Tailored design of vortex behaviour and its visualisation with high-speed magneto-optical video

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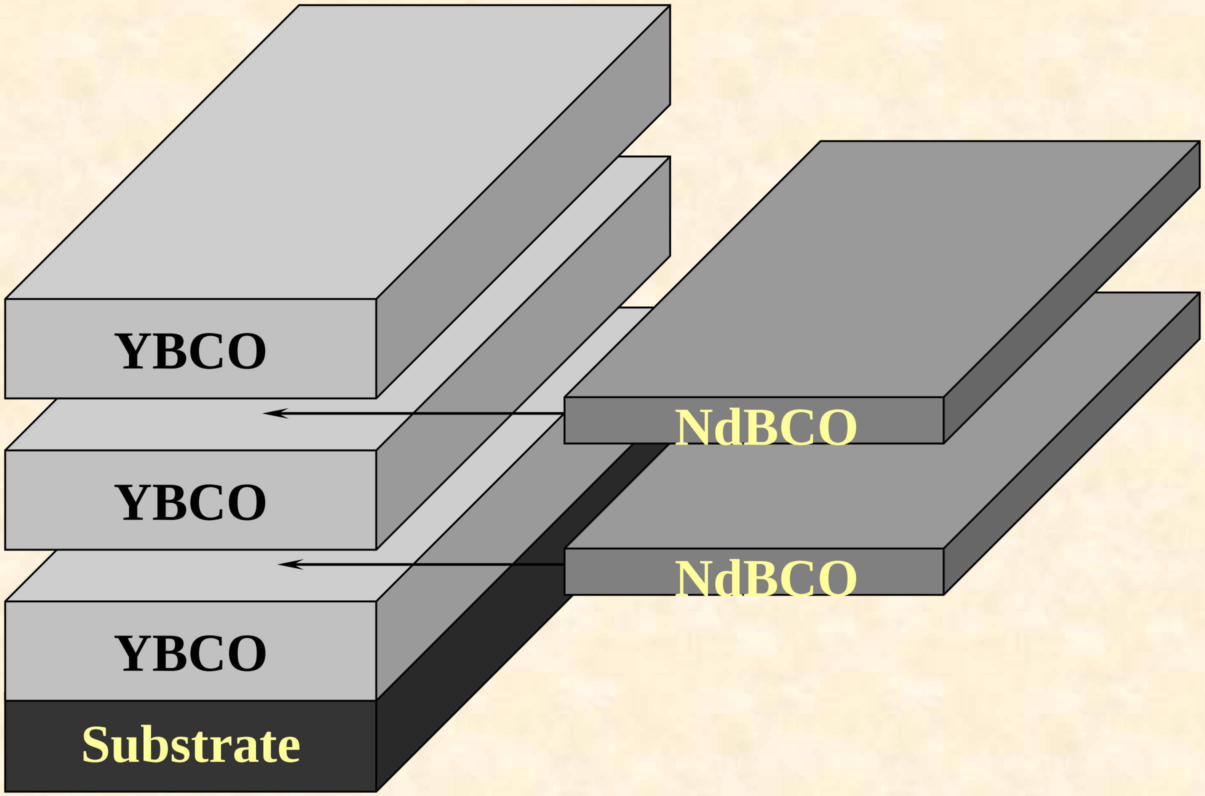
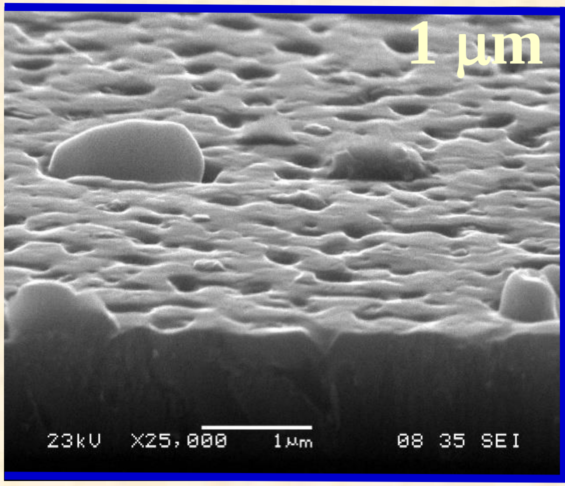
PLD YBCO film multilayering: An alternative to nano-doping

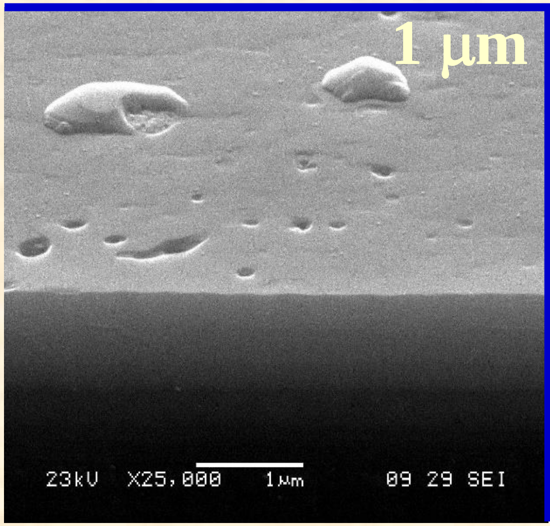


A.V. Pan, *APL* 88, 232506 (2006)
A. V. Pan, *et al.*, *IEEE Trans. Appl. Supercond.* **17**, 3585 (2007)

Surface morphology of YBCO film



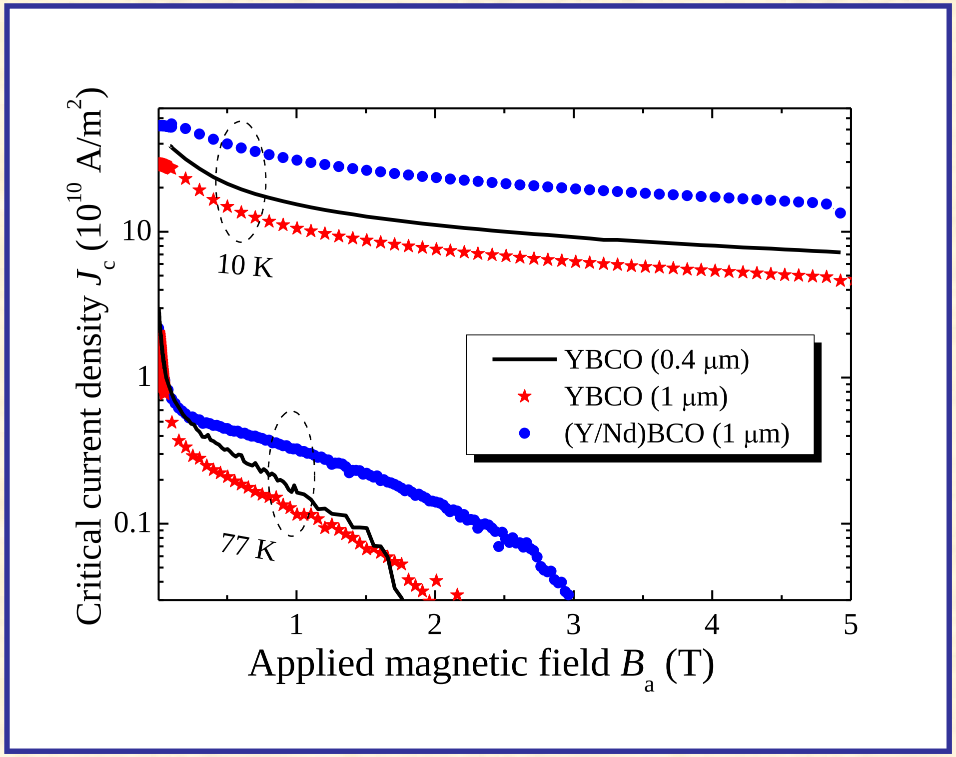
(Y/Nd)BCO multilayer

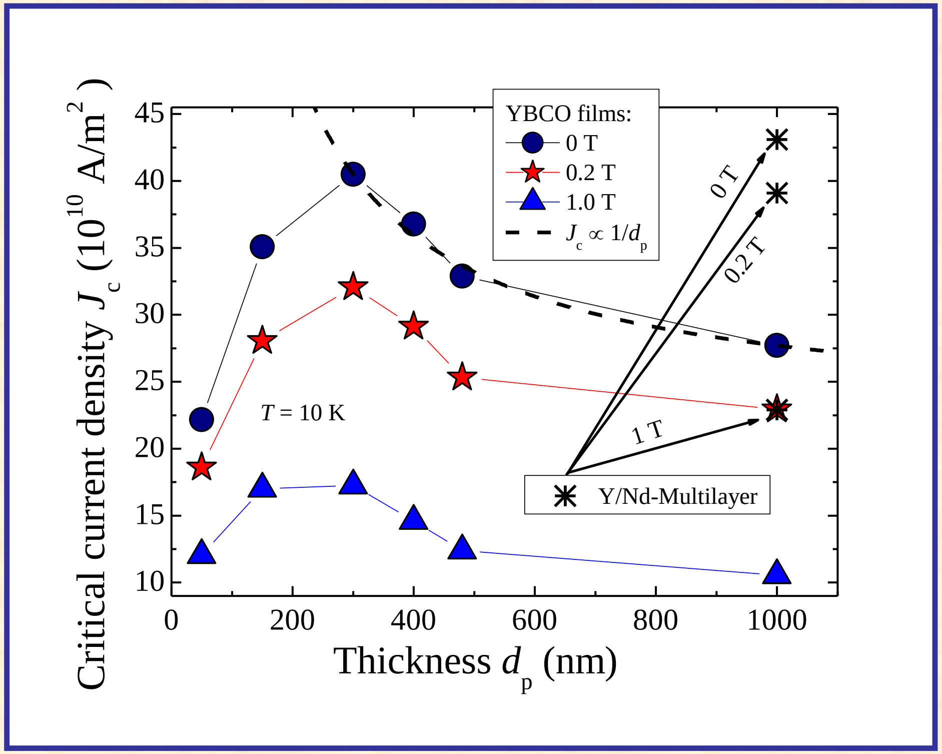


- Much smoother surface;
- 10% – 30% denser films;
- Additional network of dislocations.

A.V. Pan et al, *APL* **88**, 232506 (2006)

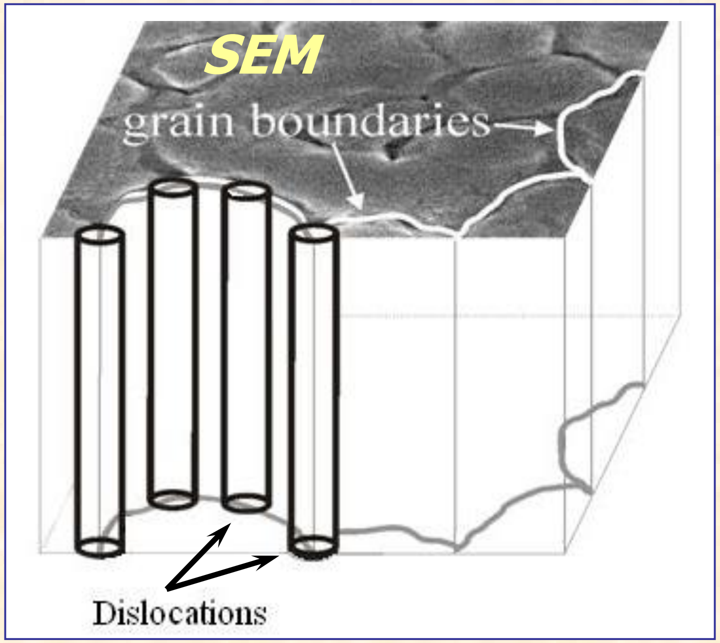
$J_c(B_a)$ enhancement over the entire field range



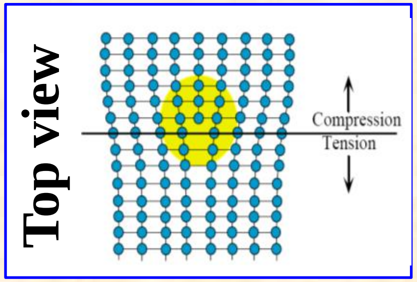


- The J_c **enhancement is by a factor of 2 to 3** in 1 μm thick multilayer compared to the monolayer film of the same thickness.
- J_c in the (Y/Nd)BCO multilayer is even larger than that in 0.4 μm thick films.

Quantitative pinning model on edge dislocations

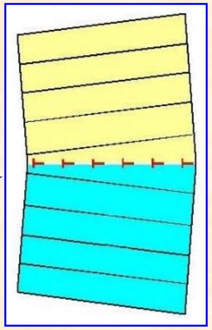


• Edge dislocations appear due to the mismatch between the substrate and film crystal lattices.



• The network of domain walls is formed due to a large number of out-of-plane dislocations.

Tilt boundary



• Domain walls possess strong vortex pinning.

These are the main assumptions for the quantitative model based on extensive structural studies of YBCO films.

V. Pan et al., *PRB* **73**, 054508 (2006); V. Pan and A. V. Pan, Low Temp. Phys. **27**, 732 (2001); A. V. Pan, et al, *IEEE Trans. Appl. Supercond.*, **19** , 3391 (2009)

Quantitative pinning model on edge dislocations: Taking into account flux creep

- Pinning energy:

$$U = U_0 \frac{n_p}{n_v} K_{sh}(d, B_a)$$

U_0 – pinning energy of single vortex on one edge dislocation;

d – distance between edge dislocations

- Electric field dissipation caused by vortex creep:

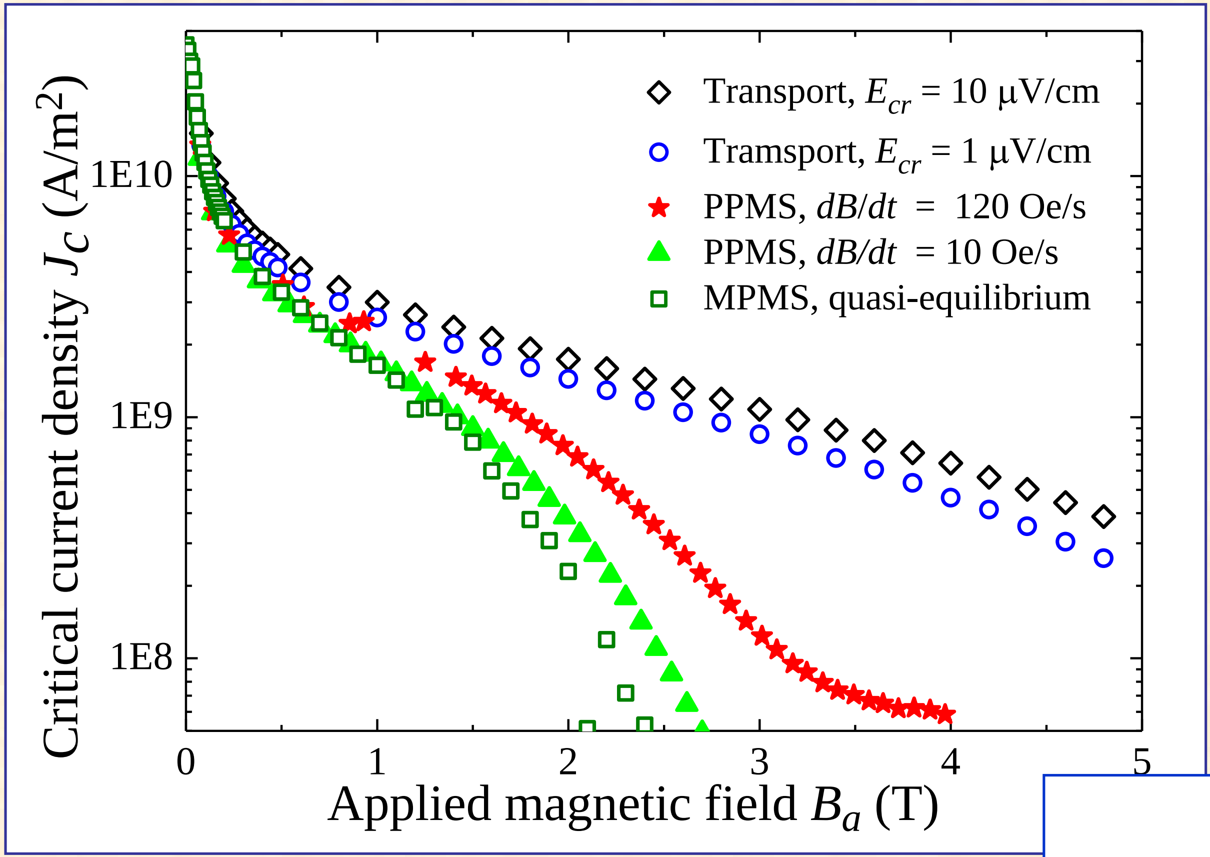
$$\vec{E} = [\vec{V} \times \vec{B}_a]$$

Model equation

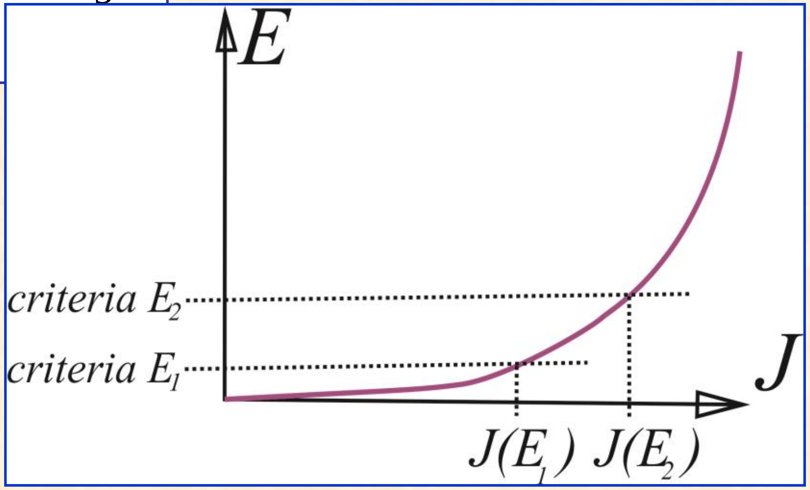
$$J_c(B_a, T, E_{cr}) = \alpha k T \sinh^{-1}\left[\frac{E_{cr}}{a_0(B_a)\nu_0 B_a} \exp\left(-\frac{U_0 \frac{n_p}{n_v}(B_a) K_{sh}(d, B_a)}{kT}\right)\right]$$

I. A. Golovchanskiy, et al., *Supercond. Sci. Technol*. **24**, 105020 (2011)
Physica C **479**, 151 (2012)

Fitting the experiment with the model

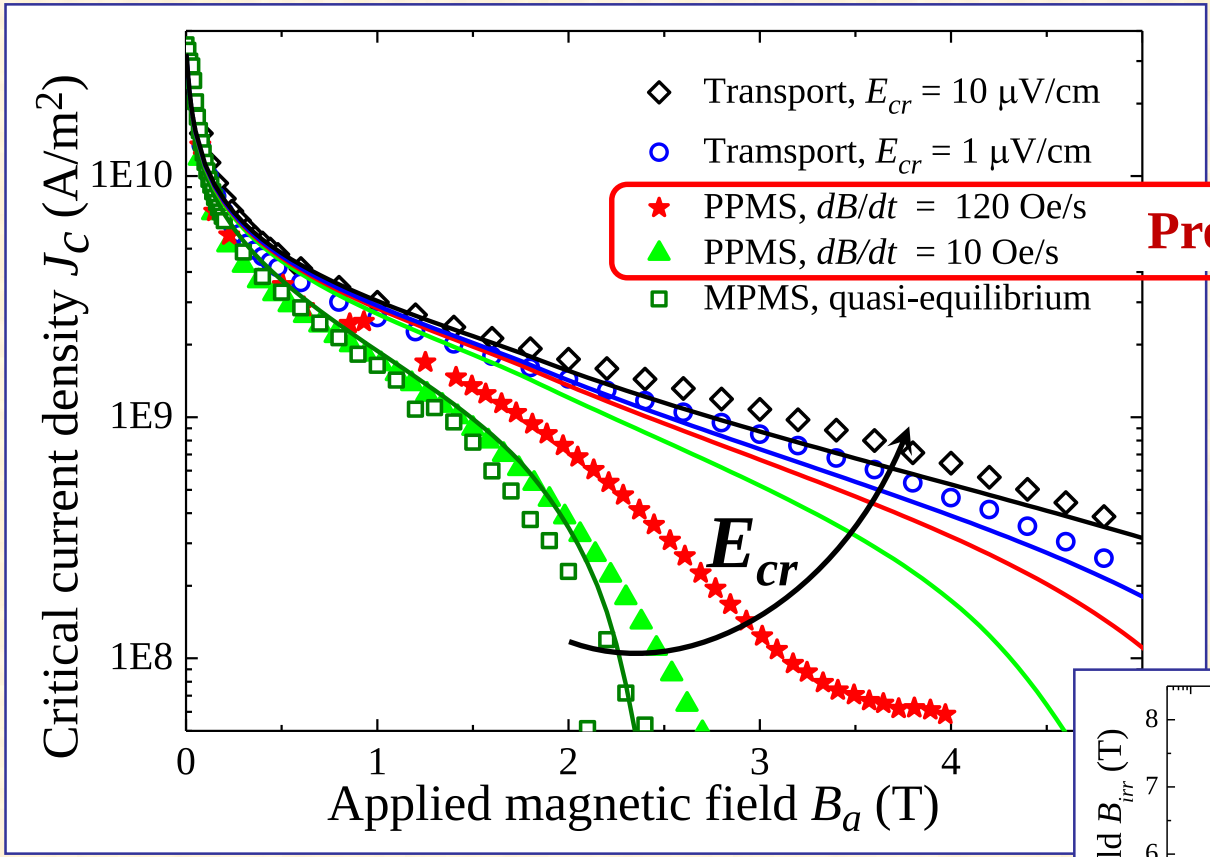


- **One PLD film shows** such huge difference in the J_c results measured by different techniques:
- More than the 4-fold difference in the so-called B_{irr}!

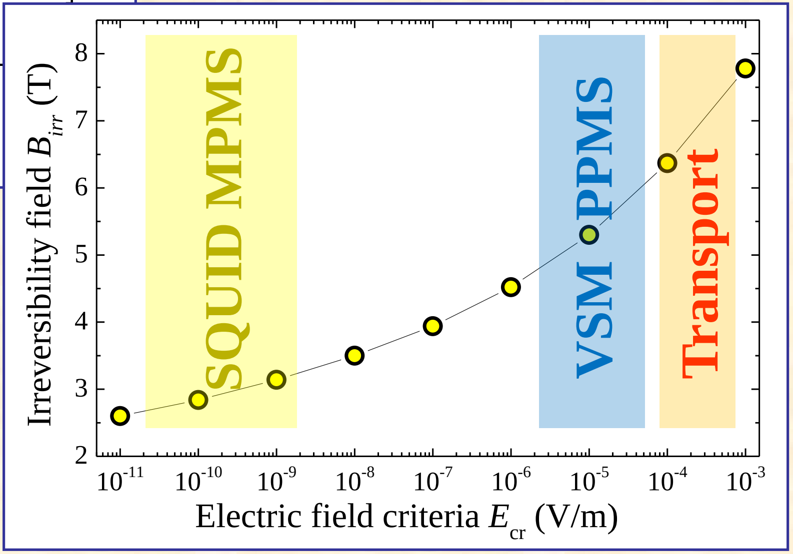


A.V. Pan et al, *EPL* **103**, 17006 (2013)
I. A. Golovchanskiy, A. V. Pan, et al. *JAP* **114**, 163910 (2013)
I. A. Golovchanskiy, A. V. Pan, et al., *SUST* **29**, 075002 (2016)

Fitting the experiment with the model



Problem with fitting PPMS!?

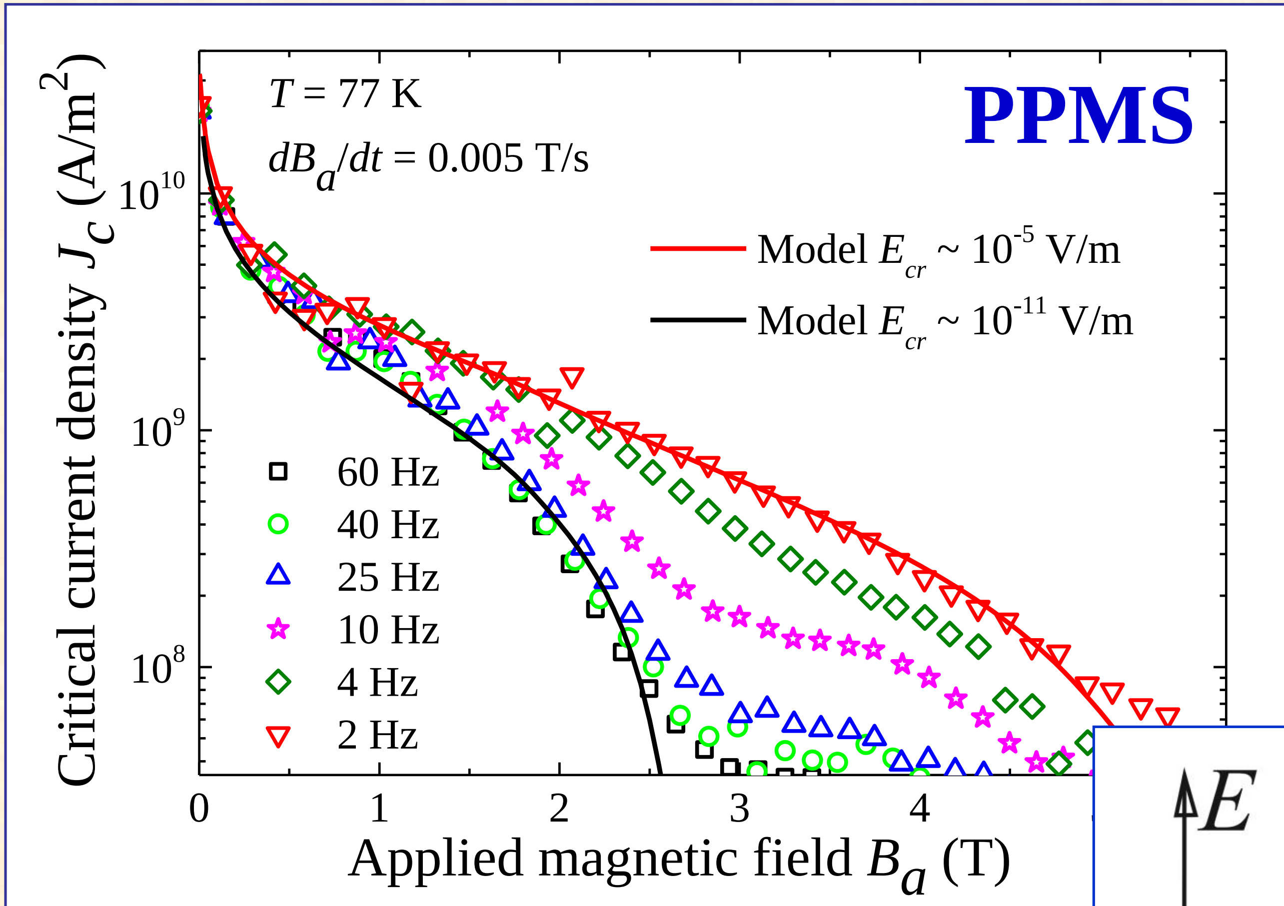


Model parameters do not change for fitting the $J_c(B_a)$ curves, only the E_{cr} criterion does.

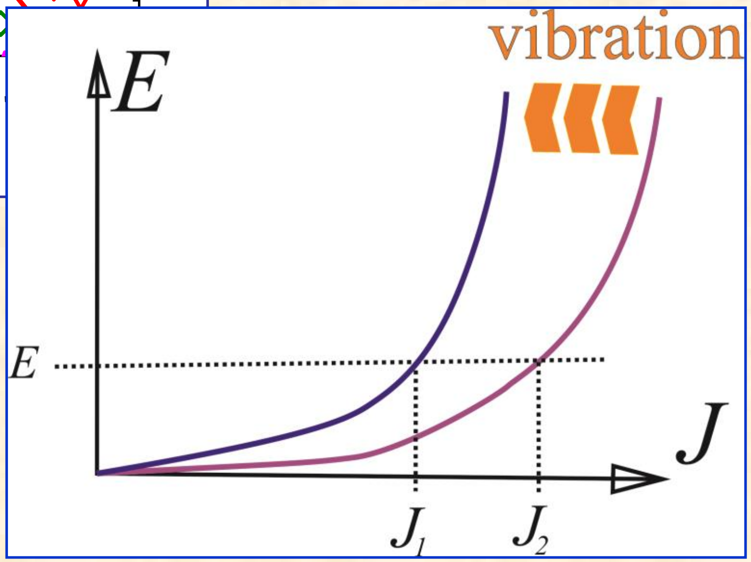
A.V. Pan et al, *EPL* **103**, 17006 (2013)

I. A. Golovchanskiy, A. V. Pan, et al. *JAP* **114**, 163910 (2013); *SUST* **29**, 075002 (2016).

Influence of vibration in applied magnetic fields



YBCO



One sample, "same" measurements, BUT...

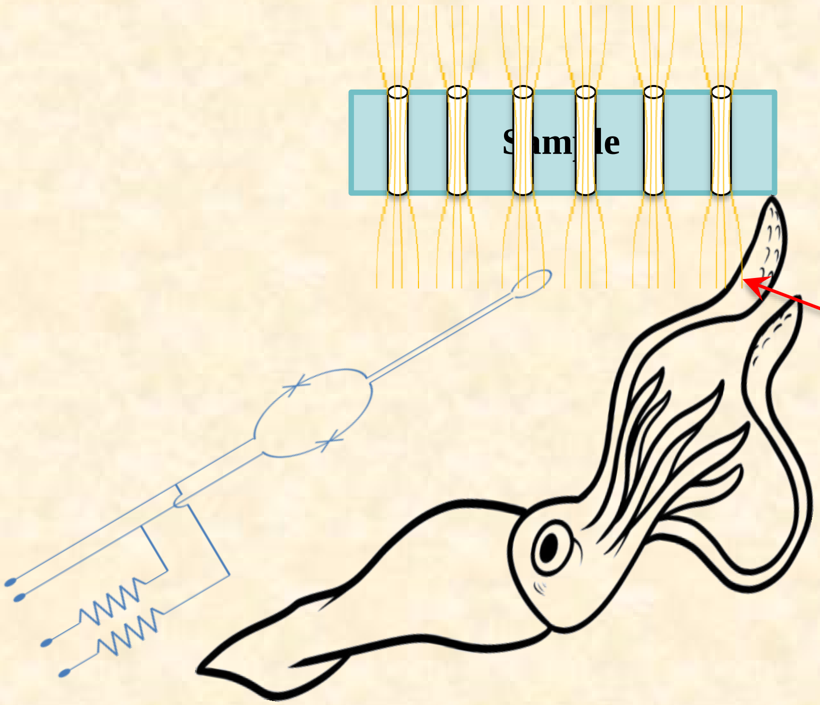
- B_{irr} changes by a factor of 2.5;
- $J_c(B_a)$ shows "different" pinning regimes.

A.V. Pan et al, *EPL* **103**, 17006 (2013)
I. A. Golovchanskiy, A. V. Pan, et al. *JAP* **114**, 163910 (2013)

Can we visualise/design these behaviour?

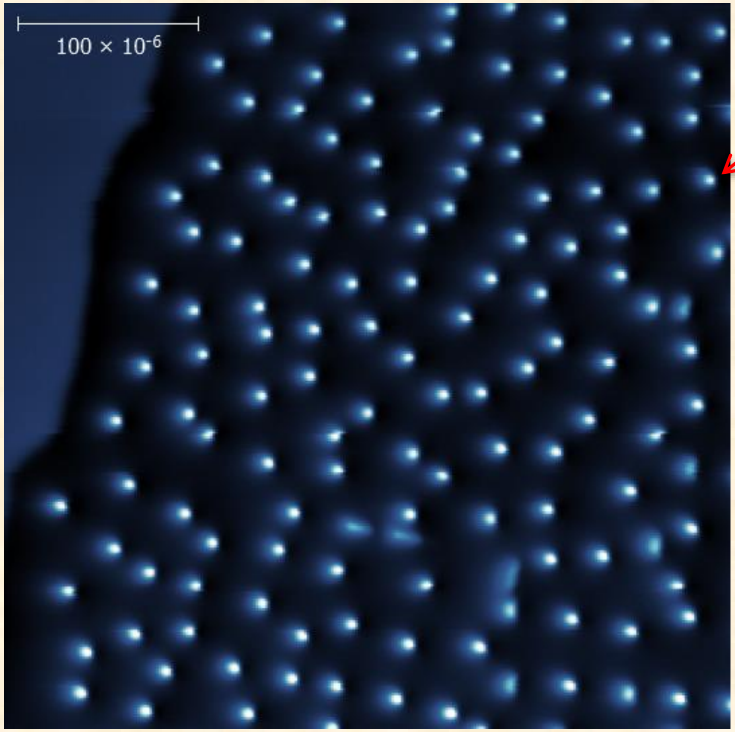
Scanning **SQUID Microscopy to see vortices**:

with a SQUID scaning across a sample



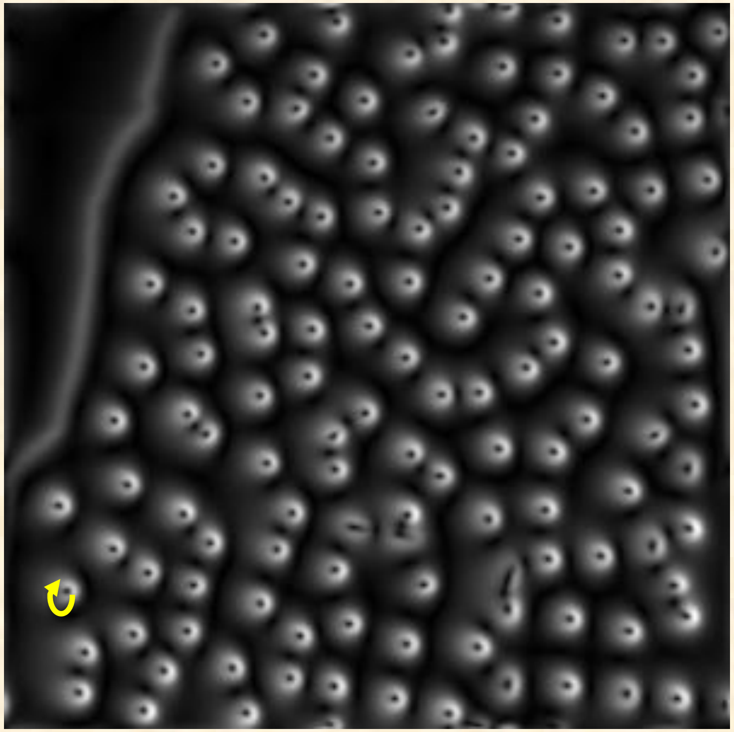
where SQUID is Superconducting Quantum Interference Device.

Vortex Visualisation with SQUID Microscopy

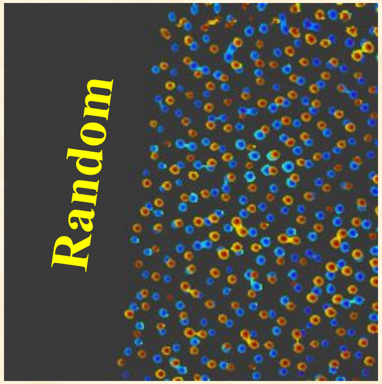


Magnetic Field Image

Calculation



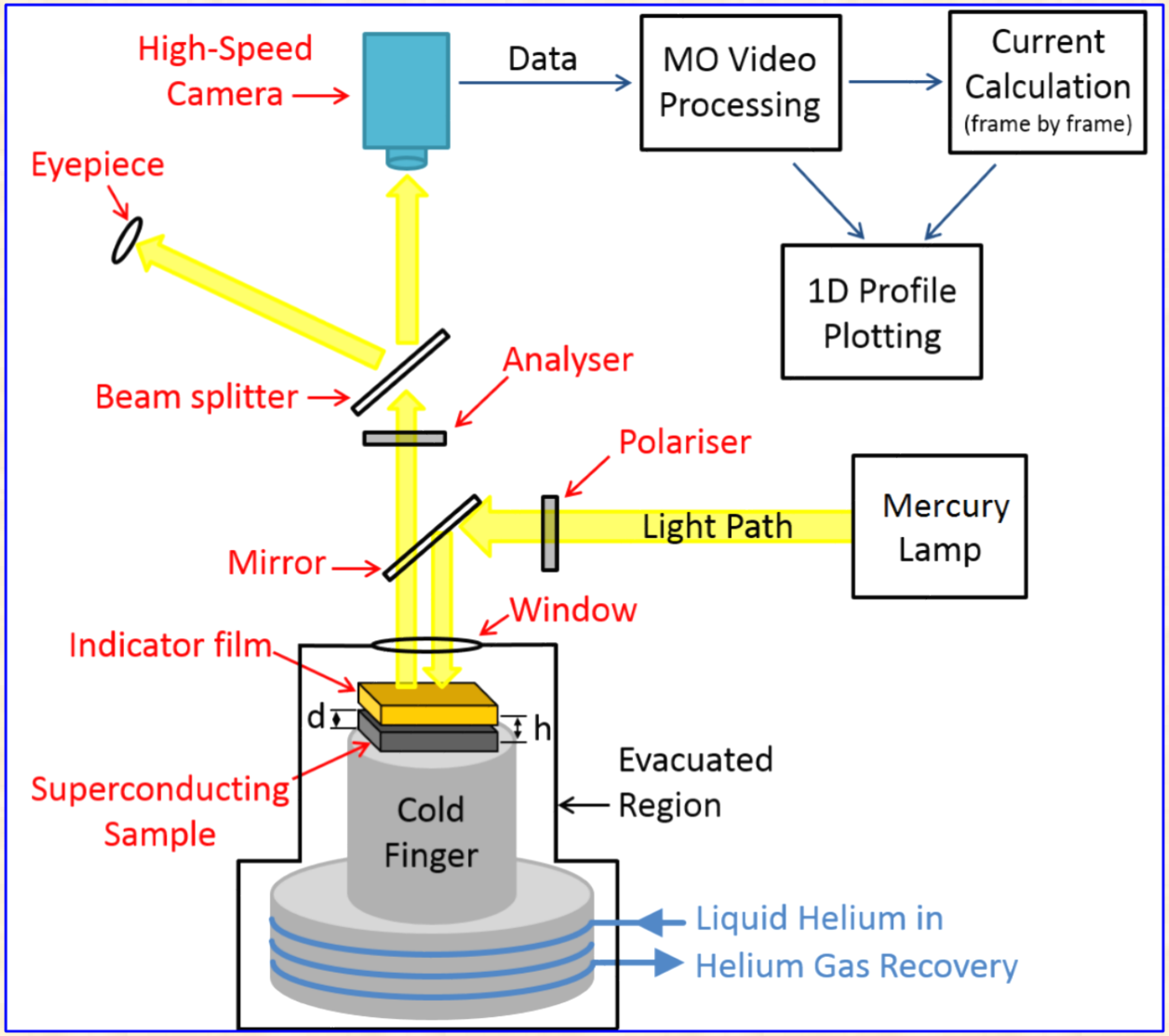
Current Image



Static imaging in the field is of the order of the **Earth** Field ~μT.

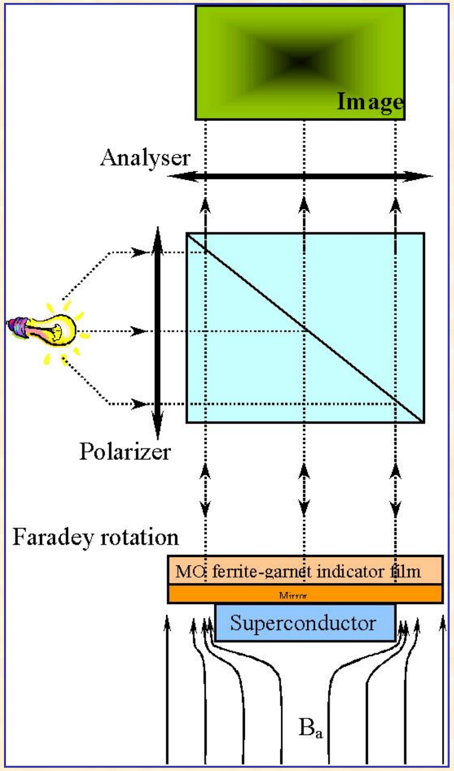
F. S. Wells, A. V. Pan, et al., *Scientific Reports* **5**, 8677 (2015)

Magneto Optical Imaging (MOI) of Flux Penetration

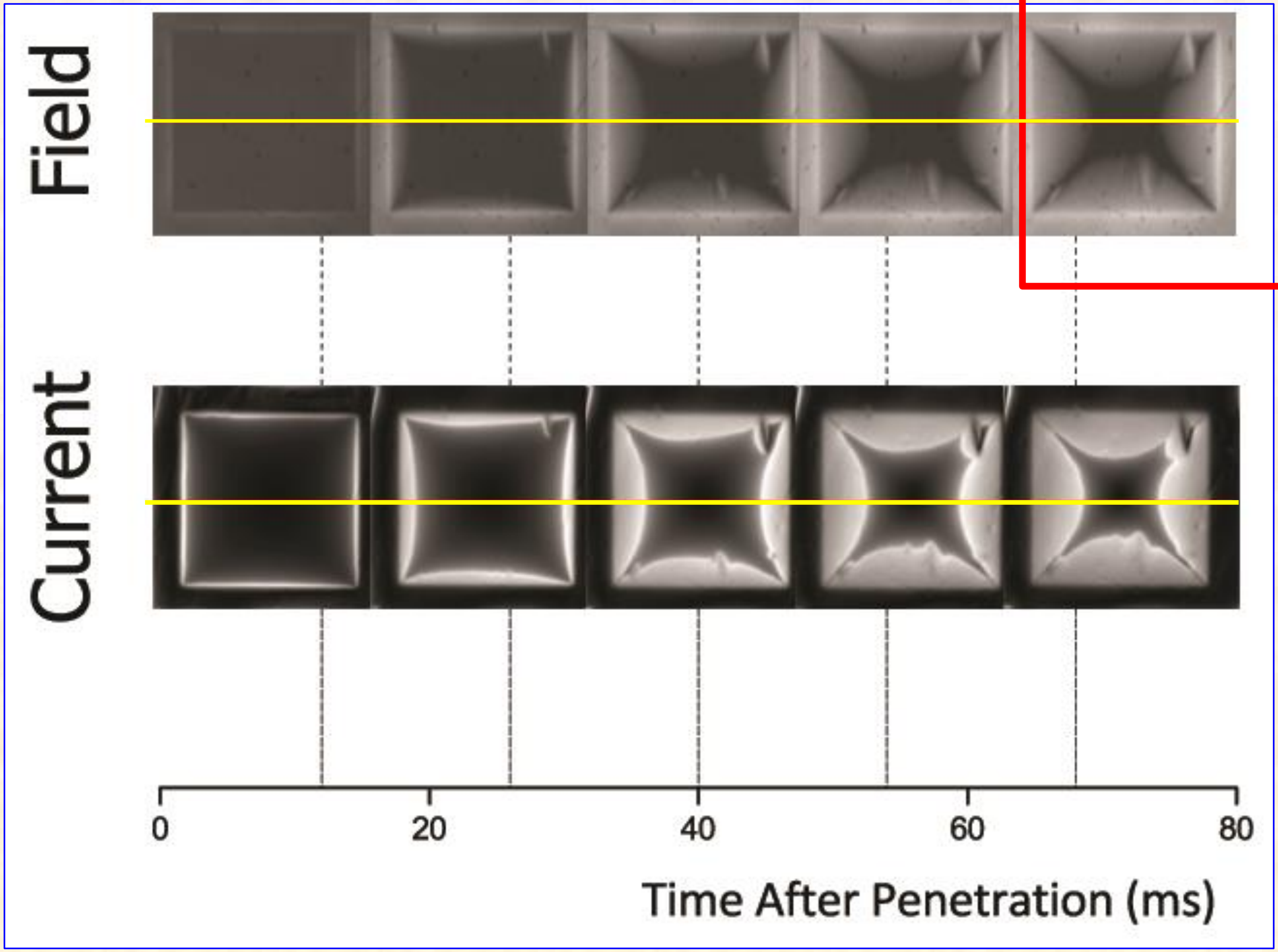


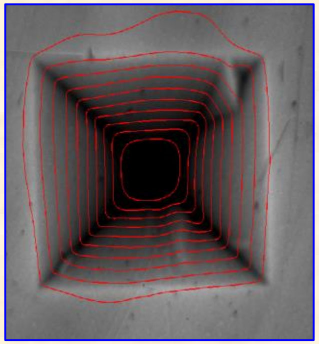
- Our MOI setup [*SUST* **29**, 035014 (2016)].

- MOI uses Faraday Effect to rotate the polarisation of linearly polarised light as it passes through the Faraday-active film.



Video Snapshots

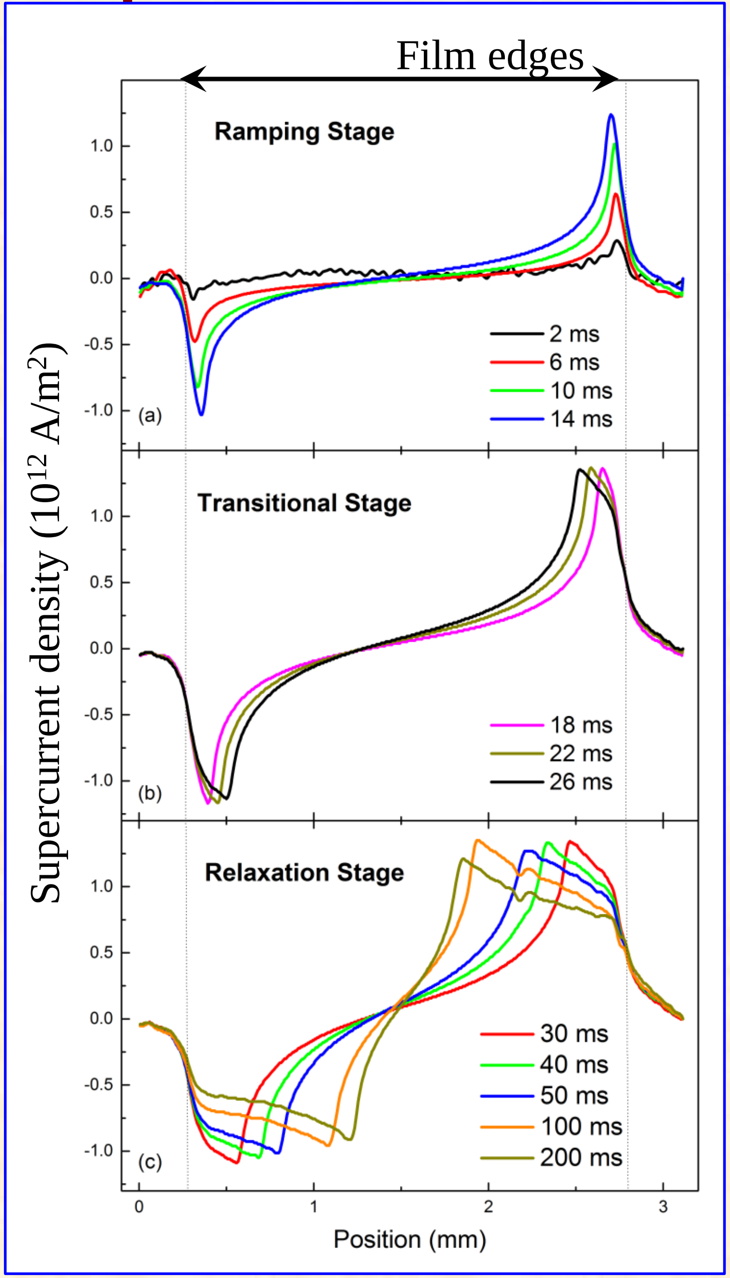




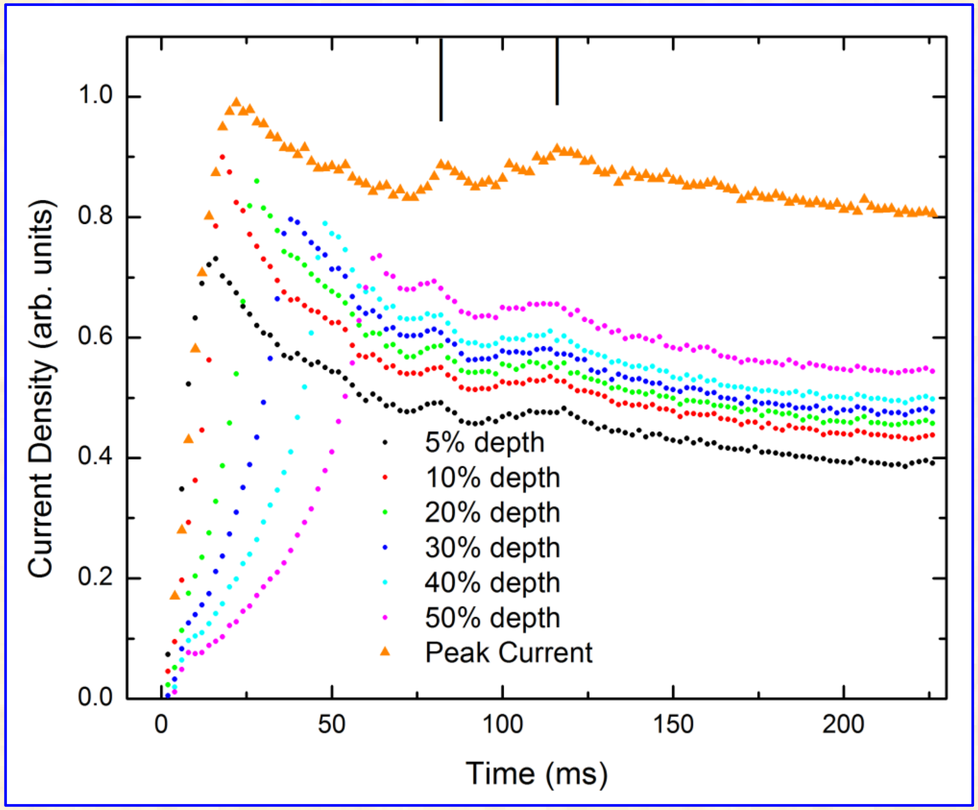
- Current streamlines

F. S. Wells, A. V. Pan, et al., *Scientific Reports* **7**, 40235 (2017)

Ultra-Fast Evolution of Supercurrent Profiles



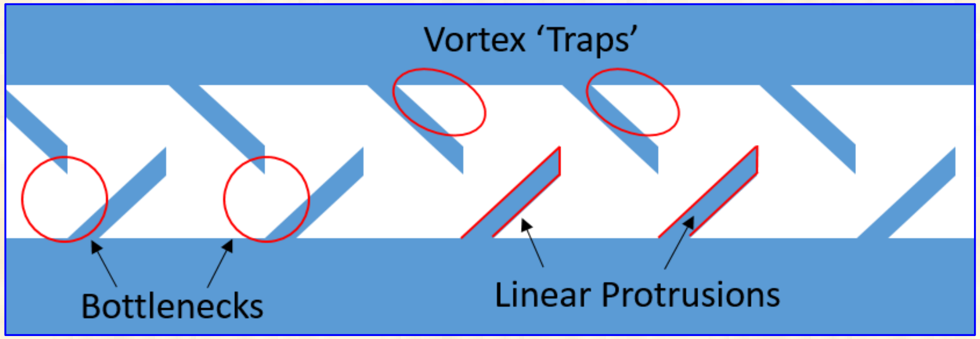
Transient <u>over-critical</u> currents up to 30% higher than that in the equilibrium

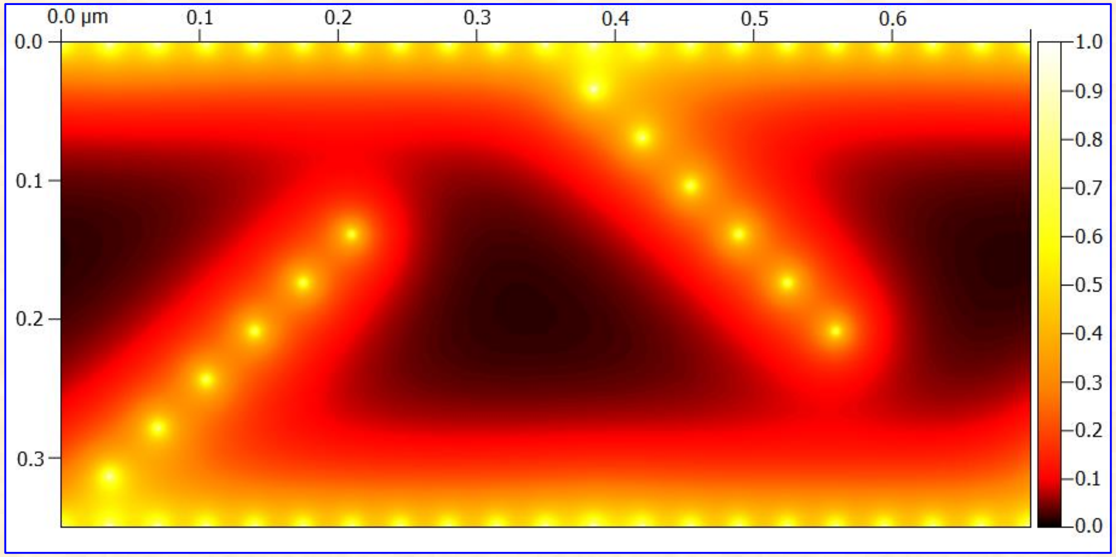


Transient behaviour relaxes to the expected Kim-like profile.

F. S. Wells, A. V. Pan, et al., *Scientific Reports* **7**, 40235 (2017)

Tailored pinning: Vortex ratchets





- Potential map of the ratchet created using vortex-vortex interactions:

$$\boxed{U^{vv}(r) = \frac{2\Phi_0^2}{4\pi\mu_0\lambda^2} K_0(r/\lambda)}$$

- Dark zones are **vortex traps**.

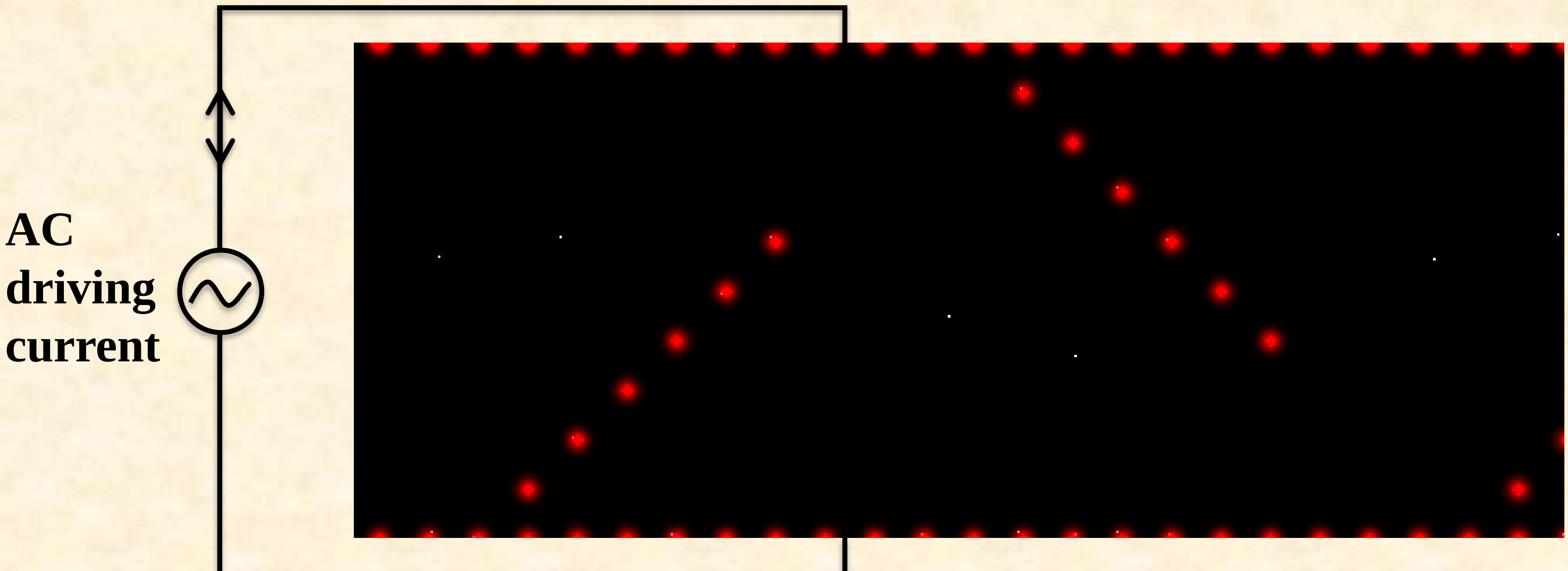
Simulation of Vortex Dynamics. Vortex Diodes or Pumps

- Overdamped Langevin Dynamics
- Vortices are assumed to be particles in a viscous fluid:

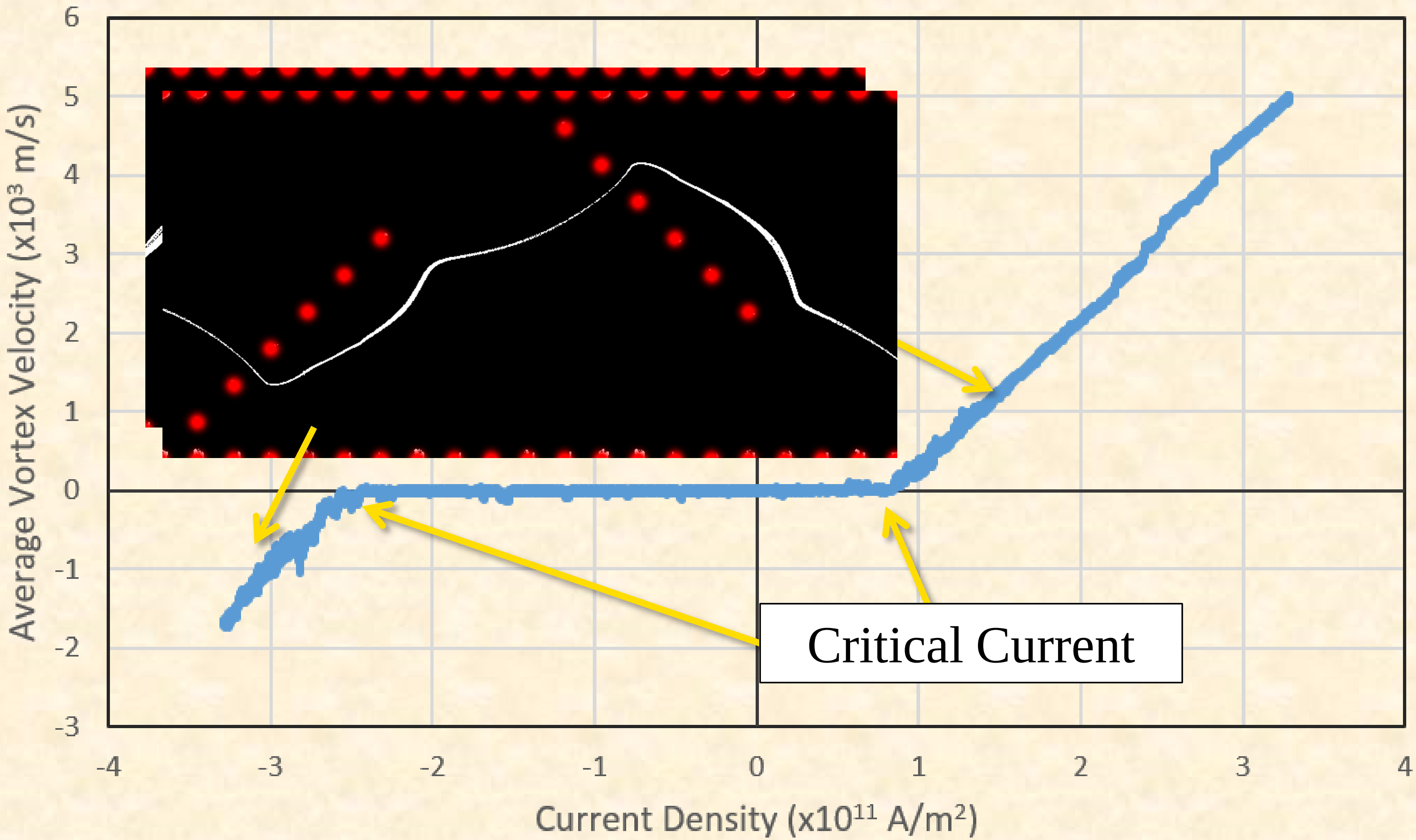
$$m\ddot{r}_i = \sum_{i \neq j} F_{ij}^{vv} + F_i^{pinning} + F_i^{Lorentz} + F_i^{thermal} - \eta \dot{r}_i$$

- Assuming inertial mass (m) of vortices ~ 0, and
- $T = 0$ K for simplicity, we can solve:

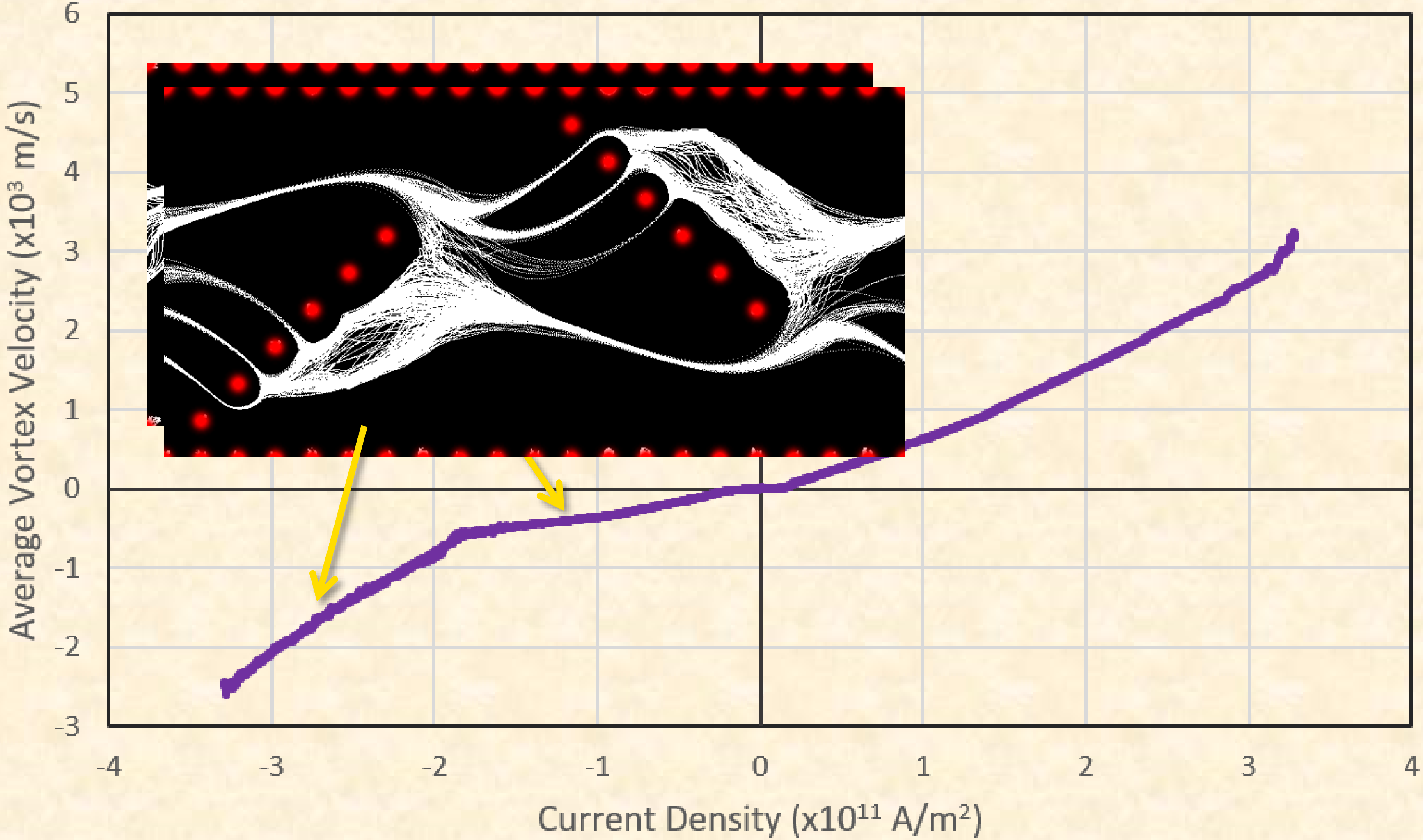
$$\boxed{\eta \dot{r}_i = \sum_{i \neq j} F_{ij}^{vv} + F_i^{pinning} + F_i^{Lorentz}}$$



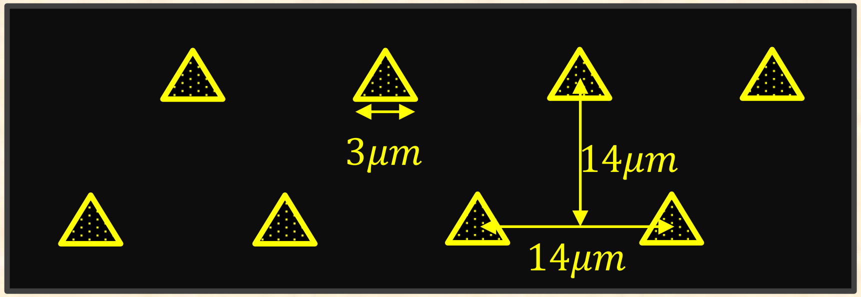
Simulation Results with One Vortex

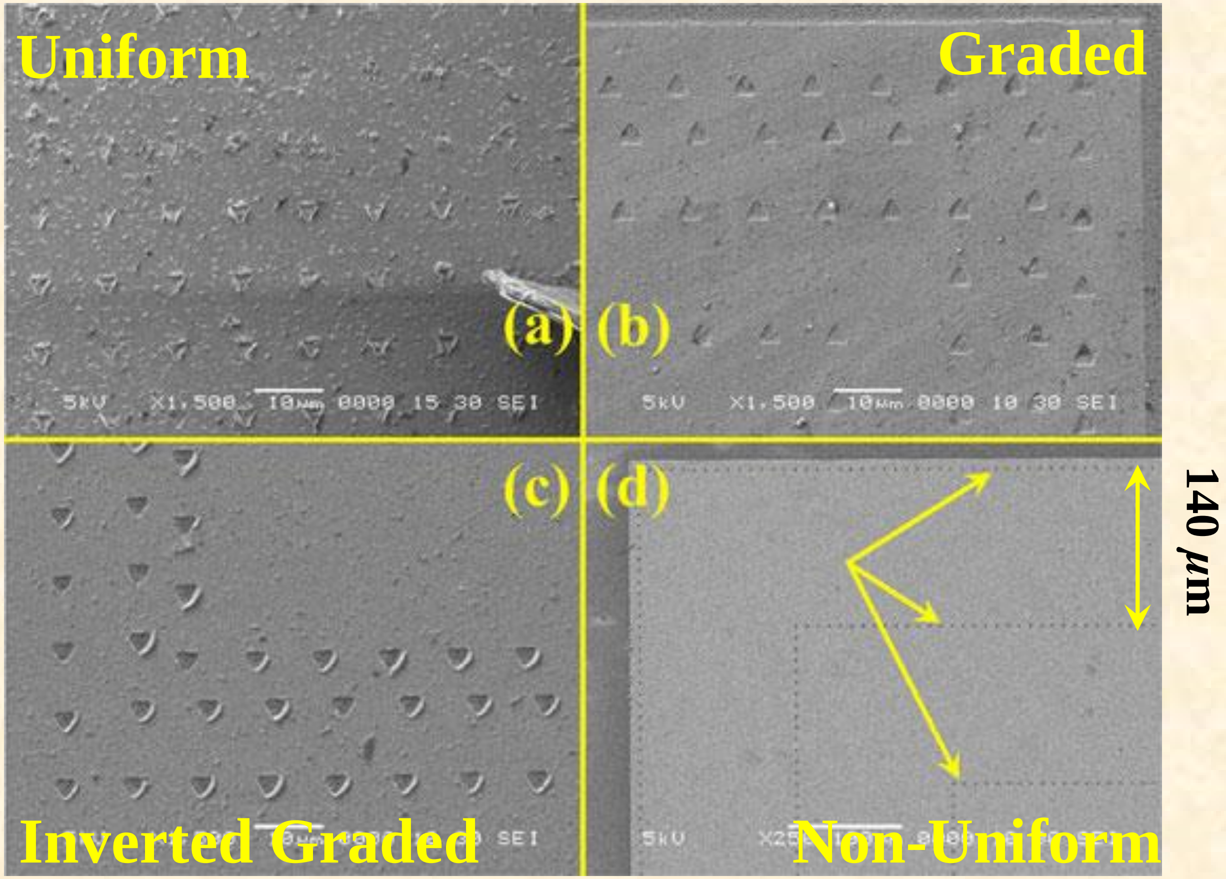


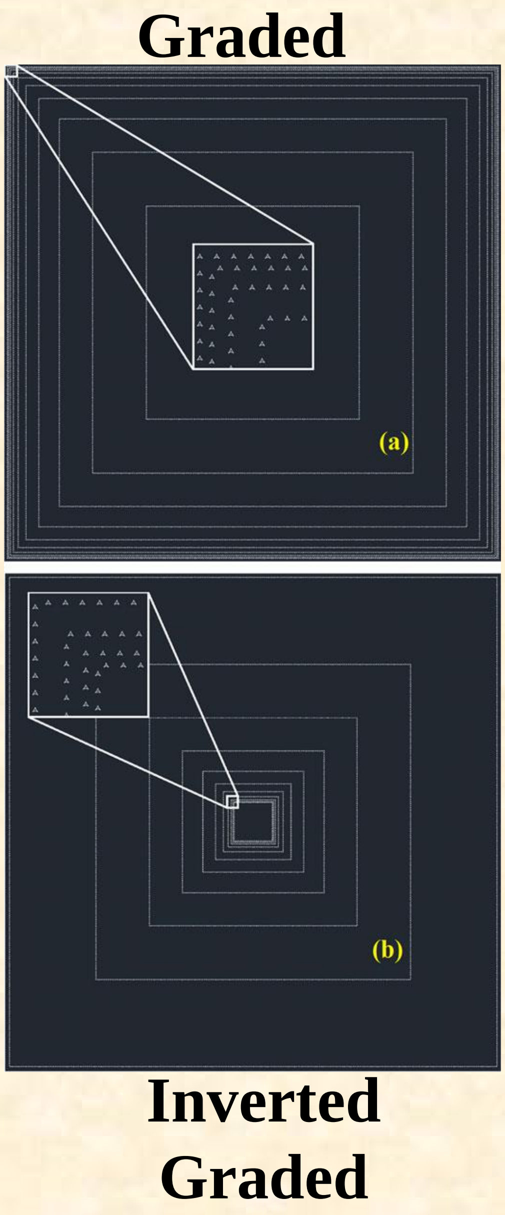
Simulation Results with Eight Vortices



<u>Large dots</u> for fast visualisation of vortex behaviour

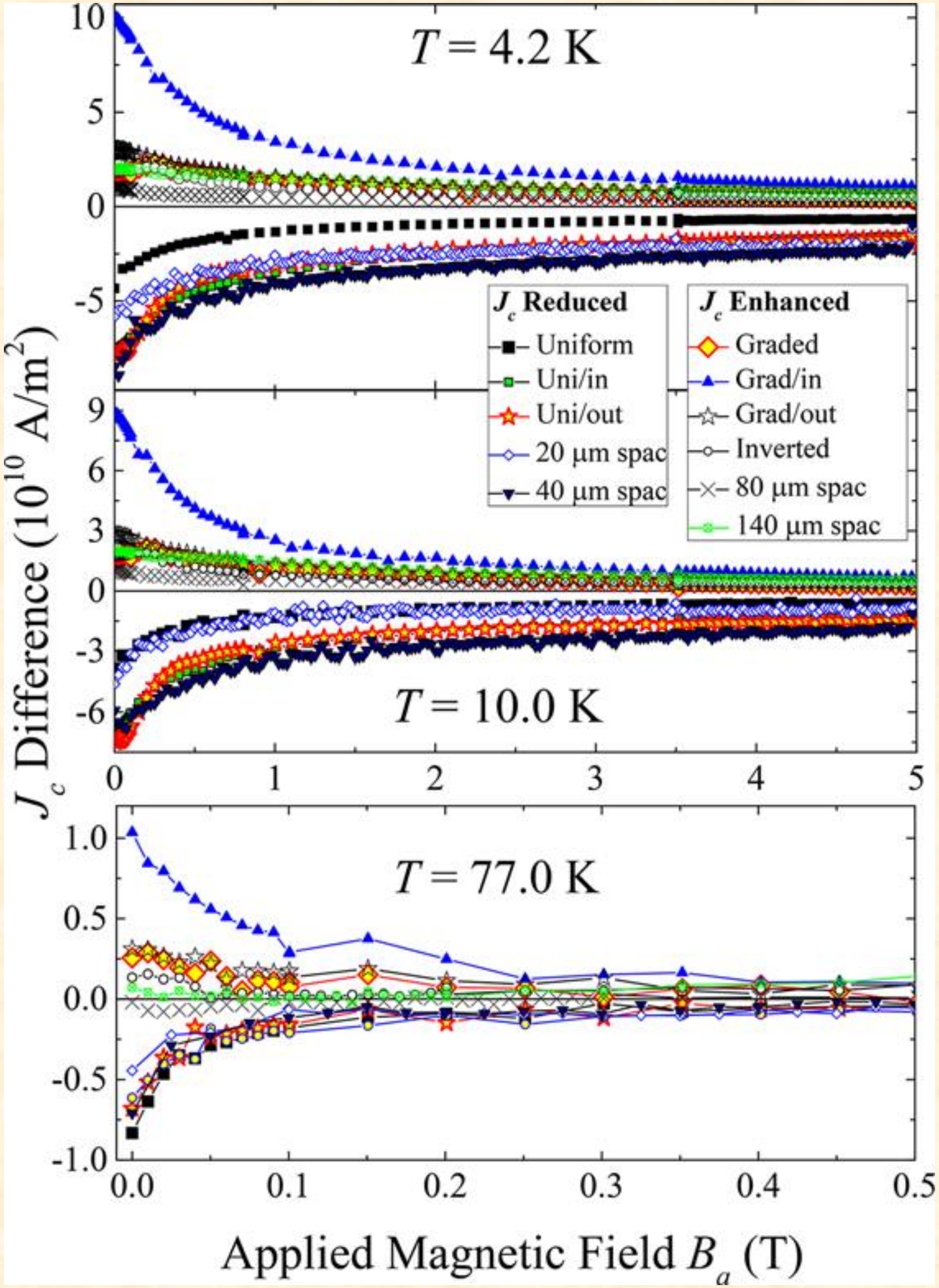






J. George, A. V. Pan, et al., *Ann. Phys.* **529**, 1600283 (2017)

J_c Difference between the Post- and Pre-Patterned Films



J_c enhancement (+):

- ALL Graded
- Inverted Graded
- Non-Uniform with large spacings

J_c reduction (–):

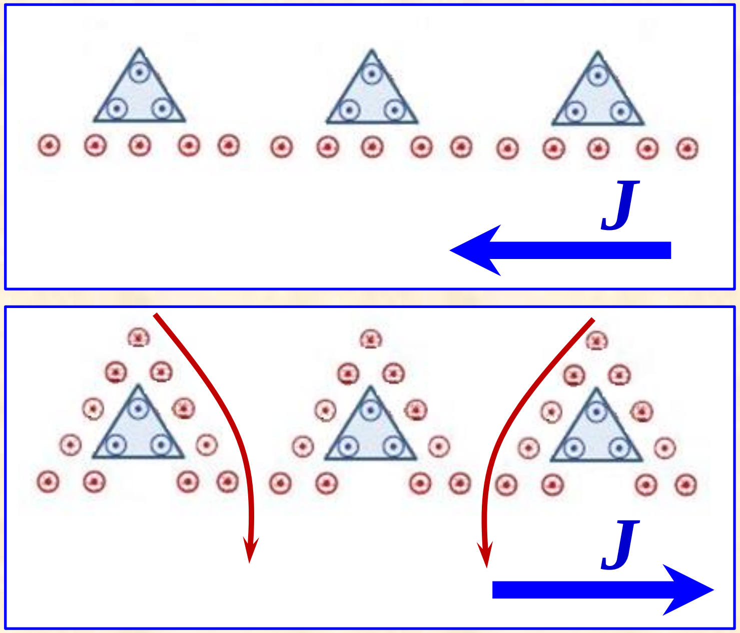
- ALL Uniform
- Non-Uniform with small spacings

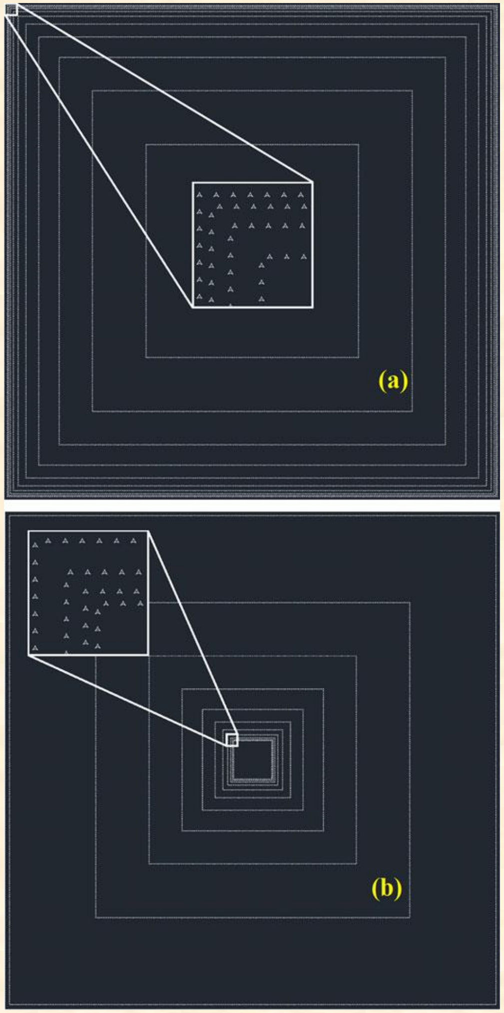
Overall:

By designing a pattern, J_c can be tuned!

J. George, A. V. Pan, et al., *Ann. Phys.* **529**, 1600283 (2017)

Qualitative explanation





- **Ratcheting**

A. Palau et al, *Phys. Rev. B* **85** (2012)
J. E. Villegas et al, *Science* **302**, 1188 (2003)

- The **non-uniform arrays** form non-Bean-like profiles with high vortex density regions and vortex "vacuum" regions.

- Obviously, the more penetration reminds the Bean profile, the smaller enhancement (or none at all) is obtained.

J. George, A. V. Pan, et al., *Ann. Phys.* **529**, 1600283 (2017)

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Summary

- J_c **strongly** depends on how it measured, so "Physics" may suffer.
- By designing a pattern, J_c can be tuned!
- **Enhancement** for non-uniform arrays; **reduction** for uniform arrays.
- World-record ultra-fast dynamic MOI has been developed to test functionality of electronic devices.
- Overcritical currents of up to 30% higher than equilibrium critical currents have been observed.
- Low-field SQUID Microscopy shows random vortex glassy patterns.
- Vortex ratchets (i.e. vortex diodes and pumps) have been simulated.