Measurements and Modelling of YBCO Cable for various HTS cables

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This work was supported by the U.S. Department of Energy, Office of Science, Division of High Energy Physics

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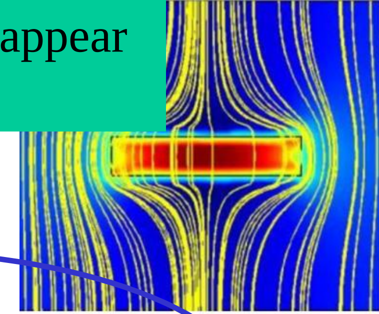
Outline

- Magnetization of YBCO and YBCO cables – the need for simple, useful, predictive expressions
- Development of analytic expressions, comparsion to FEM
- Measurement of M-H for CORC and Roebel tape using two different magnetometers, and comparison to expressions developed

What does the magnetization of HTS, esp YBCO, look like?

Summary of Loss expressions will appear in next edition handbook



$$Q = 2N\mu_0 H_0 J_c a$$

$$N = \left(\frac{H_0}{H_d}\right) g\left\{\frac{H_0}{H_d}\right\}$$

$$g\left\{\frac{H_0}{H_d}\right\} = \frac{H_d}{H_0}\left[\frac{2H_d}{H_0}\ln\left(\cosh\left(\frac{H_0}{H_d}\right)\right) - \tanh\left(\frac{H_0}{H_d}\right)\right]$$

For flat strands with B ⊥ tape

1. For B perpendicular, $B >> B_p$

$$\Delta M = aJ_c$$

a is half width

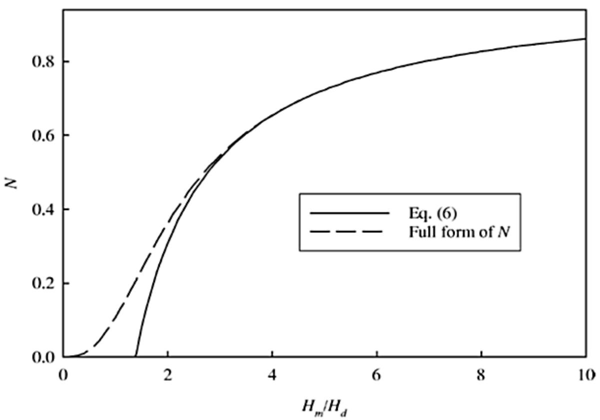
slabs

2. For B perpendicular, $B << B_p$

$$M = -\infty$$

As the width becomes infinite

3. For B perpendicular, $B \approx B_p$



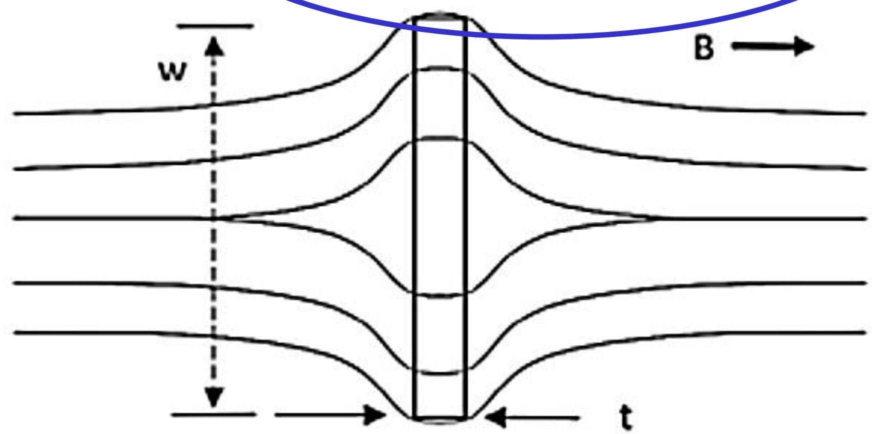


Figure 3. Field penetration into a thin slab (coated conductor).

The penetration field in this case is given by

$$H_p = \frac{J_c t}{\pi}\left[Ln\left(\frac{w}{t}+1\right)\right] = \frac{5}{2\pi}H_d\left[Ln\left(\frac{w}{t}+1\right)\right]$$

where $H_d = 0.4\,J_c t$ is a characteristic field. We note from Ref [16], that for $H_0/H_d > 3$

$$N \approx 1 - 2\left(\frac{H_d}{H_0}\right)Ln(2)$$

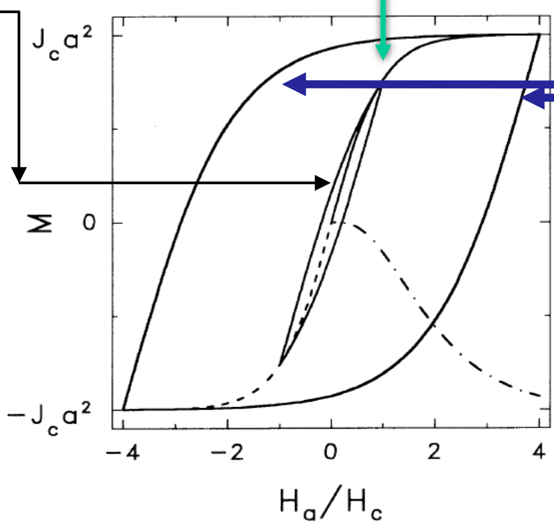
What does the magnetization of HTS, esp YBCO, look like?

4. For B perpendicular, if we want M=f(H)

$$M_{\downarrow\uparrow} = \pm J_c a^2 \left[\tanh \frac{H_0}{H_c} + 2\tanh \frac{H_a \mp H_0}{2H_c}\right]$$

$$M = \pi a^2 H_a (1 - H_a^2/3H_c^2) \qquad H_a << H_c$$

$$M = J_c a^2 [1 - 2\exp(-2H_a/H_c)] \qquad H_a \gg H_c$$



$M_{\uparrow\downarrow} = M/L = J_c t a^2 = J_{cs} a^2$

a is half width of tape

H_a is applied field

$H_c = J_c/\pi$, where *J* is sheet current A/m

J_{cs} = usual J_c*t

$H_0 = H_{max}$

$M_{\uparrow\downarrow}$ is moment per unit length

$M = m/Lta$

PHYSICAL REVIEW B VOLUME 48, NUMBER 17 1 NOVEMBER 1993-I

Type-II-superconductor strip with current in a perpendicular magnetic field

Ernst Helmut Brandt and Mikhail Indenbom*

CSMM Center fo

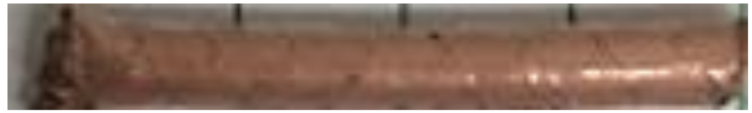
But What about Cables?

- A lot more Difficult for CORC and Twist stack!

(helical, super high aspect ratio, node-hogging, multiple tape, tape-tape interaction, several loss components)

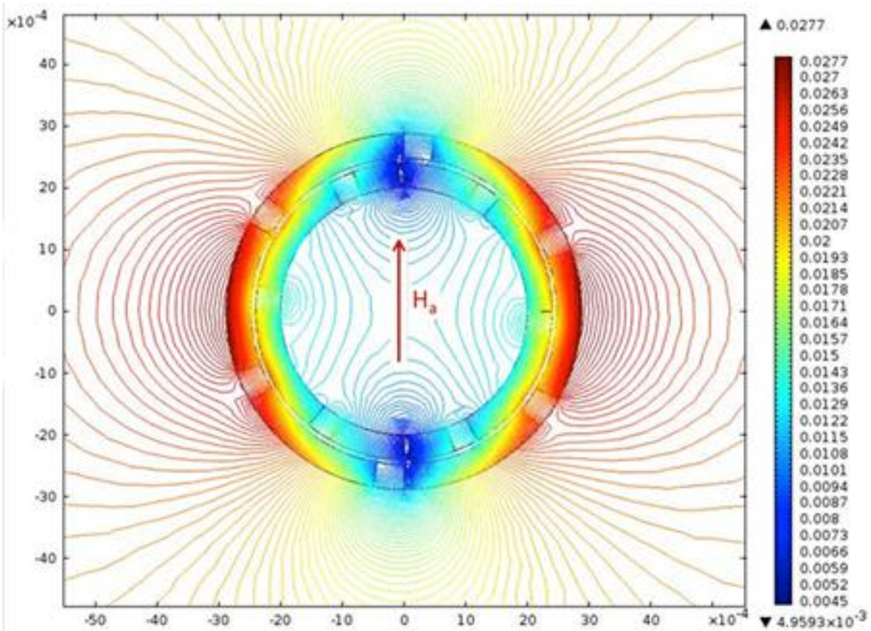
- Even Roebel has its complications!
- **<u>But, let us begin</u>**

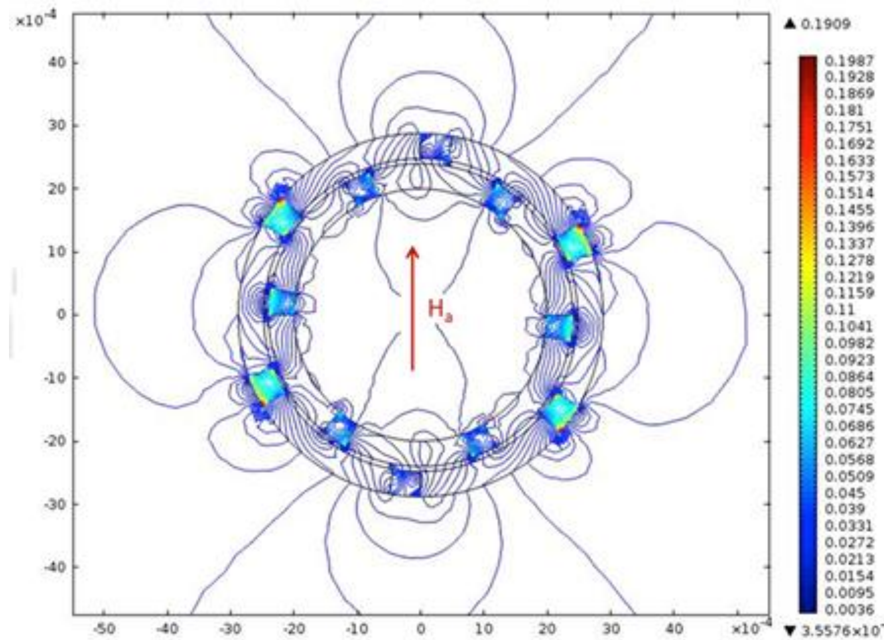
First question: What does flux distribution even look like for a CORC wire/cable?



More like this? – mostly flux exclusion?

Or More like this? – mostly flux penetration?



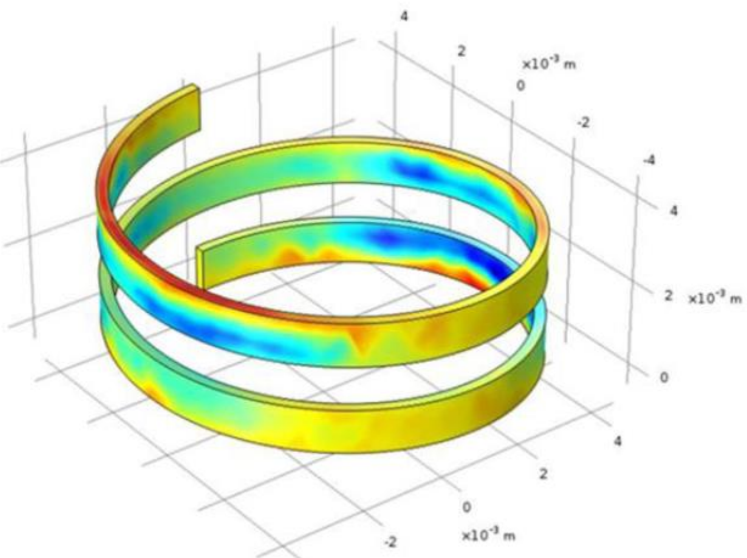


That is: Does the CORC cable act like a solid rod, or like a slotted stack of tapes?

Unravelling the CORC (and Twist Stack) Cable I

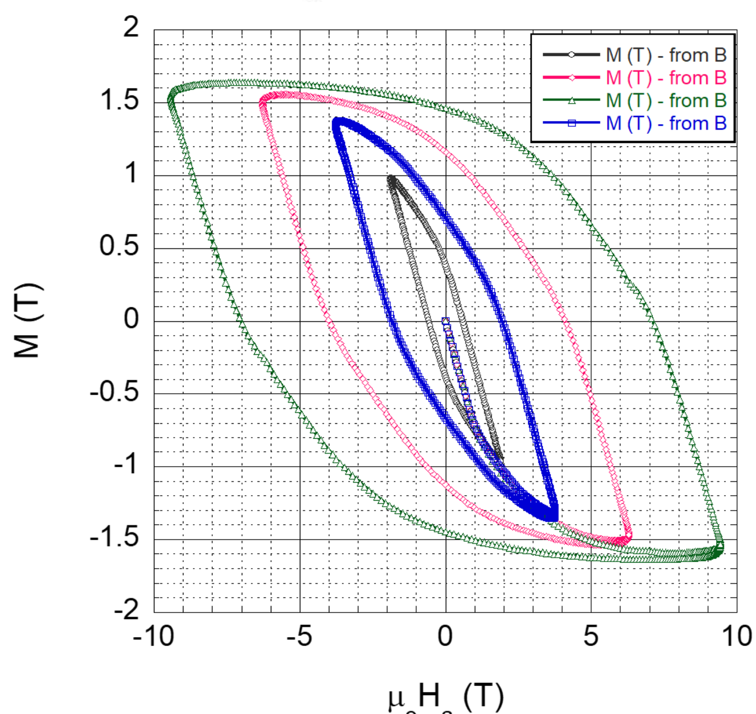
- Magnetization for coated conductor tapes is known
- A direct, analytic calculation for the loss of a CORC cable or a twist stack had not been performed, except at at $L_p \to \infty$, where $M_{hel} = \frac{2}{\pi} M_{tape}$
- For all samples not in this limit (most samples), the magnetization is lower, but not known.
- FEM approaches are computationally intensive, and give no insight
- Desired is a simple expression to give the magnetization of CORC and twist stack cables
- Below we focus on the hysteretic component first -- other contributions to be added later – and then give simple result and compare to experiment

Consider one tape of a CORC conductor – a helical wrap



This computation can be performed, but is quite demanding in terms of computation time

w_hel	1 mm	Tape width
th_hel	w_hel/4 = 0.25 mm	Tape thickness
r_hel	4.5 mm	Radius of helix axis
l_hel	(N_turns + 1)*w_hel + N_turns*gap = 5 mm	helix height
gap	w_hel = 1 mm	Gap between helix turns
pitch	w_hel + gap = 2 mm	Helix twist pitch
N_turns	2	Number of turns in helix
l_tape	N_turns*sqrt(pitch^2+(2*pi*r_hel)^2)=56.6899 623 mm	Tape length in helix
V_tape	w_hel*th_hel*l_tape =14.17249058 mm^3	Tape volume in helix
J_c	10^{10} A/m^2	Critical current density



$$\Delta M_{tape} = J_c a = 10^{10}\left(\frac{0.001}{2}\right) = \frac{5x10^6 A}{m}$$

$$= 6.25\ T$$

5000 kA/m

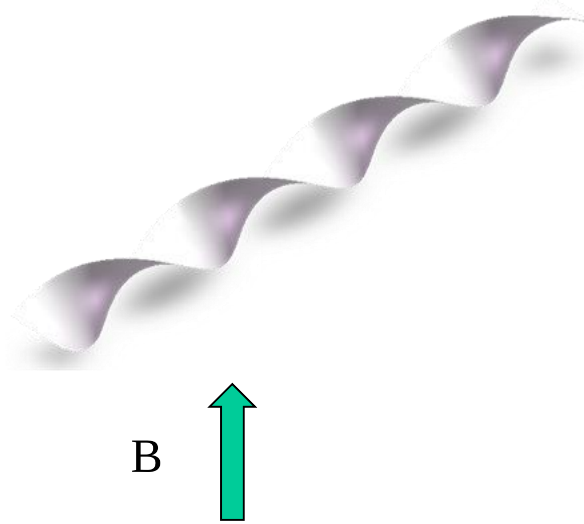
$$M_{helix} = \frac{2}{\pi} M_0 \frac{1}{2} = 1.59\ x\ 10^6 \frac{A}{m} = 2\ T$$

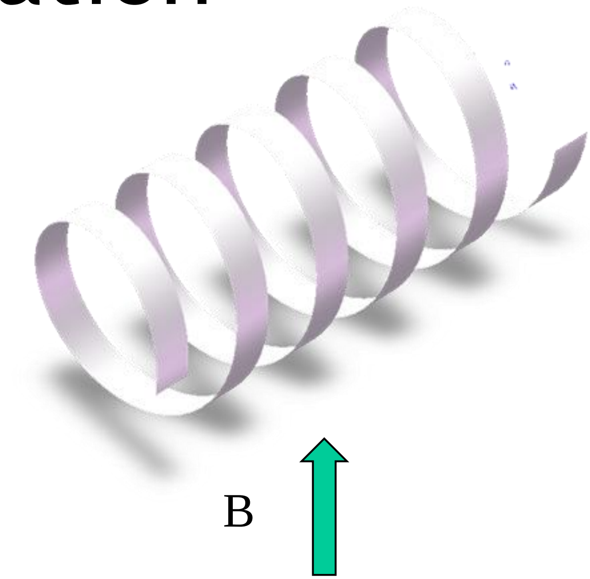
Magnetization of a helical Tape or CORC cable in Saturation

In general, in full penetration,

$$Q_0 = 2\mu_0 H_0 J_c w$$

(here w is the half width)





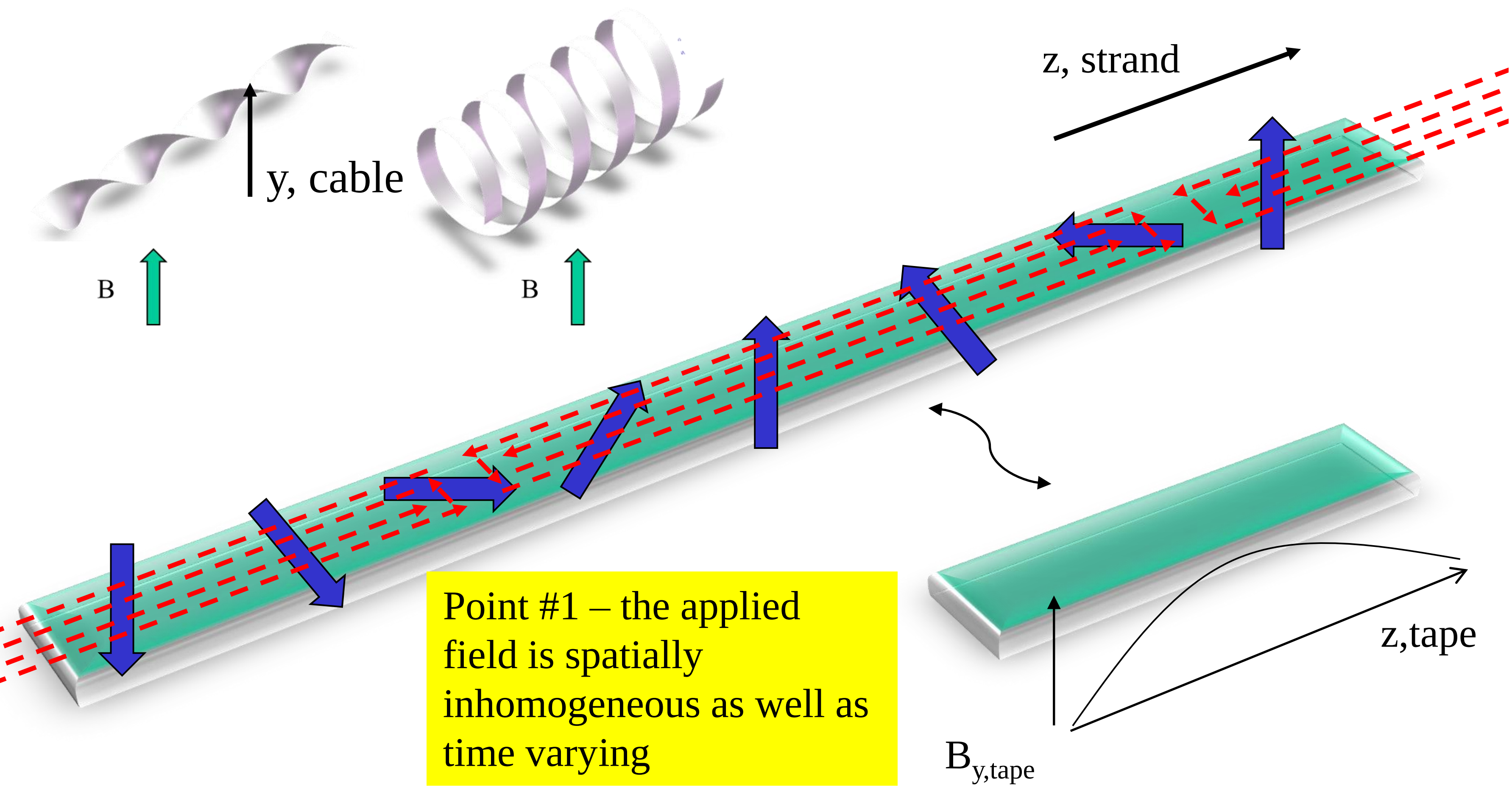
We might then imagine that that loss could be calculated by the simple expedient of integrating the average of Eq (5) over a spatial field cycle, such that

$$Q = \frac{2\mu_0 J_c w H_0}{{L_p}/{2}} \int_0^{\pi} sin\left(\frac{2\pi z}{L_p}\right) dz = \frac{2\mu_0 J_c w H_0}{{L_p}/{2}} \frac{L_p}{2\pi}(2) = \left(\frac{2}{\pi}\right) 2\mu_0 J_c w H_0 = \boldsymbol{\left(\frac{2}{\pi}\right) Q_0}$$

This leads to $M = (2/\pi)M_0$. **Is this true?** Yes if $L_p >> w$, but in general, not……

Carr, AC Loss and Macroscopic Theory of SC, p 189, 2nd Ed

Let us consider the general case -- Magnetization of a helical Tape or CORC cable in Saturation II

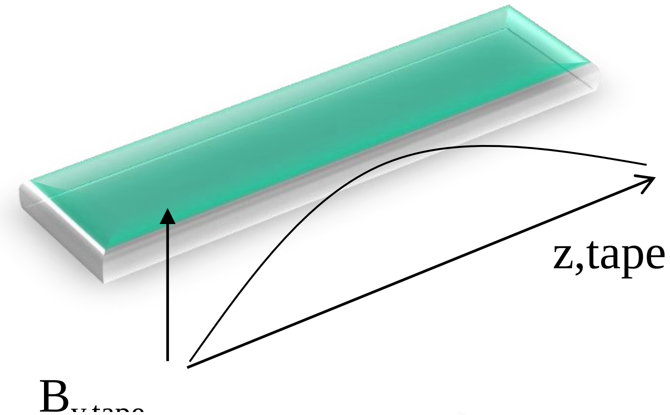


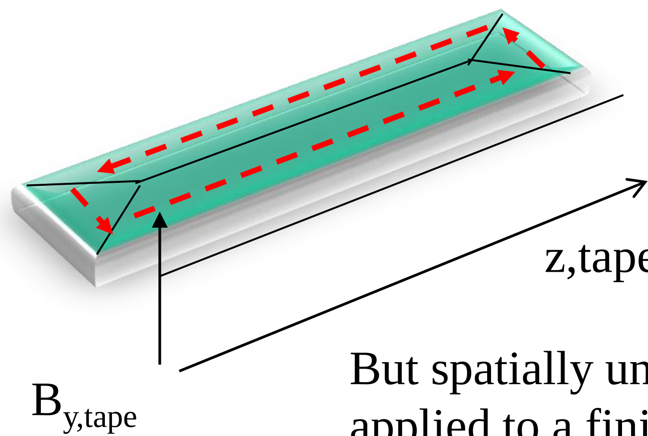
Point #1 – the applied field is spatially inhomogeneous as well as time varying

Magnetization of a helical Tape or CORC cable in Saturation III

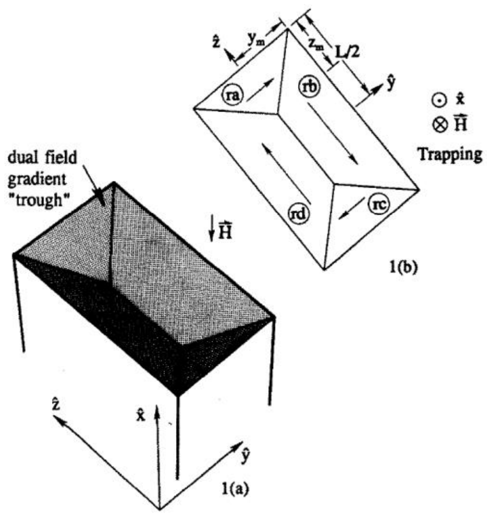
2. In general, currents in the presence of spatially inhomogeneous fields not a solved problem

3. The current flow is also spatially varying, leads to "end effects!"





But spatially uniform field applied to a finite length sample is a solved problem



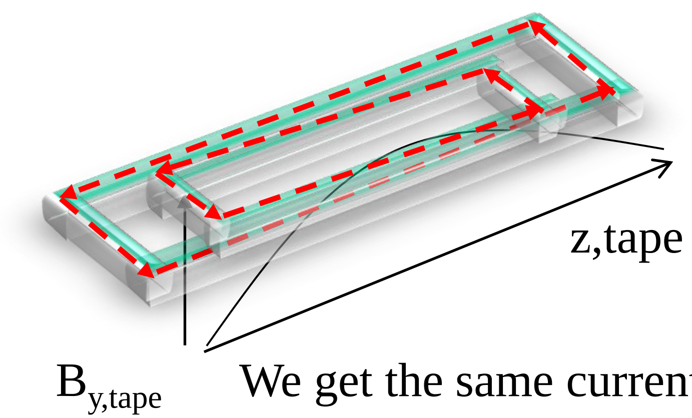
2. E. M. Gyorgy, R. B. vanDover, K. A. Jackson *et al.*, *Appl. Phys. Lett* **55**, 283 (1989).
3. F. M. Sauerzopf, H. P. Wiesinger and H. W. Weber, *Cryogenics* **30**, 650 (1990).
4. S. Hu, H. Hojaji, A. Barkatt *et al.*, *Phys. Rev. B.* **43**, 2878 (1991).

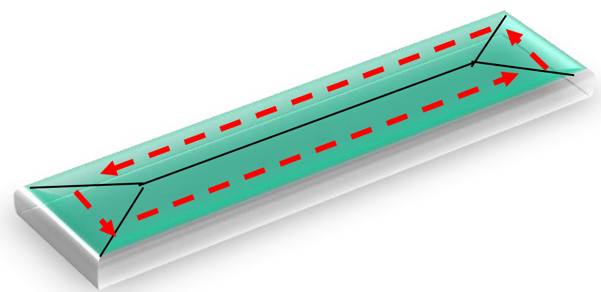
$$\Delta M = J_c y_m \left(1 - \frac{2y_m}{3L}\right) \qquad L/2 > Z_m$$

$$\Delta M = J_c \frac{L}{2} \left(1 - \frac{2y_m}{3L}\right) \qquad L/2 < Z_m$$

Magnetization of a helical Tape or CORC cable in Saturation IV

If we consider the field penetration layer by layer in a concentric shell configuration





We get the same current paths as the short sample in uniform field

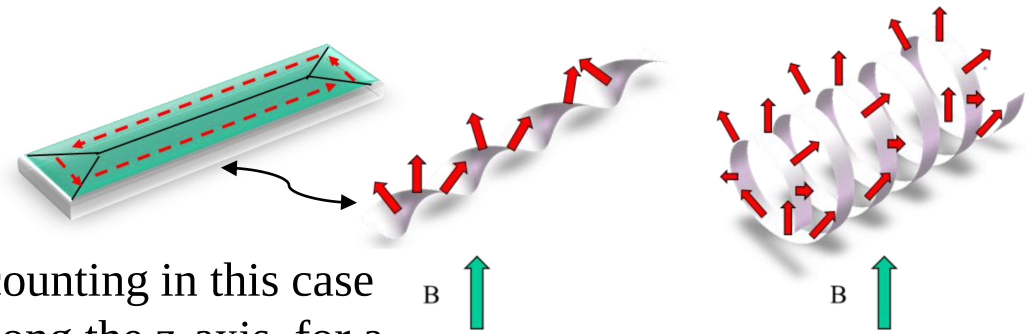
If $B >> B_p$,
in this case, B (at $L_p/2$-w/2) > $J_c w/2$

The local magnetization is changed, since M = <B>/μ0-<H> and <H> is lower
(*M* is reduced)

But, much more relevant for transforming back to the external field coordinates, the moment is the same as that of the finite sample in homogenous field (the demag leads to a lower local M)

Magnetization of a helical Tape or CORC cable in Saturation V

We can then use the moment of the short finite length calculation, breaking the twist or helix into a series of short samples



Integrating around the helix and accounting in this case for the component of the moment along the z-axis, for a twisted tape we get

$$\Delta M = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2y_m}{3L}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{w}{3\,\frac{L_p}{2}}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2w}{3L_p}\right)$$

Analytic Result!

For the helix it will be the same, but with L_{eff} in place of L_p

$$L_{peff} = \sqrt{L_h^2 + (\pi D_h)^2}$$

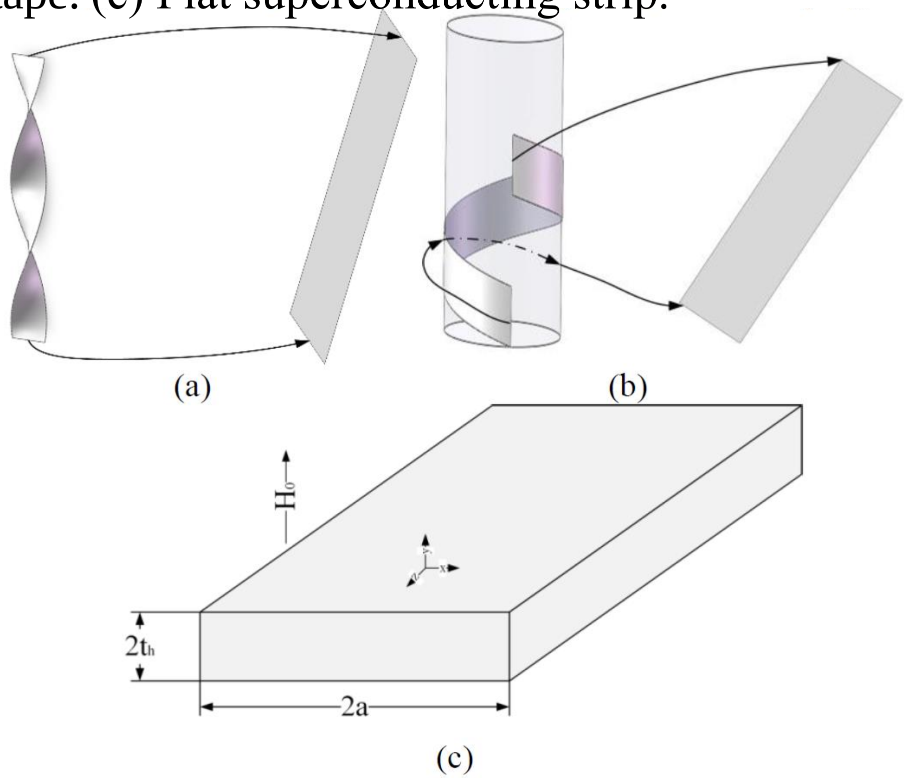
Twisted Tape: If L_p > 20/3 w (2.7 cm for 4 mm wide tape), $\Delta M_{twisted} \approx (2/\pi)\Delta M_{tape}$ with err < 10%

Helical/CORC Tape: **<u>Example 1:</u>** CORC Cable with L_h = 34 mm, OD = 4.76 mm, and L_{peff} =37 mm gives $\Delta M_{helical} \approx 0.85(2/\pi)\Delta M_{tape}$

<u>Example 2:</u> CORC wire with $L_h \approx 10$ mm, OD = 3 mm, L_{peff} = 13.7 mm, $\Delta M_{helical} \approx 0.80(2/\pi)\Delta M_{tape}$

Parallel FEM Approach – Again Unravelling the CORC (and Twist Stack) Cable

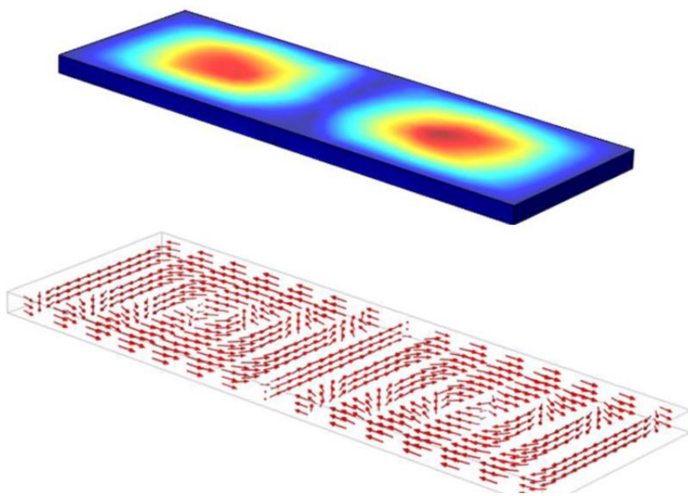
We consider first one tape from a CORC or a twist stack cable
Untwist the twisted superconducting cable into the mathematical model flat superconducting tape. (b) Unwind a single CORC tape into the flat superconducting tape. (c) Flat superconducting strip.



For a simple twisted Conductor, the twist pitch is straightforward, while for the helical wrap,

$$L_{peff} = \sqrt{L_h^2 + \left(\pi D_h\right)^2}$$

We then use Finite Element methods to calculate the Magnetization of a slab in a spatially inhomogeneous and time changing field



$$M = \left(\frac{1}{V} \int_V H_{local}\, dV - H_{applied} \right)$$

For a spatially uniform field

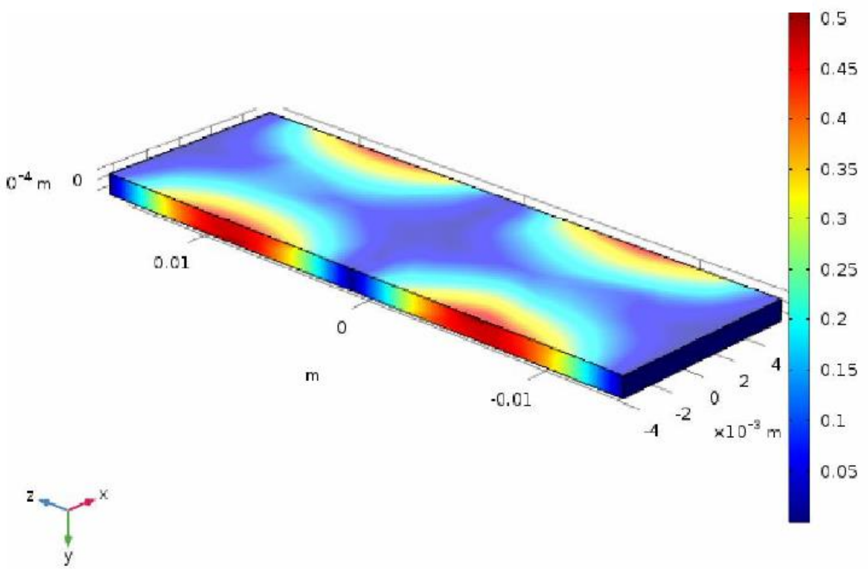
$$H_{applied} = H_{max} \sin(\omega t)$$

For a spatially varying field

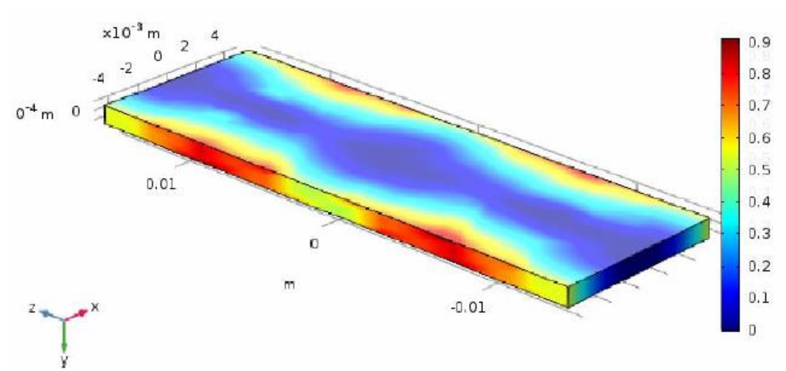
$$\boldsymbol{H_{applied} = H_{max} \sin(\omega t) \sin\left(\frac{2\pi z}{L_p}\right)}$$

- The expressions for M are the same,
- Only the applied field is different.
- Since M=B/μ-H, the magnetization is the same except at very low fields

Simulations I

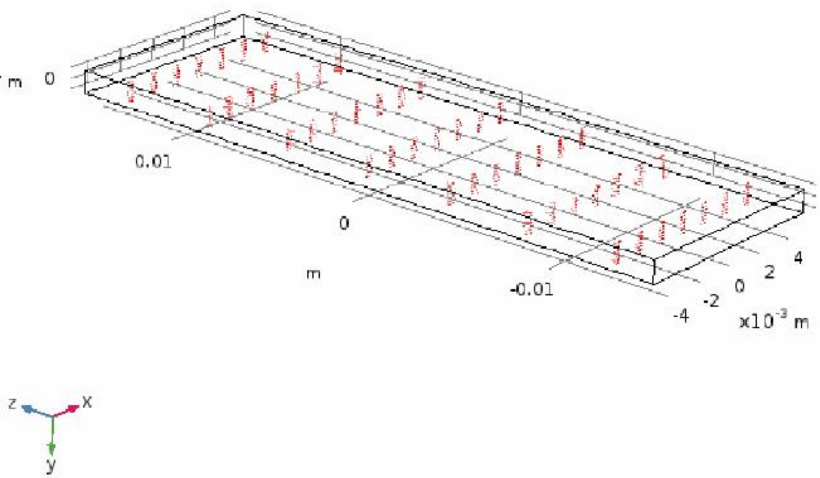


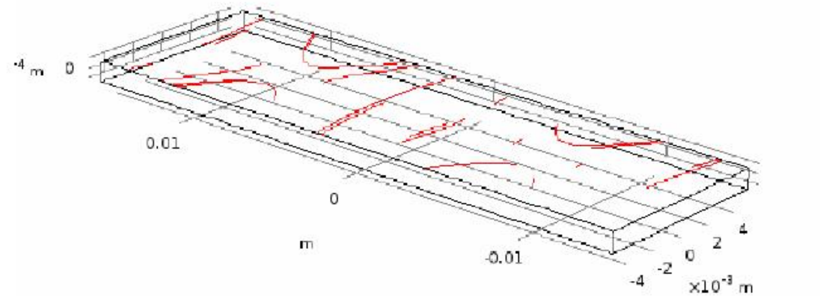
Normal Magnetic Field



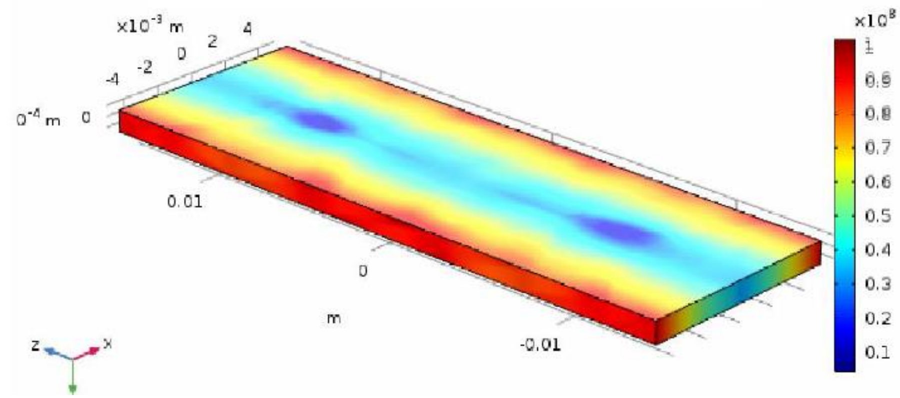
Electric Field

Simulations II –Electric field

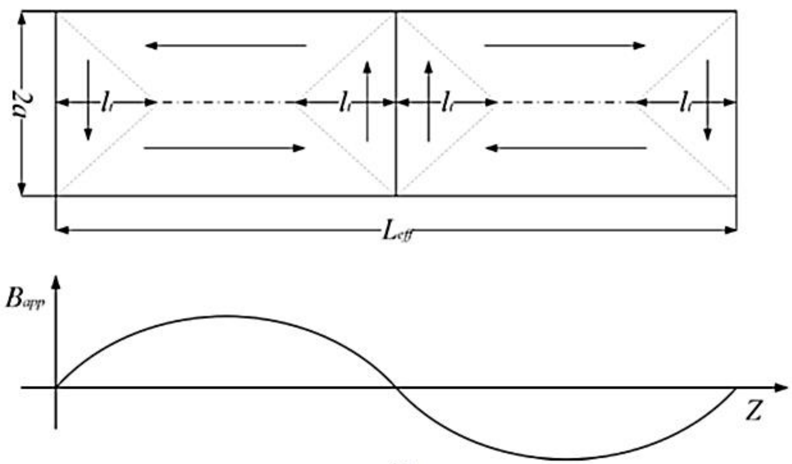




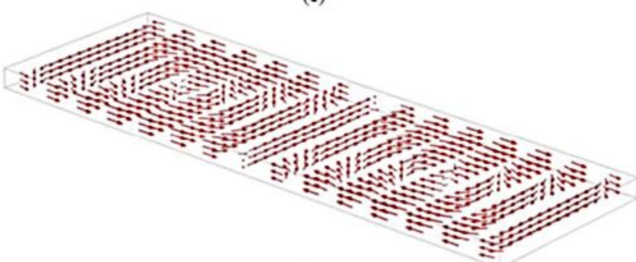
Supercurrent Density



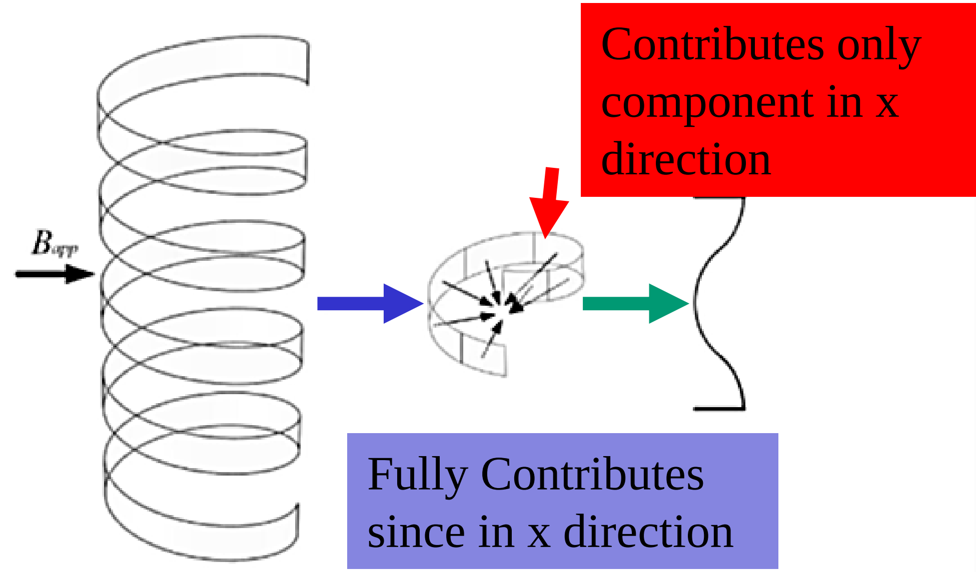
Then magnetic moments are re-assembled to generate the magnetization



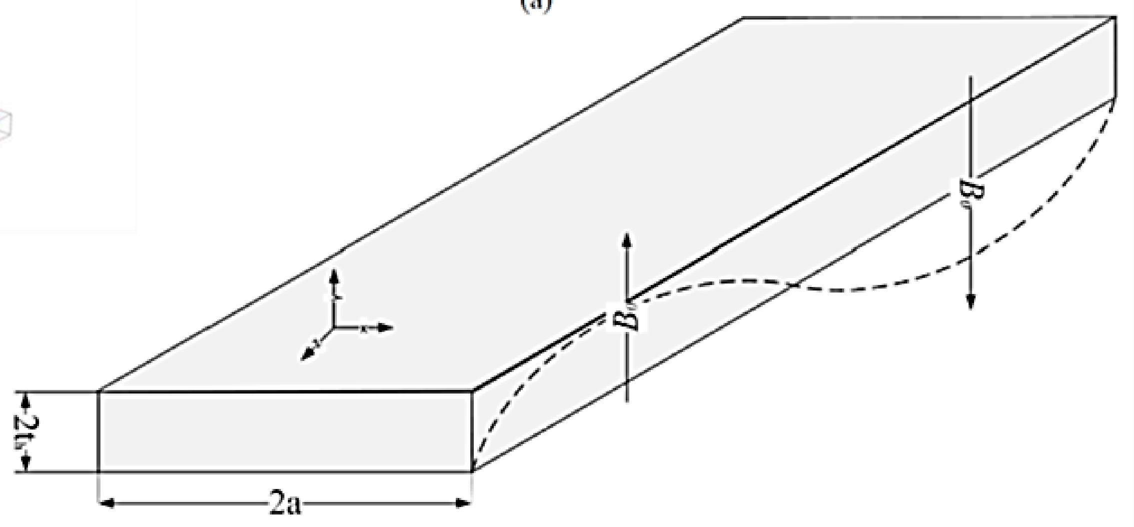
(c)



(d)



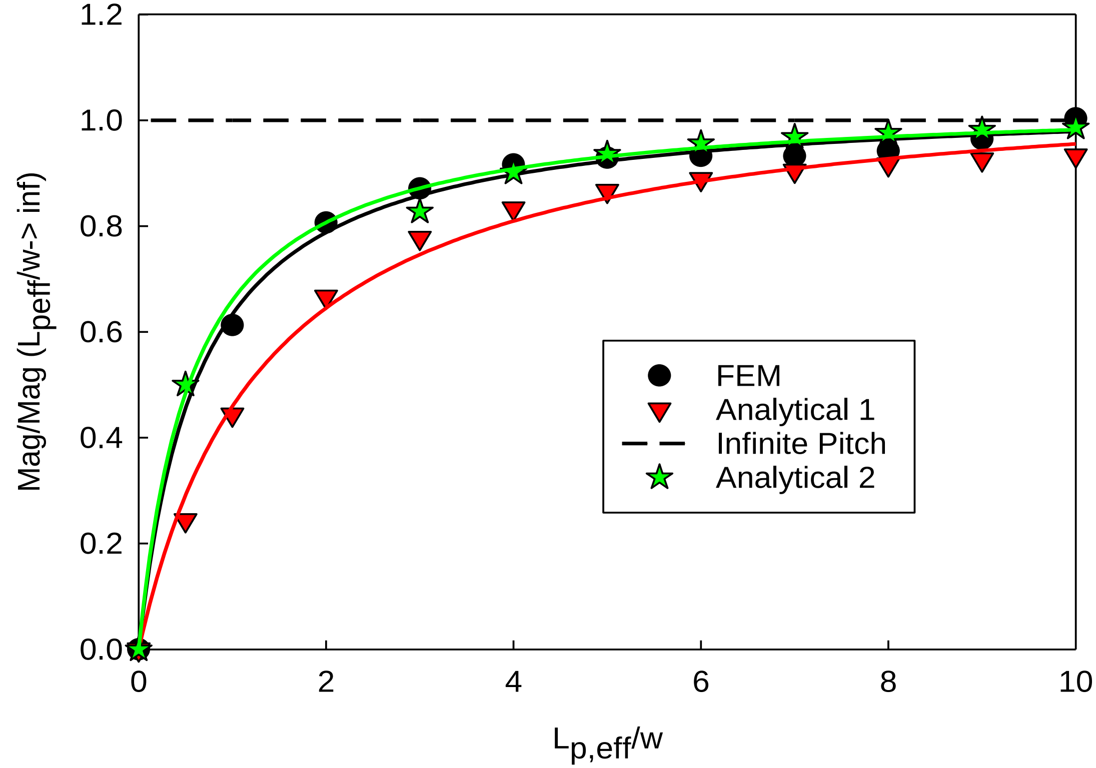
(a)



(b)

Comparison of FEM and analytic results

- Dashed line gives infinite pitch
- Shorter L_{peff}/w ratios give lower mag
- Agreement between FEM and analytic OK with Analytic 1
- Agreement even better when WF included – Analytic 2



Analytic 1

$$\Delta M = \Delta M_0 \frac{2}{\pi}\left(1-\frac{2y_m}{3L}\right) = \Delta M_0 \frac{2}{\pi}\left(1-\frac{w}{3\frac{L_p}{2}}\right) = \Delta M_0 \frac{2}{\pi}\left(1-\frac{2w}{3L_p}\right)$$

Analytic 2

$$\Delta M = \Delta M_0 \frac{L_p}{\pi w} \cos\left[\frac{\pi L_p}{4}\left(1-\frac{w}{L_p}\right)\right]$$

$$WF = \frac{L_p}{\pi w} \cos\left[\frac{\pi L_p}{4}\left(1-\frac{w}{L_p}\right)\right]$$

Estimations for LBNL CORC samples

CORC A: 16-tape wire, wire OD 3.21 mm (including the heat shrink tubing), I_c = 4 kA at 4.2 K, self-field

For Tape A: I_c = 262 A per tape (0.04 mm thick, 2 mm wide, gives J_e = 262/.08 mm^2 = 3275 A/mm^2 = 3.27 x 10^9 A/m^2)

Magnetization Tape A: $M=J_c a/2$=3.27 x 10^9 A/m^2 * 10^{-3} m = 3270 kA/m

Magnetization CORC A: $M=(2/\pi)M_{tape}$*0.38*0.8= 633 kA/m [cable volume normalized]

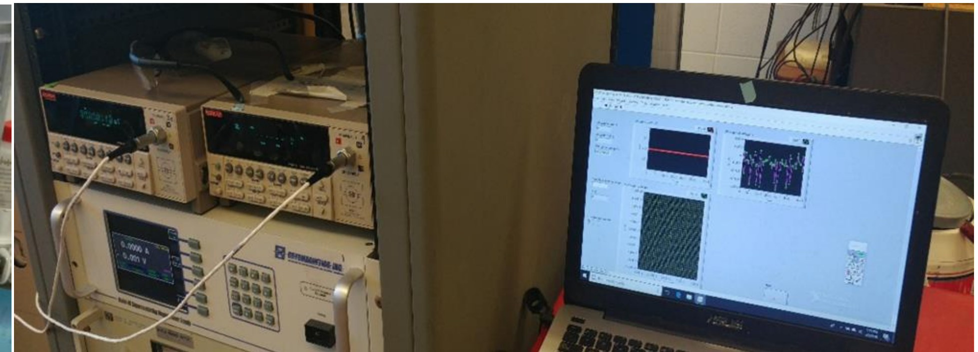
Above B_p, but see below!

Let's now compare to experiment!

If this had been a single tape $B_p = (\mu_0 J_c t/\pi)[(\mathrm{Ln}(w/t)+1] \cong 120$ mT

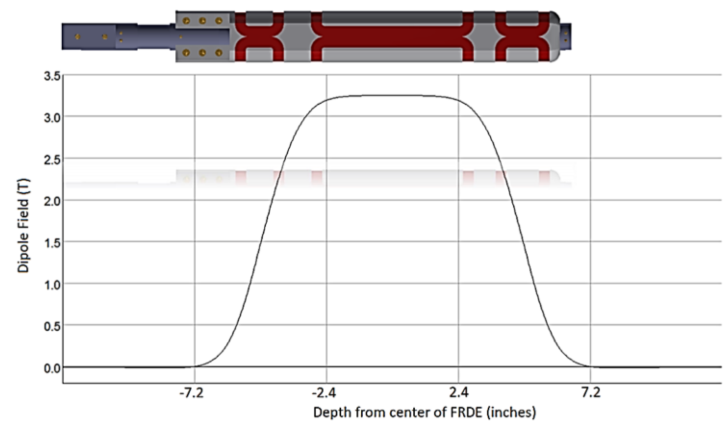
Note factor of 10 X difference in penetration fields of tapes and cables!
This difference is right in regime of injection field

3 T Dipole Magnet Cable Magnetization System

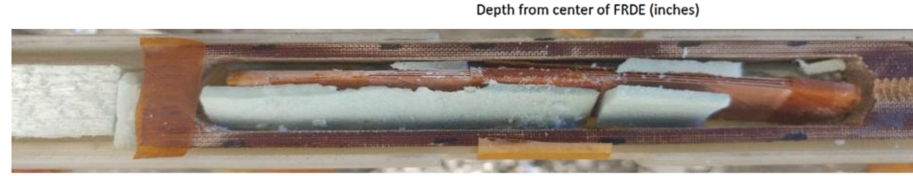


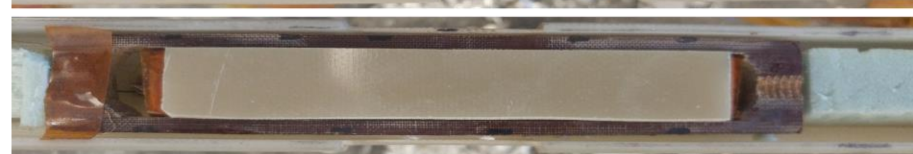
Data Acquisition, Magnet Supply, Control Computer

B = ± 3 T



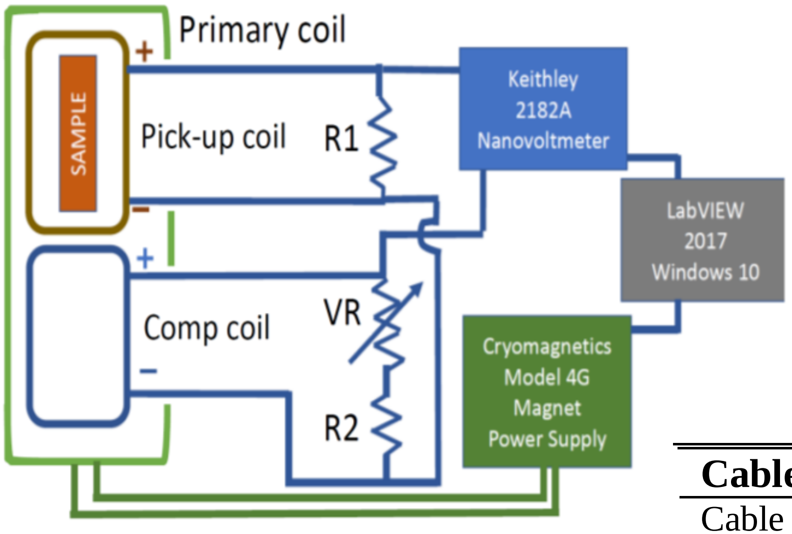
Sample holder, Pickup Coils, Dipole Magnet





Samples in pick-up coils

Cable Samples Measured



CORC: Provided by LBNL, ID 160823-Berkeley 250-C. Tape I_c = 69.5 A at 77 K, SF (16 tapes), cable I_c was 4.1 kA at 4 K; the cable was used for the canted cosθ dipole denoted C0a.

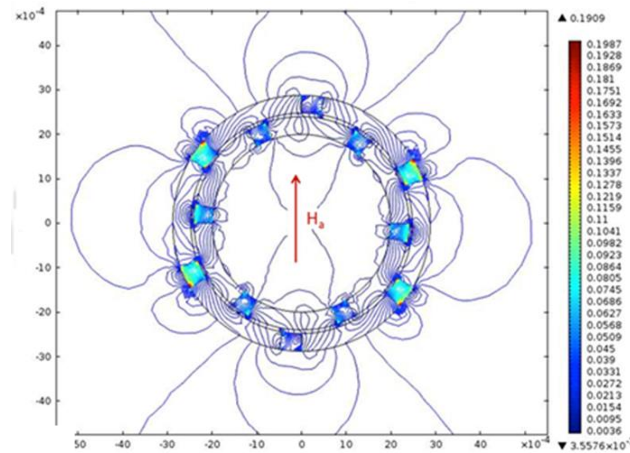
Roebel cable: KIT/ Super-Power tape, 77 K Ic = 1168 A for cable, giving 129 A per

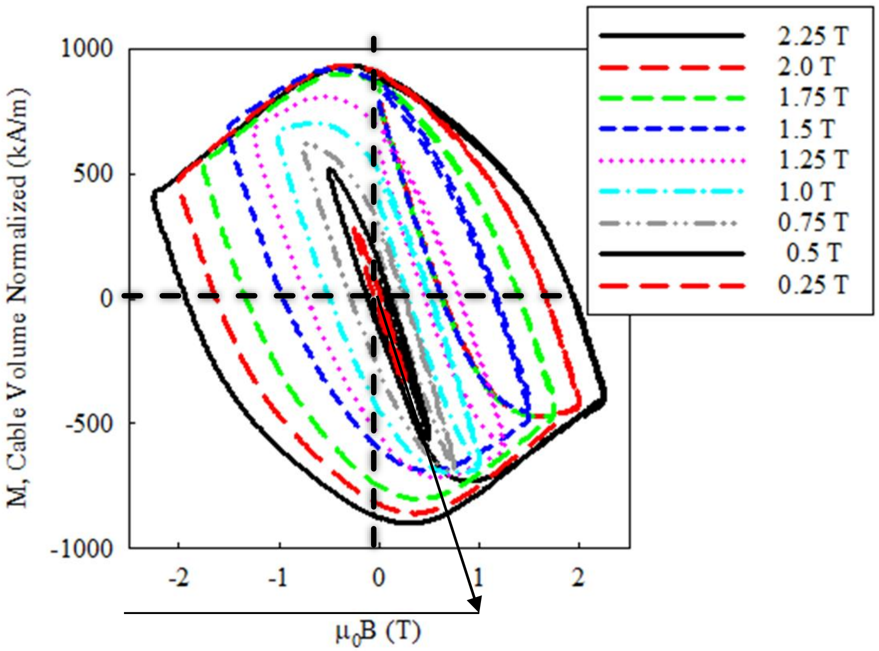
Cable Properties	CORC™	Roebel
Cable dimension (mm)	3.21 (OD)	12 x 0.48
No. Tapes	16	9
Tape width (mm)	2	5.6
Tape thickness (mm)	0.045	0.096
Cable Pitch (mm)	6.22	126

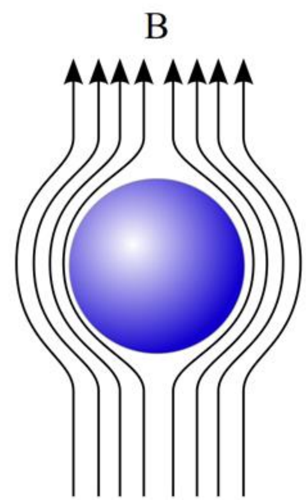
Sample Properties	CORC™	Roebel
Sample Length (cm)	9.42	9.07
Number of segments	6	4
Pack Dimensions (mm)	10 (OD)	4.3 x 12
V_{cable} (cm^3)	4571	2089
V_{strand} (cm^3)	1591	1755

Cable – like a solid rod or sum of tapes?

- A calibration was performed using a Ni strip
- This calibration was then used to measure the M-H for the CORC cable
- CORC measurement gives χ_{DC} =-2, full flux exclusion

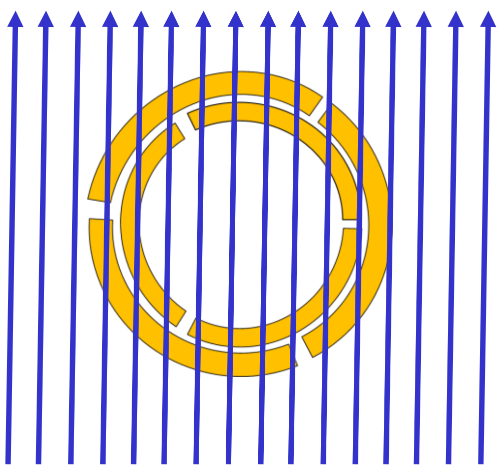






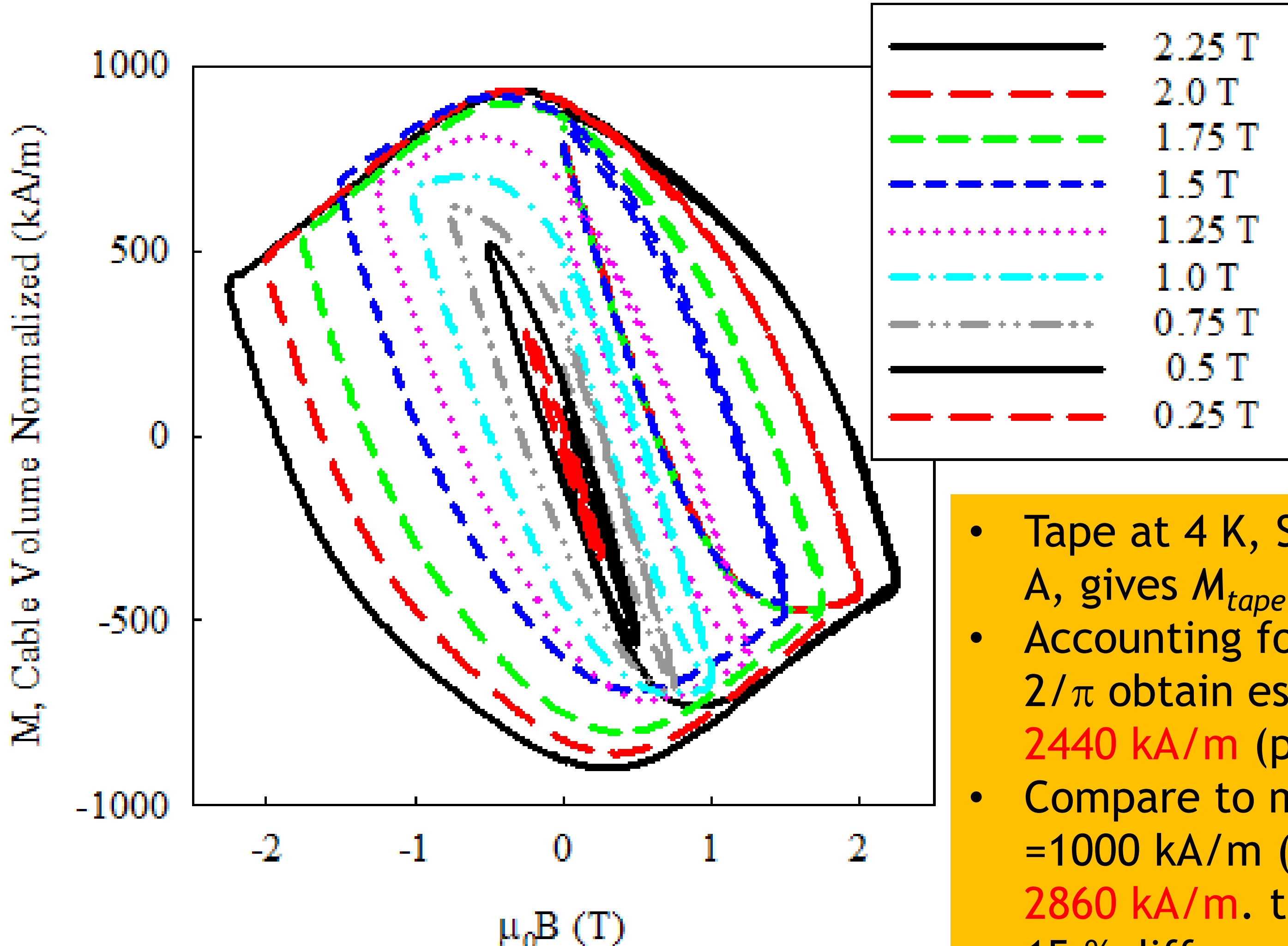
<u>So at low field sweep amplitudes,</u> flux is excluded from CORC – acts like a rod!

At higher field sweep amplitude, CORC acts like a summation of tapes, but with twist



$$M = \frac{\sum M_{helices}}{V_{cable}} \approx \frac{2}{\pi} \frac{M_{tapes}}{V_{tape}} \left(\frac{V_{tape}}{V_{cable}} \right)$$

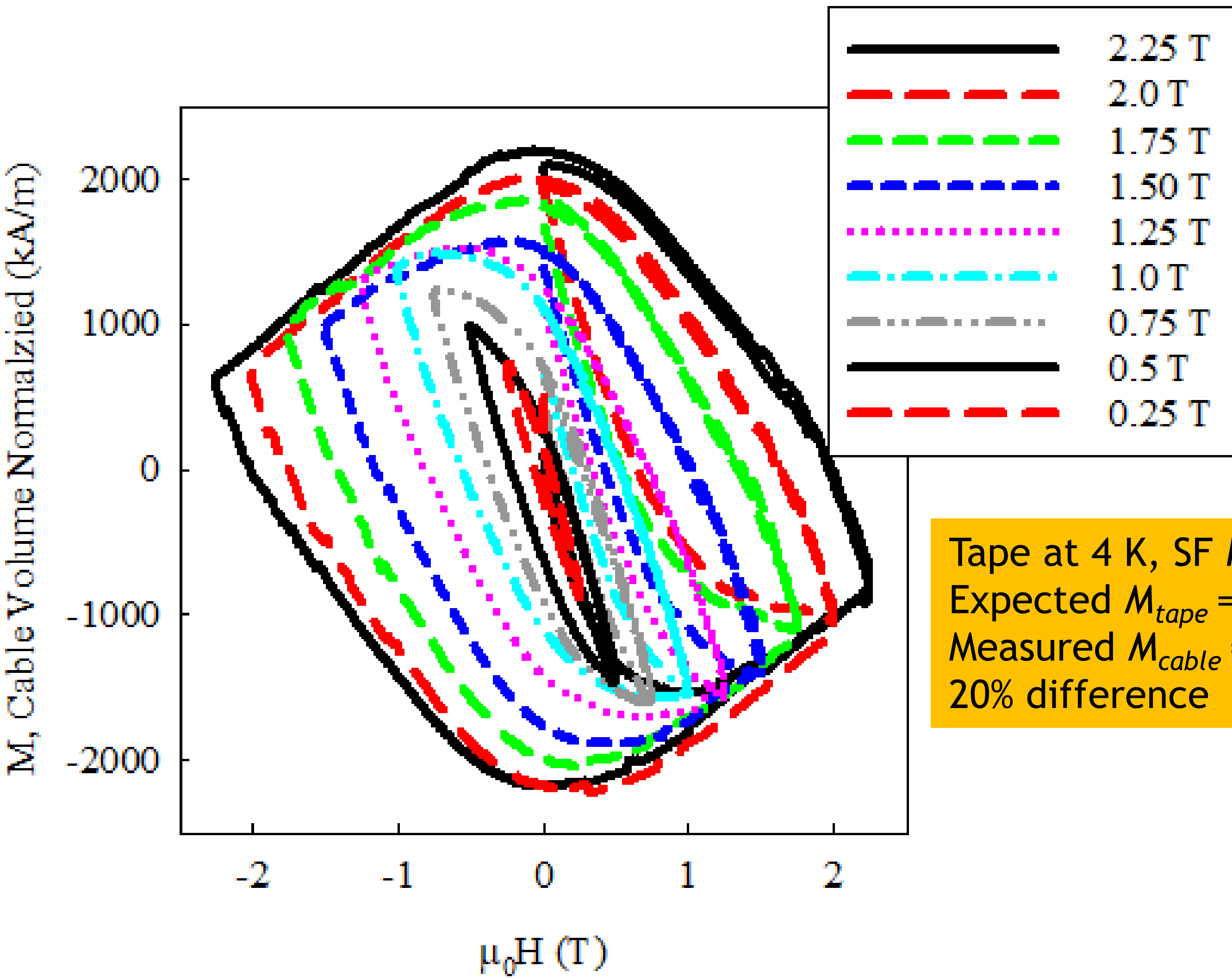
M-H Loops for CORC wire/cable (3 T Dipole)



- 4 K *M-H*
- $B_\perp$
- Normalized total cable volume

- Tape at 4 K, SF, estimated I_c = 690 A, gives $M_{tape} = J_c w/4$ = 3833 kA/m
- Accounting for helical twist, apply $2/\pi$ obtain estimate for CORC = 2440 kA/m (per tape vol)
- Compare to measured M_{CORC} (B=0) =1000 kA/m (cable Vol) X 2.86 = 2860 kA/m. tape vol
- 15 % difference

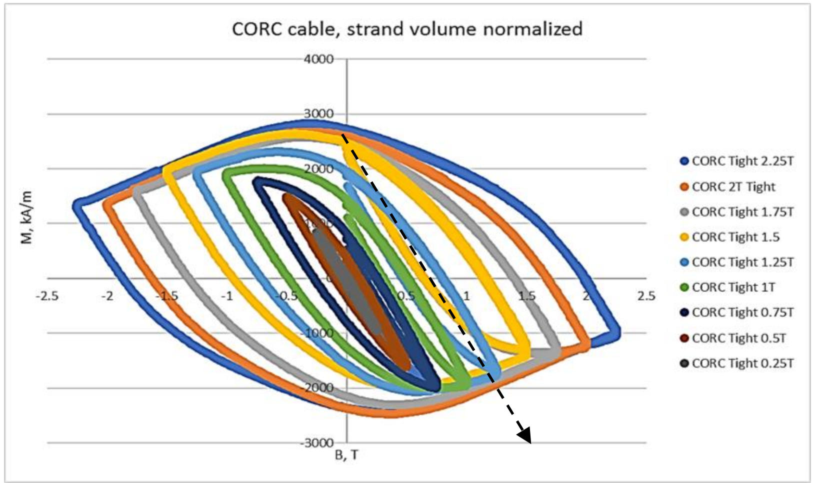
M-H Loops for Roebel Cable (3 T Dipole)



- 4 K *M-H*
- $B_{\perp}$
- Normalized total cable volume

Tape at 4 K, SF I_c =1290 A.
Expected M_{tape} = 3220 kA/m (tape vol)
Measured M_{cable} = 2640 kA/m (strand vol)
20% difference

CORC Magnetization -- Initial Permeability



Very generally, the CORC can be treated as a simple tape of effective width

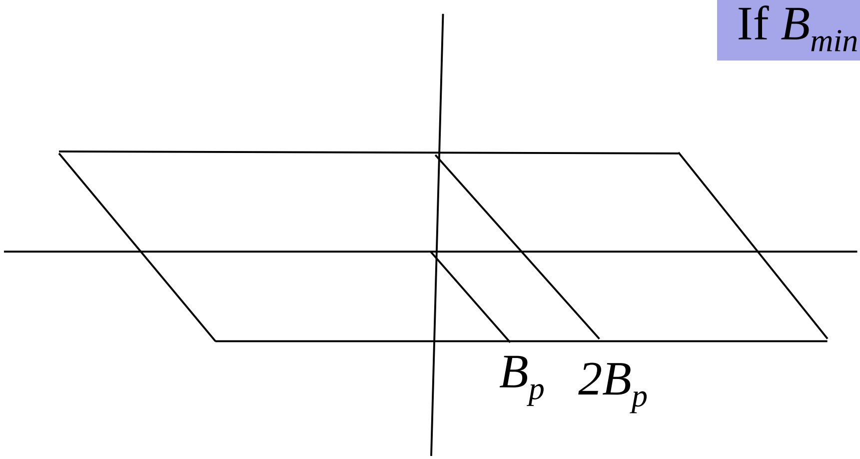
w_{eff} = (2/π)(fill factor)(1-$w/3L_p$)

If $B_{min} = 0$

$$M = M_{max}\left[1-\left(\frac{B}{B_p}\right)\right] = \frac{2}{\pi}\frac{J_c a}{2} FF\left[1-\frac{w}{3L_{p,eff}}\right]\left[1-\left(\frac{B}{B_p}\right)\right]$$

If $B_{min} \neq 0$

$$M = M_{max}\left[1-\left(\frac{B-B_{min}}{B_p}\right)\right]$$
$$= \frac{2}{\pi}\frac{J_c a}{2} FF\left[1-\frac{w}{3L_{p,eff}}\right]\left[1-\left(\frac{B-B_{min}}{B_p}\right)\right]$$

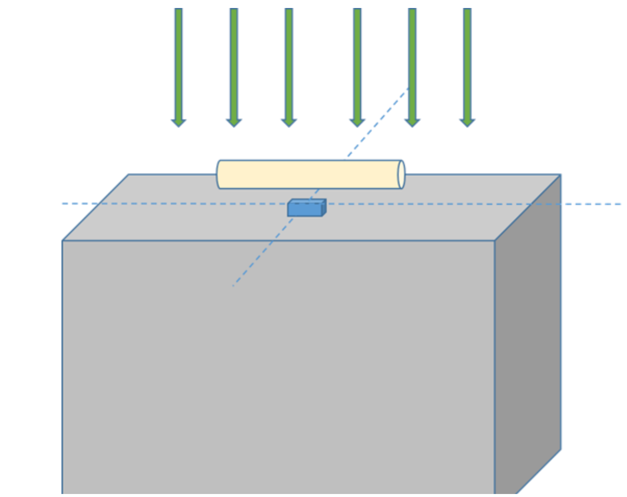


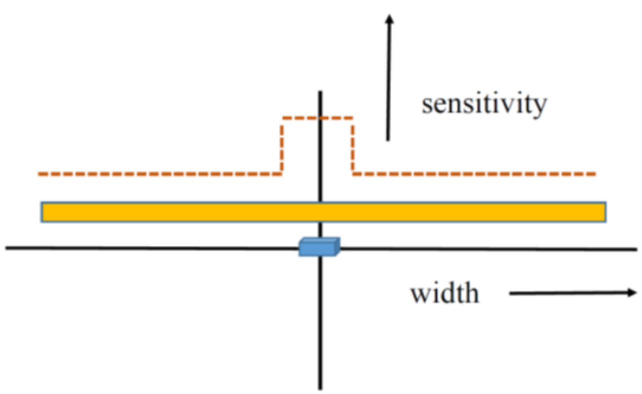
In full penetration

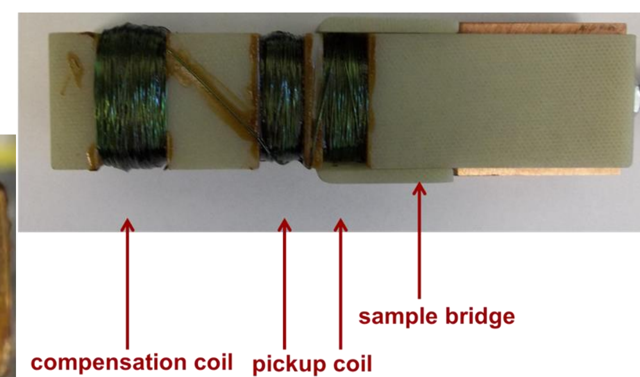
$$M = M_{max} = \frac{2}{\pi}\frac{J_c a}{2} FF\left[1-\frac{w}{3L_{p,eff}}\right]$$

12 T Hall Probe Cable Magnetometer

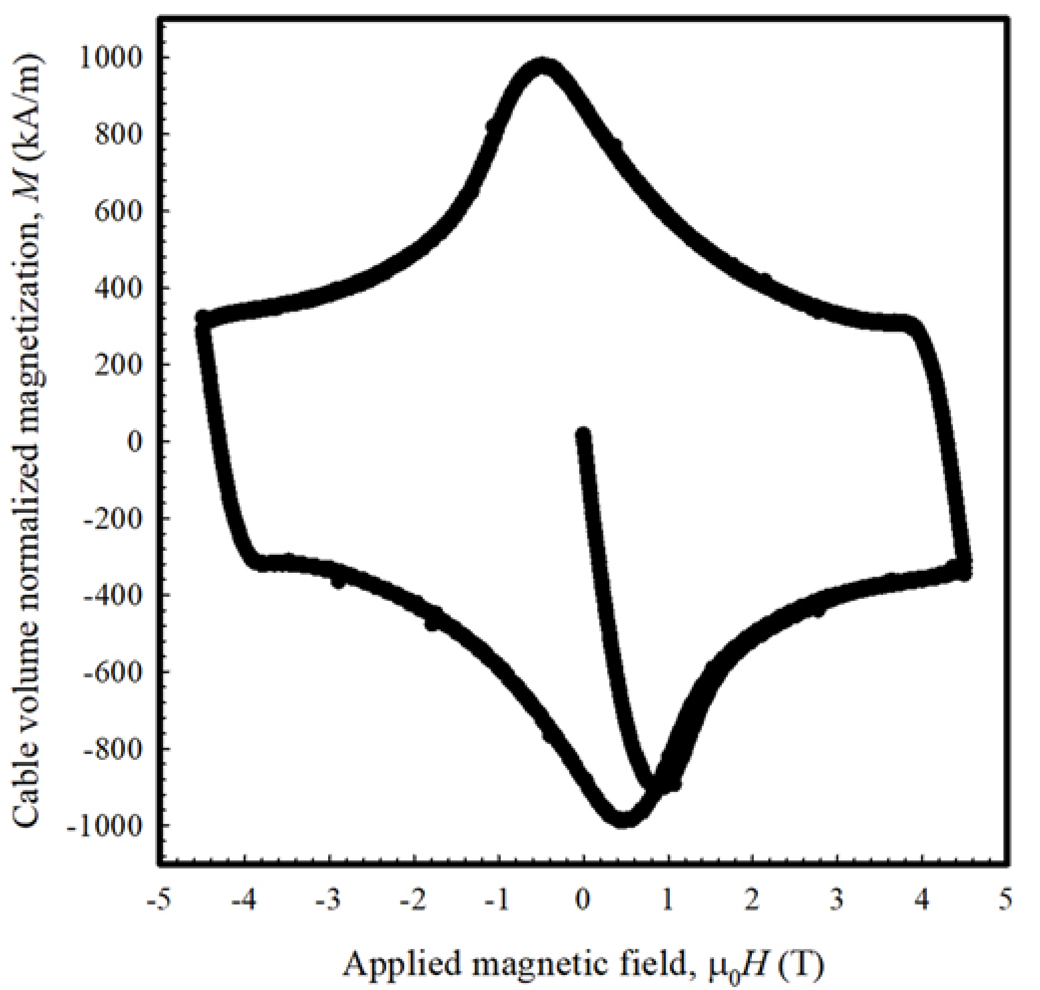
- Measurement made by ΔB between sample and no sample
- Field generated by 12 T, liquid cryogen free, RT bore magnet
- Cooling provided by varitemp dewar





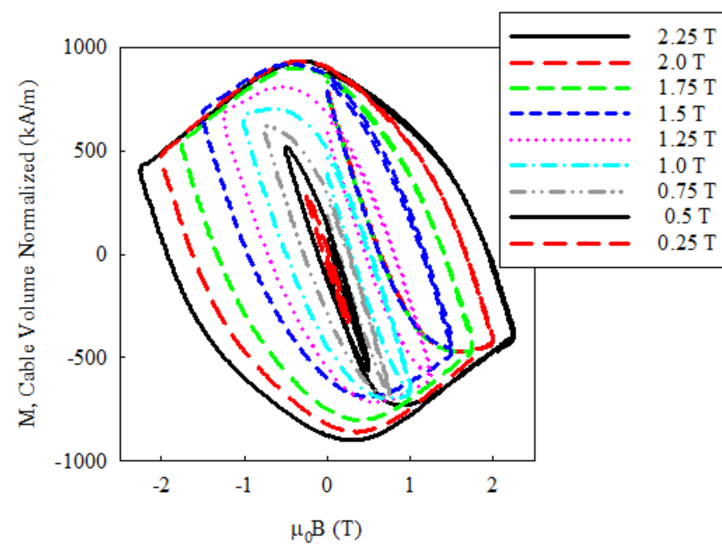


M-H of CORC ± 4 T, Hall probe



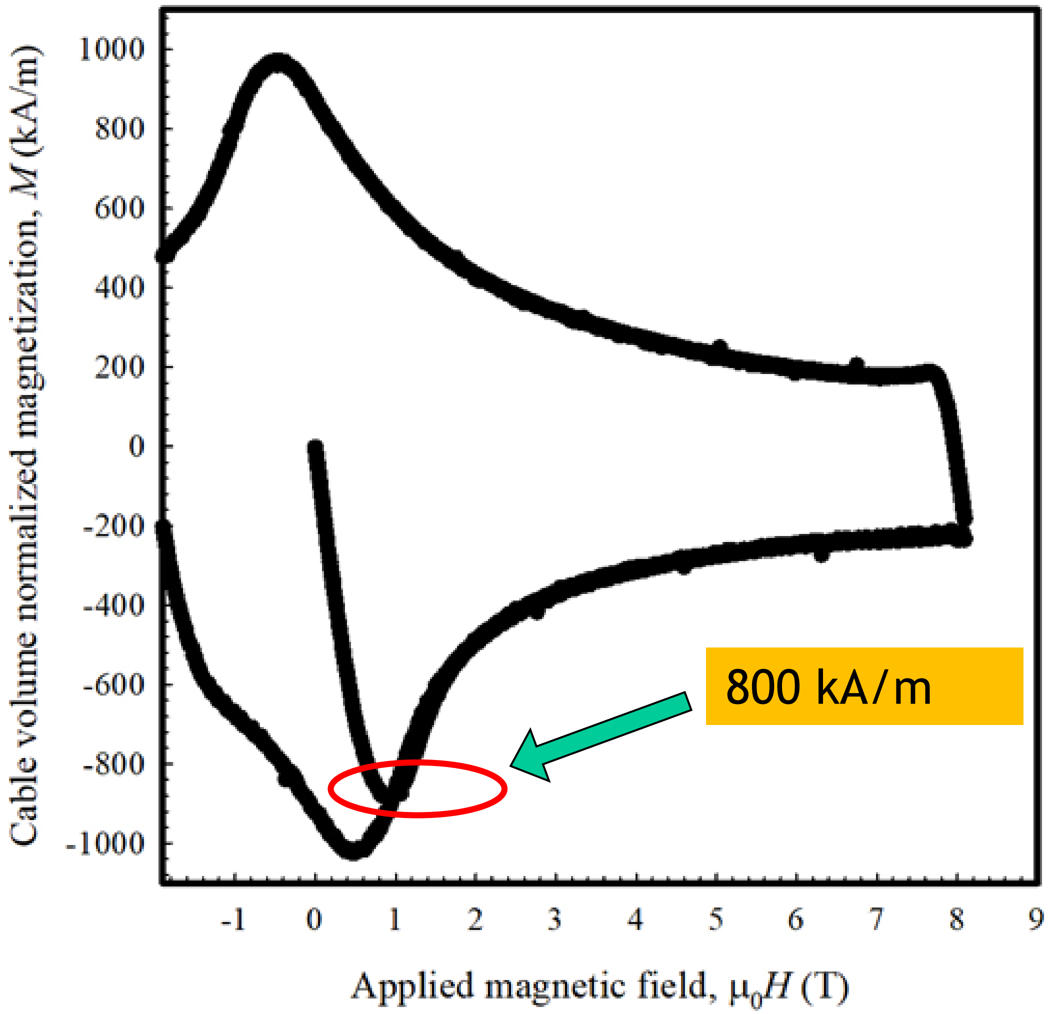
The Berkeley tape ID was 160823-Berkeley 250-C, used in their magnet C0a (Same as measured in 3 T dipole)

- 4 K *M-H*
- $B_{\perp}$
- Normalized total cable

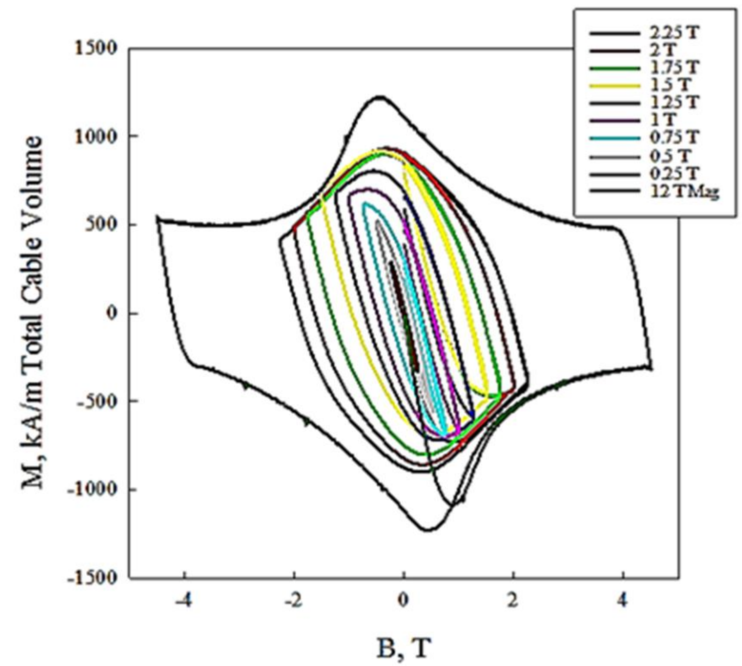


3 T Dipole

M-H of CORC -2 T to 8 T, Hall probe



- 4 K *M-H*
- $B_\perp$
- Normalized total cable volume



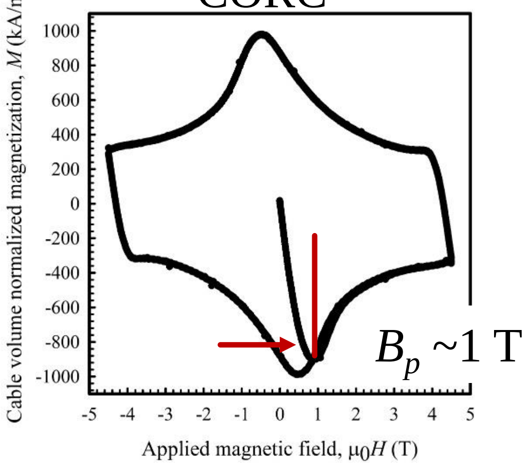
So, how is Cable Magnetization different than tape? Let’s compare gross shape

2.7 cm

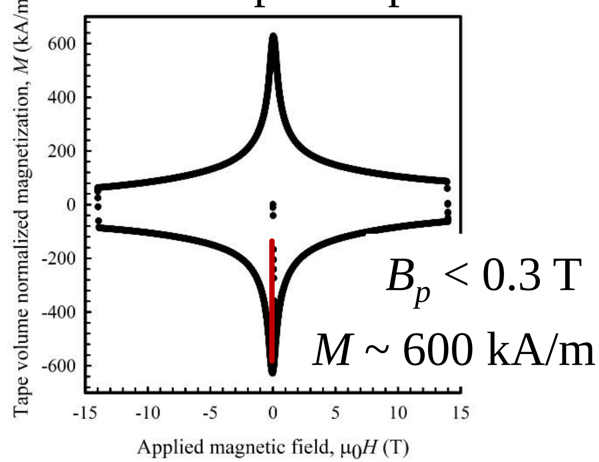
3.21 mm

3 x 2 mm

CORC ®



Tape sample



Answer:

1. **Magnetization** at full penetration is **similar**, but different by factors of **up to 2**
2. **Penetration field** for **Cables >> Tapes** (1 T as compared to 0.1 T)
3. Because of (2), (1) can be ***very different in tapes and cables in the area of interest (injection), depending on pre-injection cycle***

(1) FOR CORC, Mcable ~2/πMtape (tape vol norm)

(2) Penetration field is much higher in cabled sample

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OK …. So Why is the penetration field larger?

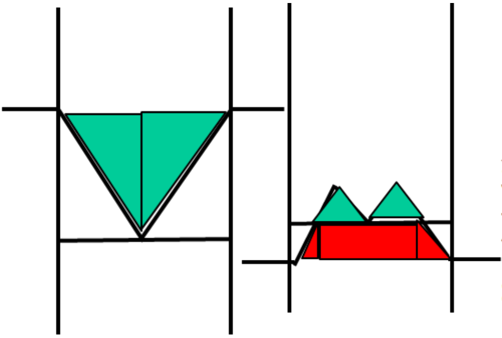
$B_p = \mu_0 J_{c,ybco} t_{ybco} = \mu_0 J_{c,ybco}(t_{ybco}/t_{tape})(t_{tape}/t_{ybco})t_{ybco}$
$= \mu_0 J_e t_{tape}$

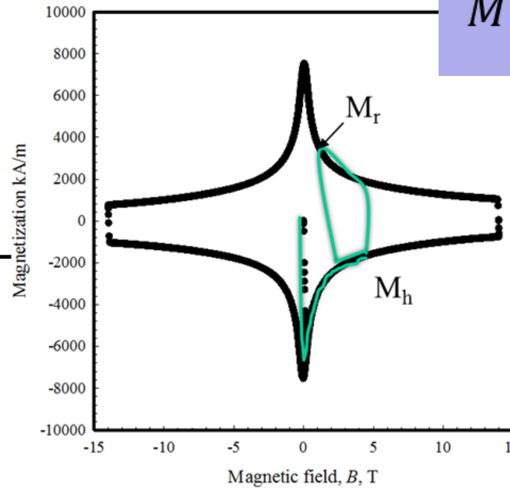
That is, is should sort of go up like the number of tapes …

If CORC has 8 layers, expect B_p to be 8 times larger on basis of above equation (so, 0.2T becomes 1.6 T)

But due to demag, $B_{edges} = 2\ B_{applied}$, thus $B_p = ½\ 1.6\ T = 0.8\ T$

So, can we predict the magnetization for various arbitrary cycles?

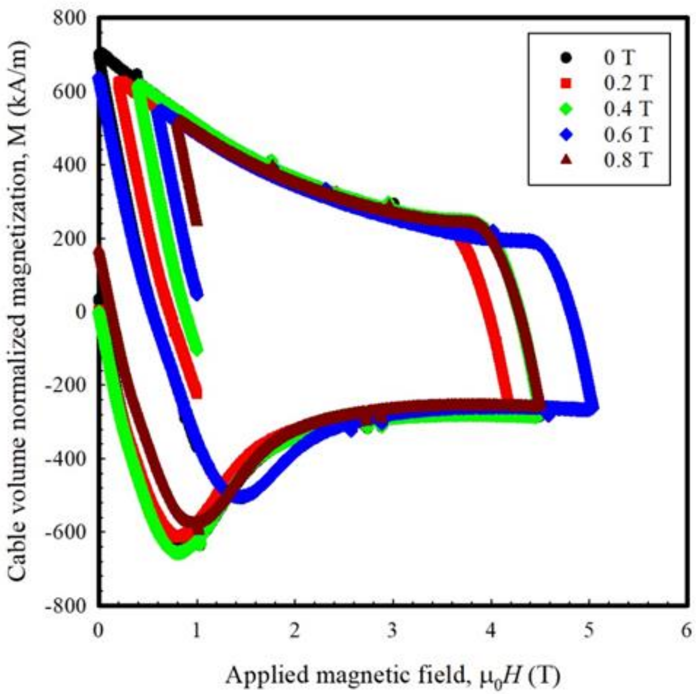




$$M = \frac{2}{\pi}\frac{J_c a}{2} FF \left[1 - \frac{w}{3L_{p,eff}}\right]\left[1 - \left(\frac{B - B_{min}}{B_p}\right)\right]$$

TABLE I
MAGNETIZATION AND DRIFT VALUES

Sample type and hold field	M_0 (kA/m)	*Mpred (kA/m)*
CORC 0 T	-430	-420
CORC 0.2 T	-280	-210
CORC 0.6 T	19	210
CORC 0.8 T	180	420



Can we now predict it? Yes!

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Summary

- *M-H* of CORC and twist stack in full penetration calculated by Analytic and FEM methods
- For long L_p, $M_{corc} = M_{twst} = (2/\pi)M_{tape}$
- *In general*

This CF ≈0.8

$$\Delta M = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2w}{3L_p}\right)$$

$$\Delta \mathrm{M} = \Delta M_0 \frac{L_p}{\pi w} \cos\left[\frac{\pi L_p}{4}\left(1 - \frac{w}{L_p}\right)\right]$$

- For Initial Permeability (more general cycle)

$$M = \frac{2}{\pi}\frac{J_c a}{2} FF \left[1 - \frac{w}{3L_{p,eff}}\right]\left[1 - \left(\frac{B - B_{min}}{B_p}\right)\right]$$

- Comparison to measurements made directly on CORC cable in two different systems – a 3 T dipole magnetometer and a 12 T Hall probe system both operating at 4 K give reasonable agreement