Discontinuity lines in superconducting films with predefined edge defects

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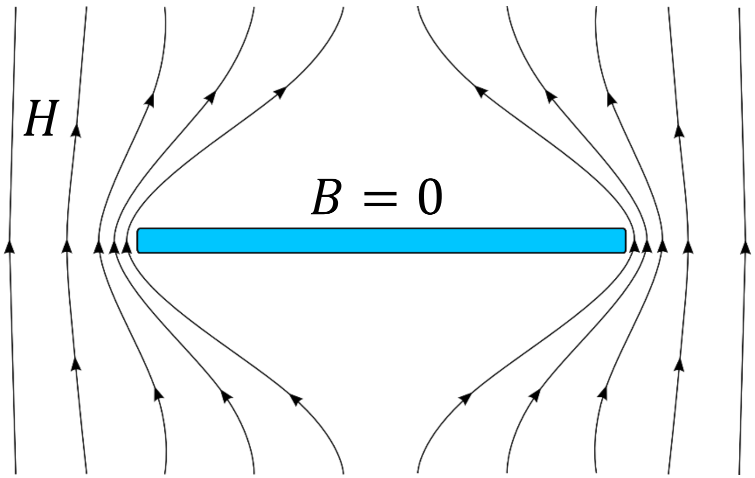
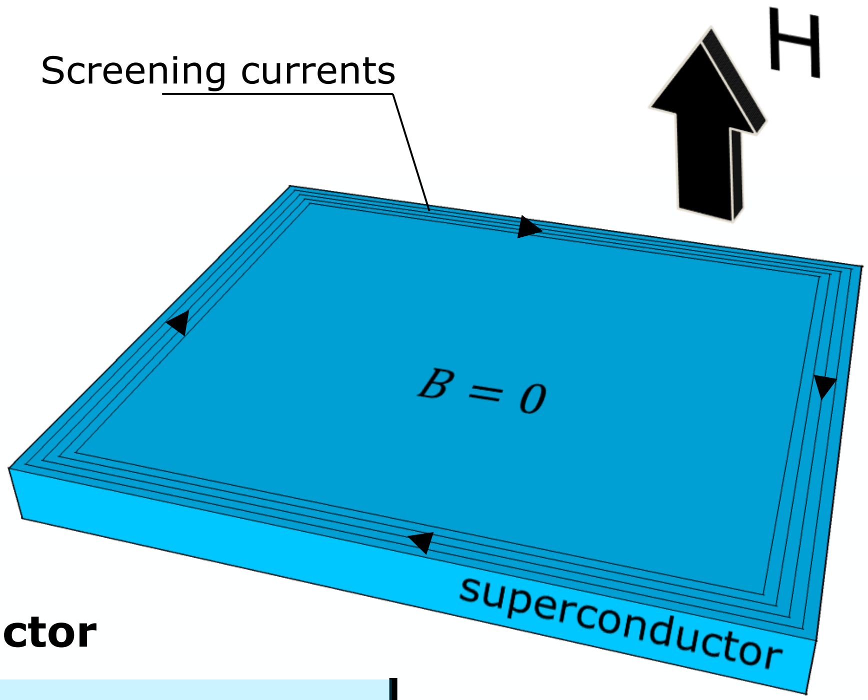
Superconducting currents





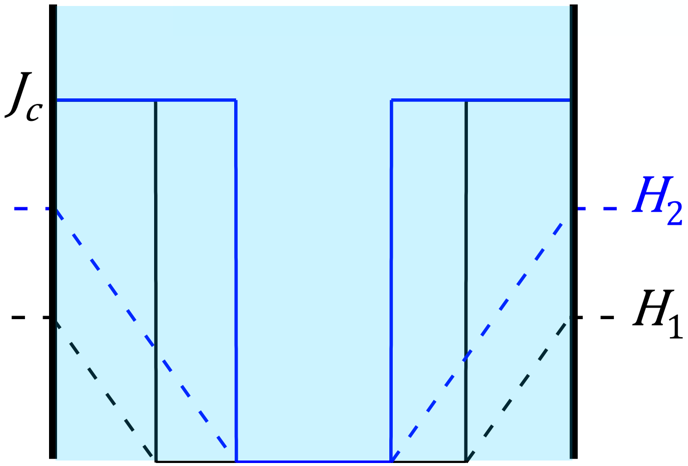
Bean model for a bulk superconductor

Where flux penetrates:

$$\nabla \times H = Jc$$

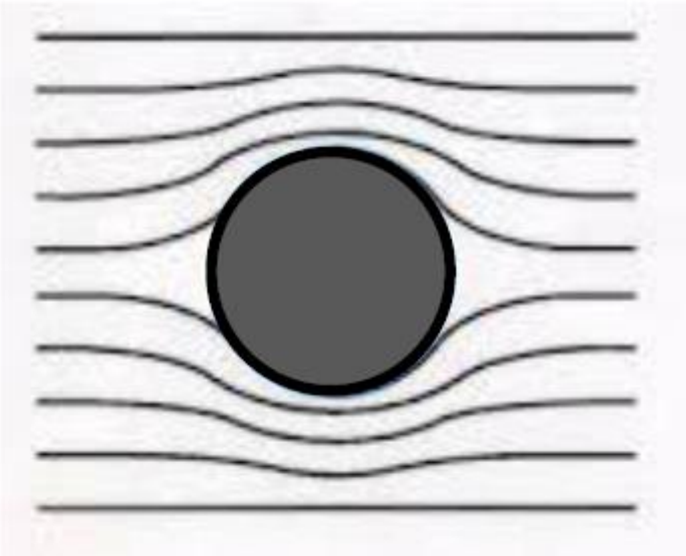
Where the field is zero:

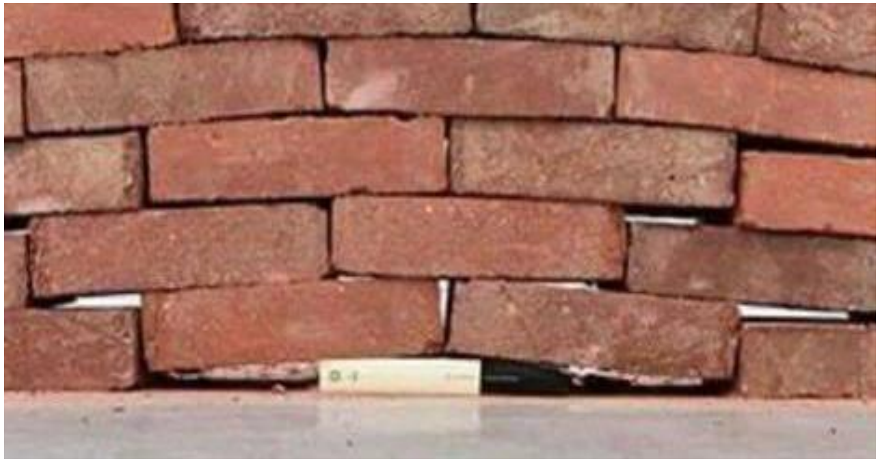
$$\nabla \times H = 0$$



Influence of defects

What happens to the current streamlines in the presence of a defect?



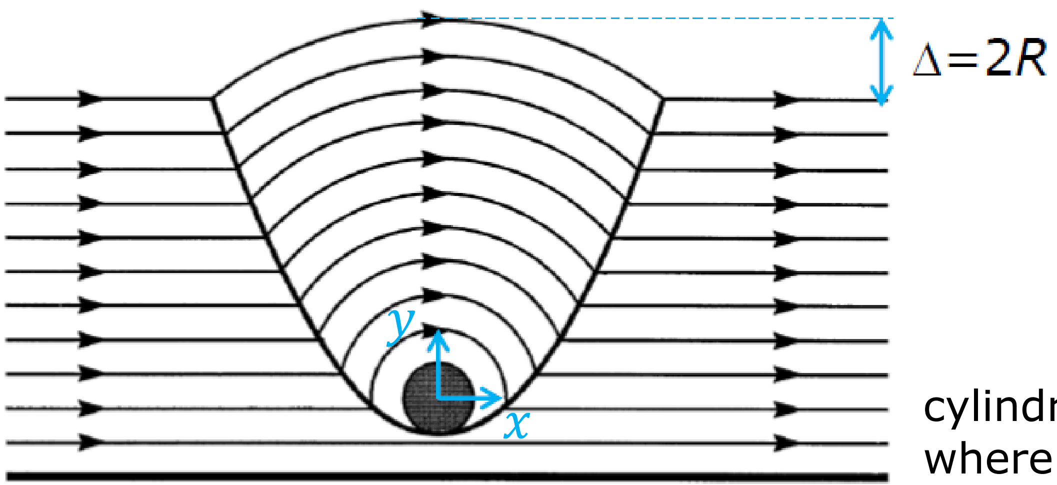


Defects are present in all materials, so it is critical to understand their influence on the superconducting properties.

F. B. Hagedorn and P. M. Hall, *J. Appl. Phys.* **34**, 128 (1963)

The role of defects

Bean model (in a bulk superconductor) shows the appearance of **discontinuity lines**, where the current is sharply bending.



$$\boxed{y = ax^2 + c}$$

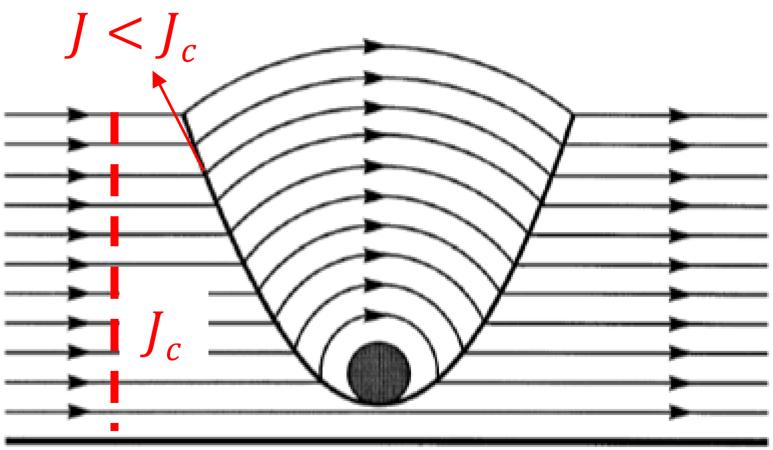
$$a = \frac{1}{2R}$$

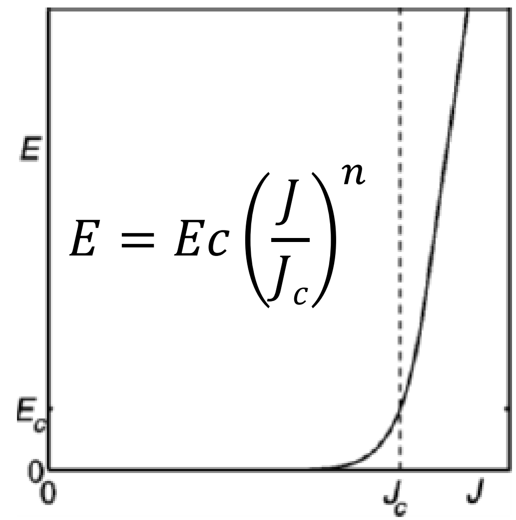
$$c = -R$$

cylindrical cavity with radius R, where $J_c = 0$.

M. Campbell, J.E. Evetts, Critical Currents in Superconductors, Taylor & Francis, London, (1972)

Vortices don't cross the *d*-lines





n = creep exponent

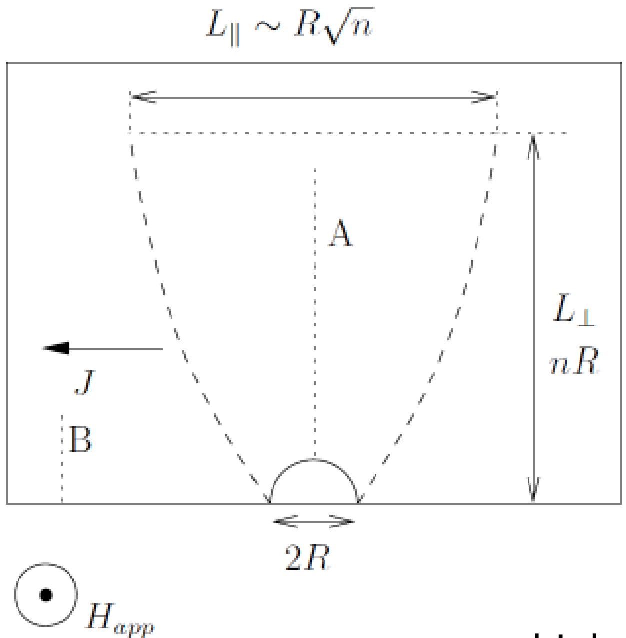
Close to the *d*-lines, $\frac{J}{J_c} < 1$: $E \xrightarrow{n \to \infty} 0$

Therefore, the velocity of vortices at the d-lines is $\mathrm{v} = \frac{E}{B} \to 0$.

Vortices never cross the *d*-lines.

Th. Schuster *et al.*, Phys. Rev. B **49**, 3443 (1994)

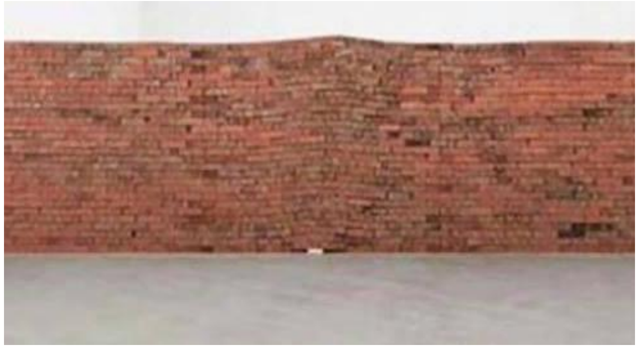
How far does the perturbation propagate?



$$L_{\perp} \sim Rn$$
$$L_{\parallel} \sim R\sqrt{n}$$
$$\longrightarrow \quad n \approx \left(\frac{L_{\perp}}{L_{\parallel}}\right)^2$$

The perturbation propagates further for higher n

high n

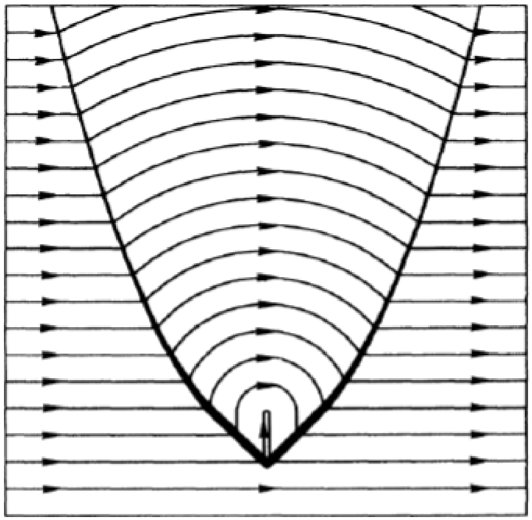


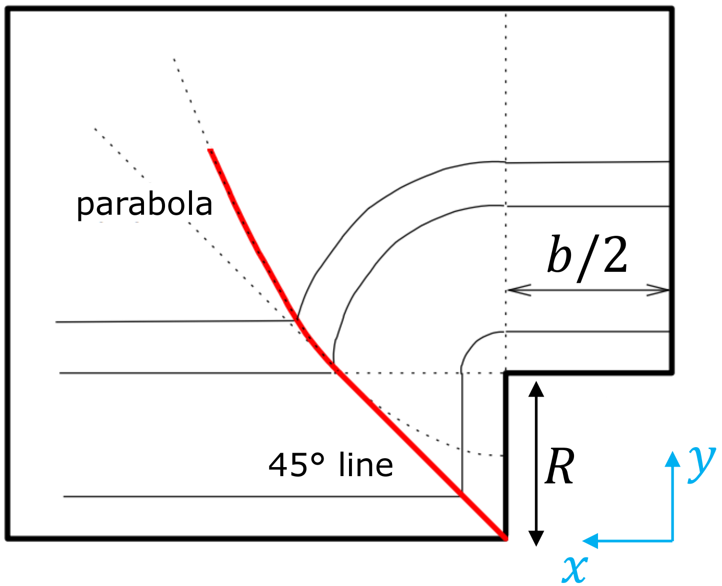
low n

Gurevich and Friesen, PRB **62**, 4004 (2000); PRB **63**, 64521 (2001)

Does the shape of the defect matter?

Rectangular defect





$$y = a\left(x - \frac{b}{2}\right)^2 + c \qquad a = \frac{1}{2R} \qquad c = \frac{R}{2}$$

There are two distinct branches separated by a distance b.

Flux avalanches in superconductors

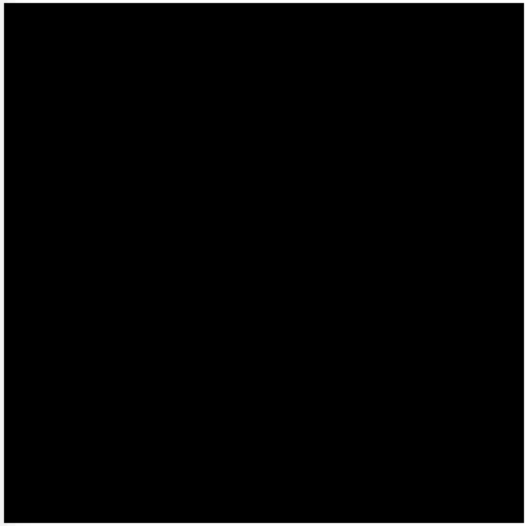
observed by magneto-optical imaging (MOI)

H increased → vortex motion → dissipation in normal core

T raises locally

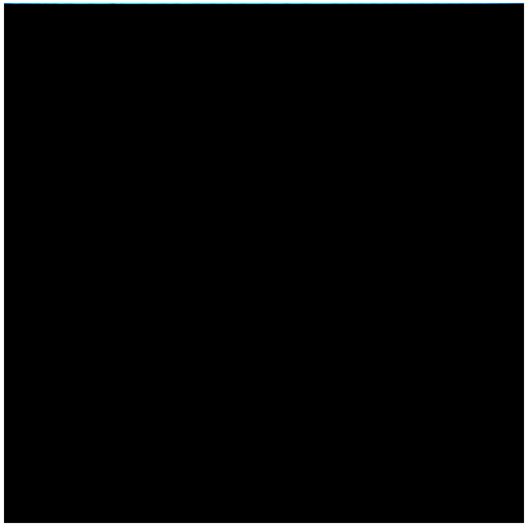
efficient heat removal

Flux avalanches

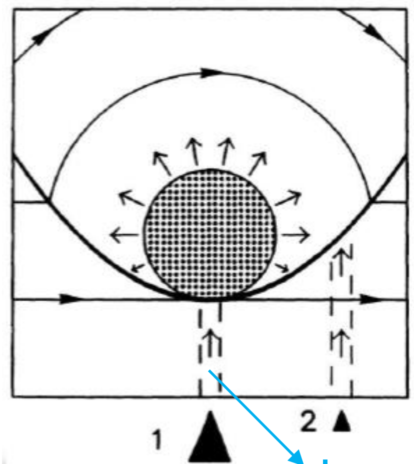


$v_{avalanches}$ ~ 100 km/s

Smooth flux penetration



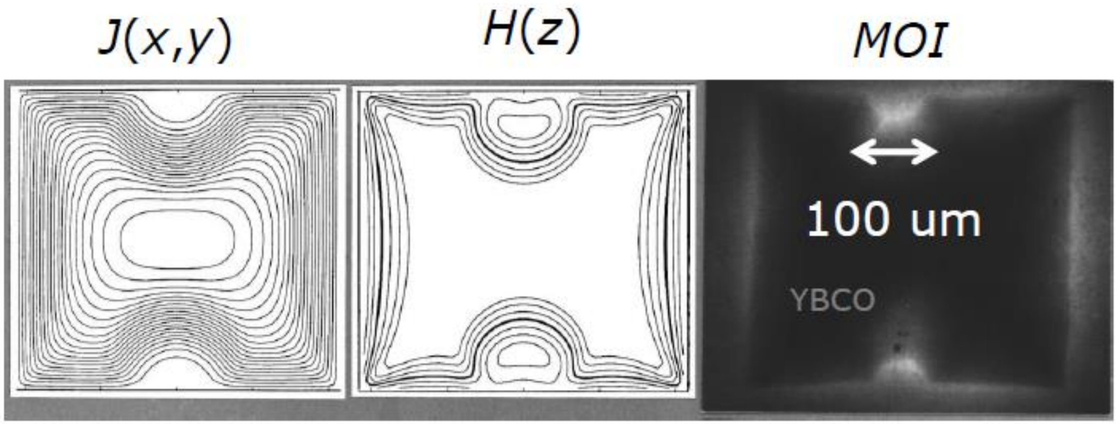
Indentations should act as nucleation points for flux avalanches

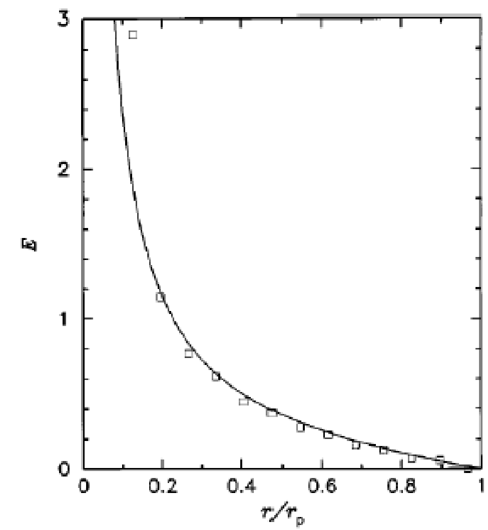


large E

All the flux inside the *d*-lines must enter via channel 1, making it a distinguished place for the nucleation of a flux avalanche.

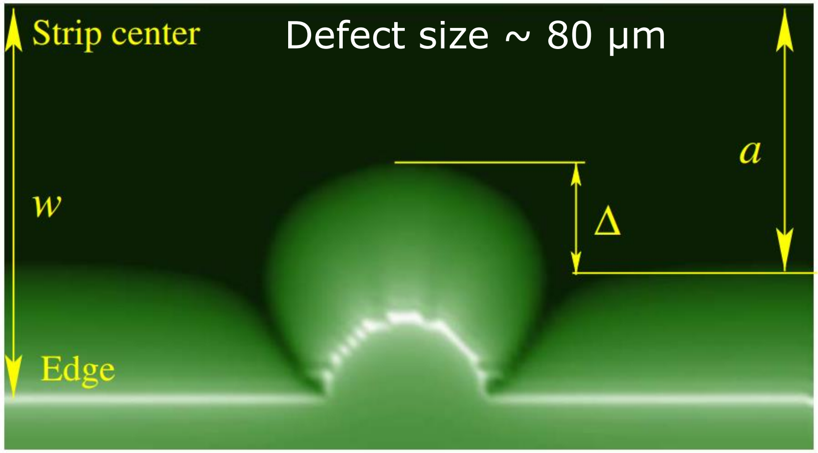
Heat: $Q = \int J.E \, dx \, dy$

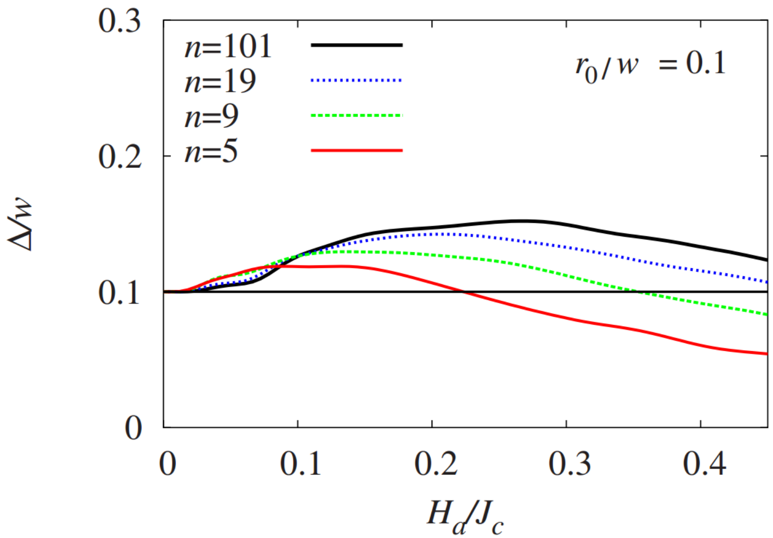




Th. Schuster *et al.*, Phys. Rev. B **54**, 3514 (1996)

What happens in thin films?





- ✓ In thin films, Δ can be larger than the indentation radius r_0
- ✓ Larger indentations produce a larger Δ
- ✓ For smaller values of *n*, smaller Δ

Locally enhanced Joule heating is predicted to facilitate nucleation of a thermal instability at the indentation, so avalanches are expected to be larger and occur more frequently at the indentation.

J. I. Vestgarden *et al.*, Phys. Rev. B **76,** 174509 (2007)

Motivations

1. So far, most of the investigations deal with indentations far larger than ξ and λ.

2. Previous investigations neither control nor study the shape of the indentations.

3. What parameters can be extracted from the shape of the *d*-lines emerging from the indentation ?

4. How does the distance between indentations affect the penetration ?

5. Do indentations trigger flux avalanches, as systematically predicted in the literature ?

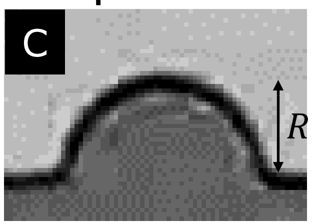
…

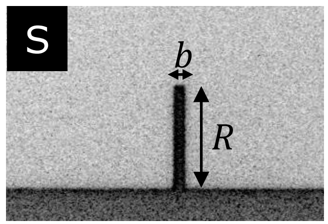
Samples layout

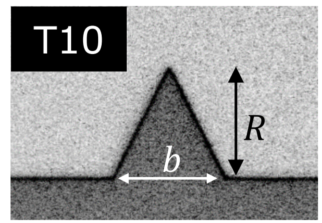
$T_c \approx 9$ K

100 nm-thick Nb films grown on the same substrate

✓ Shape

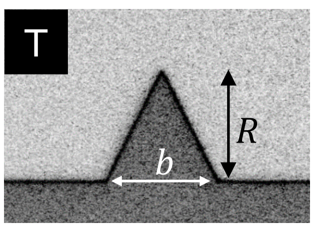






$R = 10$ μm

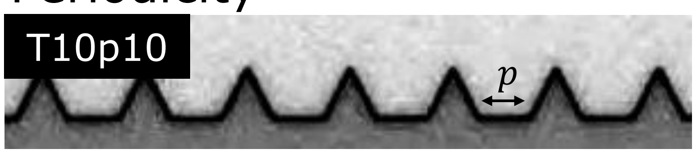
✓ Size



T10 $R = 10$ μm, $b = 20$ μm

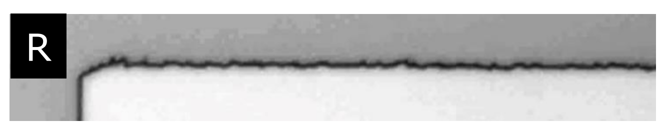
T0.5 T5 T2 T8 $R = b = 0.5,\ 2,\ 5,\ 8$ μm

✓ Periodicity



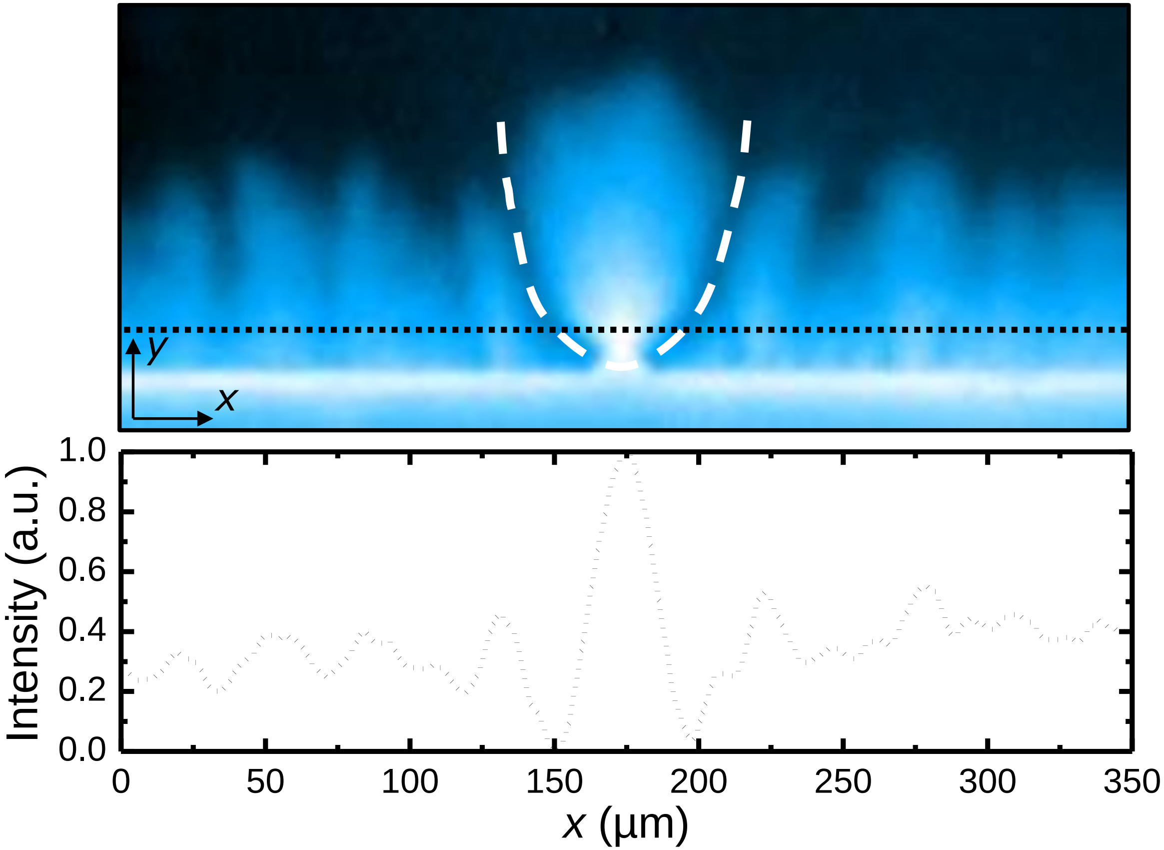
T10p0 T10p50 T10p10 T10p100 $p = 0, 10, 50, 100$ μm

✓ Roughness



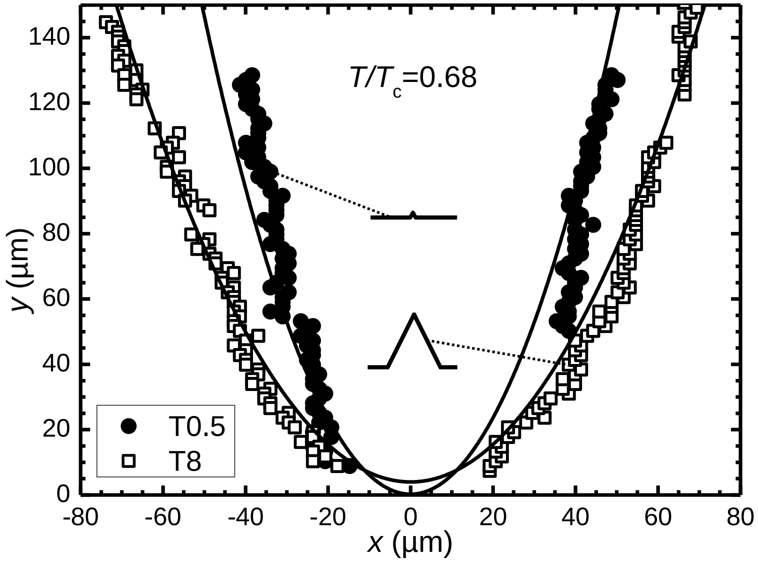
J. Brisbois *et al.*, Phys. Rev. B **93**, 54521 (2016)

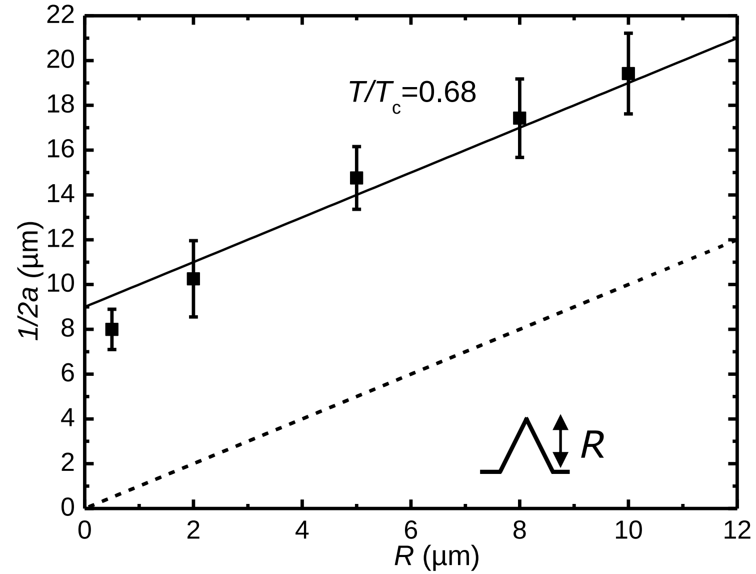
Determination of *d*-lines



d-lines = local minima in the magnetic field

Influence of defect size





$$y = ax^2 + c$$

$$a = \frac{1}{2R}$$

The defect sizes *R* deduced from the Bean model are far larger than the predicted values.

What are the possible sources of disagreement between experiments and the Bean model for longitudinal geometry?

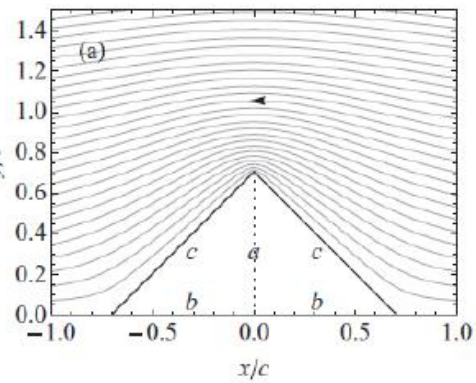
(i) current crowding?

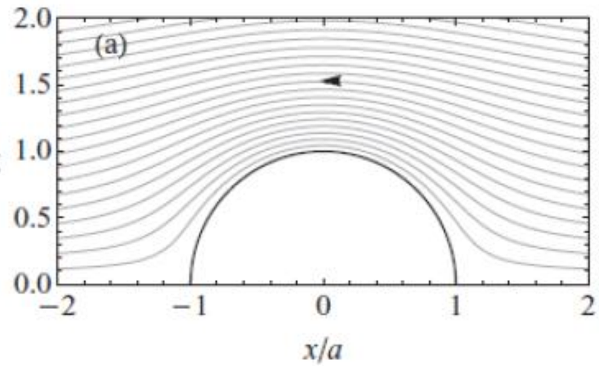
(ii) unrealistically high creep exponent *n*

(iii) nonlocal nature of thin films?

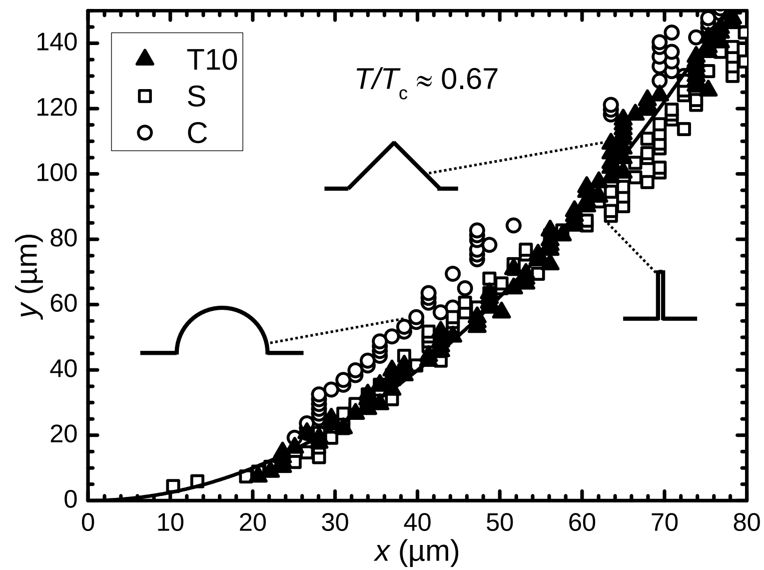
(iv) field-dependent critical current density j_c?

(i) Influence of the defect shape





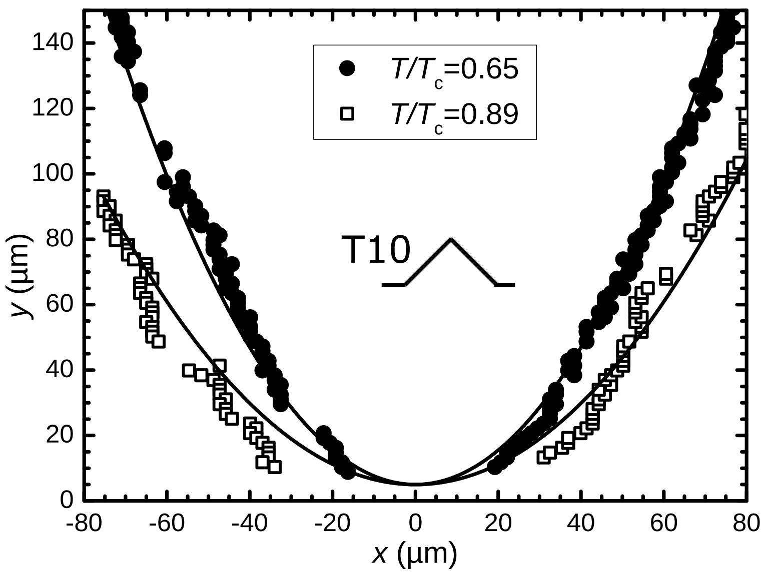
Accumulation of current lines (current crowding) eases vortex penetration

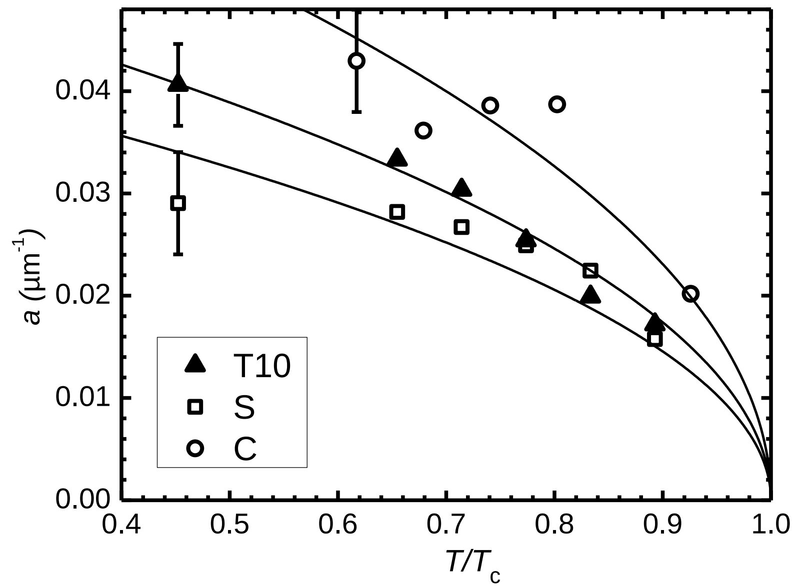


Current crowding plays a minor role in the parabola shape.

Clem and Berggren, Phys. Rev. B **84**, 174510 (2011)

(ii) Influence of the creep exponent *n*



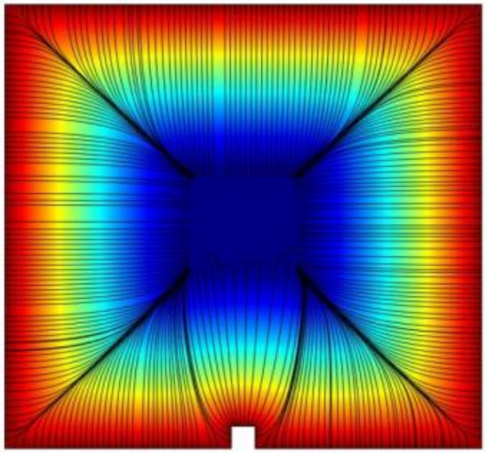


$$n = \frac{U_0}{k_B T}$$

parabola widening as T increases (as n approaches 1).

Finite values of n give R even further from the Bean model.

(iii-iv) Numerical simulations

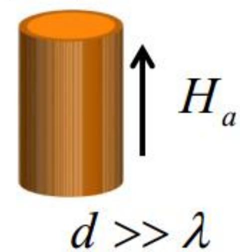


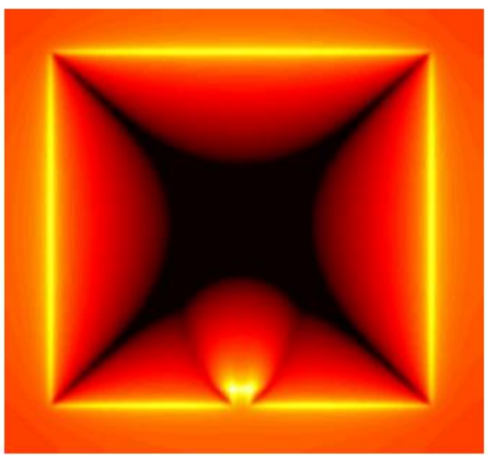
Without demagnetizing field (local)

$$h(x,y,t) = H(x,y,t) - H_a(t)$$

$$\frac{\partial h}{\partial t} = \nabla \cdot \left(\rho \nabla h\right) - \frac{\partial H_a}{\partial t} \qquad j(x,y,t) = \left|\nabla h\right|$$

$$\rho = \begin{cases} \left|\nabla h / J_c\right|^{n-1} & \text{for } \left|\nabla h\right| < J_c \\ 1 & \text{for } \left|\nabla h\right| > J_c \end{cases}$$

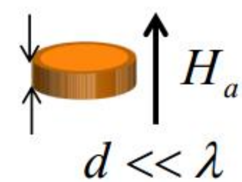




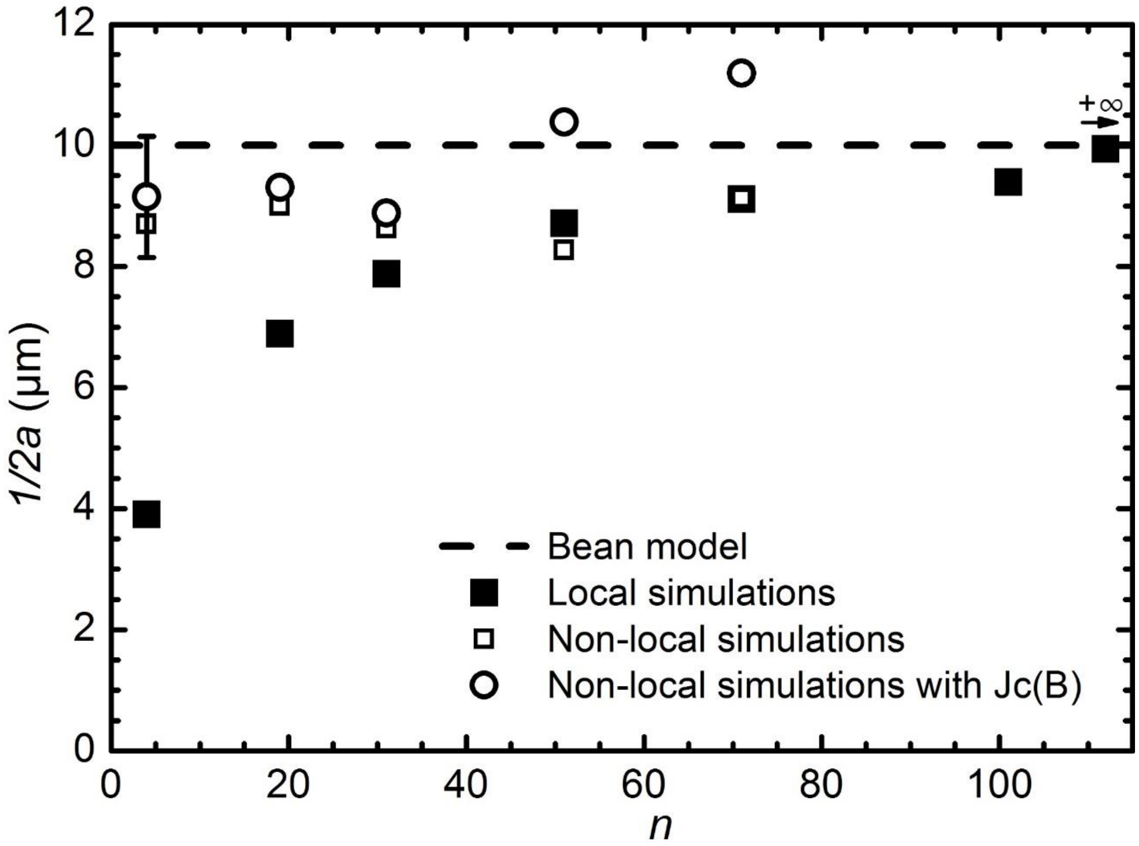
With demagnetizing field (non-local)

$$\iint Q \frac{\partial g}{\partial t} d^2 r = \frac{\nabla \cdot \left(\rho \nabla g\right)}{d} - \frac{\partial H_a}{\partial t}$$

$$\rho = \begin{cases} \left|\nabla g / J_c\right|^{n-1} & \text{for } \left|\nabla g\right| < J_c \\ 1 & \text{for } \left|\nabla g\right| > J_c \end{cases}$$

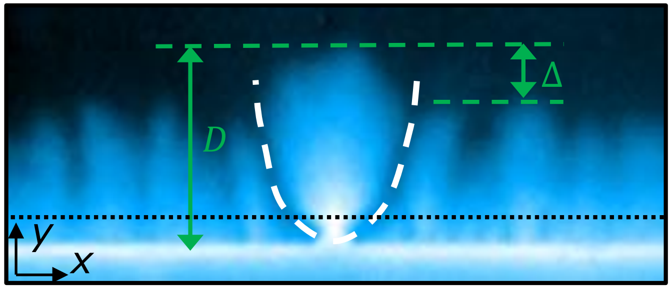


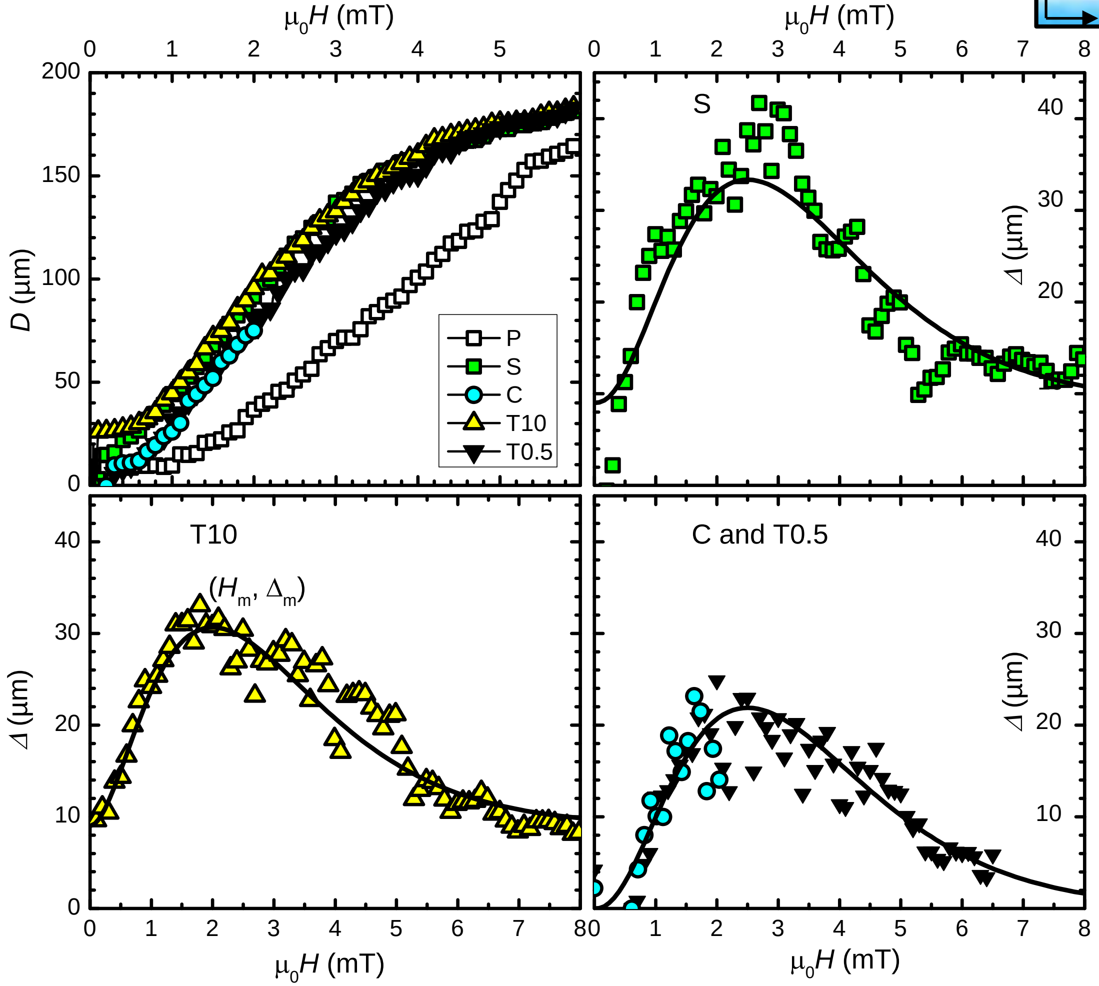
(iii-iv) Numerical simulations



The parabola should shrink as T increases (n decreases), but this is not verified in the experiments.

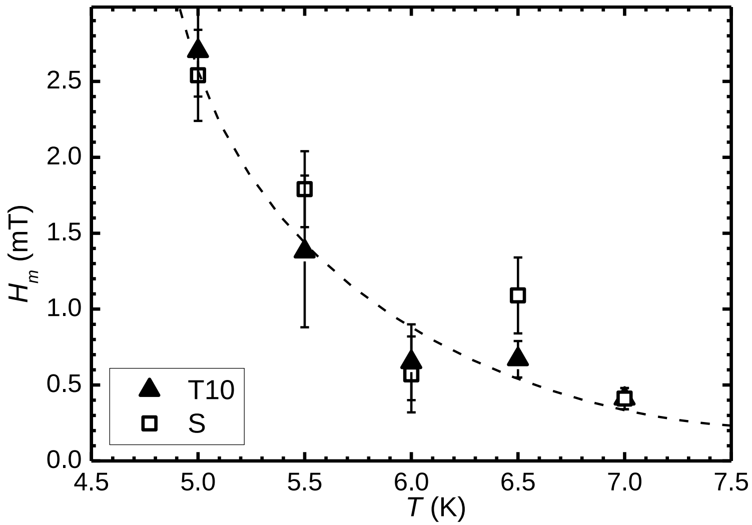
Excess flux penetration

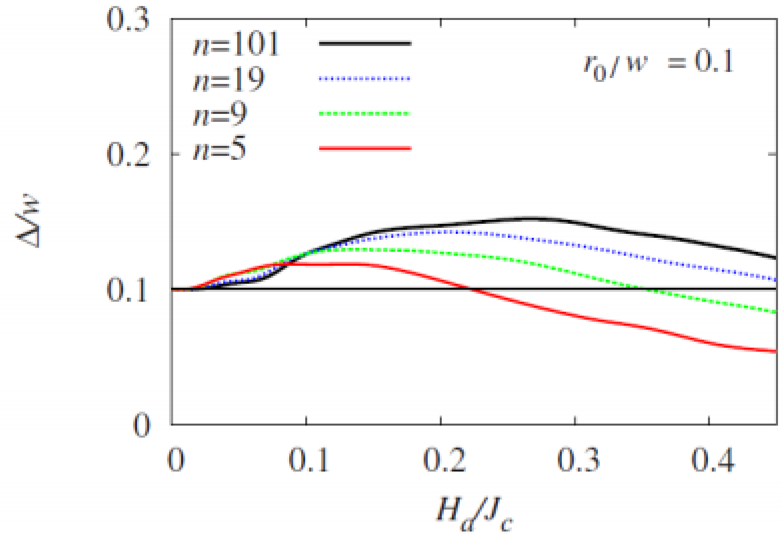


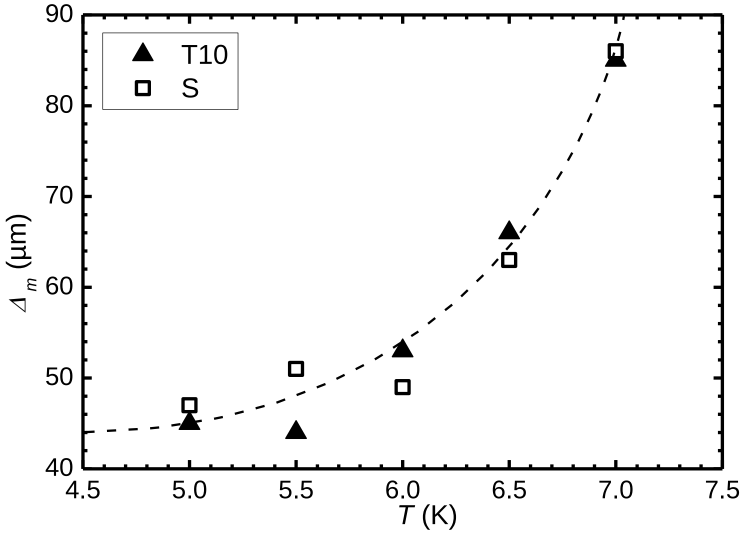


The maximum excess flux penetration Δ_m increases as current crowding is more pronounced (S, T10).

T dependence of Δ_m and H_m







Δ_m increases with T (n decreases), contrarily to what was predicted by simulations.

J. I. Vestgarden *et al.*, Phys. Rev. B **76,** 174509 (2007)

Do indentations trigger flux avalanches?

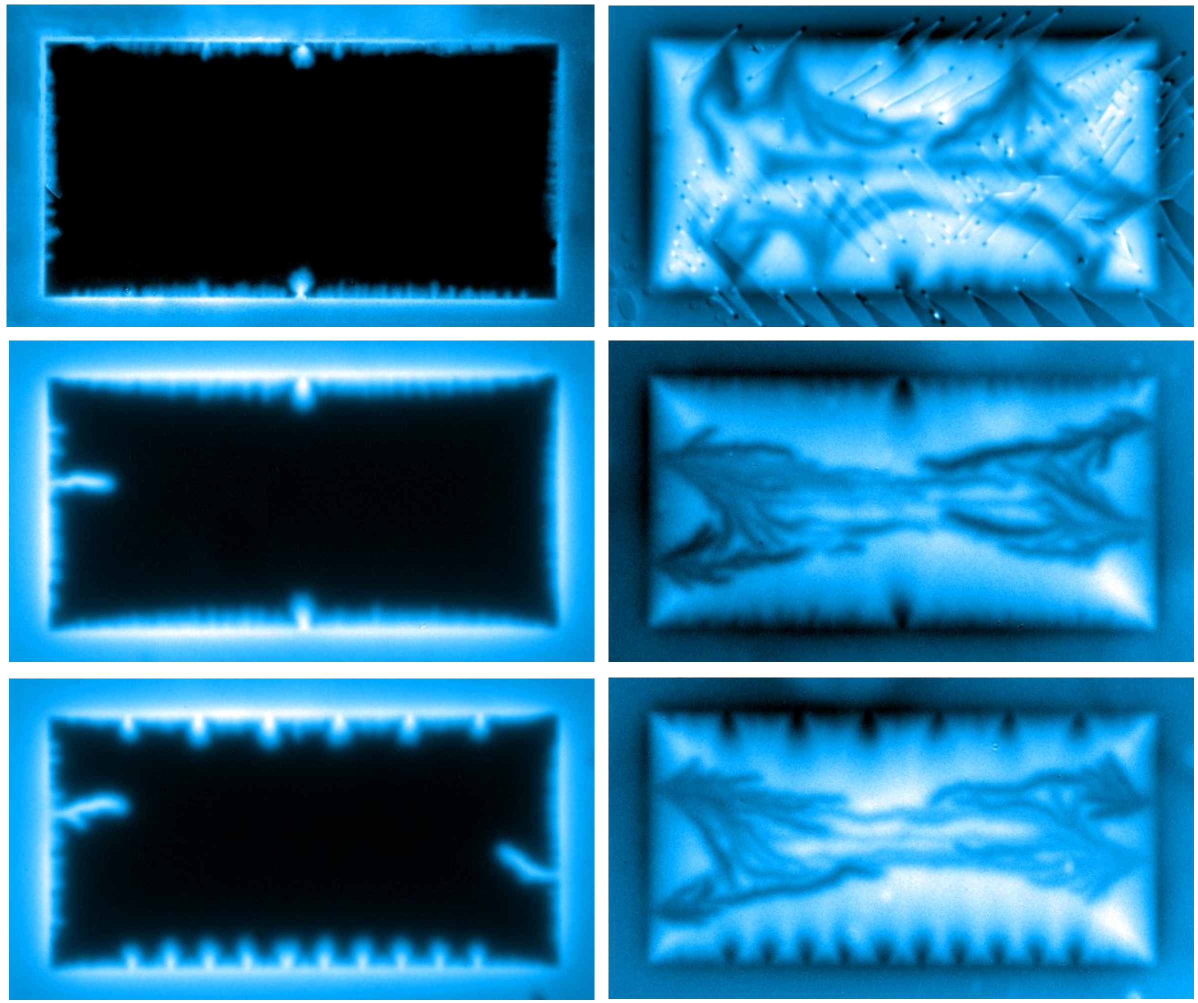
Zero field cooling

Field cooling

4 smooth sides

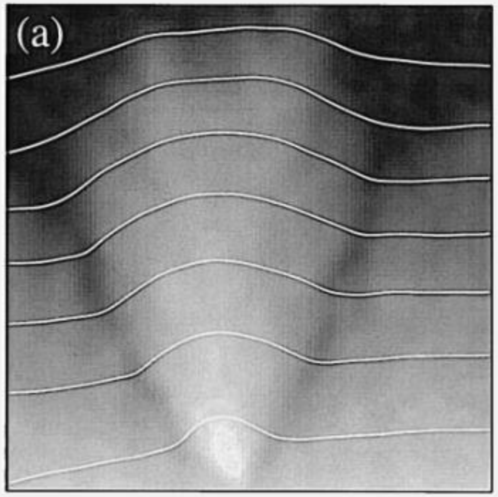
2 smooth (short sides) + 2 rough (long sides)

2 smooth (short sides) + 2 rough (long sides)



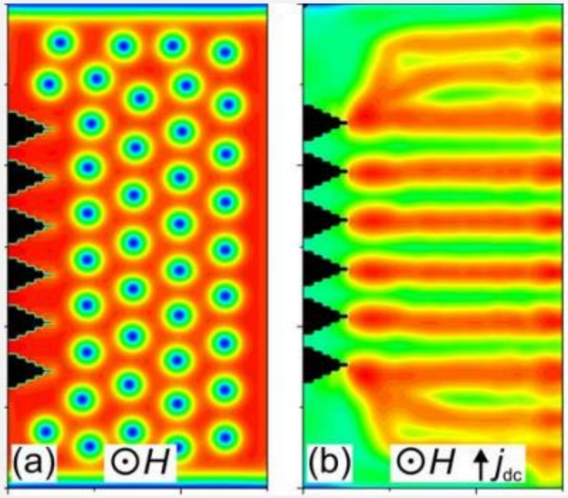
Some possible explanations

Extended Bean model
jc=jc(B)



Ch. Jooss *et al.*
Physica C **299**, 215 (1998)

Lower surface barrier

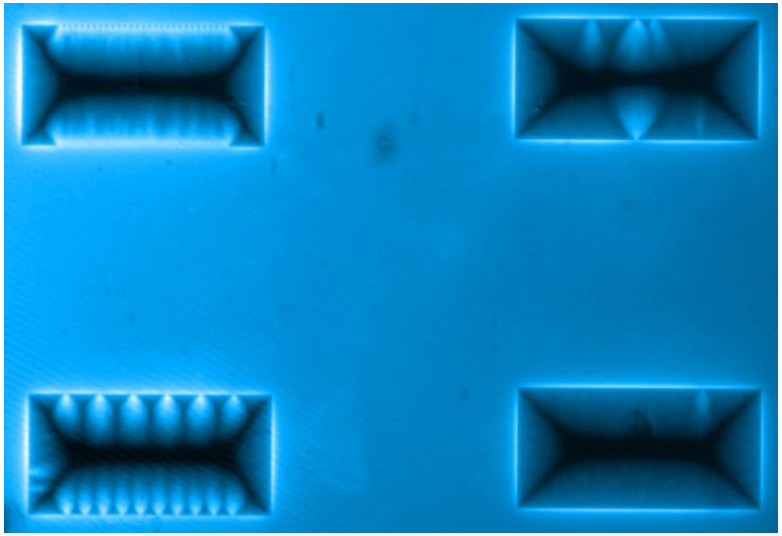


Cerbu *et al.*
New J. Phys. 15, 063022 (2013)

Conclusions

We demonstrate that the *d* lines encode information about

- ✓ the demagnetization effects
- ✓ the size and shape of the defect
- ✓ the creep exponent *n*
- ✓ the field dependence of the critical current density.



Against the common wisdom, indentations do not seem to be preferred places for triggering flux avalanches.

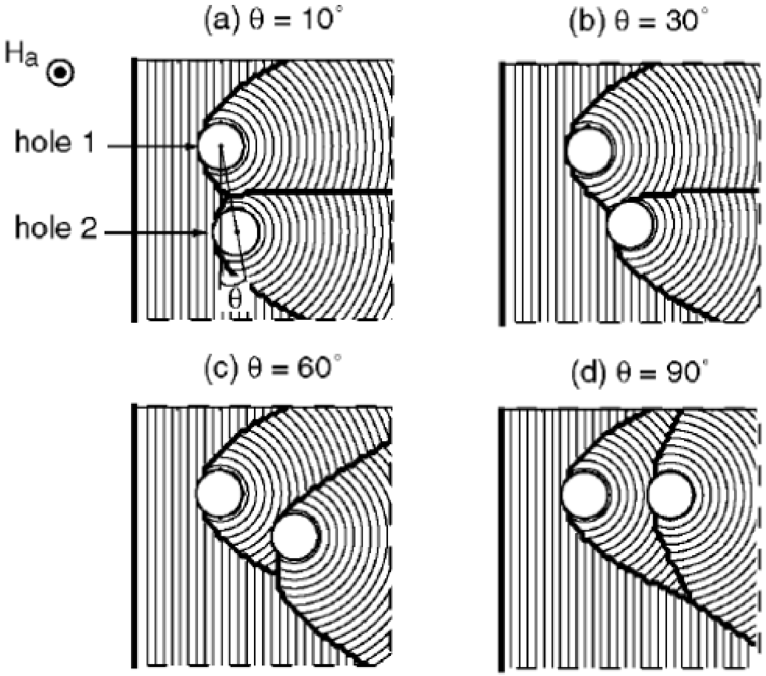
J. Brisbois *et al*., Phys. Rev. B **93**, 54521 (2016)

Practical application

Drilled HTS for better oxygen diffusion and better heat exchange.

Where to place the holes to maximize the trapped flux?

The trapped magnetic flux is maximized if the center of each hole is positioned on one of the discontinuity lines produced by the neighboring holes.



Lousberg *et al.*, SUST **21**, 025010 (2008)

Thank you for your attention!

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