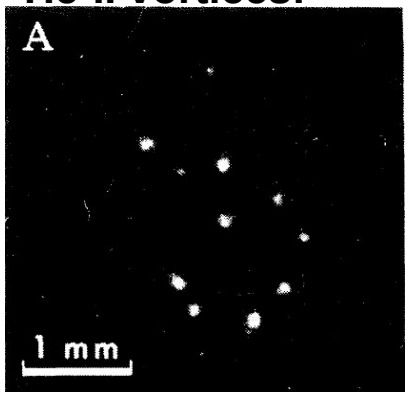
Vortices in Classical Systems

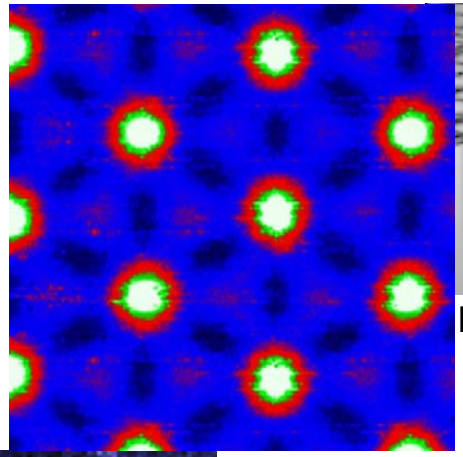
Vortices in Quantum Systems

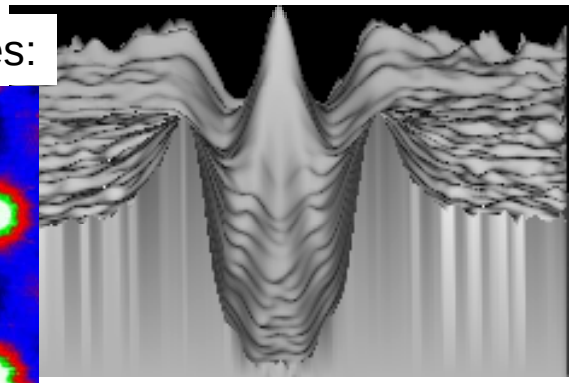
^{4}He-II vortices:



G. A. Williams, R. E. Packard, *Phys. Rev. Lett.* 33, 280 (1974)

STM of $NbSe_2$ vortices:

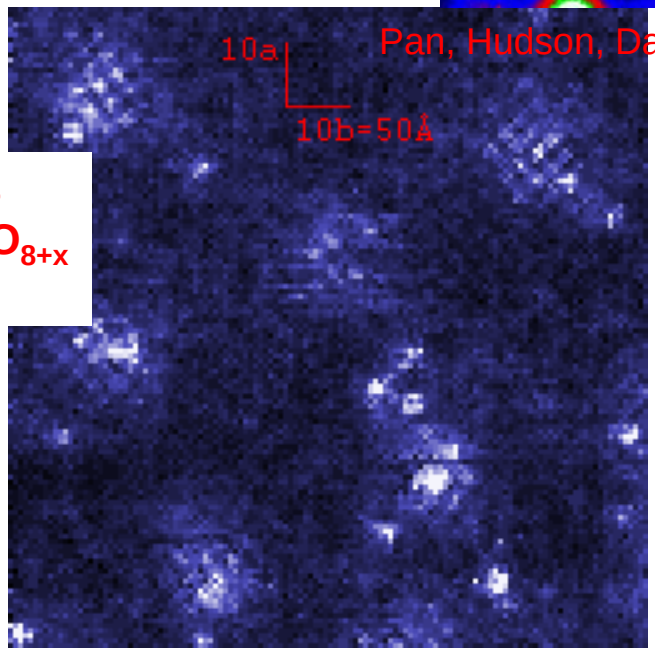




Hess *PRL* (1989).

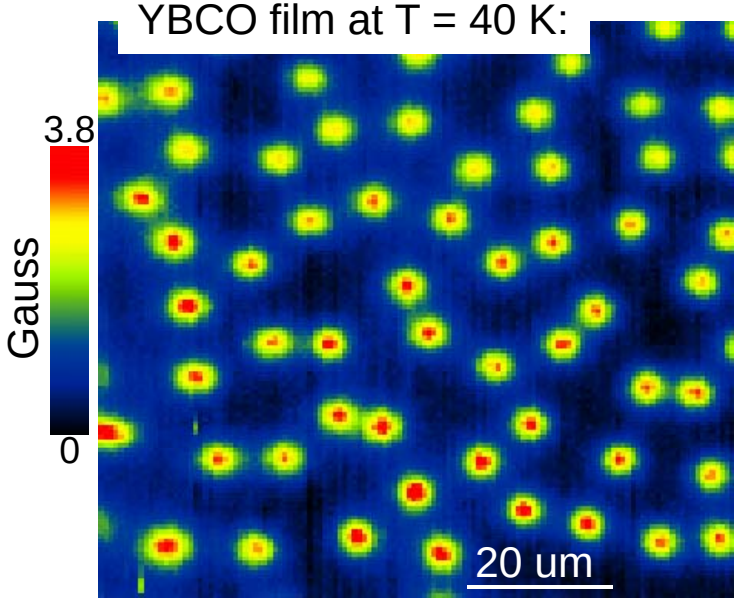
Pan, Hudson, Davis, *RSI* (1999)

Checkerboards in $Bi_2Sr_2CaCu_2O_{8+x}$ vortices:



Hoffman et al, *Science* (2002)

Hall probe image of YBCO film at T = 40 K:



$B_{applied}$ = 1 Gauss

Single Vortex Manipulation in Superconducting Nb

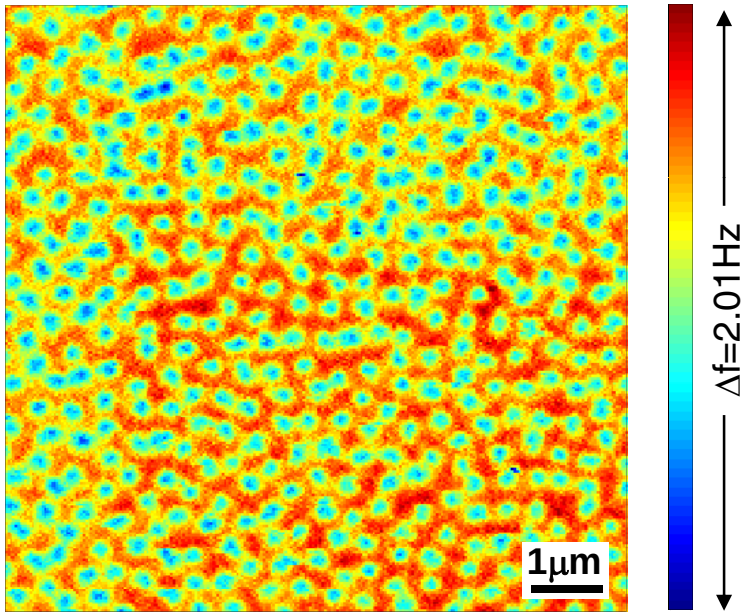
Eric Straver

Jenny Hoffman

Dan Rugar

Kathryn Moler

Vortices in Nb Film Cooled to 5.3K in 100G



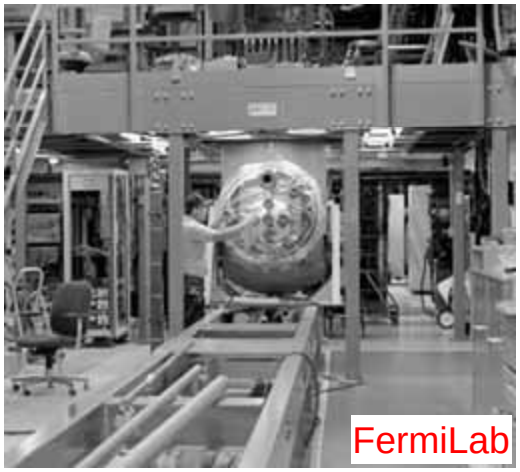
Stanford University

Funded by Packard and AFOSR

Goals

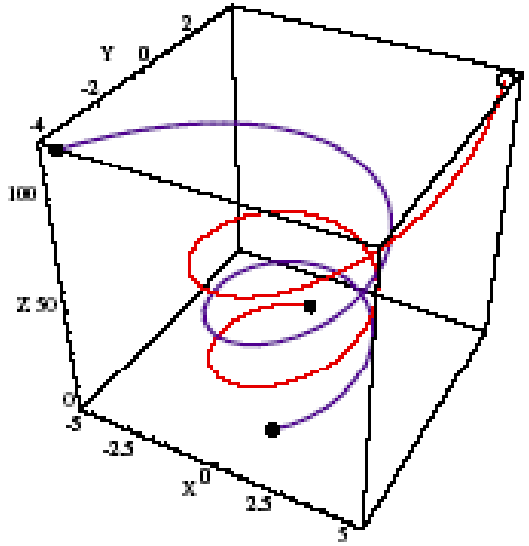
Part I: eliminate uncontrolled vortex motion

- bigger magnets
- efficient power lines
- quieter sensors & circuits



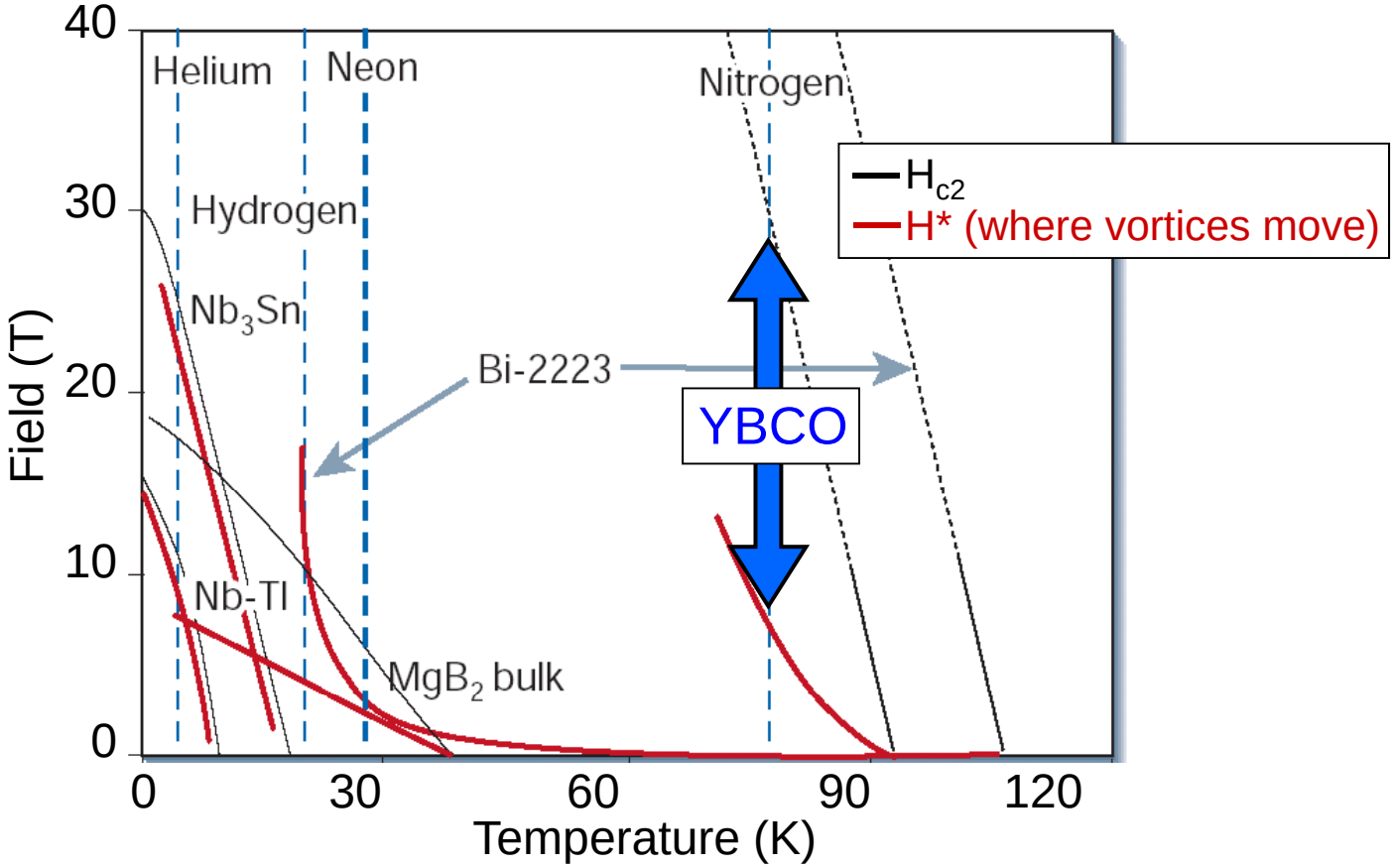
Part II: controlled single-vortex manipulation

- model for soft condensed matter
- vortex entanglement
- vortex ratchet automaton
- Luttinger liquid



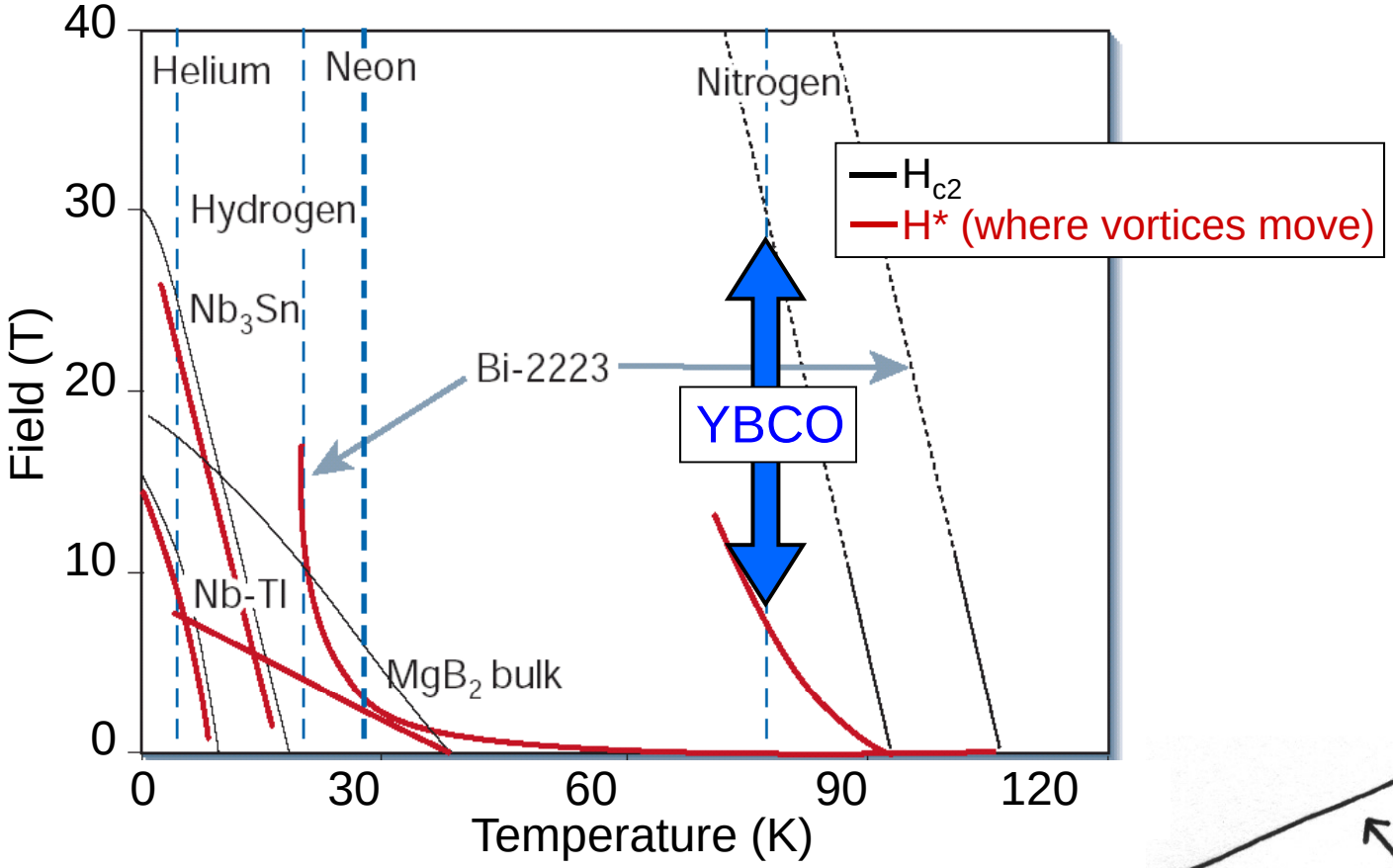
Part I: eliminate uncontrolled vortex motion

Motivation: eliminate uncontrolled vortex motion

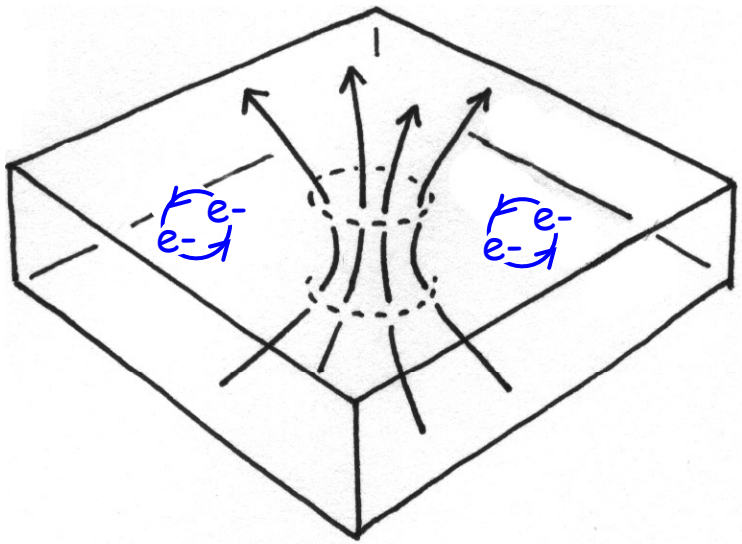


Larbalestier, Nature 414, 368 (2001)

Motivation: eliminate uncontrolled vortex motion



Larbalestier, Nature 414, 368 (2001)



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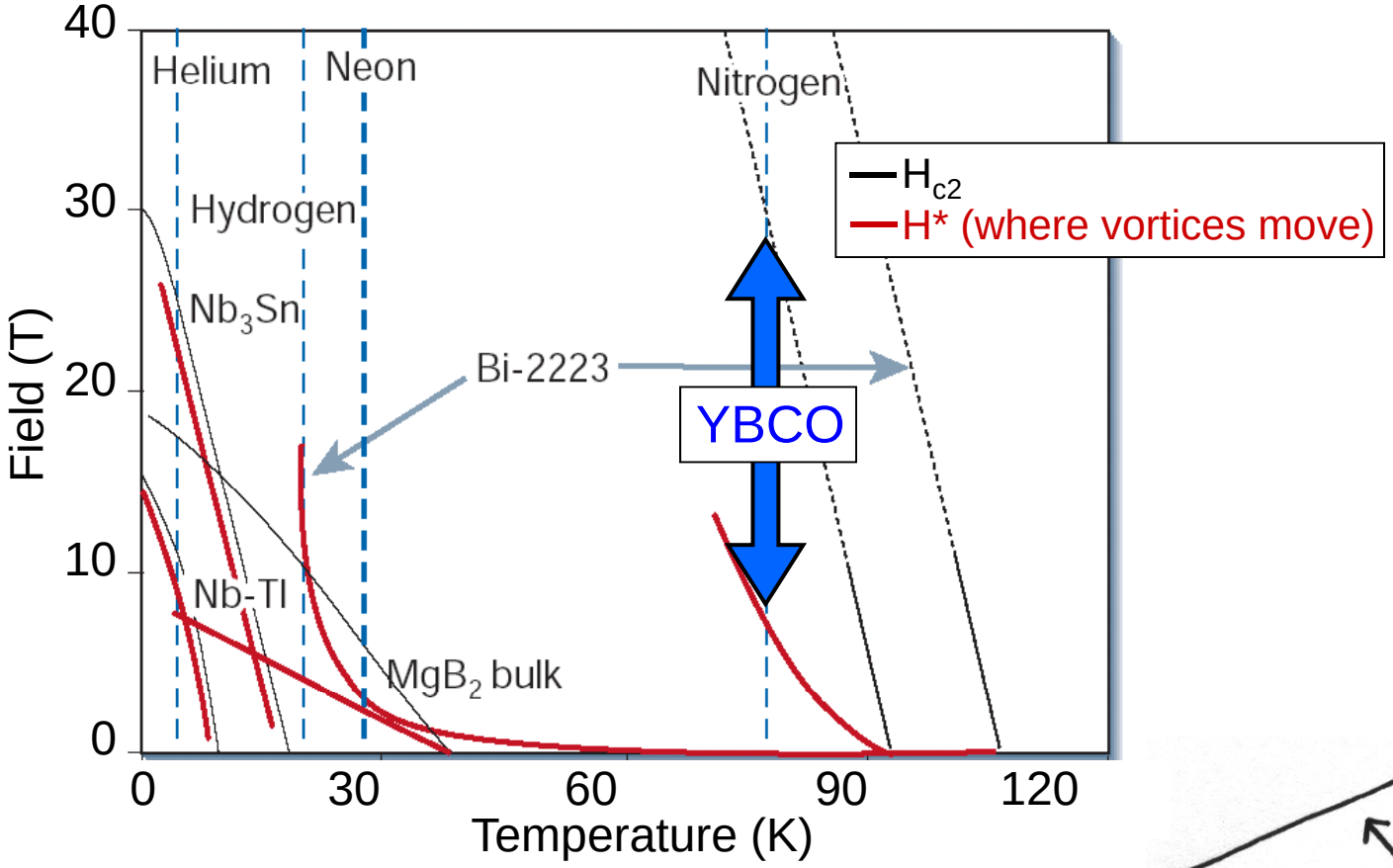
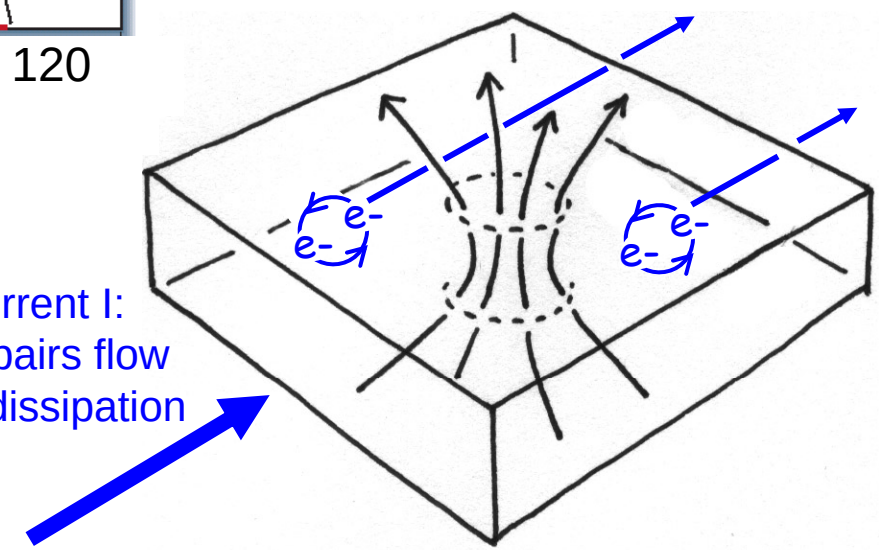
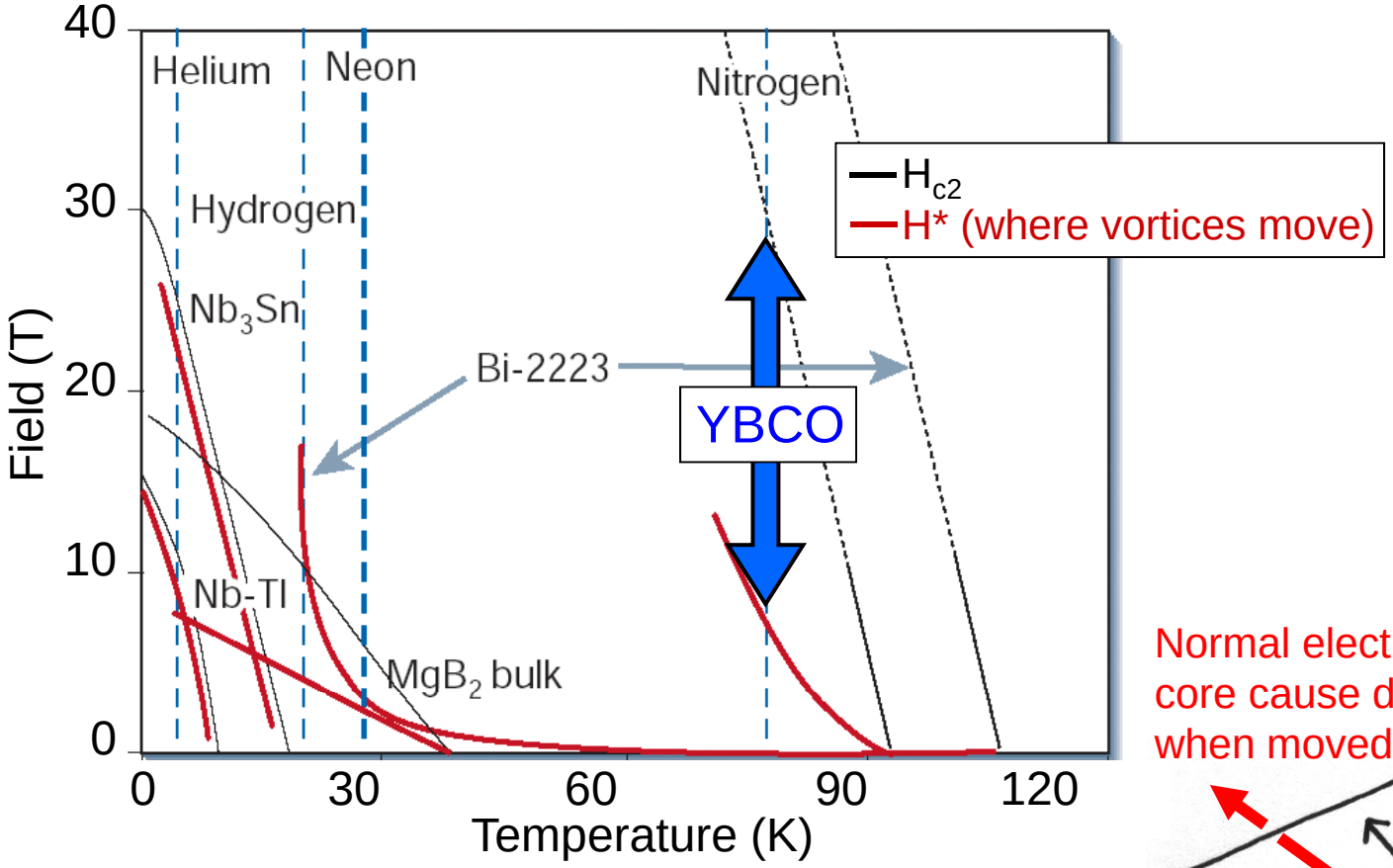


Larbalestier, Nature 414, 368 (2001)



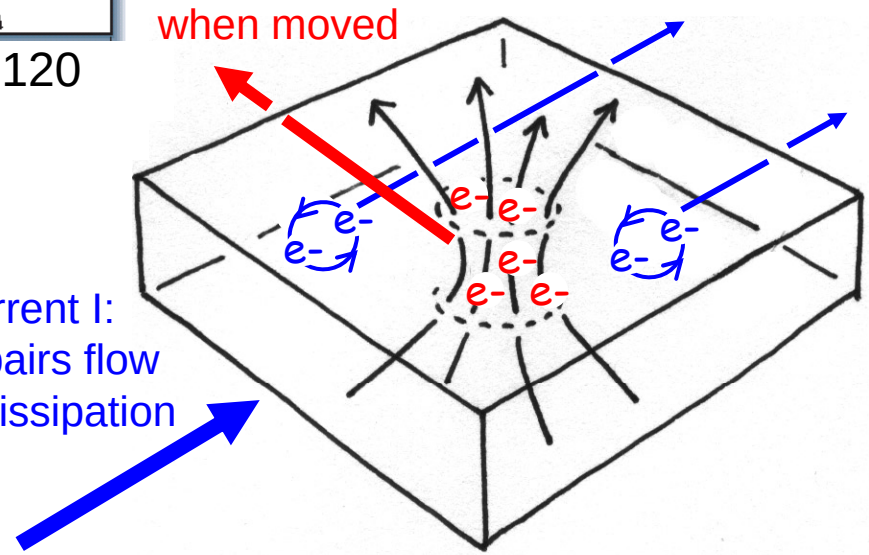
Apply current I:
Cooper pairs flow
without dissipation

Motivation: eliminate uncontrolled vortex motion



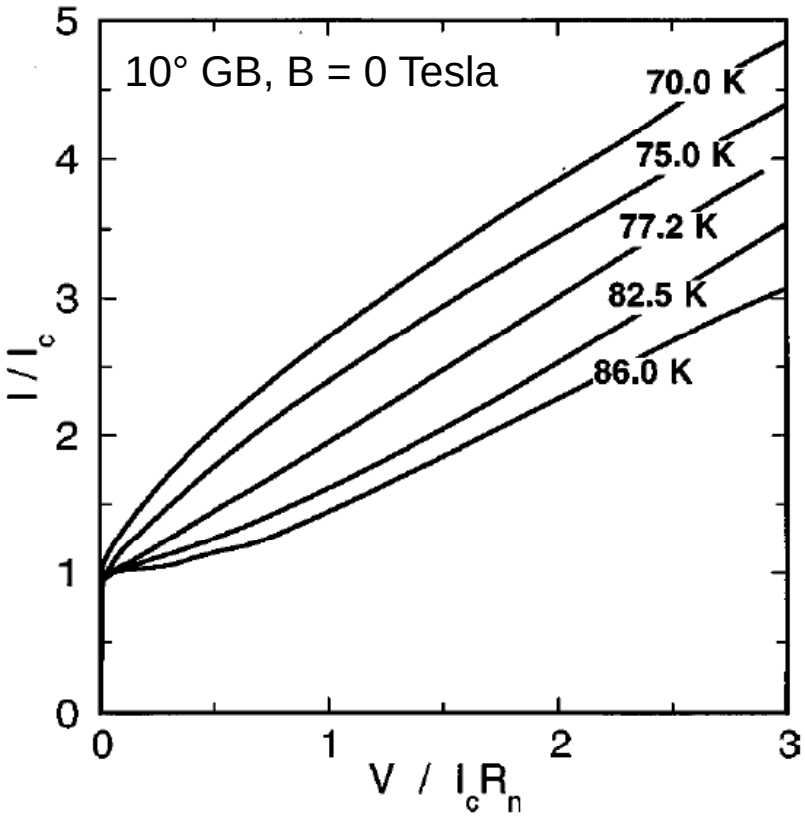
Larbalestier, Nature 414, 368 (2001)

Normal electrons in vortex core cause dissipation when moved

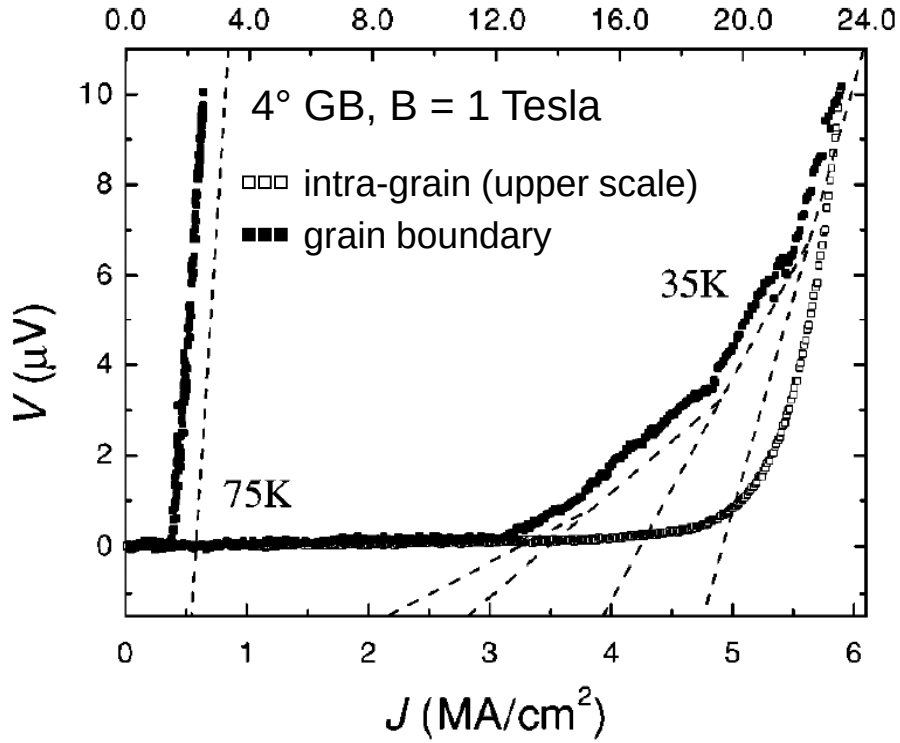


Apply current I: Cooper pairs flow without dissipation

Vortex Pinning Measurements: Bulk Transport

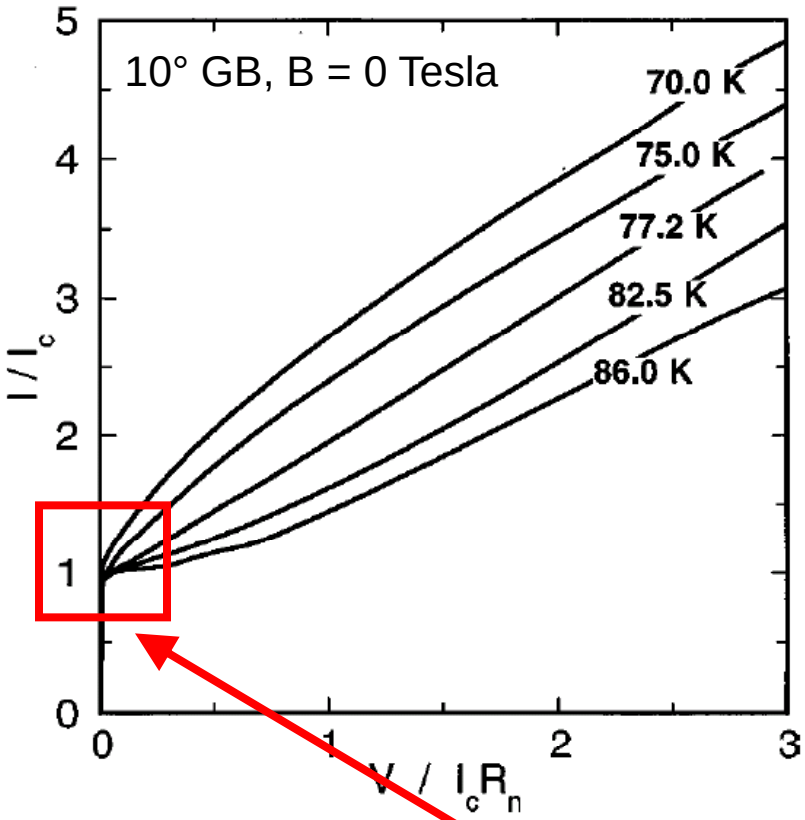


Redwing *et al*, APL 75, 3171 (1999).



Hogg *et al*, APL 78, 1433 (2001).

Vortex Pinning Measurements: Bulk Transport



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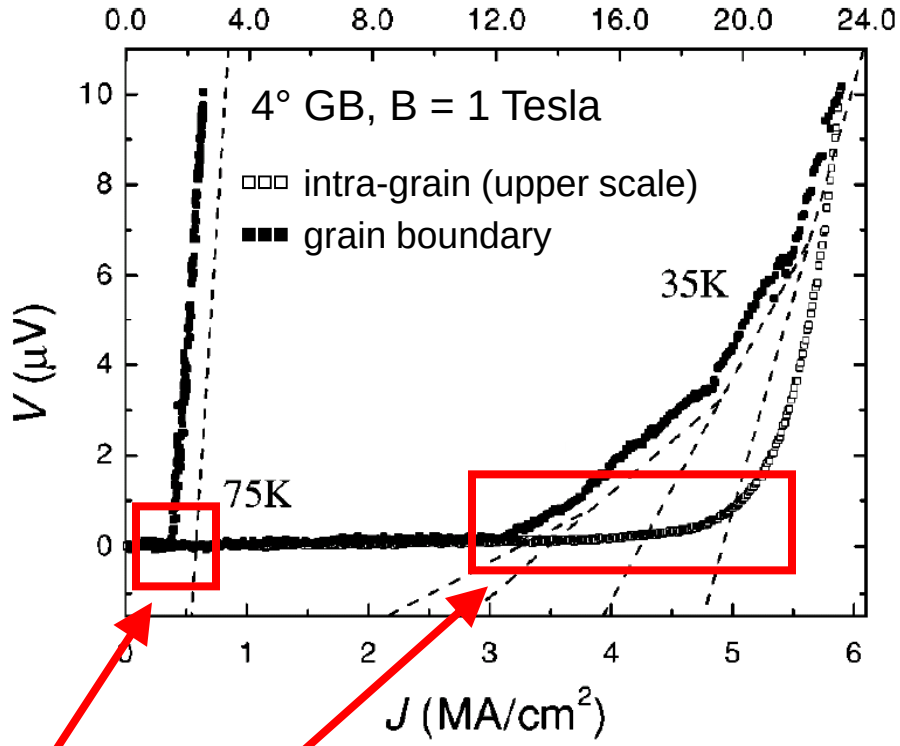


Hogg *et al*, APL 78, 1433 (2001).

What's really going on here?

First detectable Voltage = **many, many** vortices

Examples of Previous Single Vortex Depinning Force Measurements with Transport Current

Finnemore and coworkers
ongoing work (1988-present)

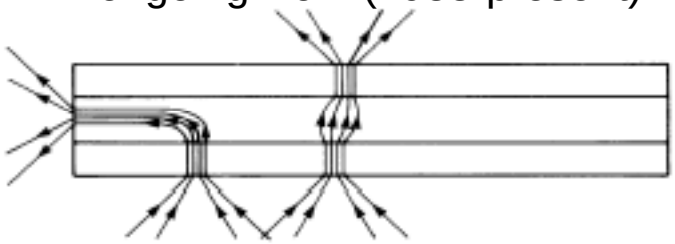


FIG. 1. Illustration of the vortex configuration trapped in the junction for $B_{\perp cool}=0.016$ G. The misaligned primary-secondary vortex is shown near the center, and the primary-only vortex is sketched at the left.

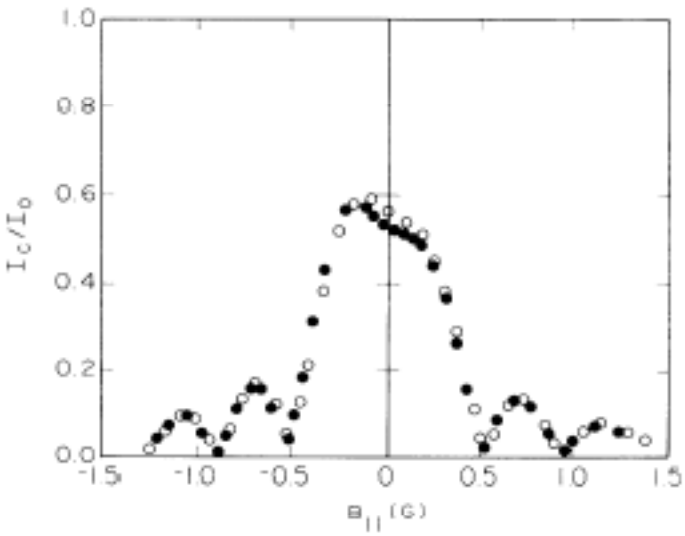


FIG. 2. Diffraction-pattern change for a small jump of the primary-only vortex in the **x** direction. Solid circles are for the vortex position (−0.59, 0.10) and open circles are for (−0.63, 0.10).

Cabrera and coworkers 1992

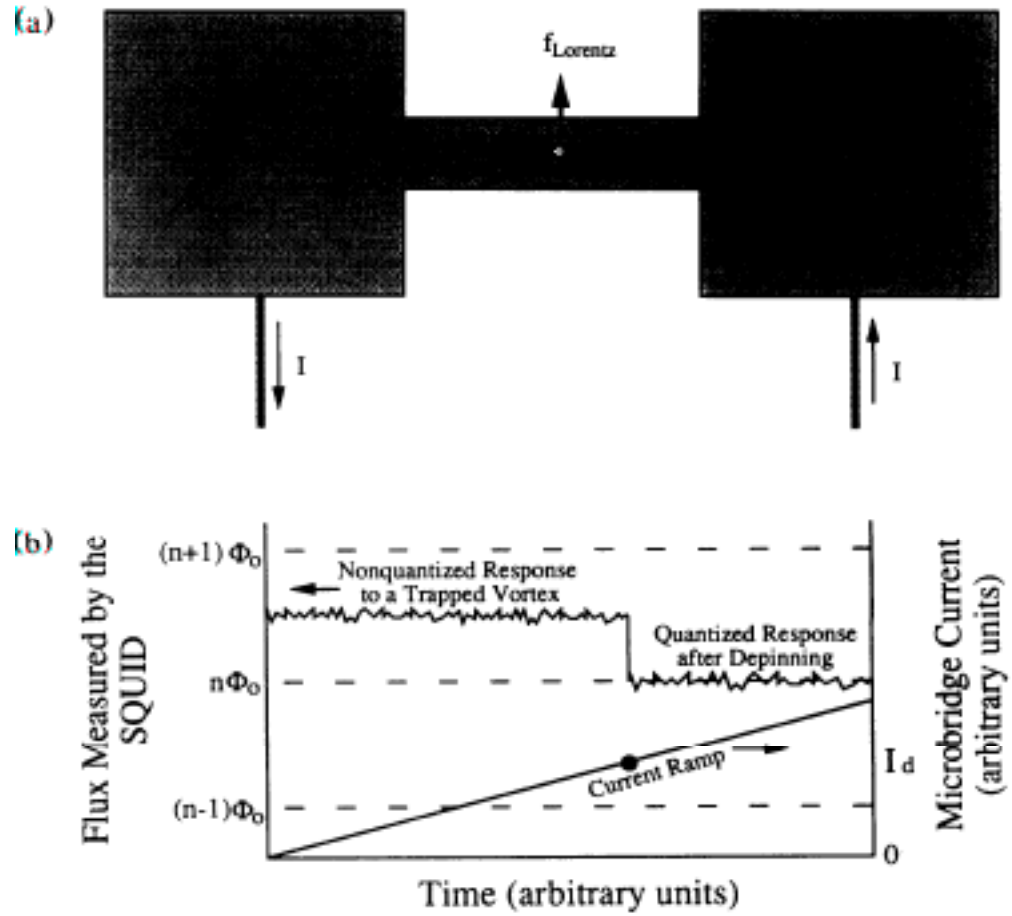


FIG. 2. (a) Current produces a Lorentz force on vortex. (b) SQUID response to vortex depinning by a current ramp through the chip (simulation).

+ several other groups

Examples of Previous Single Vortex Depinning Force Measurements with Transport Current

Finnemore and coworkers
ongoing work (1988-present)

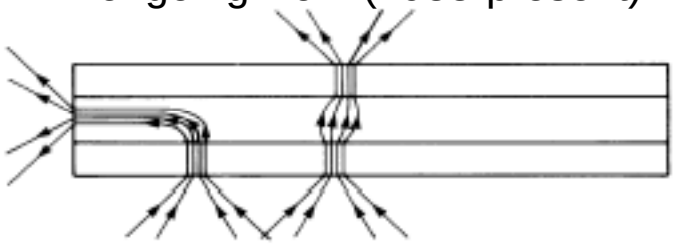
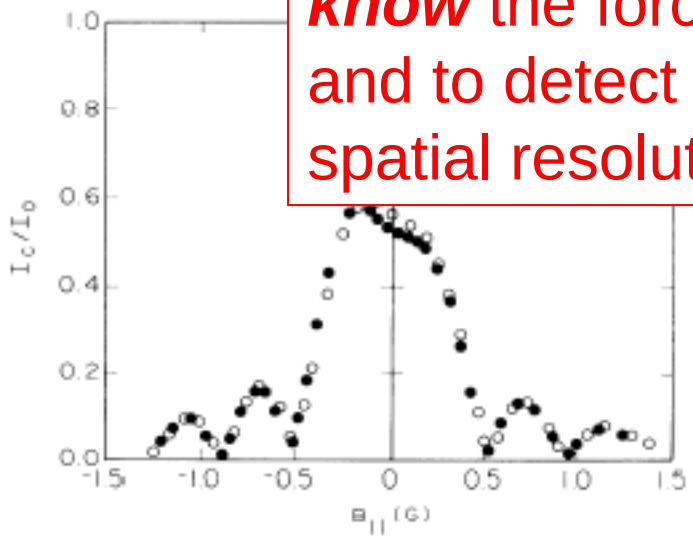


FIG. 1. Illustration of the vortex configuration trapped in the junction for $B_{\perp cool}$ = secondary vortex is show only vortex is sketched at



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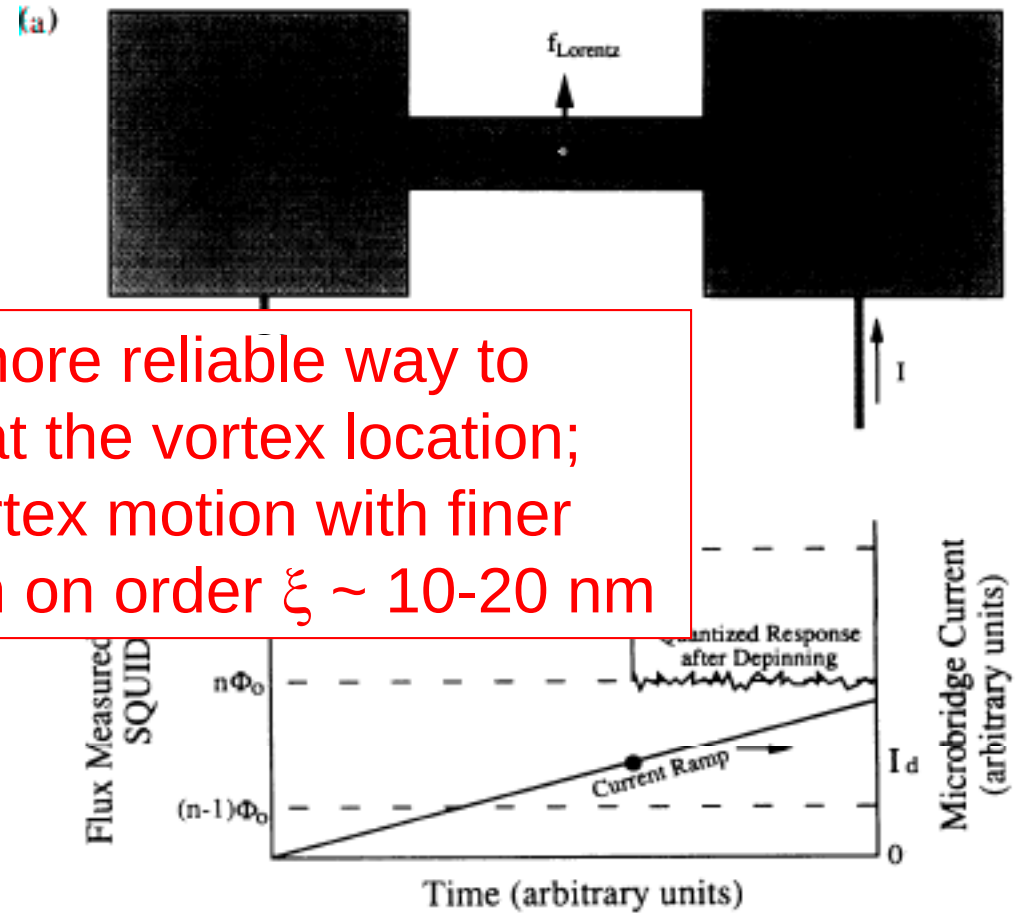
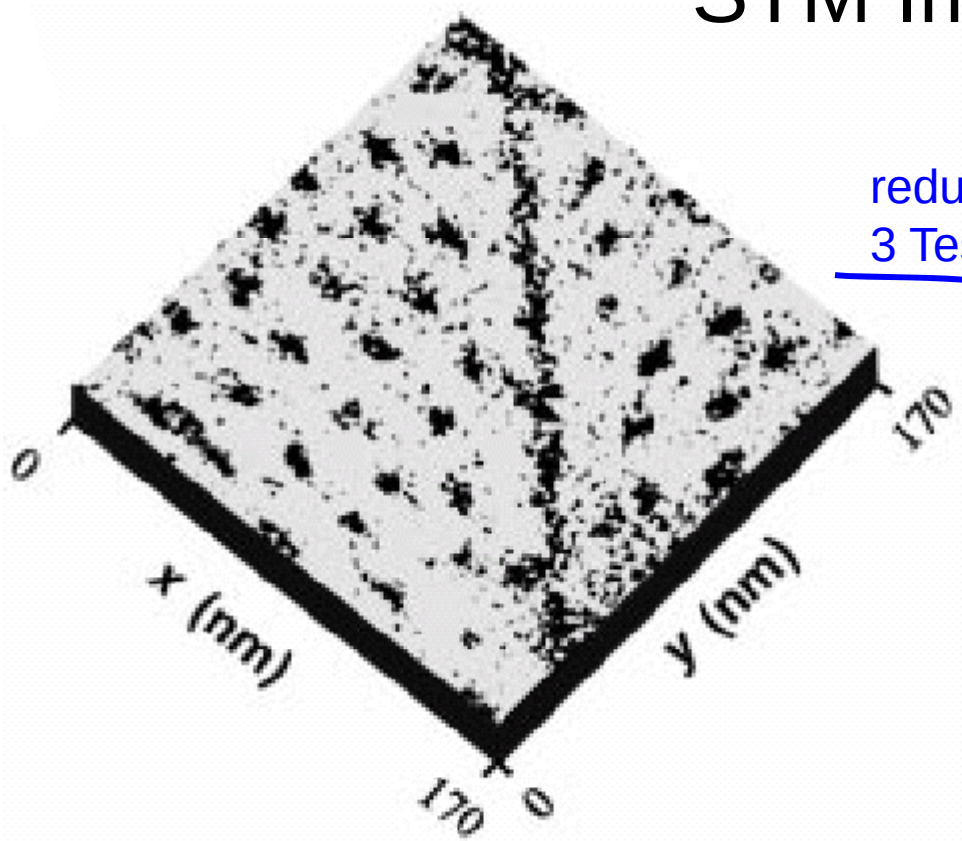


FIG. 2. (a) Current produces a Lorentz force on vortex. (b) SQUID response to vortex depinning by a current ramp through the chip (simulation).

But we'd like a more reliable way to ***know*** the force at the vortex location; and to detect vortex motion with finer spatial resolution on order $\xi \sim$ 10-20 nm

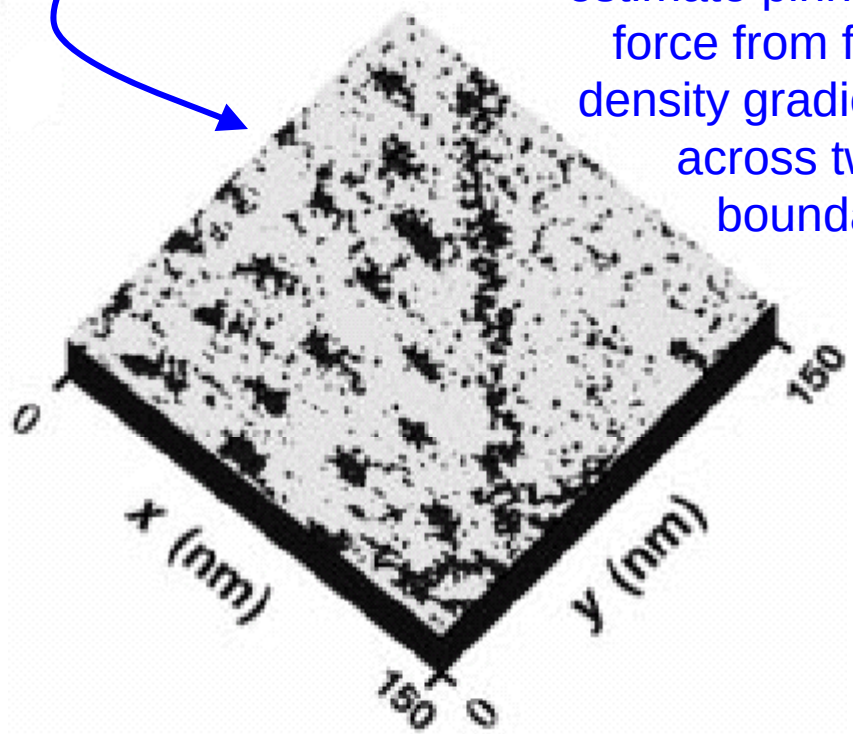
+ several other groups

Vortex Pinning Measurements: STM Imaging



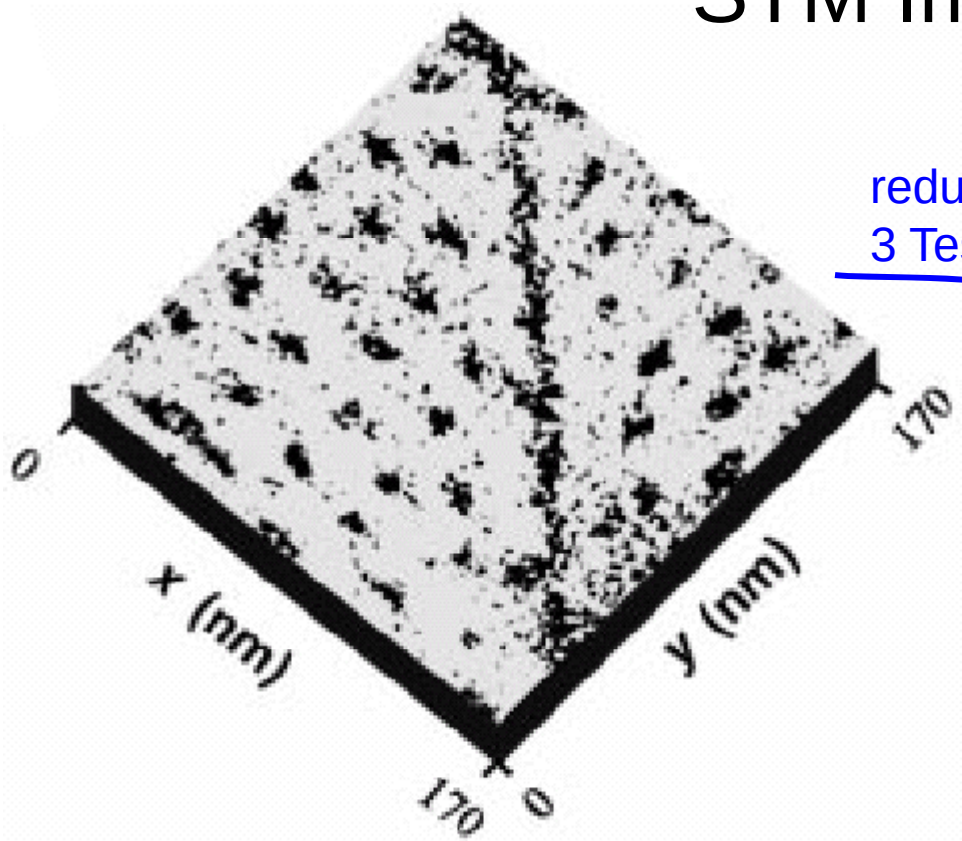
reduce field from
3 Tesla to 1.5 Tesla

estimate pinning force from flux density gradient across twin boundary



Maggio-Aprile et al, Nature 390, 487 (1997)

Vortex Pinning Measurements: STM Imaging



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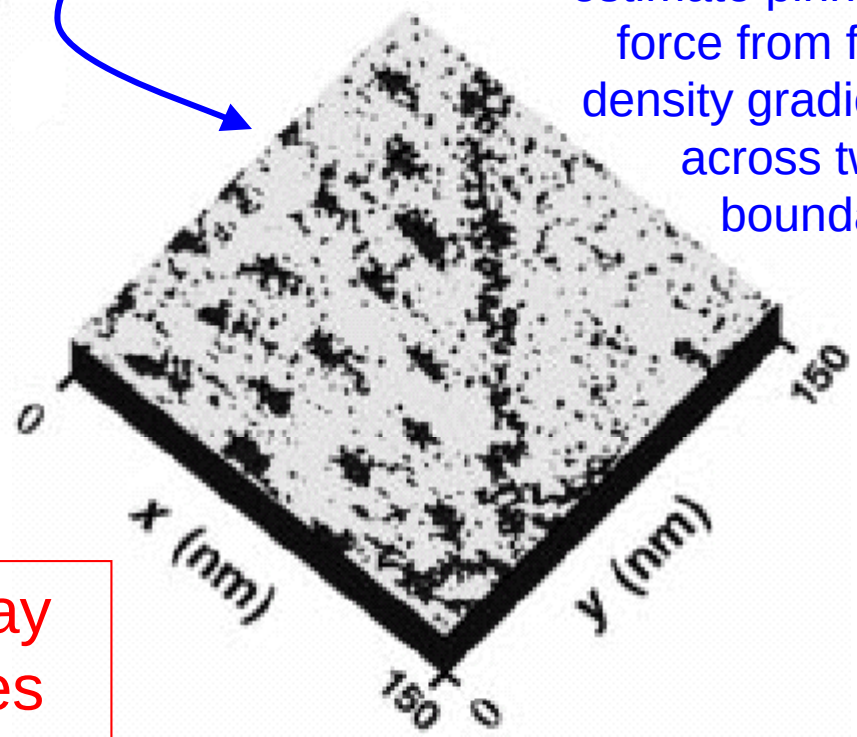
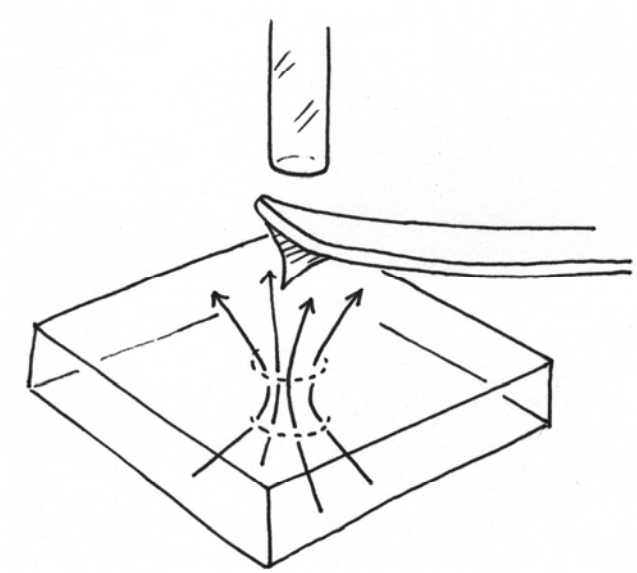


Maggio-Aprile et al, Nature 390, 487 (1997)

But we'd like a more versatile way to directly measure pinning forces at arbitrary defects.

Magnetic Force Microscopy



Force between tip and sample:

$$\mathbf{F} = \nabla(\mathbf{m} \cdot \mathbf{B})$$

Image cantilever resonant frequency

$$\Delta f_0 \sim dF_z/dz$$

better signal-to-noise

Vertical force gradient → imaging
Horizontal force → manipulation

<u>Pros and Cons of MFM</u>

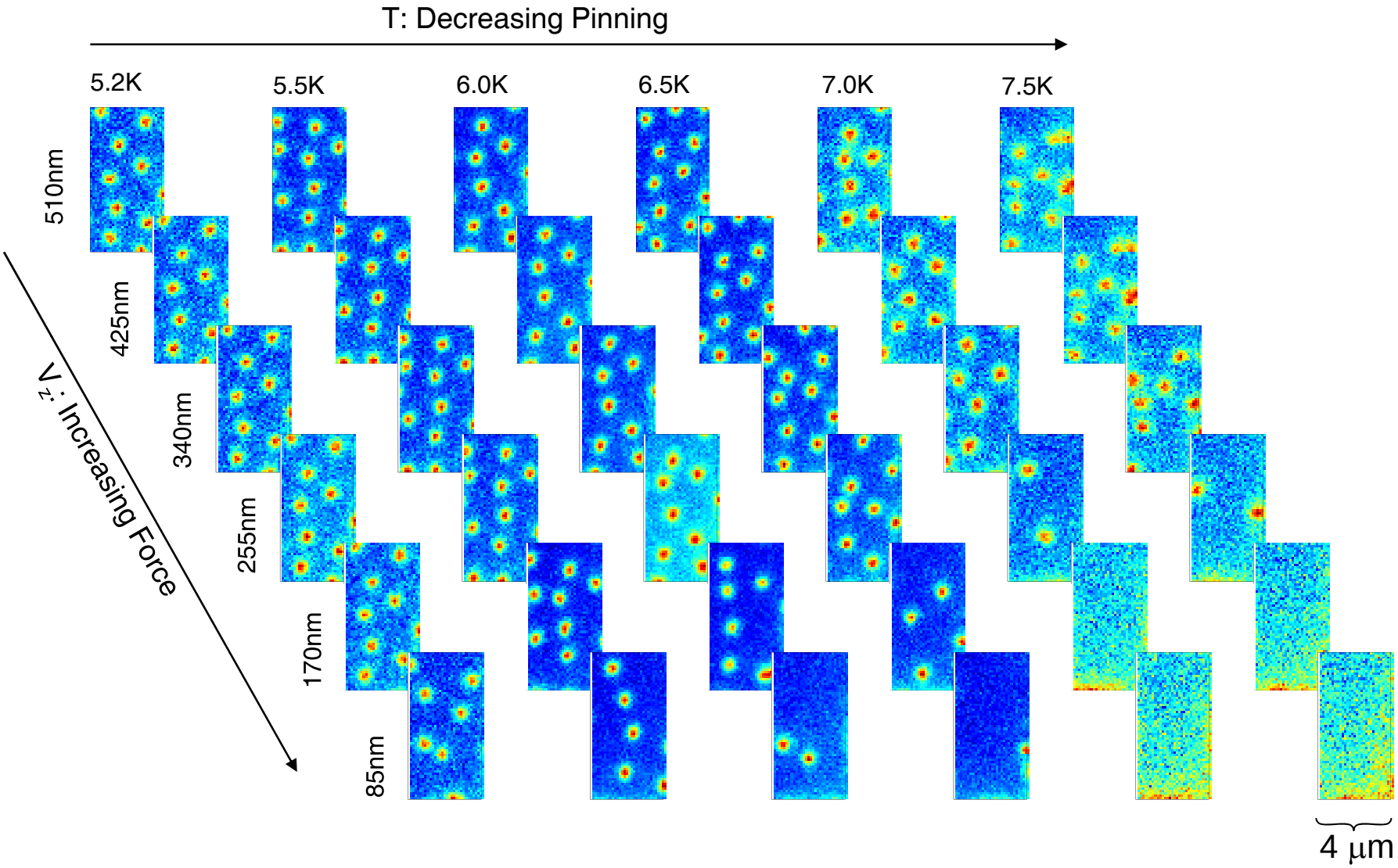
Tip Geometry
Con: Imperfectly known
Pro: Up to 20 nm spatial resolution

Signal to Noise
Con: Not as good as SQUIDs, Hall probes
Pro: Good enough to see vortices

Other signals
Con: See atomic forces too
Pro: Simultaneous topography

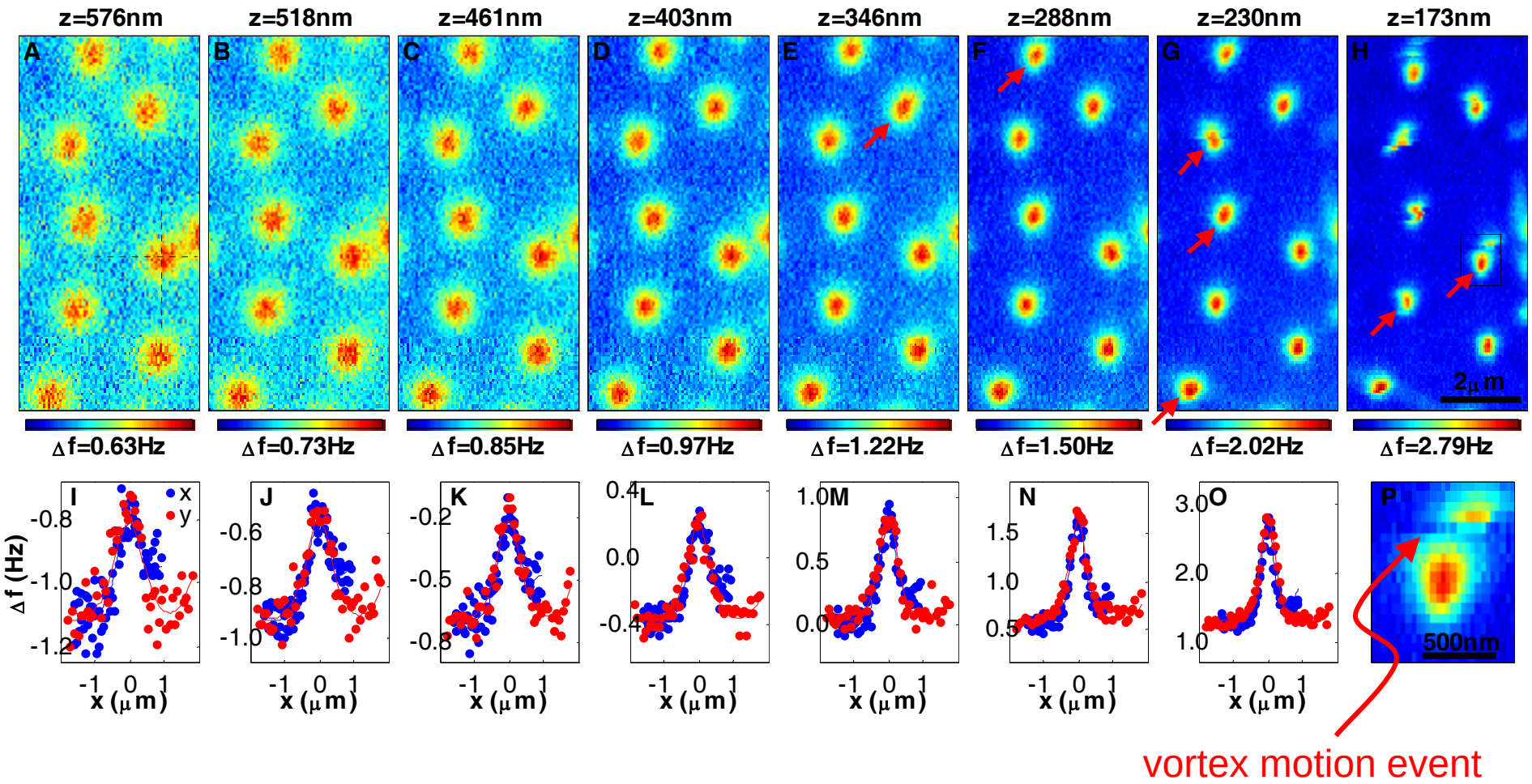
Invasiveness
Con: Tip exerts force on vortex
Pro: Tip exerts force on vortex

Vortex Depinning in Nb



Colormap adjusted separately for each image.

Vortex Pinning vs. Height at T = 5.5 K



vortex motion event

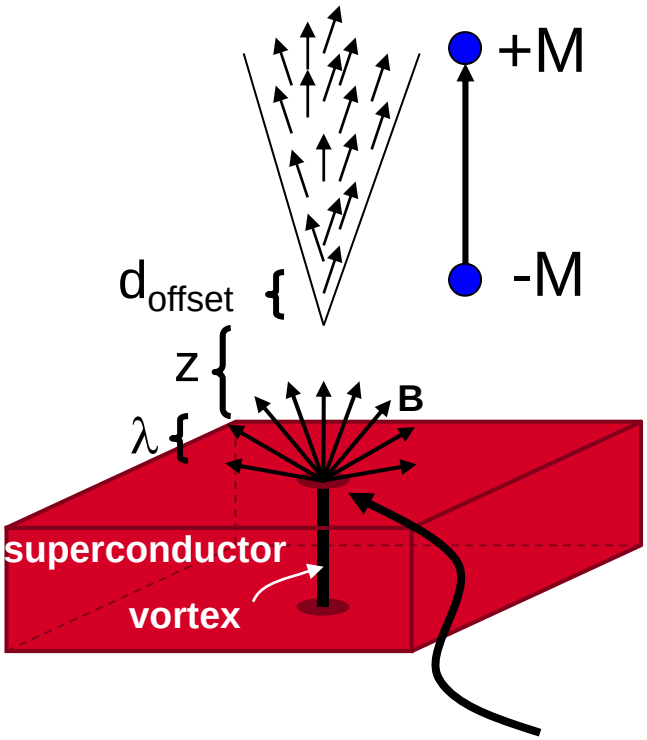
Important parameters:

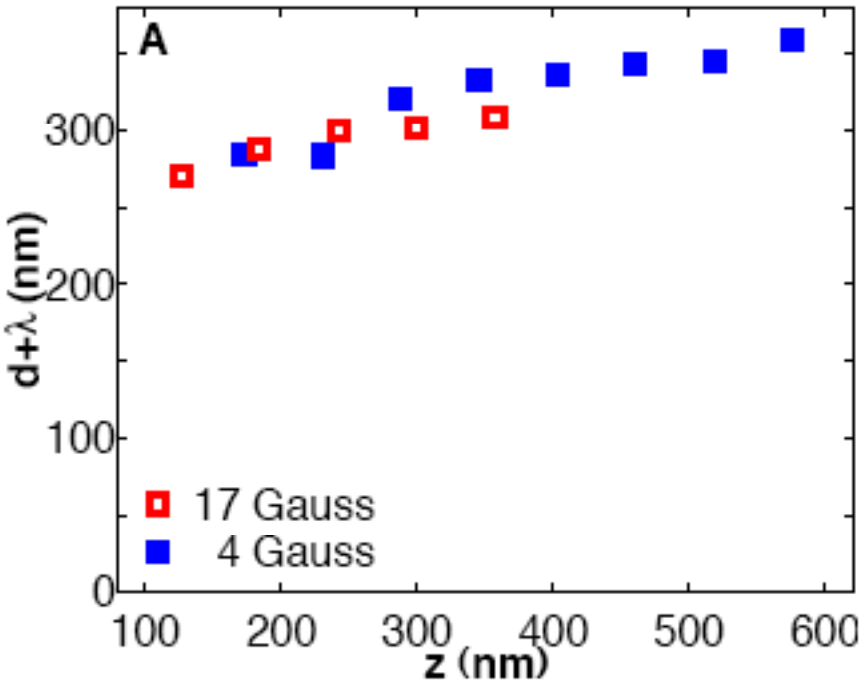
k_{spring} = 2.1±0.7 N/m

f_0 = 71128.28 Hz

λ_{Nb} = 90 nm

Model: Monopole Tip – Monopole Vortex



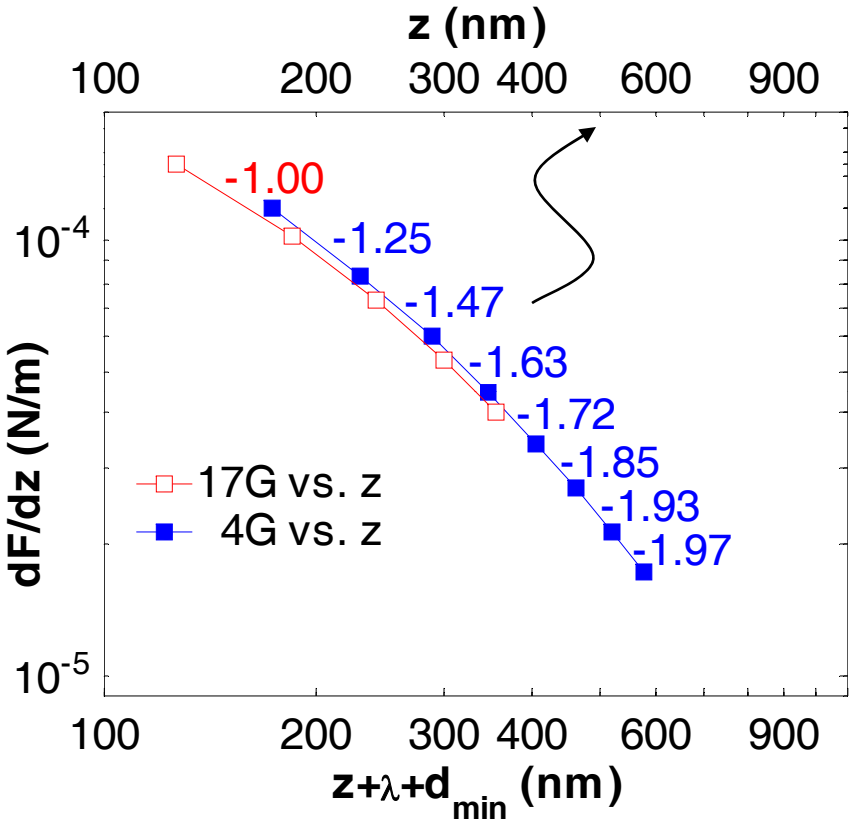


model vortex as monopole
distance λ beneath surface

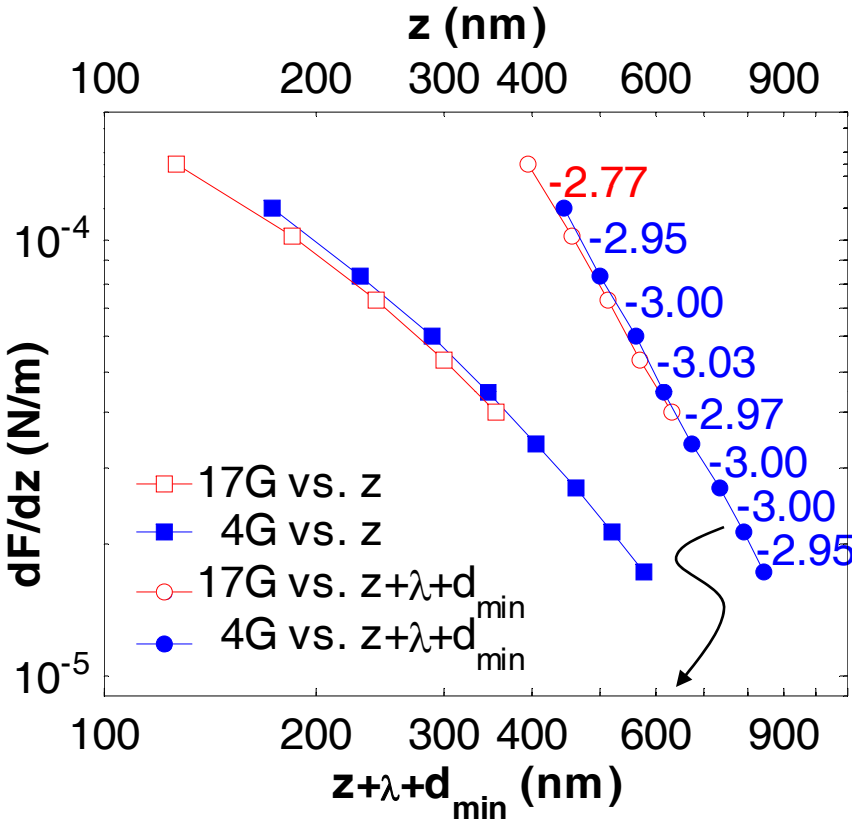
--J. Pearl, J. Appl. Phys. ***37****, 4139 (1966).*

$$\frac{dF_z}{dz} = -2k_{spr}\frac{df}{f_0} = \frac{M_z\Phi_0}{2\pi}\frac{-(x-x_0)^2-(y-y_0)^2+2(z+\lambda+d_{offset})^2)}{\left((x-x_0)^2+(y-y_0)^2+(z+\lambda+d_{offset})^2\right)^{5/2}}$$

Quantifying the Depinning Force at T = 5.5 K

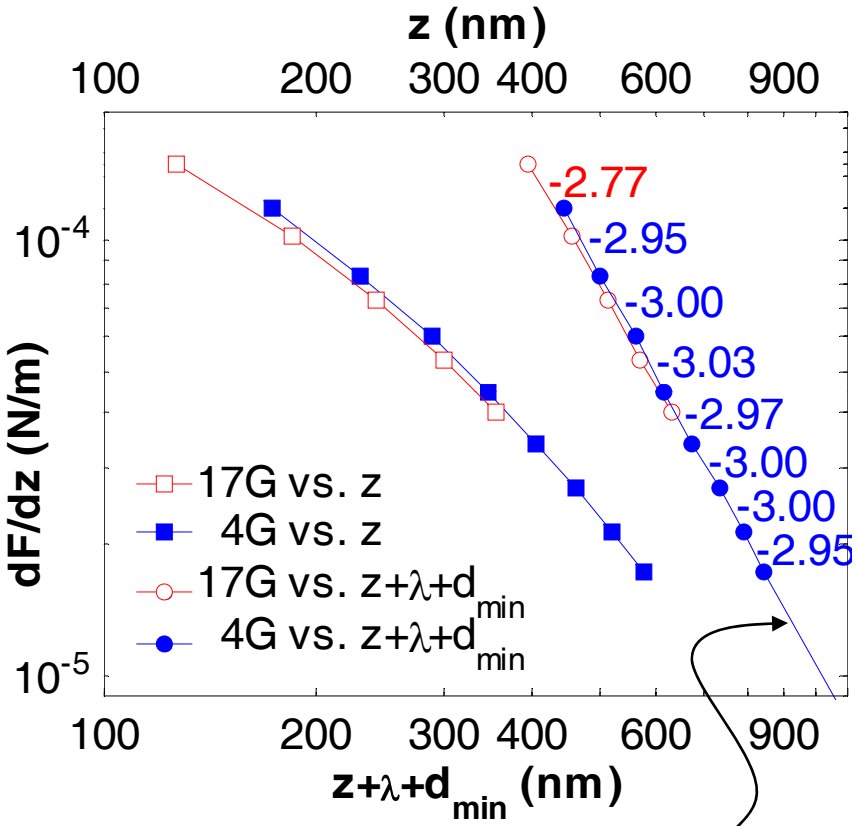


Quantifying the Depinning Force at T = 5.5 K



$$dF_z/dz \sim (z+\lambda+d)^{-3}$$

Quantifying the Depinning Force at T = 5.5 K



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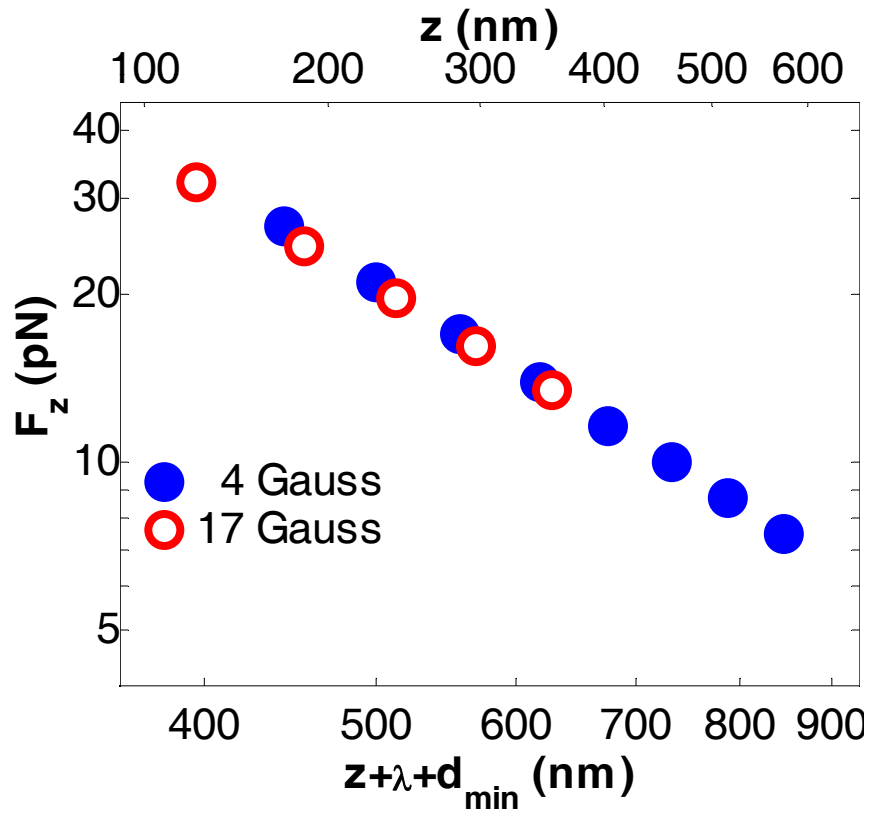

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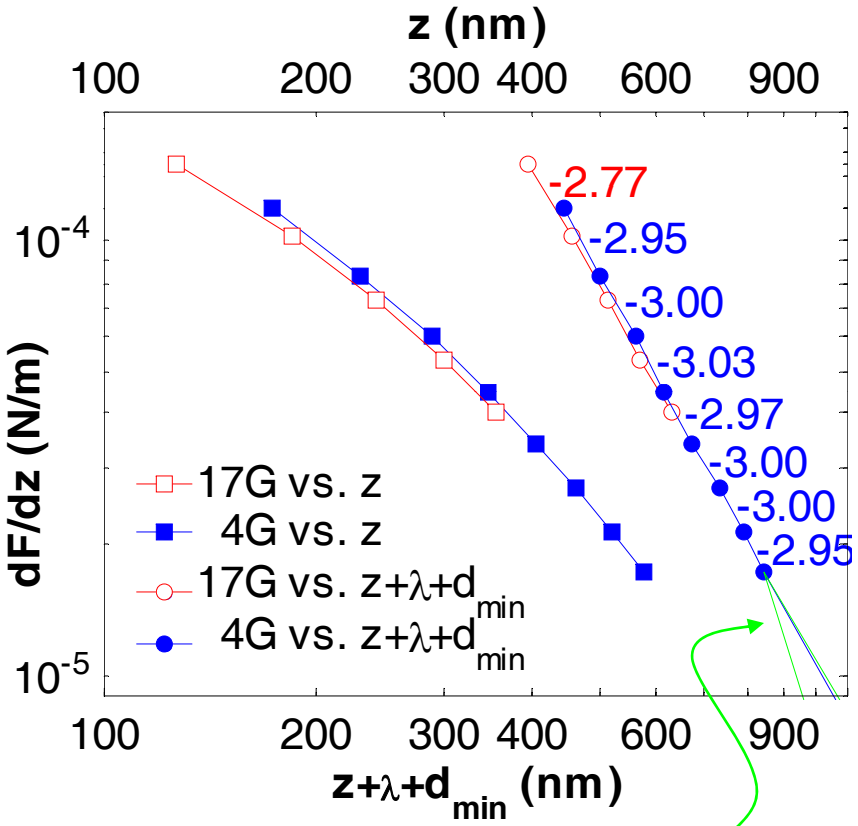
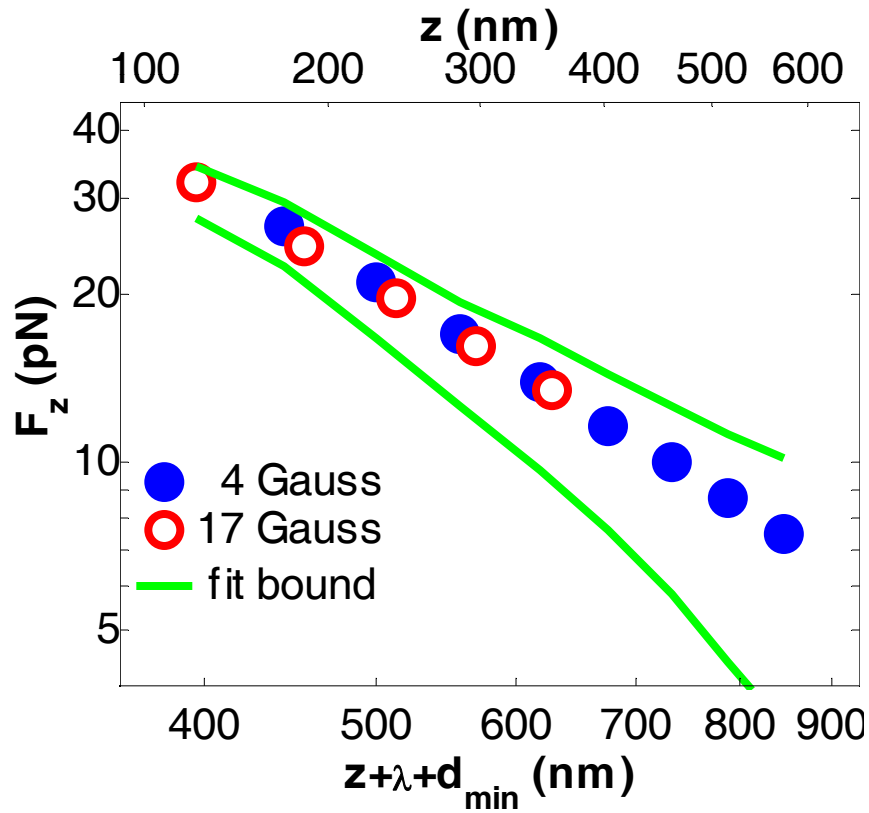
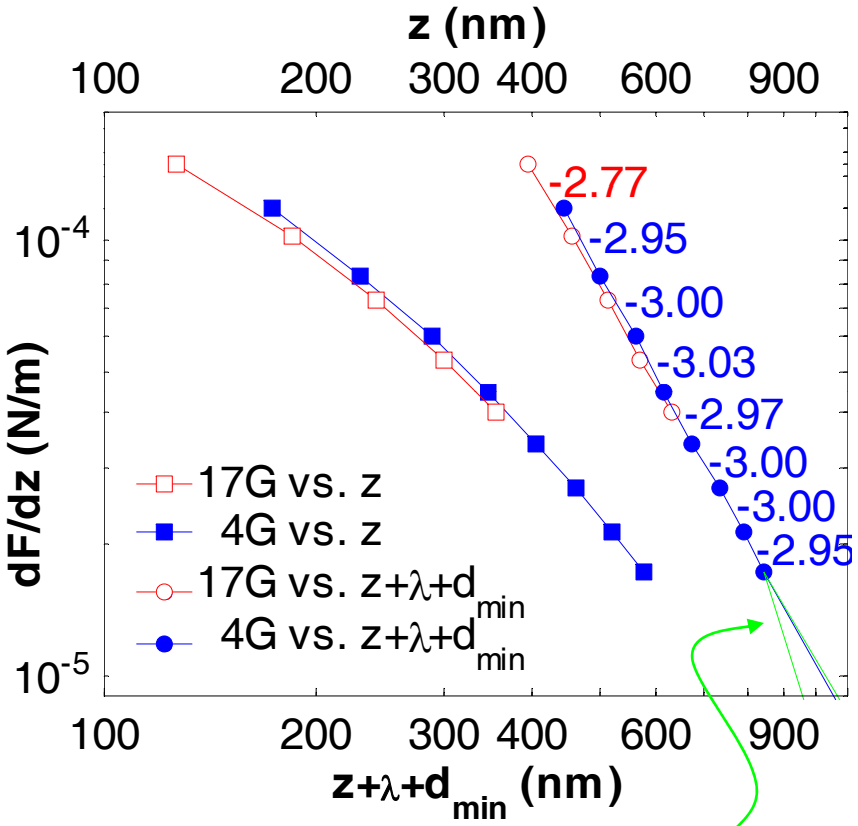


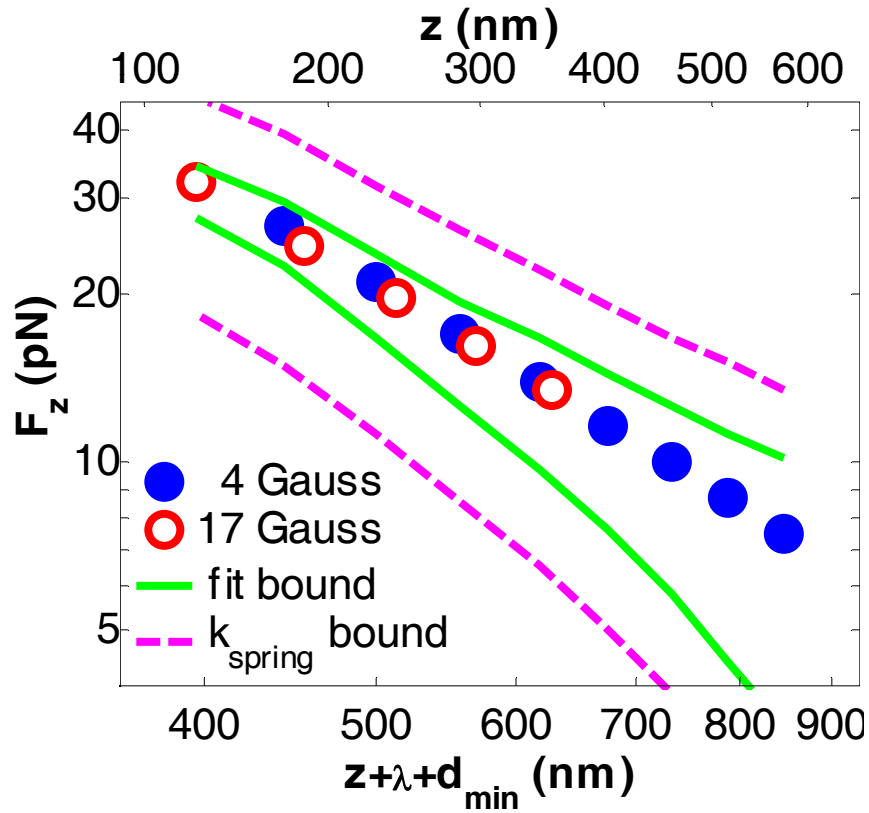
$dF_z/dz \sim (z+\lambda+d)^{-4}$



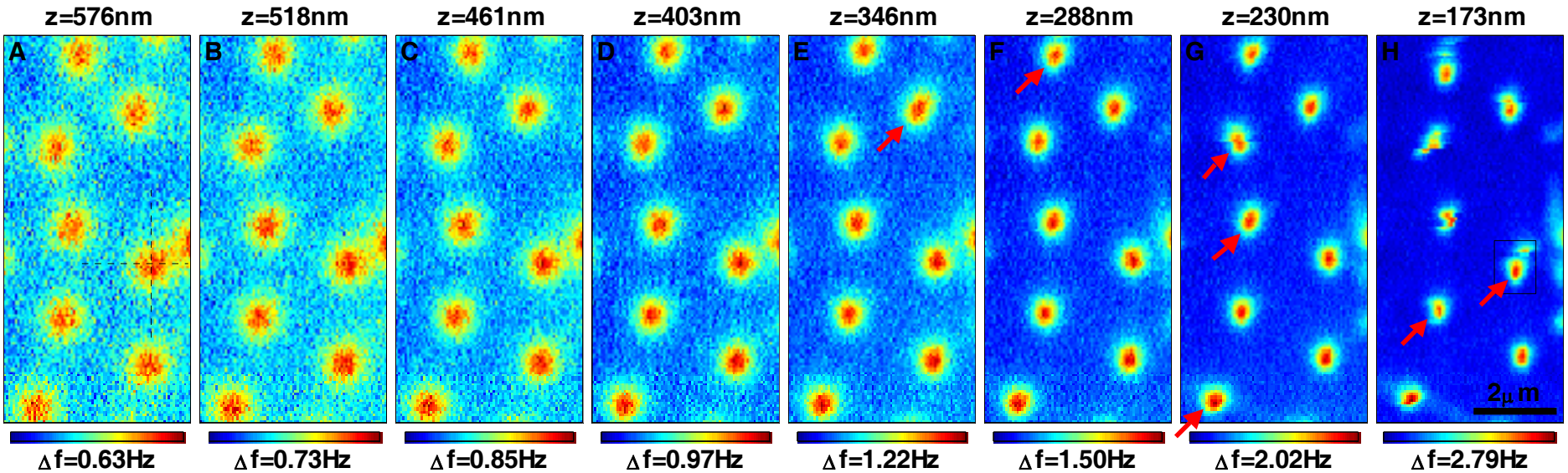
Quantifying the Depinning Force at T = 5.5 K

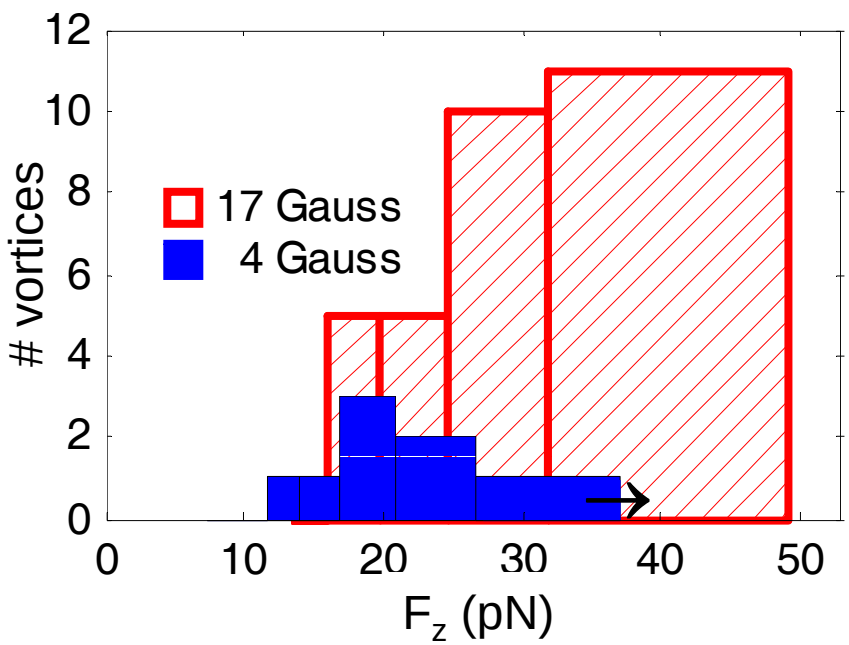


$dF_z/dz \sim (z+\lambda+d)^{-4}$



Depinning Forces in Two Datasets at 5.5 K

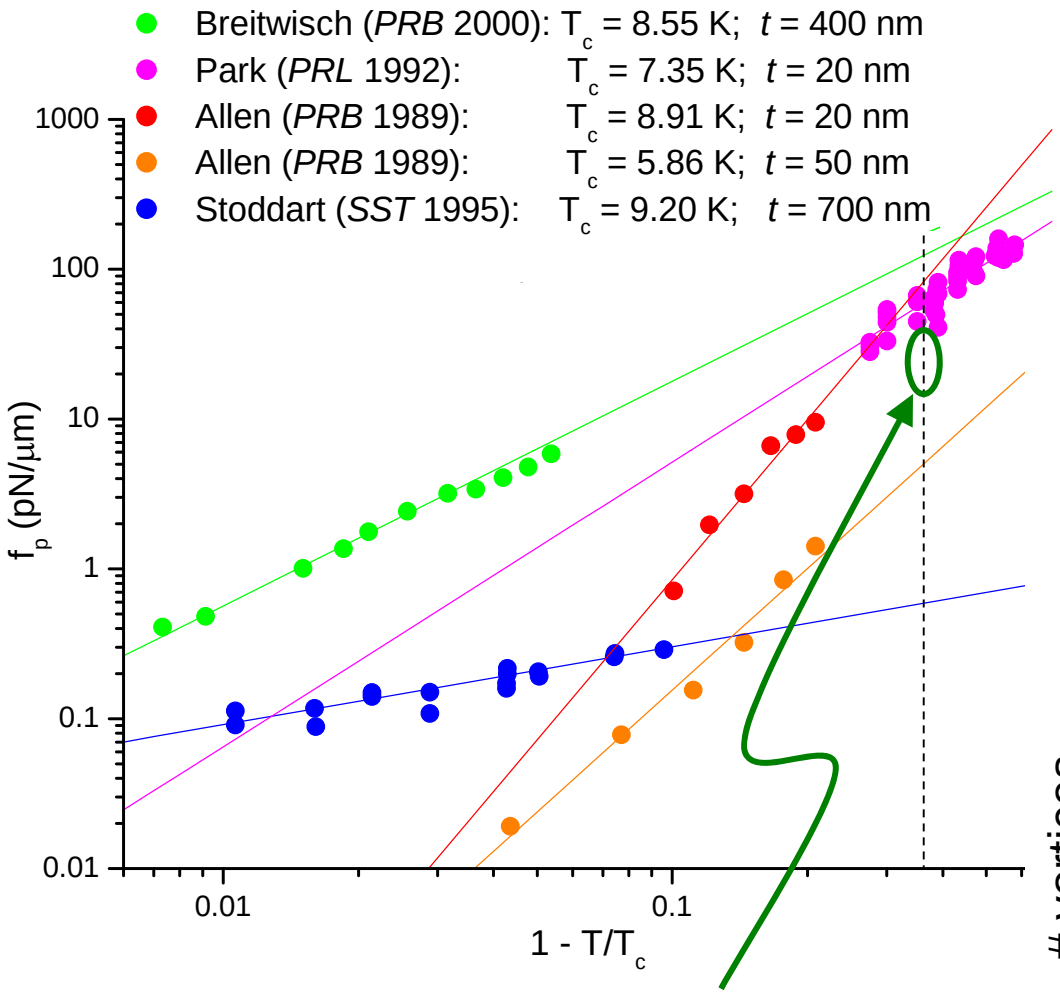




$F_{lateral,max} = 0.38 * F_{z,max}$

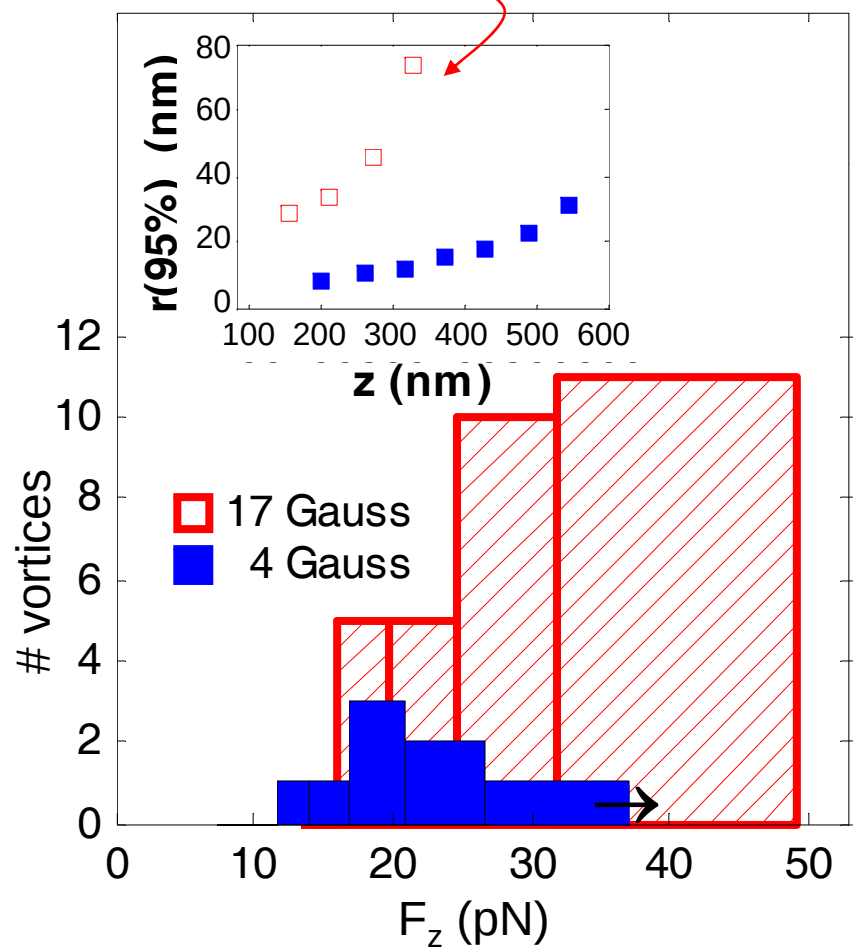
F_{depin} ranges from 4 to 12 pN at 5.5 K

Nb Depinning Forces: Quantitative Comparison



F_{depin} ranges from 15 pN/μm to 40 pN/μm

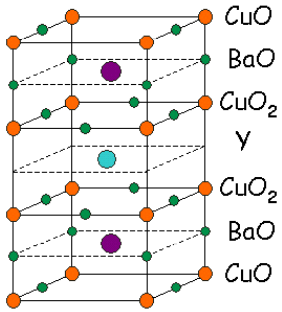
Limits on motion detection from bootstrapping vortex fits: limited by S/N, can be improved

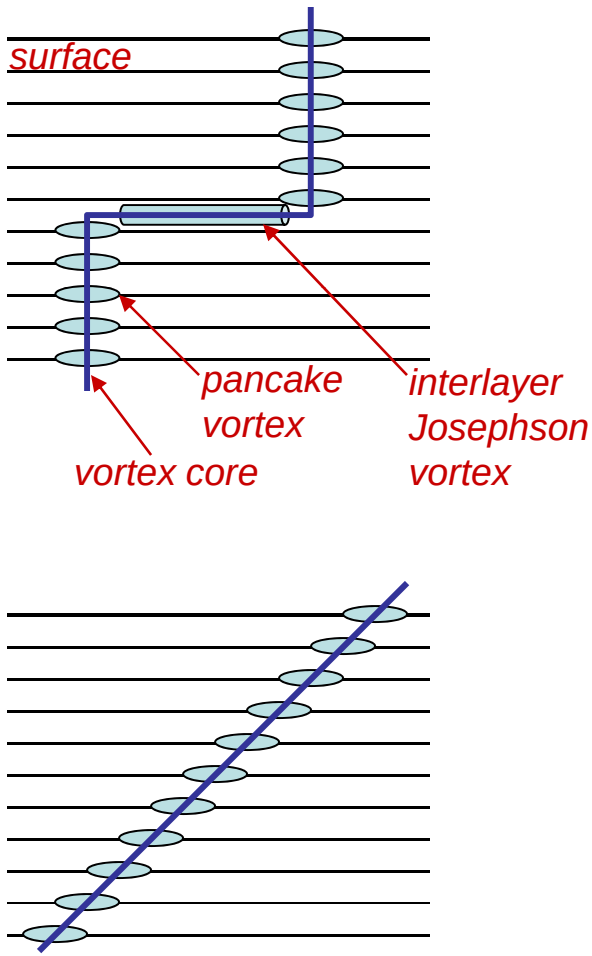


Part II: controlled single-vortex manipulation

Motivation: soft condensed matter physics

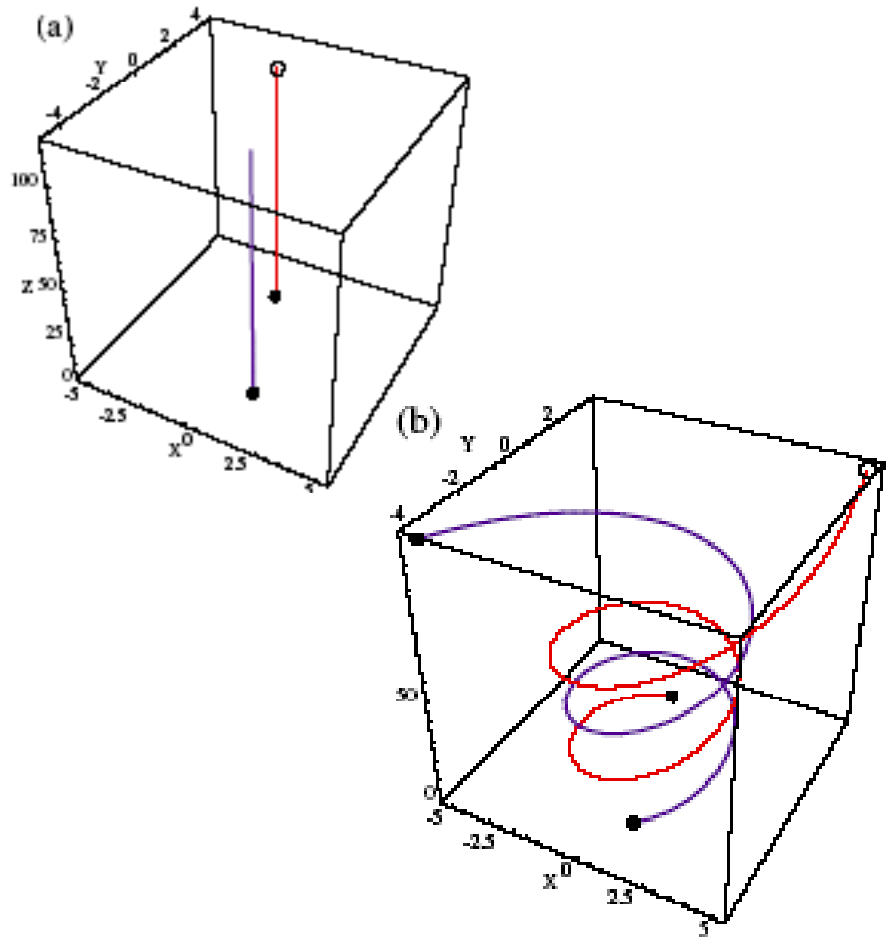
Do vortices split or tilt…





Clem, PRB 43, 7837 (1991)

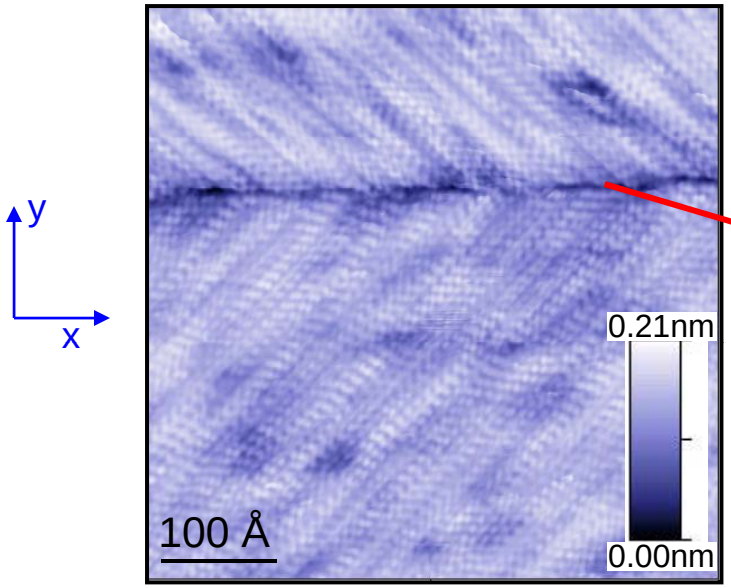
…and do vortices entangle?



Reichhardt & Hastings, PRL 92, 157002 (2004)

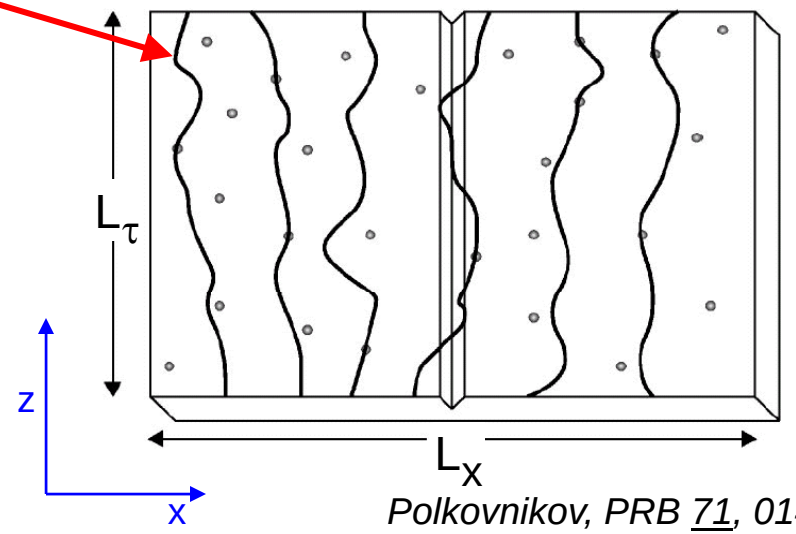
Motivation: Luttinger liquid physics

STM: twin boundary in CuO chain plane of $YBa_2Cu_3O_{7-x}$



Eric Hudson, *et al*

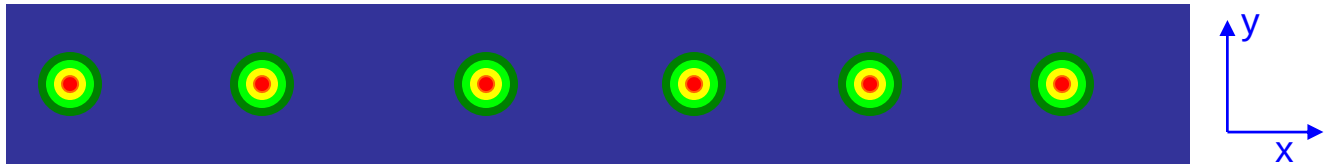
pin vortices in twin boundary plane



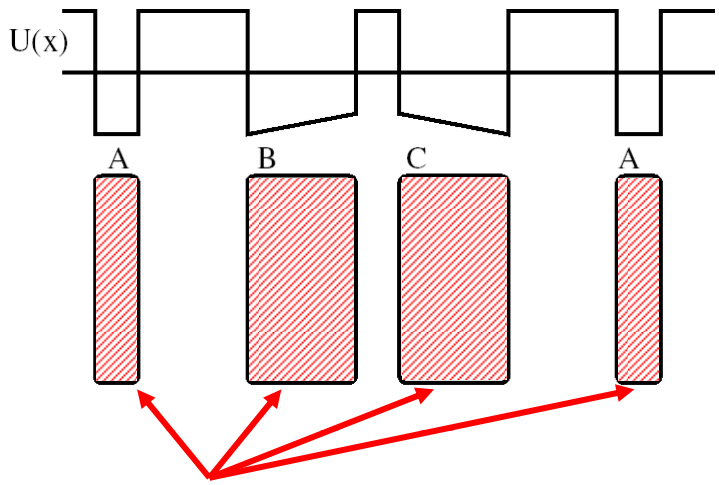
Polkovnikov, PRB 71, 014511 (2005)

vortex wandering in z-direction ←→ 1D particles moving in time

Vortices are like 1D bosons in Luttinger liquid!!



Motivation: vortex ratchet computing

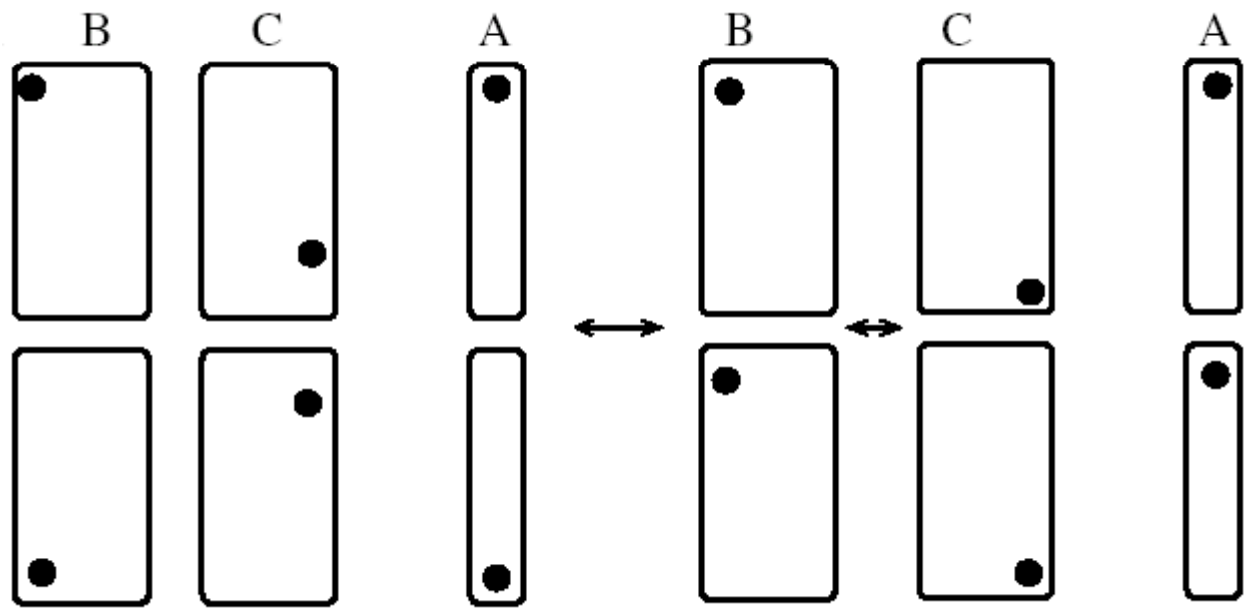


Fabricated defects in a superconductor, used to pin vortices

Real material parameters for MgB_2:

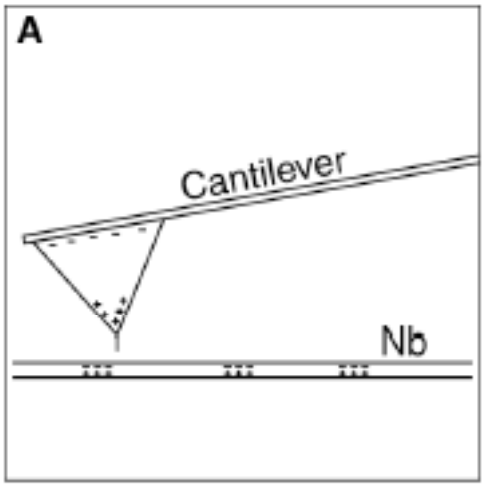
- Maximum speed: simulations show 315 MHz, pair-breaking is in the THz range.
- Minimum size: $\lambda \sim 100$nm
- Power dissipation: 10^{-17} Joules / single cell flip

NAND gate:

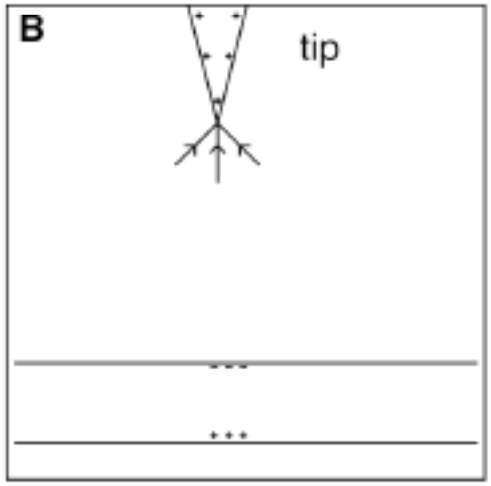


Hastings, Reichhardt, Reichhardt, PRL 90, 247004 (2003)

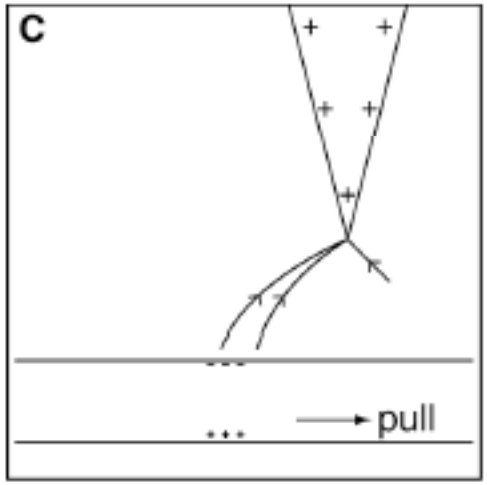
Our Procedure for Single Vortex Manipulation using Magnetic Force Microscopy



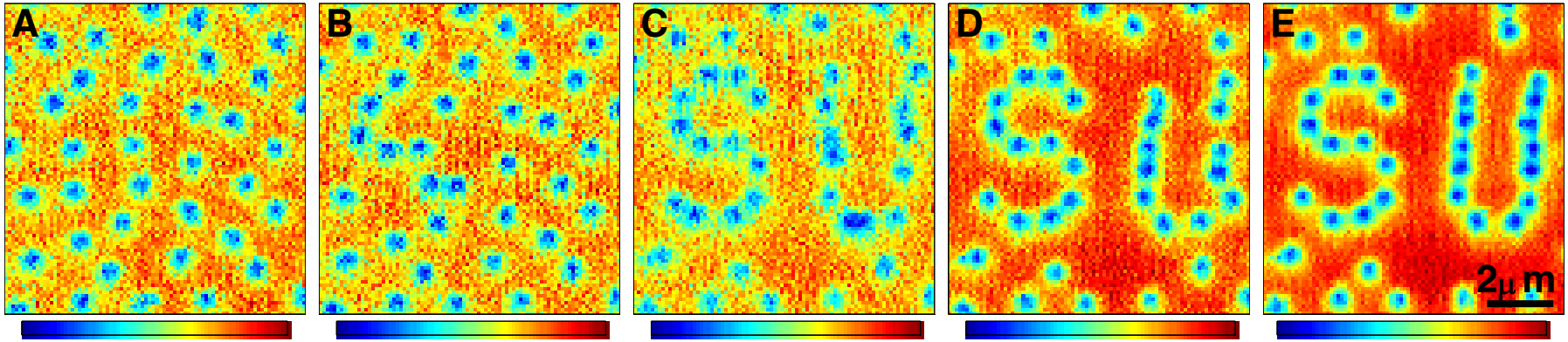
surveillance height



manipulation height

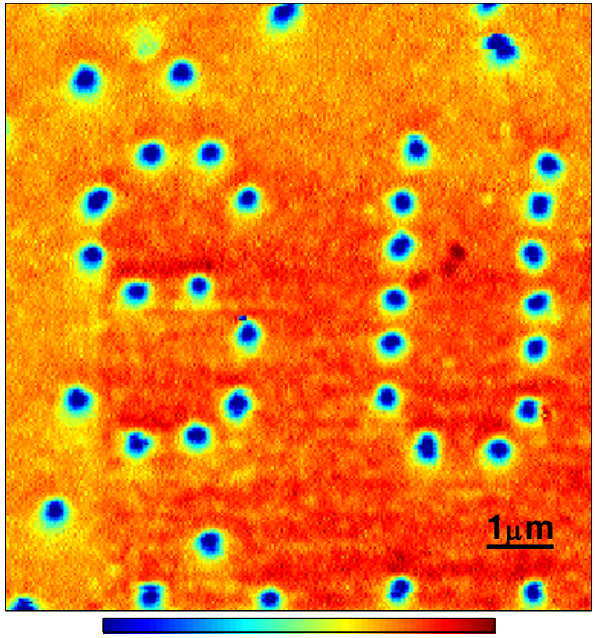


Vortex Manipulation Results



Δf=79mHz Δf=87mHz Δf=96mHz Δf=74mHz Δf=70mHz

T = 7 → 7.2 K
h = 288 nm



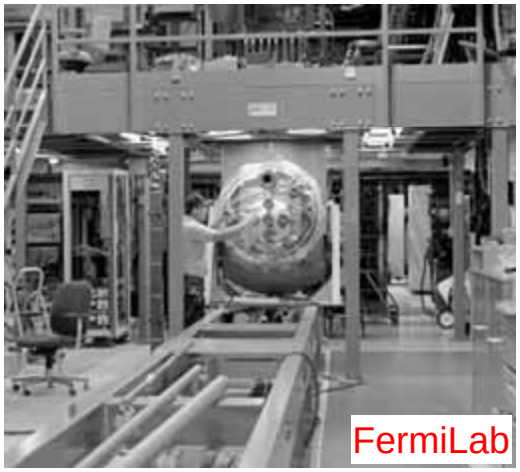
T = 5.53 K
h = 86.4 nm

Δf = 3.21 Hz

Goals

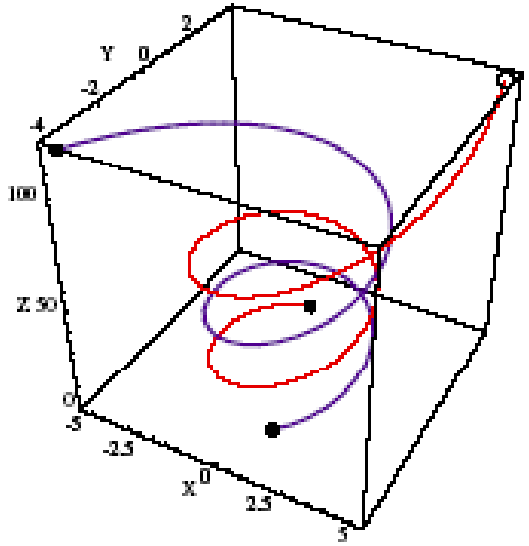
Part I: eliminate uncontrolled vortex motion

- bigger magnets
- efficient power lines
- quieter sensors & circuits



Part II: controlled single-vortex manipulation

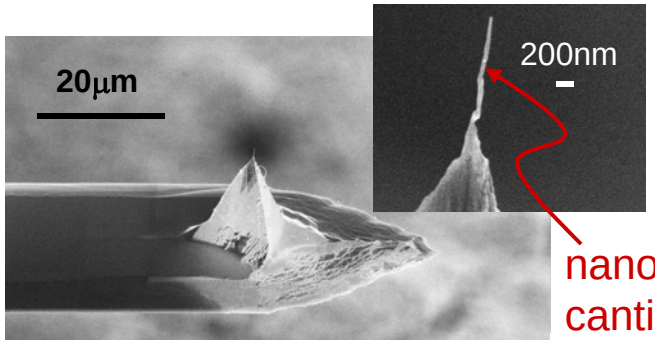
- model for soft condensed matter
- vortex entanglement
- vortex ratchet automaton
- Luttinger liquid



Future directions

- Vortex studies in YBCO

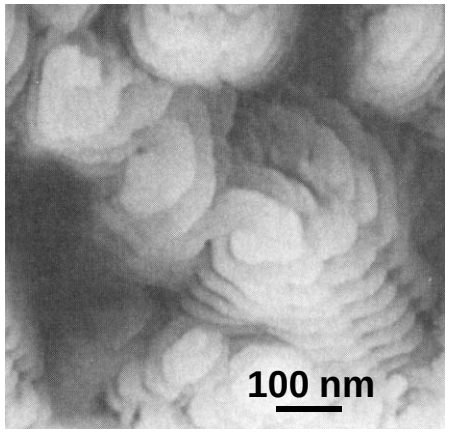
- Better MFM tips:
  - model as monopole



Deng, APL (2004)

nanotube on cantilever tip

  - better AFM spatial resolution, correlate with topography

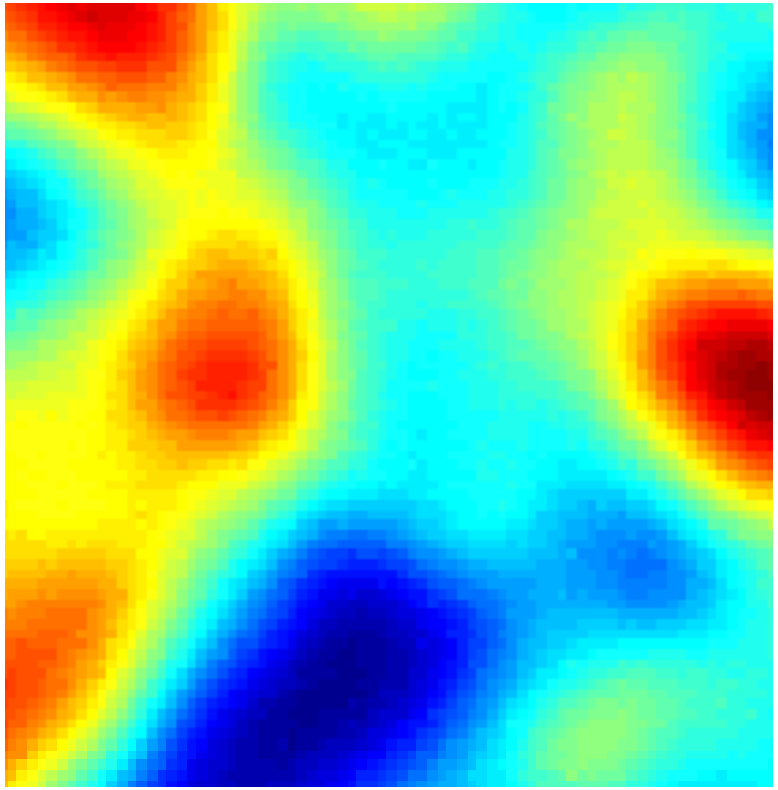


Hawley, Science, 1991

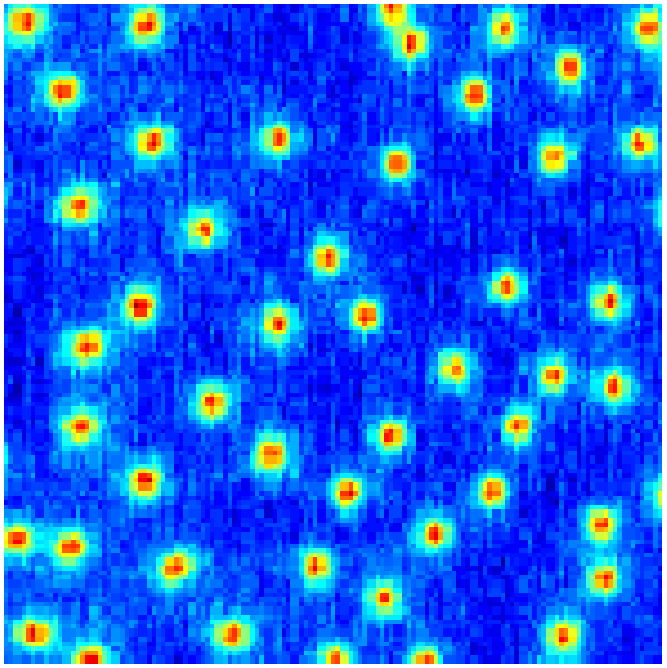
- STM studies: image with $\xi \sim 15$ Å resolution, 100× better than $\lambda \sim 150$ nm

Spatial Resolution

8μm SQUID
0.5 Gauss

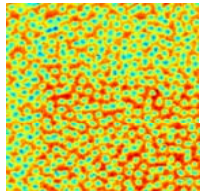


0.5μm Hall Probe
1.1 Gauss

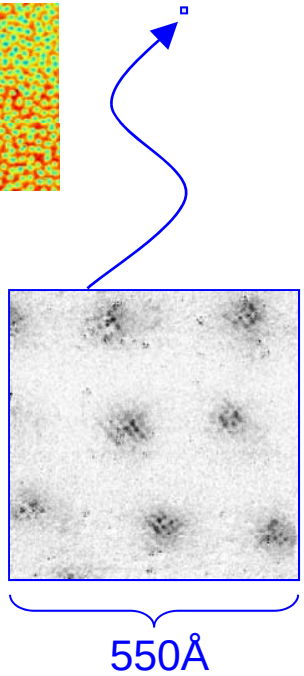


10μm

MFM
100 Gauss



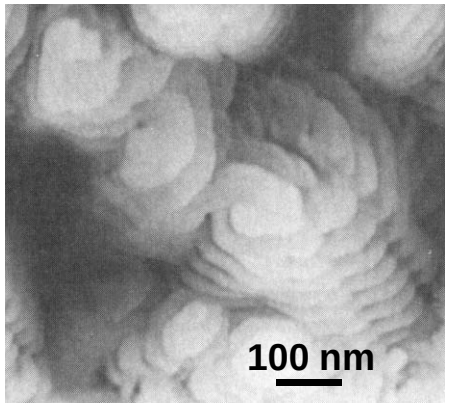
STM
5 Tesla



Future: How to Pin Vortices in YBCO?

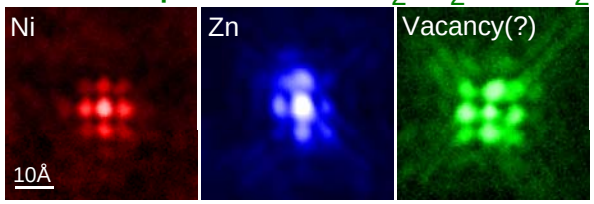
(1) Screw dislocations
(2) Chemical inclusions
(3) Oxygen dopants
(4) Twin boundaries

STM: spiral growth patterns



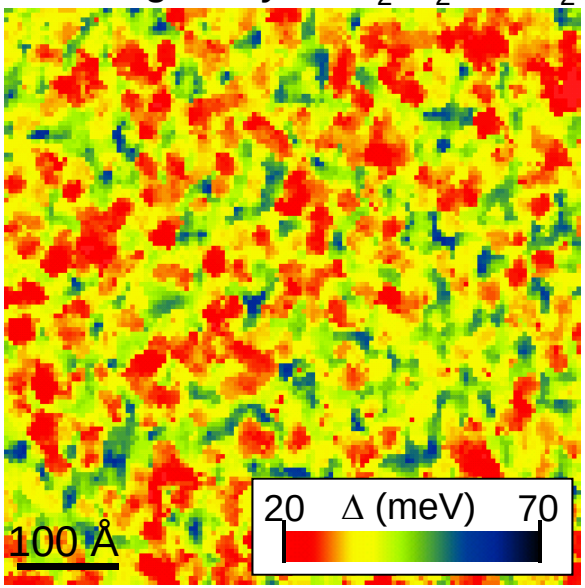
Hawley, Science, 1991

STM: impurities in $Bi_2Sr_2CaCu_2O_{8+x}$



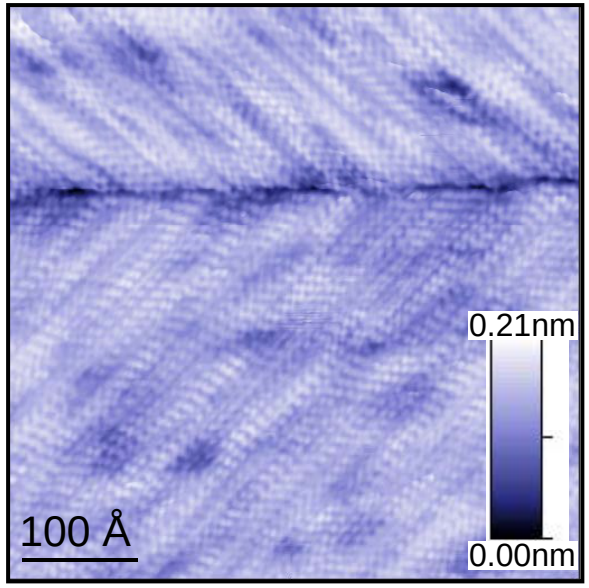
Hudson *et al*, Nature 411, 920 (2001).
Pan *et al*, Nature 403, 746 (2000).
Hudson *et al*, Physica B 329, 1365 (2003).

STM: superconducting gap inhomogeneity in $Bi_2Sr_2CaCu_2O_{8+x}$



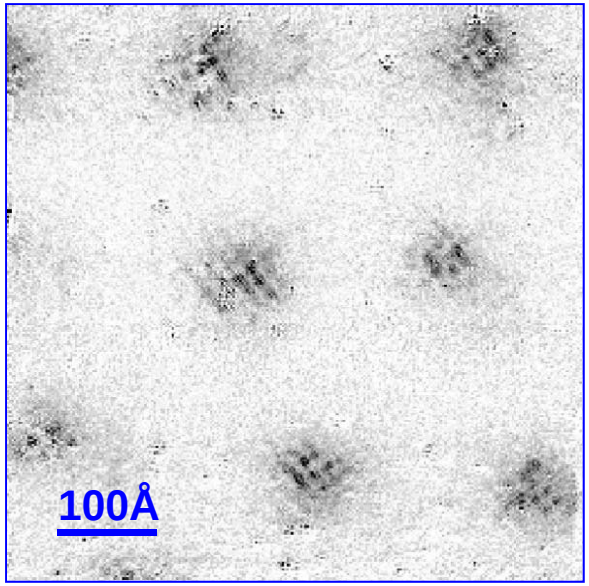
Lang *et al*, Nature 415, 412 (2002).

STM: twin boundary in CuO chain plane of $YBa_2Cu_3O_{7-x}$



Eric Hudson, unpublished.

Vortex imaging in $Bi_2Sr_2CaCu_2O_{8+x}$

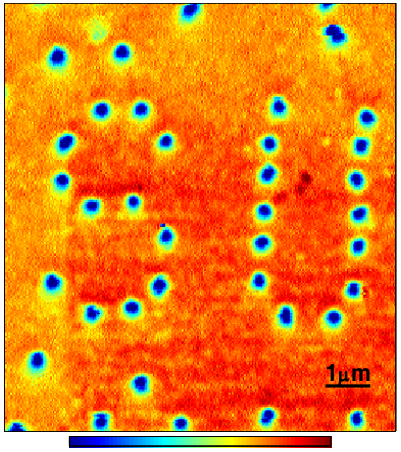


Hoffman, Science (2002).

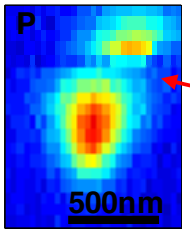
Summary

- Manipulate single vortices with nanoscale control
- Measured directly the depinning forces in Nb

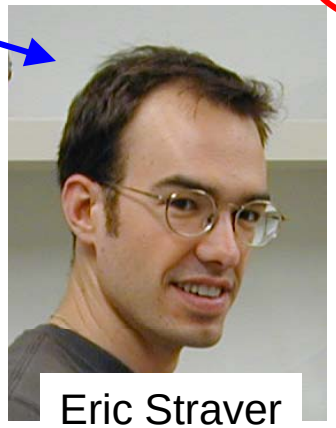
  → already applying same technique to YBCO



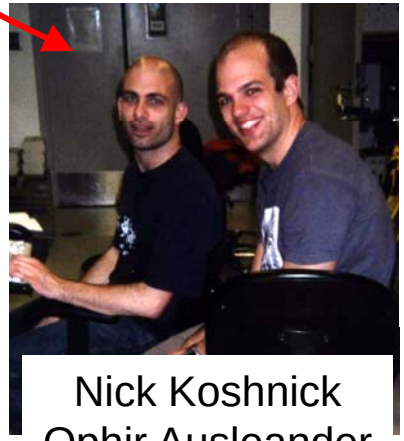
Δf = 3.21 Hz



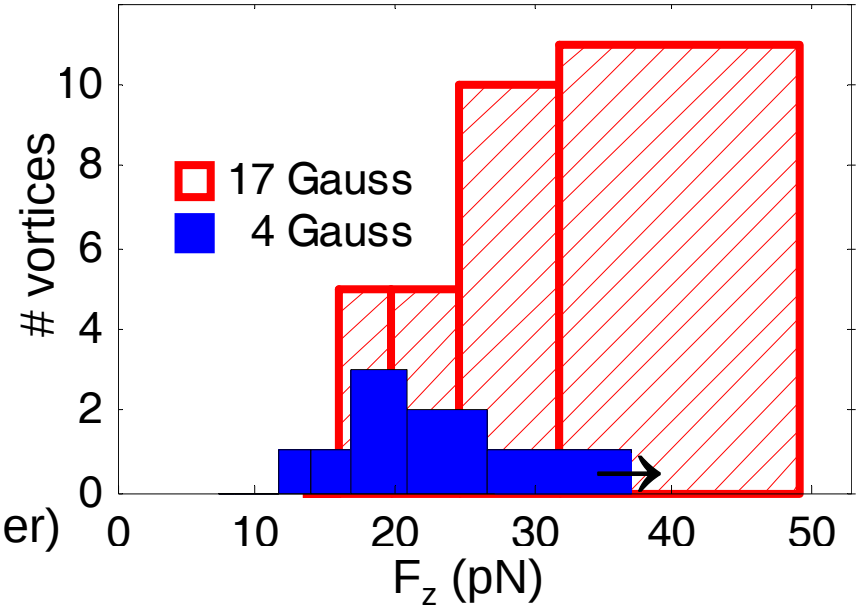
vortex motion event



Eric Straver



Nick Koshnick
Ophir Ausleander



Next:
- correlate depinning forces with topography (Moler)
- STM studies to explore higher fields (Hoffman)