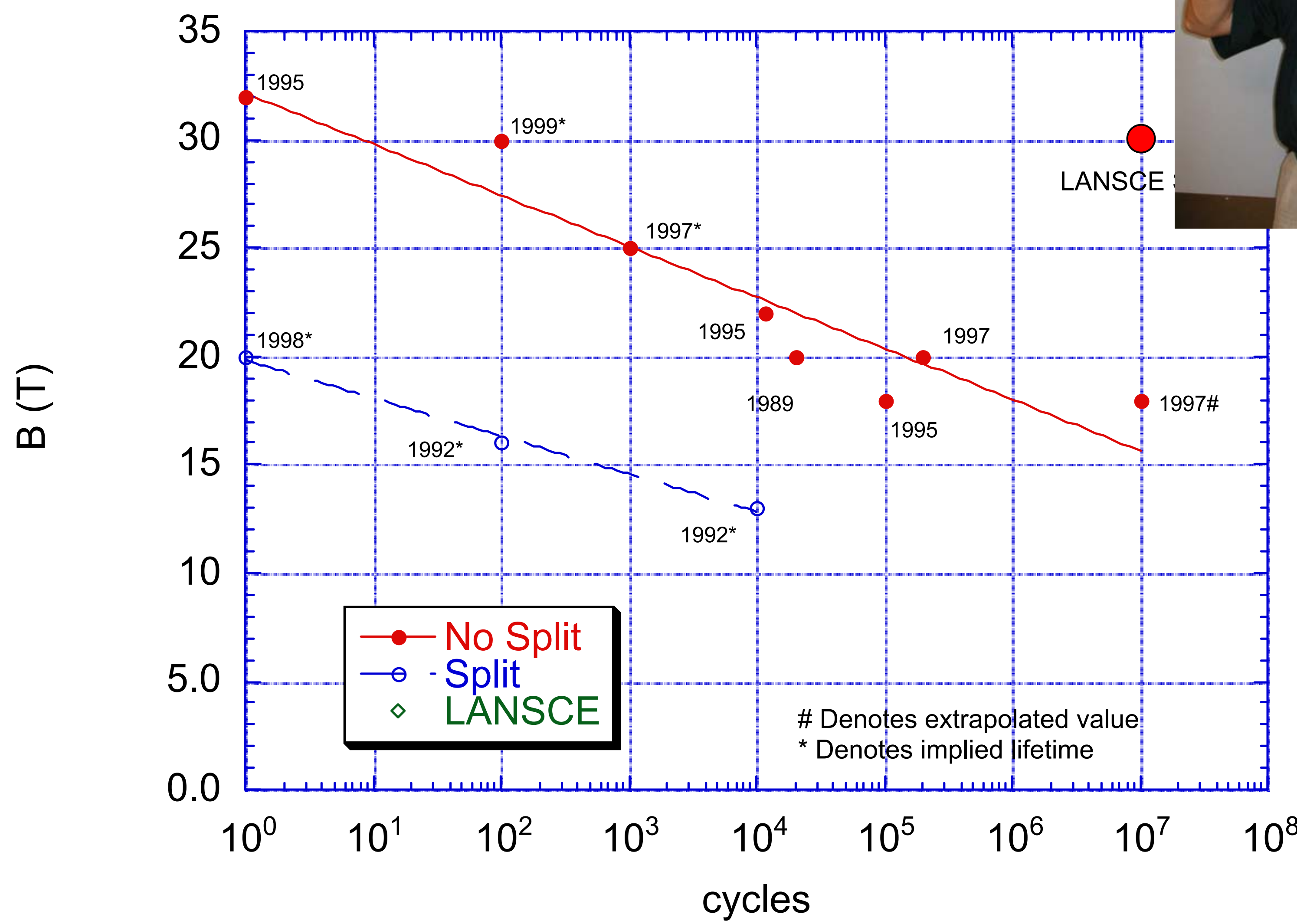
THERMAL

Thermal coupling to insulated conductors
Continuous cooling of pulsed-current buswork

CHEMICAL

Galvanic corrosion
Corrosion from the deionized cooling water
Chemical incompatibilities

History of Repetitive Pulsed Magnets



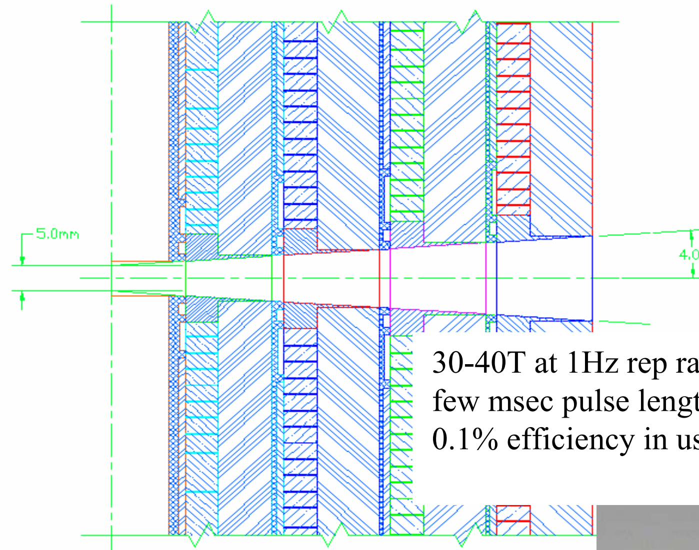
Magnets at Light Sources: Synchrotrons and Free-Electron Lasers

0.1–100 nm X-ray/VUV photons

100 psec pulses
1 - 10 MHz rep rate

1 – 10 micron focused beam

10^8 photons per pulse



30-40T at 1Hz rep rate
few msec pulse length
0.1% efficiency in using the x-ray source

X-ray Free Electron Lasers
10 – 100 fsec pulses
10Hz – 10kHz rep rates
10^{12} photons/pulse

APS, Argonne National Lab

Copper microcoil
(50 micron I.D.
150 micron O.D.
30 micron tall)
40T, 1Hz
10 nanosecond pulse length
relatively simple to operate

Might be able to design…
40-50T with 1kHz rep rate
few nanosecond pulse length
0.1% efficiency in using the x-ray source

Showstoppers ?

MATERIALS

Challenges in Producing High Magnetic Fields

Pressure Under Water

4 m	**Ears**	**6 psi**
1000 m	**Submarine**	**1000 psi**
4000 m	**Ocean Floor Submersible**	**6000 psi**

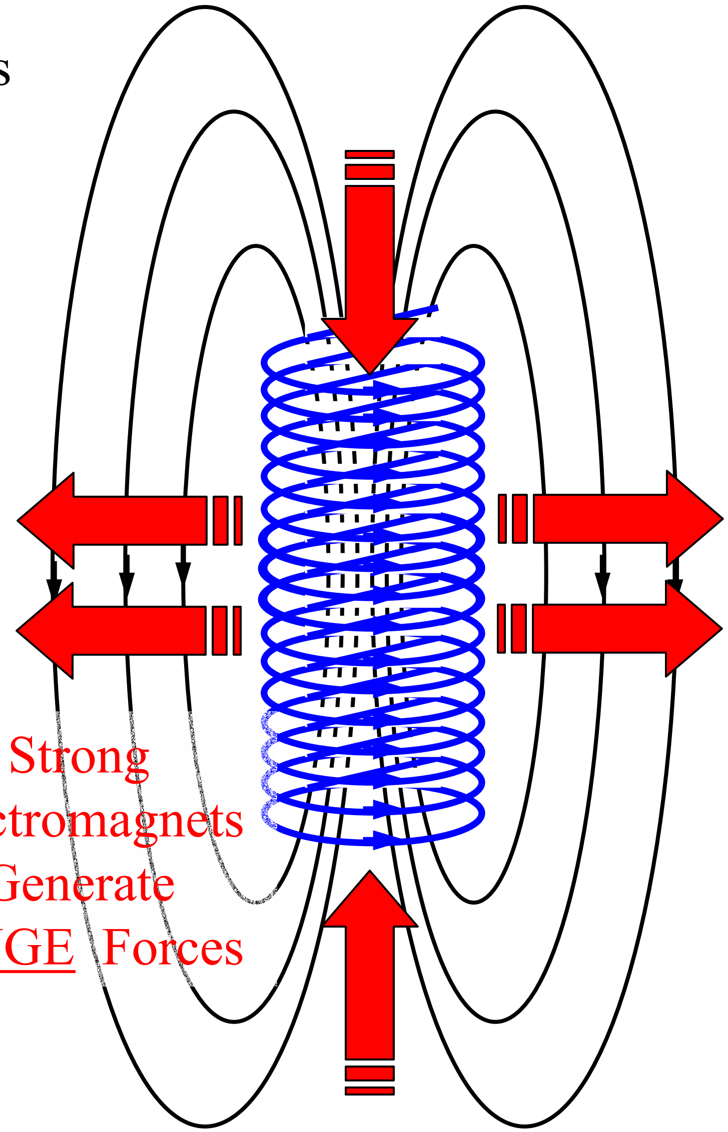
Pressure inside NHMFL Magnets

80T Pulsed Magnet	**200,000 psi**

(1.3GPascals, 130 kg/mm^2)

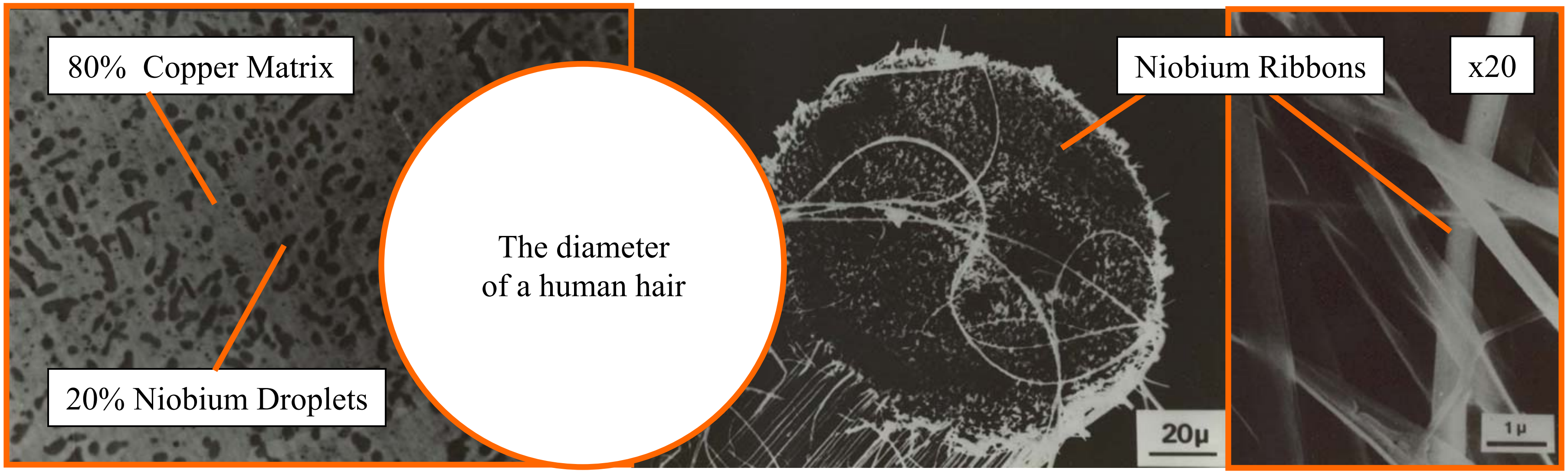
…exceeds the strength of most materials…

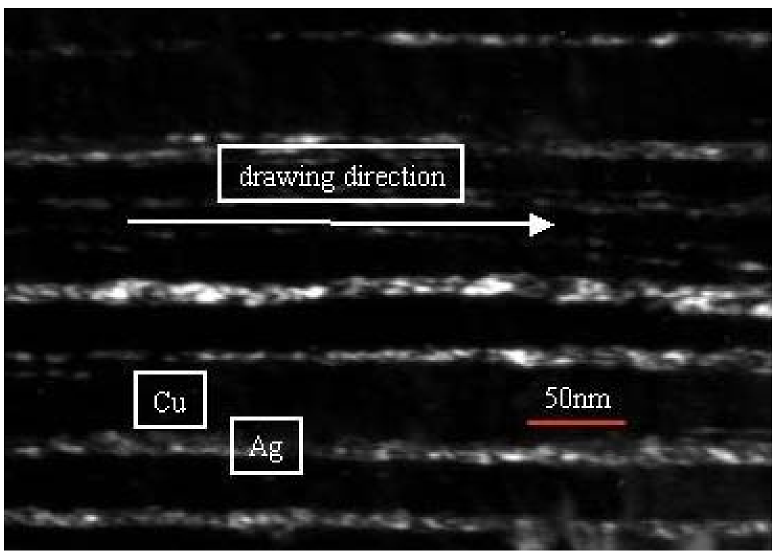
…within a factor of three of theoretical ultimate tensile strength…



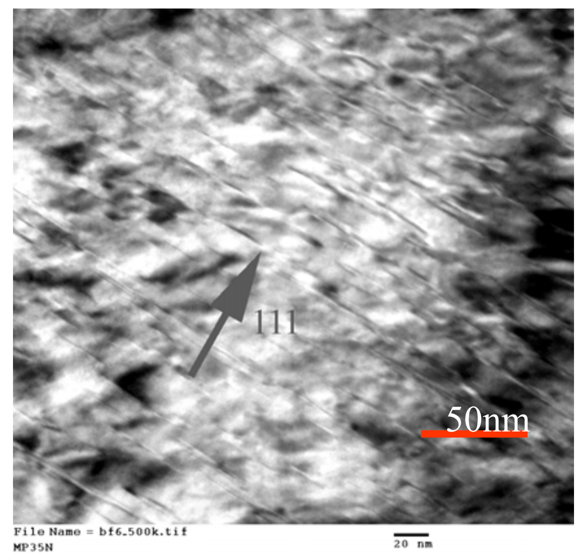
Strong
Electromagnets
Generate
HUGE Forces

Micro- and nano-structured materials **…work far better than rebar in cement**





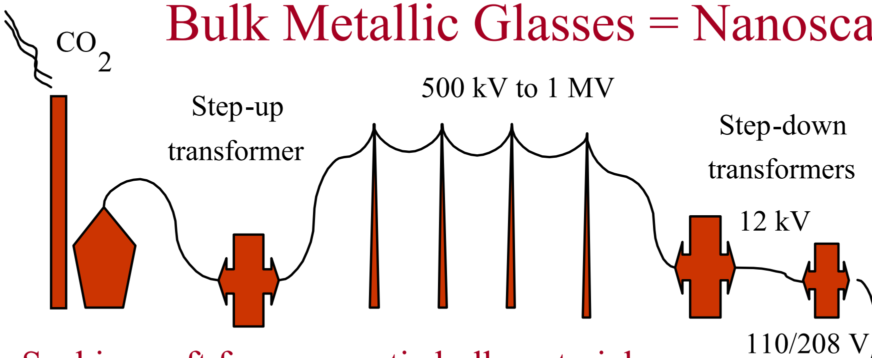
Conductors: High strength, high conductivity
Nano-structured Cu-Ag conductor retains conductivity but strengthens 2.5-fold over pure copper or gold.



Reinforcement Materials
high strength, toughness and fatigue endurance
Co-Ni-Cr-Mo alloys strengthened with nano-platelets. The achievable strength is more than 2GPa at 300K.

Bulk Metallic Glasses = Nanoscale Metallurgy

Shen and Schwarz, Acta Mater. **49**, 837 (2002)
Shen, et al, Mat. Science Forum **386-388**, 441 (2002)
Shen, et al, J. Appl. Physics **91**, 5240 (2002)



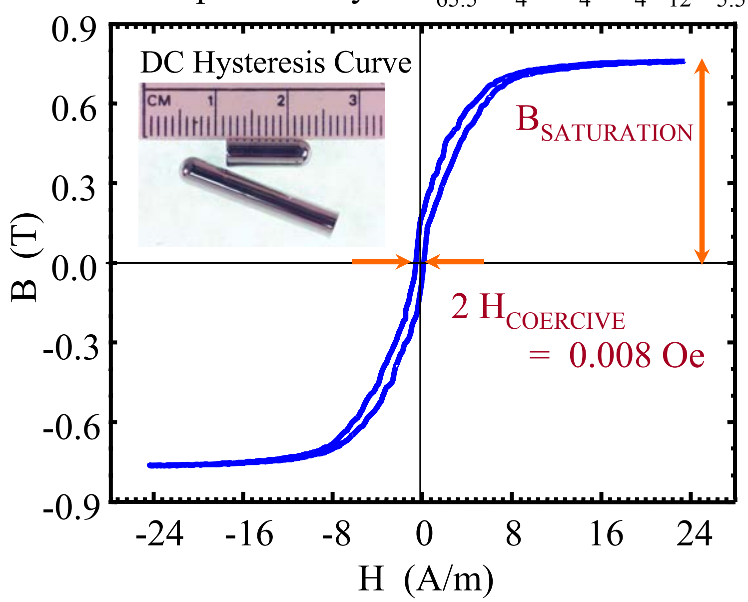
Seeking soft ferromagnetic bulk materials

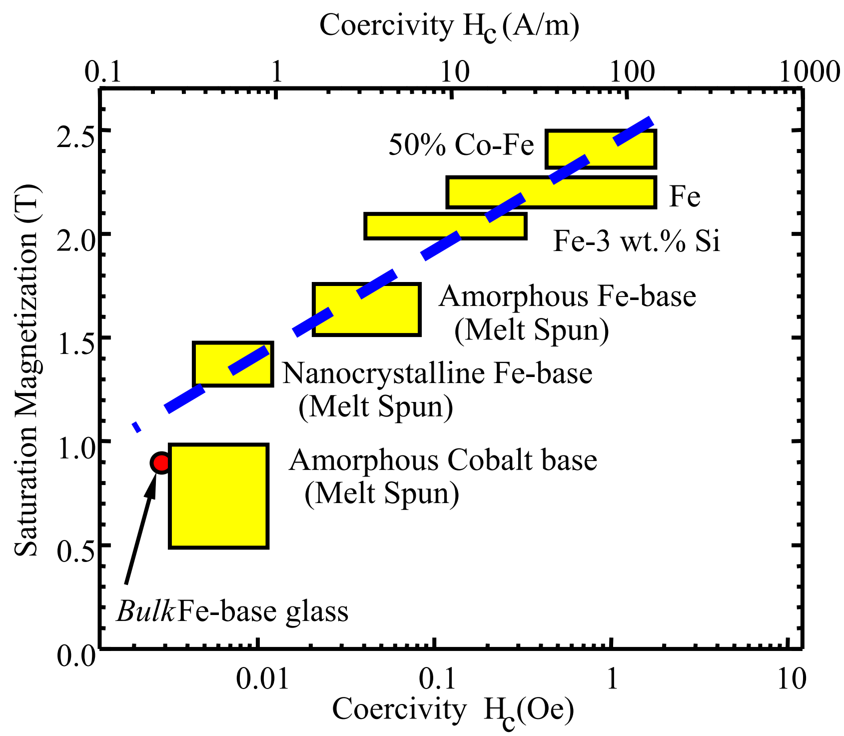
Transformer core losses are 1% of total power generated

= 60 x 10^9 kW-hr / yr (in 1990)
= \$7 Billion (at \$0.12 / kW-hr)
= ??? additional tons of emitted CO_2 per year

In the fluid phase, short range polytetrahedral order.
In the solid phase, fcc or hcp order has octahedral groups.
Avoid heteronucleons (typically oxide particles).
Undercool the melt….and…..
Optimize packing by adding Cr, Mo, Ga to make the polytetrahedra more stable and to slow diffusion.
Cr, Mo, Ge have nearly zero heats of mixture with Fe. (Negative forms compounds; Positive segregates)
P, B, C all have negative heat of mixture with Fe.

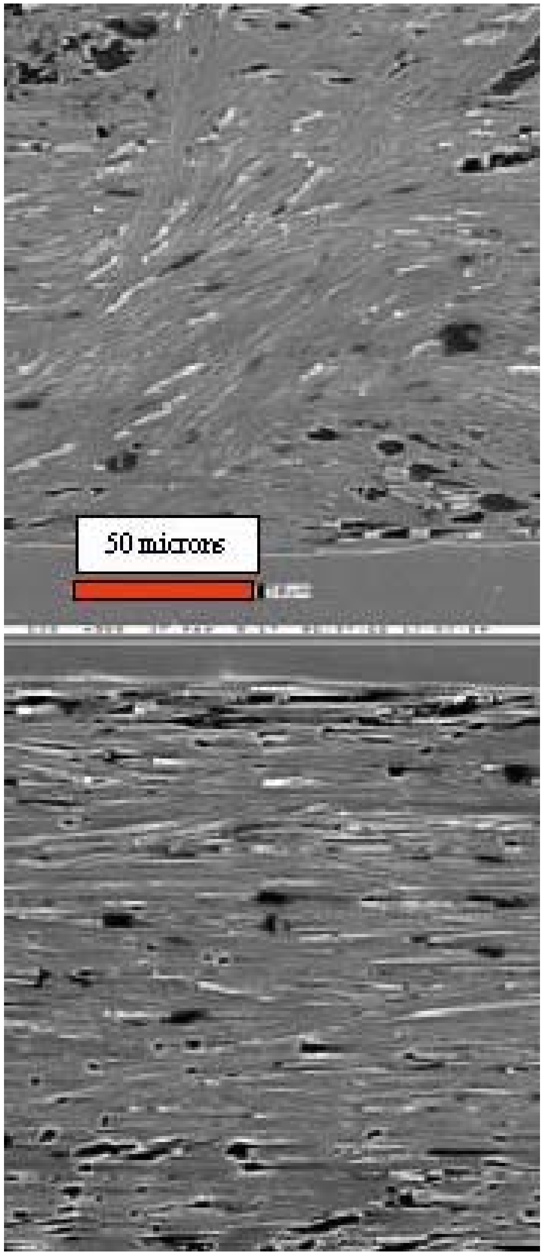
Bulk amorphous alloy: $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}B_{5.5}C_5$





Initial (still-unfunded) studies of the copper-silver composite show promise for high-strength, large cross-section conductor directly from the melt. **- R. Schwarz, et al.**

High-temperature, High Magnetic Field Processing of Materials



High-Tc superconducting tapes

Critical current in films dominated by grain alignment in the conductor.
Magnetic field processing aligns grains and enhances critical current density and peak current.
Incorporated carbon nanotubes improve magnetic vortex pinning and increase upper critical magnetic fields.

Nanocrystalline Iron-Based Materials

Magnetic field processing alters the microstructure of Invar alloy, *doubling* the volume fraction of ferromagnetic bcc phase, implying the possibility of extremely high strength-to-weight alloys.
Will magnetic field processing alter the phase diagram and induce nanocrystalline grain growth in steels, other metals ?

High Temperature Texturing of Nd-Fe-B permanent magnets

Anneal at 1200 °C for 3 hours under Ar,
Texture decreases and remains random without magnetic field.
Texture increases and becomes directional with magnetic field processing.

Carbon Nanotube Composites

Thermally cure epoxy dispersed with 3wt.% CNT in a magnetic field.
Tenfold increase in the electrical conductivity, 30% increase in thermal conductivity with magnetic field processing.