Pulsed Magnetic Fields

Physics 590B

Eundeok Mun
Magnet User Facilities

- Dresden, Germany
- Toulouse, France
- ISSP Kashiwa, Japan
- Nijmegen, Holland
- Tsukuba, Japan
- Grenoble, Switzerland
- Hefei, China
- USA
- Pulsed
- Resistive

NATURAL HIGH MAGNETIC FIELD LABORATORY

USA

Resistive

Pulsed

Resistive

Pulsed

Resistive

Pulsed

Resistive

Pulsed

Pulsed

Pulsed

Pulsed

Resistive
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

Funded by the NSF
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 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...
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.
Electromagnets

Strength of electromagnets: \( H = \mu n I \)

- \( n \): number of turns in a coil
- \( I \): amount of current in the coil

Permeability 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
- MRI machines for imaging
- Electromagnets actuate windows, locks, etc.
- Hard drives
- Airport security
- Magnetic pulse-echo
- 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

\[ B = \mu n I \]

\( \mu = 4\pi \times 10^{-7} \text{ NA}^{-2} \)
\( n = \text{turns/length} \)
\( I = \text{current} \)

10 T magnetic field: 100 turns \( \times \) 8,000 Amps / 0.1 m

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

- Joule’s (heating) Law: \( Q = I^2 R t \sim 38 \text{ MJ for 60 sec} \)
- Temperature \( Q = m C_p \Delta T : \Delta T \sim 664,000 \degree C \)
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 (Nb₃Sn) 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

Holes are for water cooling
Staggered pattern maximizes strength

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

World record: 35 Tesla
NHMFL, Tallahassee, FL

Francis Bitter

Invented the Bitter plate used in resistive magnets
Magnets: Resistive Magnet

The world's 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: \( Q = I^2 R t \sim 19 \text{ kJ for 0.03 sec} \)
- Temperature: \( Q = m C_p \Delta T \sim 332 \text{ K} \)
Magnets: Pulsed Magnets

0.6 MJ of energy

\( \frac{dB}{dt} \propto \text{Charge voltage} \)

Max Field \( \propto \text{Charge voltage} \)

Pulse length \( \propto \)

Magnet Inductance

Circuit Resistance

50-75 tesla

25-250 msec
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 (LN₂ cooling)
Magnets: 60 T / 65 T Short Pulse

Limit: strong electromagnets generate big forces

\[
\vec{F} = q\vec{v} \times \vec{B}
\]

Hendrik Antoon Lorentz

Pressure under water:
- ears: 4m, 0.3kPa
- submarine: 600m, 50kPa
- ocean floor: 3600m, 300kPa

Pressure inside electromagnets:
- 80 Tesla pulsed field: ~10000kPa ~ 130 kg/mm² huge!

Huge pressure: more pressure than most materials can handle!
Magnets: 60 T / 65 T Short Pulse

Limit: strong electromagnets generate big forces
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

2 seconds total, 100 ms at 60 T

20 T provides quasi-continuous fields essential for heat capacity, time-resolved spectroscopy, reduced eddy currents, etc.
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
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

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: 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

\[ B \times \text{area} \]

\[ V = IR \]

Voltage = area \times dB/dt

\[ \text{Ohms law} \]

\[ \text{EMF} = B \times \text{area} \]
User Support Program at Los Alamos

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

Capacitor Bank-Driven Magnets + $^3$He
60 T / 65 T short pulsed field
300 T Single Turn

Generator-Driven and Multi-Shot Magnets + $^3$He
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 magnetostriction (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
- digital lockin
- piezoelectric magnetometry
- optical strain gauge
100 T experiments

Diverse experimental tools for extreme magnetic fields

- Susceptibility
- Electric polarization
- Pulsed field heat capacity
- In-situ rotation

\[ \frac{d\tilde{P}}{dt} \propto \frac{dH}{dt} \]

\[ \propto \]

\[ \propto \]
100 T experiments

Multiple parallel experiments in record fields

100 tesla probe:
Determining the spin state in technologically relevant multiferroics

$\text{Ca}_3\text{CoMnO}_6$ ideally functional material combining ferroelectric and ferromagnetic properties

$\text{Mn}^{4+} : S = \frac{3}{2}$

$\text{Co}^{2+} : S = \frac{3}{2} \text{ not } S = \frac{1}{2}$

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)

10-4-8 phase
$T=3.87 \text{K}$
User Support Program at Los Alamos

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

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

(a) 10-4-8 phase $x=0.02$ $H \parallel ab$

(b) 10-4-8 phase $x=0.02$ $H \parallel c$

$\mu_0 H (T)$ $\Delta F (MHz)$

$T = 4K$

$26K$ $25$ $24$ $22$ $20$ $18$ $16$ $14$ $12$ $10$ $4$ $1.4$

$26K$ $25$ $24$ $22$ $20$ $18$ $16$ $14$ $12$ $10$ $4$ $1.4$

$100T$ $100T$

$T_c = 26.5$

$T_c = 4K$

$\Delta F (MHz)$ $\mu_0 H (T)$

$WHH(\alpha)$ $WHH$

$\alpha_0 = -0.11 \eta = 0.019$

$\alpha_0 = 0.11 \eta = 0.04$

$H \parallel ab$ $H \parallel c$

$\gamma_H$ $\Delta F (a.u.)$ $T/(T_c)$
Pulsed-field measurements of the electric polarization (pyroelectric current)

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

Sub pC/cm\(^2\) resolution: \( \frac{dP}{dt} \propto \frac{dH}{dt} \)
Pulsed-field measurements of the electric polarization (pyroelectric current)

\[ I \propto \frac{d\overline{P}}{dt} \propto \frac{dH}{dt} \]

Sample Current (nA/cm²)

# 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