Demagnetisation in Crossed Fields

Archie Campbell, Mehdi Bagdhadi, Anup Patel, Difan Zhou,
K.Y.Huang Tim Coombs

1) Mikitic Brandt Theory
2) Numerical Calculations
3) Comparison with Experiments

Materials: YBCO pucks and YBCO tapes.

In many application of superconductors the field changes direction as well as magnitude.

In general this involves currents where J is not perpendicular to B and flux cutting, which cannot be described by the Bean model.

However layered materials like YBCO these effects are probably not great.

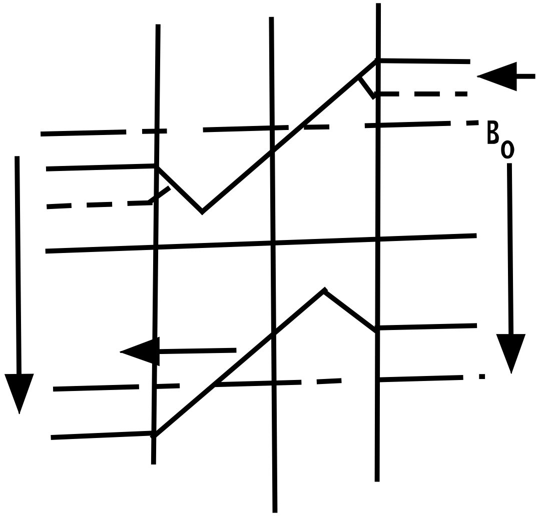
On the other hand we applying fields in a different direction to a trapped current so the usual assumption that E is parallel to J is questionable.

However there is one geometry in which the pure Bean model is valid. This is a long strip normal to the paper with a trapped field and transverse field in the plane of the paper.

This was solved by Mikitic and Brandt

The Dynamic Resistance

We apply a current and then a field B_o. Keeping the current fixed we oscillate B_o.

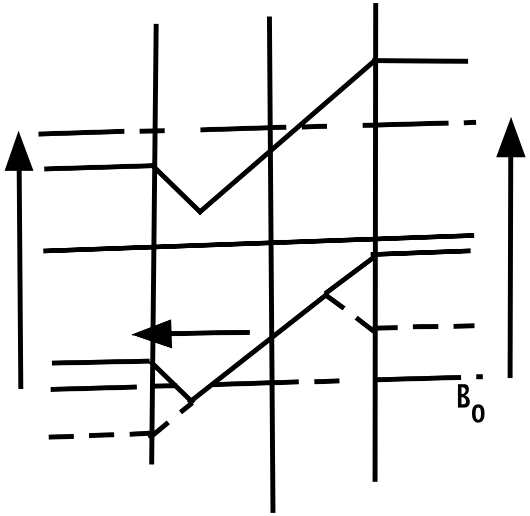


If we oscillate B_o at this amplitude the central flux does not move. E=0 at the two cusps

However when the critcal state on the left penetrates to the cusp it disappears.

$B_p(I)=B_p(0)(1-I/I_c)$

Now all the flux in the centre starts moving out left. None crosses the right hand cusp



When the field is now increased and the critical state penetrates to the cusp on the rght, this disappears and flux moves in to the centre.

On each cycle the electric centre where E=0 switches discontinuously from one side to the other and flux is moved in to the centre and out at the other side.

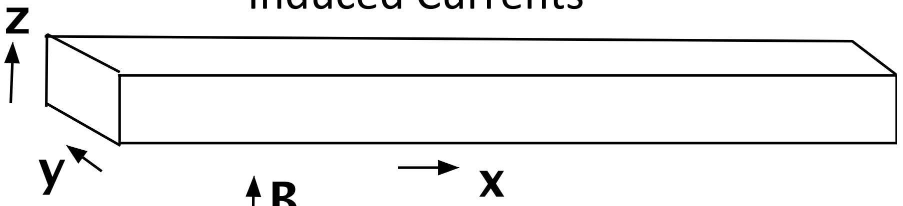
There is a DC component to E and if Bo is a trapped field it decreases until $I/I_c=1-B_o/B_p(0)$

At $I=I_c$ $B_p(I)=0$

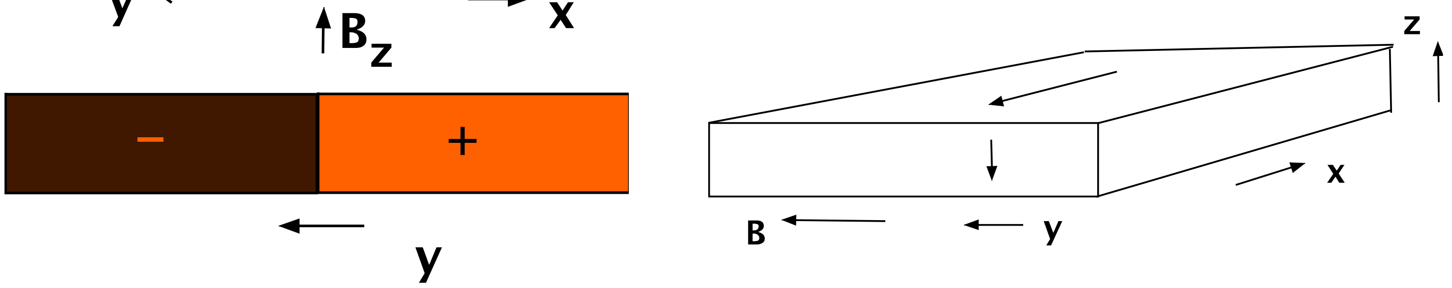
At $I=0$ $B_p=B_p(0)=\mu_o j_c d$

N. Sakamoto, F. Irie, and K. Yamafuji, J. Phys. Soc. Jpn. **41**, 32 (1976).

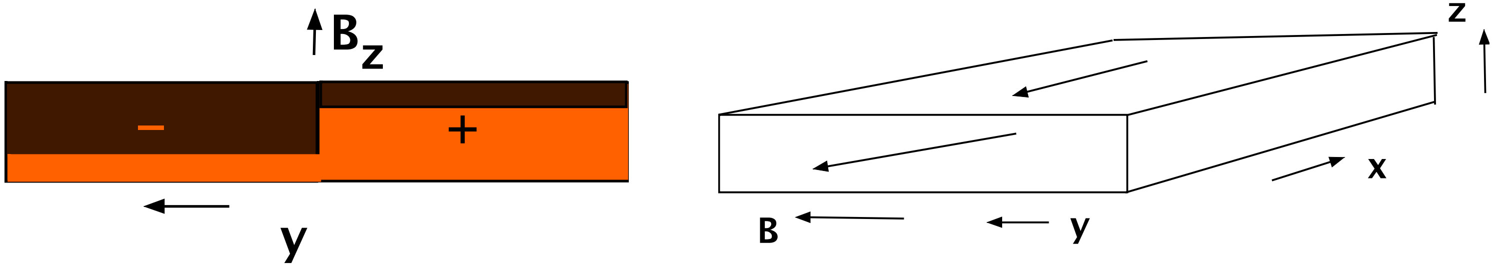
Induced Currents



Trapped field



Apply B_y

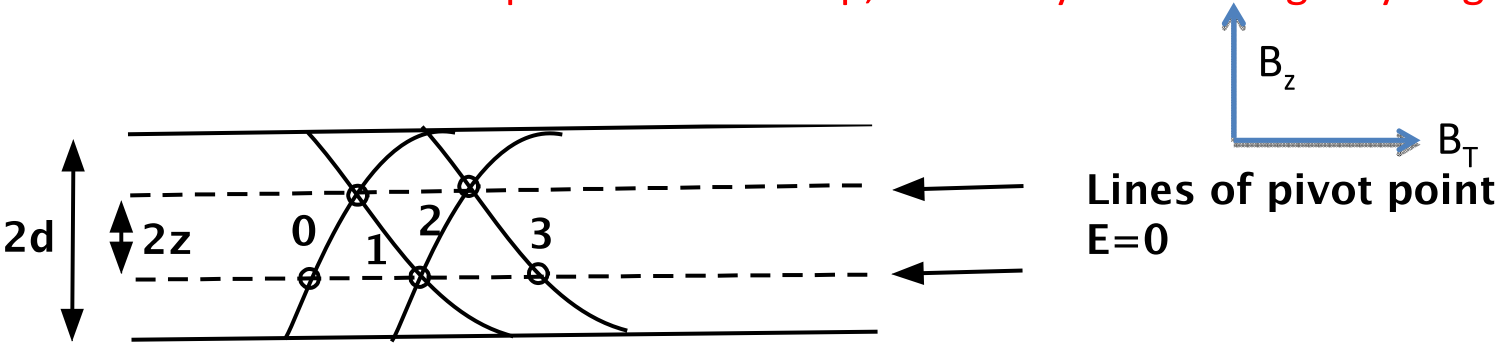


We see the extra current on top and bottom surfaces removes current that was contributing to the z moment.

However it is not obvious why a field greater than B_p does not destroy the magnetisation in one cycle.

There can also be end effects for square samples.

Flux lines walk out of the sample.
Hence if the sample is thin BT>> Bp,   but they have a long way to go.



Lines of pivot points.
E=0

J is sheet current A/m

$$z/d = J/J_c = 1 - B_T/B_P$$

Positions of pivot points

$$B_p(J) = \mu_o\left(J_c - |J|/2\right)$$

This is the current dependent penetration field

$$\Delta x = \frac{2J}{J_c B_z}\left[B_T - B_p(J)\right]$$

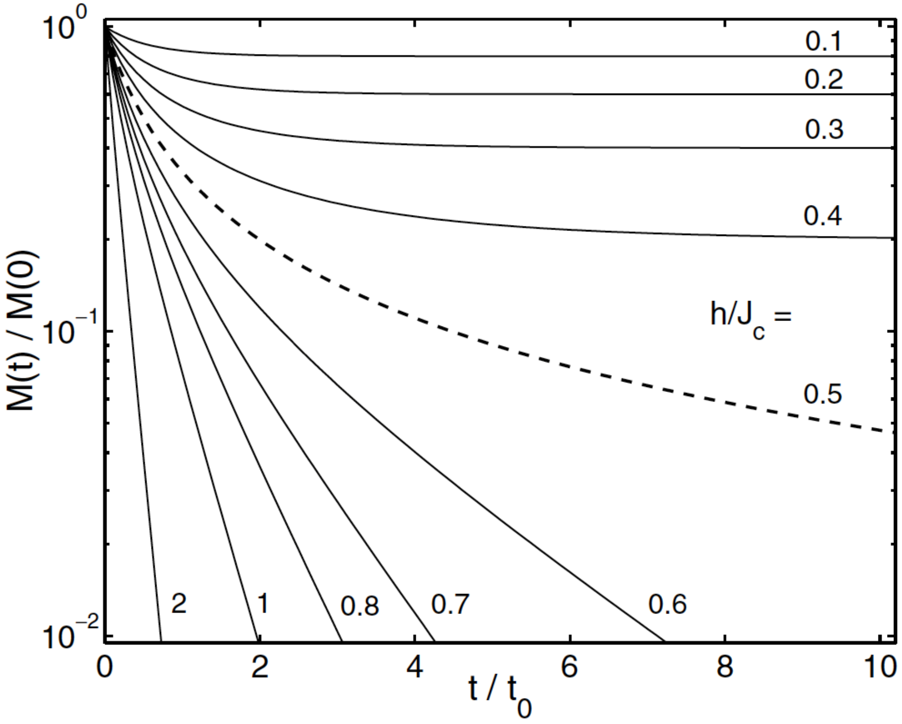
The distance moved per cycle

$$E_y = \frac{2\,fdJ}{J_c}\left[B_T - B_p(J)\right]$$

The mean electric field for frequency *f*

Faraday's law plus Biot Savart then gives change of J with time.
(With a 'well known' numerical solution of an integral equation.

Mikitic, G. and Brandt, E.H. PRL, 89, 027002-1, (2002).



μ

If $B_T<B_p$ $M_{sat}=M_o(1-B_T/B_p)$

w=width, d thickness

$n_o=ft_o=w/4d$ cycles M saturates after about w/d cycles.

For a 1μ thick YBCO tape this is 10000 cycles.

However B_p is only about 16mT so this is not very useful for tapes.

However this is the important regime for bulks.

If $B_T>B_p$ at large times M decays exponentially with a time constant, in cycles

$$n_o = \frac{wB_p}{2\pi d(0.64)\left(B_T - B_p\right)}$$

It is important to realise that we cannot model the tape by increasing *d* and reducing j_c in proportion to give the same B_p.

However for thin samples and large B_T $n_o=0.25(w/d)(B_p/B_T)$

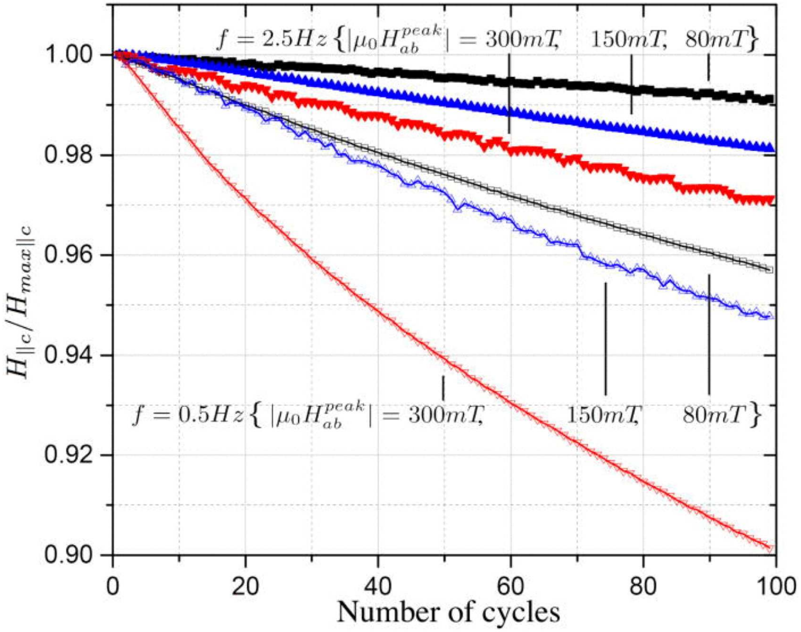
Notice that although Mikitic and Brandt asssume a large normal field, the result does not contain it. *The decay time is independent of a uniform applied field.*

For tape with I_c=300A , width 12mm YBCO thickness 1μ J_c=250A/cm B_p=15.7 mT

At B_T=300mT n_o=175 cycles

Decay in Stacked Tapes Showed Surprisingly Slow Decay

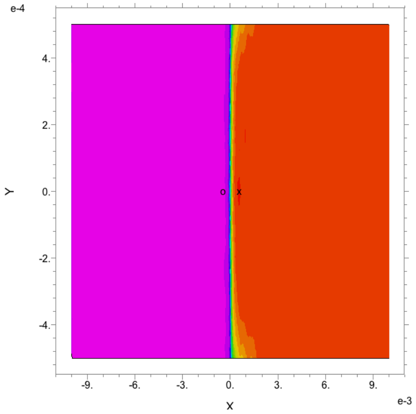
M. Baghdadi[1,a)], H. S. Ruiz[1] and T. A. Coombs[1]
Appl. Phys. Lett. 104, 232602 (2014); http://dx.doi.org/10.1063/1.4879263



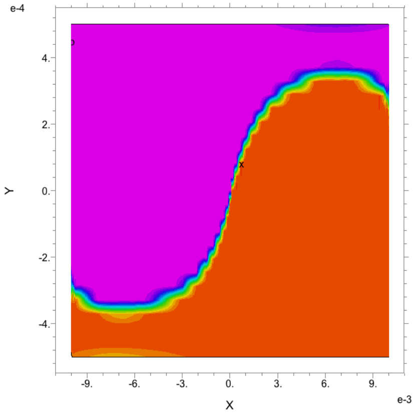
16 tapes, 12 mm sq

Mikitic Theory n_o=175 Cycles
At 300 mT n_o=1000 cycles, 6x theory

To investigate the validity of the theory a number of simulations were made on a 2cmx1mm bulk using FlexPDE.

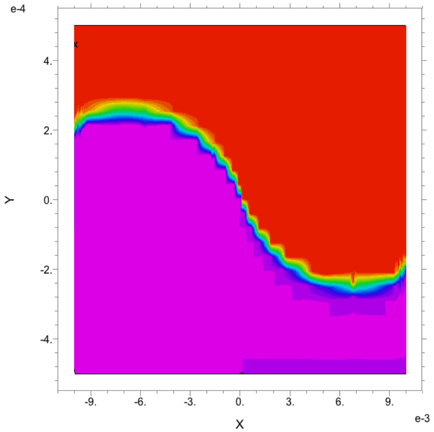


Trapped field B_T=0

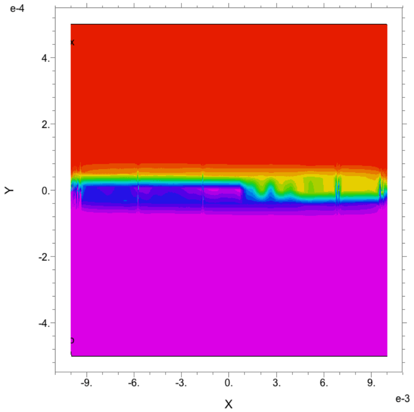


Plus half cycle BT=300 mT

20mm wide 1mm thick
YBCO puck.
Large penetration.
$B_T=5B_p$

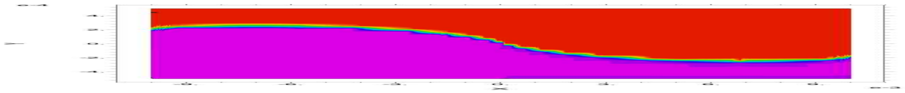


Bt=-300 mT



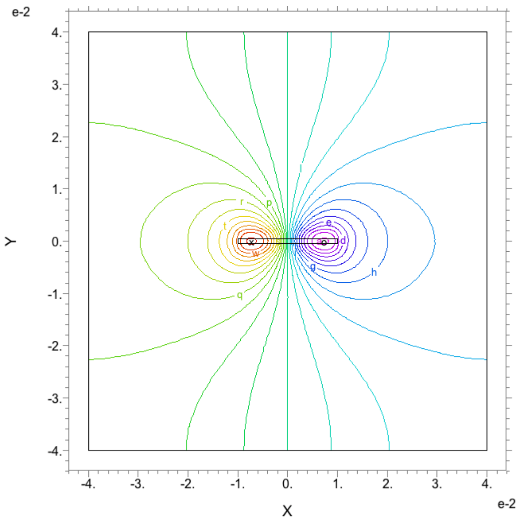
After 6 cycles

Current patterns are as expected. Most of the Mz has disappeared.

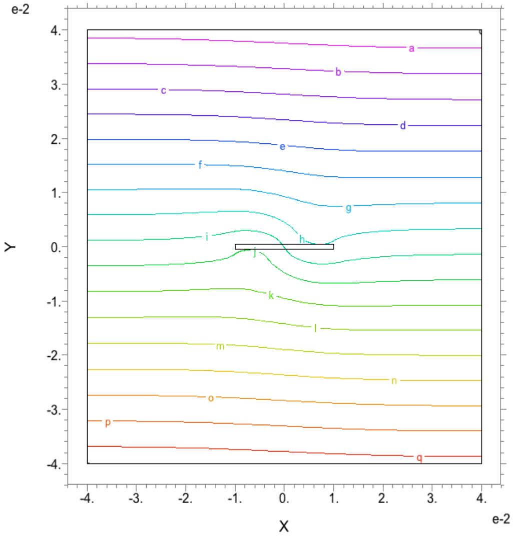


Real Shape

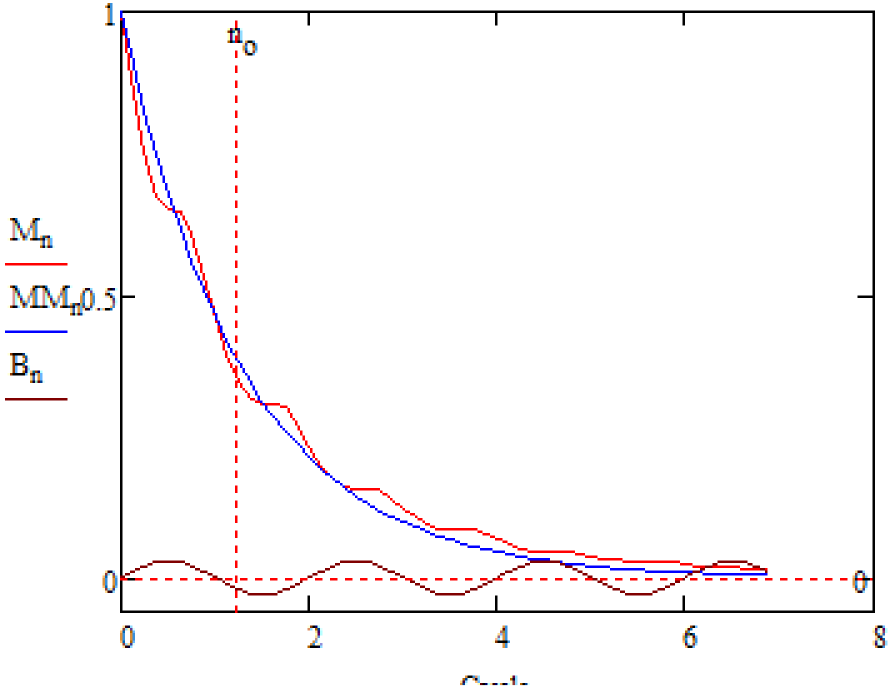
Aspect ratio 20 B_T=300mT B_p=60mT 1mmx20mm Jc=10^5 A/cm^2 B_T/B_p=5



Start B



Final B



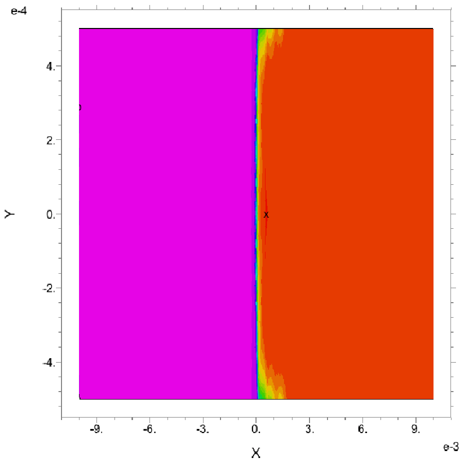
Red:- Flexpde

Blue:- Mikitk

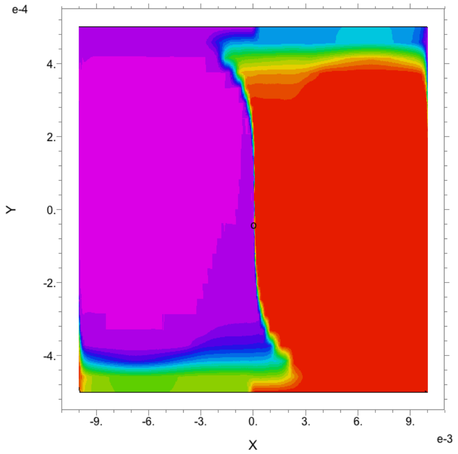
Black:- Transverse field, 300mT

Good agreement, even although no applied field

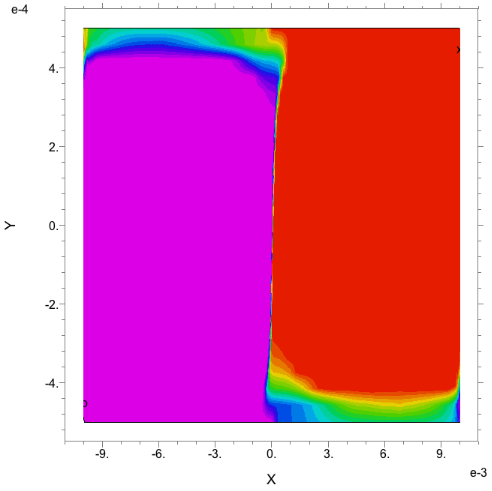
Low B_T .8xB_p,, expect saturation of M



Trapped Field

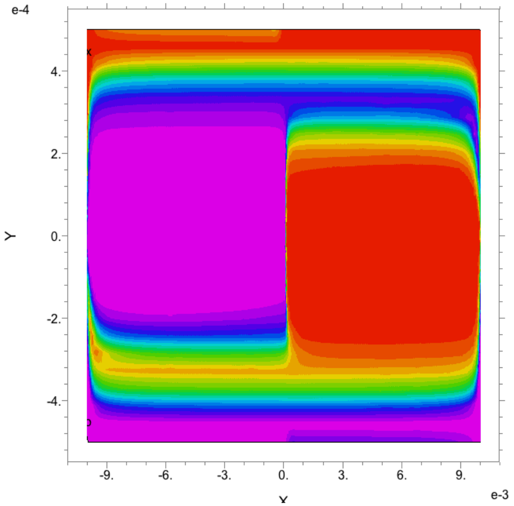


50 mT

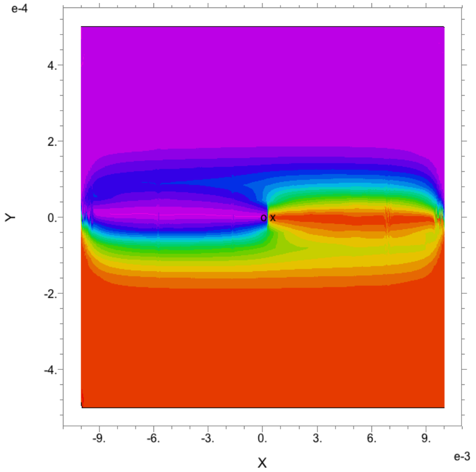


-50mT

Still
Trapped
Field



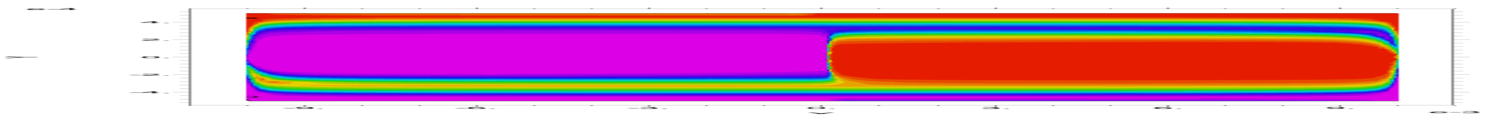
30 cycles



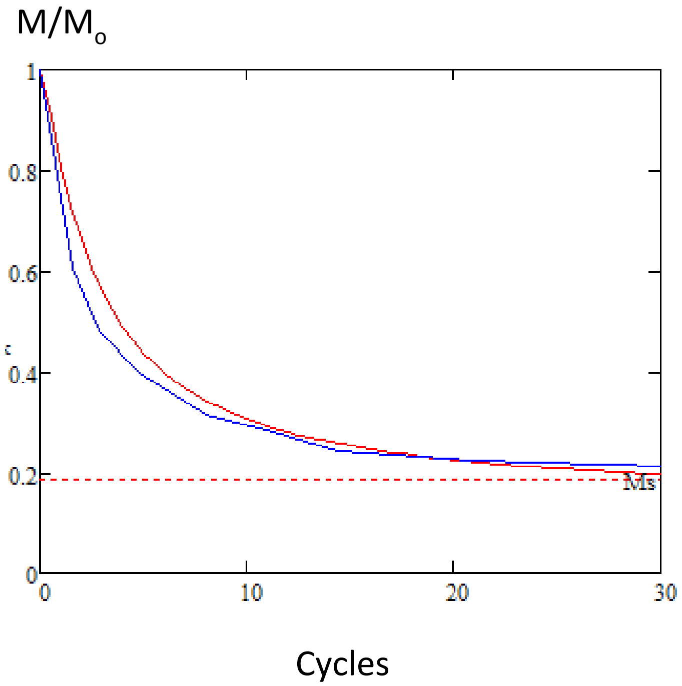
260 cycles

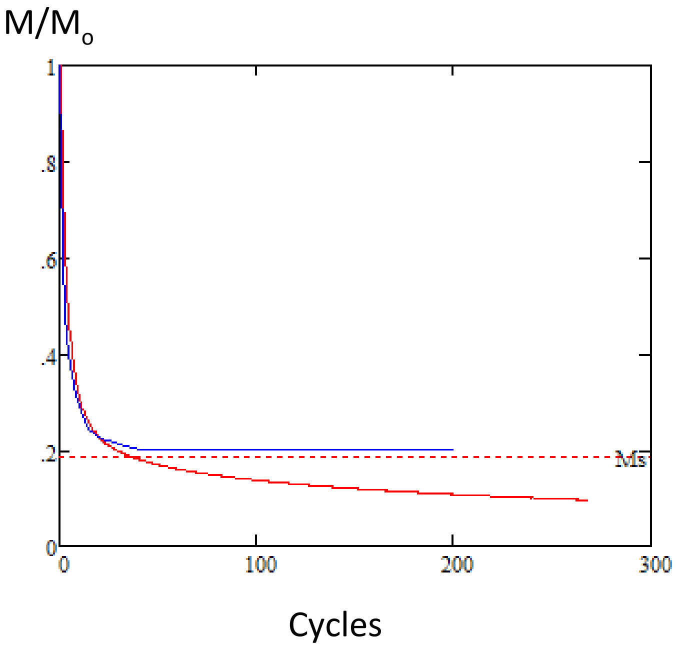
Much Less
Trapped
Field

30 Cycles



Magnetisation Decay, numerical results.





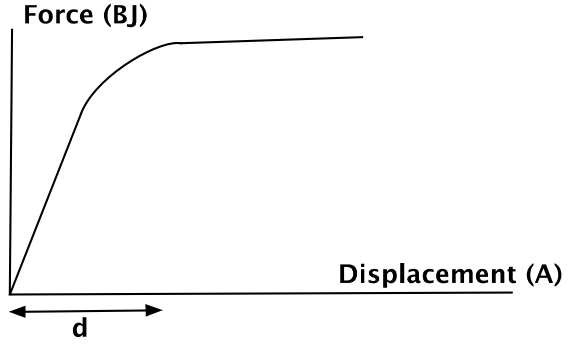
Red Flexpde
Blue Mikitic

Aspect Ratio 20
Bt/Bp=0.8
d=3e-7

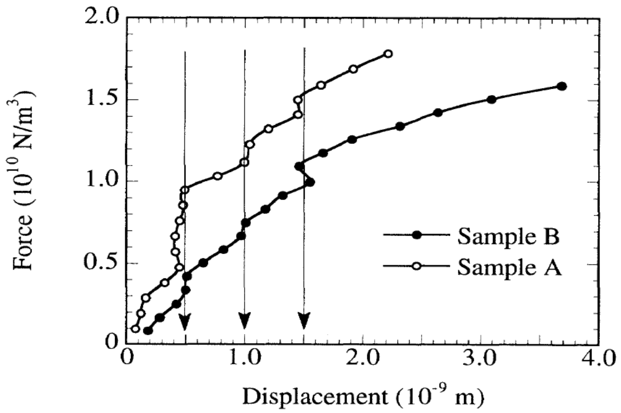
Up to 30 cycles good agreement.
However there is a slow continuous decay after this.
This can only B rounding errors or a deviation from the Bean model

The A Formulation Used

Force Displacement Curve for Flux Lines



Experiment, AC V-I Characteristic

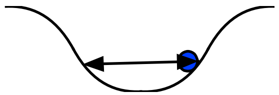


R. A. Doyle and A. M. Campbell and R. E. Somekh
PRL **71**, 4242-4244, 1993

We solve the force balance equation

$$J = \mathrm{curl}\ \mathrm{curl}(A) = BJ_c(1-\exp(-A/d))$$

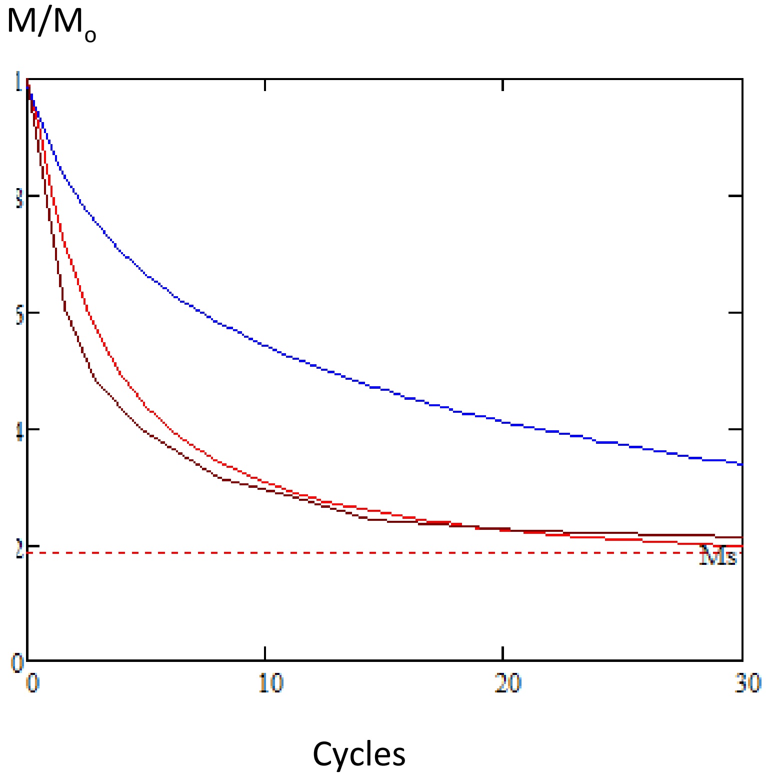
The parameter ‘d’ defines how close to the true critical state we are.
d=0 is Bean model. Large d gives a linear London equation.

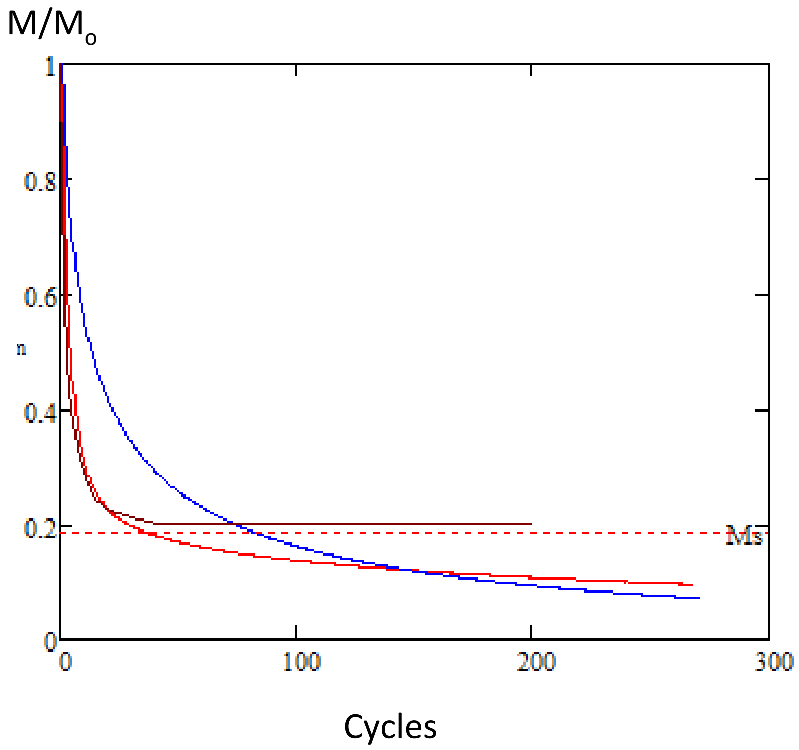


The flux movement is small in thin layers and
if in linear regime could explain long decay times.

In atomically thin layers there is no space for the critical state so there would be no decay. However intermediate values give a long term decay.

Magnet Decay. Larger Reversible Movement

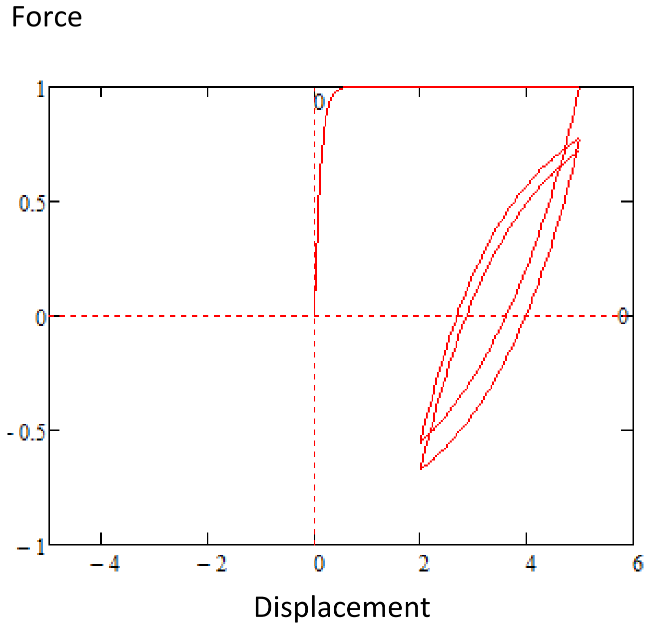




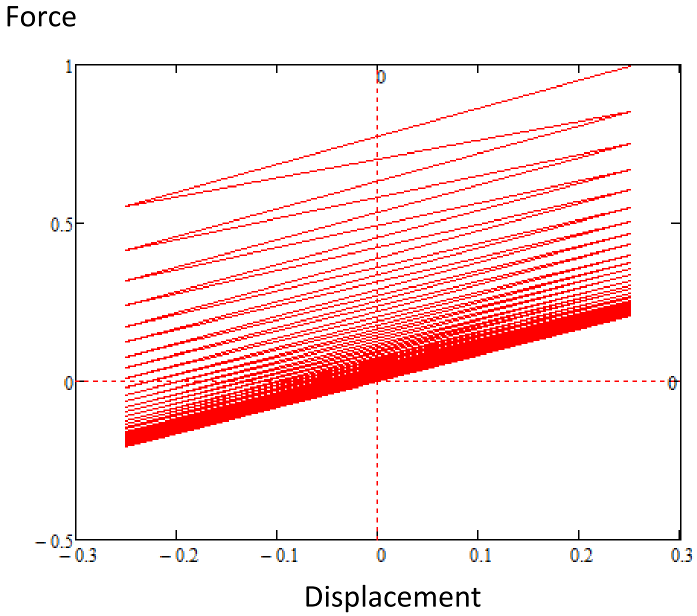
Black Mikitic (Bean Model)
Red d=3. 10^{-7}
Blue d=10^{-5}

Increasing d reversible movement decreases decay for up to 30 cycles.
However it increases the long term decay.

Minor Hysteresis Loops



Initial flux displacement plus two minor loops



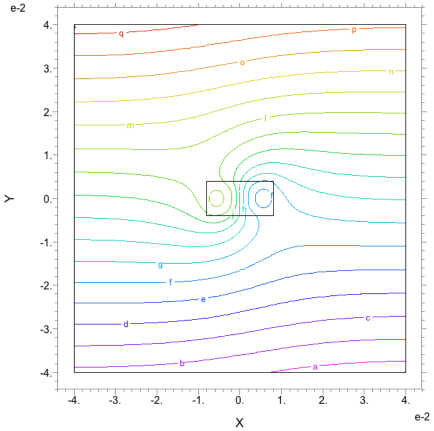
Many Loops

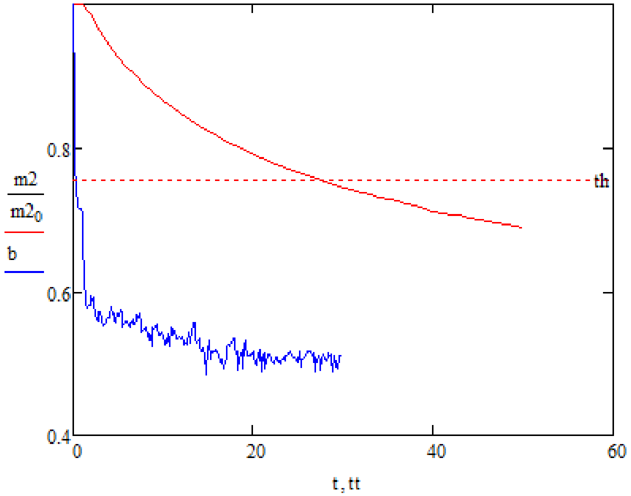
For a minor hysteresis loop we impose the same gradient at the start of each sector.
We also impose the condition that it saturates at plus or minus BJ_c as appropriate.
In general minor hysteresis loops do not close.
The only closed Rayleigh loops are symmetric about zero force.

Hence all hysteretic systems must decay to equilibrium after a sufficient number of cycles.
(e.g. Stress and Permanent Magnetisation).

Bulk Experiment on Puck, (Central Trapped Field)

8mm x16
Bp .7
Bt .17
B_T/Bp=0.287
We expect saturatation





Red is experiment, Blue FlexPDE

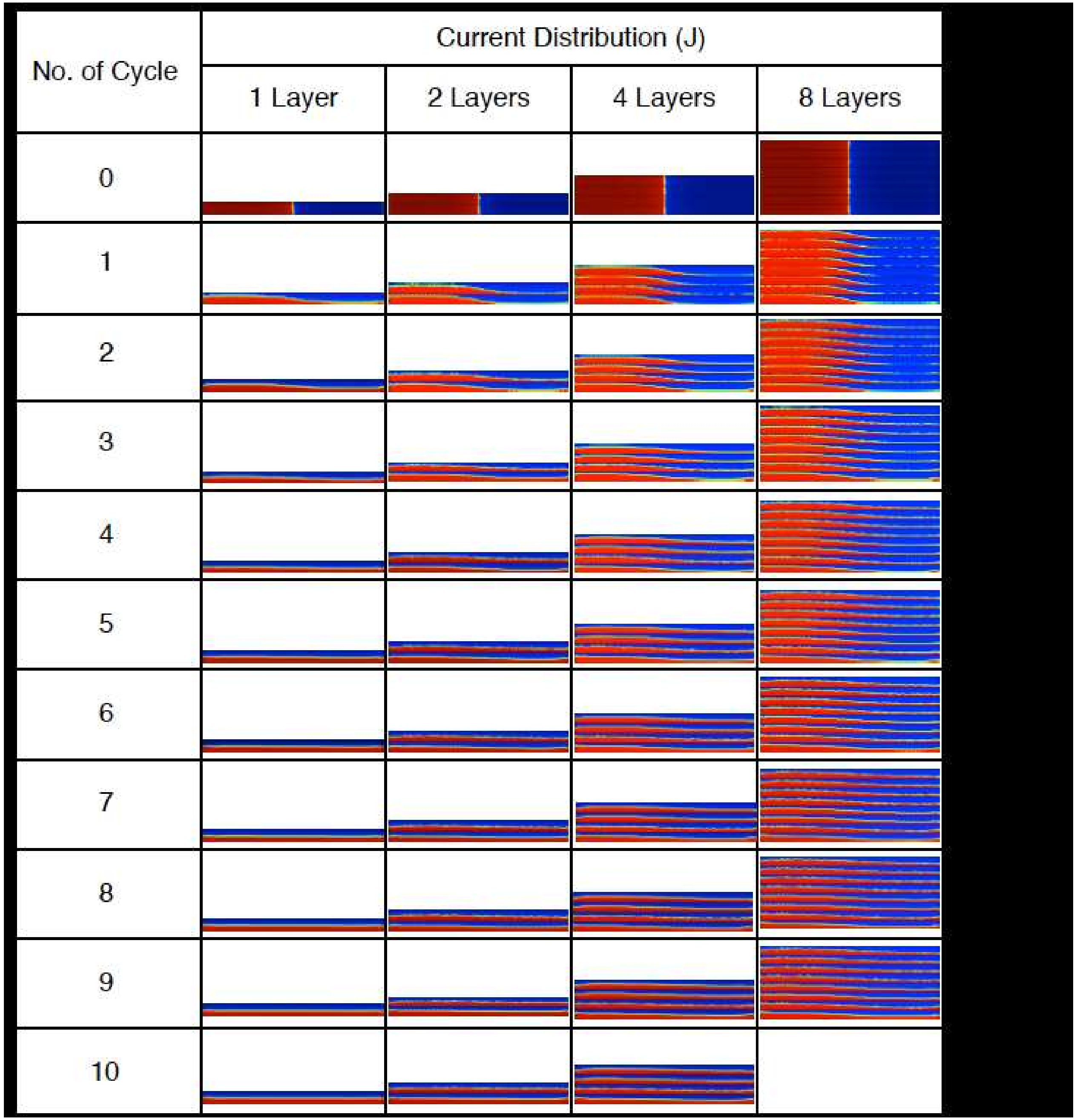
The experimental decay is much slower than than the simulation.
Could be end effects, enhanced by anisotropy.

How does a stack behave?

The Mikitic theory is only for a single sheet. Since an external field does not affect the decay time we might expect the tapes to behave independently.

Mehdi Bagdhadi has done a simulation for up to eight decoupled layers,
each 20mm wide by 1mm thick.
He found a large effect.

(These are graphs of integrated B_z across the face using Comsol and the H formulation)

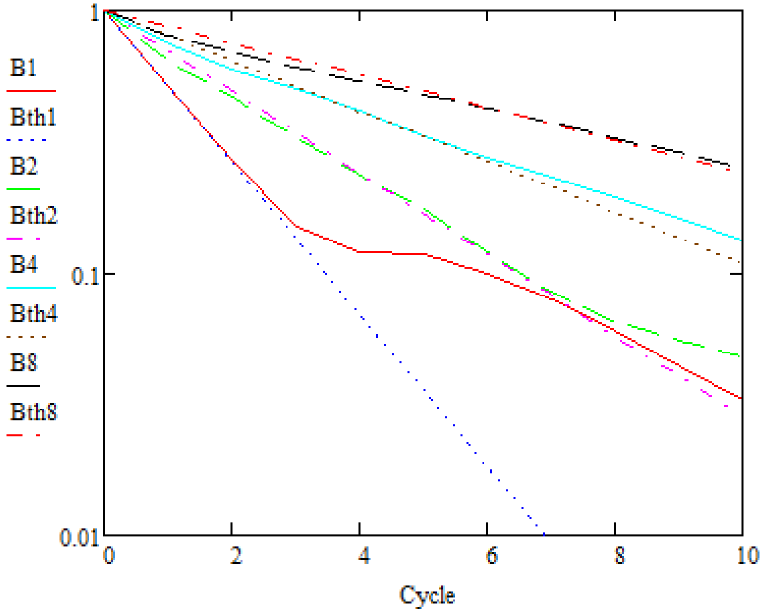


Multilayer Simulations

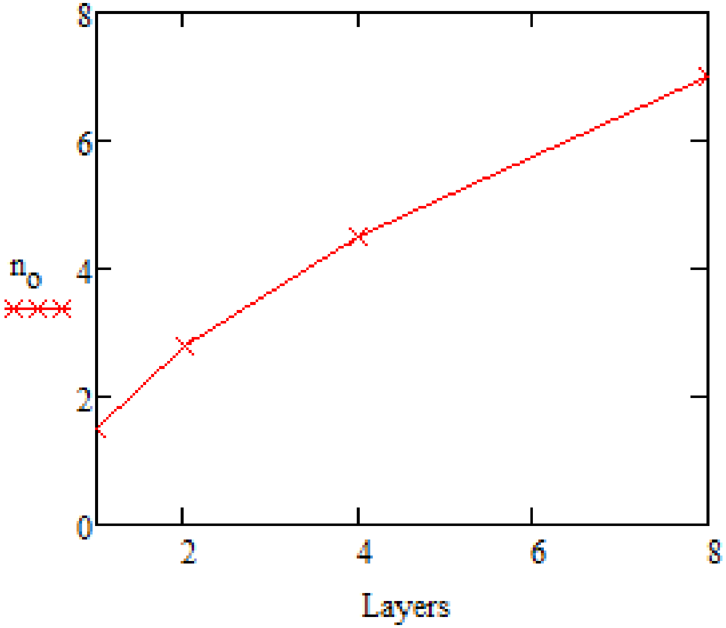
Up to eight decoupled layers.
20mm wide by 1mm thick
B_T=140 mT
B_p=60mT

B_T/B_p=2.7 (Full penetration)

H Formulation
Comsol

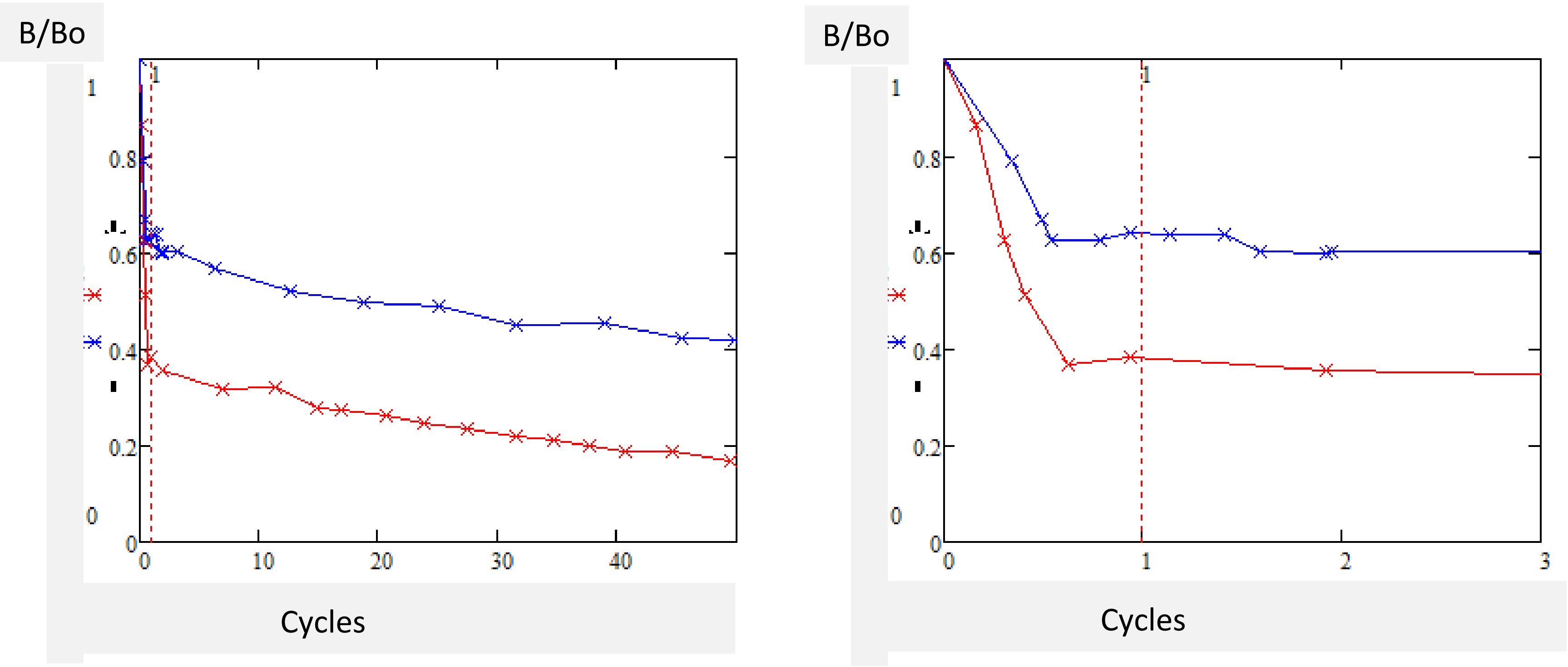


Integrated Field Decay, normalised,
For 1,2,4,8 Layers, log scale.



Decay constant, cycles

The decay constant is increasing with the number of tapes.
Mikitic theory gives 175 cycles for one tape.
So for 16 tapes we expect about 2800.
Experimental value was 1000, so this probably explains the stack results.



Bath group results on YBCO tapes.

Min Zhou, Weijia Yuan

300mT 0t peak, equivalent to 150mT, large cross field

Blue one tape, red three.

Again decay time lengthens with number of tapes.

However the very sharp drop followed by a faster decay than theory is hard to fit with other experiemnts,

Min 1 and three stack slop 40 cycles

Conclusions

For samples which can be modelled the Miktic Brandt theory works well.

However for large numbers of cycles the magnetisation continues to drop slowly
This could be explained by reversible flux line motion.

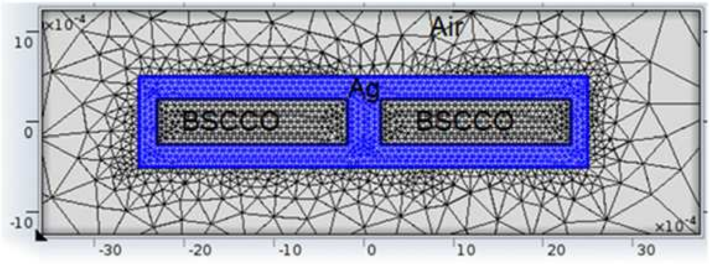
This effect can also cause long decay times in very thin samples.

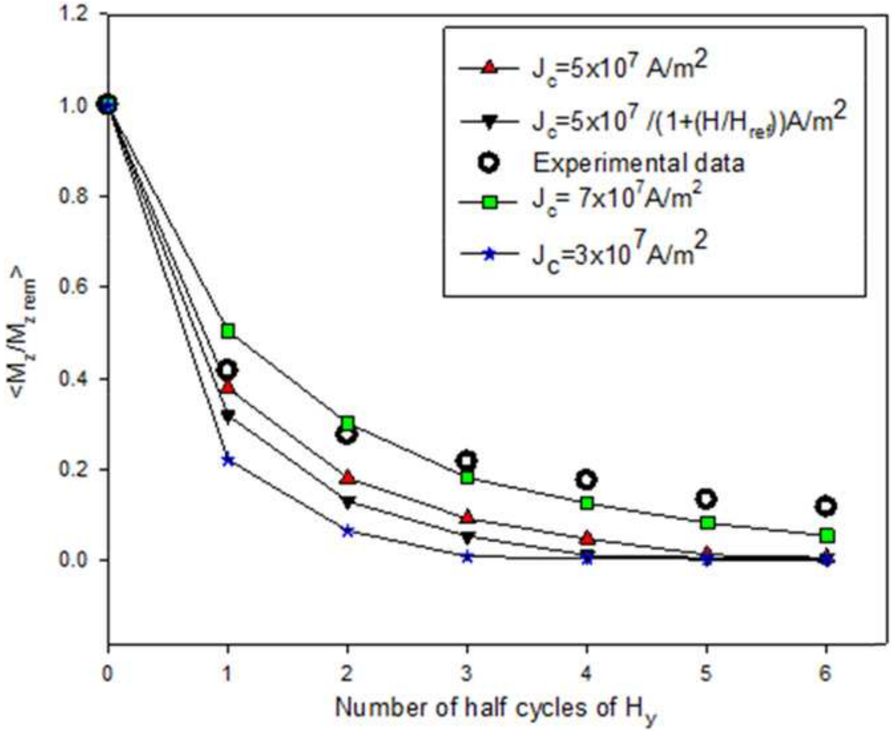
Tapes are too thin to model but stacks of thicker samples show
the decay time increases with the number of layers.
This can explain the slow decay time of YBCO tape stacks.

Experiments on bulk samples show much longer delay times than simulations.

Collapse of the magnetization by the application of crossed magnetic fields: observations in a commercial Bi:2223/Ag tape and comparison with numerical computations.

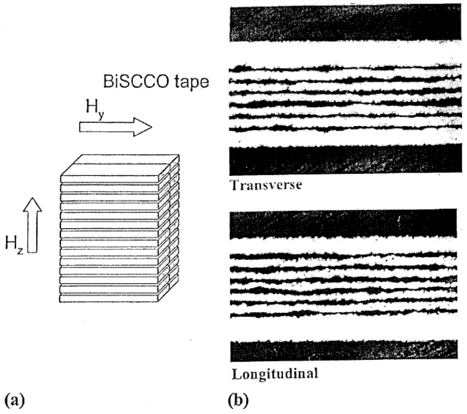
S Celebi1, F Sirois2 and C Lacroix2. Supercond. Sci. Technol. 28 (2015) 025012 (9pp)

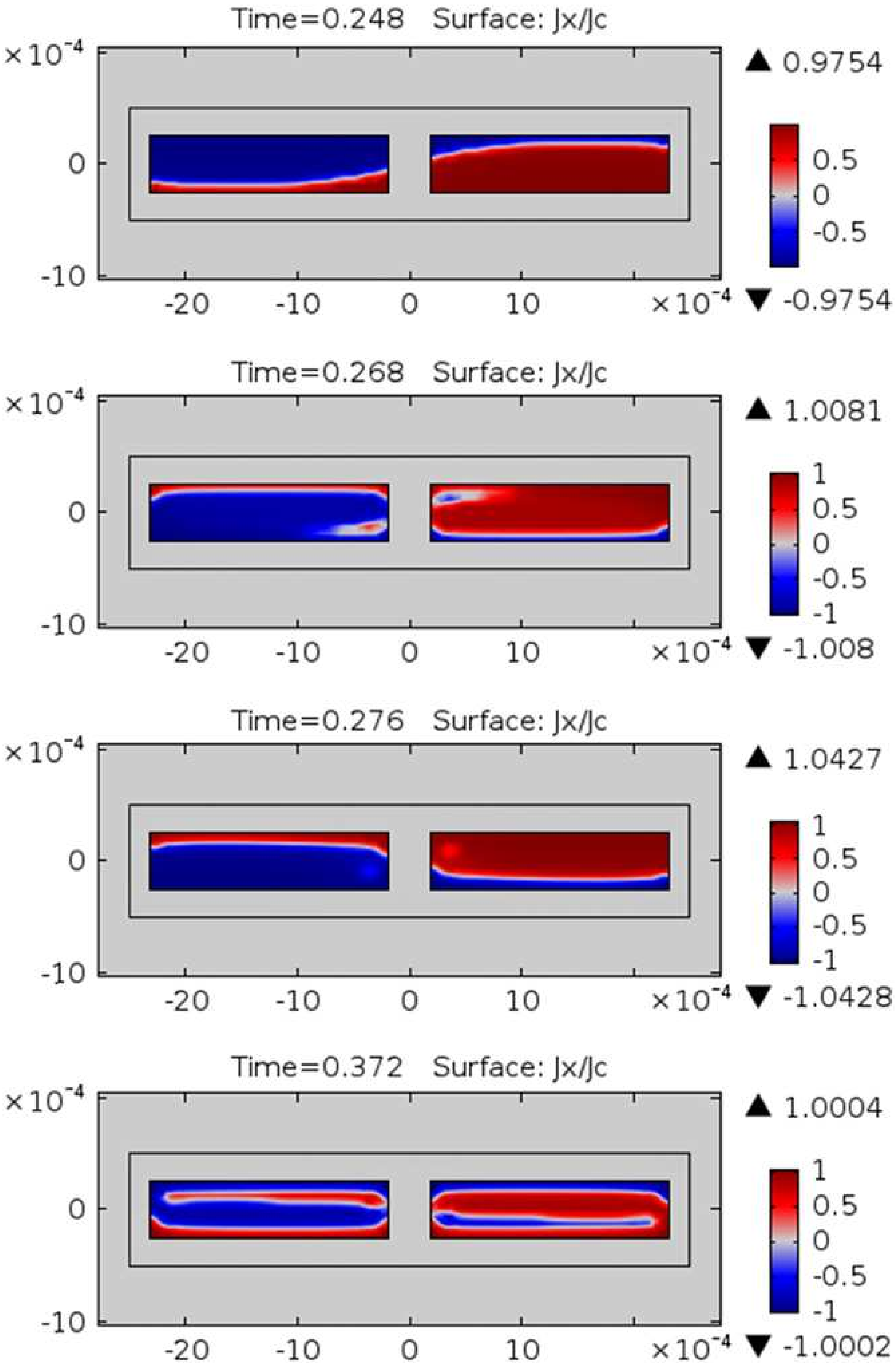


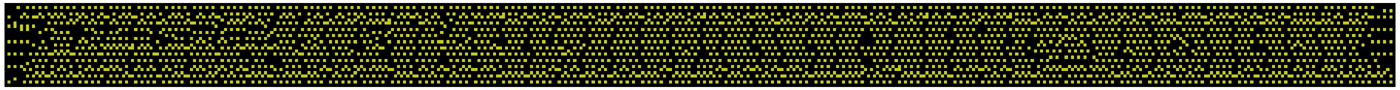


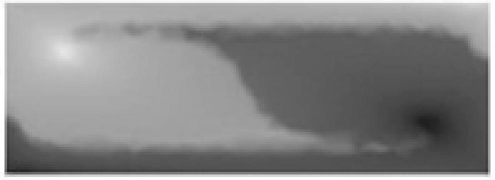
Long tapes, so no end effects, no force free.

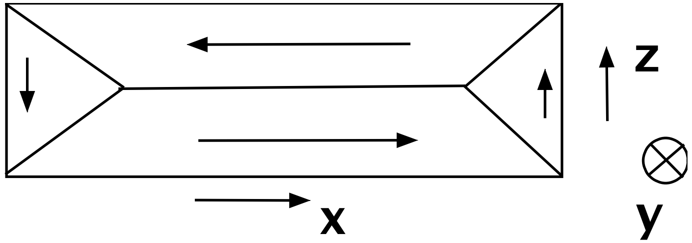
However tape stack treated as solid?

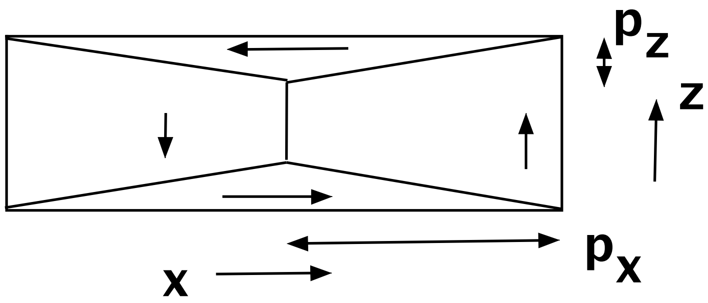


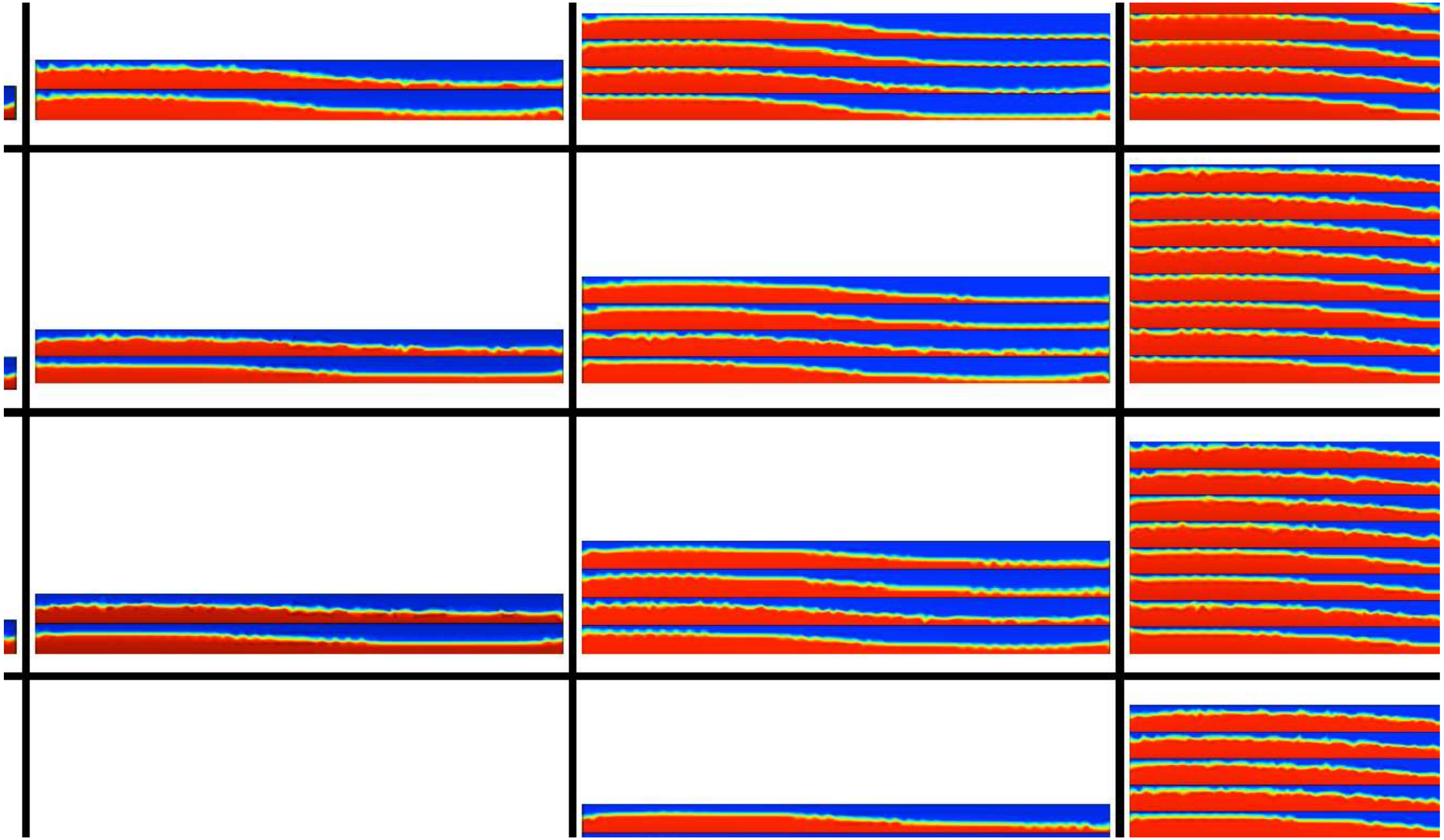

Time=0.248 Surface: Jx/Jc
×10⁻⁴
0
-10
-20
-10
0
10
×10⁻⁴
▲ 0.9754
0.5
0
-0.5
▼ -0.9754
Time=0.268 Surface: Jx/Jc
×10⁻⁴
0
-10
-20
-10
0
10
×10⁻⁴
▲ 1.0081
1
0.5
0
-0.5
-1
▼ -1.008
Time=0.276 Surface: Jx/Jc
×10⁻⁴
0
-10
-20
-10
0
10
×10⁻⁴
▲ 1.0427
1
0.5
0
-0.5
-1
▼ -1.0428
Time=0.372 Surface: Jx/Jc
×10⁻⁴
0
-10
-20
-10
0
10
×10⁻⁴
▲ 1.0004
1
0.5
0
-0.5
-1
▼ -1.0002

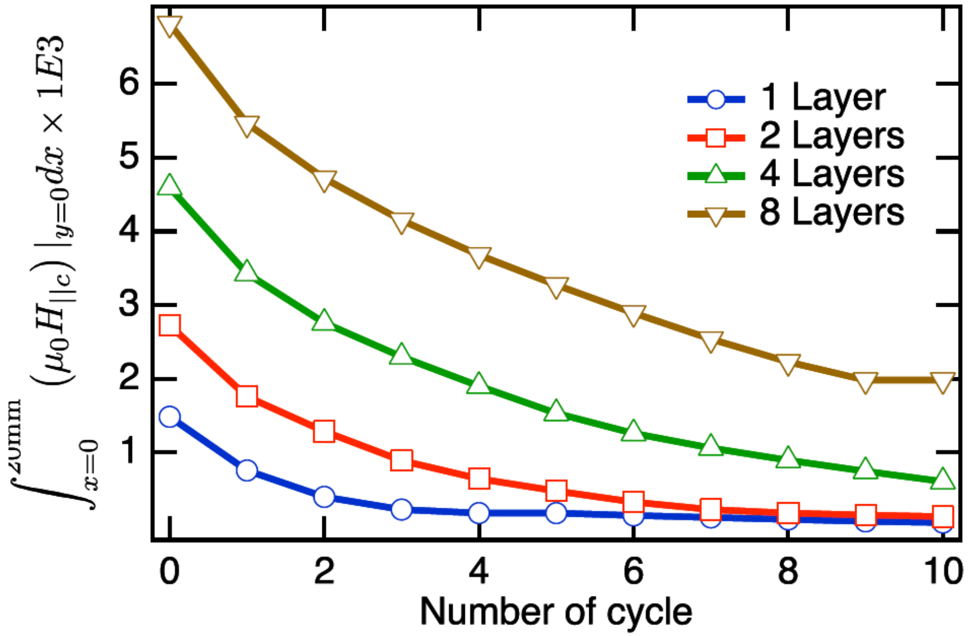





z
x
y


p_z
z
p_x
x





H formulation   n value

140 mT