Challenges and opportunities for Superconductors in High Magnetic Fields

CCA 2021

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**Recent collaborators:** Maxime Leroux,1,1 Christopher Mizzi,1 Fedor Balakirev1, Masashi Miura,2 Jens Haenisch3, & Leonardo Civale1

1 Los Alamos National Laboratory
2 Seikei University, Tokyo Japan
3 Karlsruhe Institute of Technology, Germany
Heike Kamerlingh Onnes proposed & built the first persistent magnet to prove R=0

- It is difficult to measure R=0
- Persistent mode experiment convinced physics community


**RECORD-BREAKING MAGNETS**

A new magnet has reached a field strength of 45.5 tesla, exceeding the maximum strengths achieved so far by other superconducting and resistive magnets.

- Superconducting magnets (lab demonstrations)
- Superconducting magnets (used in applications)
- Resistive magnets
- Hybrid superconducting−resistive magnets
- New cuprate superconductor

American Maglev Technology

SMES
How much do we know about critical currents?

- HTS based coated conductors offer the highest performance
- No data above 45T
- We need $J_c$ measured at higher fields
National High Magnetic Field Laboratory’s Pulsed Field Facility (NHMFL-PFF) offers a variety of tools

New states of matter revealed in Ultra-High Magnetic Fields

The Pulsed Magnet was Engineered and built at LANL

LANL’s 1.43 GW generator can safely deliver a 600 MJ electrical pulse, a key capability giving the US a lead in high magnetic field generation capability.

Very high magnetic fields are essential for revealing the material’s quantum energy states which yield electronic structure and electron mass.

Fiber Grating detects minute length changes from the magnetic ordering.

Marcelo Jaime & Scott Crooker (LANL) have developed an optical technique to sense the "magnetostriction" of a magnetic material.
Measurements in pulsed field: ‘standard’, long and duplex magnets

- 65T pulsed magnetic field our ‘standard’
- \( J\perp H \) (maximum Lorentz force configuration)
- \( \rho(H) \) measured by AC (~100 kHz)
- Measurement in \(^4\text{He}\) and \(^3\text{He}\)

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

Large \( \text{d}H/\text{dt} \) prevents use of metallic components
Measurements in pulsed field: ‘standard’, long and duplex magnets

- 65T pulsed magnetic field. **77T NEW DUPLEX**
- \( J \perp H \) (maximum Lorentz force configuration)
- \( \rho(H) \) measured by AC (~100 kHz)
- Measurement in \(^4\text{He}\) and \(^3\text{He}\)

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

Large \( dH/dt \) prevents use of metallic components

**DUPLEX MAGNET**

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**STANDARD’ MAGNET**

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Invited presentation MS-6 was given at the virtual CCA 2021, October 11-15, 2021.
Measurements in pulsed field: ‘standard’, long and duplex magnets

- 65T pulsed magnetic field. **New long pulse magnet**
- \( J \perp H \) (maximum Lorentz force configuration)
- \( \rho(H) \) measured by AC (~100 kHz)
- Measurement in \(^4\text{He} \) and \(^3\text{He} \)

Large \( dH/dt \) prevents use of metallic components
Angular dependent resistivity measurement set-up in high pulsed magnetic fields in thin films

- $J \perp H$
- $\rho(H)$ measured by ac (100 kHz)
- Also measured $\rho$ vs $T$ in DC-field

- Field vs Time graph
- Angular resolution $\sim 0.2^\circ$
Single band: $H_{c2}(\Theta)$ dependence follows single anisotropy with $\gamma \sim 5$

- Samples of with different additions and growth methods follow similar angular dependence
- Small decrease in $\gamma$ is observed with respect to YBCO
- In single band superconductor $\gamma_H = H_{c2}(||ab)/H_{c2}(||c) = (m_c/m_{ab})^{1/2}$

![Diagram showing angular dependence and fit data for different samples.](image)

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Los Alamos National Laboratory

Invited presentation MS-6 was given at the virtual CCA 2021, October 11-15, 2021.

B. Maiorov (maiorov@lanl.gov)
Determination of critical current in superconductors

- Increasing current until dissipation shows
- Critical current set by a criterion (~1µV/cm)
- Dissipation grows rapidly, danger of destroying sample if current not stopped
- Typical measurement several seconds

\[
V = (I/I_c)^N
\]

![Diagram](image.png)
Critical current measurements can be done up to the highest fields available in pulsed fields

- Samples patterned in a meander
- 5cm effective length, field compensated
- YBCO and YBCO+BaHfO$_3$ nanoparticles
- We started by taking data only at peak field to reduce possible detrimental $dH/dt$ effects
- Compared with data taken in DC fields
- Optimization of integration time
- **New design** with better field compensation
- Shorter meander:
  - Less chances of bad spot
  - Lower impedance = no peak in V nor slope
- Lower background = better signal/noise relation

![YBCO+3BHO Significant Meander](image)

Current – Voltage curves are reproducible and agree with $J_c$ values in DC fields

- V-Is do not depend on current step size or integration time
- V-I are reproducible
- Results agree with DC measurements
- Some deviation at low $E - J$

Critical currents measured in DC and pulsed fields agree in values and field dependence

- Data at low fields agrees with DC fields (small shift due to thermometry)
- IV curves taken up to $H_{irr}$
- $J_c$ shows continuation of power law
- Rapid decrease near $H_{irr}$

The shape of Voltage-Current curves changes at higher $dH/dt$

- Two regimes are observed
- Higher E-J back to non-linear
- Linear regime in J increases with $dH/dt$ almost linearly
- Higher $dH/dt$ is detrimental for $J_c$ measurements
Voltage-Current curve shape changes with higher \( dH/dt \): Two different regimes

- DC field, uniform current, movement due to current induced force
- Pulse: Fast enter/exit (diffusion time \( \propto 1/H \) ) \( V = 0 \)
- Applied Electric field + induced electric field. \( E_J + E_H \); \( E \propto (J/J_c)^\alpha \)

![Diagram showing current and voltage relationships with changes in magnetic field](image)

- Current \( I \)
- Voltage \( V \)
- Magnetic field \( B(x) \)
- Current density \( J(x) \)

**IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.**
Invited presentation MS-6 was given at the virtual CCA 2021, October 11-15, 2021.
Field profile symmetry is broken with large $dH/dt$ and applied DC current

- Symmetric field/current profile with changing magnetic field
- Applied current breaks symmetry: now total current takes into account both
  
  \[ E(x) = E_J + E_{\tilde{H}}(x) \quad (\text{we use } E = E_c(J/J_c)) \]

Integrate $J$ over sample to obtain current

\[ \epsilon = \frac{1}{2} W \tilde{H} \text{ variable} \]

\[ \tilde{J}_H(x) = J_c \left| \frac{E_J - \mu_0 \tilde{H} x}{E_c} \right|^{1/n} \text{sign}(E_J - \mu_0 \tilde{H} x) \tilde{J}_x, \]

\[ I = \frac{dJ_c}{\mu_0 \tilde{H} E_c^{1/n}} \frac{n}{n + 1} \left[ \frac{V}{L} + \frac{\mu_0 \tilde{H}}{2} W^{(n+1)/n} \right] \]

\[ - \left[ \frac{V}{L} - \frac{\mu_0 \tilde{H}}{2} W^{(n+1)/n} \right]. \]

Voltage-Current curve shape changes with higher $dH/dt$: Two different regimes

- Two regimes are observed
- Higher E-J back to non-linear
- Linear regime in $J$ increases with $dH/dt$ almost linearly
- $J_c$ can be extracted from linear term if $dH/dt$ is known

$$R_{\text{eff}} = \frac{L}{W^{1/n} d} \frac{E_c^{1/n}}{J_c} \left( \frac{\mu_0 \dot{H}}{2} \right)^{(n-1)/n}$$

Similarities with AC losses work
Multiples samples of YBCO with different pinning landscapes measured (nanoparticles, nano-rods, point defects...)

- All samples show end of power-law at $T = 4$ K at $\mu_0 H < 60$T
- Working on the correlation between $H_{irr}$ and $H^*$
Experiments up to 65T determine the onset of fluctuations on $J_c$ at low temperatures

- Power law regime in $J_c(H)$ followed by faster decrease dominated by fluctuations
- Sample with self-assembled columnar defects (YBCO+BZO by PLD)
- Collapse of curves with extrapolated melting line
- Field dependences showcase different pinning characteristics
Summary

- $J_c$ measurements are routinely done, and keep improving
- New vortex regimes observed in V-I curves for high $dH/dt$ (share physics with AC-losses)
- $J_c$ measurements show ‘continued’ increased at higher fields
- Onset of fluctuation related to melting line is observable at 65T (YBCO)