Flux penetration in a superconducting thin film with edge indentations

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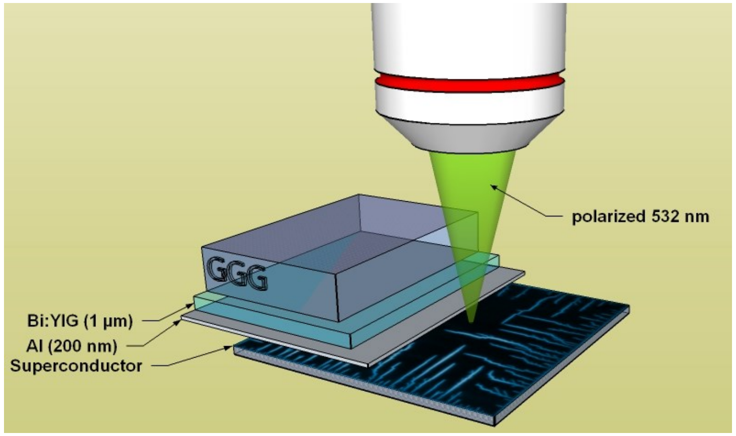
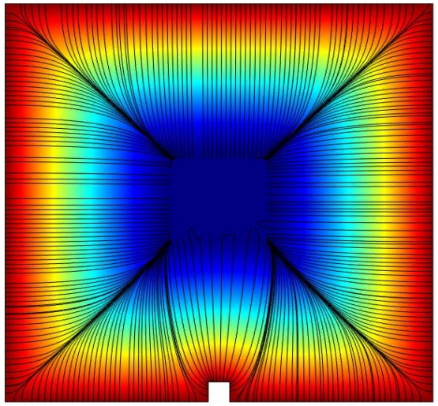
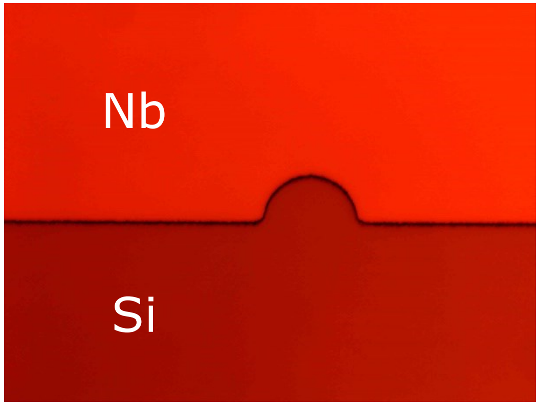
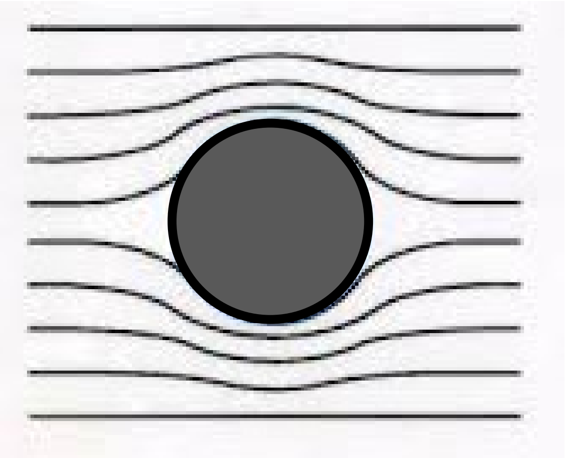






Review of previous results

How far propagate the perturbation on the current stream lines?

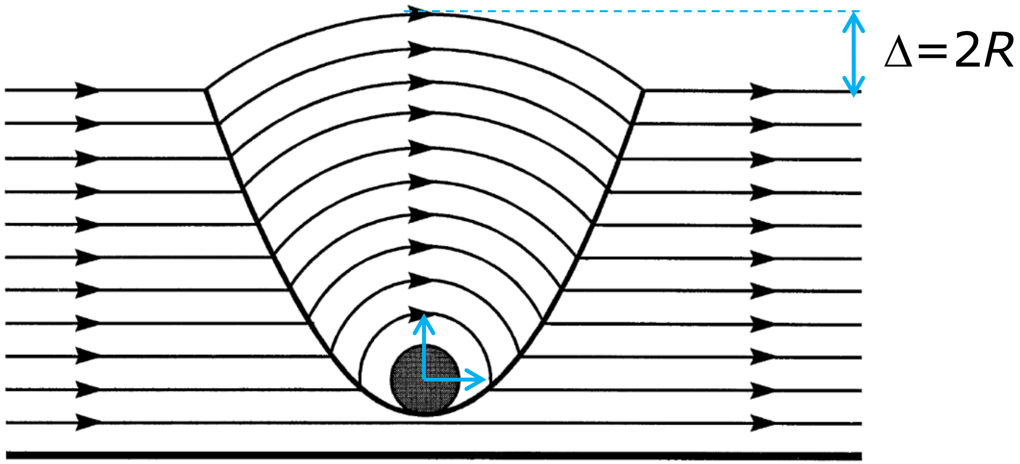


Hagedorn and Hall, J. Appl. Phys. 1963

And in a type II superconductor?

M. Campbell, J.E. Evetts, Critical Currents in Superconductors, Taylor and Francis, London, 1972

Bean model a macroscopic defect in a **bulk** superconductor as a cylindrical cavity with j_c=0, and showed the appearance of **discontinuity lines**, where the current is sharply bending.

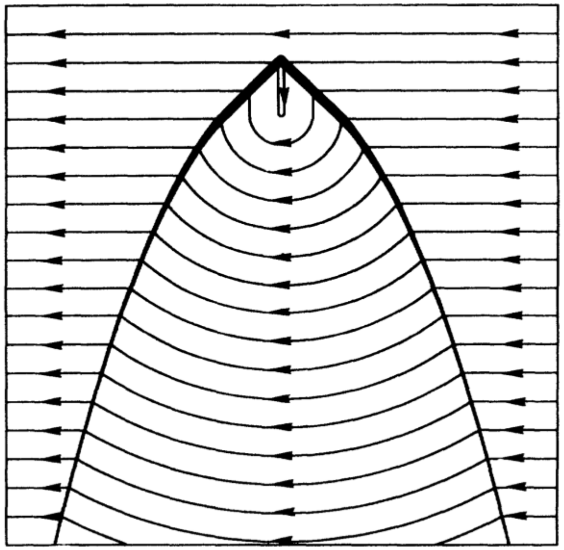


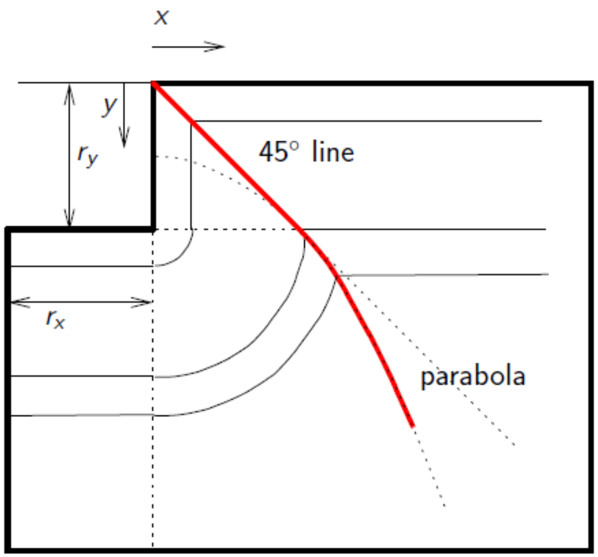
$$y = ax^2 + b$$

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

$$b = -\frac{R}{2}$$

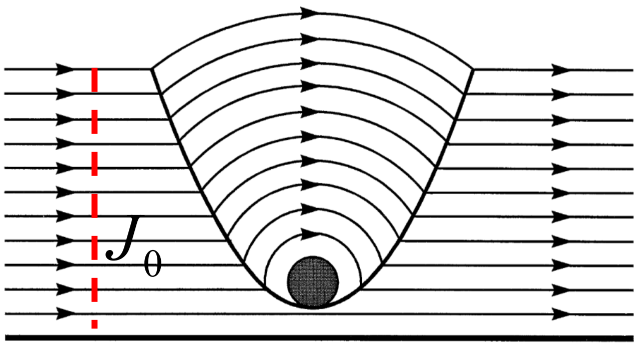
Does the shape of the hole matter?

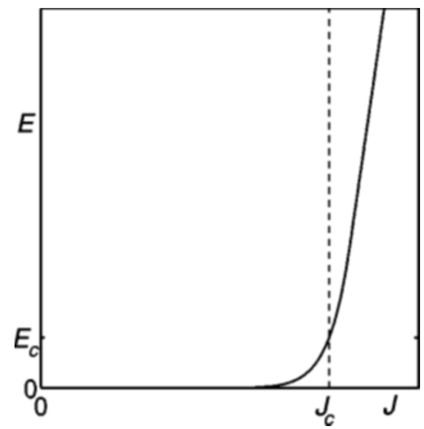




- Parabola equation: $y = r_y/2 + \frac{x^2}{2r_y}$.
- Parabola radius of curvature: r_y.
- Beware they are two distinct branches separated by $2r_x$!

How can vortices penetrate into the region enclosed by the parabola?





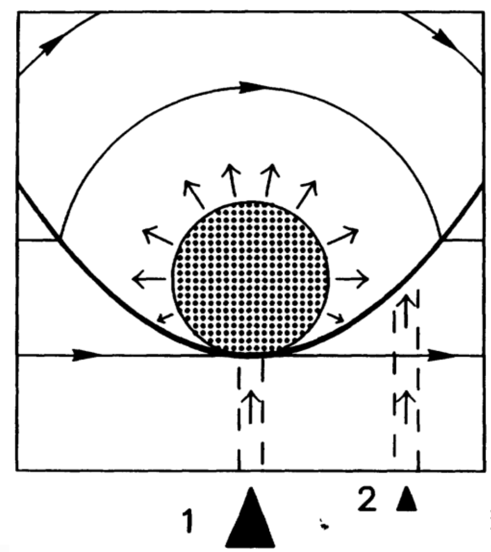
$$E = E_0 (J / J_0)^n$$

$$J / J_0 < 1$$

$$E \xrightarrow[n \to \infty]{} 0$$

$$v = E / B \to 0$$

Vortices can never cross the *d*-lines lines

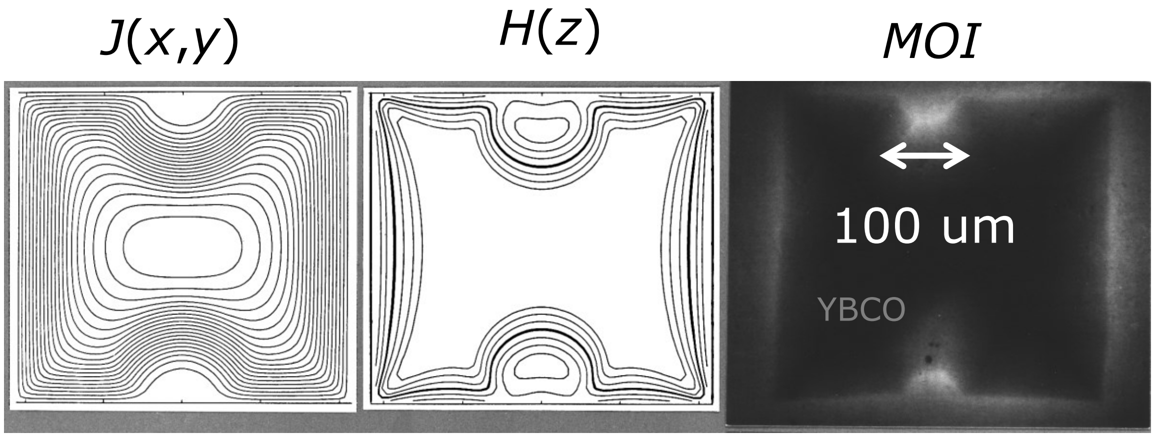


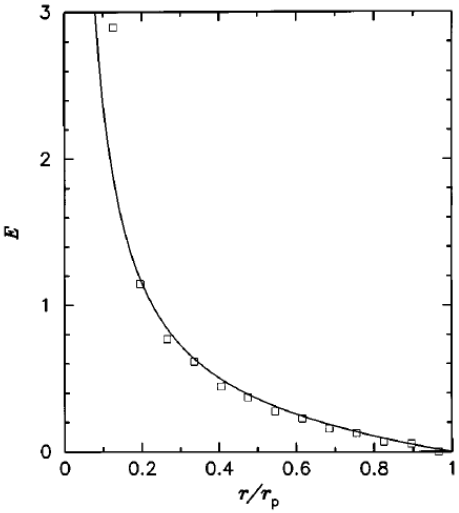
Channel 1 is a distinguished place for the nucleation of a **thermal jump**

Th. Schuster *et al.* PRB **49**, 3443 (1994)

Indentations should act as nucleation points for vortex avalanches

The large electric fields at indents along the conductors may trigger flux jumps and thus lead to thermal instabilities.





$$Q = \int J \cdot E \, dxdy$$

Th. Schuster *et al.* PRB **54**, 3514 (1996)

From Ohmic to Bean regime

Beyond Bean model $E = E_0 (J / J_0)^n$

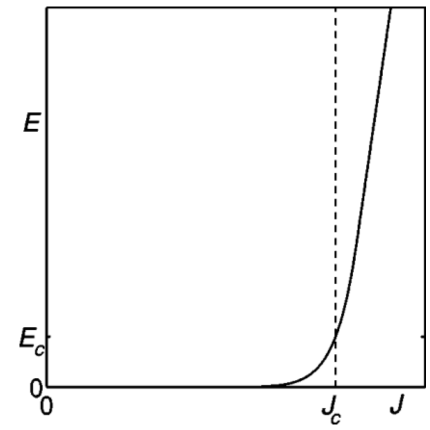
$$L_\perp \sim Rn$$

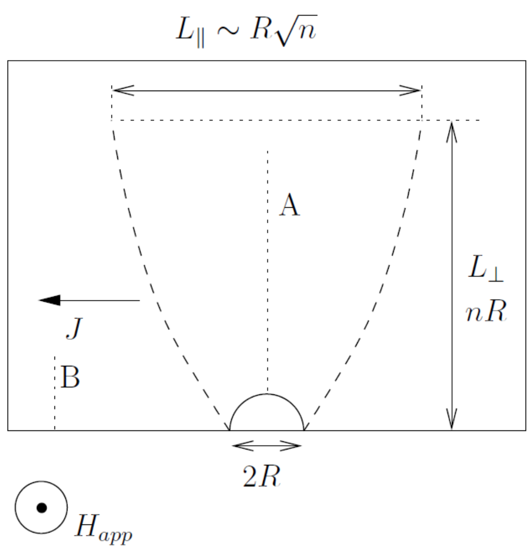
$$L_\parallel \sim R\sqrt{n}$$

By measuring the scales $L_\perp$ and $L_\parallel$ of magnetic-flux disturbance, one can extract:

$$n \approx \left(L_\perp / L_\parallel\right)^2$$

$$R \sim L_\perp / n$$

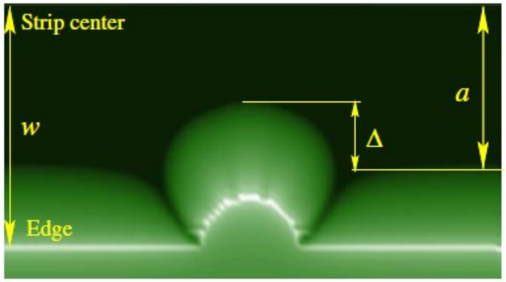


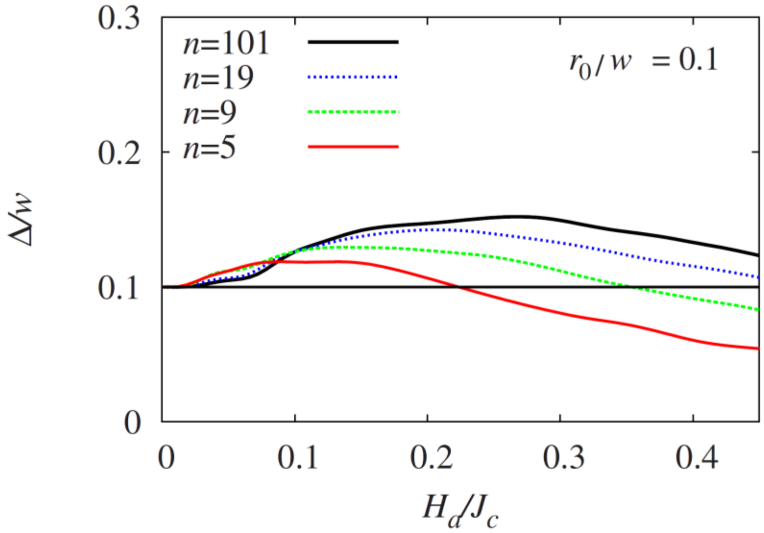


Gurevich and Friesen *et al.* PRB **62**, 4004 (2000), PRB 63, 064521 (2001)

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
Defect size ~80 μm





A locally enhanced Joule heating is predicted to facilitate nucleation of a thermal instability at the indentation

The avalanches are expected to be larger and occur more frequently at the indentation

J I Vestgarden *et al.*, PRB **76,** 174509 (2007)

Motivation

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

2. Previous investigations do not control neither study the shape of the indentation.

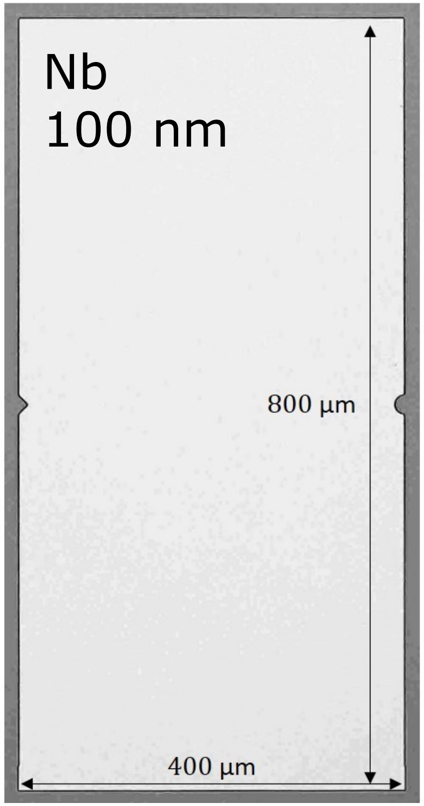
3. Do indentations trigger flux avalanches as systematically predicted in the literature ?

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

5. How the distance between indentations affect the penetration ?

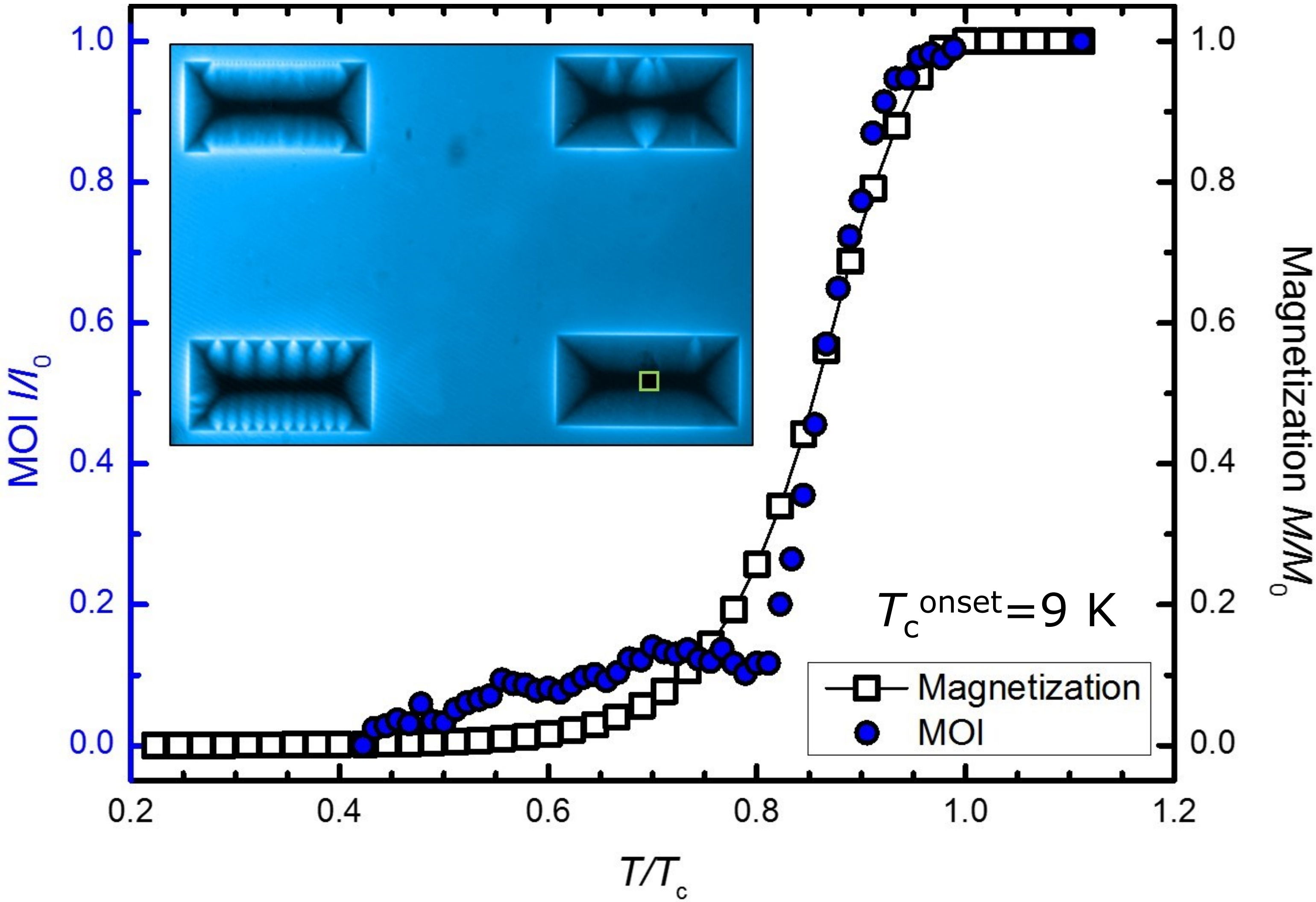
…

Samples layout

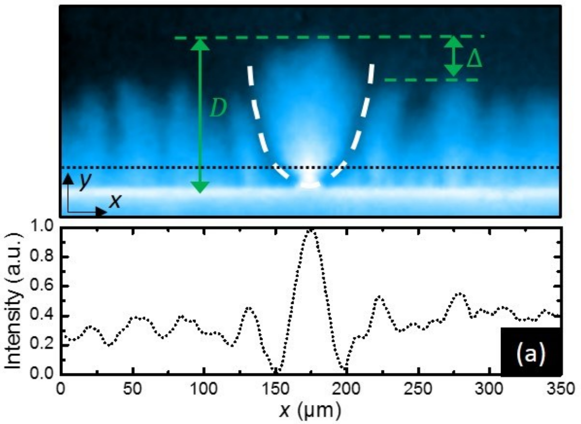


R. Kramer, Grenoble

Simultaneous MOI imaging



Determination of *d*-lines

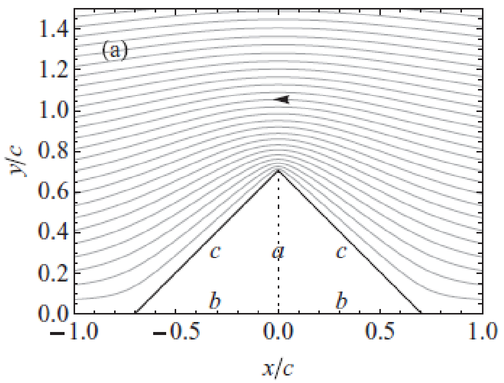


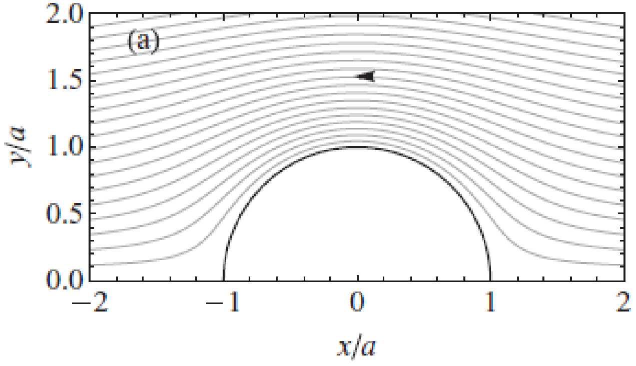
$$y = ax^2 \approx \frac{x^2}{2h}$$

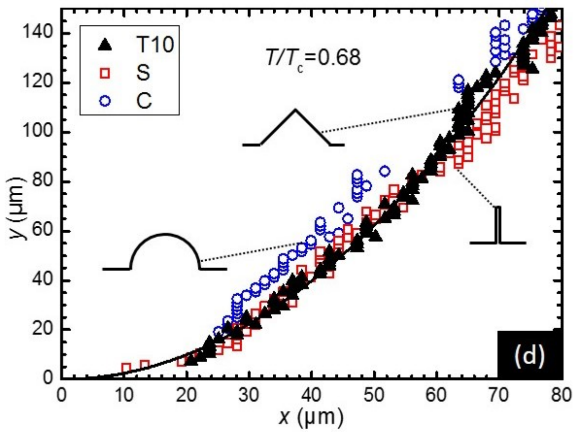
The *h* values deduced from the Bean model are far larger than what actually should be.

Possible sources of disagreement are
(i) the fact that the Bean model corresponds to an unrealistic creep exponent *n*,
(ii) that the 3D local Bean model fails to describe the demagnetizing effects and the non-local nature of thin films

Importance of the creep exponent *n*



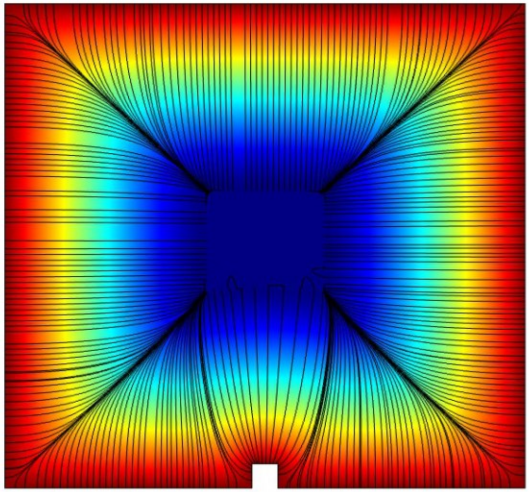


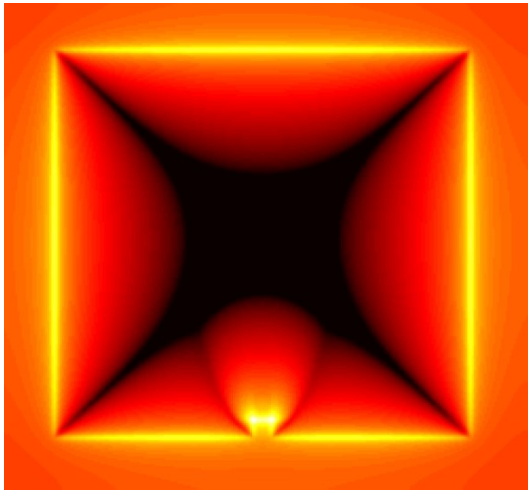


$$n = \frac{U_0}{k_B T}$$

Clem and Berggren, PRB **84**, 174510 (2011)

Numerical simulations



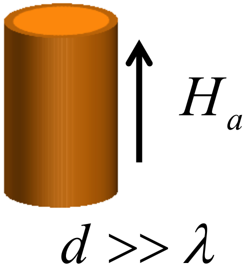


Without demagnetizing field (local)

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

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

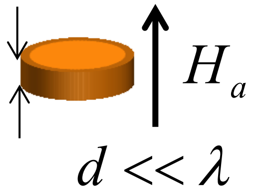
$$\rho = \begin{cases} \left|\nabla h / J_c\right|^{n-1} & \text{for } \left|\nabla h\right| < J_c \\ 1 & \text{for } \left|\nabla h\right| > J_c \end{cases}$$



With demagnetizing field (non-local)

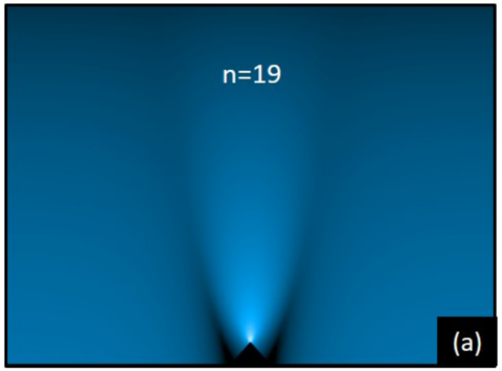
$$\iint Q \frac{\partial g}{\partial t} d^2 r = \frac{\nabla \cdot \left(\rho \nabla g\right)}{d} - \frac{\partial H_a}{\partial t}$$

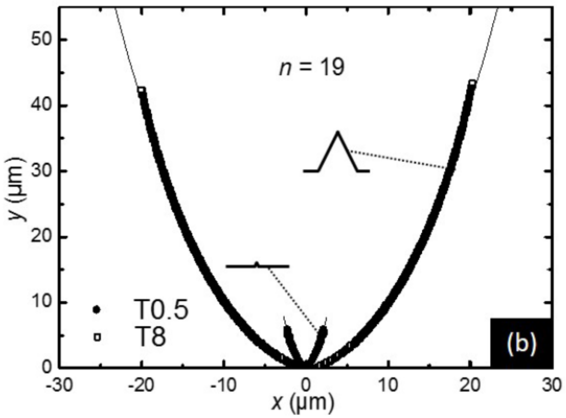
$$\rho = \begin{cases} \left|\nabla g / J_c\right|^{n-1} & \text{for } \left|\nabla g\right| < J_c \\ 1 & \text{for } \left|\nabla g\right| > J_c \end{cases}$$

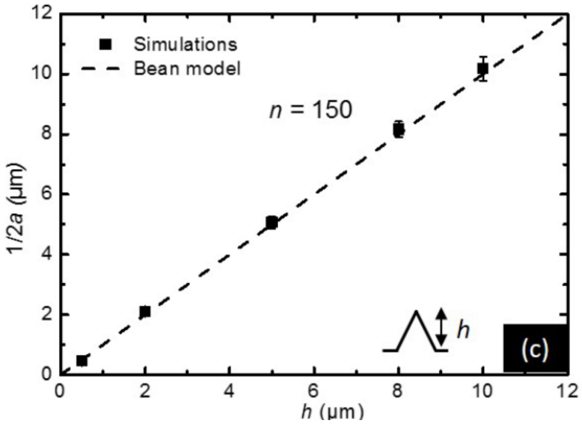


E.H. Brandt, PRB **52**, 15442 (1995)

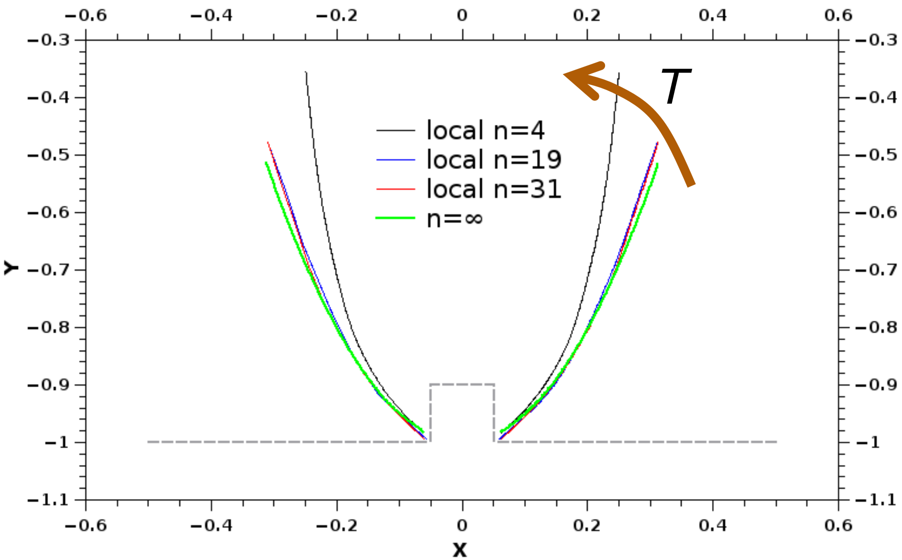
COMSOL longitudinal geometry



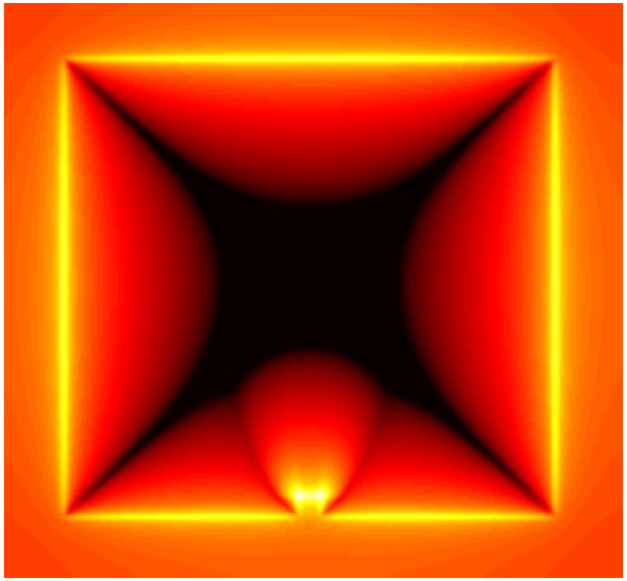


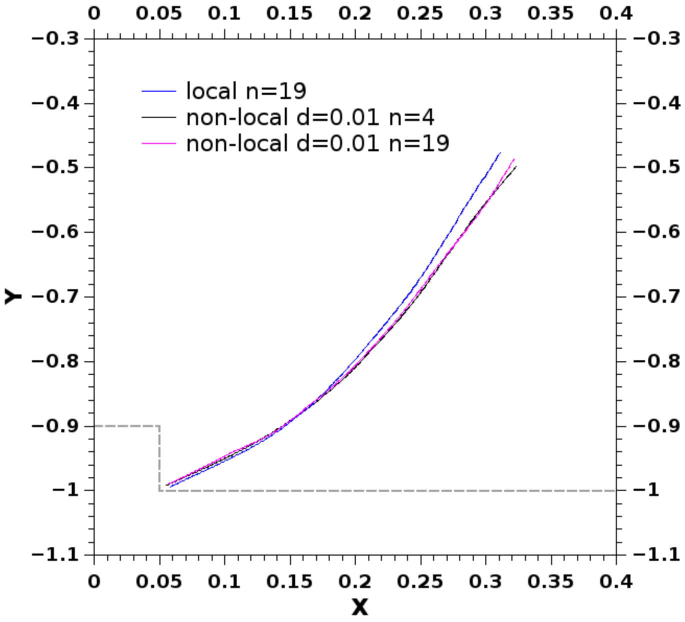


The parabola should shrink as *T* increases ?



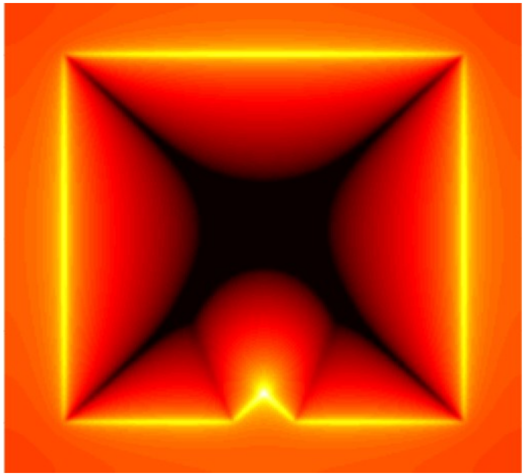
Demagnetizing effects

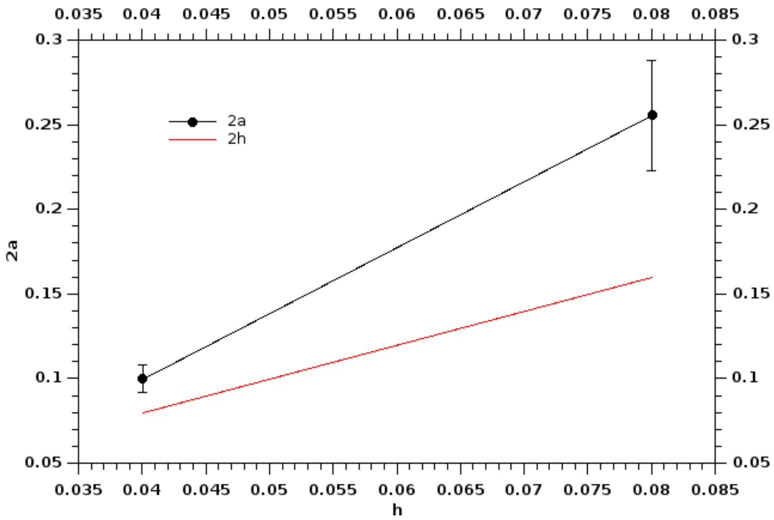


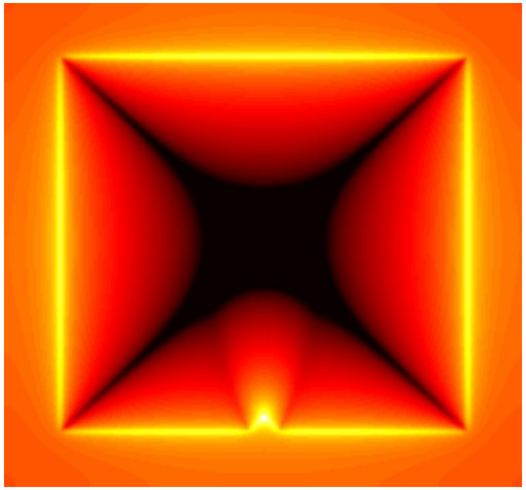


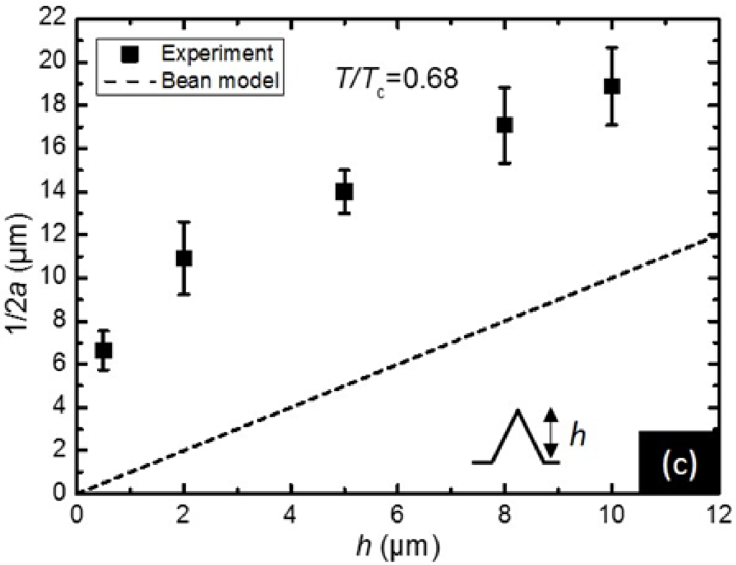
The parabola should expand in a thin film

Numerical simulations

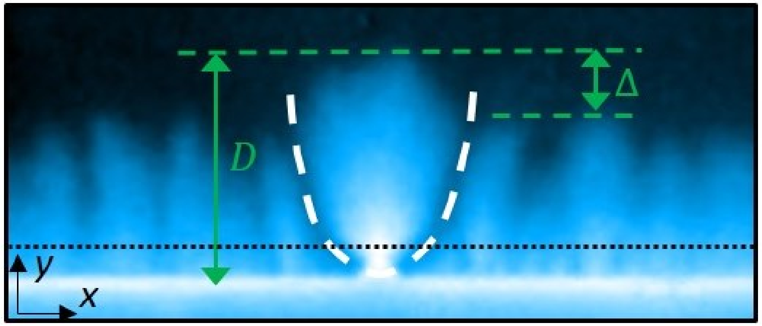


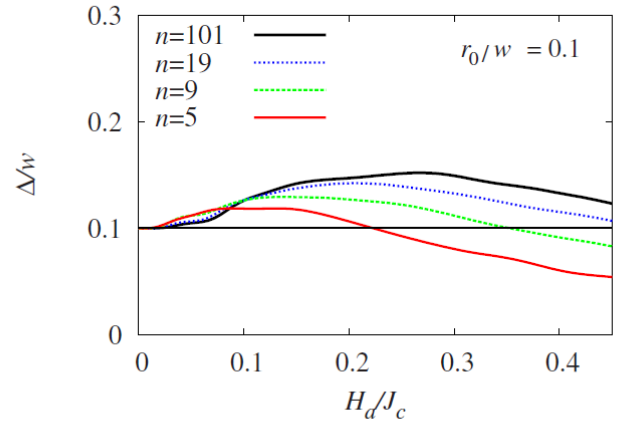


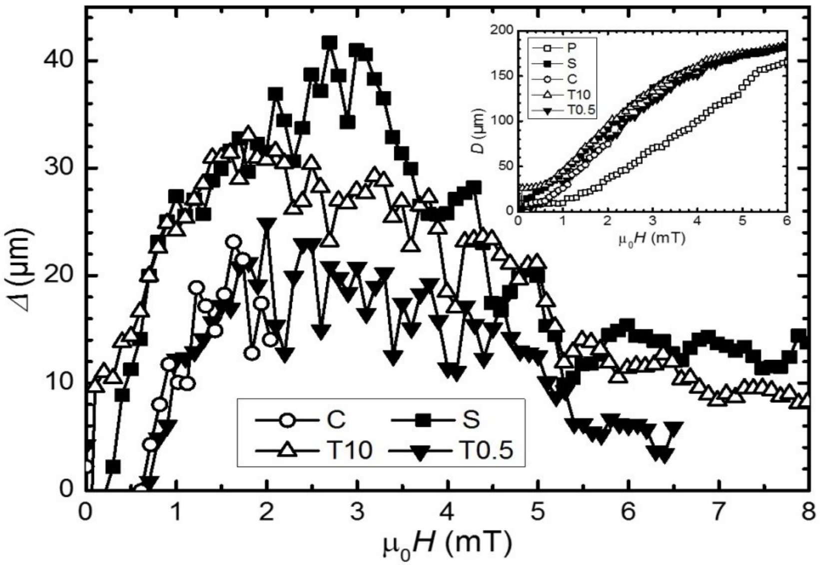


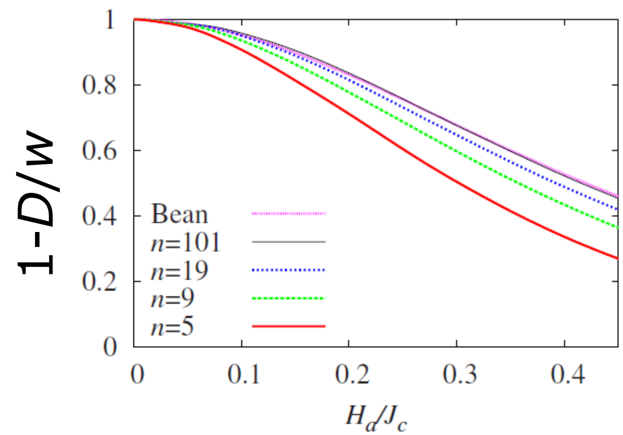


Excess penetration

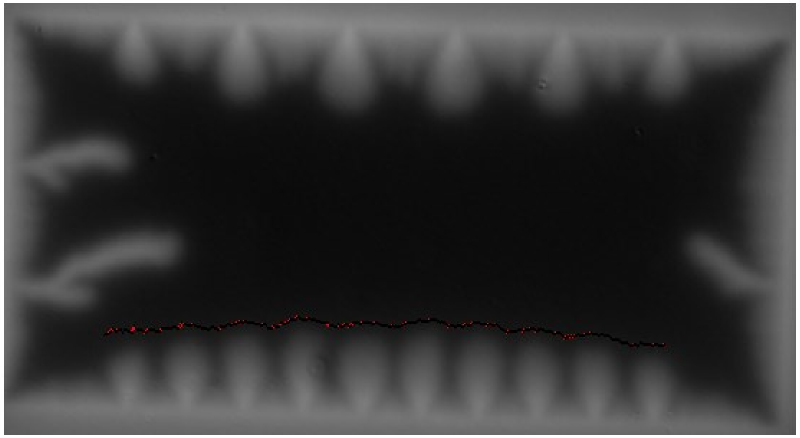


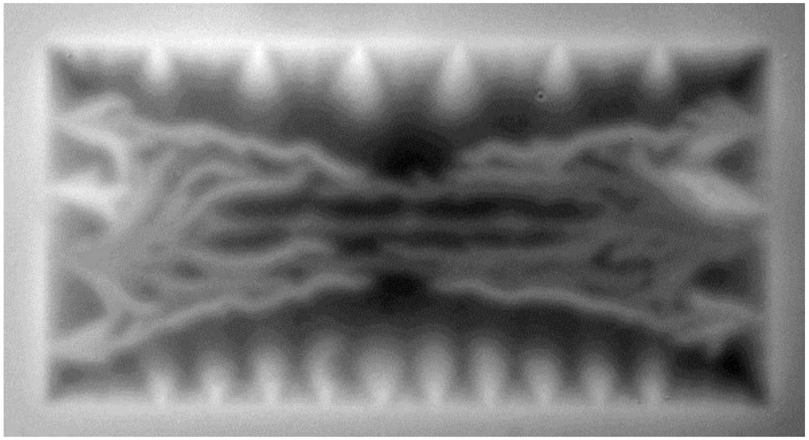






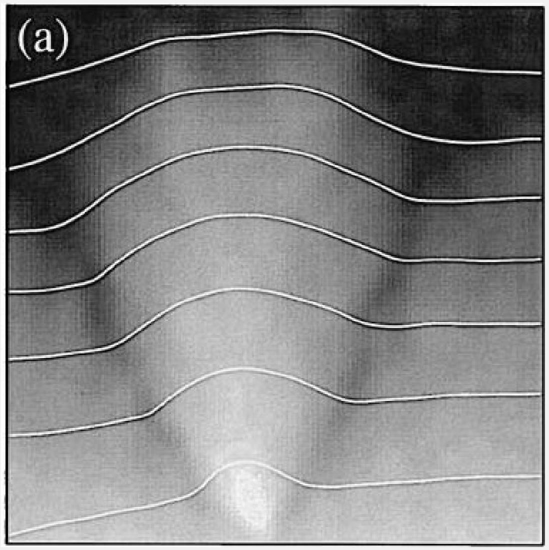
Do indentations trigger flux avalanches ?





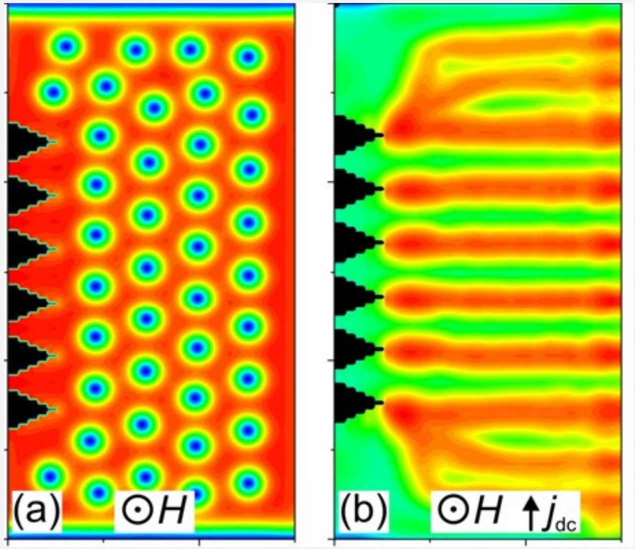
Some possible explanations

Extended Bean model
jc=jc(B)



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

Lower surface barrier

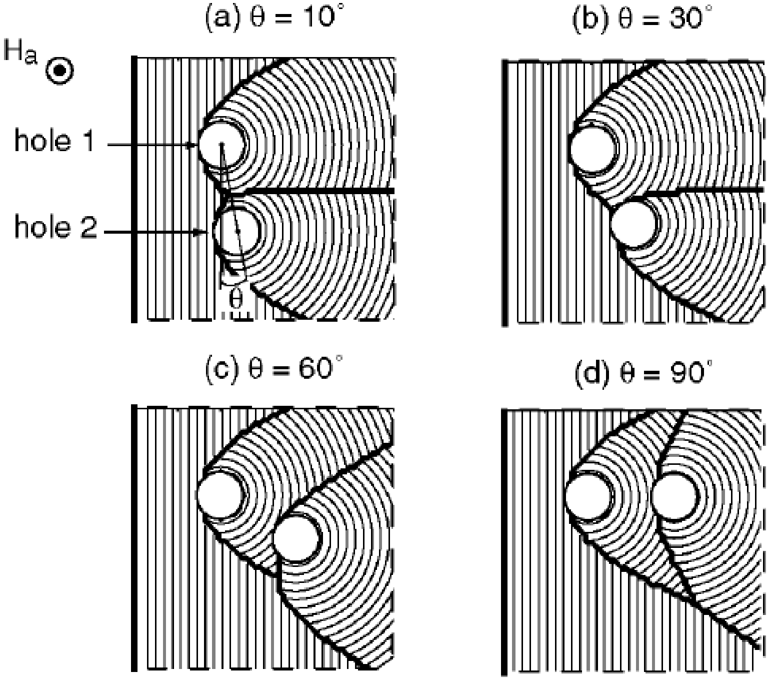


Cerbu *et al.*
New J. Phys. 15, 063022 (2013)

Practical application

Drilled HTS for better oxygen diffusion and better heat exchange.

Where to place the holes to maximize the trapped flux?

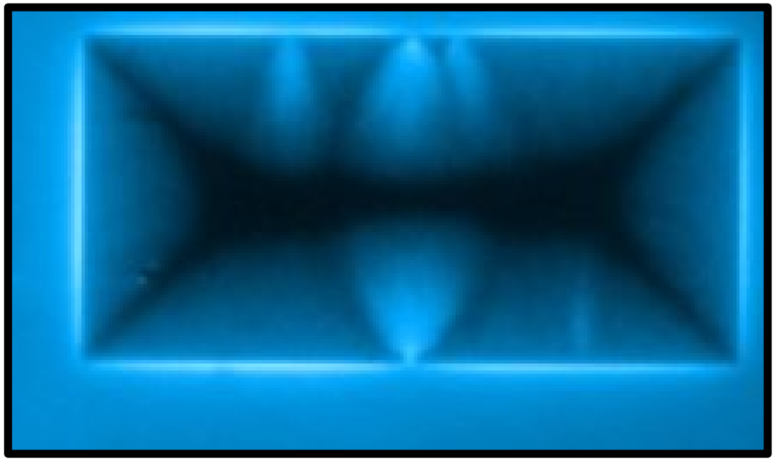


The trapped magnetic flux is maximized if the center of each hole is positioned on one of the discontinuity lines produced by the neighboring holes.

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

Preliminary conclusion

- The “parabolic” *d*-lines encode information about the demagnetization effects, the size and shape of the defect, and perhaps the non-linear exponent *n*.



- Our preliminary measurements seem to contradict the statement that avalanches will be triggered at the indentation

Acknowledgements

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