THE OHIO STATE UNIVERSITY

Magnetization, Decay, and Influence on Error Fields in HTS accelerator magnets --

Center for Superconducting & Magnetic Materials (CSMM), The Ohio State University, Columbus, OH, USA

M. D. Sumption, C. Myers, M. Majoros, E. W. Collings

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D. van der Laan

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W. Goldacker

KIT Karlsruhe Institute of Technology

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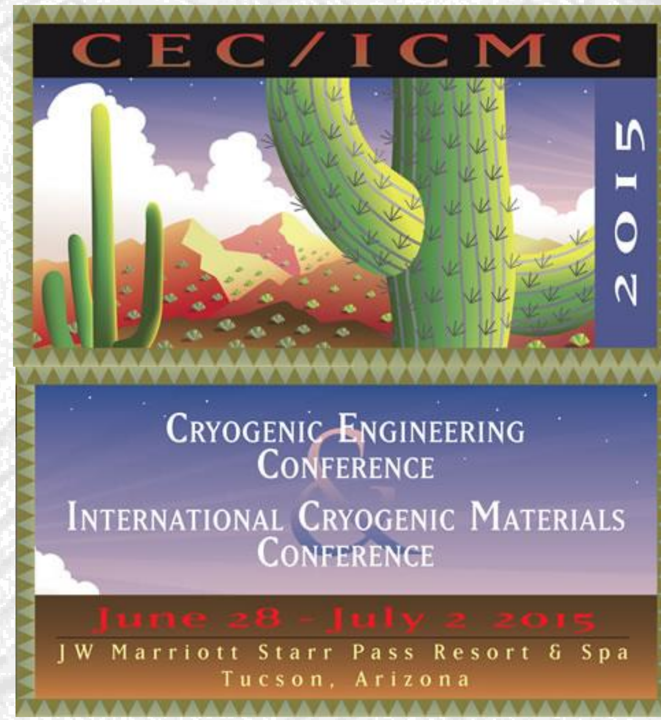


Department of Materials Science and Engineering

Motivation – error fields and drift

- While near-term (luminosity) LHC upgrades will require only NbTi and/or Nb_3Sn, the subsequent ***energy upgrades*** of the LHC are expected to require ***HTS/LTS hybrids***
- In addition, a high energy future circular collider ***may require YBCO or Bi:2212*** (and Nb_3Sn)
- The fact that strand and cable magnetization lead to field errors is well known, tools for predicting likely error components in a more global way is needed.
- This includes YBCO, Bi:2212, and ongoing Nb_3Sn assessment
- Below we will start with NbTi dipole magnet characteristics, and explore the relative magnetic properties of ***Nb_3Sn, YBCO, and Bi:2212***
- To key collider issues will be, what is the ***size of b3*** (the sextupole error field), and what might the use of HTS do to ***drift in b3***

Field Errors at collision and injection

In accelerator operation, there is

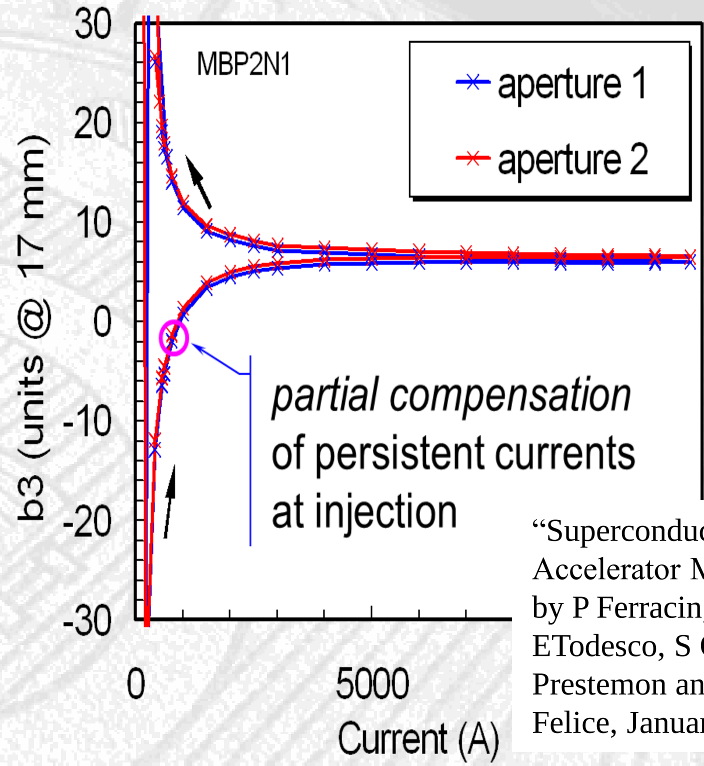
(1) ***a low field injection phase***, where the dipole magnets operate for some ***20 minutes or more at a nominal 1 T*** injection "porch"

(2) An energy ramp, coast (beam collision)

(3) An energy dump, where the magnets are then ***cycled back to near zero, followed by a rise to the beam injection*** field to repeat the cycle

Any strand magnetization leads to deviations from the pure dipole field which tend to defocus the beam.

Such errors are described in terms of the high order multipoles of the field, ***a good measure is the sextupole component, b3***



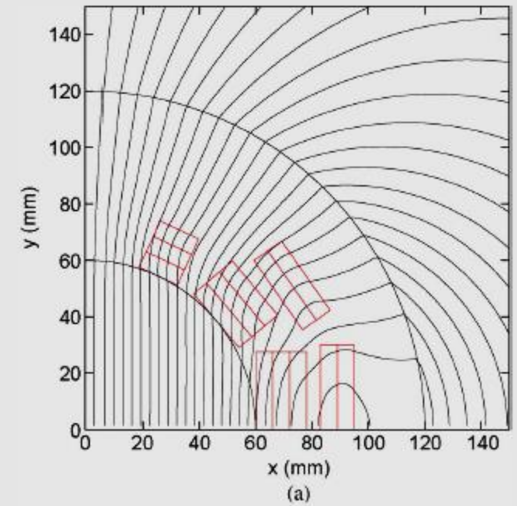
"Superconducting Accelerator Magnets" by P Ferracin, ETodesco, S O. Prestemon and H Felice, January 2012

*The above process leads to a partial compensation of the error fields at injection, a (hopefully small) negative value usually dominated by the **sextupole component, b3**.*

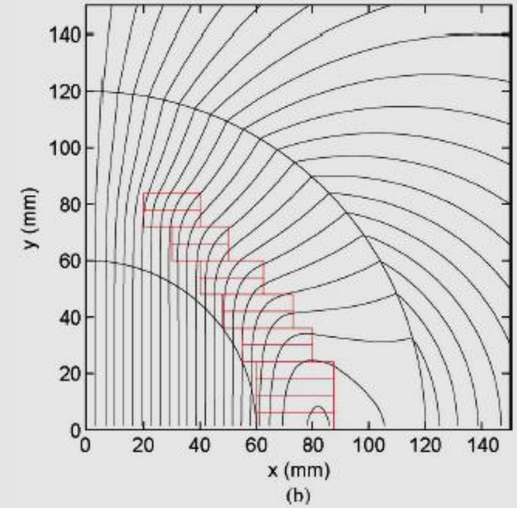
Magnetization Error Criteria

Different "stackings" of HTS can change error contributions

- The magnet designers criteria for ***magnet quality is terms of the multipole error fields***, a good error to key in on for dipoles in the sextupole component, b_3.
- b_3 should be about "1 unit" or less
- 1 unit is 0.01% of the main field
- The correlation between strand magnetization and error fields is ***magnet design dependent***
- cos theta dipoles and block magnets of different designs magnet cross section will have different magnetization to error field correlations



(a)



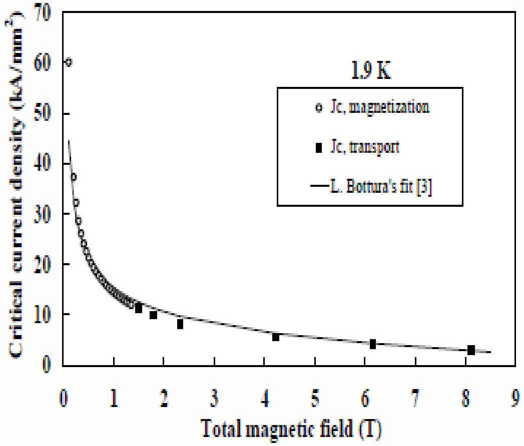
(b)

Amemiya, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 20, NO. 3, JUNE 2010

NbTi Mag as a compare to

S. Le Naour, L. Oberli, R. Wolf
CERN, Geneva, Switzerland

IEEE Trans. 9 1999



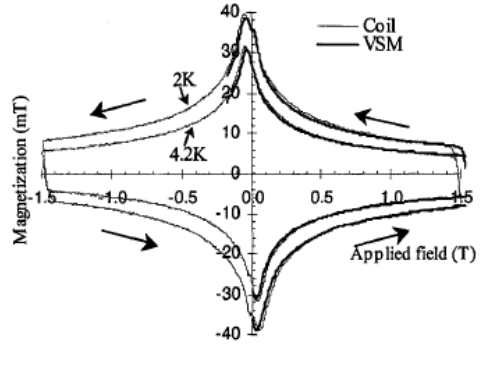
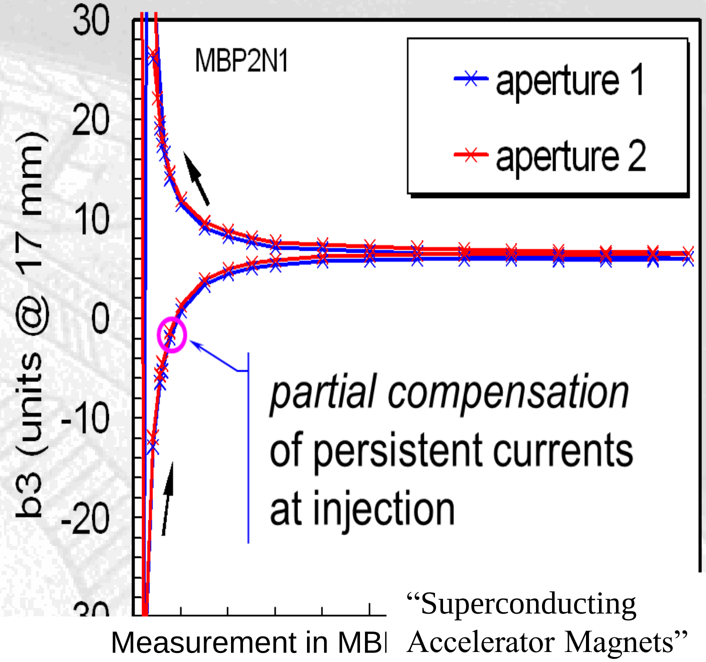
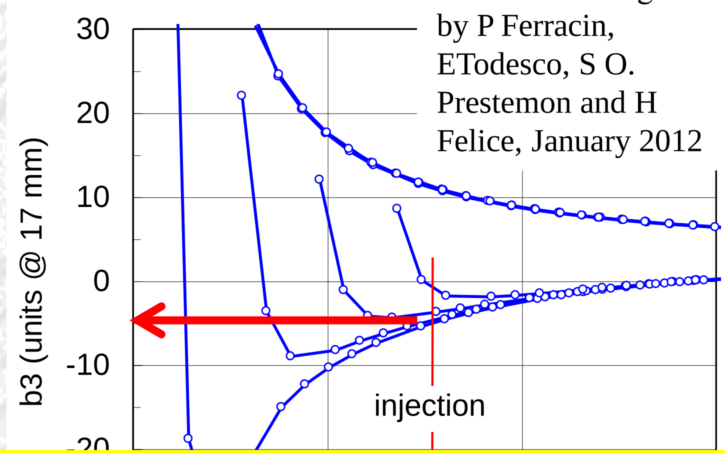


Fig. 5. Comparison of a magnetization measurement made on reference strand 01D95276AE by the two setups.





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

Critical Current Density in Superconducting Nb-Ti Strands in the 100 mT to 11 T Applied Field Range

LHC Project Report 885

T. Boutboul, S. Le Naour, D. Leroy, L. Oberli and V. Previtali

0.5 T, 15 mT => 12000 A/m

From d_f and J_c, at 0.54, the values $M_{coup,LHC}$ = 2.64 kA/m and $\boxed{M_{sh,inj,LHC} = 10.3\text{ kA/m}}$, may be regarded as bench-marks against which the corresponding properties of Nb_3Sn cables can be compared.

b_3 is about 3, and M about 10 kA/m – but this will depend on magnet design. Is there a way to separate or partially separate magnet design and strand influence?

Simple Model of b_3 ratio estimation---Partial separation of strand and magnet variables

Any given dipole magnet will have a set of multipoles that depend on conductor magnetization in a design-specific way. This is in particular true for b_3, thus

$$b_{3_i} = \chi_i M_{sh,i} V_i$$

Here and below, the error field b_3 is given in units, and χ, ψ are for a specific injection field

Here $M_{sh,i}$ is the magnetization of the i^th part of the winding, located at position x,y,z, V_i is the volume of a small region surrounding this point, $b_{3,i}$ is the contribution of this region to the total b_3, and χ_i is the coupling between these two. Then,

$$\mathrm{b}_3 = \sum_{i=1}^{n} b_{3,i} = \sum_{i=1}^{n} \chi_i \mathrm{M}_{sh,i} V_i = \int \chi(x,y,z) M_{sh}(x,y,z)\,dxdydz$$

Where χ and M_{sh} are now continuous that depend on position within the winding. This can then be written

$$b_3 = M_{sh}(o) \int \chi(x,y,z) \frac{M_{sh}(x,y,z)}{M_{sh}(o)}\,dxdydz$$

where

$$b_3 = M_{sh}(0)\psi \qquad and \qquad \psi = \int \chi(x,y,z) \frac{M_{sh}(x,y,z)}{M_{sh}(0)}\,dxdydz$$

For LHC $\psi = 3 \times 10^{-4}$ units*m/A

Angular Anisotropy, field dependence, history

$M_{sh}(0)$ is the magnetization at injection, a field alignment for maximum magnetization, and standard field history . Then

$$M_{sh}(B)=M_{sh}(0)(J_c(B)/J_c(0))\eta(x,y,z)\beta(x,y,z) =$$
$$M_{sh}(0)\gamma(B\{x,y,z\},\theta\{x,y,z\})\eta(\theta\{x,y,z\})\beta(x,y,z,B_p\{\theta\})$$

here $\gamma=J_c(\mathrm{B})/J_c(0)$,

θ represents the orientation of the local segment of conductor with respect to a reference orientation

η ($0<\eta<1$) characterizes the fraction of the magnetization at a given angle relative to the position of maximum magnetization (purely geometric),

and β ($-1<\beta<1$) represents the influence of field history on M_{sh}, being = 1 for field sweep protocols where B is swept to B_0 -2B_p or greater before being brought up to B_0, *then*

$$\psi = \int \chi(x,y,z)\gamma(B\{x,y,z\}\vartheta\{x,y,z\})\eta(\theta\{x,y,z\})\beta(x,y,z,B_p\{\theta\})\, dxdydz$$

Weighted χ

We can also define

$$\langle\chi\rangle = \frac{1}{V_{mag}} \int \chi(x,y,z)\gamma(B\{x,y,z\},\theta\{x,y,z\})\eta(\theta\{x,y,z\})\beta(x,y,z,B_p\{\theta\})dV$$

where

$$b_3 = M_{sh}(0)\psi = M_{sh}(0)V_{mag}\langle\chi\rangle = m_{sh}(0)\langle\chi\rangle, \quad \text{and also} \quad \psi = \langle\chi\rangle V_{mag}$$

ψ is a constant (with units –units*m/A) connecting b_3 to a reference magnetization

$<\chi>$ is a related constant (units- units* $A^{-1}m^{-2}$) connecting b_3 to a reference moment

We will not attempt to calculate ψ or $<\chi>$ in detail, nevertheless, the former will have some utility for estimating b_3 from strand magnetizations, the latter is computational useful, as we will see below.

Equal Volume Replacement

Let us consider LHC-type dipoles in which the NbTi cable is replaced by equal volumes of Nb_3Sn, Bi:2212, and YBCO-wound cables, then

$$\frac{b_3'}{b_3} = \frac{\psi'}{\psi}\frac{M_{sh}'(0)}{M_{sh}(0)}$$

Where again

$$\psi = \int \chi(x,y,z)\gamma(B\{x,y,z\}\vartheta\{x,y,z\})\eta(\theta\{x,y,z\})\beta(x,y,z,B_p\{\theta\})\,dxdydz$$

Let the replacement conductor is isotropic (true for NbTi, Nb_3Sn, and Bi:2212 conductors, CORC, and TSTC.

In this case the θ dependencies drop out, and η =1.

Let us, for the sake of a direct comparison, set $\beta'(x,y,z) = \beta(x,y,z)$, i.e., we assume the same magnet ramp sequence will be used for the two magnets.

Equal Volume Replacement II

Then
$$\frac{b_3'}{b_3} = \frac{\psi'}{\psi}\frac{M_{sh}'(0)}{M_{sh}(0)} = \frac{M_{sh}'(0)}{M_{sh}(0)}\frac{\int \chi'(x,y,z)\gamma'(B\{x,y,z\})dV}{\int \chi(x,y,z)\gamma(B\{x,y,z\})\,dV}$$

The integral terms are then essentially the field dependence of J_c-weighted integrals of χ.

If we choose a linear field dependence for γ (referenced to B_0), then $\gamma=1+b[(B_0-B)/B_0]$, then

$$\frac{b_3'}{b_3} = \frac{\psi'}{\psi}\frac{M_{sh}'(0)}{M_{sh}(0)} = \frac{M_{sh}'(0)}{M_{sh}(0)}\left\{1+\frac{(b'-b)\int \chi'\frac{(B_0-B)}{B_0}dV}{\int \chi dV}\right\}$$

Where the second term is just the different in the linear coefficient in the Jc dependence of the two conductors multiplied by a factor which weights their contributions over the magnet.

This term will be small (< 1) and positive; if it is << 1, then we find the simple approximation that $b_{3'}/b_3 \cong M_{sh}'(0)/M_{sh}(0)$.

Magnetization and field error for "Equal volume replacement"

Strand type	NbTi(1)	Nb_3Sn(2)	Bi:2212(3)	YBCO	YBCO	YBCO
Cable type	**Rutherford**	**Rutherford**	**Rutherford**	**TSTC**	**Roebel**	**CORC™**
Cable packing factor, λ_c	0.88	0.855	0.87(4)	0.56	0.80	0.58
Strand filling factor, λ_s	0.385	0.455	0.26	0.01(5)	0.01(5)	0.01(5)
Layer CCD, J_c, kA/mm^2	20.4	-	1.75	88(6)	88(6)	88(6)
Eng. CCD(7), J_e, kA/mm^2	7.85	-	0.455	0.88	0.88	0.88
Fil. (strand) size, d_s, µm	7	61	278	4000(8)	2000(9)	4000(10)
$M_{sh,inj,cable}$ (calc.)(11), kA/m	10.3		23.4	418	298	433
$M_{sh,inj,strand}$ (meas.) , kA/m	10.7	198	15-37	-	-	-
$M_{sh,inj,cable}$ (meas.)(12), kA/m	9.4	169	13-32	612	383	346
b_3, units	3	50	4-10	184	115	104

Target Field Replacement

- Under the equal volume replacement, a lower Jc strand lead to a lower magnetization – but also a lower bore field
- Now, however, let us imagine a scenario where we want to replace a magnet made from NbTi strand with one made from a different stand type – but the target field is equal to or higher than the NbTi magnet, then

$$b_3 = M_{sh}(0)\langle\chi\rangle V_{mag}, \qquad \frac{b_3{}'}{b_3} = \frac{M_{sh}{}'(0)\langle\chi\rangle' V_{mag}{}'}{m M_{sh}(0)\langle\chi\rangle V_{mag}}$$

and

$$\langle\chi\rangle = \frac{1}{V_{mag}} \int \chi(x,y,z)\gamma(B\{x,y,z\},\theta\{x,y,z\})\eta(\theta\{x,y,z\})\beta(x,y,z,B_p\{\theta\})dV$$

Target Field Result

An isotropic Jc with a linear B dependence leads to

$$\frac{b_3{}'}{b_3} = \frac{M_{sh}{}'(0)\langle\chi\rangle' V'_{mag}}{M_{sh}(0)\langle\chi\rangle V_{mag}} = \frac{M_{sh}{}'(0)V'_{mag}}{M_{sh}(0)V_{mag}}\left[\frac{\int \chi'(x,y,z)dV}{\int \chi(x,y,z)dV} + \right.$$

An isotropic Jc with an exponential B dependence leads to

$$\frac{b_3{}'}{b_3} = \frac{M_{sh}{}'(0)V'_{mag}}{M_{sh}(0)V_{mag}}\left[\frac{\int \chi'(x,y,z)exp\left[\frac{(B_0 - B)}{B^*}\right]dV}{\int \chi(x,y,z)exp\left[\frac{(B_0 - B)}{B^{*\prime}}\right]dV}\right]$$

If we make no simplifying assumptions

$$\frac{b_3{}'}{b_3} = \frac{M_{sh}{}'(0)V'_{mag}}{M_{sh}(0)V_{mag}}\left[\frac{\int \chi'(x,y,z)\gamma'(B\{x,y,z\},\theta\{x,y,z\})\eta'(\theta\{x,y,z\})\beta'(x,y,z,B_p\{\theta\})dV}{\int \chi(x,y,z)\gamma(B\{x,y,z\},\theta\{x,y,z\})\eta(\theta\{x,y,z\})\beta(x,y,z,B_p\{\theta\})dV}\right]$$

Or $$\frac{b_3{}'}{b_3} = \frac{M_{sh}{}'(0)V'_{mag}}{M_{sh}(0)V_{mag}}\Gamma$$

Result for field target

However, $V_{mag} = L_{mag}A_{mag}$ where L_{mag} is the length of the magnet and A_{mag} is the cross-sectional area of the magnet, giving us, upon substitution (assuming that magnet length remains constant),

$$\frac{b_3'}{b_3} = \frac{J_c'(0)\lambda_c'\lambda_s'd_{eff}'A'_{mag}}{J_c(0)\lambda_c\lambda_s d_{eff}A_{mag}}\Gamma$$

The magnet load line is given by $B_{bore} = CI_{mag}$ and $B_{bore}' = C'I_{mag}'$, where C and C' are magnet constants, and I_{mag} is the current in the whole of the magnet cross section, such that $I_{mag} = N*I_{strand}$, and N is the number of strands in the magnet cross section. The C is $(1/N)$ times the magnet constant as defined with respect to I_{strand}. Then $I_{mag} = A_{mag}*J_{mag}$. Then

$$A_{mag} = \frac{B_{Bore,coll}/C}{\nu J_{c,coll,peak\ winding\ field}}$$

Which leads to

$$\frac{b_3'}{b_3} = \frac{J_c'(0)\lambda_c'\lambda_s'd_{eff}'B'_{bore,coll}C\nu J_{c,coll,peak}}{J_c(0)\lambda_c\lambda_s d_{eff}B_{bore,coll}C'\nu' J_{c,coll,peak}'}\Gamma$$

Magnetization and field error "Target Field Replacement"

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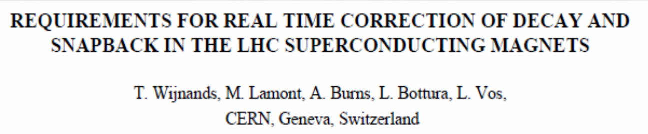
Cable packing factor, λ_c	0.88	0.855	0.87[4]	0.56	0.80	0.58
Strand filling factor, λ_s	0.385	0.455	0.26	0.01[5]	0.01[5]	0.01[5]
Layer CCD, J_{cinj}, kA/mm^2	20.4	-	1.75	88[6]	88[6]	88[6]
Eng. CCD[7], J_{einj}, kA/mm^2	7.85	-	0.455	0.88	0.88	0.88
Fil. (strand) size, d_s, μm	7	61	278	4000[8]	2000[9]	4000[10]
$J_{cable,inj}$ kA/mm^2	6.91	13.0	0.396	0.493	0.704	0.510
$J_{cable,Coll}$, kA/mm^2	0.704	0.855	0.348	0.244	0.320	0.232
B_{coll}, T	8	15	20	20	20	20
b_3, units	3	76	34	960	480	960

With C'/C = 1 and Γ=1

Some Clarifications

- HTSC magnets are presumably to be hybrids, using, say Nb_3Sn to reach 15 T, and HTS to get to 20T. **Also YBCO will be used in some mixed field orientation**
- The final effective "average" contribution could be a 75%/25% mix – pushing YBCO/Nb_3Sn hybrids to significantly lower mag –
- However, the HTS will be presumably closer to the beam.
- One final Note: While striating the YBCO will not influence Roebel cable Magnetization, it will reduce CORC and TSTC cable magnetization.
- From the above considerations, it seems that the striation target should be 100 filaments in a 4 mm wide strand

Drift on the injection Porch


REQUIREMENTS FOR REAL TIME CORRECTION OF DECAY AND SNAPBACK IN THE LHC SUPERCONDUCTING MAGNETS

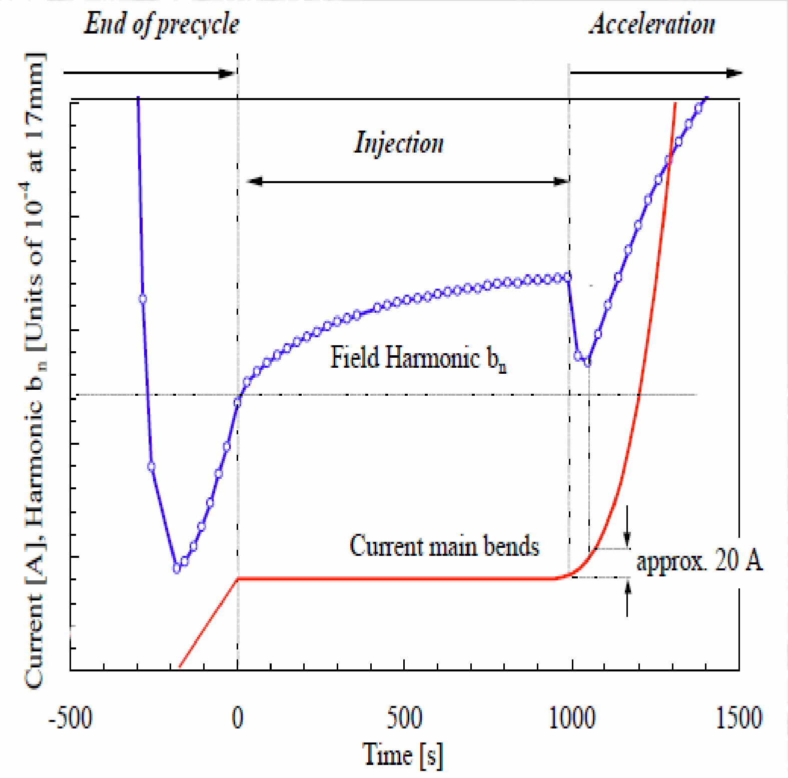
T. Wijnands, M. Lamont, A. Burns, L. Bottura, L. Vos,
CERN, Geneva, Switzerland

- Just as important as the absolute value of b_3 is any ***change with time*** during the injection porch

- It is possible to compensate for error fields with corrector coils, but the presence of ***drift*** makes this much more difficult

- At right is shown the drift of the error fields as a function of time from zero to 1000 seconds for LHC magnets, followed by a snap-back once the energy ramp begins

- The underlying mechanism for drift in NbTi magnets is the decay of coupling currents, (especially inhomogeneous and long length scale coupling currents) and their influence on the strand magnetization



Need to keep both b_3 and its drift below 1 unit

For NbTi and Nb_3Sn based magnets, this is possible

Important to control drift

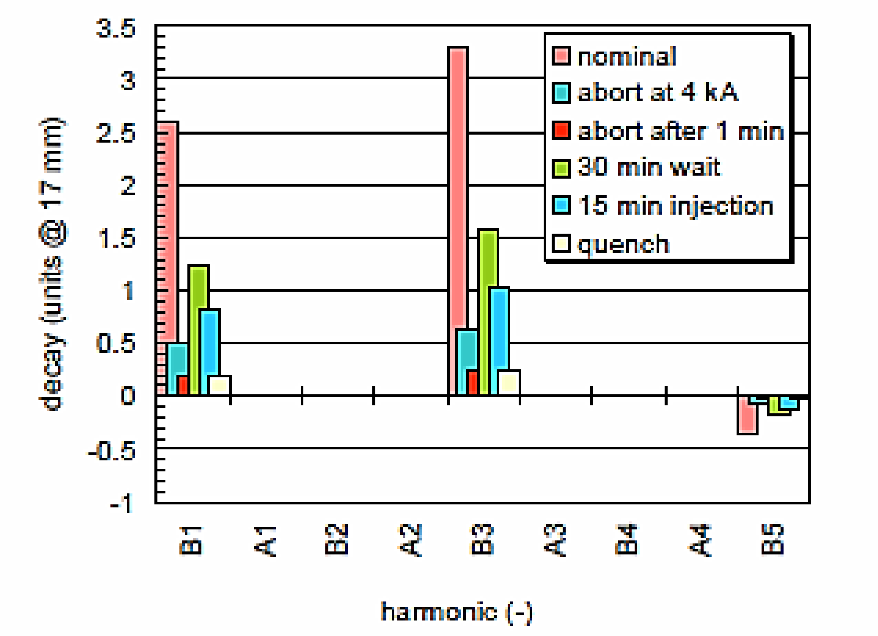


Figure 2: The magnitude of the decay of field errors in the main bends (in units of 10^{-4} of the main dipole field) for various operational scenarios.

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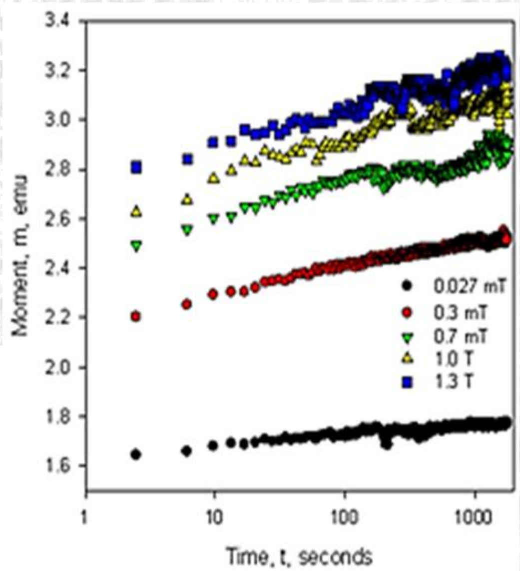
So, right now we are at several units of drift

Drift in LTS is due to influence of long range coupling current decay on strand magnetization

But HTS materials famously exhibit Giant Flux Creep (Y. Yeshurun and A. P. Malozemoff)

But, Creep goes like kT, so its not a problem at Low Temperatures, ***right?***



No – at right is data of PRB paper at 4 K

Even though creep reduced, still significant

Especially for precision field

Magnetization Creep and b3

Sample	B, T	orientation	$-M_0$, kA/m	$-M_{20min}$, kA/m	M_{20min}/M_0	ΔM, kA/m	$\%b_3$
Bi:2212	1 T	$\perp$	15	12	0.80	3.0	20
	12 T	$\perp$	2.7	1.5	0.58	1.1	42
YBCO							
	1 T	$\perp$	991	906	0.91	90	10
	1 T	45°	933	811	0.86	120	14
	12 T	$\perp$	280	187	0.67	93	33
	12 T	45°	229	200	0.87	29	13

If we use the Bi:2212 projection of b3 = 35 units, then a 20% change is 7 units

If we use the YBCO projection of b3 = 500-1000 units, then a 15% change is 75-150 units.
Downrated for insert, 20-40 units

Summary and Conclusions

- Projected Accelerator injection Magnetization contributions for YBCO, Bi:2212, and Nb_3Sn have been compared against NbTi directly
- D_{eff} is not the whole story
- A simple method for correcting for conductor J_c (at collision and injection), and the magnet target field leads to a more useful metric, assuming magnet design remains “constant”.
- Bi:2212 strands will cause lower magnetization errors than expected on a deff basis alone, because of the flatness of J_c vs B.
- YBCO contributions are highly dependent on the amount of field perpendicular to the tape, but a striation target was suggested : 100 filaments/4 mm width
- Potential contributions to drift on the injection porch from creep (as opposed to the standard LTS mechanism) in Bi:2212 and YBCO were considered
- 10-20% changes in magnetization over a 20 minute time window were seen at 4K, for an 18 stack Bi:2212 with OK d_{eff} and moderate magnetization, this leads to 1 unit or so – *maybe OK*
- For YBCO, tending to have higher Magnetization, 30-40 units was seen, would be diluted by hybrid implementation or parallel field orientation
- The above striation target, implemented in CORC cable, would make drift also OK for YBCO

J_c (B) curves of YBCO CCs

A. Xu, J. J. Jaroszynski, F. Kametani, Z. Chen, D. C. Larbalestier, Y. L. Viouchkov, Y. Chen, Y. Xie and V. Selvamanickam SUST, vol. 23, p. 014003, 2010

- Dropping from 77 K SF to 4.2 K SF increases J_c by x 10.
- Increasing from SF to 20 T decreases ⊥ by about 10
- Increasing from SF to 1 T, about 2 times less
- So, we expect
- $M_{inj} \approx 500$ kA/m
- $M_{20\ T} \approx 100$ kA/m
- This is expected for any field orientation, since cable is cylindrically symmetric