CONTROL OF STATIC AND DYNAMIC FIELD-ERROR (AC LOSS) IN COS-Θ DIPOLES

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INTRODUCTION

Copper-wound, DC-excited, cos-θ dipoles can, in principal, be designed to deliver a very uniform transverse bore field (i.e. with small or negligible harmonic or multipolar field distortion).

But if the Cu is replaced by (a) **superconducting strand** that is (b) present in the form of **Rutherford cable** the extra magnetizations present within the windings cause distortions of the otherwise uniform bore field.

The magnetizations take two forms:

(a) static or persistent-current magnetization of the superconducting filaments.

(b) dynamic magnetizations due to dB/dt-generated coupling currents between the strands of the cable, currents that also give rise to AC loss.

We discuss these effects and go on to show how they can be compensated and suppressed.

THE STATIC MAGNETIZATION

Referred to here is the intrinsic diamagnetism of the superconductors shielding critical state. The strand magnetization, M_{str}, is proportional to the filament's critical current density, J_c, and effective diameter, d_{eff}. It is negligible at the magnet's maximum operating field. But as the operating field decreases, M_{str} increases and hence becomes disproportionately large at injection field.

Over the years M_{sat} has been minimized by reducing d_{eff}. As for the residue, several active and passive compensation schemes (involving the ferromagnetic elements Fe or Ni) have been devised.

DYNAMIC MAGNETIZATION

During field ramping circulating B-dot-generating coupling currents are another source of field error. As "AC loss" they contribute to the system's cryogenic loading, and by augmenting the transport current they reduce the stability of the magnet.

Both the "normal interstrand coupling currents" and widely-circulating, long-time-constant "Boundary Induced Coupling Currents" can be suppressed by increasing the interstrand contact resistance, an upper limit to which is imposed by stability (current-sharing) constraints.

The desired interstrand contact resistance is achieved by applying strand coatings or the introduction of an "insulating" core.

STATIC MAGNETIZATION

The half-height of the filament magnetization loop, or the magnetization in the shielding critical state, say, is

$$M_{str} = (\frac{0.2}{3p})\, J_c\, d_{eff}$$

With the SSC strand it was found that with decreasing d, M_{str} minimized at a d = 6 μm. Proximity effect coupling then took over to produce d_{eff}s > 6 μm until the introduction of the dilute **Cu**-Mn matrix.

As an interesting aside, the Mn idea would not have surfaced had the filaments not been clad in a protective barrier film of Nb. Niobium helps to launch NbTi's superelectrons into the surrounding Cu matrix.

As a second interesting aside, the apparent PE-suppressing action of Si additions to the Cu matrix is probably due to the absence of the Nb barrier in the NbTi/Cu-Si test strands.
The fine-filament NbTi/Cu strands still needed to be magnetically compensated, for which purpose various schemes have been suggested including:

(i) The placing of small pieces of ferromagnetic material within the bore of the magnet or in one of the coil wedges.
(ii) The inclusion of ferromagnetic material, in particular Ni, within the strand itself.

MAGNETIC COMPENSATION

The goal off magnetic compensation is to cancel out the shielding (i.e. field-increasing) magnetic moment resident in the superconducting windings. On a per-unit-length basis this is achieved by setting:

$$s_s A_{FM} = M_{SC} A_{SC}$$

where σ_s is the saturation magnetization of the ferromagnetic element and M_{SC} is the magnetization of the SC. The As represent cross sectional areas.

Taking for pure Ni a σ_s of 507-521 emu/cm^3 we found that SSC-type NbTi/Cu strand could be compensated at fields of 0.5-0.7 T by:

(1) applying an electroplated Ni coating of thickness 2.4-1.9 μm, or

(2) replacing some of the NbTi filaments with Ni ones, NbTi/Ni ratios 47/1-57/1.

Calculations of sextupole ratio at R = 1 cm by M. Green predicted substantial reductions in both cases.

MAGNETIZATIONS OF NbTi AND Nb_3Sn

For NbTi we might expect a J_c of about 8,500 A/mm^2 at 0.5 T, yielding for d = 6 μm a $J_c d$ product of 5.10 in the units "A/mm^{2}cm".

For a Nb_3Sn strand we find a non-Cu J_c by taking some recently published $J_c(B)$ data, scaling it to 2200 A/mm^2 at 12 T and using a Kramer plot to extrapolate to 0.5 T. The result was 46,300 A/mm^2. Taking a d_{eff} of 20 μm we obtain a $J_c d_{eff}$ product in the above units of 93.

Based on a $J_c d_{eff}$ 18X larger than that of NbTi, the magnetization of Nb_3Sn, and its effect on injection field quality, becomes a serious problem. Even so, ferromagnetic compensation of the Rutherford cable through the insertion of a Ni ribbon may be worth serious consideration. For compensation we require

$$s_{Ni} A_{Ni} = \left(\frac{0.2}{3p}\right) J_c d_{eff} \, (f_c \, l \, w t)$$

where

A_{Ni} is the c/s area of the Ni ribbon
f_c is the packing factor of the standard cable
w and t are the width and thickness of the original cable
λ is the nonCu/(Cu+nonCu) ratio for the strand

STRIP THICKNESS

Picture a cable of dimensions 1.5 cm x 0.2 cm wound with the above Nb_3Sn strand; assume nonCu/(Cu+nonCu) = 0.5, and a packing factor of 90%. Then the thickness, t_{Ni} cm, of a 1.3-cm wide strip of Ni (assume σ_s = 510 emu/cm^3) that would provide magnetic compensation at 0.5 T is given by

$$510\,x\,(1.3\,x\,t) = 0.9\,x\,0.5\,x\,(1.5\,x\,0.2)\left(\frac{0.2}{3p}\right) J_c\, d_{eff}$$

which yields a t_{Ni} of 0.400 mm (i.e. "**15.7 mils**").

DEPLOYMENT AND PROPERTIES OF THE STRIP

At half the thickness of a typical strand, the strip is fairly thick. It may be preferable to employ three strips each of thickness **5** mils., sandwiching the cable between two of them and employing the other as a core.

Stabrite cables with stainless steel cores of thicknesses **0.5**, **1**, and **2** mils have already been successfully produced.

Such cores increase the effective interstrand contact resistance and by so doing suppress dynamic field error.

USE OF IRON INSTEAD OF NICKEL

With an M_s of 1745 emu/cm^3 compared to Ni's 510 emu/cm^3 the core thickness could be reduced by a factor 0.29 down to a value of 0.117 mm or 5 mils.

Such a core would not be unreasonable from the standpoints of fabrication and space utilization.

However, demagnetization considerations would require the field to be directed **parallel** to the surface of the cable rather than normal to it.

SUPPRESSION OF DYNAMIC MAGNETIZATION -- CORE-TYPE CABLES

During excitation of the magnet the induced interstrand coupling currents (ICRs) cause both energy losses and distortions of the field at the beam line. They are moderated by the magnitude of the interstrand contact resistance (ICR). There are both "normal" ICRs that can be envisioned as looping around a half pitch of the cable, and "supercurrents" (Schmidt) otherwise known as Boundary Induced Coupling Currents (BICCs, Verweij) that can flow over a whole cable length and induce field errors that vary with the period of the twist pitch. The latter are caused by a dB/dt or an ICR that varies sharply with distance along the cable (hence the term "boundary").

Coupling currents are suppressed by increasing the crossover and side-by-side ICRs -- R_c and R_a, respectively. For a standard uncored LHC-type cable, it is generally agreed that R_c should be not less than 15±5 $\mu\Omega$ and R_a not less than 0.2 $\mu\Omega$.

In the case of a cored cable, we have replaced R_c by a numerically equivalent R_{eff}.

R_c (or R_{eff}) is upper limited by a need to preserve interstrand current sharing and hence cable stability.

CHANGING THE ICR

Over the years various groups have modified ICR by:

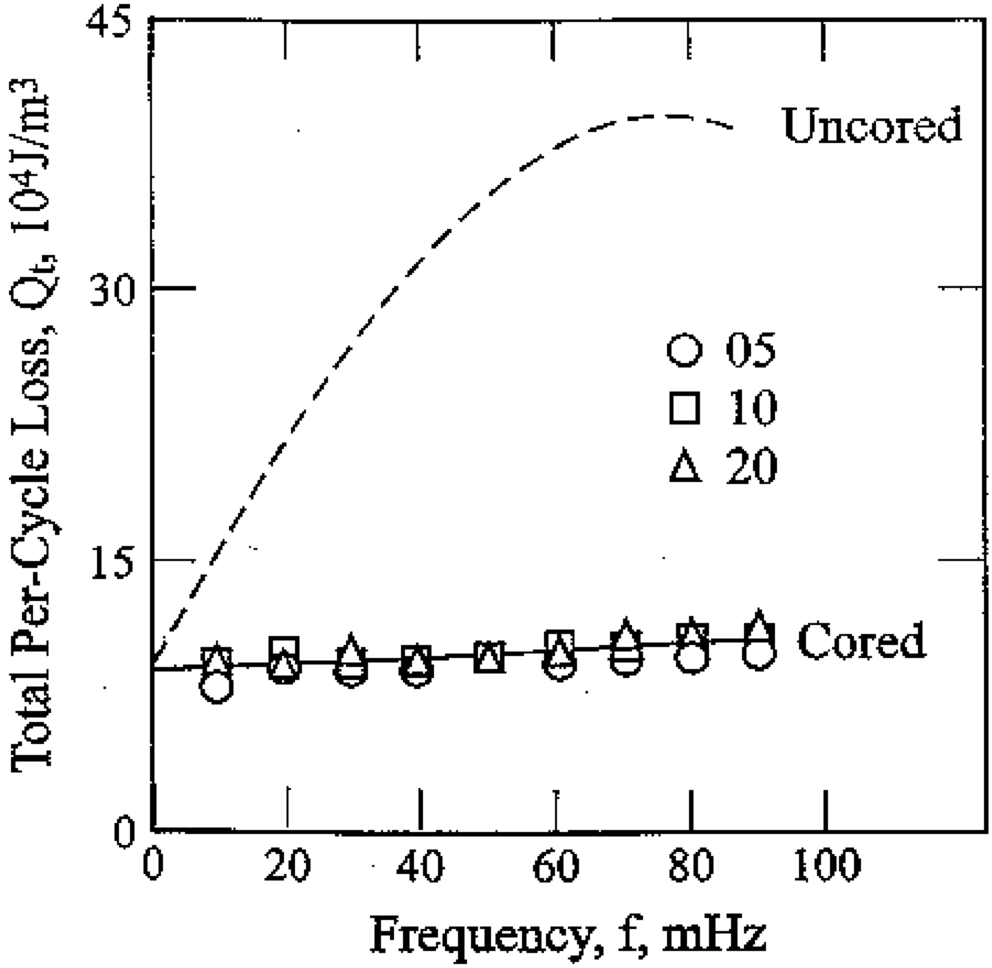
(1) applying metallic or insulating coatings to the individual strands of the cable.
(2) inserting a metallic or insulating ribbon between the two layers of the cable

We ourselves have applied almost a dozen coatings and have measured AC loss in cables with cores of titanium, kapton, stainless steel, and nichrome-80. The latter was used as a core for HTSC-2212/Ag cables, and we have settled on AISI 316 stainless steel ribbon as a core for cables wound with:

bare NbTi/Cu
stabrite-coated NbTi/Cu
Cu-stabilized Nb_3Al
Nb_3Sn.

The core can increase R_c by two orders of magnitude.

For Nb_3Sn cables the effect of a core on AC loss is illustrated by the following pair of curves:



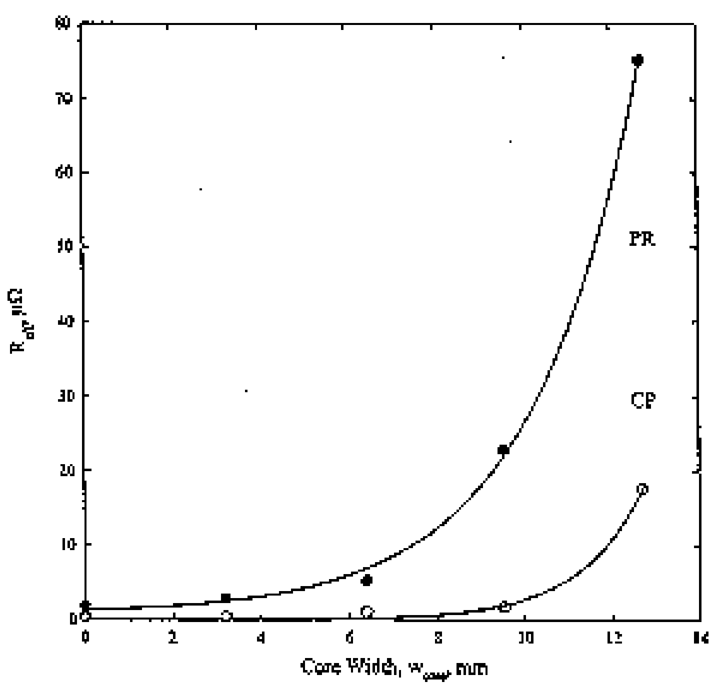
AC loss in uncored and cored Rutherford cables wound with Nb_3Sn strand and heat treated under uniaxial compactions of 5, 10, and 20 MPa

CONTROL OF ICR AND STABILITY

The ICR of a fully cored cable will vary with processing conditions -- heat treatment temperature and level of uniaxial pressure and its application cycle. For example:

Cable Type	HT Temp, deg.C	$R_{eff,LHC}$, $\mu\Omega$
(1) stabrite NbTi	170	75
(2) Nb_3Sn	660	36
(3) Nb_3Al	750	5

With cables (1) and (2) the R_{eff}s were too high to ensure stability; however we have shown that they can easily be reduced (fine-tuned, in fact) by reducing the width of the core.



CONCLUDING DISCUSSION

I MAGNETIZATION

High-J_c Nb_3Sn strands will have correspondingly higher J_cs at injection field. Assuming a $J_{c,4K,12T}$ of 2200 A/mm^2 and a Kim $J_c(B)$ model, the J_c at 0.5 T is expected to be a factor of 22 higher, or 48.4 kA/mm^2

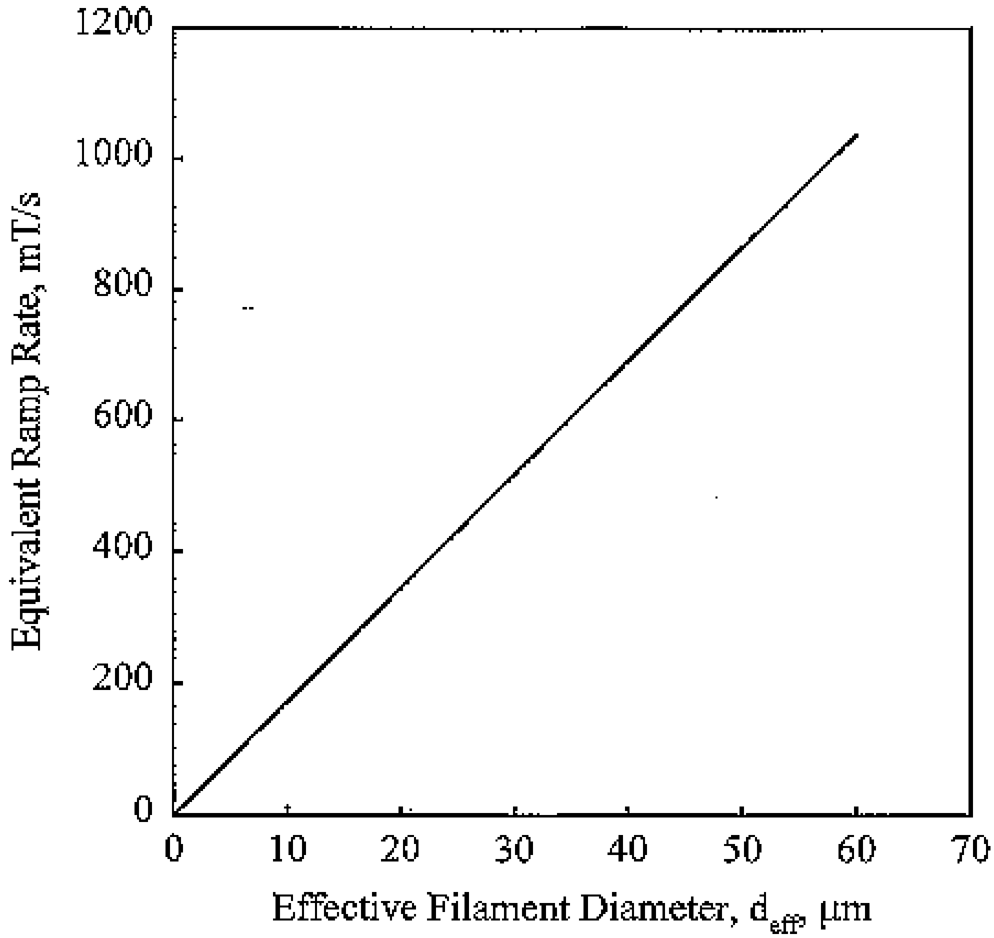
Associated with this is critical-state magnetization proportional to J_c x d_{eff}. This magnetization has two consequences that have to be borne in mind during the development of strands with higher and higher J_c.

(1) Field Error

There is the magnetization itself which contributes multipolar field distortion of the dipole magnet. Already at 2200 A/mm^2 (12 T) and d_{eff} = 20 μm the calculated magnetization, viz. $\Delta M = 3.93 \times 10^2$ emu/cm^3, is equivalent to that contributed by 346 mT/s-generated coupling currents.

The question of compensation becomes very important. For passive ferromagnetic compensation the volume of added Ni would need to be 20% of the strand volume.

Line of equal dynamic and static 0.5 tesla magnetizations, the latter calculated on the basis of a 12 tesla J_c of 2200 A/mm^2



Influence of effective filament diameter on a Sytnikov-calculated LHC-type cable equivalent ramp rate

(2) Flux-Jump Instability

The strand tends to become adiabatically flux-jump unstable. It has been shown, in terms of the full hysteresis-loop height, ΔM, that the flux-jump threshold for adiabatic flux-jump instability can be expressed in the form

$$\Delta M < \left(\frac{0.2\,T_c}{p}\right)\sqrt{\left[\frac{10^9}{3p}\,b_{SC}\right]}\,.T(1-t^2)^{-3/2}$$

where $t = T/T_c$ and the heat capacity of the SC is represented by $\beta_c T^3$.

At $\Delta M = 2.67 \times 10^2$ emu/cm^3 this is already smaller than the above-mentioned loop height of 3.93×10^2 emu/cm^3.

Clearly some extra dynamic or cryostabilization is playing a role, nevertheless the strand must be approaching its flux-jump stability limit.

The Significance of d_{eff}

As indicated above, the controlling low-field parameter is the **MAGNETIZATION.**

d_{eff} is just a secondary parameter associated with magnetization; furthermore it cannot be derived at low fields where J_c is immeasurably large in most laboratories. Nevertheless its high-field-measured value is still a useful number from a processing standpoint, since it indicates very clearly the extent to which interfilament bridging has taken place.

II COUPLING CURRENTS IN CABLES

To suppress coupling in Nb_3Sn Rutherford cable a core is needed.

In case the full width core produces too much R_{eff} a fine tuning can be achieved by varying the width of the core. This has already been demonstrated with stabrite cables.

By selecting Ni for the core partial magnetic compensation can be achieved.

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