EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 59

QUENCH LOCALIZATION AND CURRENT REDISTRIBUTION AFTER QUENCH IN SUPERCONDUCTING DIPOLE MAGNETS WOUND WITH RUTHERFORD-TYPE CABLES

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Abstract

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LHC Division

ASC Pittsburgh '96

CERN
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Geneva, 6 novembre 1996

Quench Localization and Current Redistribution after Quench in Superconducting Dipole Magnets wound with Rutherford-Type Cables

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I. INTRODUCTION

Models and prototype superconducting magnets for the future LHC machine [1], suffer from premature quenches. In the past a program has been started to locate the starting position longitudinally as well as in the cross section of the magnets with the help of sets of pick-up coils called "quench antenna" [2,3]. This system is used today in combination with voltage taps on the magnet windings.

By studying the shape of the flux-signals in the coils, induced by the changing current pattern in the quenching cable, the current redistribution during the first milliseconds after the quench start can be reconstructed.

II. FINDING QUENCH START LOCATIONS

When a quench starts somewhere in the magnet cable, the current distribution will change in the region of this spot. In first approximation this redistribution can be simulated by superposing a magnetic moment on the original current distribution. The magnetic moment, which changes in time, induces a flux in a pickup coil in the magnet bore. As an illustration a cross-section of one quadrant of a magnet with a long moment perpendicular to the x,y plane is given (Fig. 1).

It can be shown that the magnetic flux ϕ generated by a magnetic moment m at radial position z_c with strength m_l per meter length in a rectangular coil, made of N turns with length l_c is:

$$\phi_i = \frac{\mu_0}{2\pi} l_c N \,\mathrm{Re}\left\{ -i \frac{m_l e^{i\alpha}}{z - z_c} - iR^2 \frac{m_l e^{-i(\alpha - 2\beta)}}{z - \frac{R^2}{z_c}} \right\} \Bigg|_{zl}^{zr} \qquad (1)$$

The left side of the coil is at radial position z_l, the right side at z_r. The relation not only holds for an infinitely long moment, but also for a short moment, with total strength m instead of m_1 per meter, as long as the moment is short compared to the pick-up coils (l_c=1 in this case). The radial positions are given in complex notation. The second term in (1) represents the image currents, describing the contribution of the iron yoke. Assuming that the origin of the moment is a displacement of current I from a quenching strand at radial position z_{c1} to a neighboring strand at radial position r_{c2}, quench location in the cross-section of a magnet can be done by taking the fluxes ϕ_i from a set of four linearly independent coils in the magnet bore, and solving the set of equations for the unknowns α, the angle between the moment vector axis and the x-axis, β, the azimuthal position of the magnetic moment, z_c, the radial position of the moment and m the magnetic moment strength. Position z_c is the average of the positions z_{c1} and z_{c2}.

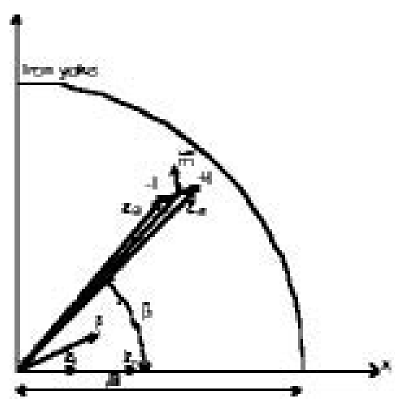


Fig. 1. Schematic view of a quadrant of the magnet cross-section with a quench taking place at z_{c1} . Current is displaced to z_{c2}, giving a change in current $+I$ and $-I$ at z_{c1} and z_{c2} respectively and a resulting magnetic moment m. The moment generates a flux in the pick-up coil reaching from z_l to z_r . All radial positions z are given in complex notation.

Presently also sets of three pick-up coils are used for this purpose, giving a trace of possible quench start positions. The typical layout for a quench antenna, constructed with five zones of three parallel and coplanar coils is shown in Fig. 2.

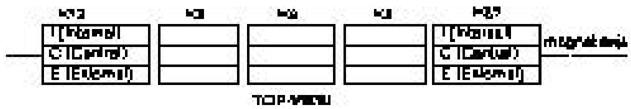


Fig. 2. Layout of the main components of one of the quench antennas used for testing one meter dipole models at CERN. Five sections (H12-H67) of three coplanar parallel coils cover the length of the magnet. The real system has four extra sets of coils to enhance the resolution in the magnet ends.

With this type of quench antenna, good agreement is obtained between voltage taps and pickup-coil method, certainly for inner layer quenches. Using the quench antenna most of the times gives the possibility to determine the block in which the quench occurred. As an example the quench start positions, shown in Fig. 3, are found by using the fluxes ϕ_i in three pickup-coils and solving numerically for the four variables. For outer layer quenches problems can arise, because, depending on the position of the quench, part of the signal can be screened by the inner layer windings.

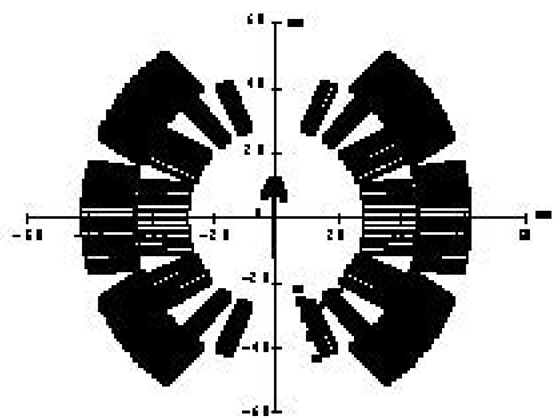


Fig. 3. Cross section of a one meter dipole magnet model, showing a solution for a typical quench using three pick-up coils. The black squares indicate the possible quench start positions, while the line gives the direction of the moment vector. The arrowgives the direction of the main dipole field.

III. Current Redistribution Models for Rutherford Cables

One can imagine several types of current redistribution to take place at quench start, giving different signals in the pick-up coils. Three possible types are discussed here.

A. Transfer to Crossing Strand

At quench start, current I_q is transferred from the quenching strand, through a contact, to a crossing strand in the other layer of the cable (see Fig. 4).

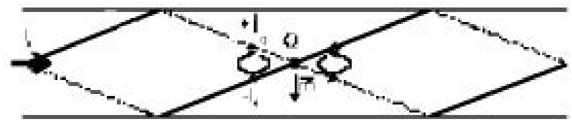


Fig. 4. Side view of a Rutherford type cable. The cable transport current flows from left to right. Current redistribution takes places at point Q from a quenched strand through a contact resistance to a crossing strand in the other layer of the cable. The change in current is $-I_q$ for the quenching and $+I_q$ for the crossing strand.

Because of the symmetry of the distribution, no resulting moment perpendicular to the broad side of the cable will be observed if the pick-up coils are very long compared to the zone in which the redistribution has taken place. The effective moment is parallel to the flat side of the cable. In pick-up coils of finite length, the perpendicular component plays a role as well. A simulation of the fluxes induced in the quench antenna is shown in Fig. 5. For the simulations a slightly modified version of (1) for calculation of the fluxes ϕ_i is used, so that the contribution of the end of the pick-up coils is taken into account [4].

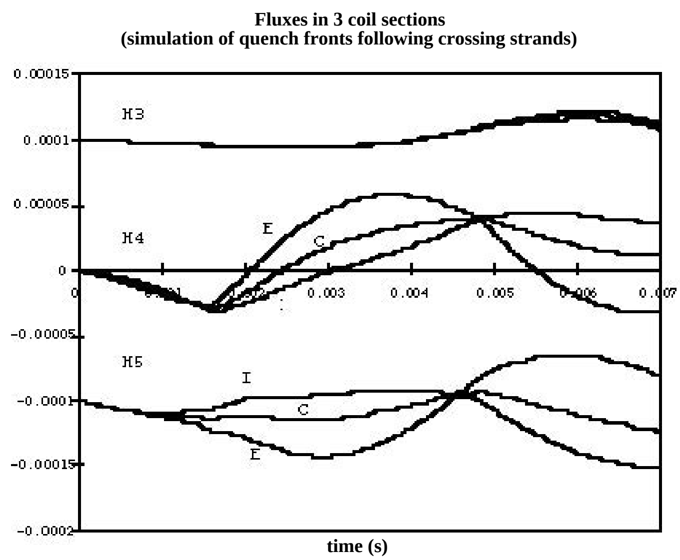


Fig. 5. Simulated fluxes in sections H3-H5 as a function of time. The current is transferred from the quenched strand to a crossing strand in the other layer of the cable.

The two components of the growing moment can be seen in the signals: the divergence of the flux through E, C and I in section H4 is generated by the perpendicular component, while the component parallel to the broad side of the cable has almost the same influence on all three fluxes and gives the variation of the average.

B. Transfer to Parallel Strand

If the current of the quenching strand is taken over by neighboring strands in the same layer, the signals depend on the relative position with respect to the twist length L_p of the cable, see Fig. 6. A simulation of the situation in which the quench starts at 1/3 L_p is shown in Fig. 7.

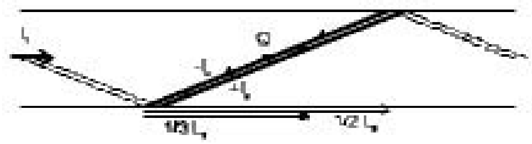
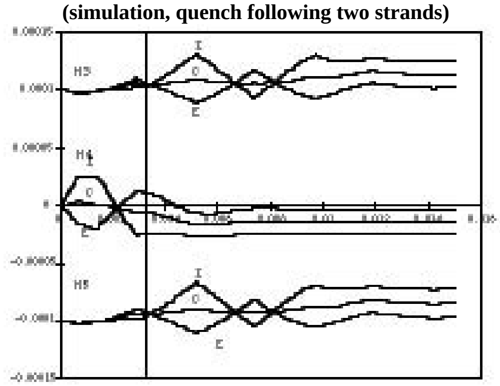


Fig. 6. The current in the quenching strand is taken over by a neighboring strand in the same layer. The magnetic moment vector is directed perpendicular to the broad side of the cable.

If the quench starts at 0 or 1/2 L_p, as long as the moment is short compared to the pick-up coils, because of symmetry, no signal is observed in the coil section where the quench starts. The magnetic moment vector is directed perpendicular to the broad side of the cable.

Fluxes in 3coil sections and position of quench fronts

(simulation, quench following two strands)



time (s)

Fig. 7. Simulated fluxes versus time in sections H3-H5 for quench fronts following the path of the strands. The dotted line indicates the moment in time at which the quench fronts run into sections 3 and 5.

At the edges of the cable, the change in moment strength changes sign, giving the periodicity in the fluxes as a function of time.

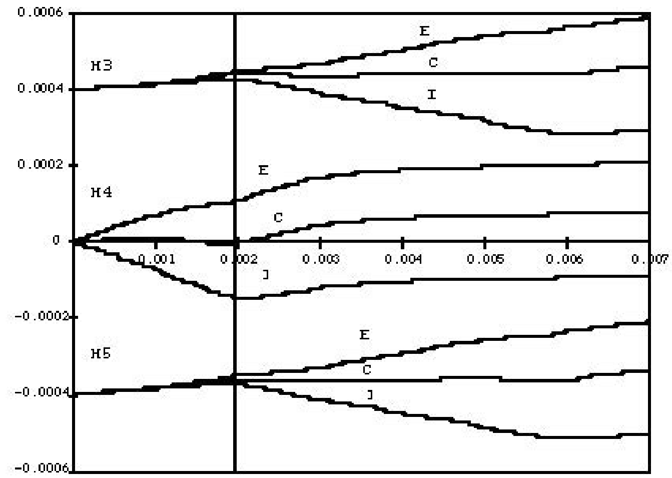
C. Running Fronts

If more than one strand quench and the current is redistributed over the wholecable width, two quench fronts start running along the cable length in opposite directions. The signals in the pick-up coils for this situation show no dependence on the twist of thecable (see Fig. 8). With a, in time, linear growing normal zone, the direction of the magnetic moment vector gives an indication of the direction of the current displacement. The origin of the linear running fronts is a combination of the magnetoresistance in the copper matrix and the variation of the contact resistance over the width of the cable.

The magnetoresistance makes the current move radially outwards into the low field region of the magnet, while the lower value of the contact resistance at the small edge of the cable tends to make the current move inwards. The direction of the magnetic moment vector observed by the quench antenna shows which of the mechanisms plays the most important role.

Fluxes in 3coil sections and position of quench fronts

(simulation, linear growing quench)

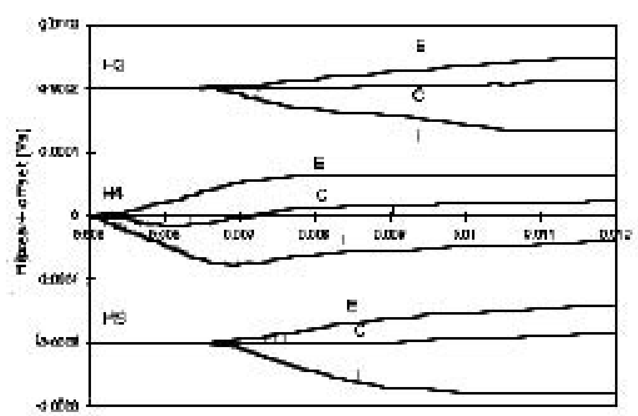


time (s)

Fig. 8. Simulated fluxes versus time for quench fronts propagating along a straight path through the cable.

IV. Comparison to Experimental Results From Model Magnets

Many of the inner layer quenches close to short sample limit observed in the dipole model magnets at CERN have a similar flux signature. As an example the flux signals from model MFISC quench 11 are given in Fig. 9. The striking qualitative similarity of this type of signature to the numerical simulations for “running fronts”(Fig. 8) indicate a resistive build-up over the full cable width in the first milliseconds following the quench start.



time (s)

Fig. 9. Measured fluxes as a function of time in the three sections of the quench antenna located in the straight part of the magnet for MFISC training quench 11. See Fig. 8 for numerical simulation.

The direction of the magnetic moment indicates whether the magnetoresistance or the variation in the contact resistance is the main factor for the redistribution (Fig. 10). If the main factor were the variation in contact resistance over thecable width, the moment vector would have been rotated by

180 degrees. For a transfer to a parallel strand both directions perpendicular to the cable are possible while for a transfer to a crossing strand, the moment vector would have its main component parallel to the cable.

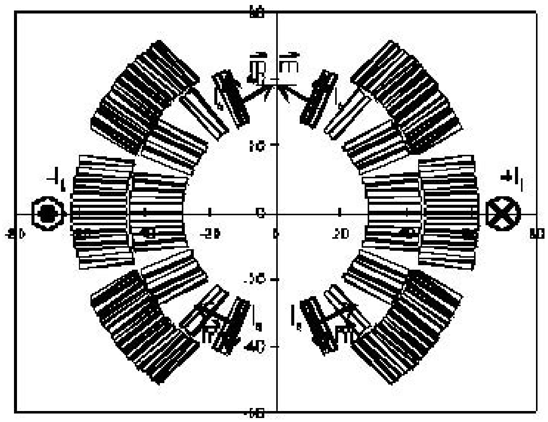


Fig. 10. Cross section of a dipole magnet with the transport current going into the plane on the right and coming out of the plane on the left. Due tothe magnetoresistance of the copper matrix the current wants to move into the low field regions of the cable (movement indicated by arrows I_q). The resulting moment direction, indicated by the arrows m, is given four all four quadrants.

Since all analyzed quenches show a magnetic moment vector pointing in a direction corresponding to the directions indicated in Fig. 10, the main mechanism behind current redistribution during the first few milliseconds for this type of quench must be the magnetoresistance of the copper matrix. This same observation was made for RHIC quadrupoles in [5].

A second example showing the power of the pick-up coil method for analyzing current redistribution is specific to the MTA3CERN model. The magnet has a copper stabilizer strip soldered to the innermost turn of the inner layer, creating a possibility for current sharing if the quench starts in the turn soldered to the strip. The flux signals for this type of quench are shown in Fig. 11. The quench happened at 95% of short sample limit.

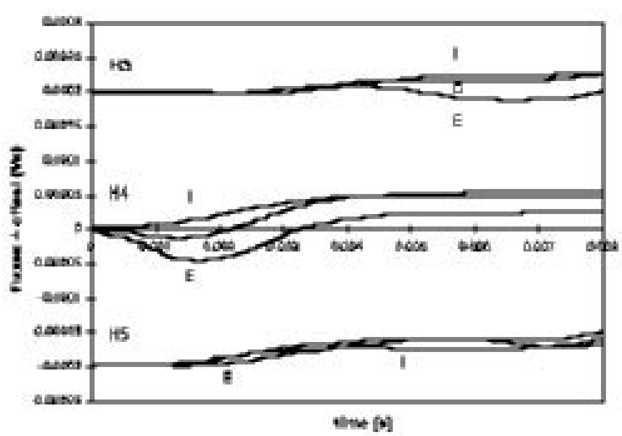


Fig. 11. Measured fluxes in the pick-up coils as a function of time for a quench starting next to the copper strip in MTA3CERN.

The shape of the flux curves can be explained by assuming that the current redistribution started with a resistive build-up in the cable, again driven by the magnetoresistance of the copper matrix. After 2 (ms) however, a part of the current starts to flow in the copper strip, thus generating a moment parallel to the broad side of the cable. The component of the moment parallel to the cable gives approximately the same signal in each of the parallel pick-up coils and shifts all three fluxes of each section up.

The direction of the moment vector as seen by the pick-up coils supports the explanation. In the first millisecond it is perpendicular to the broad side of the cable before turning to a direction more parallel to the cable.

V. Conclusion

The pick-up coil method has proved to be a reliable way of localizing quenches in the LHC model magnets. It proves to be a very valuable tool to locate premature quenches in superconducting magnets.

By studying experimental data from the pick-up coils it is possible to get information about the current redistribution after quench in the tested magnet. Comparison to numerical simulations shows that the magnetoresistance of the copper matrix plays an important role in this redistribution for training quenches in the analyzed model magnets, at least in the time scale of milliseconds.

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