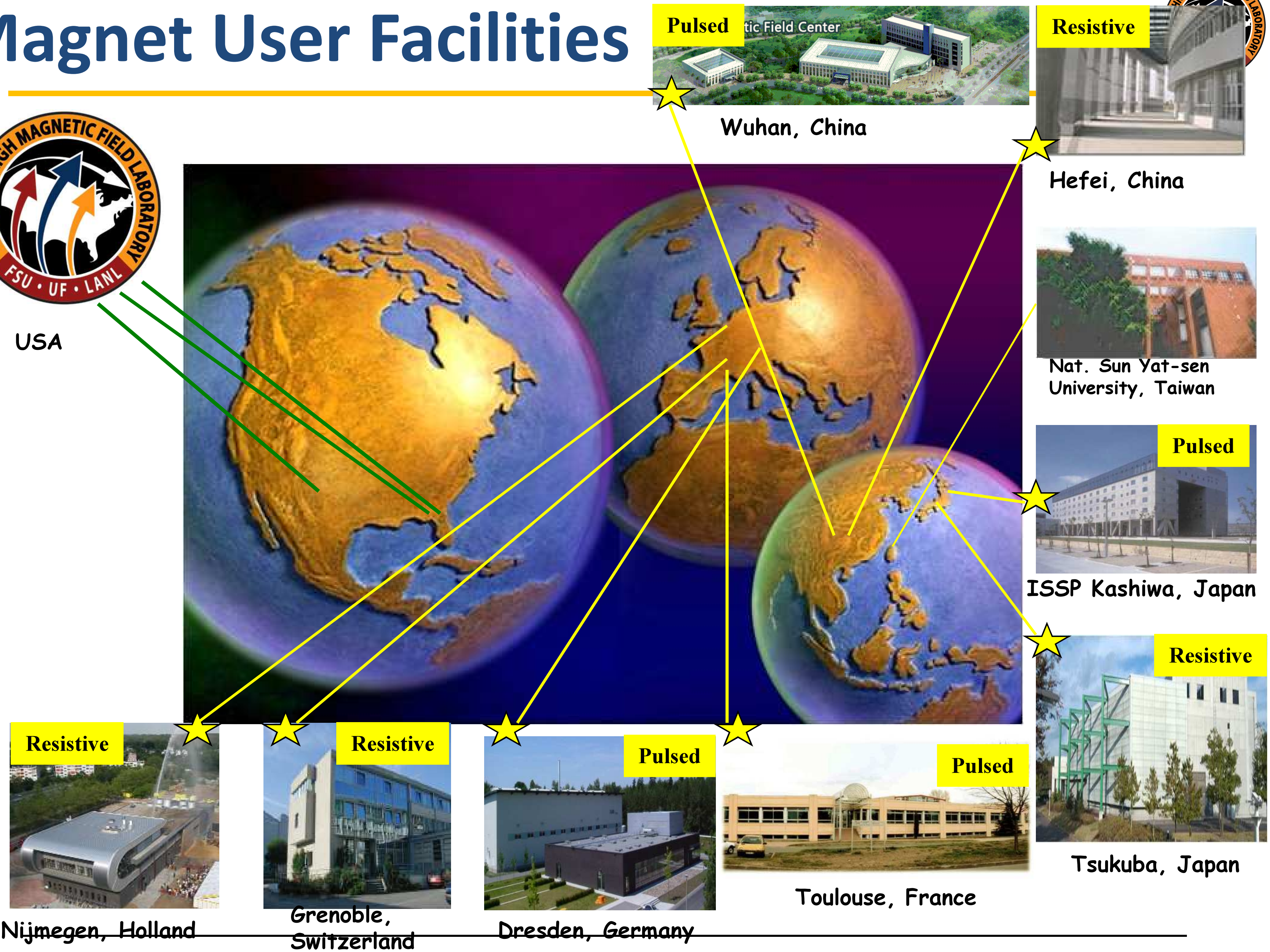
Pulsed Magnetic Fields

Physics 590B

Eundeok Mun

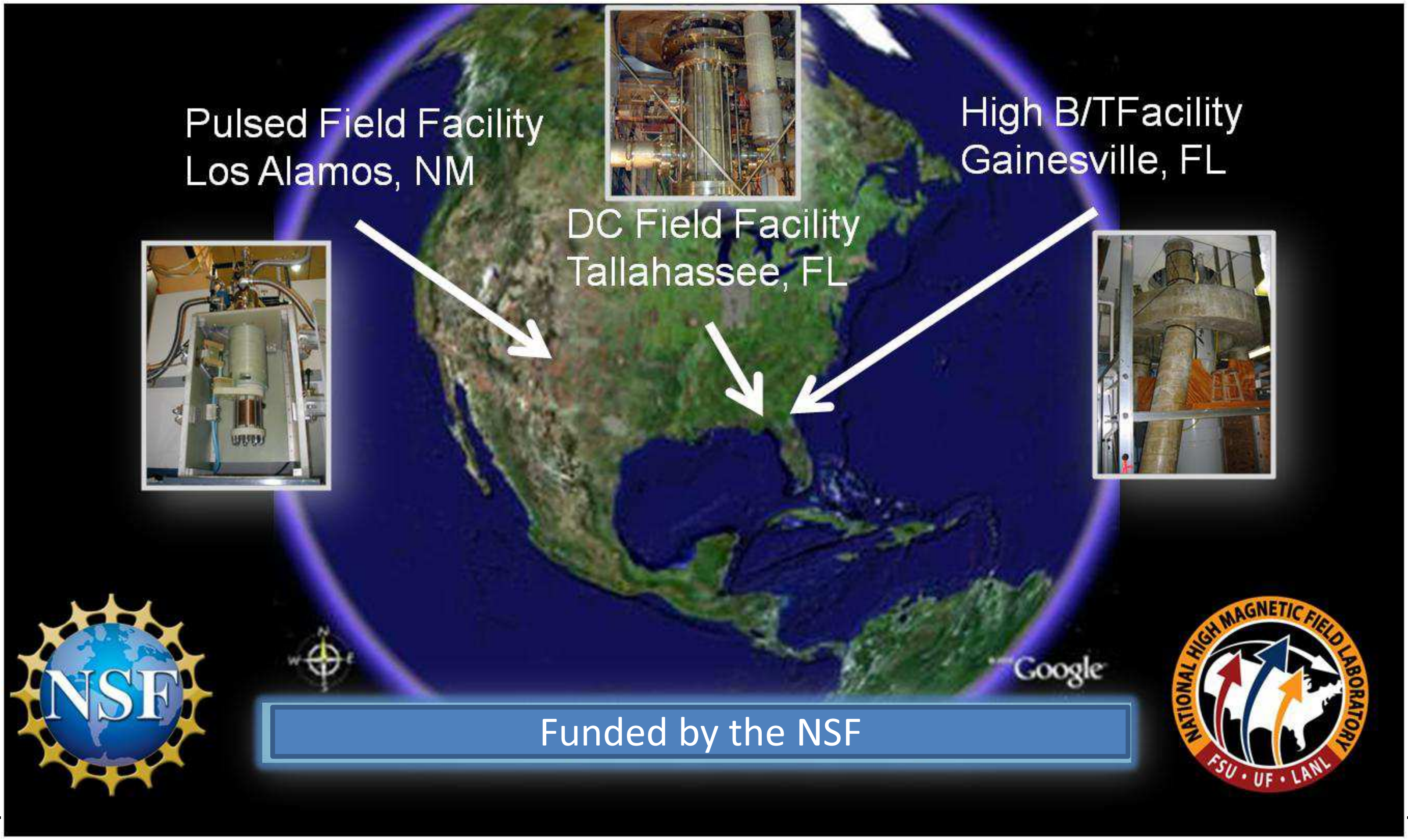
Magnet User Facilities



The NHMFL (Three Sites)

The National High Magnetic Field Laboratory

Founded in 1990 by the National Science Foundation (NSF)
A **user facility** open to scientists from around the world



Life at Los Alamos

2011 Los Alamos
Population : ~18,000
The smallest county in NM in 109 square miles
Located at 7,355 feet altitude
The people of Los Alamos have among the highest levels of educational attainment of any community anywhere.

Areas of Interest : Pajarito Mountain, Valles Caldera National Preserve, Bandelier National Monument, Eight Northern Pueblos, Santa Fe Opera, Wilderness
Recreation : Skiing, Hiking, Golfing, Biking, Ice Skating, Aquatic Center



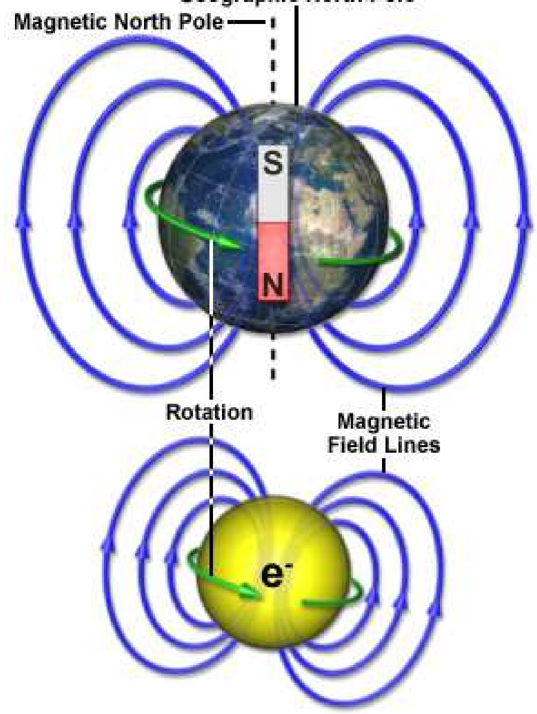
Permanent Magnets

A lodestone attracting iron filings and nails.

A **permanent magnet** is an object made from a material that is **magnetized** and **creates its own persistent magnetic field**.

Holds a magnetic force can not be turned on and off

Uses : Frig Magnet, Speaker, Electric Motors, and many more…



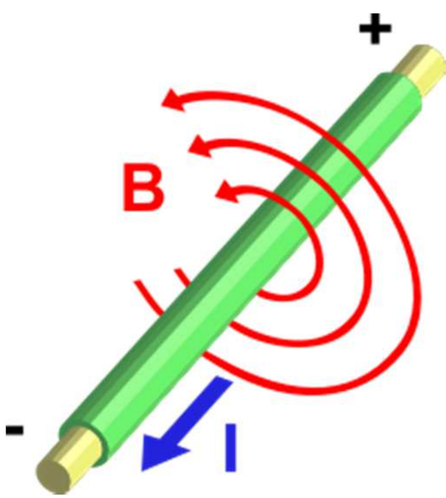
The Earth and electrons are both magnets.

Electromagnets

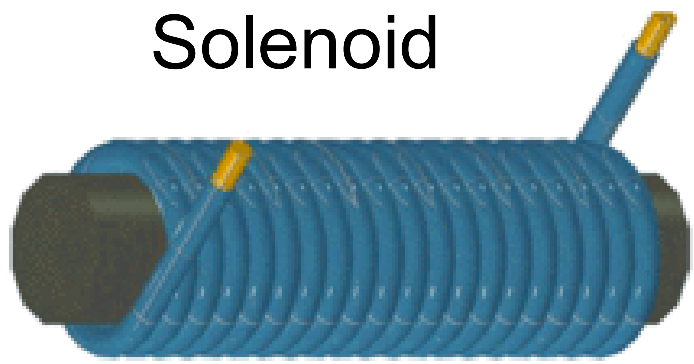
An **electromagnet** is a temporary magnet that is magnetized by the **magnetic field produced by an electric current** in a wire. Electromagnets have magnetic properties only while the current is flowing. Can be controlled the strength of magnetic field (on and off).

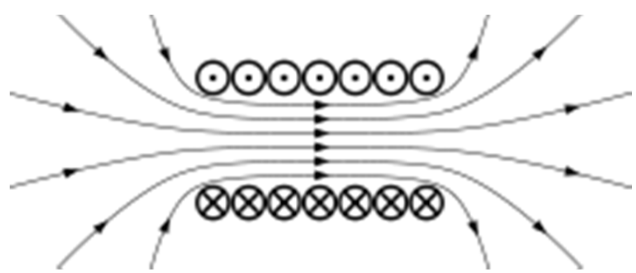
Current (I) through a wire produces a magnetic field (**H**). The field is oriented according to the right-hand rule.

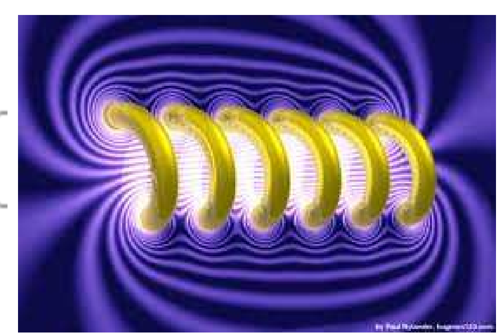
Wire



Solenoid





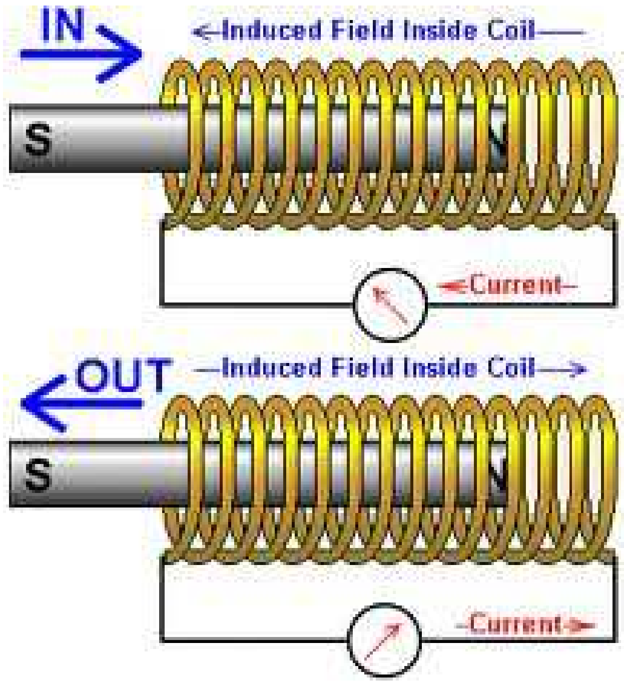


Electromagnets

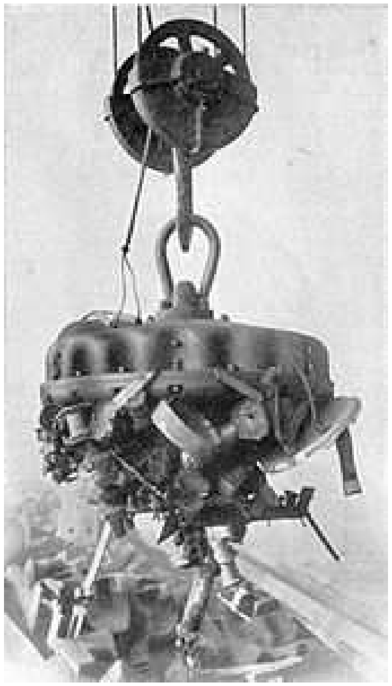
Strength of electromagnets : $\mathbf{H} = \mu\, n\, \mathbf{I}$

n : number of turns in a coil
I : amount of current in the coil
Peameability of the core material : air would be a weak magnet, Iron would make a strong magnet

Uses : Buzzers, Switches, Locks, Bells, Transformers, Industry, Sensors, Motors…



electromagnet with movable core called a plunger



Industrial electromagnet lifting scrap iron, 1914

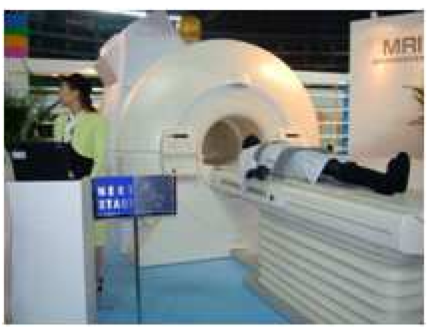
Magnets in Daily Life

Computer memory

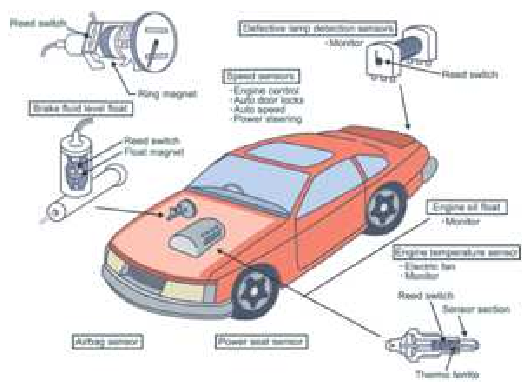

Hard drives


Airport security
Magnetic pulse-echo

Magnets



MRI machines for imaging



Electromagnets actuate windows, locks, etc.


Maglev trains

The NHMFL (Three Sites)

The National High Magnetic Field Laboratory

Founded in 1990 by the National Science Foundation (NSF)
A **user facility** open to scientists from around the world

- **Los Alamos National Laboratory**

  Pulsed magnetic fields up to 100 Tesla, Single Turn up to ? (Limit?)

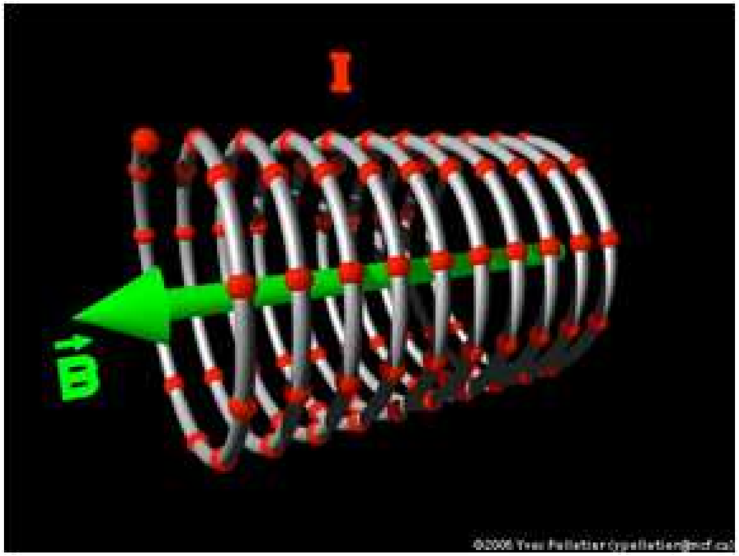
- **Florida State University, Tallahassee, FL**

  Continuous fields (DC, resistive magnet) up to 45 Tesla

- **University of Florida, Gainesville, FL**

  Continuous fields up to 21 T combined with some of the lowest temperatures in the universe (~ 1 mK and down to μK)

Magnets : generating magnetic field



Solenoid coil

$$\mathbf{B} = \mu \, n \, \mathbf{I}$$

$\mu = 4\pi$ x 10^{-7} NA^{-2}
n = turns/length
I = current

10 T magnetic field : 100 turns X 8,000 Amps / 0.1 m

!!! 8,000 [A], practical and realistic ?

- Joule's (heating) Law : $\mathbf{Q = I^2 R \, t}$ ~ 38 MJ for 60 sec
- Temperature $\mathbf{Q} = \boldsymbol{m} \, \mathbf{C_p} \, \Delta\mathbf{T}$: $\Delta T \sim 664{,}000$ °C

Magnets : Superconducting Magnet

20 Tesla ~ 4000,000 times earth's magnetic field

A coil made out of superconducting wire

- A superconductor has no electrical resistance: ***R* = 0** No heating!
- The electricity will keep running practically forever
- No heat is generated in the process
- But needs to be cooled to low temperatures (liquid helium)
- Eventually magnetism and current kill superconductivity: H_{c2} **and** J_c
- Limit 23 T

Example: MRI magnet (1.5 T)

Niobium-titanium (NbTi) wire
(max 9 Tesla)

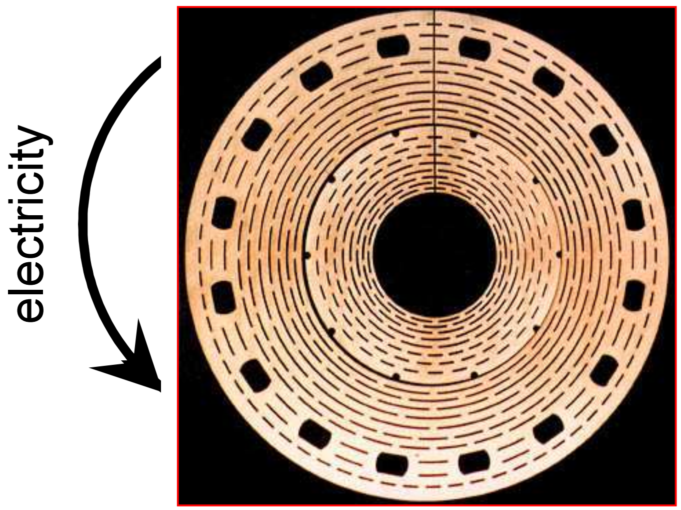
Niobium-tin (Nb_3Sn) wire
(max 21.3 Tesla)

Magnets : Resistive Magnet

Exceeding 23T: back to resistive wire. Let’s try cooling water

Superconducting magnet : superconductivity is destroyed by high magnetic fields
To go beyond 21 Tesla, switch to copper alloys
Problem : power is needed and heat is generated

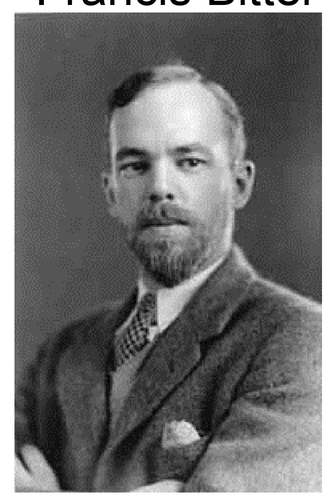
“Florida-Bitter” magnets



World record: 35 Tesla
NHMFL, Tallahasse, Fl

Holes are for water cooling
Staggered pattern maximizes strength

Francis Bitter



30 foot tall cooling tower (runs two 33 T magnets at a time)

Invented the Bitter plate used in resistive magnets

Magnets : Resistive Magnet

The worlds largest DC magnetic field (Hybrid)
Resistive magnet (33 T) + superconducting magnet (12 T)

45 Tesla

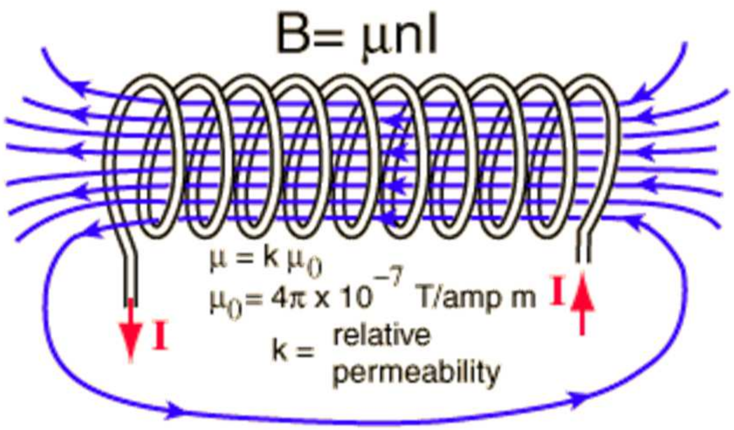
32 mm bore

- Electricity budget of ~ $1 million per year
- 8,000 liters of cooling water per second
- Cryostat designed to handle a fault load of 6 MN ≈ 27 times the thrust of a Boeing 747

Magnets : Pulsed Magnets

Exceeding 45 T : **reduce the energy needed by shortening the time**

Los Alamos – Pulsed Field Facility



60 s/ 2000 = 0.030 s

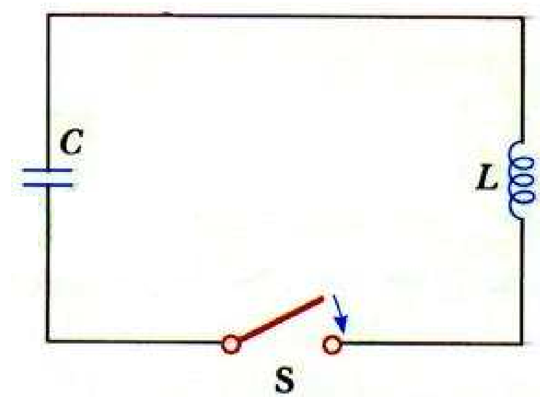
38 MJ/2000 = 19 kJ

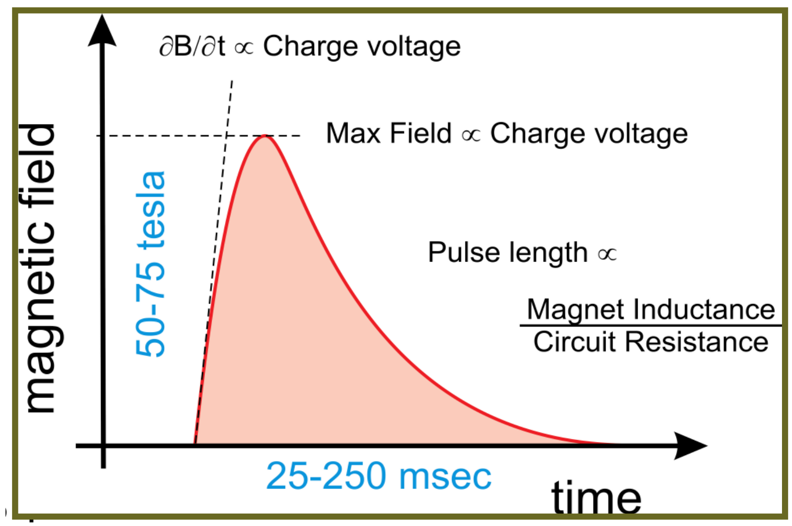
10 T magnetic field : 100 turns X 8,000 Amps / 0.1 m

- Joule's (heating) Law : $\mathbf{Q=I^2\,R\,t}$ ~ 19 kJ for 0.03 sec
- Temperature $\mathbf{Q=}\boldsymbol{m}\,\mathbf{C_p\,\Delta T}$: **ΔT ~ 332 K**

Magnets : Pulsed Magnets

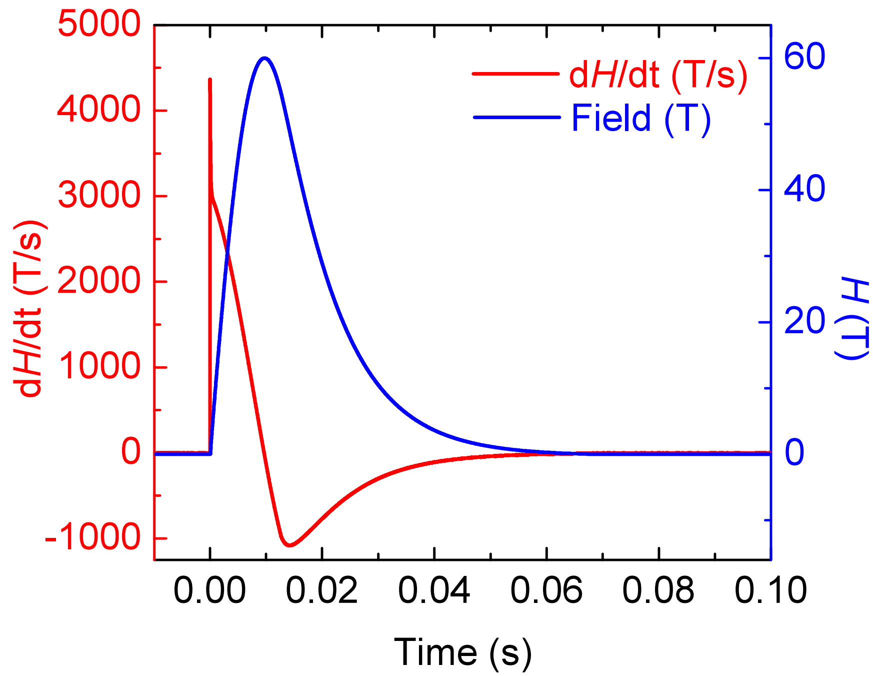
0.6 MJ of energy





Magnets : 60 T / 65 T Short Pulse

A million times earth's magnetic field!



- 10 milli seconds to peak field

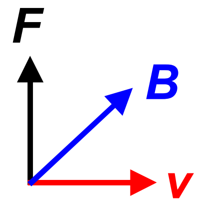
  10 ms rising and 40 ms falling time
- Life-time of ~500 full field shots
- 45 min ~ 2 hr cooling time between full field shots (LN_2 cooling)

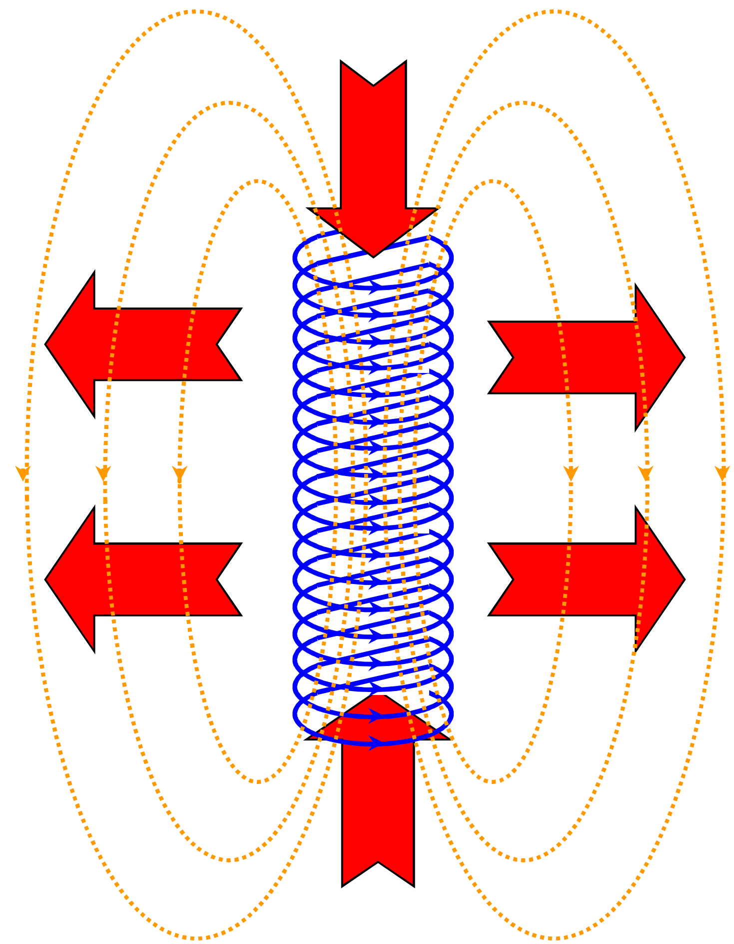
Magnets : 60 T / 65 T Short Pulse

Limit : strong electromagnets generate big forces

Hendrik Antoon Lorentz

$$\vec{F} = q\vec{v} \times \vec{B}$$





Pressure under water :

ears	4m	0.3kPa
submarine	600m	50kPa
ocean floor	3600m	300kPa

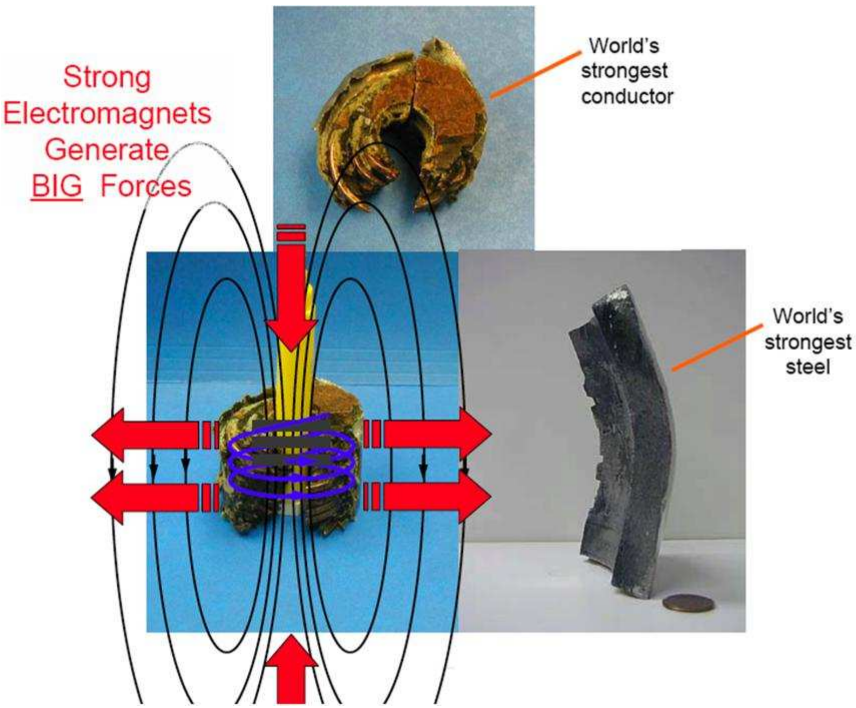
Pressure inside electromagnets :

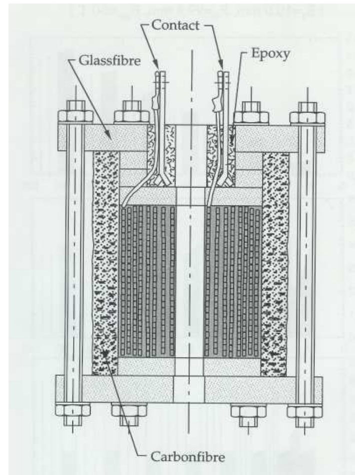
80 Tesla pulsed field ~10000kPa ~ 130 kg/mm^2 huge!

Huge pressure : more pressure than most materials can handle!

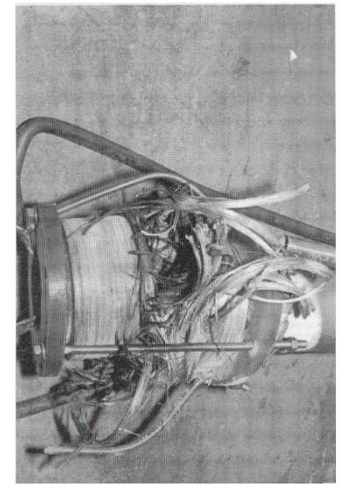
Magnets : 60 T / 65 T Short Pulse

Limit : strong electromagnets generate big forces

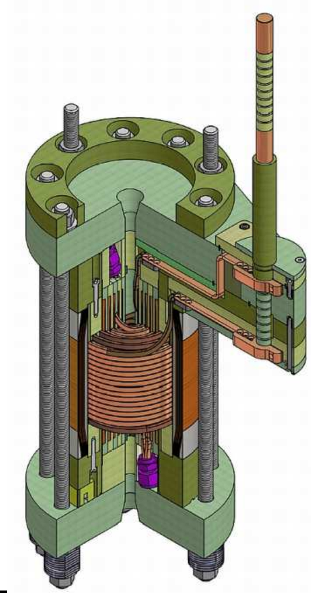




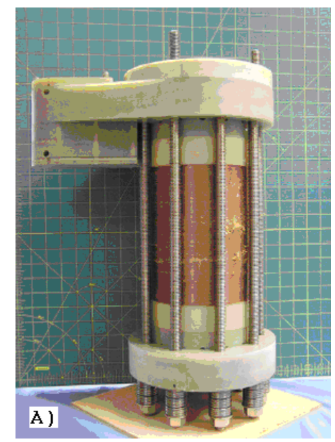
1994



Electrical Fault



2005



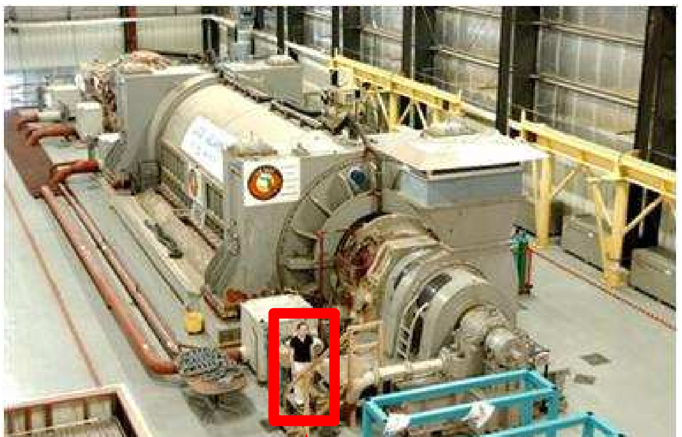
Electrical Fault

Magnets : 60 T Shaped-Pulse (long pulse)

60 T provides quasi-continuous fields

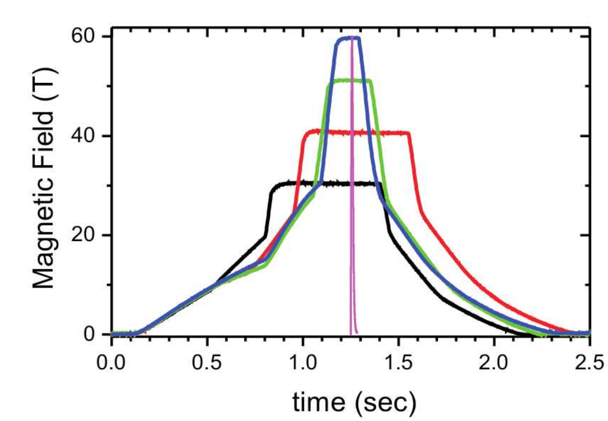
essential for heat capacity, time-resolved spectroscopy, reduced eddy currents, etc…

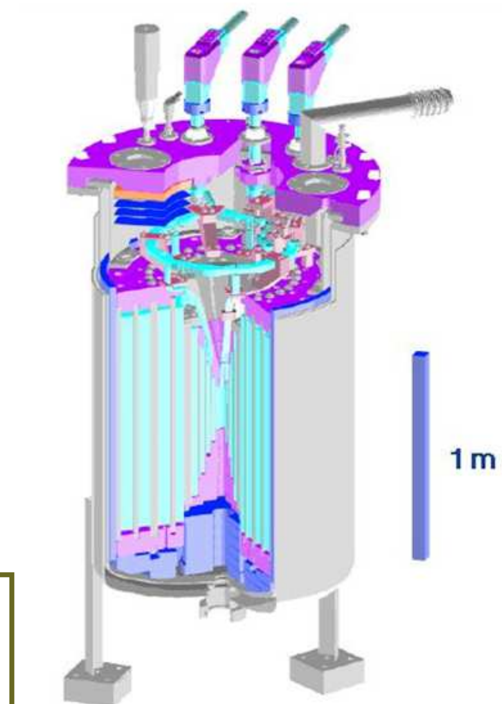
1.6 Gigawatt generator



person

2 seconds total, 100 ms at 60 T





Shaped pulse

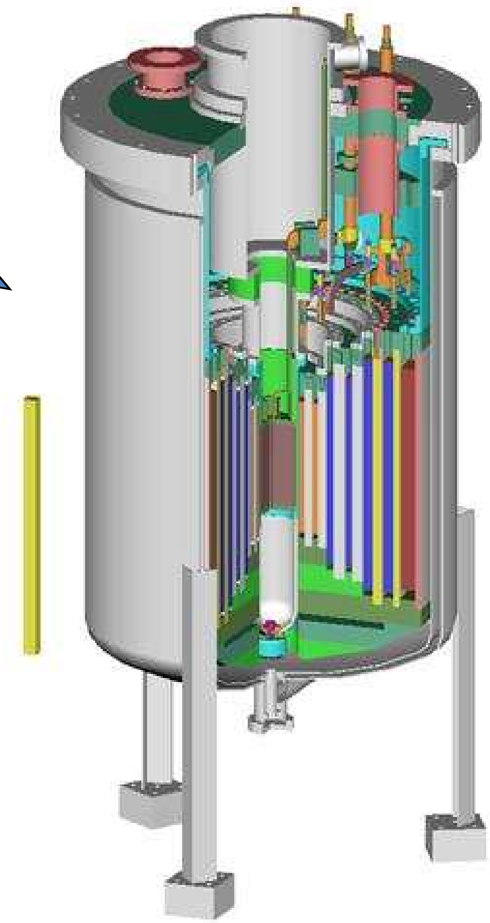
Magnets : 100 T multi-shot

World Record, Los Alamos, 2012 :

The first time 100 T has been generated without destroying the magnet

1.4 Gigawatt generator

Megajoule Capacitor bank



Magnets : 100 T multi-shot

World Record, Los Alamos, 2012 :

The first time 100 T has been generated without destroying the magnet

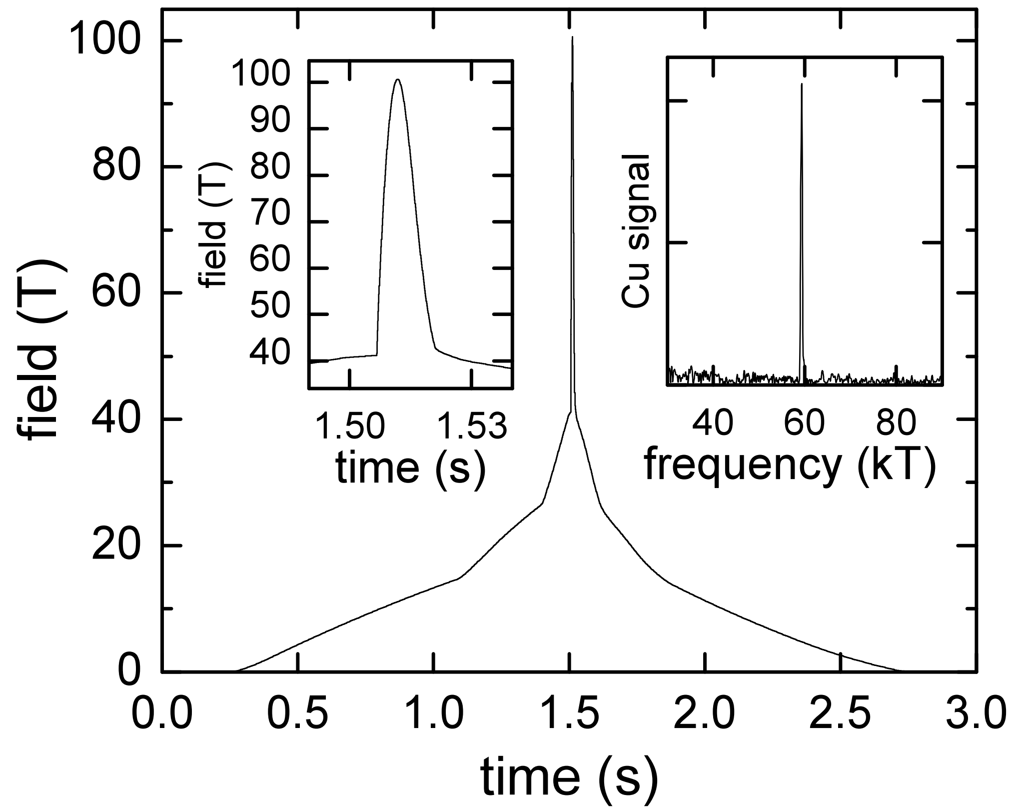
100.7 tesla confirmed via magneto quantum oscillations in poly-crystalline copper

NATIONAL HIGH MAGNETIC FIELD LAB

NSF

U.S. DEPARTMENT OF ENERGY | Office of Science

Los Alamos NATIONAL LABORATORY

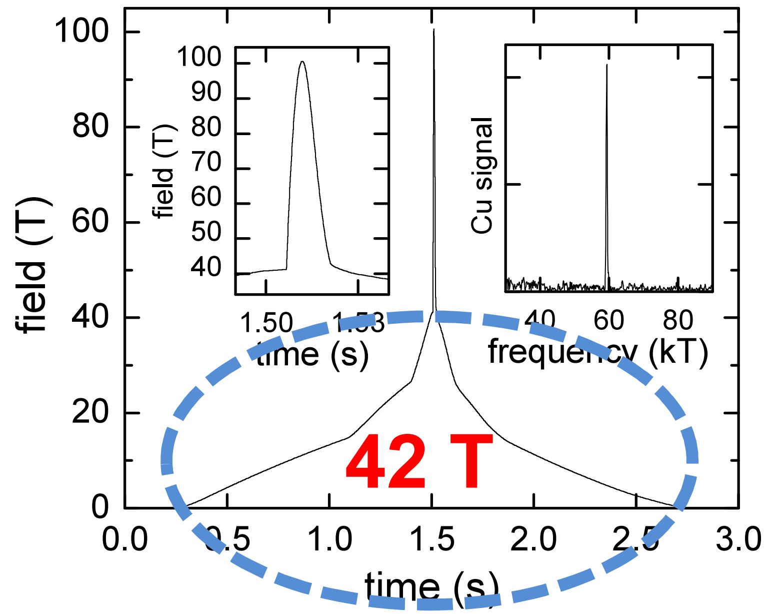


2011 : 97.4 T — User support 95 T → User support 100 T — 2012 : 100 T

Magnets : 100 T multi-shot

Two key factors in record breaking experimental fields

(1) precision control of "outsert" magnet



- **Energy source**

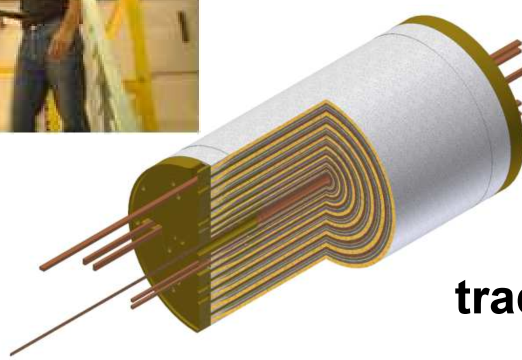
1.4 GW generator — large degree of flexibility

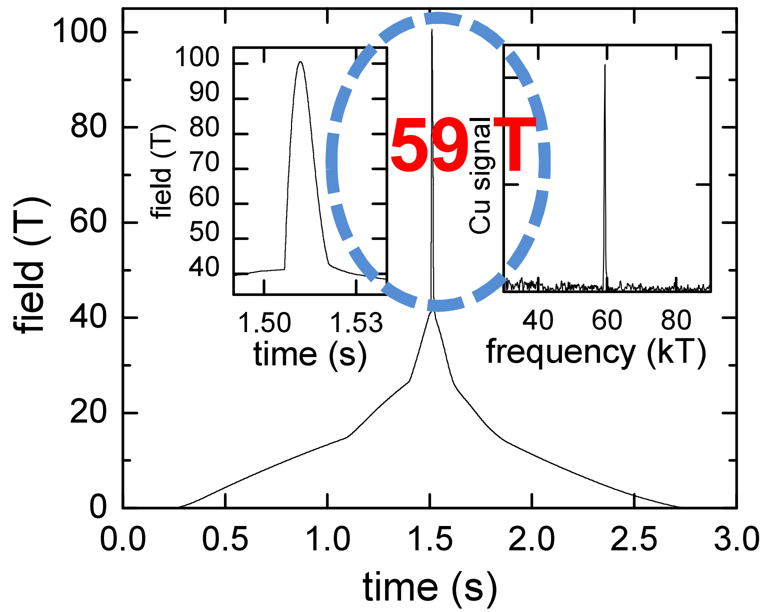
- **Engineering and operations team**

Magnets : 100 T multi-shot

Two key factors in record breaking experimental fields

(2) strong conductors in 10 mm bore "insert"

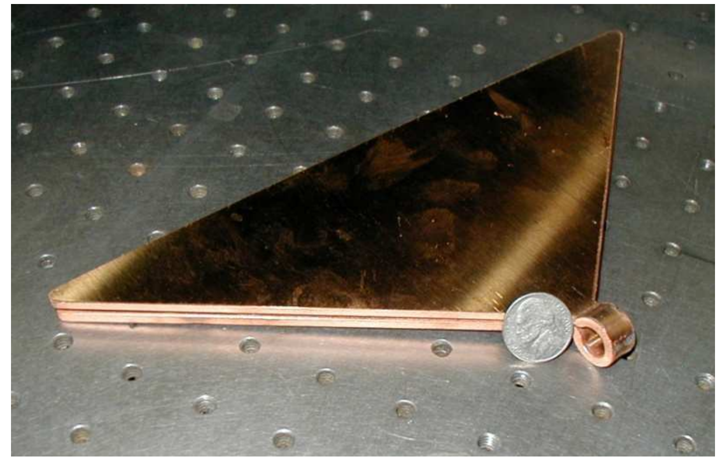




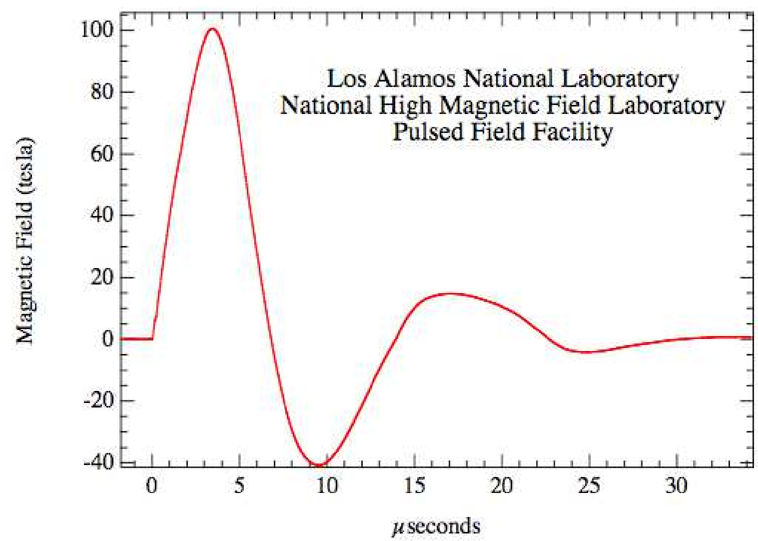
trade experimental space for field intensity

Magnets : Single Turn exceeding 100 T boom!

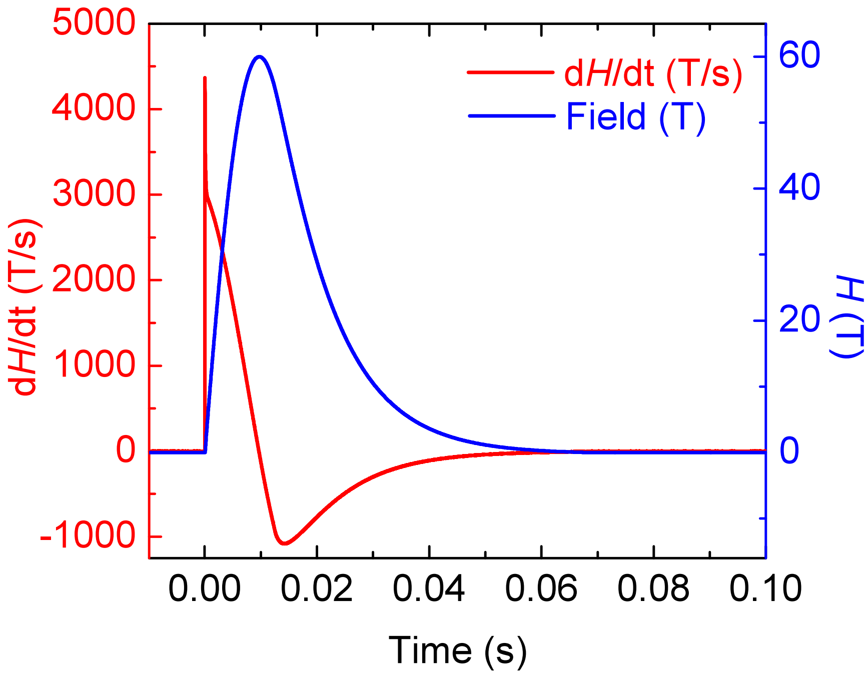
Science Enabled by Unique NHMFL Pulsed Field Facility



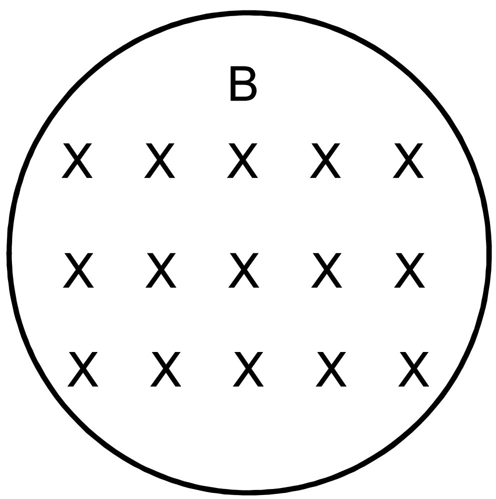
200 T + single turn magnet



Determination of Magnetic Fields



Using dB/dt coil and
quantum oscillations of copper



area

EMF = B X area

Ohms law
V=IR

Voltage = area X dB/dt

User Support Program at Los Alamos

Superconducting Magnets

15/17 T (52 mm), 15/17 T (35 mm) with ^3He, 20 T (52 mm) with Dilution refrigerator,
14 T PPMS with Dilution refrigerator option

Capacitor Bank-Driven Magnets + ^3He

60 T / 65 T short pulsed field
300 T Single Turn

Generator-Driven and Multi-Shot Magnets + ^3He

60 T long pulsed field
100 T multi-shot

Measurements : routinely measured thermodynamic and transport properties

Heat capacity, resistivity, Hall, magnetization (VSM, extraction magnetometer), thermal expansion and magneto-striction (capacitive dilatometer), ESR, thermoelectric power, Nernst, electric polarization, dielectric constant.

High frequency transport, magneto-optics (IR through UV), pulse echo ultra-sound spectroscopy, AC specific heat (mid and long pulse)

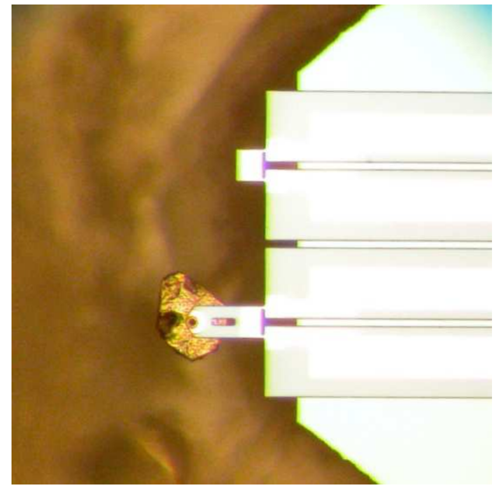
PDO – extremely sensitive to detect phase transition and quantum oscillation
Electrical Polarization – pyroelectric current

100 T experiments

Diverse experimental tools for extreme magnetic fields

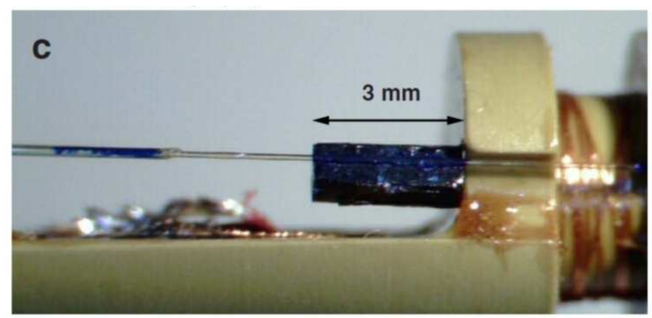
rf contactless conductivity

piezzoelectric magnetometry



digital lockin

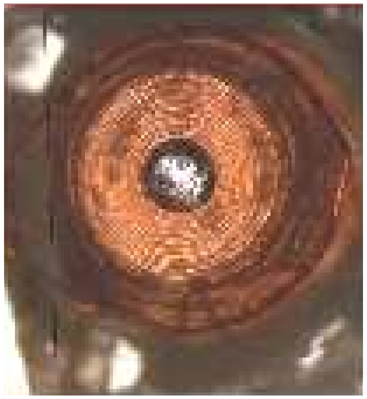
optical strain gauge



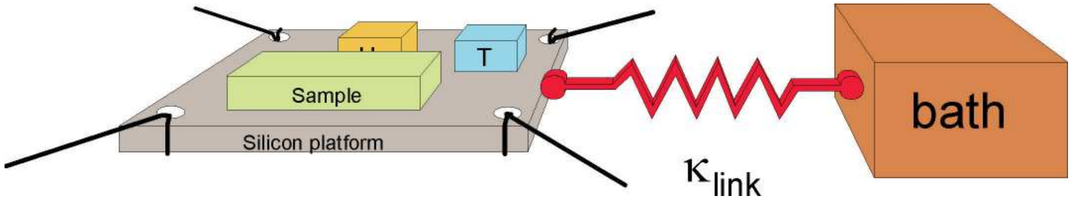
100 T experiments

Diverse experimental tools for extreme magnetic fields

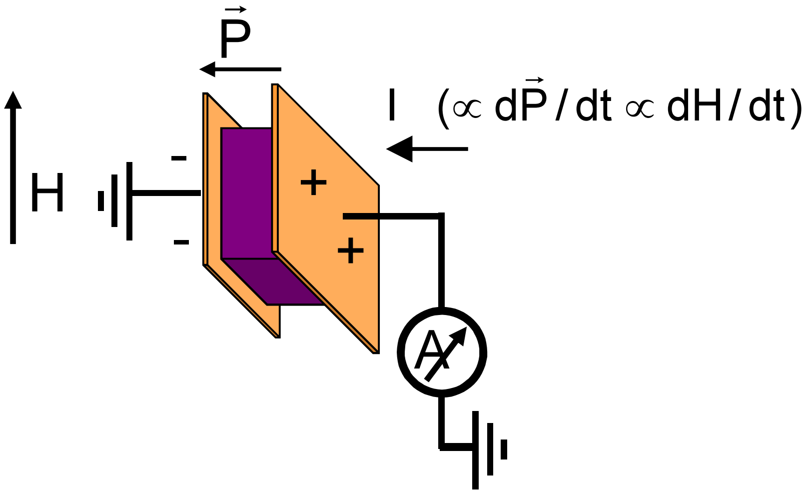
susceptibility



pulsed field heat capacity



electric polarization



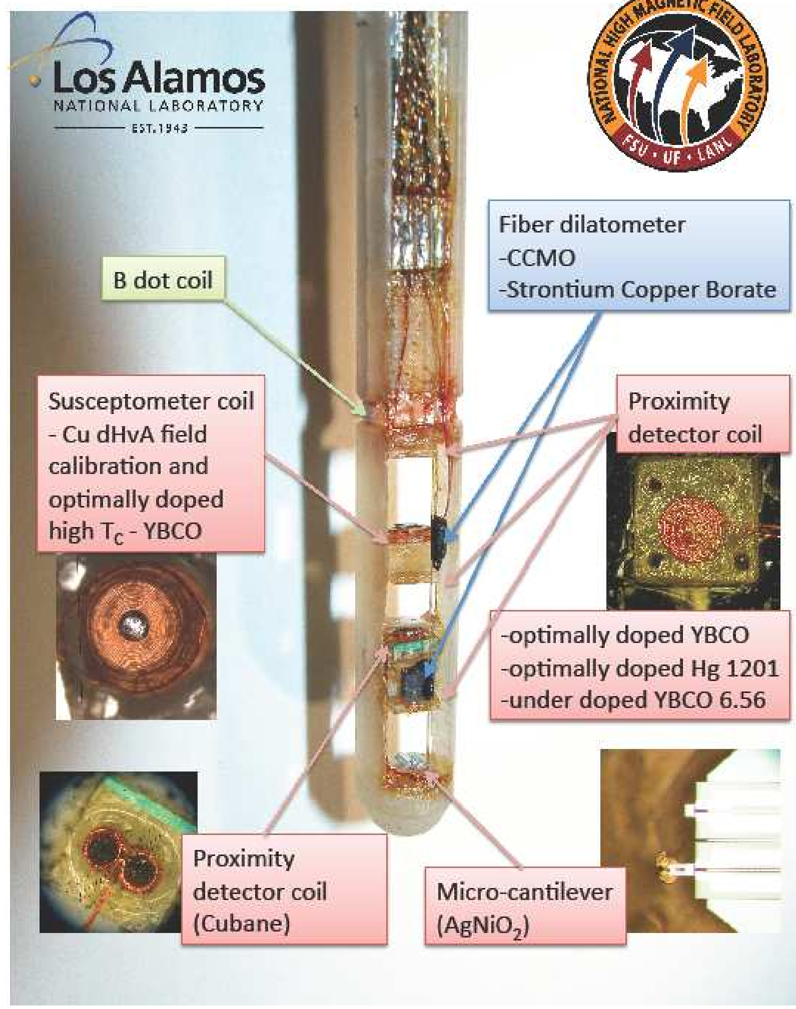
in-situ rotation

100 T experiments

Multiple parallel experiments in record fields

100 tesla probe:

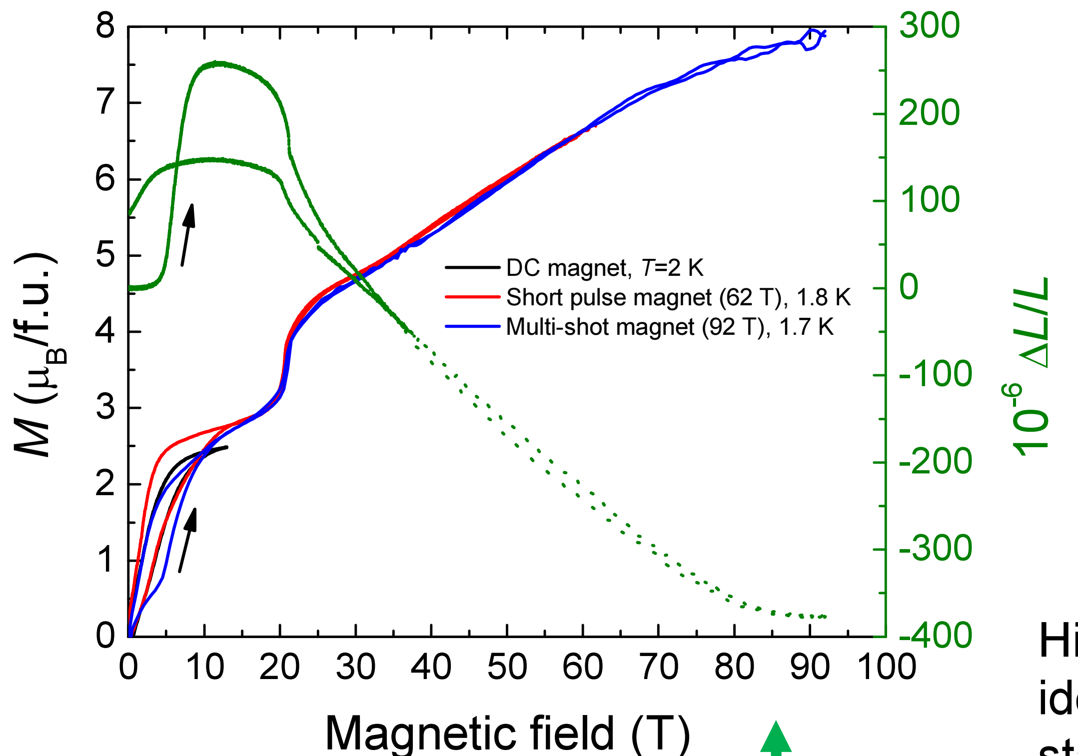
100T Multi-sample probe March 12



User Support Program at Los Alamos

Determining the spin state in technologically –relevant multiferroics

Ca_3CoMnO_6 ideally functional material combining ferroelectric and ferromagnetic properties



Mn^{4+} : S = 3/2

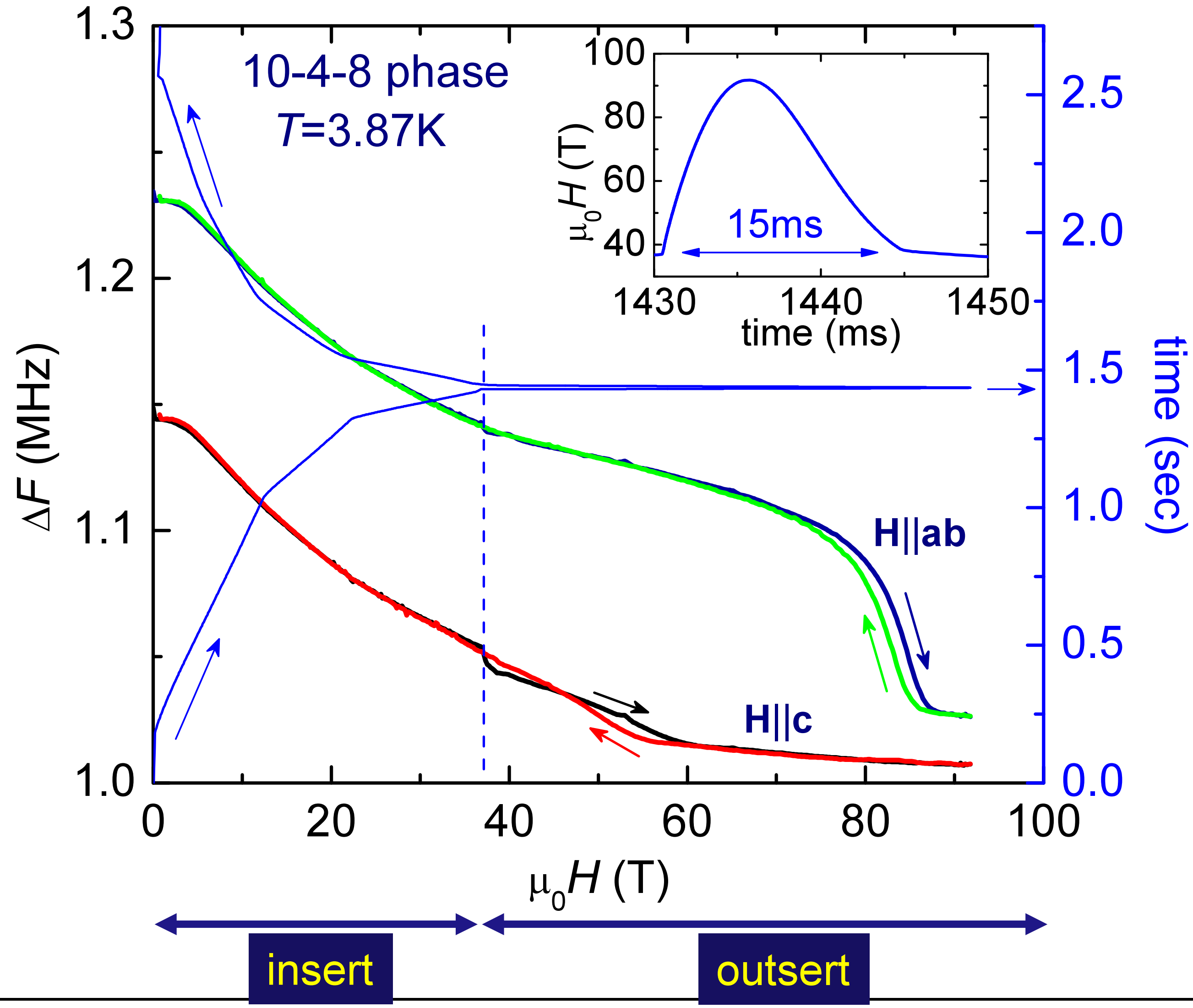
Co^{2+} : S = 3/2 **not S** = 1/2

Saturation near 85 T
Significant Magnetostriction

High field saturation enables identification of relevant Co spin state
i.e. high spin state

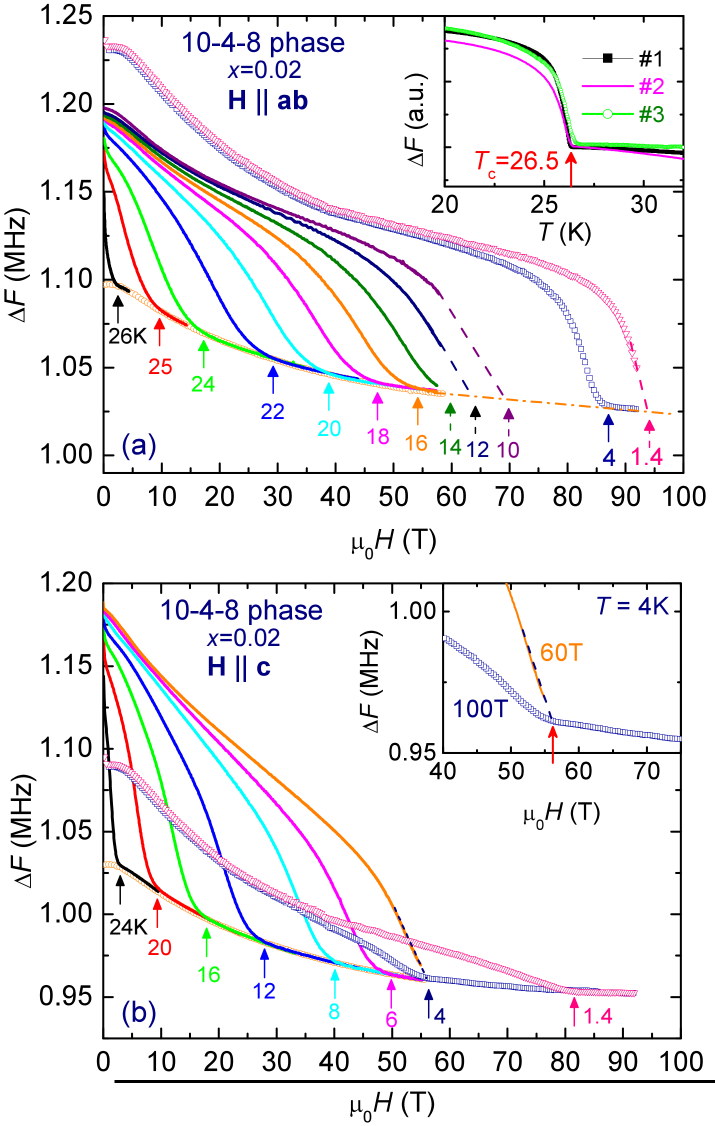
User Support Program at Los Alamos

TDO(Tunnel Diode Oscillator) and **PDO**(Proximity Detector Oscillator)

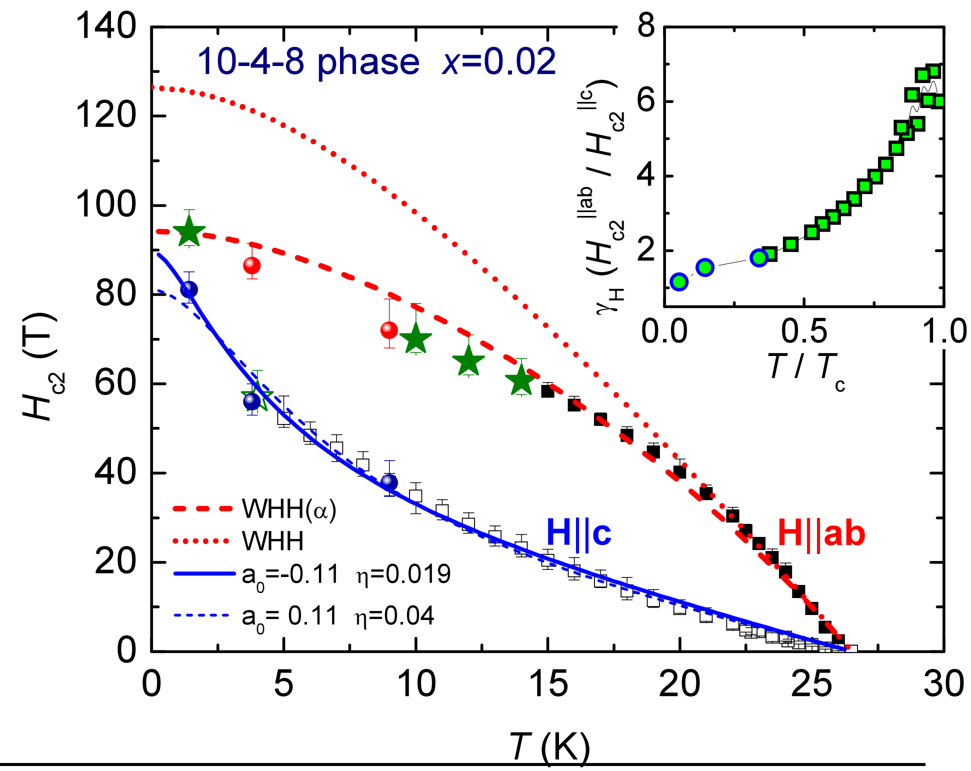


User Support Program at Los Alamos

TDO(Tunnel Diode Oscillator) and **PDO**(Proximity Detector Oscillator)
radio frequency (rf) contactless penetration depth : resistivity + magnetic susceptibilty

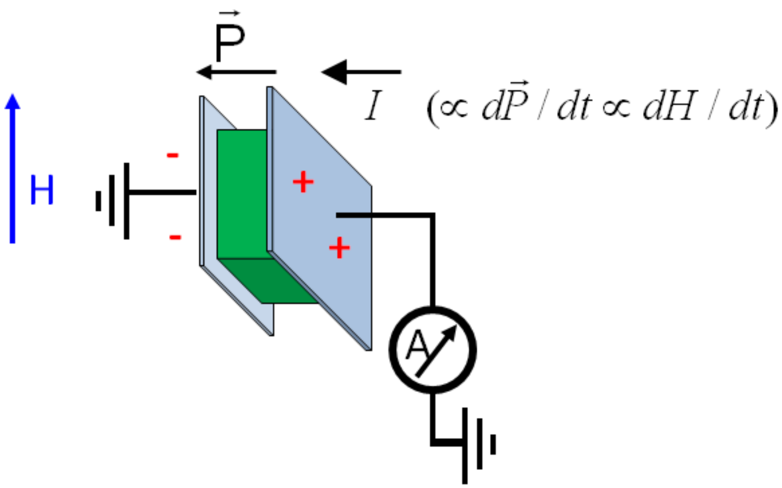


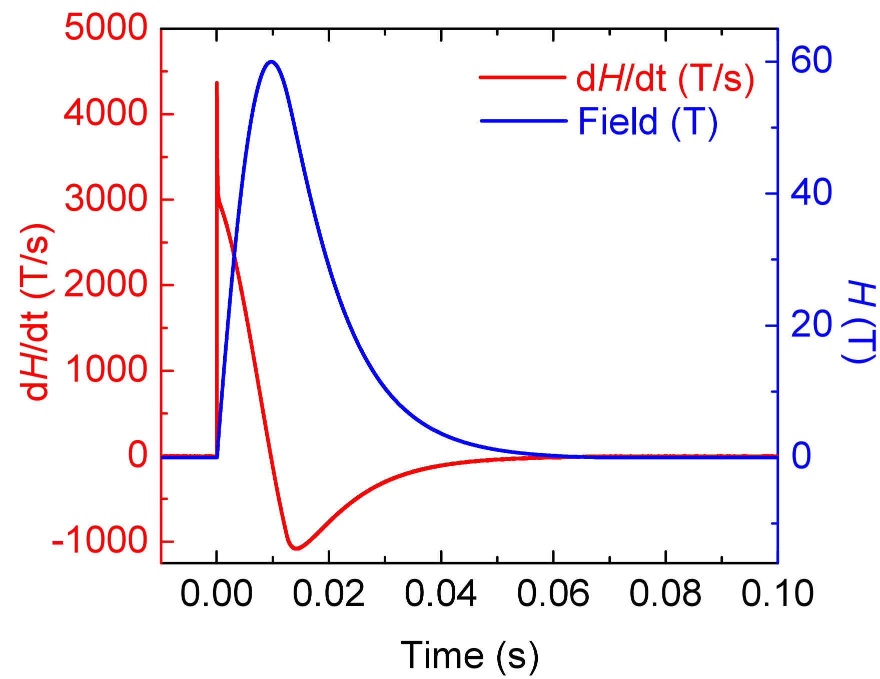
H-T phase diagram (H_{c2})
3 days measurements



User Support Program at Los Alamos

Pulsed-field measurements of the electric polarization (pyroelectric current)



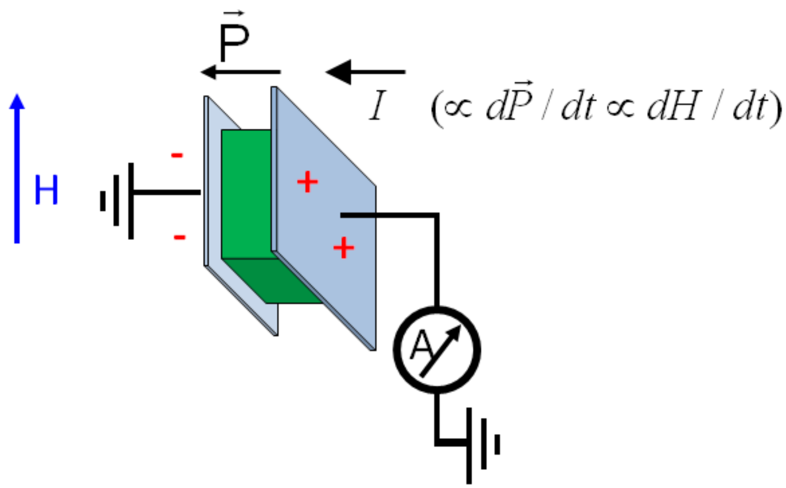


P(*H*) up to 65 T (95 T)

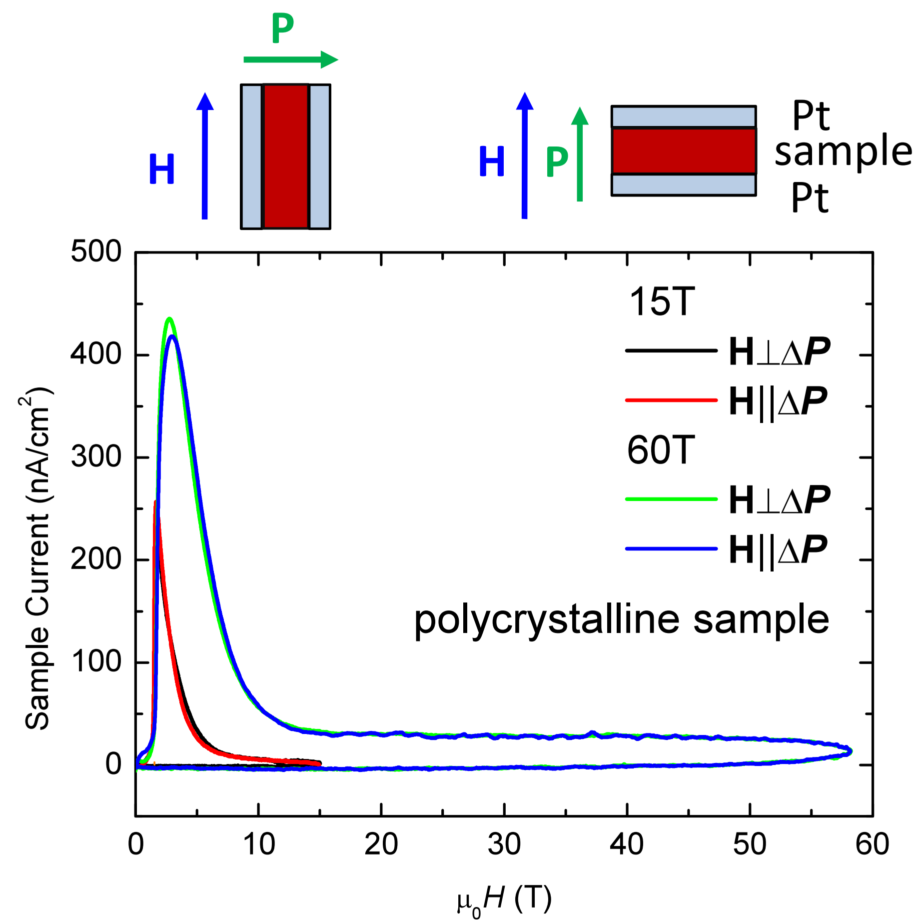
Sub pC/cm² resolution : $\frac{\mathrm{d}P}{\mathrm{dt}} \propto \frac{\mathrm{d}H}{\mathrm{dt}}$

User Support Program at Los Alamos

Pulsed-field measurements of the electric polarization (pyroelectric current)



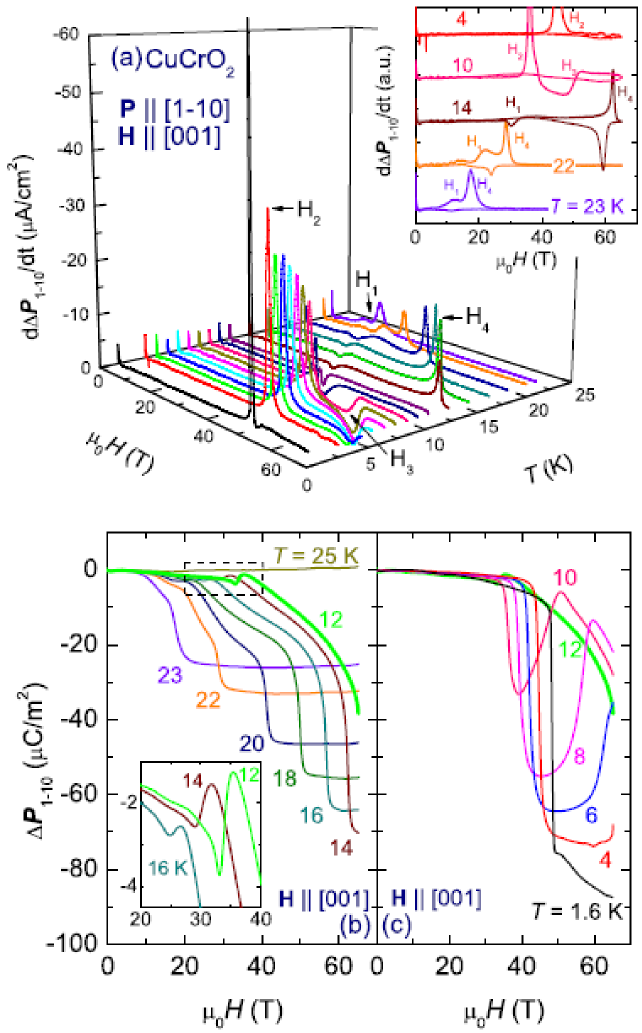
dB/dt contribution? open loop?



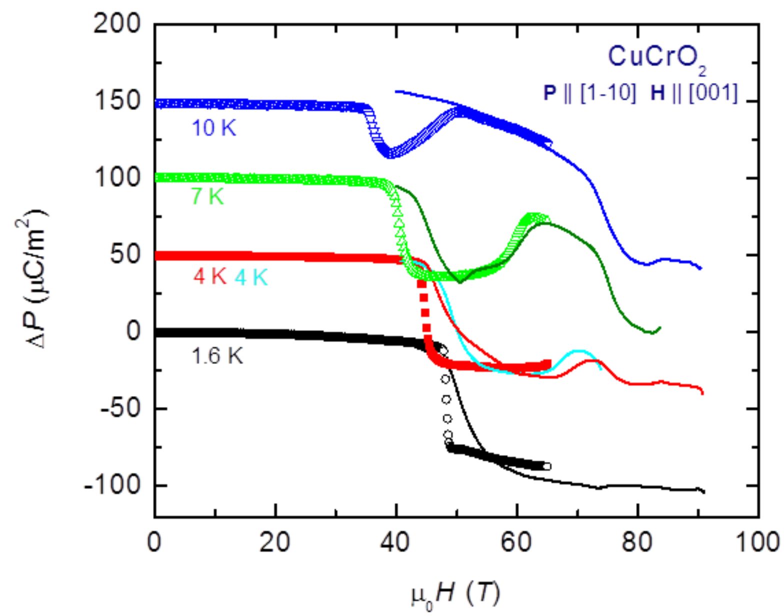
Magnetocaloric effect : intrinsic, heating and cooling

User Support Program at Los Alamos

Pulsed-field measurements of the electric polarization (pyroelectric current)



Triangular lattice antiferromagnet $CuCrO_2$



65 T : routine measurements

Very good signal to noise ratio

100 T : available

not super clean data, but capturing important physics