Magnetization and Analysis of CORC, TWST, and Roebel Cables for HEP applications and Associated Error fields

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D. Van Der Laan
Advanced Conductor Technologies and University of Colorado

Twisted Strand:
University of Houston

Karlsruhe Institute of Technology

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Department of Materials Science and Engineering

Outline of talk

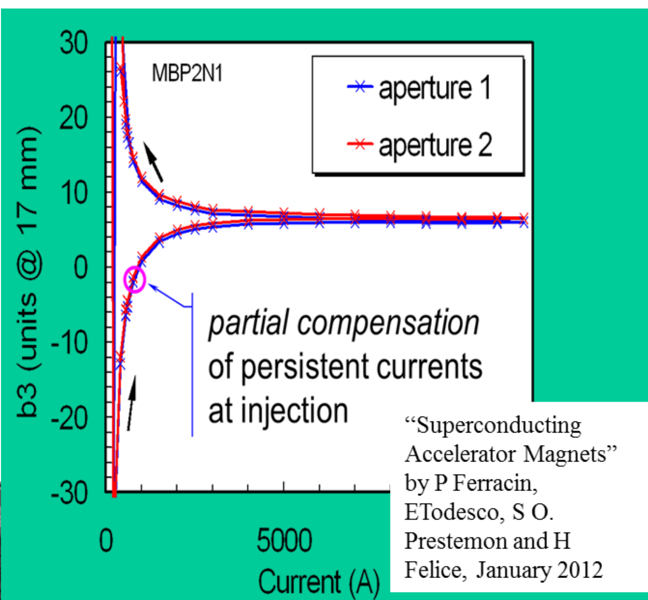
- Motivation – accelerator quality
- Comparison of accelerator and b3
- Expressions for Magnetization of Tape vs Cable
- Measurements and Analysis of Magnetization of various cable types
- Coupling -- Magnetization -- loss?

Why the focus on Magnetization? – its b3 and its change for accelerator magnets

Strand type	NbTi[1]	Nb_3Sn[2]	Bi:2212[3]	YBCO	YBCO
Cable type	**Rutherford**	**Rutherford**	**Rutherford**	**TSTC**	**CORC™**
Cable packing factor, λ_c	0.88	0.855	0.87[4]	0.56	0.58
Strand filling factor, λ_s	0.385	0.455	0.26	0.01[5]	0.01[5]
Layer CCD, $J_{c,inj}$, kA/mm^2	20.4	-	1.75	88[6]	88[6]
Eng. CCD[7], $J_{e,inj}$, kA/mm^2	7.85	-	0.455	0.88	0.88
Fil. (strand) size, d_{eff}, μm	7	61	278	4000[8]	4000[10]
$J_{cable,inj}$ kA/mm^2	6.91	13.0	0.396	0.493	0.510
$J_{cable,coll}$, kA/mm^2	0.704	0.855	0.348	0.244	0.232
$B_{b,coll}$, T	8	15	20	20	20
b_3, units [11]	3	41	19	330[12]	330[12]
b_{3*}, units [13]			37	99	99

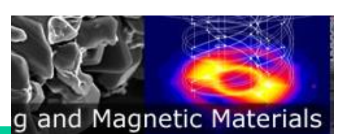
This is based on an estimation from Tape

Weighted ave Hybrid mag



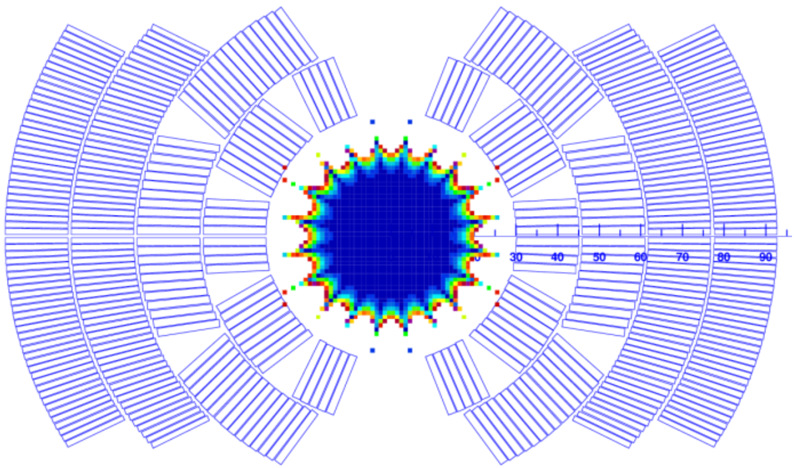
"Superconducting Accelerator Magnets" by P Ferracin, ETodesco, S O. Prestemon and H Felice, January 2012

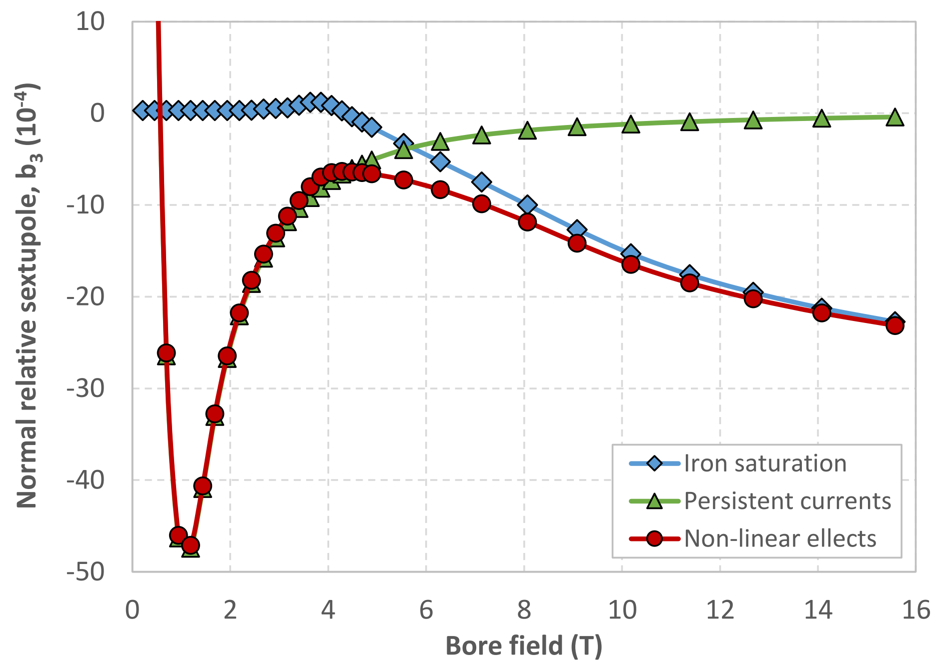
Sample	B, T	orientation	$-M_0$, kA/m	$-M_{20min}$, kA/m	$\Delta M_{20min}/M_0$, %	Δb_3, %
Bi:2212						
	1 T	⊥ axis	15	12	20	20
	12 T	⊥ axis	2.7	1.5	42	42
YBCO						
	1 T	$B//c$	991	906	9	9
	1 T	45°	933	811	14	14
	12 T	$B//c$	280	187	33	33
	12 T	45°	229	200	13	13



Cos theta coil MDP

Nb$_3$Sn RRP Conductor





A Zlobin, “15 T dipole design concept, magnetic design and quench protection”, Presentation at the US MDP workshop Jan 2017

Canted cos theta Dipole

NbTi Strand

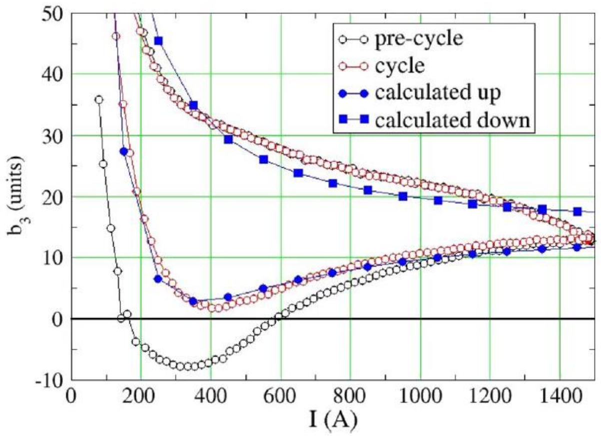
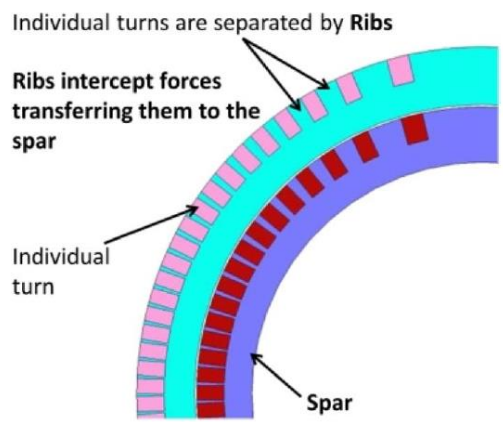


Fig. 11. Combined geometric and magnetization sextupole up to 1500 A.

TABLE I
CCT1 MAGNETIC PARAMETERS

Symbol	Units	Value
Strand diameter (SSC outer)	mm	0.65
Strands per cable		8
Bare cable	mm	2.72x1.07
Insulated cable	mm	3.02x1.37
Cable keystone angle	Deg.	0
Channel size	mm	3.02x1.59
Clear bore dia.	mm	50.8
Number of layers		2
Layer1/2 radial spar thickness	mm	3.07
Between layers radial insulation	mm	0.25
Layer1/2 canted angle	Deg.	15
Layer 1/2 No. of turns		78/72
Layer 1/2 single turn length	mm	499/604
Mandrels length	mm	841.1
Axial pitch length	mm	7.60
Minimum rib thickness (mid-plane)	mm	0.38
Maximum rib thickness (pole)	mm	6.02

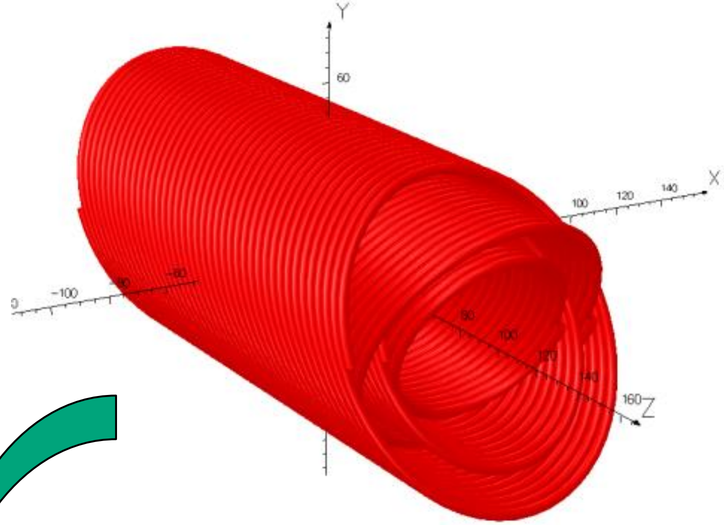


IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 25, NO. 3, JUNE 2015

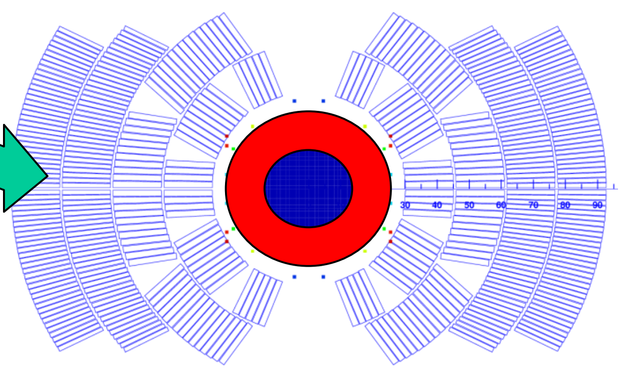
Test Results of CCT1—A 2.4 T Canted-Cosine-Theta Dipole Magnet

S. Caspi, L. N. Brouwer, T. Lipton, A. Hafalia Jr, S. Prestemon, D. R. Dietderich, H. Felice, X. Wang, E. Rochepault, A. Godeke, S. Gourlay, and M. Marchevsky

Canted Cos Theta dipole 2



X. Wang, "REBCO accelerator magnet development: status and plans", Presented at the USMDP NAPA, Jan 2017

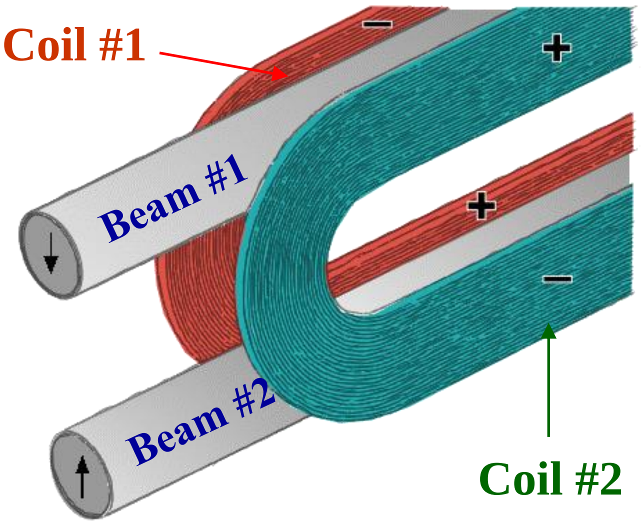


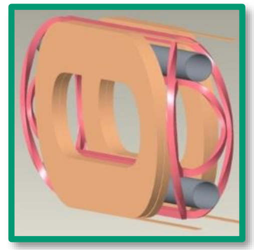
X Wang of LBNL proposes to make a 4 layer canted cos dipole using YBCO cable

- As part of LBNL-OSU collaboration, Nb3Sn magnetization measurements and Bi:2212 magnetization data have been provided for error field calculations in other magnet designs
- This collaboration is expanded to include YBCO conductor and cable magnetization for magnets, and collaboration on error field determination

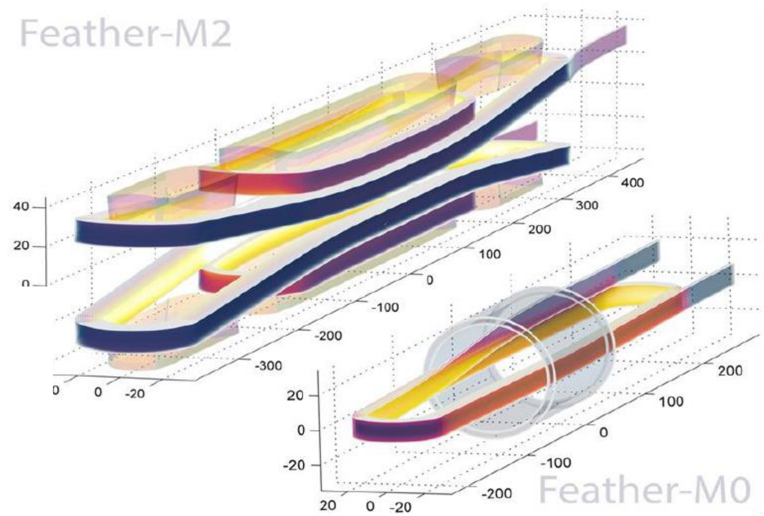
- If we consider for a moment the simplest case of an HTS insert in a background Nb3Sn magnet, then at injection, it may be reasonable to approximate field on CCT as a "uniform 1 T"
- Initial error estimates using biot savart (and a doublet approach) suggest significant b3 for CCT wound with YBCO cables, as expected extrapolating from CCT1 > 25 unit

A number of other designs and possibilities





Ramesh Gupta, "Hybrid Configuration and BNL Activities", USMDP, 2017



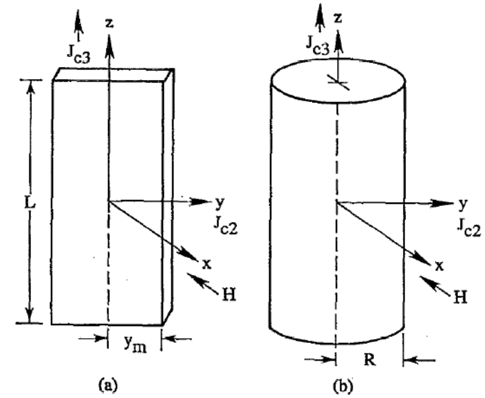
1. Aligned block development HTS magnets, (bottom right) Feather-M0
ıch detection development coil, (top left) Feather-M2 the EuCARD-2 five
a standalone approaching accelerator field quality insert magnet.

Accelerator Quality HTS Dipole Magnet Demonstrator Designs for the EuCARD-2, 5 Tesla 40 mm Clear Aperture Magnet

G. A. Kirby, J. van Nugteren, A. Ballarino, L. Bottura, N. Chouika, S. Clement, V. Datskov, L. Fajardo, J. Fleiter, R. Gauthier, L. Gentini, L. Lambert, M. Lopes, J.C. Perez, G. de Rijk, A. Rijllart, L. Rossi, H. ten Kate, (CERN), M. Durante, P. Fazilleau, C. Lorin (CEA), E. Härö, A. Stenvall, (TUT), S. Caspi, M. Marchevsky, (LBNL), W. Goldacker, A. Kario, (KIT)

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

For round strands – Nb_3Sn, Bi2212, the simple rules are



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

Full field penetration

$$\Delta M = \frac{4}{3\pi} d_{eff} J_c$$

$$B_p = \mu_0 0.8 J_c d_{eff}$$

cylinders

$$\Delta M = a J_c$$

$$B_p = \mu_0 J_c a$$

slabs

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

No or nearly no penetration

$$M = -2H$$

cylinders

$$M = -H$$

slabs

Only true if B // to thin edge

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

For flat strands with B ⊥ tape

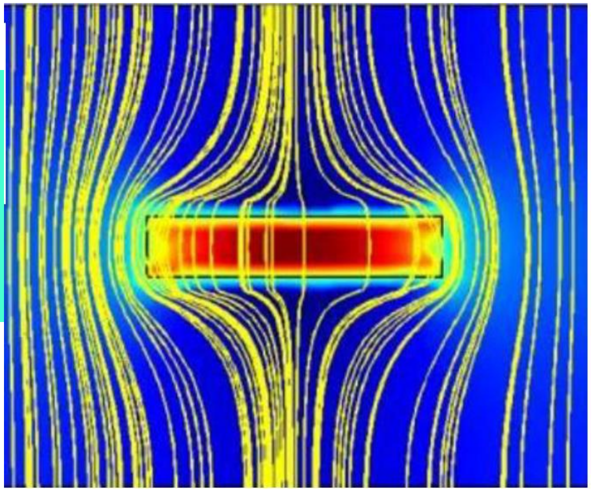
1. For B perpendicular, $B >> B_p$

$$\Delta M = aJ_c$$

a is half width

slabs

But, B_p for $B_\perp$ slab much much lower than B_p for cylinder or slab with B // slab



$$H_p \approx J_c \left(\frac{t}{\pi}\right)\left(\ln\frac{w}{t} + 1\right)$$

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

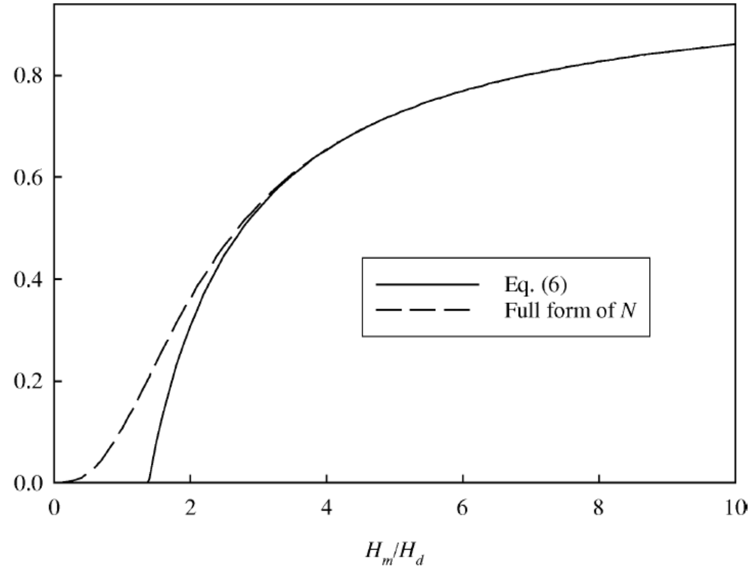
$$M = -\infty$$

As the width becomes infinite

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

$$\Delta M = NaJ_c$$

$$N = 2\left(\frac{H_d}{H_m}\right) \mathrm{Ln}\left(\cosh\frac{H_m}{H_d}\right) - \tanh\left(\frac{H_m}{H_d}\right) \approx \left(1 - \frac{1.4}{(H_m/H_d)}\right).$$



H_m is the applied field and $H_d = 0.4J_ct$

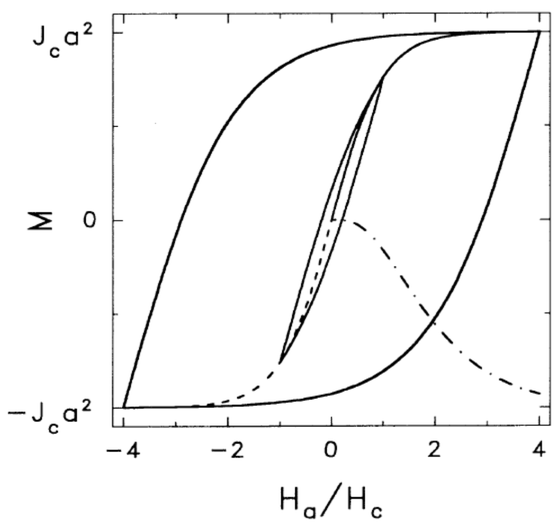
What does the magnetization of HTS, esp YBCO, look like?

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

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

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

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



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

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*

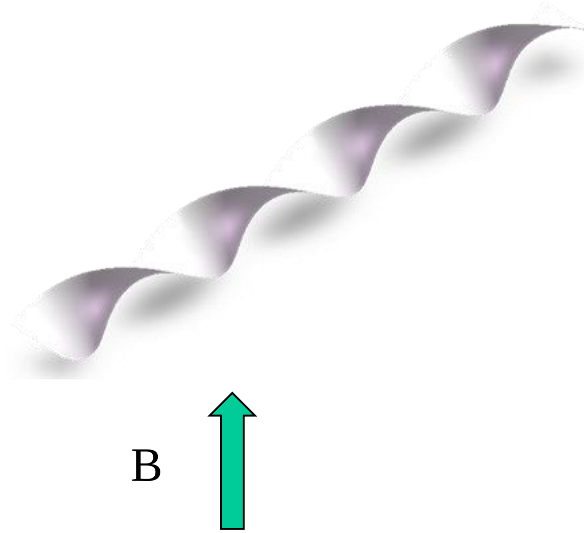
CSMM Center fo

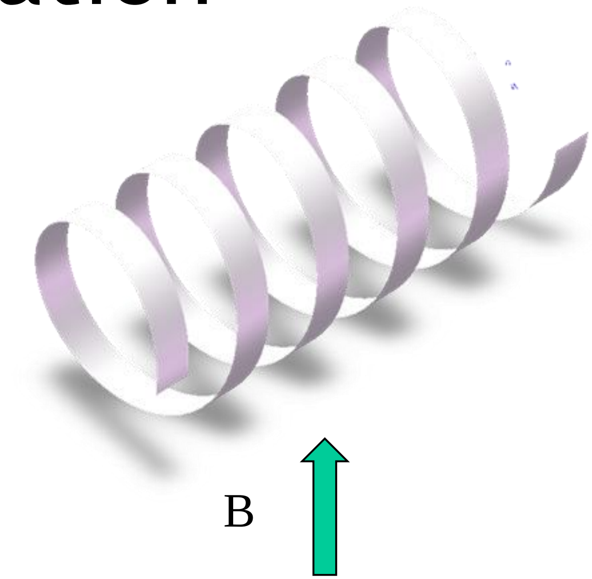
Magnetization of a helical Tape or CORC cable in Saturation

In general, in full penetration,

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

(here w is the half width)





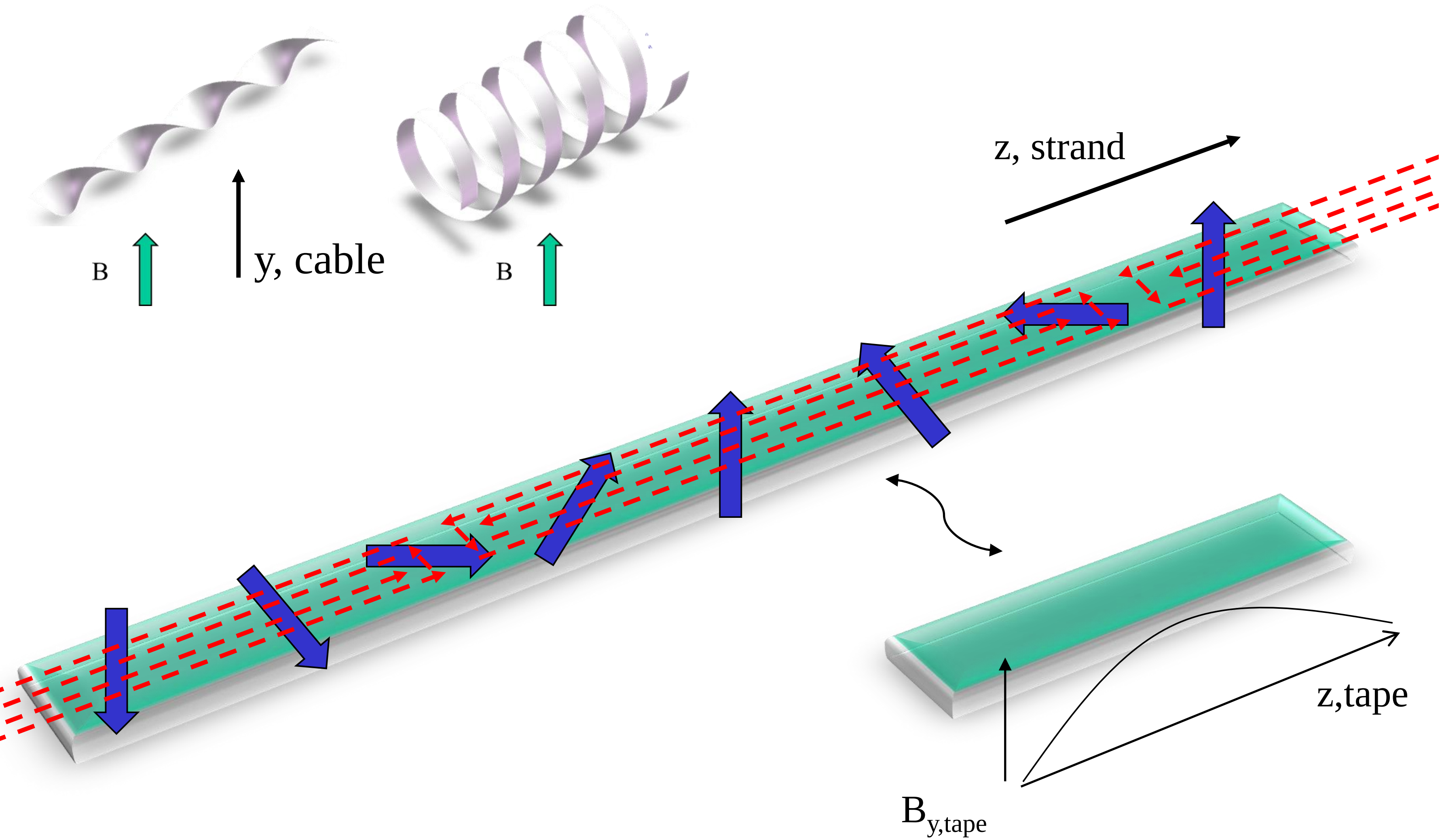
We might then imagine that that loss could be calculated by the simple expedient of integrating the average of Eq (5) over a spatial field cycle, such that

$$Q = \frac{2\mu_0 J_c w H_0}{L_p/_2} \int_0^{\pi} sin\left(\frac{2\pi z}{L_p}\right) dz = \frac{2\mu_0 J_c w H_0}{L_p/_2} \frac{L_p}{2\pi}(2) = \left(\frac{2}{\pi}\right) 2\mu_0 J_c w H_0 = \left(\frac{2}{\pi}\right) Q_0$$

Where Q_0 is the loss for a slab or strip where the field is a field that is time varying and spatially uniform of maximum amplitude H_0. For L_p >> w,

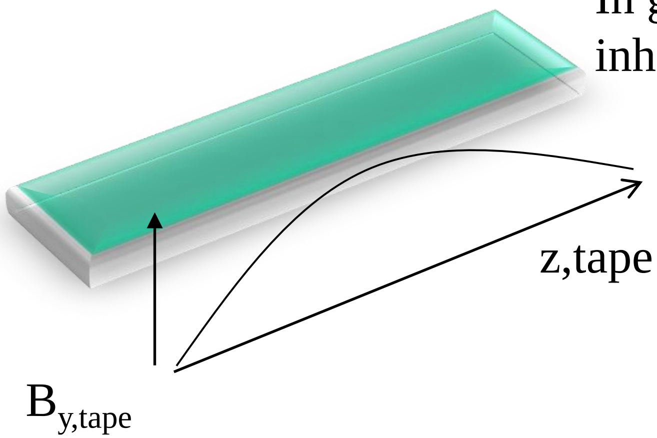
Carr, AC Loss and Macroscopic Theory of SC, p 189, 2nd Ed

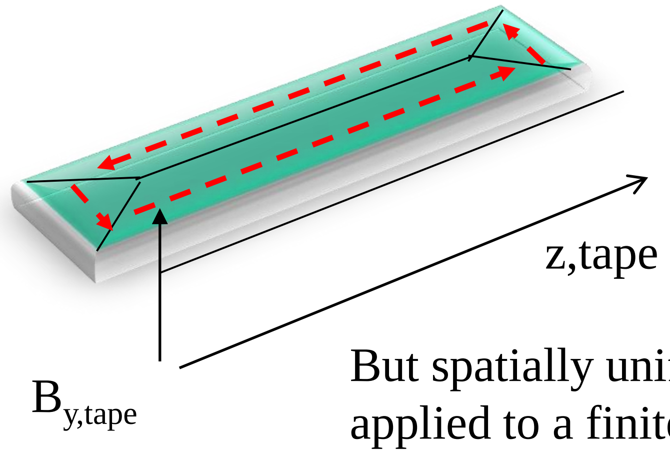
Magnetization of a helical Tape or CORC cable in Saturation II



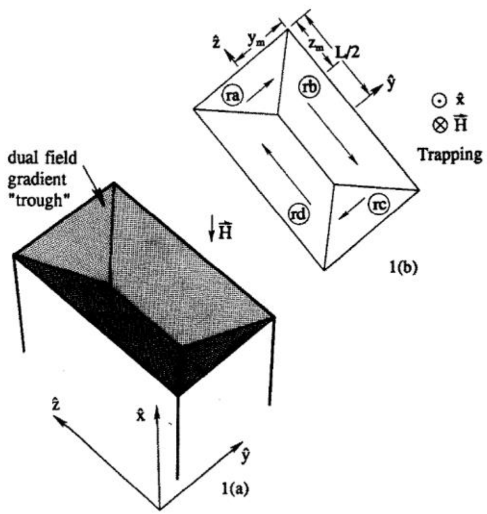
Magnetization of a helical Tape or CORC cable in Saturation III

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





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



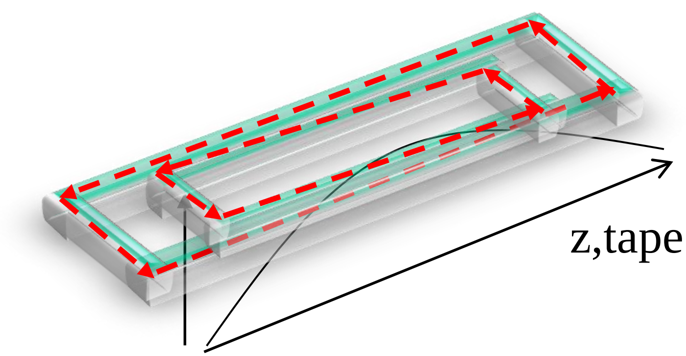
2. E. M. Gyorgy, R. B. vanDover, K. A. Jackson *et al.*, *Appl. Phys. Lett* **55**, 283 (1989).
3. F. M. Sauerzopf, H. P. Wiesinger and H. W. Weber, *Cryogenics* **30**, 650 (1990).
4. S. Hu, H. Hojaji, A. Barkatt *et al.*, *Phys. Rev. B.* **43**, 2878 (1991).

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

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

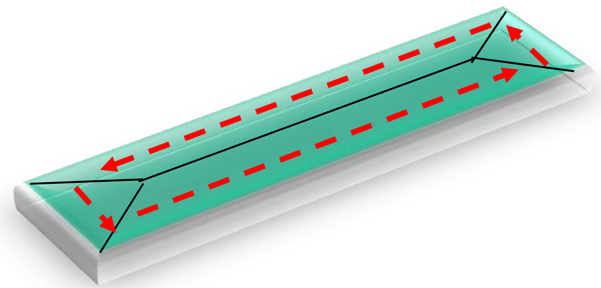
Magnetization of a helical Tape or CORC cable in Saturation IV

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



$B_{y,tape}$

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)

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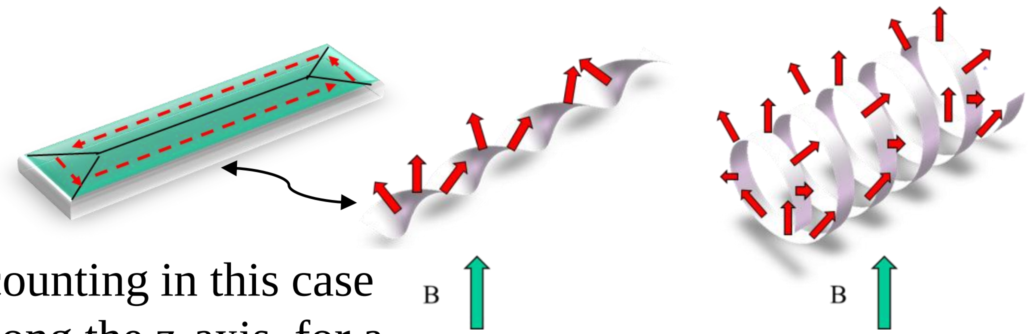
Magnetization of a helical Tape or CORC cable in Saturation V

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

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

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

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

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

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

So, let's try some numbers for Tape

Conductor spec

t	2 microns	0.000002	m
w	4 mm	0.004	m
Jc		2.5E+11	A/m2
Ic		2000	A

4 K, 200 A 77 K

If the sample was very thick --

$B_p = \mu_0 J_c a \approx 1000\ T\ (4\ K)\ or\ 100\ T\ 77\ K$

But for real YBCO which is quite thin …

$$H_p \approx 0.4 J_c t \left[\mathrm{Ln}\left(\frac{d}{t}\right) + 1 \right]$$

Bp YBCO		1.520280467	T	4 K
		0.152028047	T	77 K

For flat strands with B ⊥ tape, $B >> B_p$

$M = (a/2)J_c =$

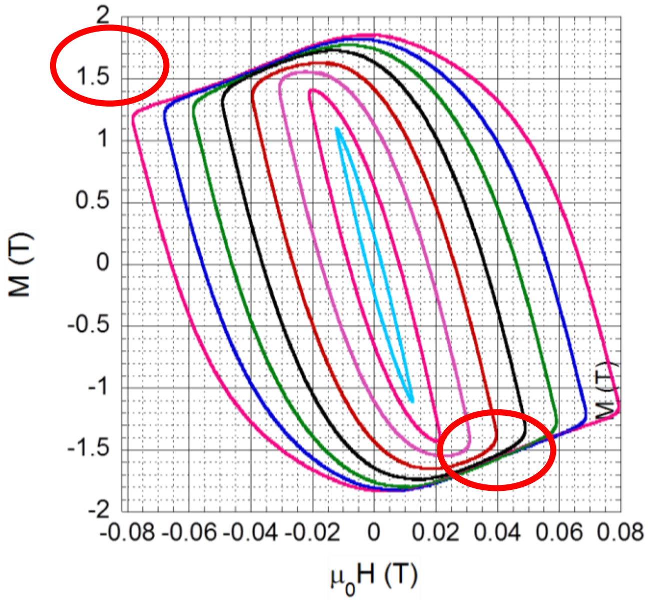
	Film norm	Film norm	tape norm
	A/m	kA/m	kA/m
del M=	500000000	500000	10000

12.56	Tesla	4 K
1.256	Tesla	77 K

4 K, 1000 kA/m 77 K

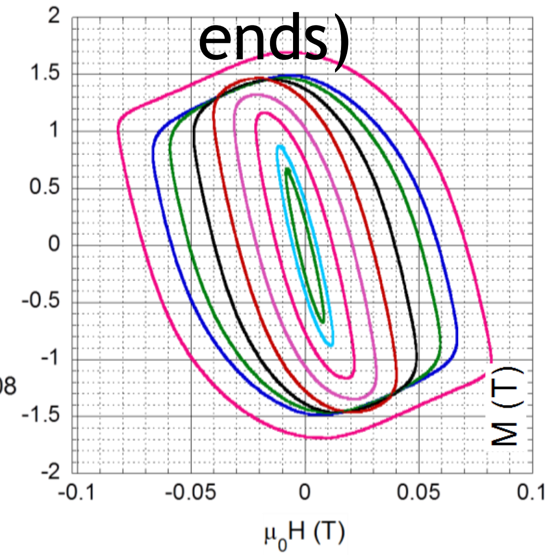
Measured Loss in Striated and Twisted YBCO
University of Houston tape samples

Un-Striated



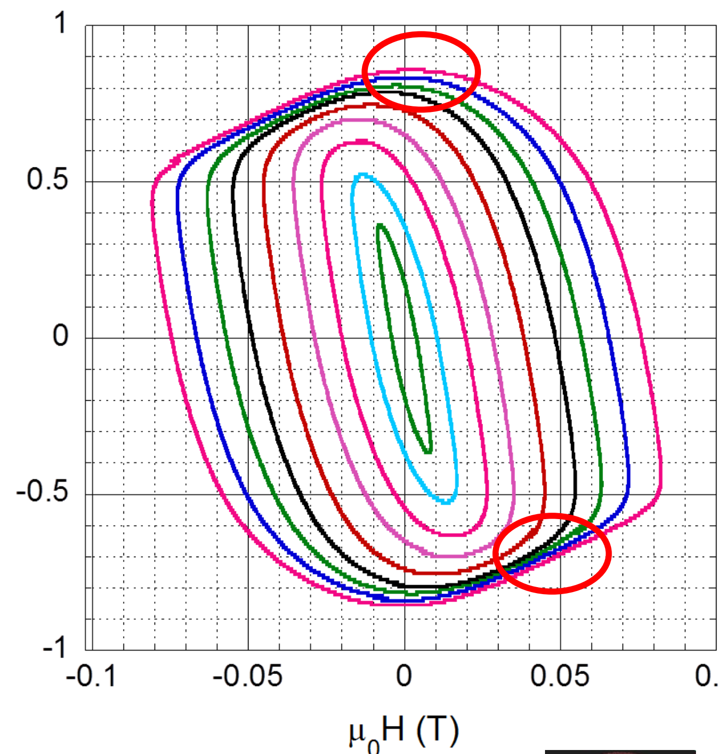
width = 12 mm
length = 16.1 cm
Thickness = 70 μm

Striated (soldered ends)



Striated and Twisted

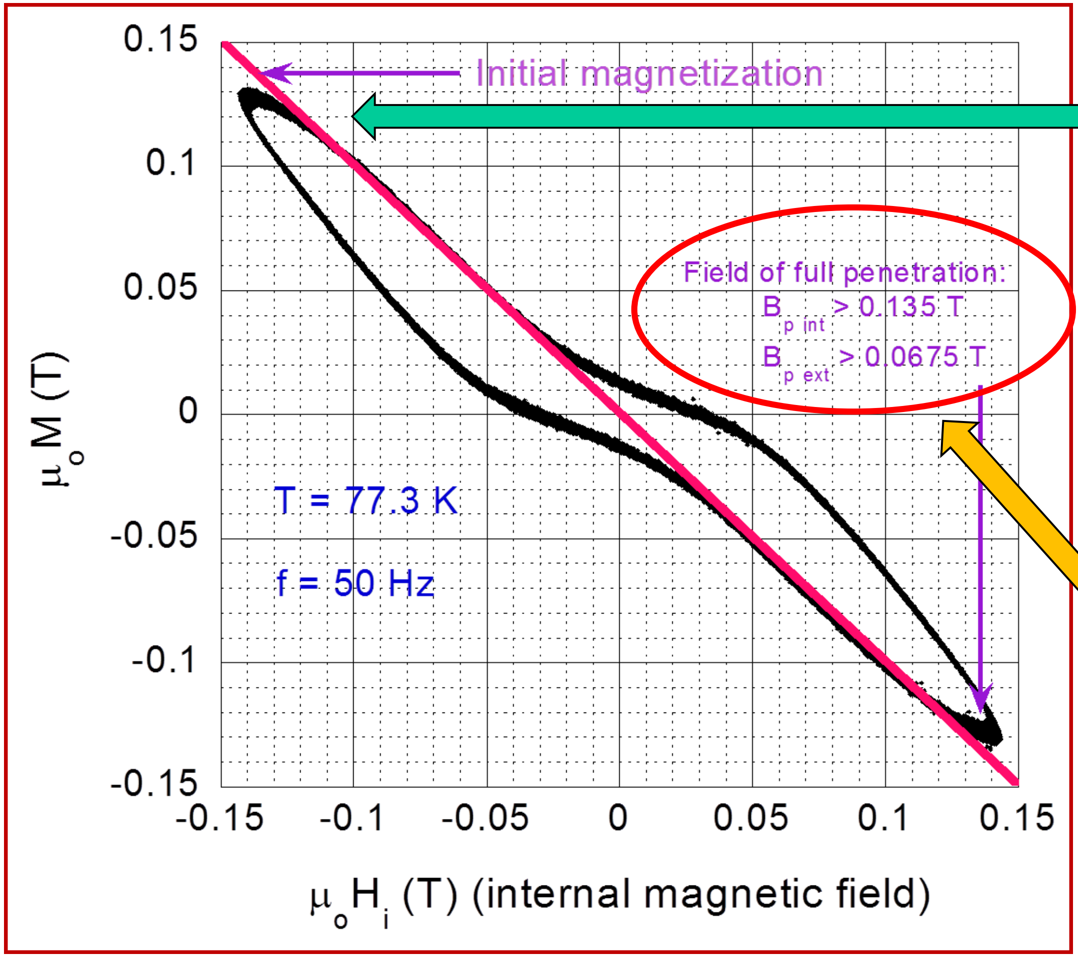
77 K data



Unstriated, B_p = 0.04 T, M = 1.5 T

Striated, B_p = 0.04 T, M = 0.8 T

Magnetization Measurements on CORC at 77 K

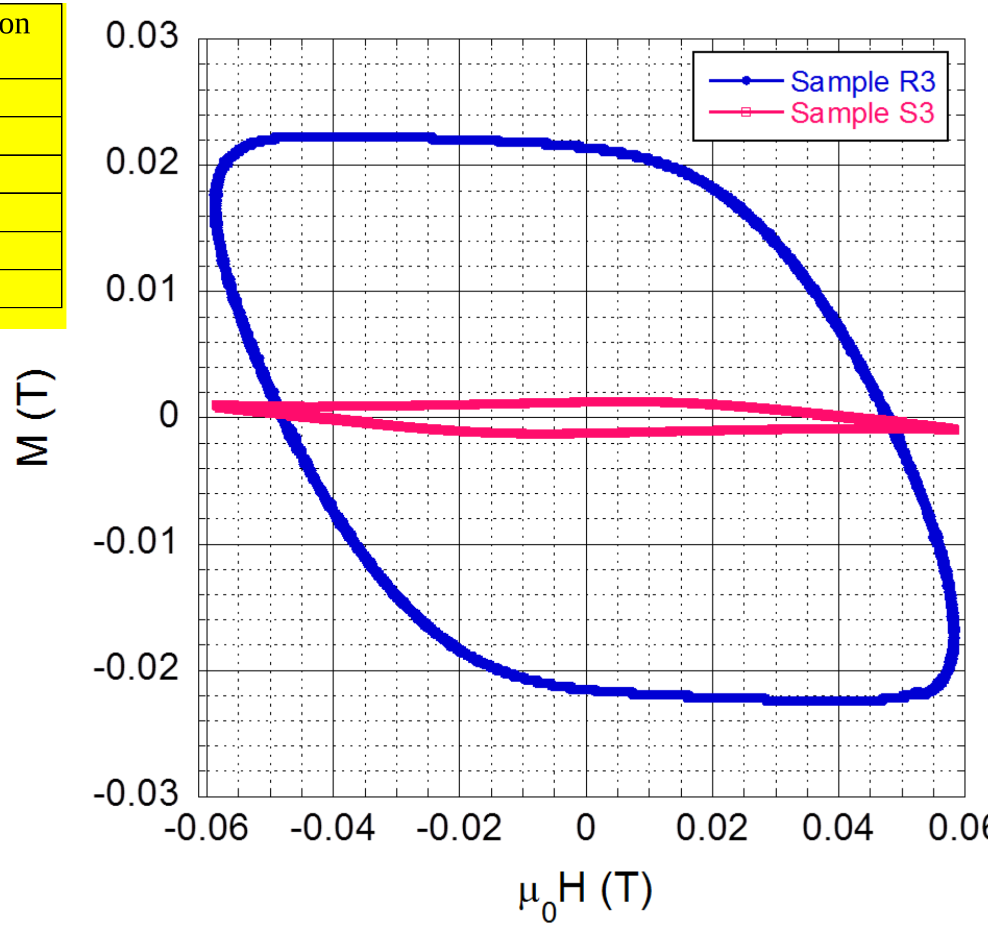


- Saturation magnetization reduced as compared to tape
- This is due to normalizing to volume of cable rather than tape **(factor of 3.3), and Jc difference (factor 3) = 10**
- But note the error field in dipoles is due to moment, not magnetization

- Apparent Bp the same as tape
- But local Bp doubled
- local fields complicated

Striated measurement results of CORC at 77 K

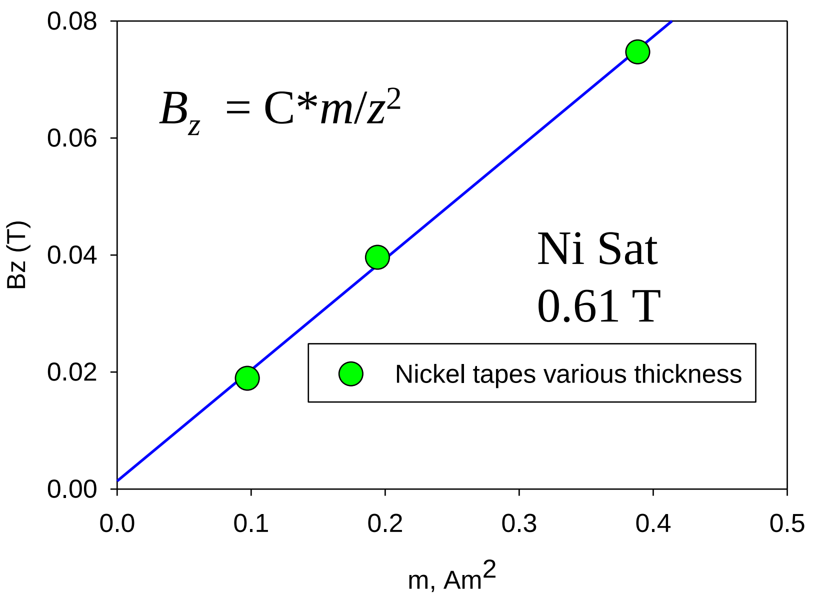
Sample	# of tapes	I_c (A)	ID (mm)	OD (mm)	Length (cm)	Striation
R1	2 x 3 = 6	607.9	4.96	6.17	11.7	None
S1	2 x 3 = 6	348.5	4.95	6.07	12.2	5
R2	3 x 3 = 9	904.2	4.93	6.37	11.7	none
S2	3 x 3 = 9	534.9	4.94	6.38	11.8	5
R3	4 x 3 = 12	1227.5	5.02	6.85	11.7	none
S3	4 x 3 = 12	749.4	4.97	6.78	11.9	5



Striations do significantly reduce loss

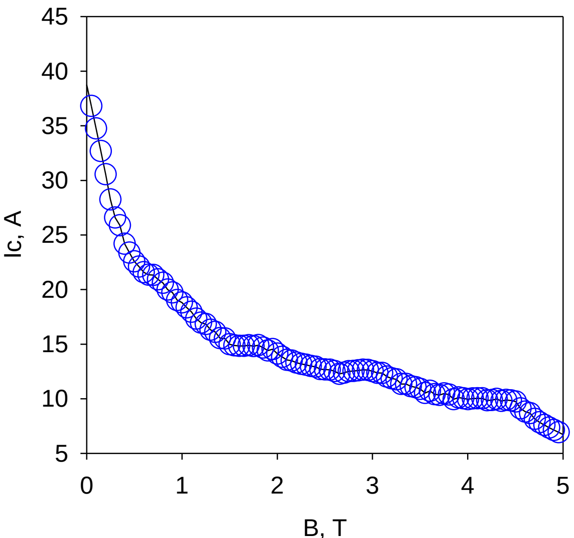
Some factor from striation, some from I_c loss

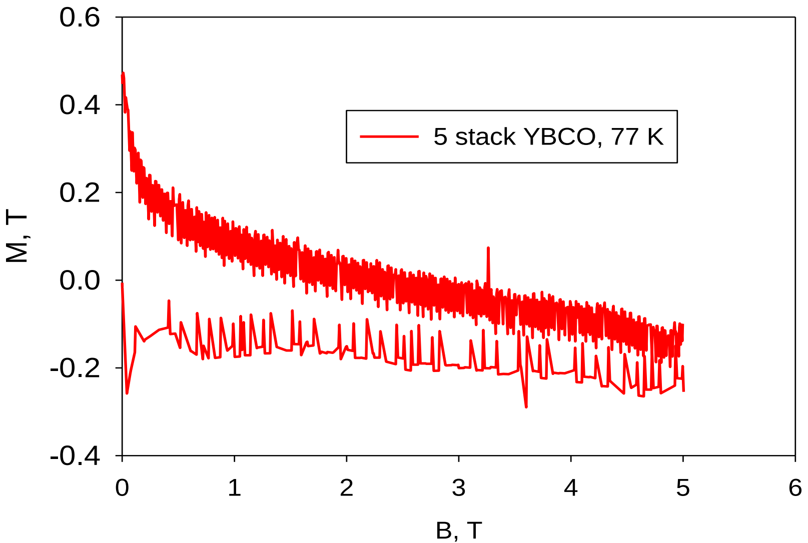
Hall Probe Magnetization in dry magnet with tail dewar – for tapes, short cables



Made for magnetization of tapes and short cables

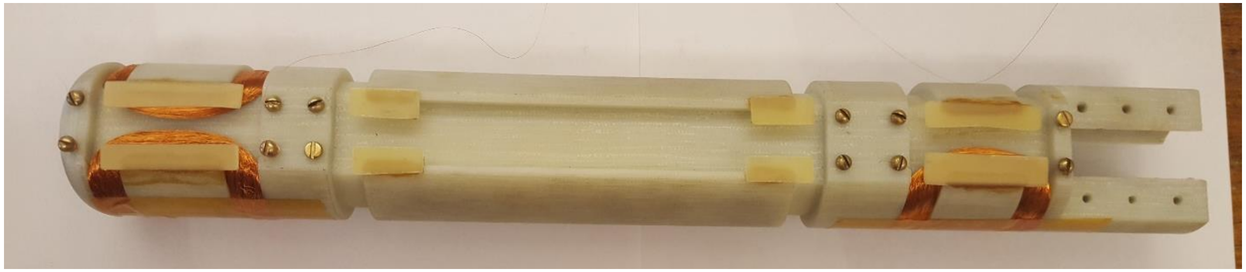
- Sample up to 6 cm long
- Current + field
- Drift, Drift + Current

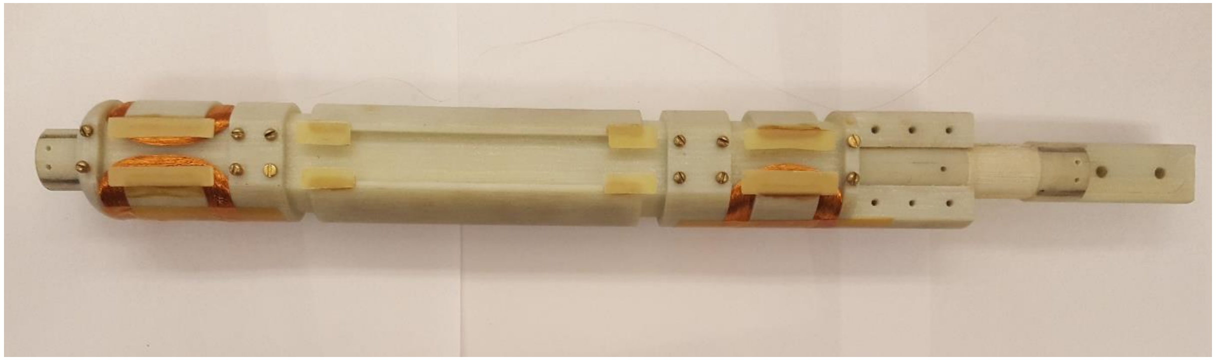




3 T Magnet Dipole Magnet

Max Field = 3.1 T
Max I = 90 A
L = 1 H
Max Ramp Rate = 70 mT/s





OSU- UoT Studies

Nijhuis and K. Yagotyntsev,
The University of Twente

- While new OSU machine is being installed, made measurements at UoT
- Measured TWST, CORC, and Roebel cables at 4 K
- AC loss (10-60 mHz, 0.4 T), M-H (0-1.4 T, 10 mHz)
- Extracting: hysteretic, coupling, Magnetization at injection, and field penetration

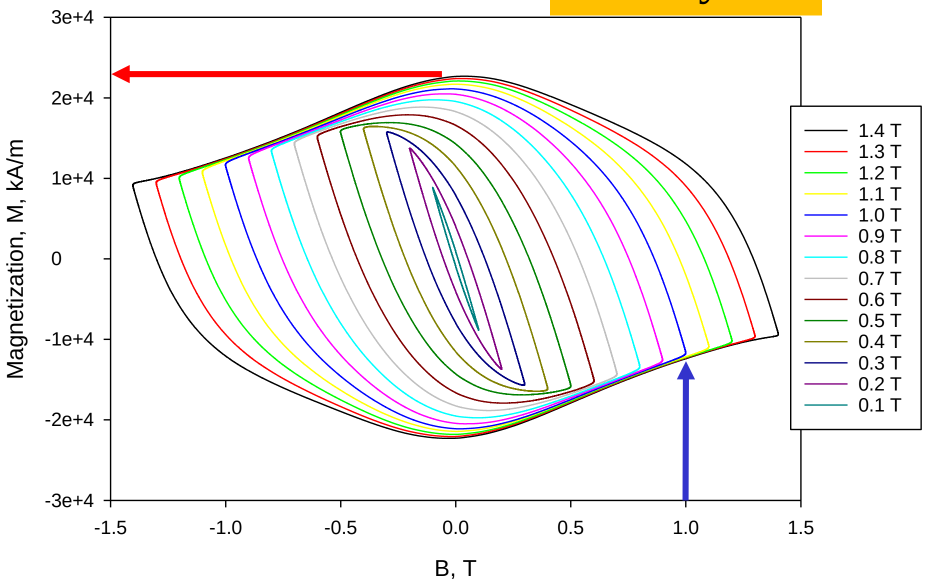
CORC M-H: Effect of layer number

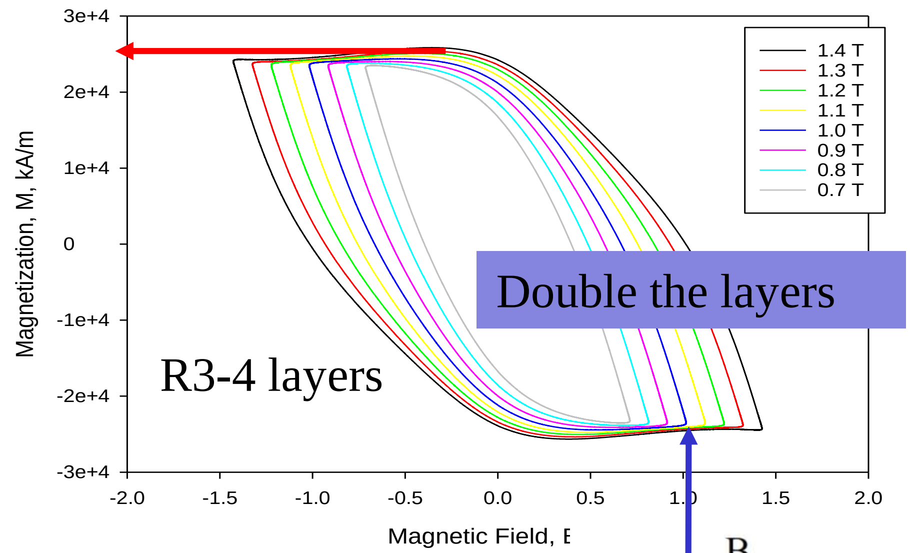
Sample	Tapes	I_c (A)	ID (mm)	OD (mm)	Length (cm)	Striations
R1	2 x 3 = 6	608	4.96	6.17	11.7	none
S1	2 x 3 = 6	349	4.95	6.07	12.2	5
R2	3 x 3 = 9	904	4.93	6.37	11.7	none
S2	3 x 3 = 9	535	4.94	6.38	11.8	5
R3	4 x 3 = 12	1228	5.02	6.85	11.7	none
S3	4 x 3 = 12	750	4.97	6.78	11.9	5

Normalized to tape volume, 4 K result

R1-2 layers

Few layers



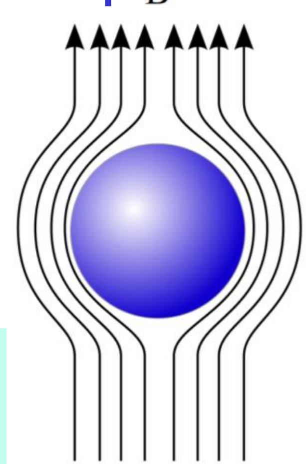


Double the layers

R3-4 layers

	Film norm	Film norm	tape norm
	A/m	kA/m	kA/m
del M=	500000000	500000	10000

This is close to what we might expect for simple tape, but that is maybe fortuitous, as field lines are complicated



$M_{max} \approx 2M_{tape}$ when tape volume normalized, not influenced by layer #

B_p similar to tape and not influenced by tape #

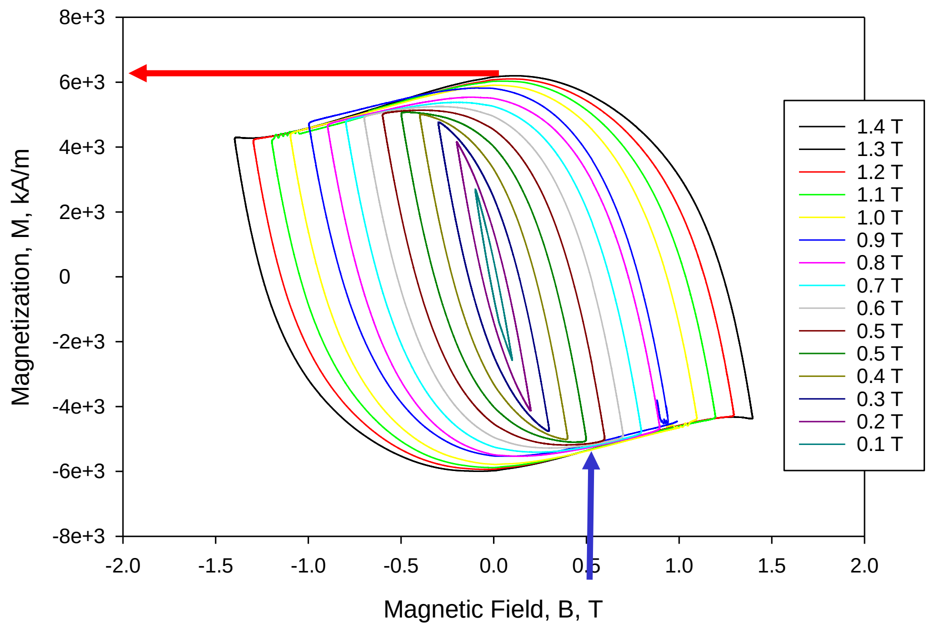
CORC M-H Effect of striation

Normalized to tape volume, 4 K result

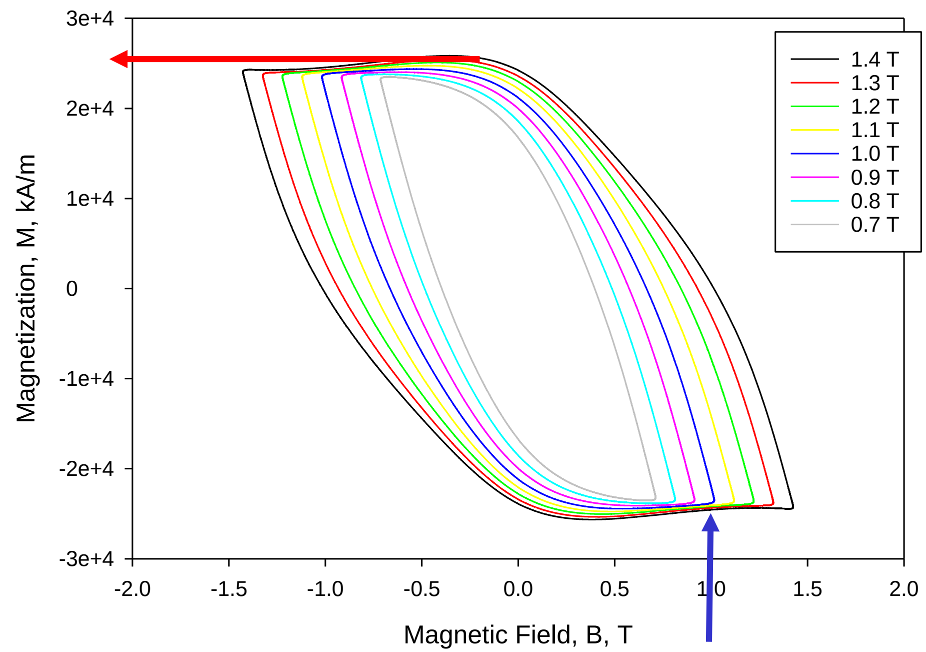
Sample	Tapes	I_c (A)	ID (mm)	OD (mm)	Length (cm)	Striations
R1	2 x 3 = 6	608	4.96	6.17	11.7	none
S1	2 x 3 = 6	349	4.95	6.07	12.2	5
R2	3 x 3 = 9	904	4.93	6.37	11.7	none
S2	3 x 3 = 9	535	4.94	6.38	11.8	5
R3	4 x 3 = 12	1228	5.02	6.85	11.7	none
S3	4 x 3 = 12	750	4.97	6.78	11.9	5

S3-4 layer-striped

6 x 5 = 30



R3-4 layers



- Striping by 5 reduces M_{max} by 4
- B_p appears to be reduced by 1/2

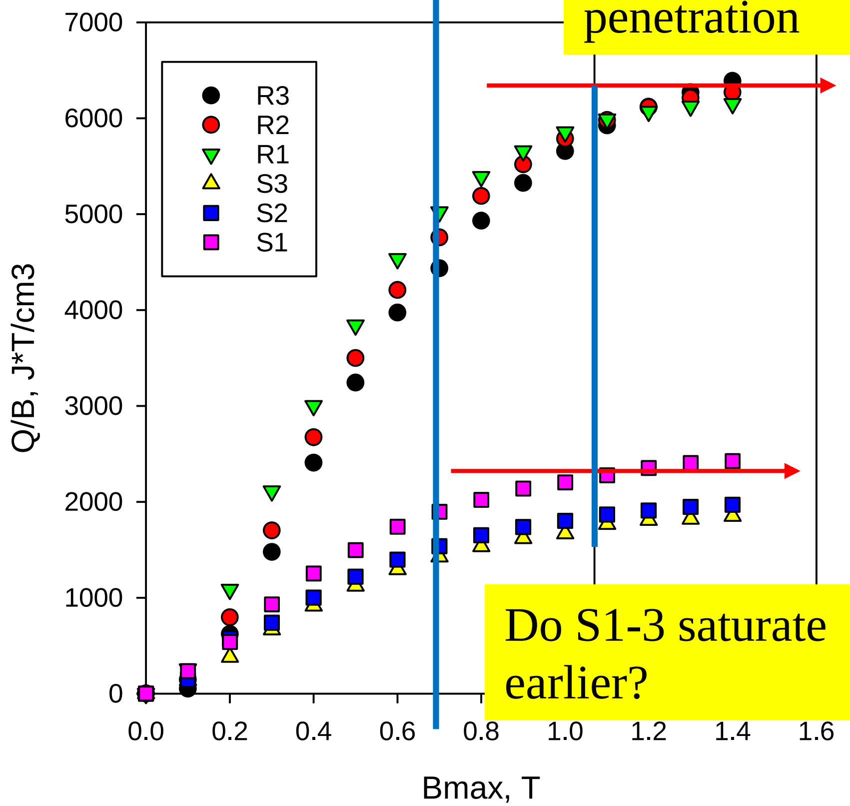
Let's further explore this:
Loss (Q) below B_p goes as B^3, above as B

Field Penetration into cables – CORC Cables

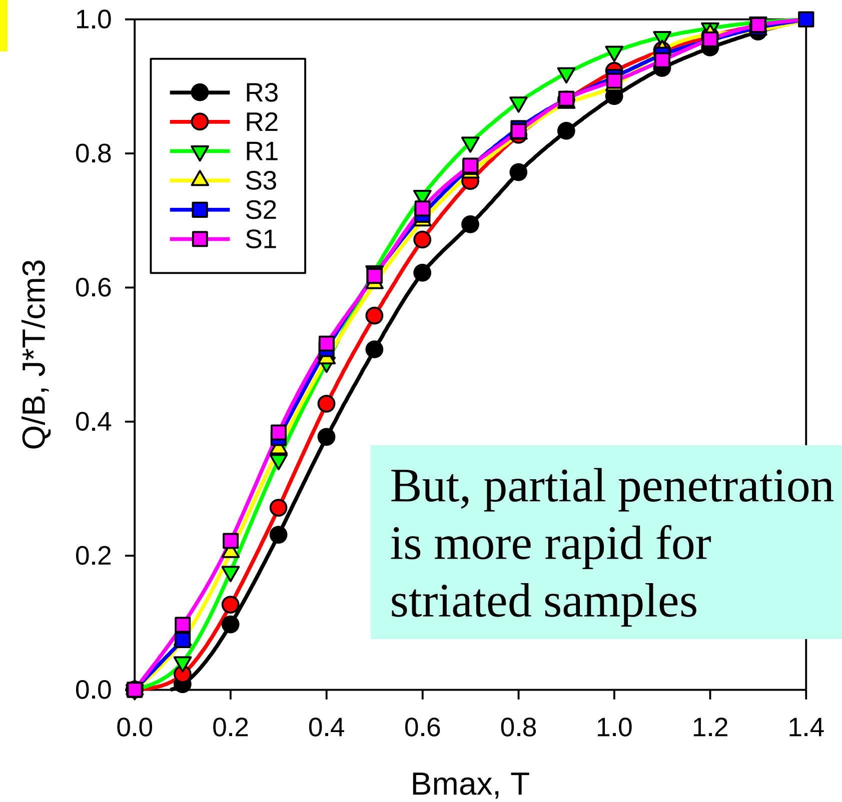
Saturation “effective width” different by x 3

Approaching full penetration

Full penetration happens at same place



Do S1-3 saturate earlier?



But, partial penetration is more rapid for striated samples

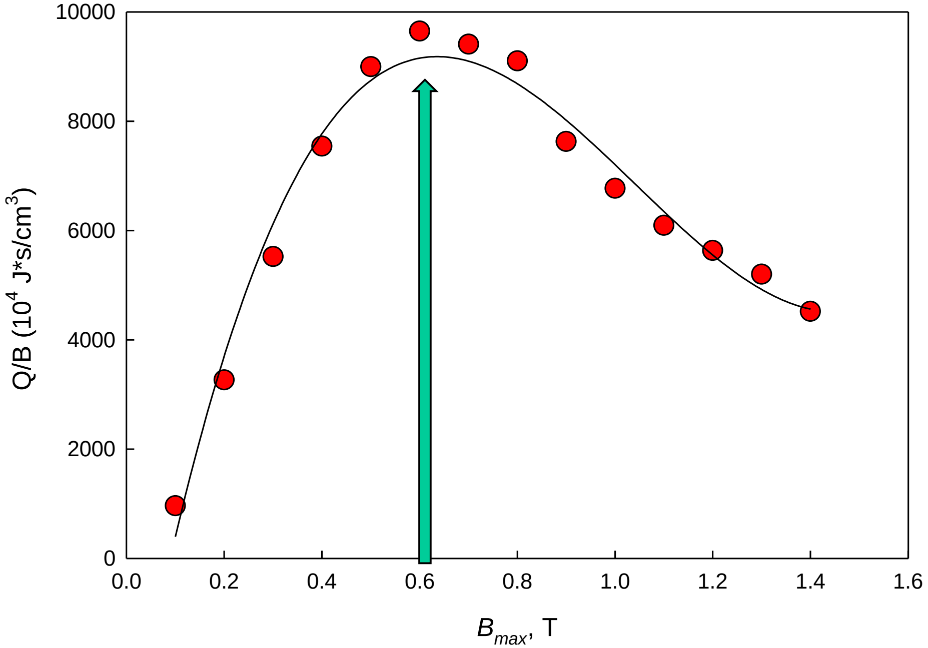
So, true B_p not really changed by striation, but apparent value is

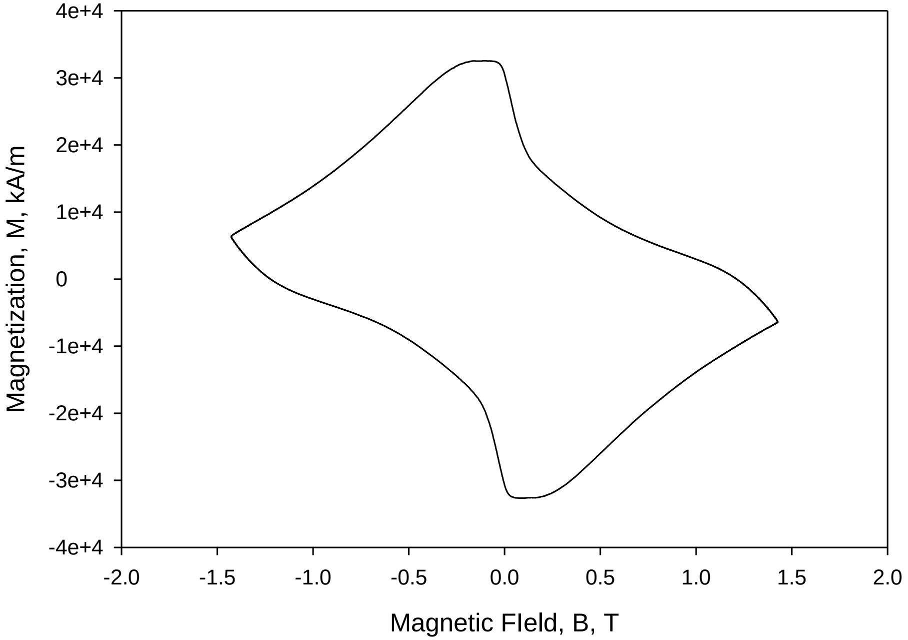
CSMM Center for Superconducting and Magnetic Materials
Department of Materials Science and Engineering

Roebel M-H

Normalized to tape volume, 4 K result

width = 13 mm
thickness = 0.5 mm
twist pitch = 12.5 cm
Made of 9 tapes, each 5 mm wide
Cable Ic(77.3K, self field) = 922.5 A





- Loss peaks at field penetration

M similar to other cables, shape mod

	Film norm	Film norm	tape norm
	A/m	kA/m	kA/m
del M=	500000000	500000	10000

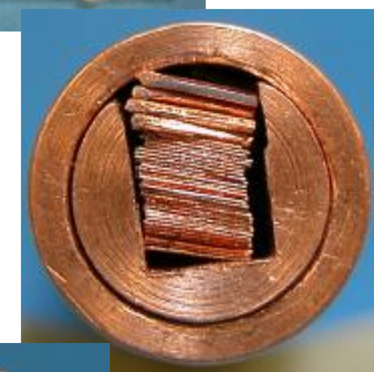
agnetic Materials

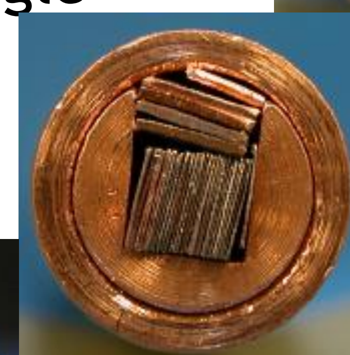
M-H, TSTC

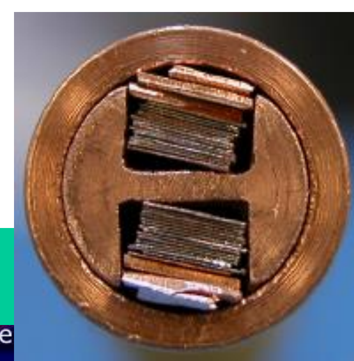
4 mm wide SuNAM Tape 150 μm SS
I_c = 200 A, 77 K, SF
Conductor Length = 200 mm, Twist Pitch = 200 mm

- TSTC-1:stacked tapes twisted between Cu strips, with retaining Cu and in plexiglass Tube

- TSTC-2: Tapes stacked Horizontally in a single helical groove in an OFHC Cu rod with sheath (05 " OD)
- TSTC-3: Tapes stacked vertically in a single helical groove in OFHC Cu with sheath
- TSTC-4: Tapes stacked in two vertical grooves in an OFHC Cu rod with a Cu sheath





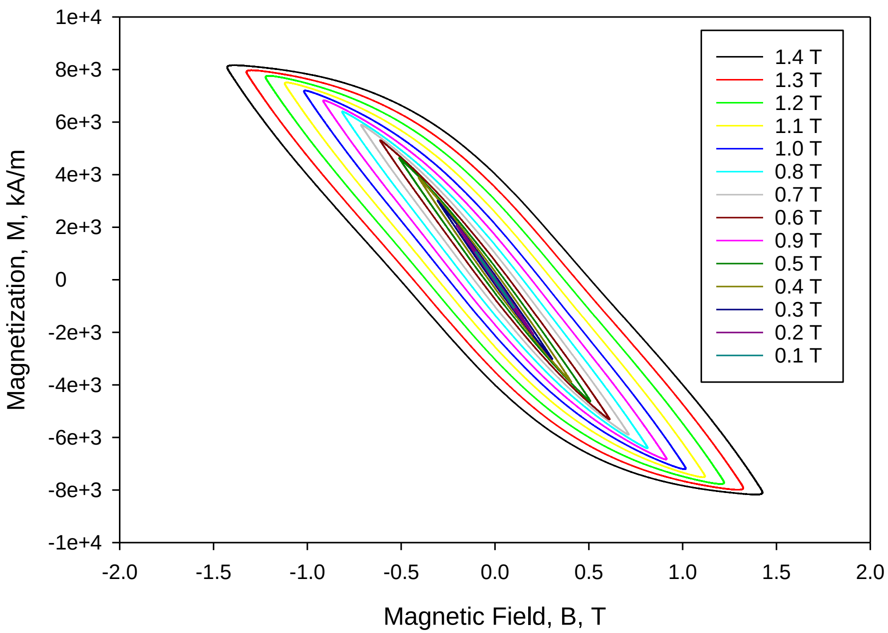


No soldering, packing only

M. Takayasu, MIT, PSFC

TWST-4 M-H and B_p

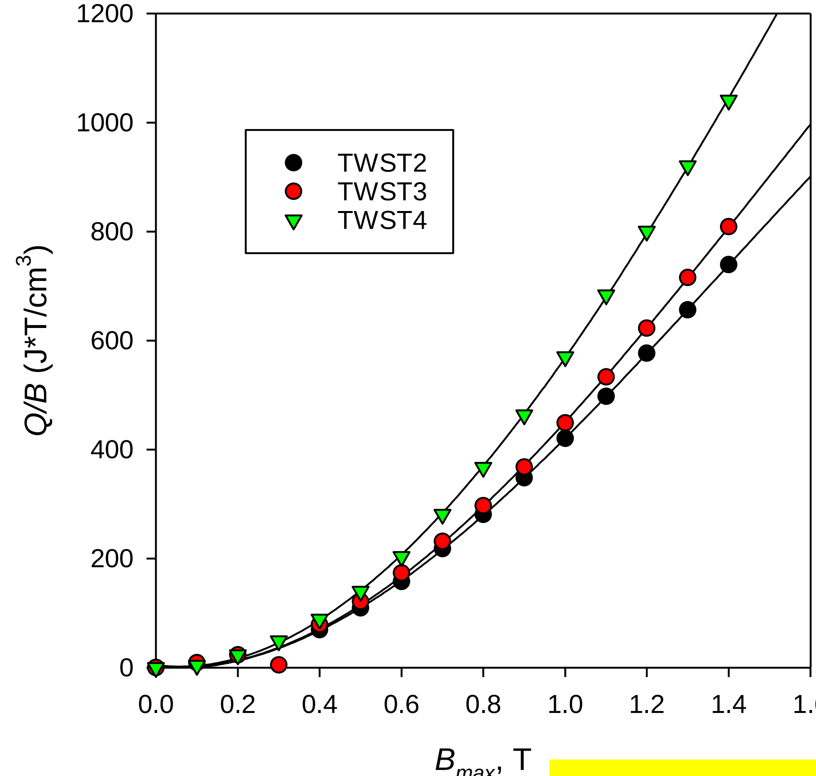
Normalized to tape volume, 4 K result



M_{max} *3.14/2 = 1.2 x 10^4 kA/m, in agreement with expected value below

	Film norm	Film norm	tape norm
	A/m	kA/m	kA/m
del M=	500000000	500000	10000

Above penetration, Q/B should be fixed, with y-intercept $w*I_c$



Below penetration, Q goes as B^3, above, as B

1.4 T does not penetrate the sample

Department of Materials Science and Engineering

Results

- $M \approx$ x $2M_{tape}$ for CORC experimentally (more than simple helical tape!)
- M similar to tape but shape mod Roebel
- $M \approx M_{tape}$ (maybe 2/3.14 M_{tape}) for TWST
- $M_{max} \approx$10000-20000 kA/m for $B_{\perp}$ tape, Roebel cable, and any orientation CORC and TWST
- B_p similar to individual tape for CORC, Roebel, and TWST
- Striping tapes in CORC reduces M and $B_{p\text{-}app}$

Discussion

- CORC cable's initial slope suggest flux exclusion from whole cable at low fields → an initial magnetization slope which is 3 x higher (this may be injection region)
- Striation of the CORC cables removes this effect, and flux exclusion volume drops below full cable volume between $B_{p\text{-}app}$ and $B_{p\text{-}true}$
- Flux exclusion for TWST and Roebel are like cable volume rather than tape, but here tape and cable volume similar

Cable	1 T Minj, kA/m
CORC	-12,000
CORC striated	-5000
Roebel	-20000
TWST	-8000

Strand type	NbTi[1]	Nb_3Sn[2]	Bi:2212[3]	YBCO	YBCO
Cable type	**Rutherford**	**Rutherford**	**Rutherford**	**TSTC**	**CORC™**
Cable packing factor, λ_c	0.88	0.855	0.87[4]	0.56	0.58
Strand filling factor, λ_s	0.385	0.455	0.26	0.01[5]	0.01[5]
Layer CCD, $J_{c,inj}$, kA/mm^2	20.4	-	1.75	88[6]	88[6]
Eng. CCD[7], $J_{e,inj}$, kA/mm^2	7.85	-	0.455	0.88	0.88
Fil. (strand) size, d_{eff}, μm	7	61	278	4000[8]	4000[10]
$J_{cable,inj}$ kA/mm^2	6.91	13.0	0.396	0.493	0.510
$J_{cable,coll}$, kA/mm^2	0.704	0.855	0.348	0.244	0.232
$B_{b,coll}$, T	8	15	20	20	20
b_3, units [11]	3	41	19	330[12]	330[12]
b_{3*}, units [13]			37	99	99

77 K Ic	4 K Ic	Jc (A/m2)	M
200	2000	2.5 x 10^11	10000
80	800	10^11	4000
70	700	0.88 x 10^11	3250

- So, for the tape, while the *M* goes up, it goes up as I_c, so less cables, and field errors are same
- But, cable vs tape differences matter – all within factor of two

Next Steps

- Further Measurements of the most recent cables, expanded up to +- 3 T at 4 K
- LBNL-OSU collaboration (X. Wang) with YBCO data detailed field error estimations canted cos and other magnets
- Explore M modification with current injection
- Consider more closely effects of creep on error fields
- Loss is of interest?

Magnetization – but loss?

- For the LHC NbTi dipoles ramping at about 7 mT/s AC loss is only a small contributor to cryogenic load
- Could be larger for YBCO cables.
- For a YBCO cable carrying a current of 10 kA at 20 T the loss at 7 mT/s is estimated to be 200 mW/m
- For an HTS insert of, say, 70 turns the winding dissipation would be 14 W/m -- more than double the LHC ring's 4.5 K/1.8 K refrigeration capacity
- This is a handle-able problem, but not of no interest

Measured CORC cable

10 kA cable			
T/s	t, sec		f
0.007	2285.7143	9142.857	0.000109
Q, J/m3	A m2	Q/m	mW/m
10000000	0.0000785	785	0.085859

So, 1/3 of simple estimate, but still substantial