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.

Challenges and opportunities for Superconductors in High Magnetic Fields

CCA 2021

Boris Maiorov

Recent collaborators: Maxime Leroux,[1,*] Christopher Mizzi,[1] Fedor Balakirev[1], Masashi Miura,[2] Jens Haenisch[3], & Leonardo Civale[1]

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[3] Karlsruhe Institute of Technology, Germany

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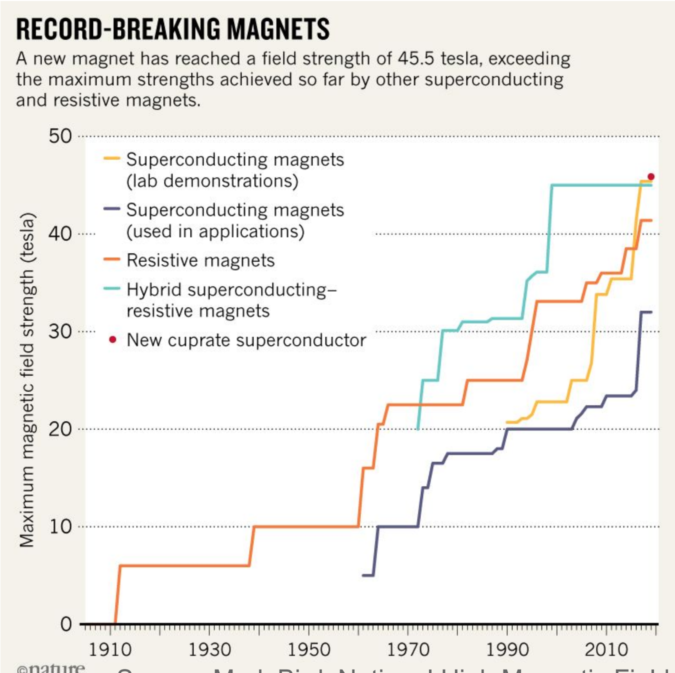
Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

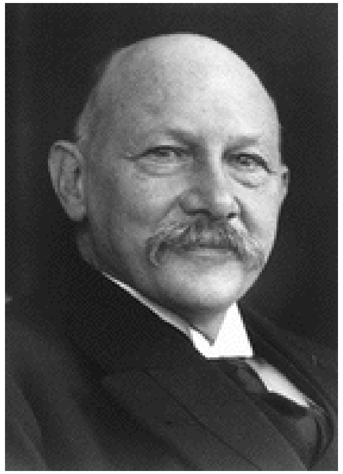
Heike Kamerlingh Onnes proposed & built the first persistent magnet to prove R=0

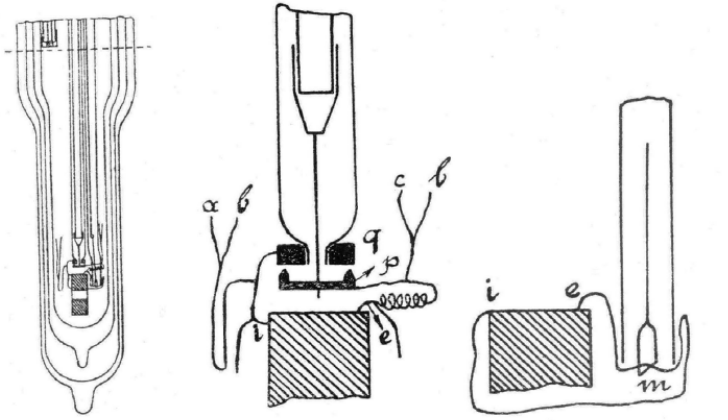
- It is difficult to measure R=0
- Persistent mode experiment convinced physics community

Hahn, S. *et al. Nature* (2019)



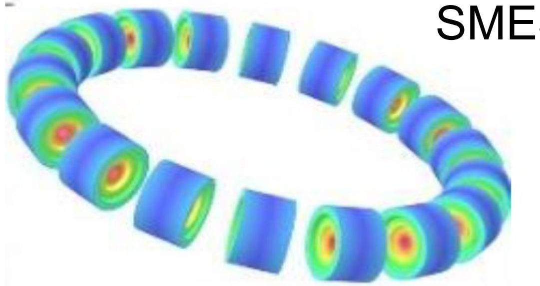
Source: Mark Bird, National High Magnetic Field Laboratory

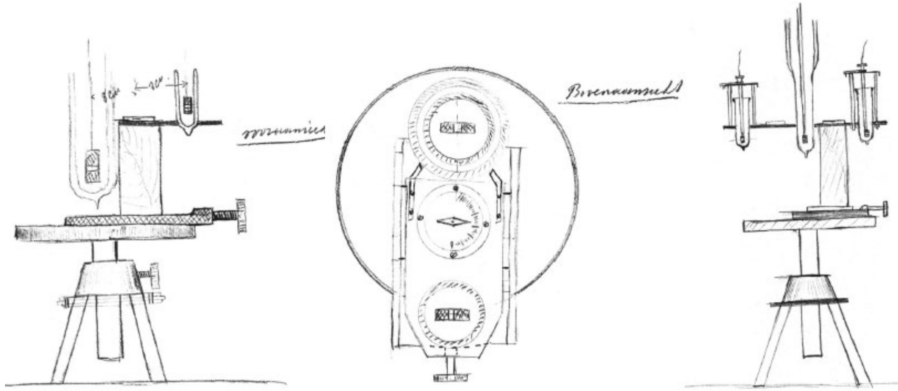




The first (mechanical) persistent mode switch and a cutting device (1914)

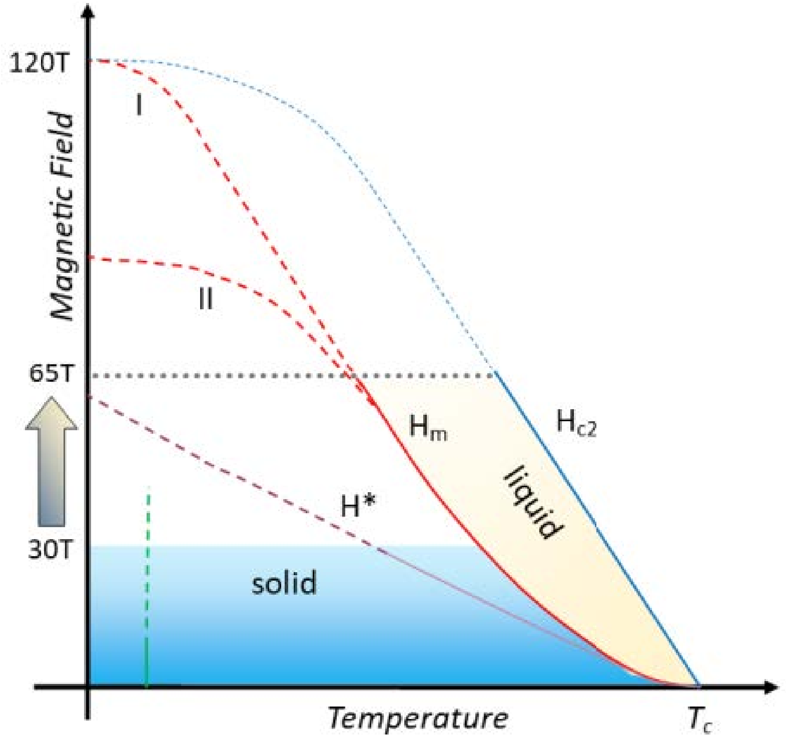
American Maglev Technology
SMES

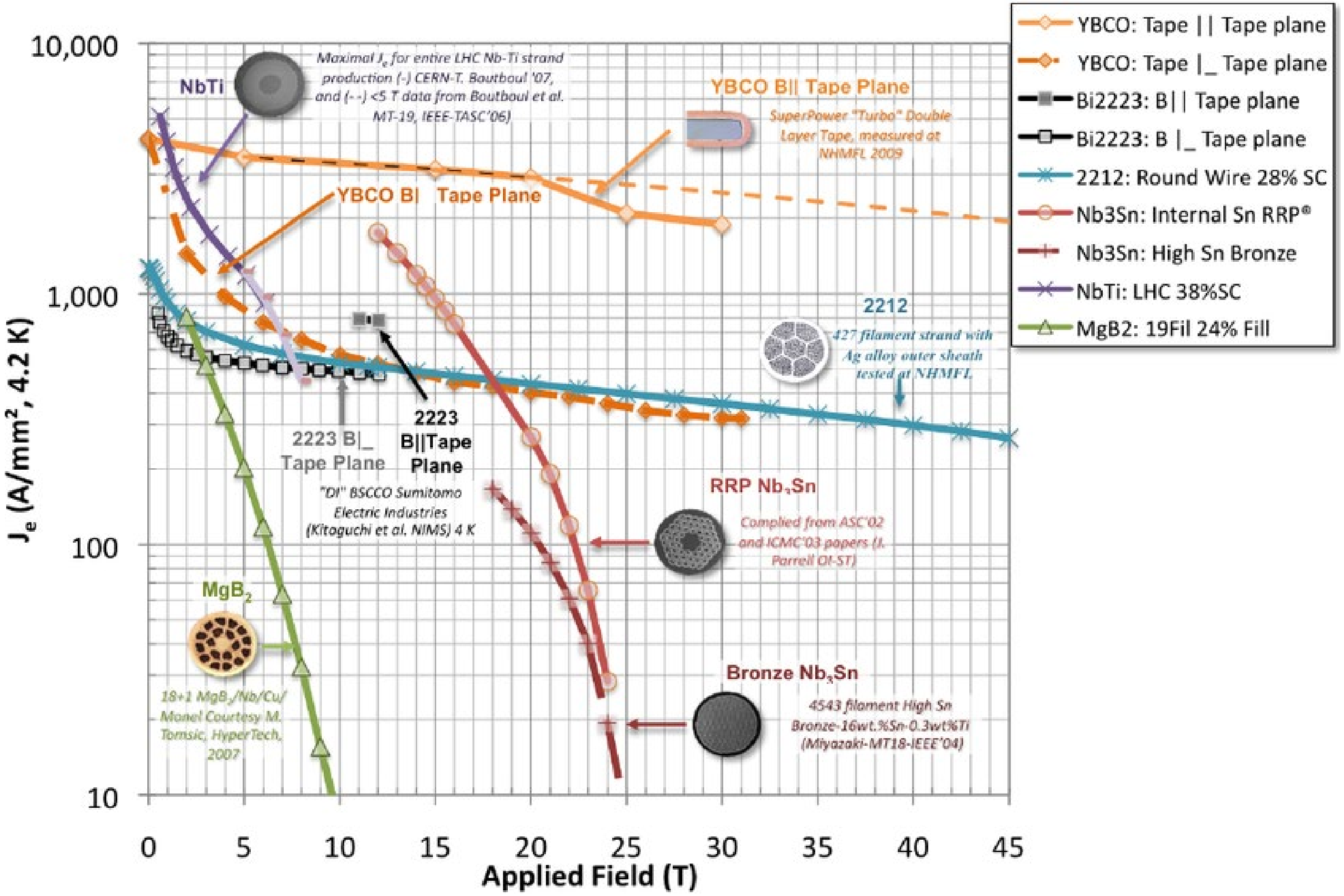




How much do we know about critical currents ?

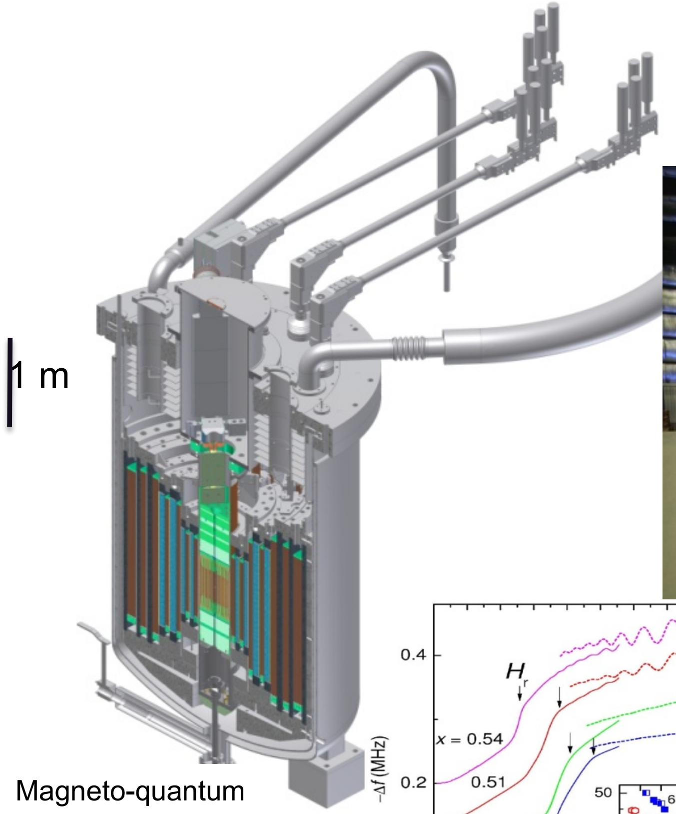
- HTS based coated conductors offer the highest performance
- No data above 45T
- **We need J_c measured at higher fields**



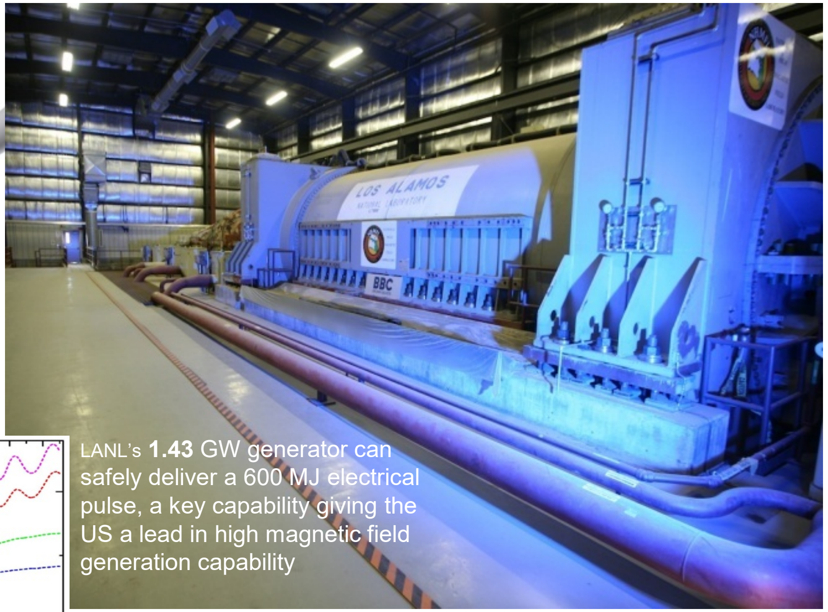


National High Magnetic Field Laboratory's Pulsed Field Facility (NHMFL-PFF) offers a variety of tools

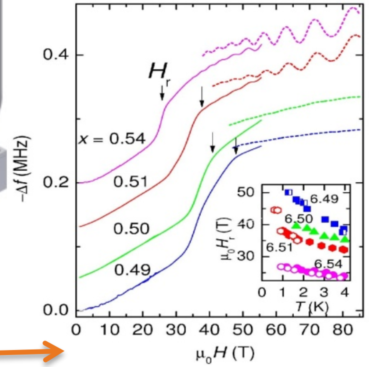
New states of matter revealed in Ultra-High Magnetic Fields



The Pulsed Magnet was Engineered and built at LANL



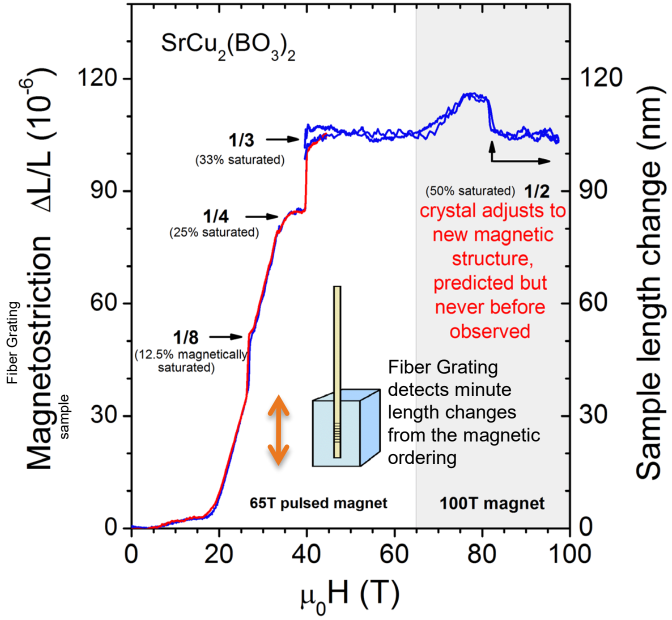
LANL's **1.43** GW generator can safely deliver a 600 MJ electrical pulse, a key capability giving the US a lead in high magnetic field generation capability

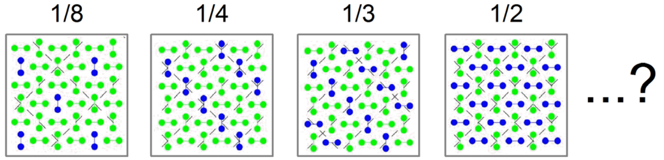


Magneto-quantum oscillations reveal the Fermi surface of materials such as High T_cs and actinides

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

Marcelo Jaime & Scott Crooker (LANL) have developed an optical technique to sense the "magnetostriction" of a magnetic material.



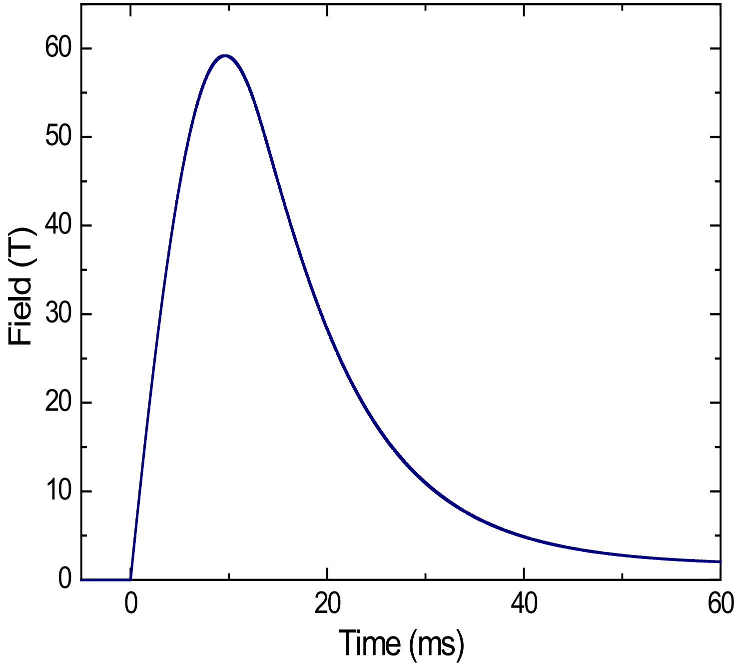


Multiple Magnetic States are driven by magnetic field

Measurements in pulsed field: 'standard', long and duplex magnets

- 65T pulsed magnetic field our 'standard'
- J⊥H (maximum Lorentz force configuration)
- ρ(H) measured by AC (~100 kHz)
- Measurement in ^{4}He and ^{3}He

Pulse defined by: C,V,L, R_{magnet}, $R_{crowbar}$



Large dH/dt prevents use of metallic components

Measurements in pulsed field: ‘standard’, long and duplex magnets

- 65T pulsed magnetic field. **77T NEW DUPLEX**
- J⊥H (maximum Lorentz force configuration)
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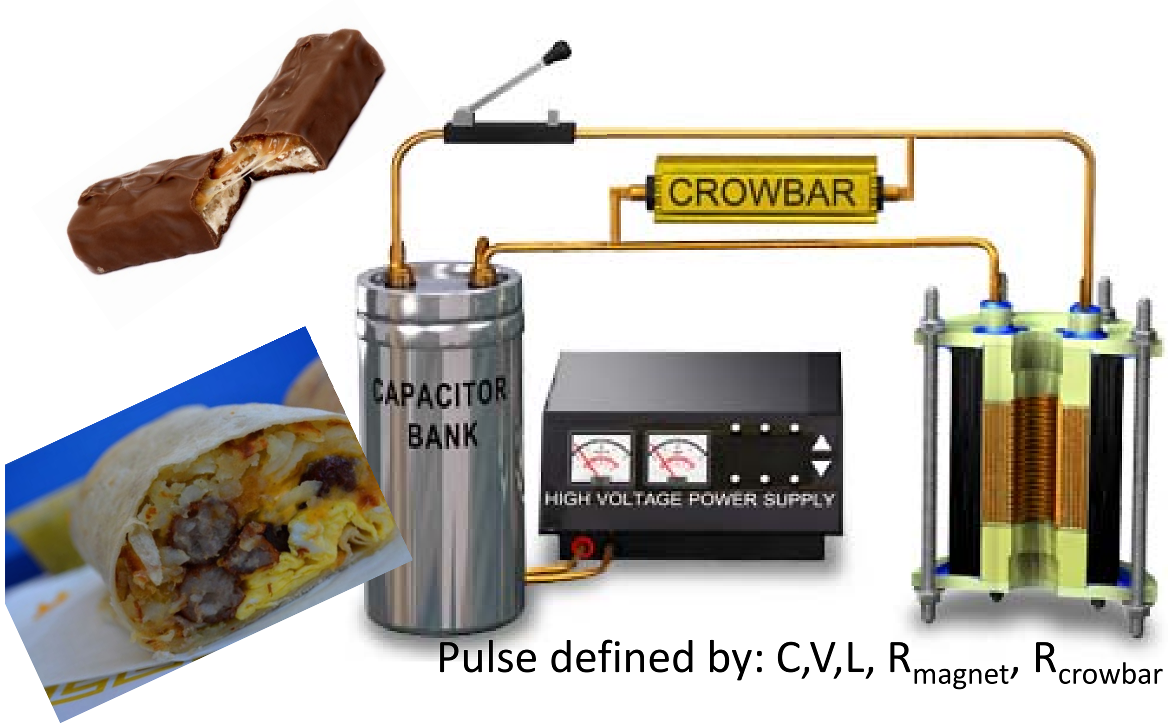
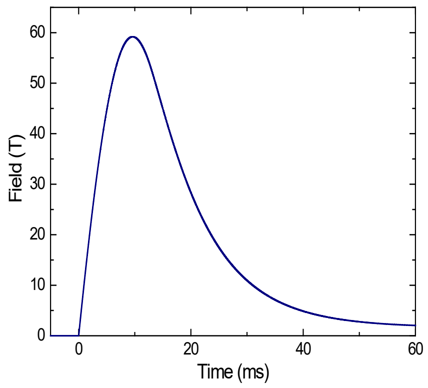
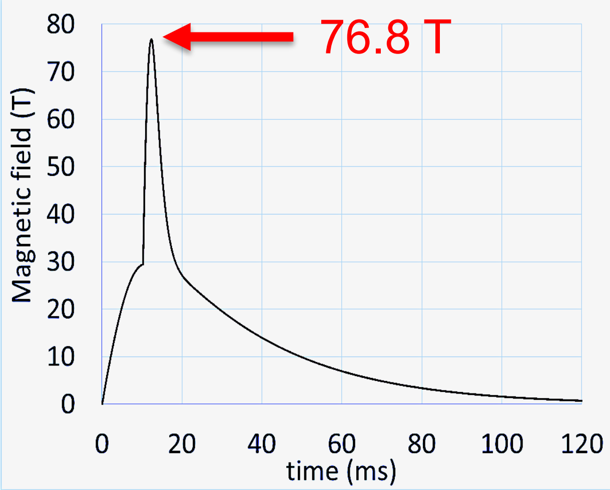


Pulse defined by: C,V,L, R_{magnet}, $R_{crowbar}$

‘STANDARD’ MAGNET



DUPLEX MAGNET



Large dH/dt prevents use of metallic components

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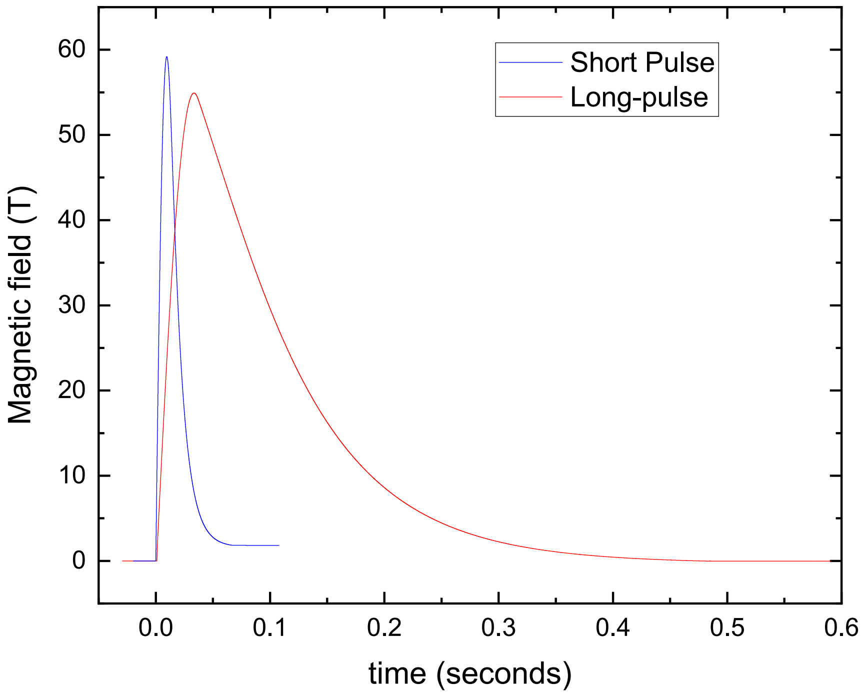
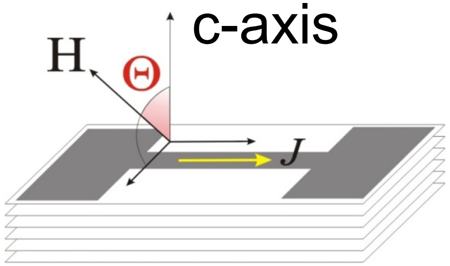
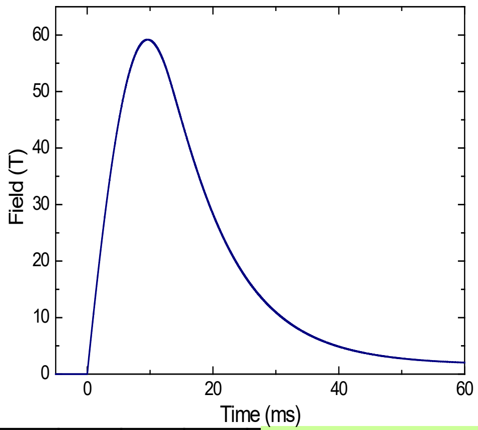


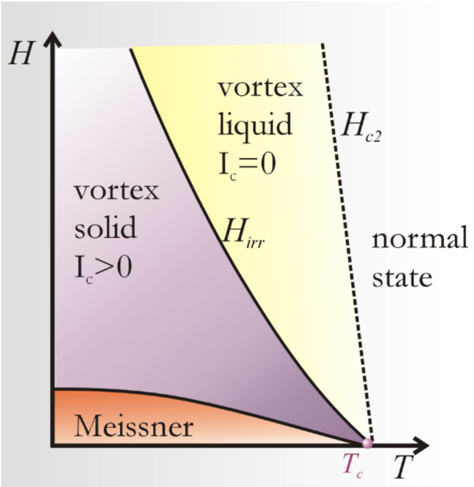
Large dH/dt prevents use of metallic components

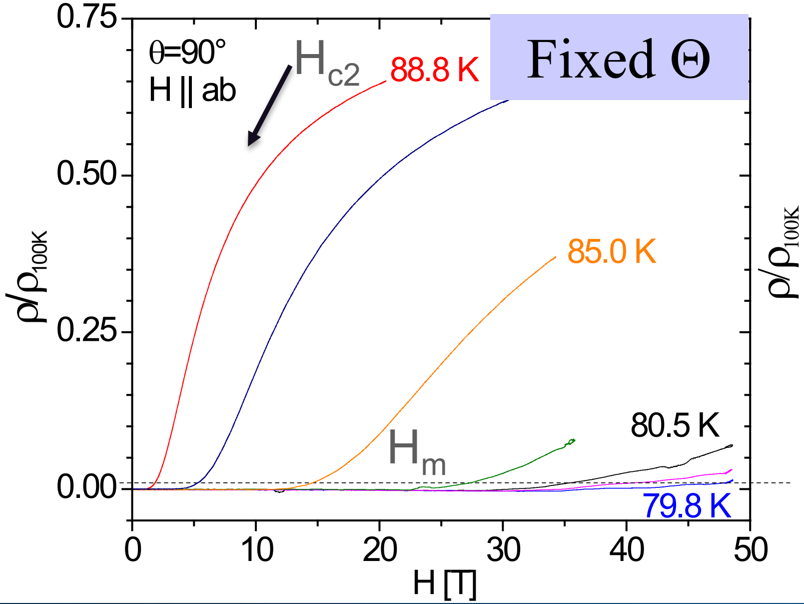
Angular dependent resistivity measurement set-up in high pulsed magnetic fields in thin films

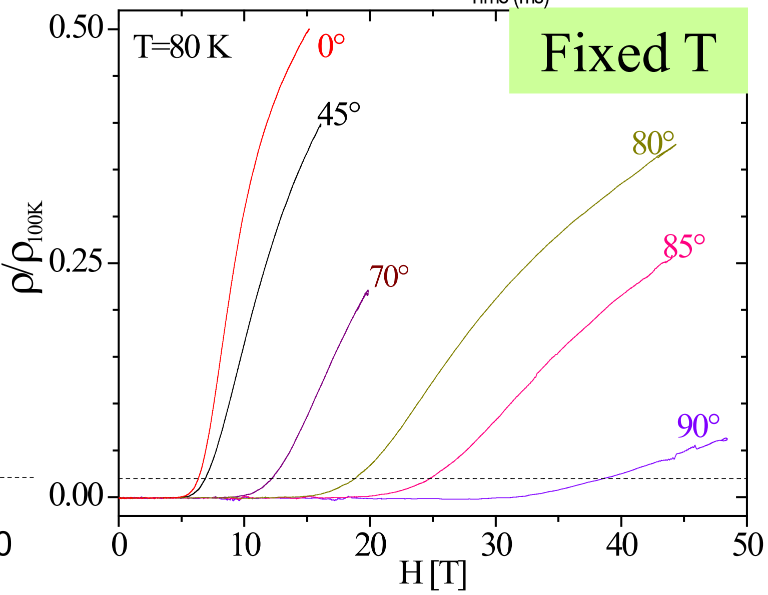


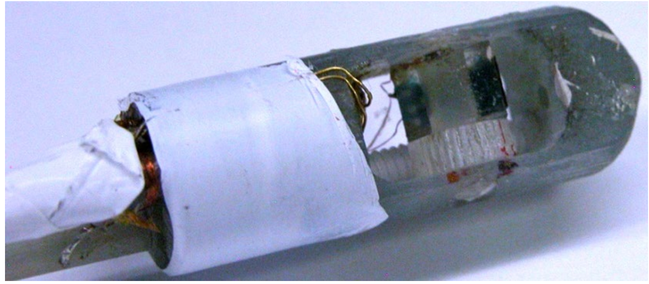
- J ⊥ H
- ρ(H) measured by ac (100 kHz)
- Also measured ρ vs T in DC-field







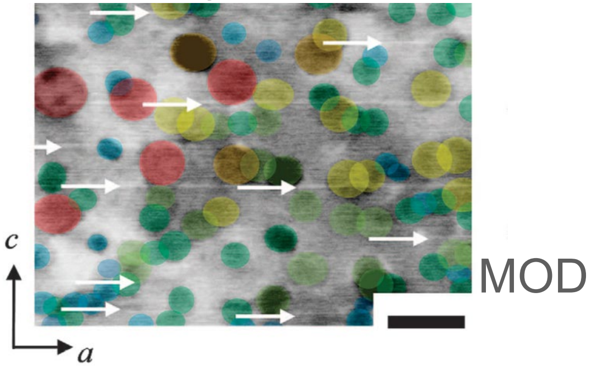


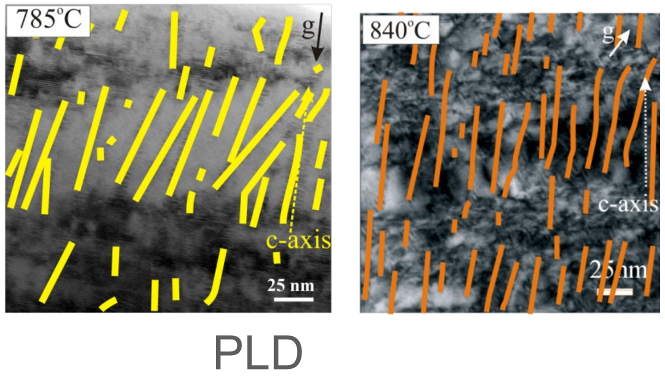


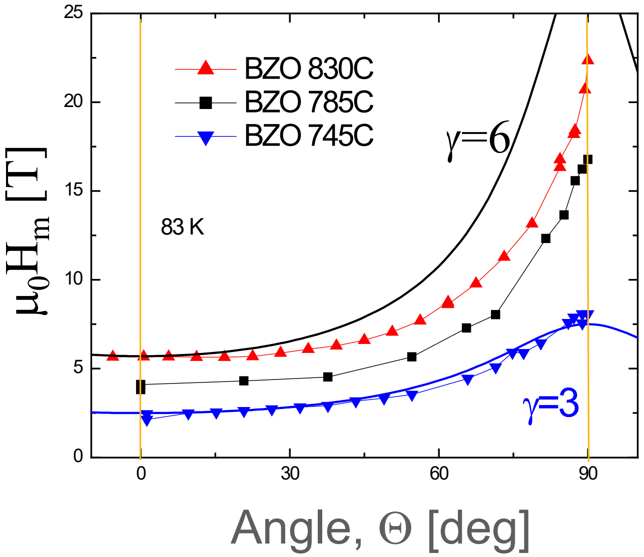
Angular resolution ~0.2°

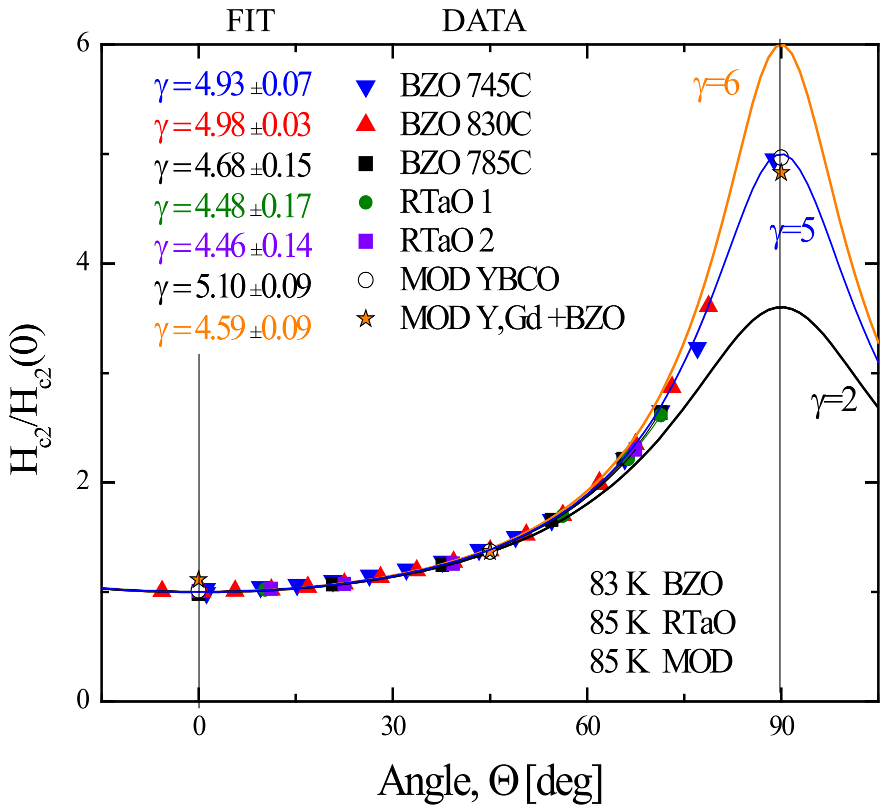
Single band: $H_{c2}(\Theta)$ dependence follows single anisotropy with $\gamma \sim 5$

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



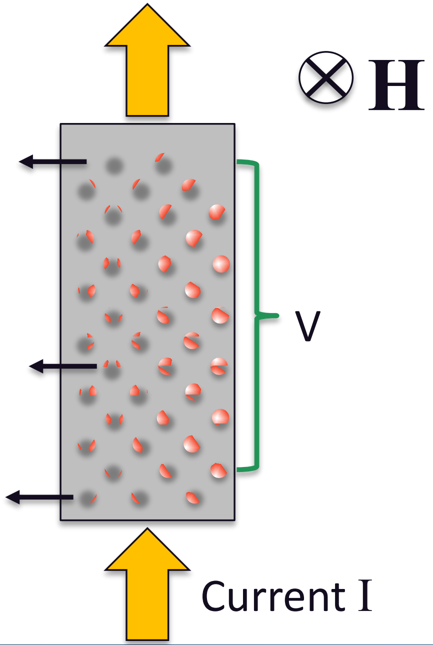


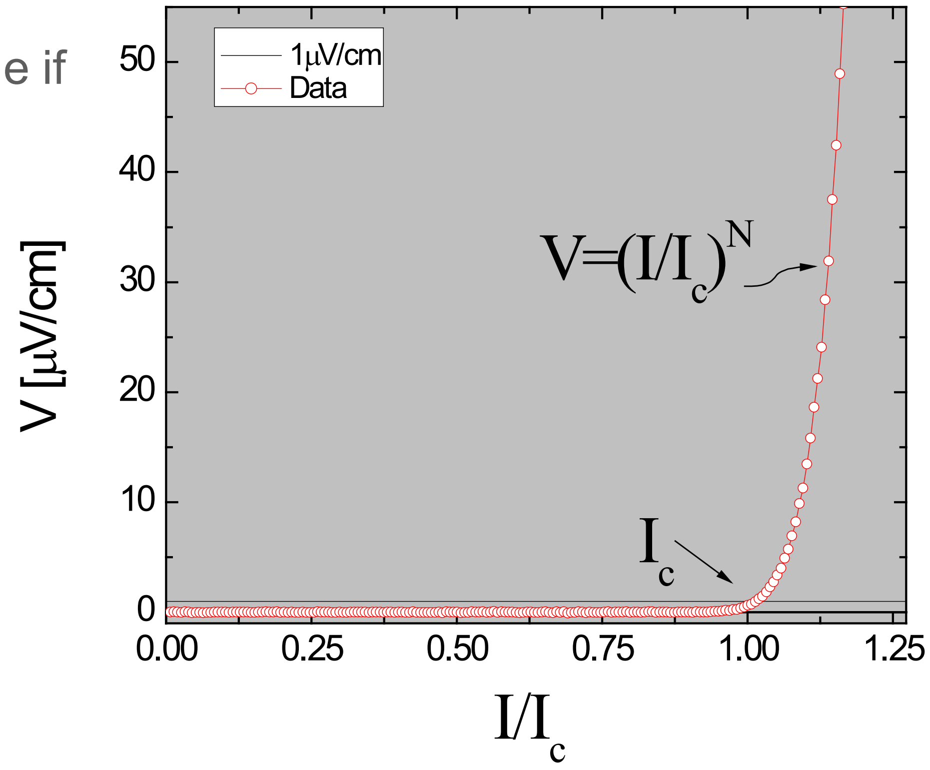




Determination of critical current in superconductors

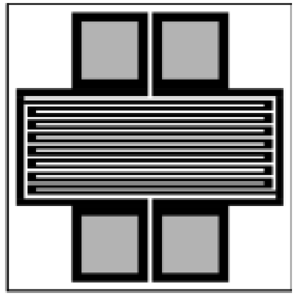
- Increasing current until dissipation shows
- Critical current set by a criterion (~1μV/cm)
- Dissipation grows rapidly, danger of destroying sample if current not stopped
- Typical measurement several seconds

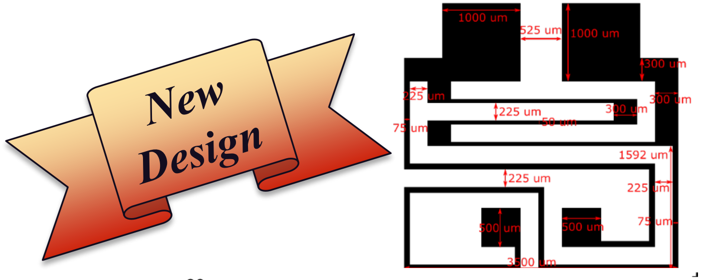


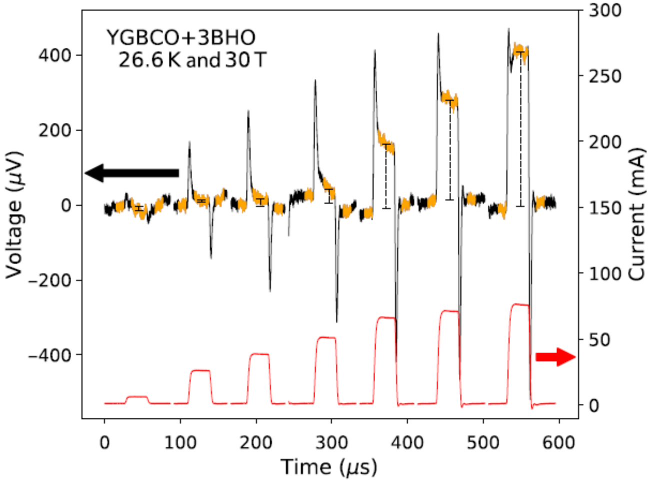


Critical current measurements can be done up to the highest fields available in pulsed fields

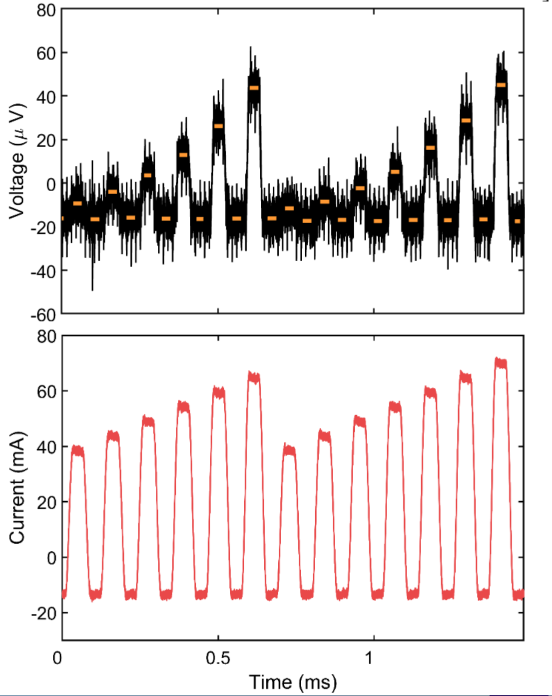
- Samples patterned in a meander
- 5cm effective length, field compensated
- YBCO and YBCO+$BaHfO_3$ nanoparticles
- We started by taking data only at peak field to reduce possible detrimental *dH/dt* effects
- Compared with data taken in DC fields
- Optimization of integration time
- ***New design*** *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







Leroux *et al.*, *Phys. Rev. Appl.* 327, 1631 (2019)



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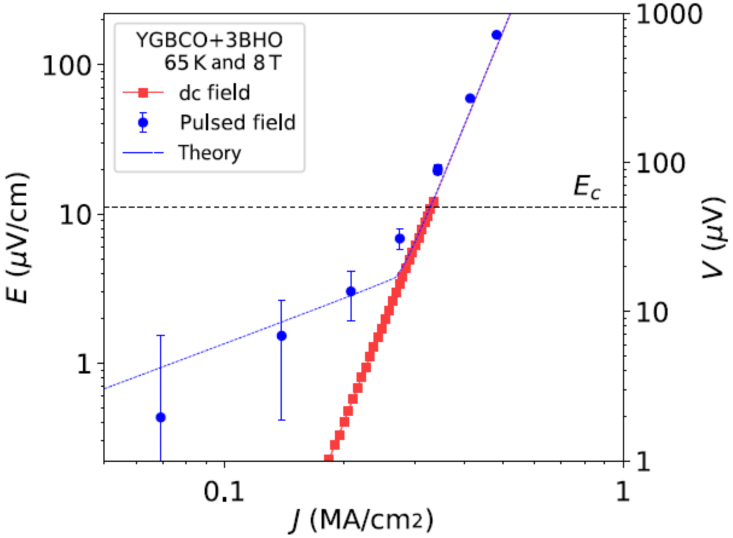
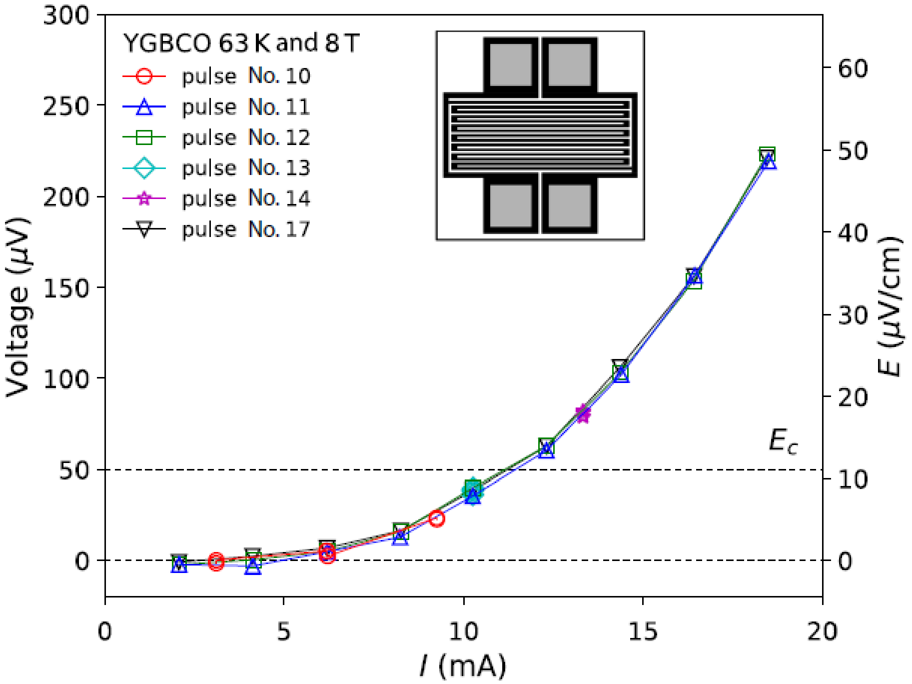
Current – Voltage curves are reproducible and agree with J_c values in DC fields

- 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*

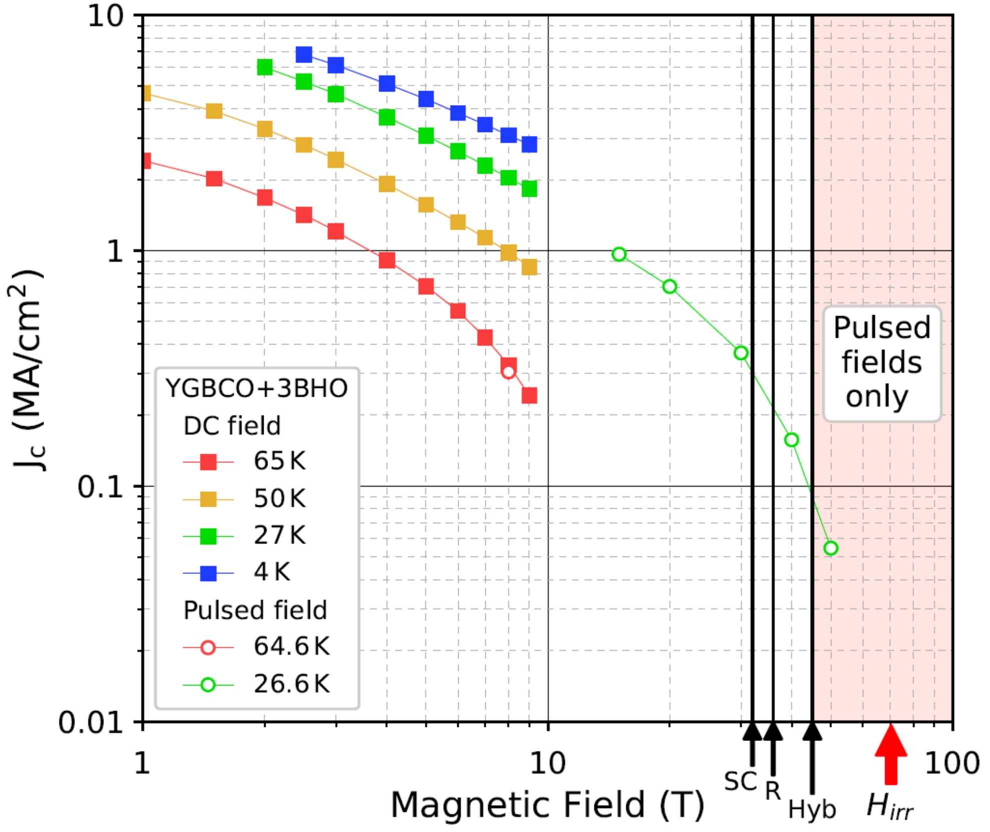




Leroux *et al.*, *Phys. Rev. Appl.* 327, 1631 (2019)

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}

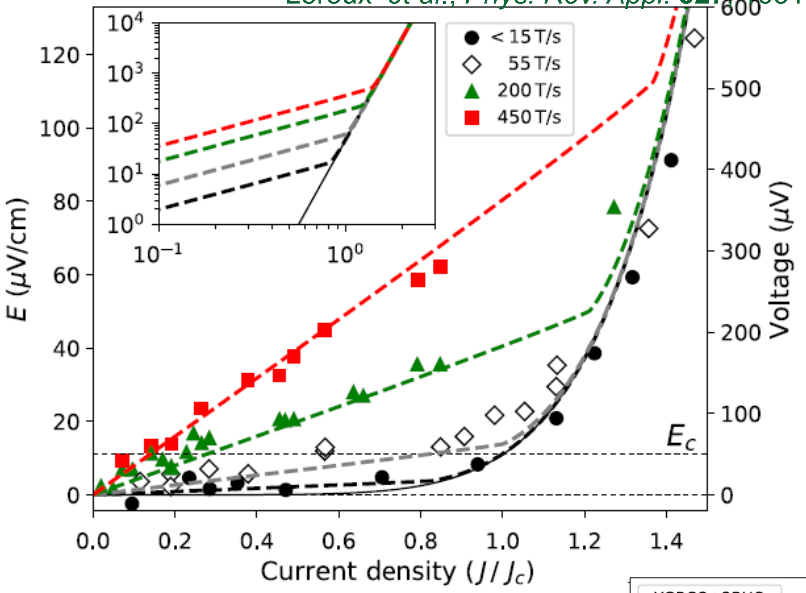


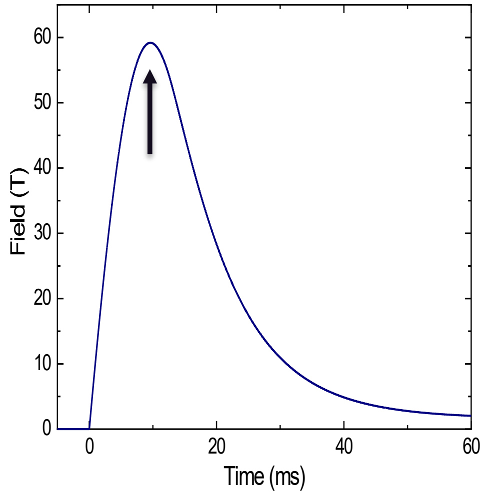
Leroux *et al.*, *Phys. Rev. Appl.* 327, 1631 (2019)

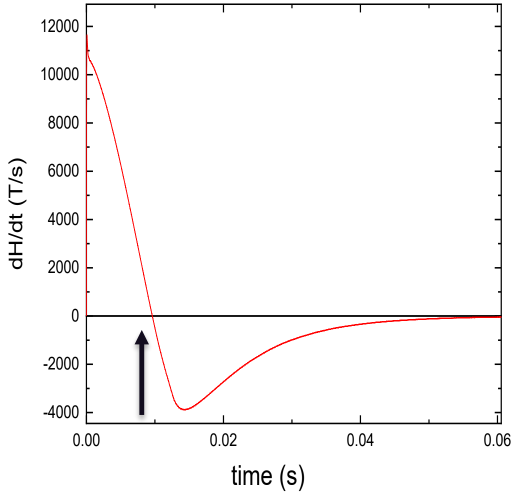
The shape of Voltage-Current curves changes at higher *dH/dt*

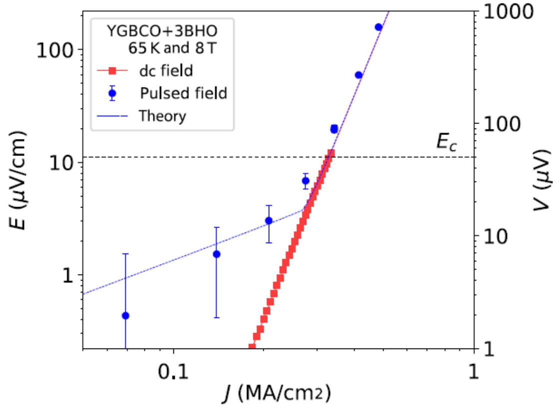
- **Two regimes are observed**
- **Higher E-J back to non-linear**
- **Linear regime in J increases with *dH/dt* almost linearly**
- **Higher *dH/dt* is detrimental for J_c measurements**

Leroux *et al.*, *Phys. Rev. Appl.* **327**, 1631 (2019)



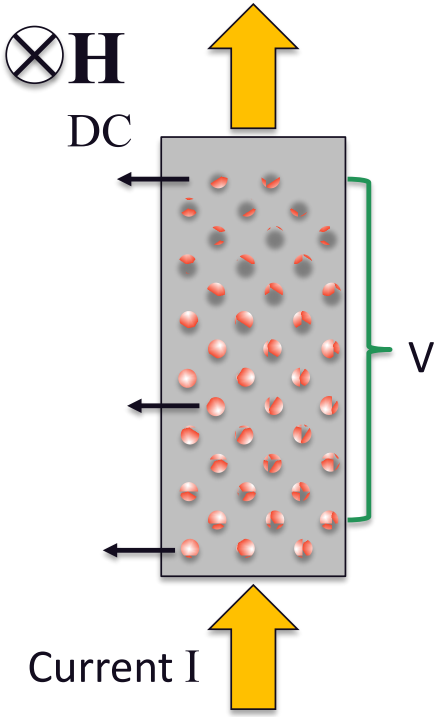


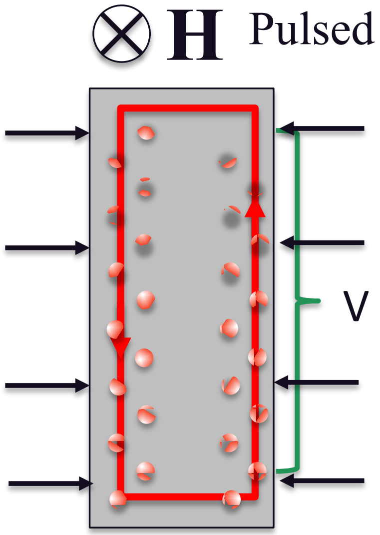




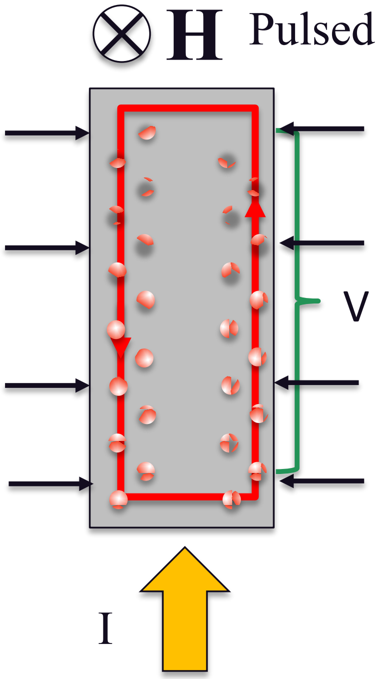
Voltage-Current curve shape changes with higher *dH/dt: Two different regimes*

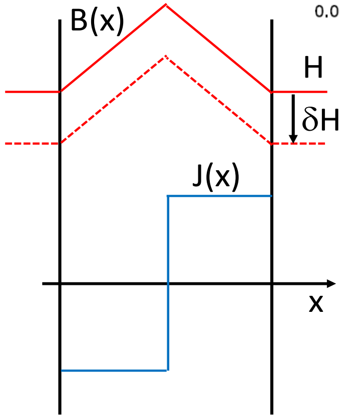
- **DC field, uniform current, movement due to current induced force**
- **Pulse:** Fast enter/exit (diffusion time ∝ $1/\dot{H}$) V = 0
- Applied Electric field + induced electric field. $E_J + E_H$; $E \propto (J/J_c)^{\alpha}$

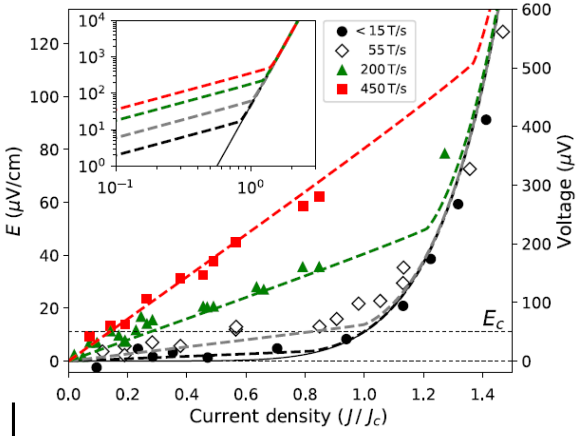




V= 0 same number entering/exiting both sides

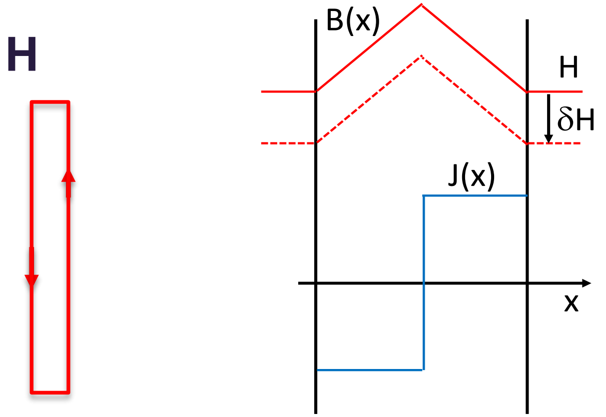






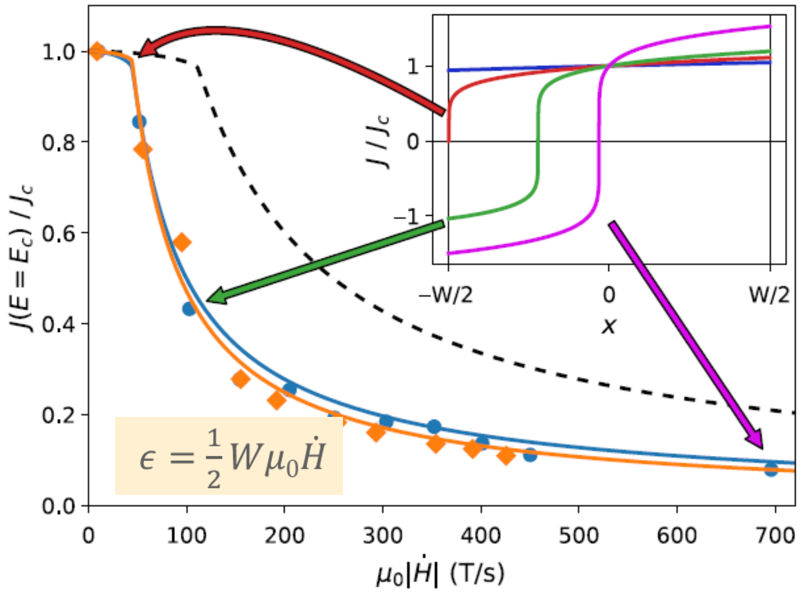
Field profile symmetry is broken with large dH/dt and applied DC current

- **Symmetric field/current profile with changing magnetic field**
- **Applied current breaks symmetry: now total current takes into account both**
- *$E(x) = E_J + E_H(x)$ (we use $E=E_c(J/J_c)$)*
- ***Integrate J over sample to obtain current***
- ***$\epsilon = W\dot{H}$ variable***



$$\vec{J}_{\dot{H}}(x) = J_c \left|\frac{E_J - \mu_0 \dot{H} x}{E_c}\right|^{1/n} \mathrm{sign}(E_J - \mu_0 \dot{H} x)\vec{e}_y,$$

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



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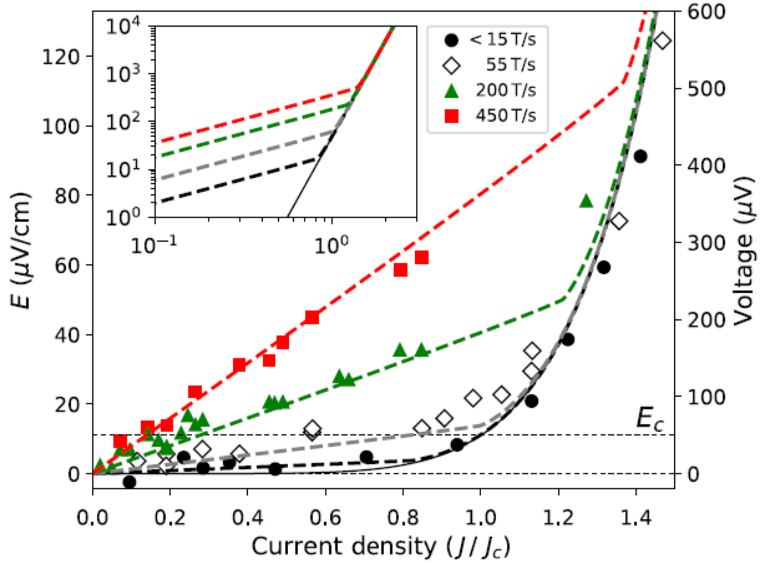
Voltage-Current curve shape changes with higher *dH/dt: Two different regimes*

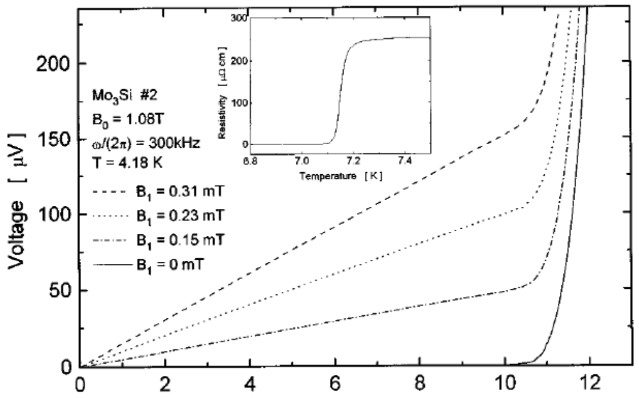
- Two regimes are observed
- Higher E-J back to non-linear
- Linear regime in J increases with *dH/dt* almost linearly
- J_c can be extracted from linear term if dH/dt is known

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



Similarities with AC losses work

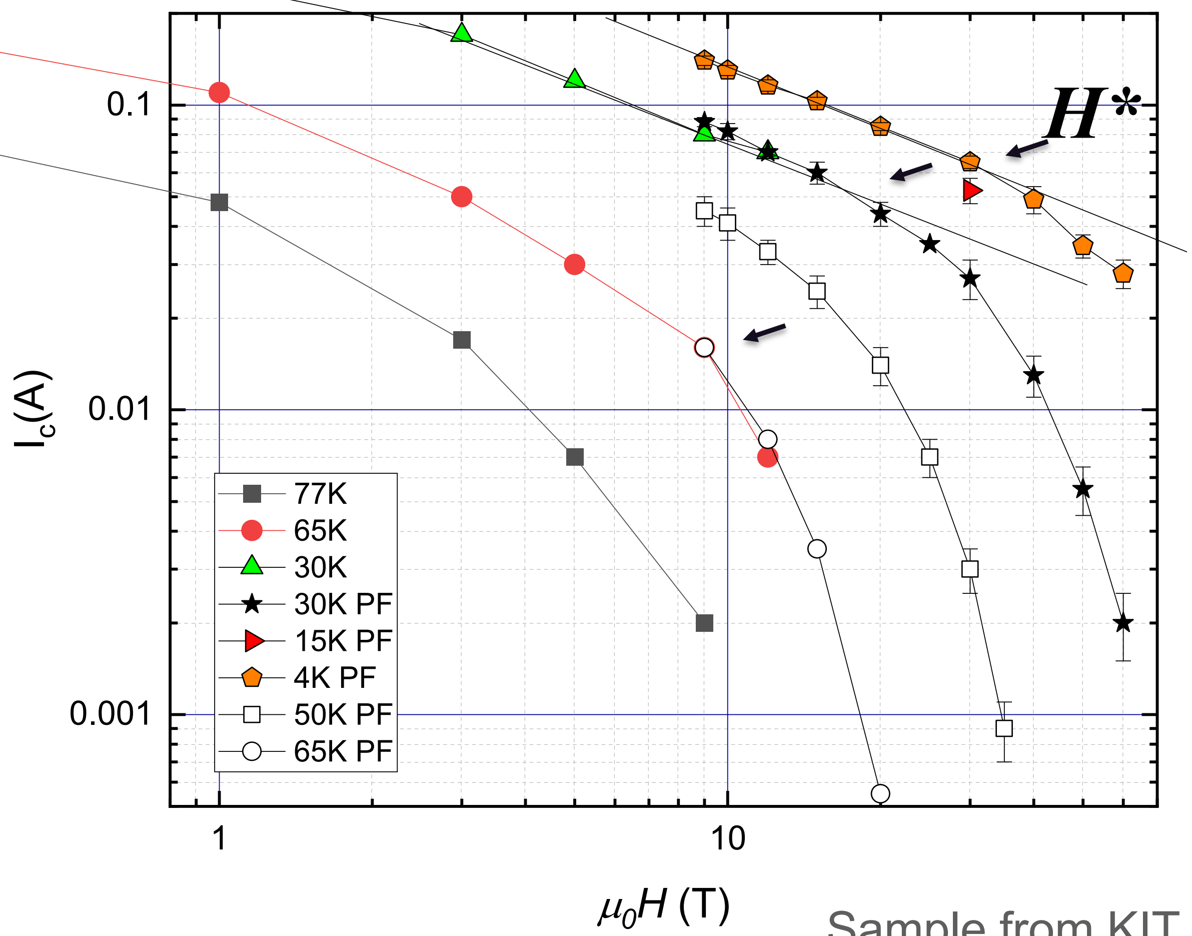
- Brandt & Indenbom, Phys. Rev. B **48**, 12893 (1993)
- Zeldov *et al* films, Phys. Rev. B **49**, 9802 (1994)
- Risse *et al* , Phys. Rev. B **55**, 15191 (1997) (very low pinning)
- Mikitik & Brandt, Phys. Rev. B **64**, 092502 (2001)
- Uksusman *et al,* J. Appl. Phys. **105**, 093921 (2009) (strong pinning)



Risse *et al*

Multiples samples of YBCO with different pinning landscapes measured (nanoparticles, nano-rods, point defects…)

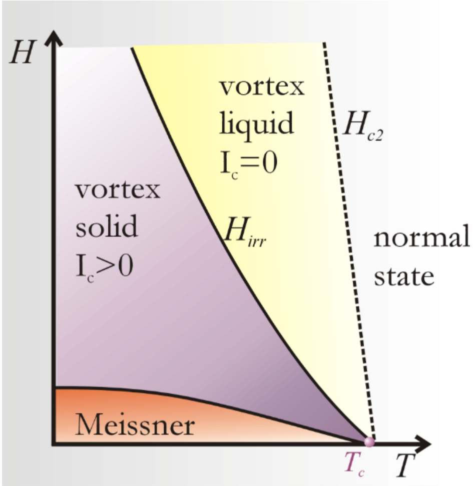
- All samples show end of power-law at $T = 4$ K at $\mu_0 H <$ 60T
- Working on the correlation between H_{irr} and H^*

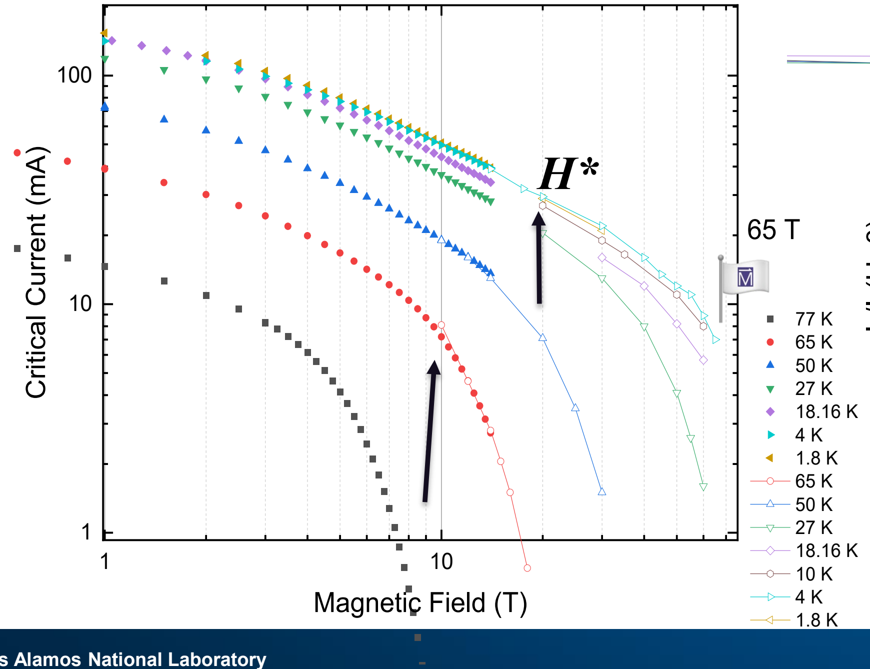


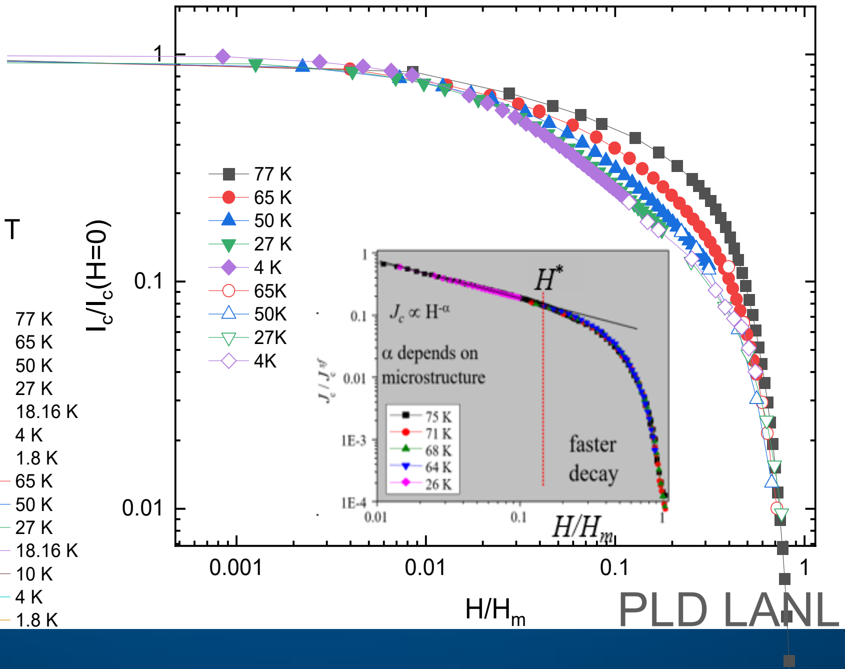
Sample from KIT

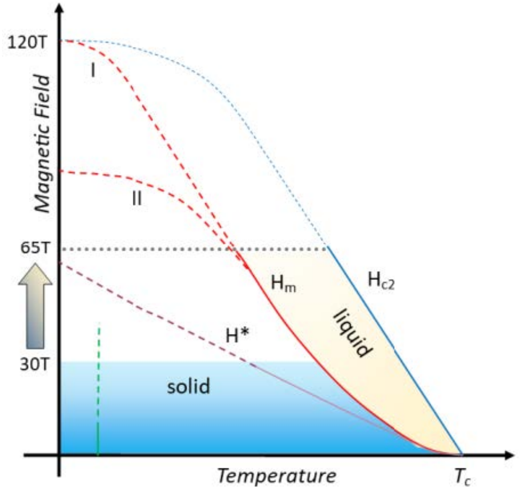
Experiments up to 65T determine the onset of fluctuations on J_c at low temperatures

- 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)