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OF THE LARGE VARIETY OF IMPREGNATED CORRECTOR MAGNETS
FOR THE LHC**

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Abstract

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ABSTRACT

The Large Hadron Collider (LHC) will be equipped with about 5000 superconducting corrector magnets of 10 different types, ranging from dipoles through quadrupoles, sextupoles and octupoles to decapoles and dodecapoles. Four wires are used with 2 copper/superconductor ratios. Magnet lengths range from 0.15 m to 1.4 m. However, the magnets are all epoxy-impregnated and wound with enameled monolithic wires. The paper highlights the features that are common in the training of all these different magnets and uses that to give some clues for the possible origin of the training.

INTRODUCTION

Six firms are producing the corrector magnets for the LHC, 4 in Europe and 2 in India. The manufacturers also train each magnet at 4.2 K to avoid that a single training magnet in the LHC would stop the operation of a whole family of magnets connected in series. The magnets have two features in common [1]: the coils are wound from enameled superconducting wires and impregnated with epoxy, and the iron laminations directly touch the coil through an insulation layer and are of “Scissor” type [2] capable of transferring the pre-stress from the external shrinking cylinders to the internal coil assembly. However, there are many important differences between the magnets (TABLE 1) such that we are comparing very different magnets, built by different manufacturers.

The results of the training tests at the manufacturers are stored in electronic documents called Travellers. This treasure of information has been used here to investigate the training phenomena. TABLE 2 gives some global results of the 8 types of analyzed magnets (note that magnets MCS-1 and MCS-2 are identical but built by different manufacturers). About one third of the magnets do not quench below the plateau current. The other two thirds show training quenches, often in quite irregular steps. It was the challenge to try and find some system in the behavior of magnets of the same type and even of different types with the ultimate aim to identify a common origin of training.

TABLE 1. Overview of corrector magnet types subject of this study

		MCB	MQT	MS	MCS-1	MCS-2	MO	MCO-1	MCD-1
Type		Dipole	Quadrupole	Sextupole	Sextupole	Sextupole	Octupole	Octupole	Decapole
Quantity		752	384	752	1232	1232	336	616	616
Coil ID	mm	28.2	28.2	28.2	29.2	29.2	28.2	30.0	32.2
Coil OD	mm	39.7	35.7	38.2	31.7	31.7	30.7	30.8	34.7
Wire section (metal)	mm ²	Φ 0.375	0.61x1.13	0.61x1.13	0.61x1.13	0.61x1.13	0.61x1.13	0.32x0.6	0.61x1.13
Cu/Supercond. Ratio		4.0	1.6	1.6	1.6	1.6	1.6	4.0	1.6
PVA enamel layer	μ	30	60	60	60	60	60	30	60
No turns/magnet		3450	480	672	156	156	168	172	200
Epoxy type*)		C and D	A and B	C and D	B	B	B	B	B
Central post material		copper	G-11	copper	G-11	G-11	G-11	G-11	G-11
Magn. Length	mm	647	320	369	110	110	320	66	66
Self inductance	H	7	0.031	0.036	0.0004	0.0004	0.0016	0.0004	0.0004
Nom. Current 1.9 K	A	55	550	550	550	550	550	100	550
Magn. Flux density	T	3.1	4.1	4.1	1.9	1.9	2.4	2.0	2.4
Crit. Current@4.2 K	A	71	670	679	950	950	915	195	915
Crit. Current@1.9 K	A	99	945	925	1300	1300	1310	297	1250
Manufacturer id.		1	2	1	3	4	4	5	5

*) A = CY1300/DY026, B = GY285/D400, C = MY753/HY956-EN, D = MY740/HY906/DY073-1

THE SHAPE OF THE TRAINING CURVES

Already in the period of prototyping [3], it was noticed that the training curve could often be matched with a power function of the type

$$I_n = I_1 * n^p \quad (1)$$

where “I” is the quench current, I_1 the current of the first quench, “n” the number of the quench in a sequence, and the exponent “p” a constant which seemed to be about 0.2. Such a power curve forms a natural choice because re-written as

$$n = [I_n/I_1]^{1/p} \quad (2)$$

it implies that $I_n^{1/p}$ advances with a fixed amount at each next quench “n”. Now $I_n^{1/p}$ has a physical meaning; I^2 for instance is proportional to the magnetic forces ($I*B$) and to the

TABLE 2. Some global results

		MCB	MQT	MS	MCS-1	MCS-2	MO	MCO-1	MCD-1
Type		Dip.	Quadr.	Sext.	Sext.	Sext.	Oct.	Oct.	Dec.
Recorded magnets		32	15	25	364	570	67	74	79
Plateau current I_p	A	74	680	660	1090	1040	990	230	1010
Magnets without training ¹	%	0	0	20	48	25	25	47	36
Average training steps		6	14.2	3.1	2	2.2	2.9	1.9	2.9
Average first quench I_1/I_p		0.56	0.51	0.82	0.85	0.82	0.82	0.83	0.82
Considered magnets ²		20	7	14	95	60	27	18	45
Average training steps ¹		6.1	10.7	3.7	3	2.6	3	2.9	3.6
Average first quench I_1/I_p		0.59	0.53	0.78	0.77	0.78	0.75	0.61	0.75

1) Up to 90% of plateau current

2) Reach plateau current / at least 3 training steps for trend line / excludes magnets without training

FIGURE 1. Distribution of exponent p for each magnet type.

magnetic energy ($B \cdot H$), and I^4 is proportional to the mechanical energy (magnetic force* magn.strain). This exponent may therefore reveal the parameters driving the training.

As a first investigation each individual training curve of each fabricated magnet has been matched with a trend line in the form of a power function using EXCELTM. The trend line parameters, exponent " p " and first quench " I_1 ", have been listed for further analysis. Before doing so we made a selection; magnets that did not reach their critical current have been discarded, considered not fully sound. Also were discarded the recorded quenches too close to critical current (90% of plateau current I_p) avoid corruption of the trend line due to the flat plateau. The "considered magnets" in TABLE 2 were left and used for the analysis.

The resulting distributions of exponent " p " have been plotted in FIG 1 for each magnet type. The average exponent of all 279 magnets, MCO excluded, is $p = 0.18$. The average for the 24 MCO magnets is about the double, $p = 0.35$. This could be expected: the MCO octupole is particular because it is an insert placed inside the MCD decapole. Trained in this constant Decapole field, the magnetic forces are proportional to the current instead of the current squared. The average exponent we found indicates that at each quench there is a constant stepwise increase of $I^{5.5}$ ($1/p = 5.5$) and for the MCO of $I^{2.9}$ in other words the mechanical energy increases more than proportional at each quench.

Relation between exponent p and first quench current I_1

Does a good magnet, starting training at a high current, show the same exponent as a bad magnet, starting training at a low current? To find an answer we plotted the exponent p as a function of first quench currents I_1 for each magnet type (FIG 2). Amazingly, the higher the current of the first quench the lower the exponent. This behavior, present in all types of magnet, means that a better magnet starting training at a higher current will reach the critical current with a flatter slope and will need nearly the same number of quenches. The exponents appear to vary more or less linearly with the first quench current. The exponent trendlines, see legend FIG 2, are characterized by 2 constants, one is close to 0.7 whereas the second appears to be close to the plateau currents I_p of each type of magnet as given in TABLE 2. Exceptions are the MCO-1 and the MCS-2 where the first constant is 1

FIGURE 2. Exponent p as function of first quench current for different types of magnet. On horizontal scale the first quench currents I_1 (arbitrary scale).

instead of 0.7. The MCO-1 exception is understandable (see above) but that of the MCS-2, the same magnet as the MCS-1 but built by another manufacturer, is at present not understood. Replacing the second constants by I_p merges the exponent trendlines into one single equation plotted in FIG. 3 among the exponents p of all the magnets together (except MCO-1). Using this expression, the general training equation (1) can now be written as:

$$I_n = I_1 * n^{0.7 [1 - I_1/I_p]} \quad (3)$$

This equation is valid for all the magnets types except MCO-1. Although there is a large spread in exponents, we can conclude that each type of magnet shows the same tendency revealing that the basic training phenomena is the same and not influenced by the large differences between the magnet types mentioned in the introduction! The equation for the MCO-1 becomes, using the p function from FIG. 2:

$$I_n = I_1 * n^{[1 - I_1/I_p]} \quad (4)$$

Brief discussion

The training curves show the following behavior: The lowest first quenches typically occur at about half the critical current, rarely below, whatever the magnet type. The reason

FIGURE 3. Exponents p as function of normalized first quench current I_1 and plateau current I_p . All magnets except MCO-1.

FIGURE 4. Example of MS Sextupole training: measured quenches and curves from equation (3).

for this is not yet understood. But this implies that the exponent p of the equation given above is practically always lower than 0.35. Magnets with a quicker training start at a higher current level but the number of training steps to reach critical current is only slightly less due to a slower progress characterized by a lower exponent p (FIG 4). Magnets with a very fast training need only one or two training steps to reach criticality. These have not been taken into account the number of steps being too small to allow a reliable curve fitting.

One might consider that the curves starting with a higher first quench in fact "jumped" the first quenches and then continue with the same "energy step" as did the curves starting with a lower first quench. Sometimes this is true but not always.

AVERAGE NUMBER OF TRAINING QUENCHES

Although all magnets behave in a similar way, the average first quench current $\langle I_1 \rangle$ is quite different for each type of magnet and so is the average number of training quenches (TABLE 2). Is a longer training only due to a low quality of fabrication or can it be due to physical constraints independent from the fabrication process? We checked for correlations with properties like type of wire, peak field, coil length, coil volume, number of winding turns, longitudinal stress and mechanical energy from the Lorentz force. Amazingly the average number of training steps is not related to the coil size although one would expect that the bigger the coil, the more defects and the more training steps. The best correlation is found with the longitudinal stress. The average number of quenches necessary to reach 90% of the plateau current I_p (see "considered magnets" in TABLE 2) is directly proportional to the longitudinal Lorentz stress reached at that current (FIG 5).

FIGURE 5. Lorentz stress in metal of wire versus average number of necessary training quenches. (Lorentz stresses in the insulation are typically one tenth of the metal stress as a result of the lower Young's modulus).

FIGURE 6. Equivalent stress in wire components. Cycles from warm to cold to powered. Three different cases: non-impregnated coil, impregnated coil and impregnated with larger copper/sc ratio. Used are a pre-compression of 30 MPa, and a longitudinal Lorentz stress in the metal of 30 MPa.

Suspicion concerning the longitudinal stress

The longitudinal stress started to be suspected during training tests on prototype MSCB corrector magnets. These magnets had the peculiarity that the dipole coil was assembled around the sextupole coil and impregnated together [3] as a nested construction. After training one of the coils to a certain current, the training of the other started at a current level corresponding to the same longitudinal force, pointing to a relation between the longitudinal force or strain, and the training. In addition, when the sextupole coils were trained inside the outer dipole field, the coils that quenched were those that felt a pulling force from the dipole field and not those in between that felt a compressive force from this field [4]. The present proportionality between the average number of training quenches and the level of longitudinal stress confirms the importance of these stresses.

Internal stress and mechanical energy density

The stresses and energy densities are generated by 3 phenomena: the static pre-compression of the coil, the static contraction from cooling down, and the dynamic magnetic forces changing the stress distribution in the pre-stressed coil and adding longitudinal stresses. These basic stress cycles have been calculated (FIG 6) for 3 cases: a non-impregnated magnet, an impregnated corrector magnets with Cu/sc ratios of 1.6, and one with Cu/sc ratio 4 respectively. The overall effect of the insulation appears to be twofold: in addition of adding highly stressed insulation material it compresses the metal components of the wire, in particular the NbTi. The mechanical energy density (FIG 7) is

FIGURE 7. Mechanical energy density in wire components. Conditions identical to those of FIG 6.

by far the highest in the insulation followed by that in the NbTi. Both are an order of magnitude higher than the about $12'000 \text{ J/m}^3$ energy release necessary to make the wire quench at half the critical current. Whereas a point disturbance that could create a quench amounts to some 10^{-5} Joules [5] corresponding to the mechanical energy contained in about 0.1 mm length of conductor. In fact it is amazing that an impregnated magnet can work in the environment of such extremely high mechanical energy densities!

WHAT CAN BE CONCLUDED ABOUT THE ORIGIN OF THE TRAINING?

The possible origins of training can be enumerated as: 1) crack propagation in the plastic insulation, 2) serrated yielding of the NbTi filaments, 3) stick-slip on faces between dissimilar materials, in particular between insulation and wire, and 4) material yielding followed by shake-down of the stresses. The similarity of the training curves for such different magnets points to a common cause independent from aspects like the symmetry of the magnet or even the Cu/sc ratio of the wire. Magnets with different internal stresses in the metal of the wire behave the same so assumptions 2), 3) and 4) seem less likely.

It also looks as if the training curve is not following the function of the temperature margin or the available enthalpy: When the training starts at a higher first quench, it does not necessarily follow the slope it would have followed had it reached this level after a few training steps. Apparently the energy release at each training quench is well above what is necessary to create a quench. This is confirmed by the training at 1.9 K, not shown in this paper, which in general continues the same curve found at 4.2 K and does not show a sudden leap to a higher quench current as a result of the increased temperature margin.

Training tests on single coils of MCS magnets [6] showed that plateau currents were reached without quenching when free or very slightly pre-compressed in azimuthal direction. Training quenches appeared when more pre-compression was exerted or when the coils were glued against a G-11 backing layer (as is the case of the corrector magnets). The training seemed to be situated outside the coil; a coil without backing stayed in virgin condition.

Our investigation shows that the quench levels are tuned by something like the magnitude of the mechanical energy that increases with constant steps. Crack propagation in the insulation might fit such behavior and is in general seen as the principal cause.

Crack propagation in the insulation

Crack progression is controlled by the mechanical energy in the crack tip. The relation between crack length “a” and stress “ σ ” is described by $a = (k^2/\sigma^2)/\pi$. A long pre-existing crack needs little stress to advance whereas a short crack needs a high stress to advance. Estimating the crack propagation factor of the insulation material to be $k_{Ic} = 1 \text{ MPa}\cdot\text{m}^{1/2}$, the actual stress in the insulation of about 150 MPa allows developing cracks as small as 15 micrometer, the order of thickness of the internal enamel peelings. The energy release in the crack tip is a material constant, $G = k^2/E = 286 \text{ J/m}$ and a crack width of 0.04 mm would be sufficient to yield the 10^{-5} Joules necessary to create a quench. Crack progression would be a plausible explanation for a behavior of training that is independent of the temperature margin, the energy released in general being well above the minimum quench energy. However, the high stress in the insulation is already present at cold, before even powering the magnet, and should already have cracked the insulation material all over. Therefore extra crack forming is possible but less likely.

CONCLUSIONS

The training curves of several hundreds of impregnated magnets have been analyzed. We found that:

- 1) The training behavior can be described by a single equation valid for all the types;
- 2) The number of training steps is not related to the coil volume or coil length;
- 3) The average number of quenches necessary to reach the critical current is shown to be proportional to the longitudinal Lorentz stress in the wire. This makes us assume that the longitudinal Lorentz force is driving the training behavior;
- 4) The high internal stress in the metallic components of the wire does not seem to cause the training because magnets with Cu/sc ratio's as different as 1.6 and 4 behave the same;
- 5) It is unclear if crack propagation in the plastic is the principal cause of the training;
- 6) It looks as if there is a strong interest to reduce the longitudinal Lorentz stress in the wire. One way of doing this is to make the central posts from copper instead of G-11 reducing the longitudinal stress by a factor of two, as is already the case with the MCB and MS magnets (TABLE 2).

Finally it is worthwhile to remind that the training of magnets wound from a monolithic wire and impregnated with epoxy suffers from 3 main drawbacks as compared to not-impregnated magnets wound from Rutherford cable. In order of severity:

- 1) The thermal contraction of the plastic insulation raises enormously the stresses in all the materials, metals included;
- 2) Once a strand quenches, the current cannot be re-distributed over parallel strands like in a cable, so the whole magnet will quench;
- 3) The cooling is worse because the coils are not impregnated with coolant (He).

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