PRE-CYCLE SELECTION FOR THE SUPERCONDUCTING MAIN MAGNETS OF THE LARGE HADRON COLLIDER

A. Verweij, N. Sammut, W. Venturini Delsolaro, R. Wolf, CERN, Geneva, Switzerland

Abstract

Pre-cycles for setting up the main magnets of the Large Hadron Collider are necessary for ensuring field reproducibility and low field-decay rates at injection. In this paper we propose standard pre-cycles for the main magnets of the LHC. We study the influence of the pre-cycle parameters on the field decay at injection by two different models. One already proven model is semi-empirical based on magnetic measurements of the magnets. The other is a new network based model of a Rutherford cable which directly calculates the current redistribution and associated magnetization change in the cable strands. The pre-cycle to be used may depend on the history of the machine or may have to be changed because of unforeseen phenomena in the machine. The choice of a new pre-cycle on the basis of magnetic measurements alone is a lengthy process. We confirm the usefulness of the network based model as a tool for selecting new pre-cycles, including decay-blocking degaussing pre-cycles, and compare with magnetic measurements.

INTRODUCTION

To assure reproducible accelerator operation, magnets have to be carefully set up for each physics run. This is common for machines made with normal magnets and with superconducting magnets. In the former, iron hysteresis is usually the dominating factor, while in the second superconductor magnetization dominates. It was however observed during the operation of the first superconducting accelerators that the field slowly changed in time during injection. Related to this, a rapid field change occurred (the “snapback”) in the magnets during the first instants of the energy ramp. The main origin of this was found to be the generation of long range coupling currents in the strands of the superconducting cables in the magnets, which interacted with the persistent currents in the superconducting filaments.

Boundary Induced Coupling Currents.

These longe range coupling currents [1] were called boundary induced coupling currents, “BICCs” [2] or supercurrents [3]. During the last 20 years a certain number of experiments have been performed which clearly demonstrate the presence of BICCs in cable pieces or entire coils. In a coil a number of spatial field variations are present, each causing BICCs with their own magnitude and time behaviour. The superposition of all these BICCs will affect the behaviour of a coil with respect to field distortions, additional losses and reduced stability.

Important is that this superposition can lead to an increase as well as a decrease of BICCs. Especially the effect of BICCs on the stability, which is a very local effect, can be very different for a series of identically built magnets, wound from the same conductor. Field distortions and additional losses, both effects which have a more global character, vary less for similar magnets, but variations of a factor 2-5 can still be expected, especially due to the variations of the contact resistances and the cable transposition.

Magnetization Change due to the BICCs

The field generated by BICCs is periodic with the same period as the cable twist pitch, as evidenced by measurements both on superconducting cables and in magnets. The amplitude of this field slowly decays when the magnet current is constant and causes an average magnetization decrease in most conditions. This is seen as a field change when injecting into the accelerator.

The Fidel Model

The Field Description for the LHC (FiDeL) [4] is the model which is presently used to describe the field of all magnets used in LHC. It's semi-empirical set of equations is based on extensive magnetic measurements. Not only can it predict the steady state magnetic field and field errors, but it can forecast the field decay during particle injection and the snapback within a residual error comparable to commissioning beam control requirements. The decay prediction has however been verified by (lengthy) measurements for only a limited set of parameters. We therefore tried to develop a method which directly calculates the current redistribution and associated magnetization change in the cable strands in the hope that it would give us guidance in improving the magnet set-up or predicting the effect of parameter changes for future unknown operational requirements.

THE CUDI MODEL

CUDI [5] is an extended Fortran code to calculate the electrodynamic and thermal behaviour of any type of Rutherford cable subject to global and/or local variations in field, transport current, and external heat load.

The model comprises a 3-dimensional cable geometry with incorporation of currents, resistances, temperatures, fields, heat flows (through the matrix, through the interstrand contacts, and to the helium), and self- and mutual inductances. Time-dependent behaviour, thermal behaviour and quench behaviour can therefore be calculated.

The cable is modelled by a large network of nodes interconnected by strands and contact resistances. The model is much more advanced than some other models from the past that were basically written to calculate the interstrand coupling currents under steady-state conditions, or calculate stability on small (2 or 3-strand) cables. *In particular it is possible to calculate the internal field change in the cable and the resulting magnetization change in the strands as function of time.*

As an example we give in Figure 1 the magnetization change calculated in a single cable 2.2 meter long cable with an applied field cycle similar to the one to be used in LHC for the main dipoles. The magnetization decay due to the BICC's and the snap back are clearly visible. The field change is applied in the centre of the cable.

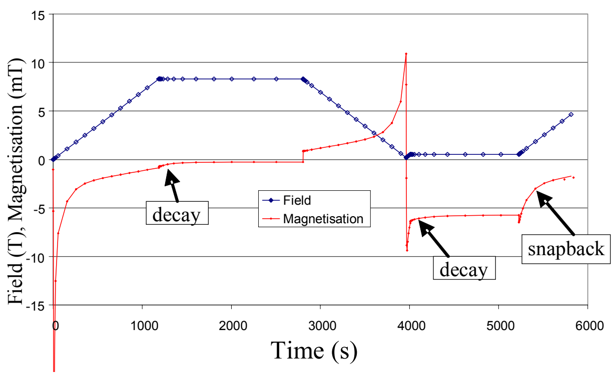

Figure 1: Calculated magnetization change of the strands in a 2.2m long 14 strand Rutherford cable.

Decay Blocking Demagnetization Cycle.

As shown experimentally in [7] it is possible to greatly reduce the decay by a proper demagnetization cycle. In Figure 2 we show the calculated effect of such a cycle on a short piece (2.2m) of Rutherford cable at the injection field level of the main dipole. Indeed CUDI calculates that there is no decay at the injection field. This favourable condition is however is attained at the cost of a higher snapback.

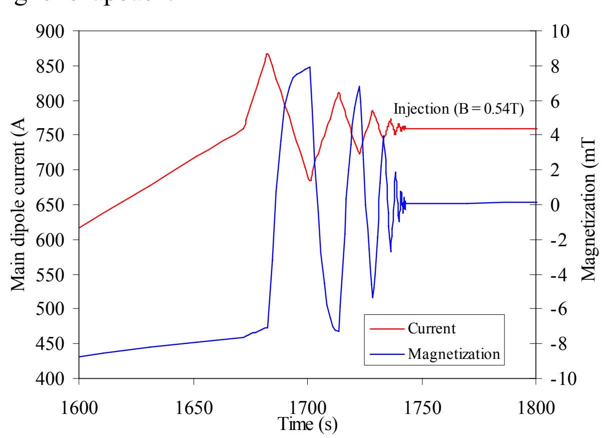

Figure 2: The effect of a demagnetization cycle calculated by CUDI. The field decay at injection is stopped.

Changes in the Magnetic Cycle.

In continuum models the BICCs current propagate following a diffusion equation. Since calculations with the CUDI network model would be prohibitively long for complete magnets, use was made, as in [3] of Fourier solutions of type:

$$I(z,t) \propto \sum_{k=1,3,5,\ldots}^{\infty} \frac{1}{k^2}\sin\left(k\frac{\pi}{2}\right)\sin\left(k\frac{\pi(z+l/2)}{l}\right)\left(1-e^{-k^2 t/\tau}\right)$$

which were adjusted to the the solutions found with the network model. This is described in detail in [6]. What is important to remember is that. the field integral change produced outside of the cable depends on the average change of the magnetization integral. In addition we found that the total magnetization decay on a flattop was approximately proportional to the change in the average amplitude of the BICCs currents multiplied by the cable length (units Am). In this study *we have sometimes used this current integral 'area' to characterize the field decay, as for example in Figure 4.*

TYPICAL LHC PRE-CYCLE

An example of a planned pre-cycle for the main LHC dipole is given in Figure 3. The magnet is first ramped up to a first current flattop of 20 min, imitating a physics run. Then it is ramped down to the minimum current and up to the pre-injection plateau. The current is here about half the current between the minimum current and the injection current. The aim of the pre-injection step is to let the most of the BICCs decay. The small field step to injection recuperates the magnetization lost during the pre-injection, but generates again some additional decay for the injection period.

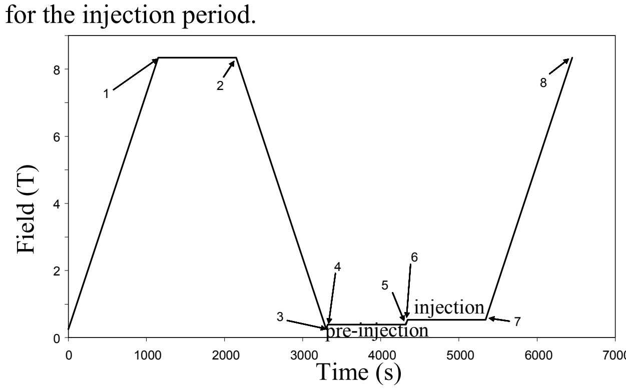

Figure 3: Typical LHC pre-cycle.

Minimizing the Decay

To minimize the decay during particle injection, we studied in detail the following parameters involved.

-*A variation in the pre-injection duration,* Figure 4. The areas reduce with increasing duration but not to zero at injection due to the effect of the subsequent step 6 (current increase from pre-injection to injection).

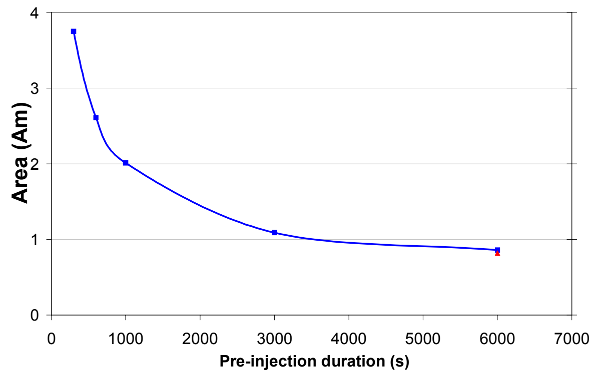

Figure 4: The influence of the pre-injection duration on the decay at injection using the typical LHC pre-cycle.

-A variation in the ramp rate from pre-injection to injection. The effect is rather small, and it seems more useful to ramp up at nominal speed (10 A/s) and spend more time at pre-injection.

-A variation in the pre-injection level. This effect is rather small, but optimising the pre-injection level remains interesting to reduce the BICCs without any consequence for the total time of the pre-cycle.

-A variation in the duration at top current This effect is strong with an increase in areas of a factor 2.

-A variation in the top current. This effect is strong with an increase in areas of about a factor 2 between 2 kA and 12 kA.

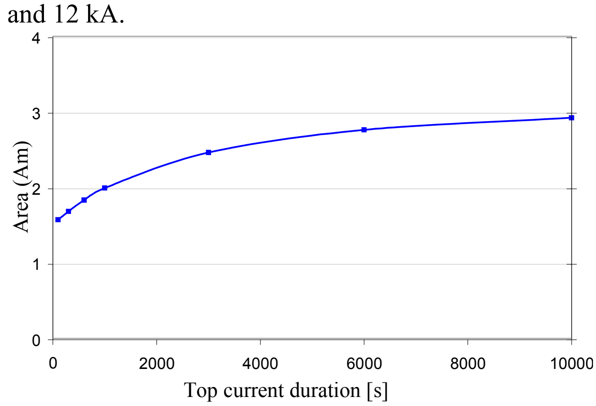

Figure 5: The influence of the pre-cycle top current duration on the decay at injection when using the typical LHC pre-cycle.

Improving the Reproducibility

One could conclude from the above that the decay and snap-back are smallest for small top current and top duration. In the LHC, however, all magnets have a field and current history and the optimum pre-cycle is a pre-cycle that gives not only a small decay and snap-back but also a reproducible one. *We concluded that it is preferable to perform the pre-cycle as fast as possible after the previous physics run, without flat top, and instead wait longer at pre-injection.*

COMPARISON WITH MEASUREMENTS

CUDI does not directly calculate the field error, but the magnetization change and the BICCs. These we expect to be proportional to the change in the field. In Figure 6 we compare with the measured sextupole field error 10 minutes after injection. There is reasonable agreement.

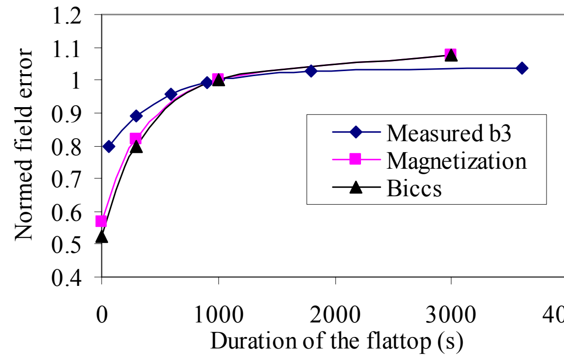

Figure 6: Comparison of calculated BICCs and magnetization decay with the measured sextupole decay.

CONCLUSIONS

The pre-cycling of the LHC main magnets is based on the knowledge of the magnet behaviour that was acquired during the series measurements, and that is embedded in the FiDel equations. We developed a code, which calculates the dynamics of the Rutherford cable from first principles and shows a reasonable agreement with measurements. This code can be useful to study various options of setting up the machine, in particular for the field decay at injection. The ability to predict blocking of the decay with a demagnetization cycle demonstrates that the field decay mechanism is now rather well understood.

REFERENCES

[1] G. Ries and S. Takács, “Coupling losses in finite length of superconducting cables and in long cables partially in magnetic field”, *IEEE Trans. on Magn.* MAG-17, pp. 2281-2284 (1981).

[2] A.P. Verweij, “Review on Boundary-Induced Coupling Currents”, LHC Project Report 152, *Adv. Cryog. Eng.* 44B, pp. 1059-1068 (1998).

[3] L. Krempasky, C. Schmidt, “Theory of supercurrents and their influence on field quality and stability of superconducting magnets”, J. Appl. Phys. 78 (9), pp. 5800-5810 (1995).

[4] N. Sammut, L. Bottura, J. Micallef, Phys. Revs ST - Accel. Beams, Vol 9 No 1, 012402 January 2006.

[5] A.P. Verweij, “CUDI: A model for calculation of electrodynamic and thermal behaviour of superconducting Rutherford cables”, *Cryogenics* 46 (2006) 619-626.

[6] A.P.Verweij, “Boundary-Induced Coupling Currents” , CERN AT-MCS Internal Note 2007-11, October 2007, EDMS Nr 880367.

[7] W. Venturini-Delsolaro, L. Bottura, M. Haverkamp, A. Kuijper, “Degaussing and Decay Reduction in the Short Superconducting Dipole Models for the LHC” *IEEE Trans. Appl. Supercond.* 12 (2002) 291-294.