Title: Quantum matter in Ultra-high magnetic field: Physics and the extreme machines

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Quantum matter in Ultra-high magnetic field: Physics and the extreme machines

Magnetic fields have become an indispensable tool for science to better understand and manipulate ground states of electronic materials. As magnetic field intensities are increased the quantum nature of these materials become exponentially more likely to be observed and this is but one of the drivers to go further in high magnetic field generation. At Los Alamos National Laboratory, the National High Magnetic Field Laboratory - Pulsed Field facility designs, builds, and operates the most extreme non-destructive magnets in the world. In direct opposition with our efforts are the tremendous electro-mechanical forces exerted on our magnets. Challenges in magnetic field generation and research will be presented. Various method of pulsed high magnetic field generation and experimentation capabilities will be reviewed, including our recent "World Record" for the highest non-destructive magnetic field.

Physics seminar at Wichita State University November 19, 2014
Background
Quantum matter in Ultra-high magnetic field: Physics and the extreme machines

*Extremes of high magnetic fields
*The NHMFL Facilities
*Pulsed magnetic field capabilities
*Research in extremes of high magnetic field
Why High Magnetic Fields?

*Magnetic fields couple to electrons in materials
*Modify energy spectrum
*Externally adjustable
*Reversible parameter

\[ r_c = \frac{m_e v_F}{qB} \]
Why Extreme?

*In order to have a relevant energy scale when compared to intersting interactions in materials

*100 tesla $\sim 134 \text{ K} (-218 \text{ F})$
100 tesla $\sim 2$ million times the Earth's field
Classic Example (superconductor)

$1.5M

21 T
Commerically available
Classic Example
(supercollider)

$15M

45 T
Hybrid Magnet

Field (tesla)
Classic Example (superconductor)

$0.1-2M$

60 T Pulsed Magnet
*Three Sites of the NHMFL
*Tallahassee, FL (DC Field)
*Gainesville, FL (High B/T)
*Los Alamos, NM (Pulsed Field)
NHMFL Headquarters
DC Field Facility
Tallahassee, FL

7 user programs
1400 users
400 employees
$33M/yr
NHMFL-FSU is home of the 45 Tesla Hybrid

* Highest continuous (DC) magnetic field
* 32 MW and 2000 gallons/min cooling required
* Superconducting + Resistive
High B/T Facility (Gainesville)
Pulsed Field Facility

Why Pulsed?
How Do Pulsed Magnets Work?

Adiabatic joule heating during the pulse and subsequently left to cool.

Less power consumption, less expensive cooling infrastructure, but requires fast measurements.

Pulse defined by: \( C, V, L, R_{\text{mag}}, R_{\text{crowbar}} \)

\[
\frac{\partial B}{\partial t} \propto V
\]

Max. field \( \propto V \)

Pulse length \( \propto L/R \)

\[
E = \int \frac{V^2(T,t)}{R(T,t)} \, dt
\]

\[
T = f(t)
\]

Constraints:

\[
\Delta T = \frac{E}{c_v} < (300 - 77)K
\]

Good thermal conductivity

CuNb, CuAg, etc.

It is all about Managing the Compromises
Machines
Safely delivers 600 MJ of energy to 8 metric ton magnets
Failed Magnets are part of the business
Forces are enormous

- 4 GPa at 100 T (simple solenoid magnet)

16,000 x pressure in a car tire
10 x pressure of the chamber of a High Power Rifle
Reduction of stress through distribution

10 MM Bore Insert @ 100 T

High Strength CuNb wire
High Strength Wire
Magnet System

- $\mu_0 H(T)$ graph
- Inset graph showing $H(T)$ over time (sec)
- Diagram showing:
  - $^4$He dewar
  - $N_2$ dewar
  - Insert magnet
  - Outer insert magnet
NHMFL breaks the megagauss barrier, reaches 100.75 tesla pulse

100.75 tesla confirmed via magneto quantum oscillations in poly-crystalline copper. First nondestructive generation of magnetic fields in excess of 100T as a research tool.

This effort represents the culmination of a 15-year project funded by:

*World Record magnetic field intensity for a Non-Destructive Pulsed Magnet (22 March 2012)*
Single Turn Technique

Real time shot to 240 tesla at NHMFL - LANL
Physics
Quantum oscillations and the Fermi surface in an underdoped high-$T_c$ superconductor


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3 Department of Physics and Astronomy, University of British Columbia, Vancouver V6T 1Z4, Canada
4 Canadian Institute for Advanced Research, Toronto M5G 1Z8, Canada

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Higher fields result in higher resolution Fermi Surface cross sections allow better theoretical description of the physics.
Pnictide (intermetallic) Superconductor with $H_{c2}$ near 100 T

Levitating YBCO superconductor
Material is a physical manifestation of a long standing theoretical challenge
Quantum magnetic states similar to stripe order
Field-tuned spin state crystallization in perovskite LaCoO$_3$

Cascade of Magnetic Field Induced Spin Transitions in LaCoO$_3$

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Multiple Magnetic States are driven by magnetic field
Graphene

Wavelength Dependence

Graphene

Control of Fermi Energy
