National High MAGNETIC FIELD LABORATORY

Pinning Mechanisms, Lengthwise Fluctuations, and Flux Jumps in REBCO Coated Conductors: A Torque Magnetometry Study up to B = 45 T

Jan Jaroszynski
CMS/DC Field user support

NSF

FSU   UF UNIVERSITY of FLORIDA   Los Alamos NATIONAL LABORATORY

It takes ~10 min to measure Ic vs angle at one B, T

If you are interested we can help:

NHMFL users

- CFS
- NHMFL 40 T
- NHMFL LittleBigCoil
- AMPeers/UT Houston
- HTSI
- SuperPower
- Faraday (as SuperOx)
- Shanghai
- Fujikura
- Tokamak Energy
- Proxima
- UKIFS
- Type One Energy
- and others approaching

NHMFL user program:
This four month period (Jan-May)
9 weeks of magnet time in 31 T resistive magnet
for REBCO CC, mainly torque

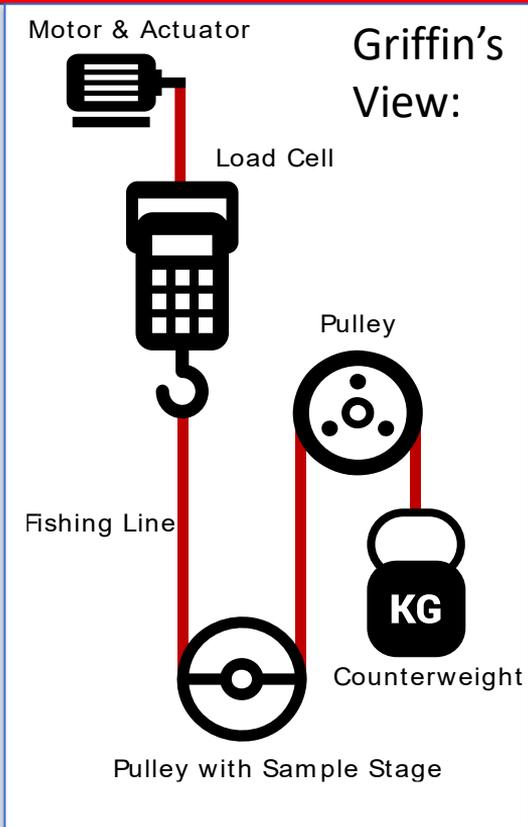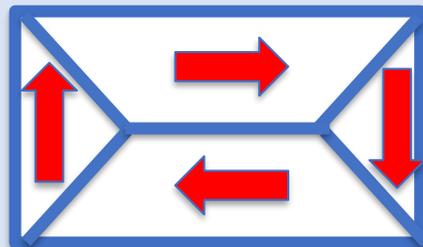Next application deadline:
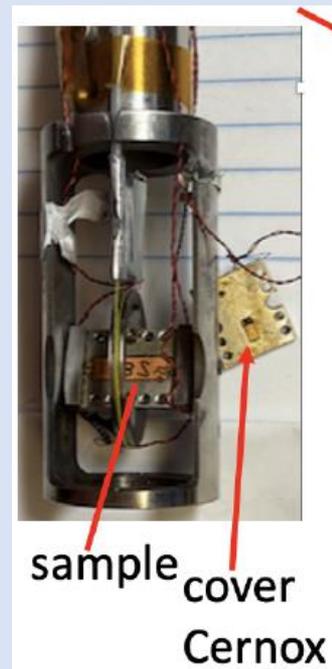March 21st
jaroszy@magnet.fsu.edu

Torque magnetometer

Motor & Actuator

Griffin's View:

Load Cell

Pulley

Fishing Line

KG

Counterweight

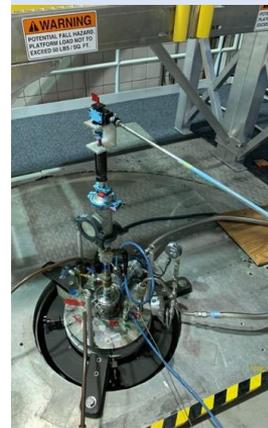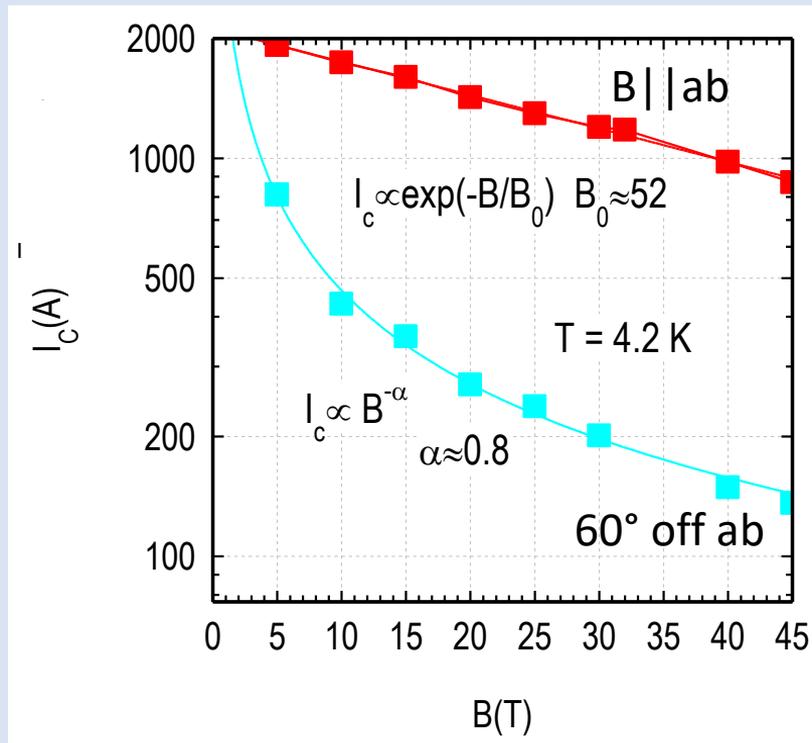Pulley with Sample Stage

screening currents,
=> magnetic moment m

$$m \propto I_c$$
$$\vec{\tau} = \vec{m} \times \vec{B}$$
$$T = \tau/R + W + F$$

sample cover

Cernox

PPMS version

J. Jaroszynski, A-M Constantinescu, A. Xu, A. Francis, G. Miller, T. Murphy, and D. Larbalestier SuST 2022, arXiv 2025
US Patent 12,181,540

M3 1352-3 H1

T=4.2 K

red: big probe
black: the hybrid probe

5 T

32, 40, 45 T

$B \| ab$

$I_c \propto \exp(-B/B_0)$ $B_0 \approx 52$

T = 4.2 K

$I_c \propto B^{-\alpha}$

$\alpha \approx 0.8$

60° off ab

45 T hybrid magnet

vs. T: exponential, stretched exponential around the ab plane

M4-526-6 LBC4-9

B = 20 T

4.2 K
10 K
15 K
22 K
35 K

M4-526-6 LBC4-9

$\sim\exp[-(T/T_+)^n]$ strong

$\sim\exp(-T/T_0)$ weak

10 K, 16 T

Experimental
G-L scaling ($\gamma = 3$)
G-L scaling ($\gamma = 2$)

$J_c(\theta) / J_c^{//c}$

Angle (deg)

there is no shortage of options for fitting Ic!

Z. Chen et al. 2009

Weak and strong pinning:

Multi component fits:

$$I_c(B,T,\theta) = \frac{a_1(B,T)}{\omega_1^2(B,T)\sin^2(\theta)+1} + \frac{a_2(B,T)}{\omega_2^2(B,T)\sin^2(\theta)+1}$$

$$a_1(B,T) = a_{11}(T)\exp(-B/B_0)$$

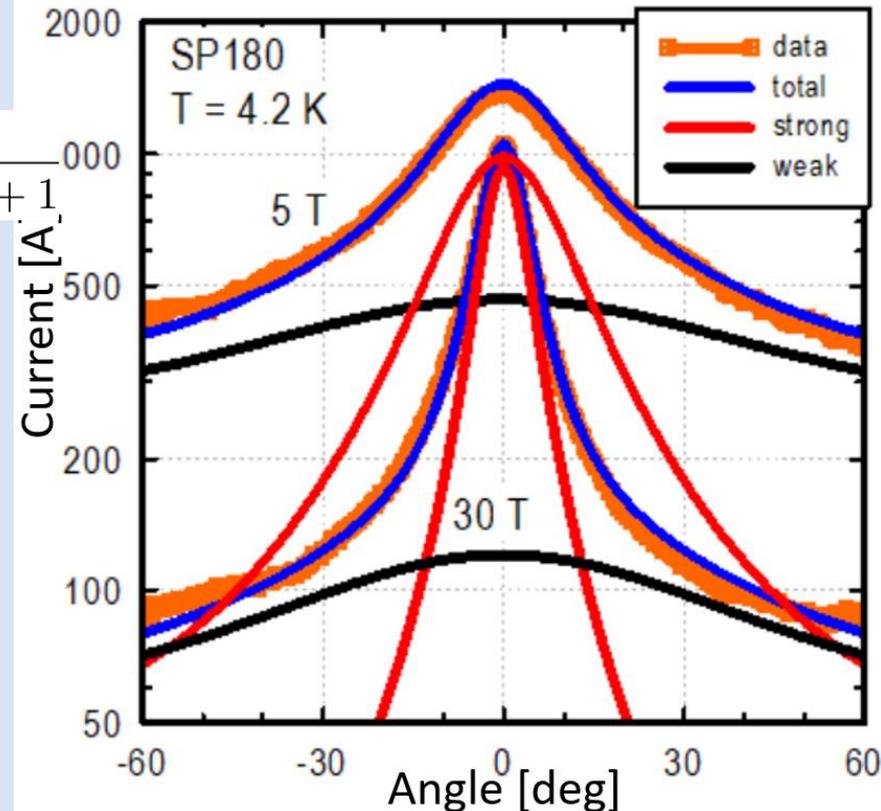$$a_1(B,T) = a_{11}(B)\exp[-(T/T_+)^2]$$

strong

$$a_2(B,T) = a_{21}(T)B^{-\alpha}$$
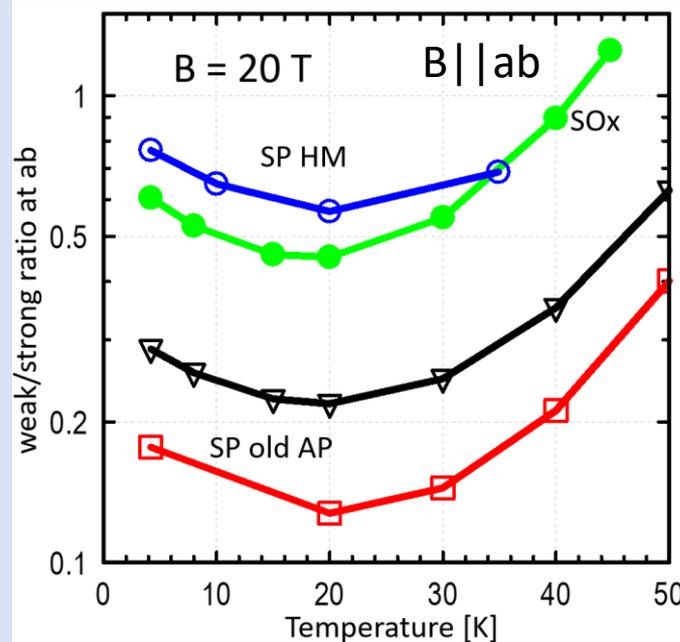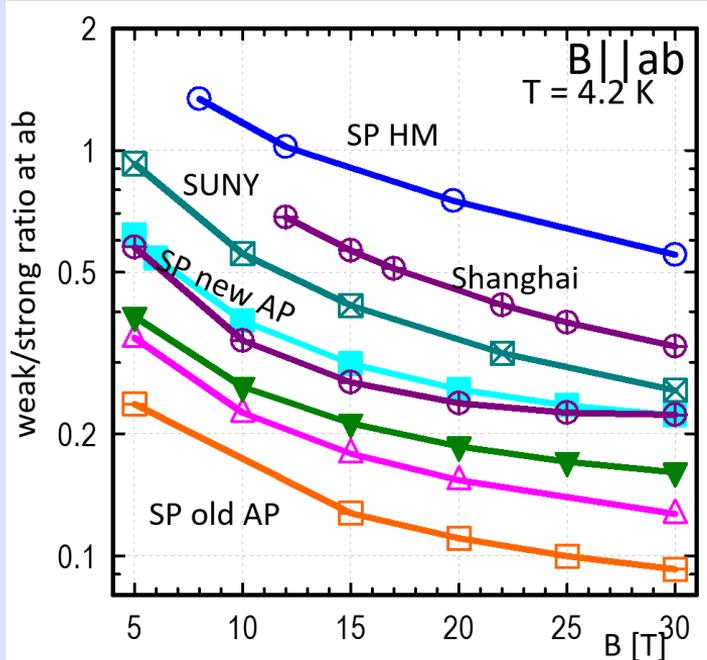
weak

$$a_2(B,T) = a_{21}(B)\exp[-T/T_0]$$

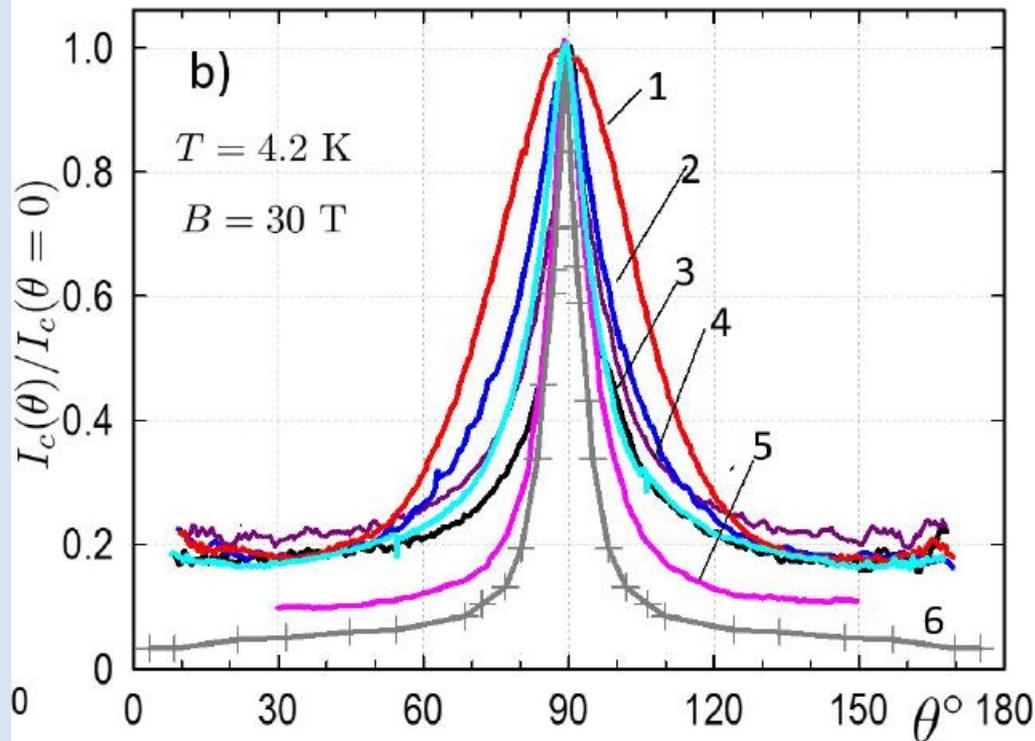=> N.M. Strickland et al. 2022, N.J. Long et al. 2013

More weak pinning in recent production!

weak/strong pinning ratios in old/new production:

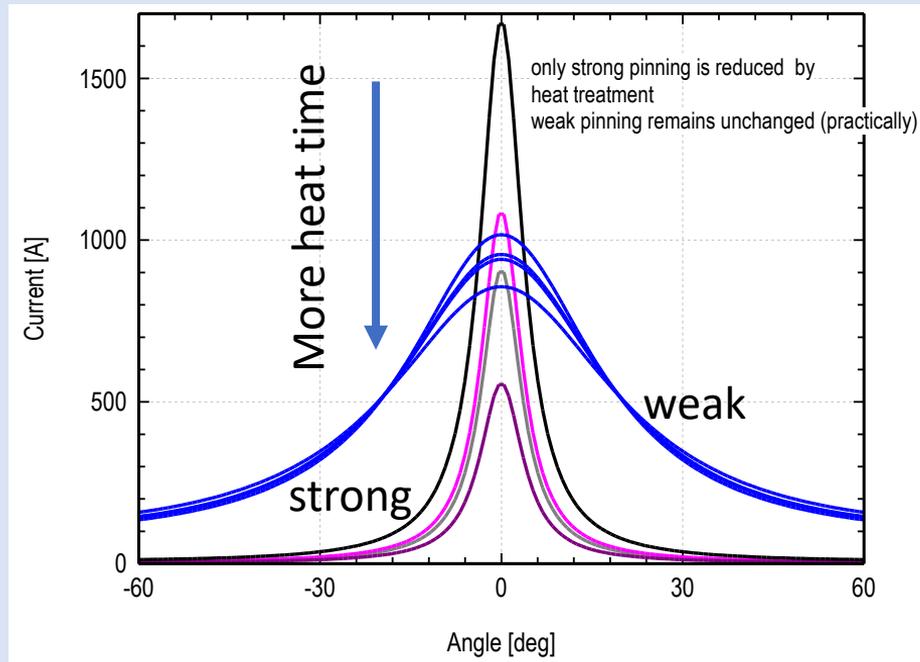# All modern samples: low anisotropy ~5

MORE WEAK PINNING
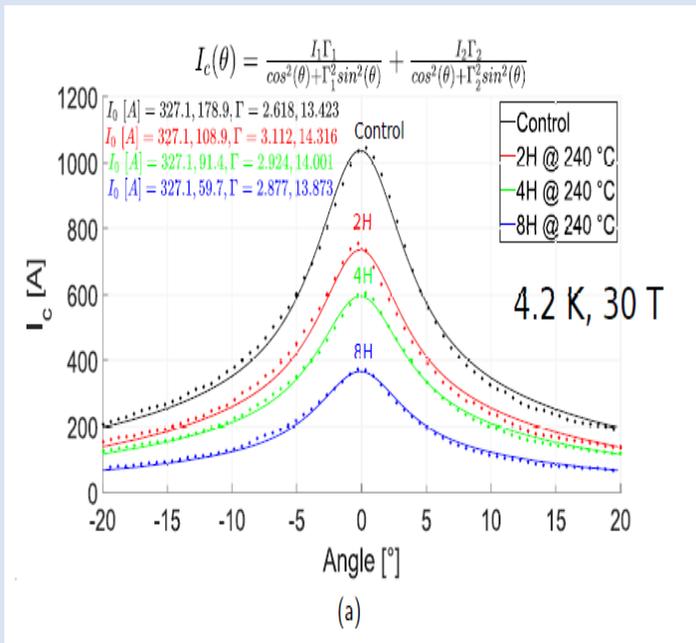

1. 15 % BZO R&D
2-4 typical modern production
   (Shanghai, FF, SuperPower)
5-6 SuperPower: old AP and no BZO

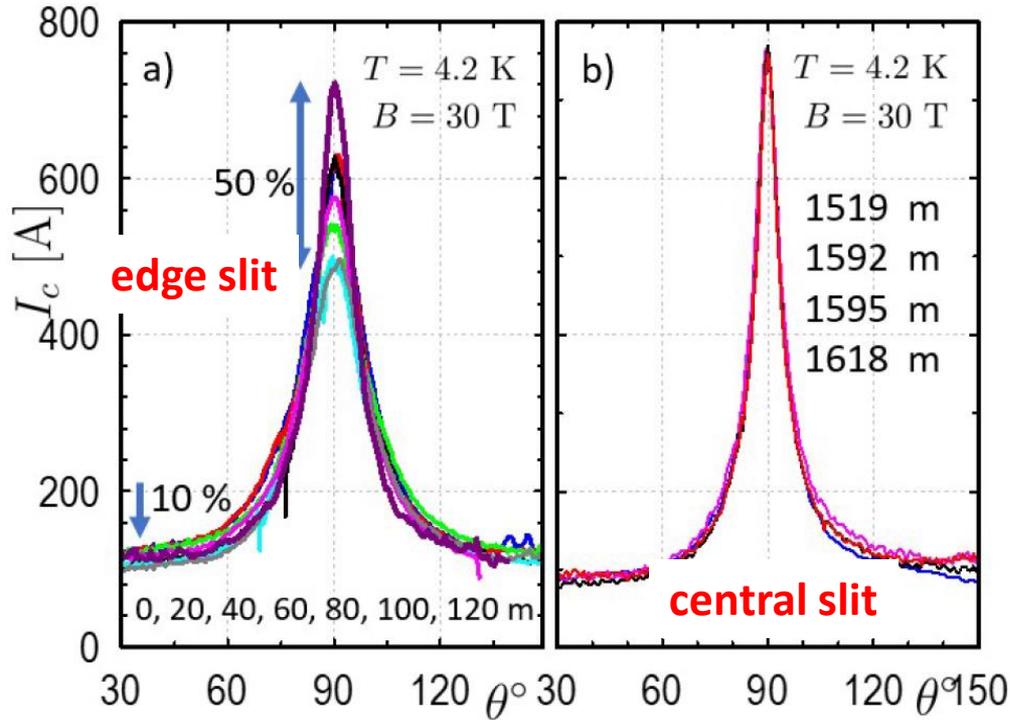Low (~5) anisotropy and wide peak
are typical nowadays: more weak pinning

Strong pinning can be modified:

$$I_c(\theta) = \frac{I_1\Gamma_1}{cos^2(\theta)+\Gamma_1^2 sin^2(\theta)} + \frac{I_2\Gamma_2}{cos^2(\theta)+\Gamma_2^2 sin^2(\theta)}$$

$I_0\,[A] = 327.1, 178.9, \Gamma = 2.618, 13.423$
$I_0\,[A] = 327.1, 108.9, \Gamma = 3.112, 14.316$
$I_0\,[A] = 327.1, 91.4, \Gamma = 2.924, 14.001$
$I_0\,[A] = 327.1, 59.7, \Gamma = 2.877, 13.873$

Control
2H @ 240 °C
4H @ 240 °C
8H @ 240 °C

4.2 K, 30 T

(a)

only strong pinning is reduced by heat treatment
weak pinning remains unchanged (practically)

More heat time

weak

strong

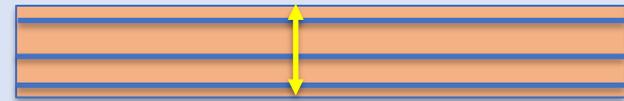G. Bradford PhD thesis, heat treatment:

Lengthwise Ic variations: strong pinning mainly

- large variations at the ab plane (strong pinning)
- stronger at edge slit
- different slitting? 2-4-4-2

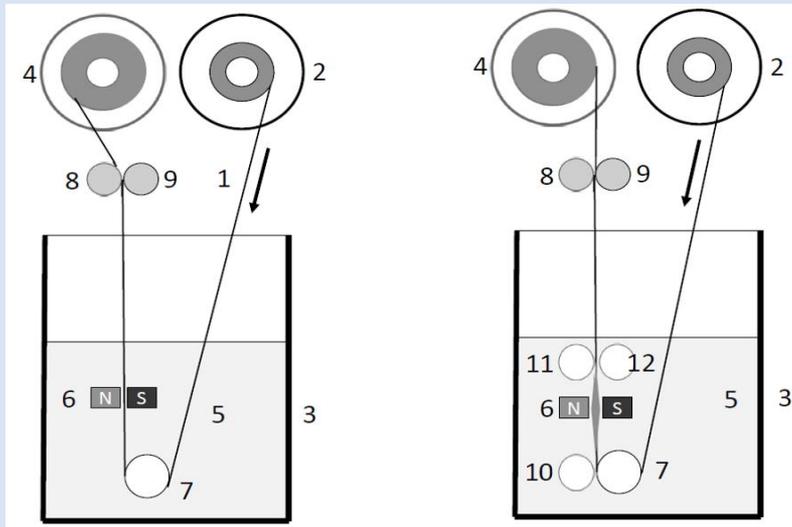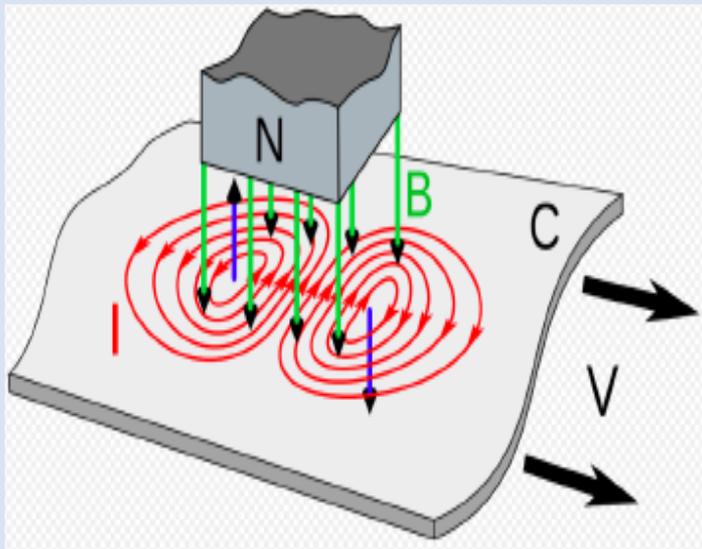- no clear correspondence between 77 K and low T

Like eddy current brakes

Patent pending

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Flux jumps in thick samples

T = 4.2 K, B = 15 T

torque

temperature

Pick-up coil

single sample:
rotation in field

MH

B||c

μ₀H

60 sample stack
Field sweep

T. Grag et al. IEEE TAS 35 (2025)

THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

Many thanks:

Anca-Monia Constantinescu
2014-2017, 2022

Aixia Xu
2007-2012
2021->

Valeria Braccini
2009-2010

Ashleigh Francis
2020-2023

Griffin Bradford, Jun Lu, Rastislav Ries
George Miller, Tim Murphy, and David Larbalestier

NHMFL User Collaboration Grants Program
-Fast fatigue and current assessment in REBCO coated conductors
-Advancing lengthwise assessment of REBCO tapes using force magnetometry

SUMMARY

- torque magnetometry: massive angular $I_c(B,T,\theta)$ characterization

- phenomenology of angular I_c at low T becomes quite clear

- in modern samples weak pinning dominates=> low anisotropy

- lengthwise fluctuation: at the edges, mainly strong pinning at ab

- heat treatment modifies anisotropy and lengthwise changes

- flux jumps observed in thick REBCO films