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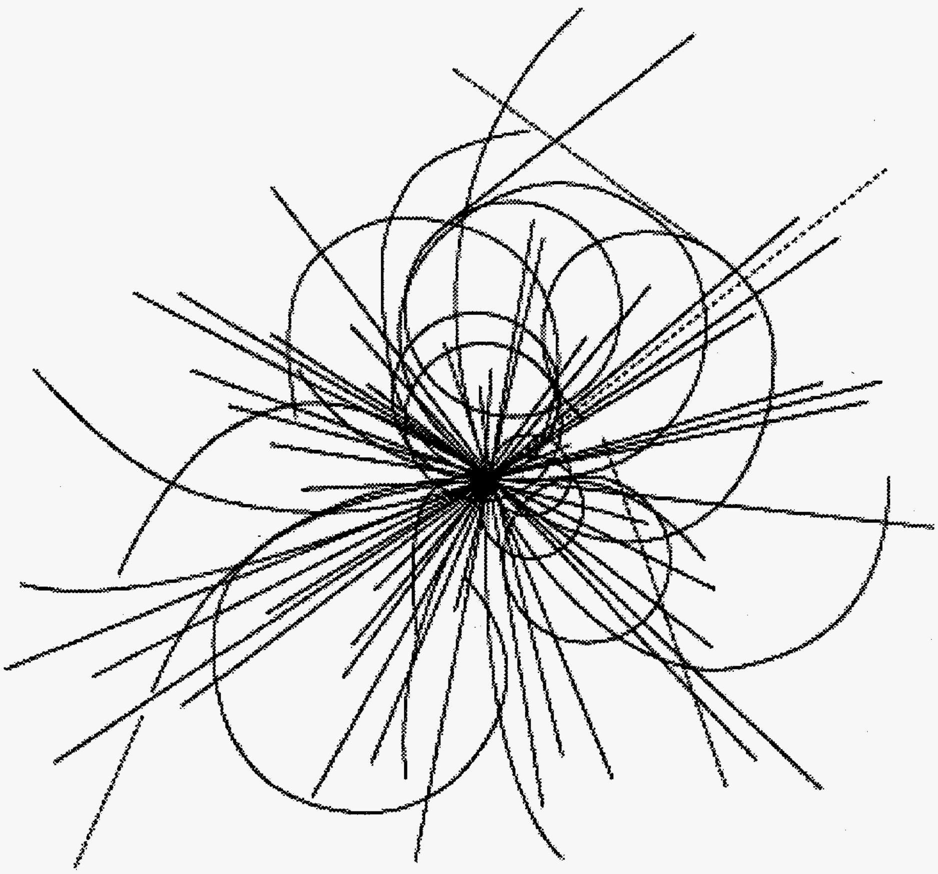

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Quench Antenna for Superconducting Particle Accelerator Magnets

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***Abstract*—We report on the design, fabrication, and test of an assembly of stationary pickup coils which can be used to localize quench origins. After describing the pickup coils configuration, we develop a simple model of current redistribution which allows interpretation of the measured voltages and determination of the turn of the magnet coil in which the quench started. The technique is illustrated by analyzing the data from a quench of a 5-cm-aperture, 15-m-long SSC dipole magnet prototype.**

I. INTRODUCTION

Most of the magnet prototypes built to date for the Superconducting Super Collider (SSC) were instrumented with voltage taps to determine quench start localizations [1]. This method, which proved to be very successful during the research and development phase of the program, cannot be used during the production phase where no voltage taps are allowed on the magnet coils. A new technique was recently developed by the European Organization for Nuclear Research (CERN), which enables the localization of quench origins without using voltage taps [2]. This new technique relies on an array of stationary pickup coils which detect field distortions resulting from quench development. Its implementation, however, requires isolation of the field distortions caused by the quench from those due to environmental noise or ripple of the magnet power supply.

To investigate how this technique could be applied to SSC magnets, a series of experiments was carried out on 5-cm-aperture, 15-m-long SSC dipole magnet prototypes at Brookhaven National Laboratory (BNL) using stationary *mole coil assemblies* [3] provided by BNL and adapted to our use at Lawrence Berkeley Laboratory (LBL). It was found that one of the mole coil configurations, the so-called *quadrupole bucking winding*, yielded suitable signals and that a combination of such windings could be used for localizing quenches. Based on these results, a new stationary coil assembly, called *quench antenna*, was jointly developed by SSC Laboratory and KEK National Laboratory for High Energy Physics. A quench antenna prototype has now been built and successfully tested at BNL. This paper briefly summarizes the design concepts of the quench antenna for dipole magnets and presents examples of measured data.

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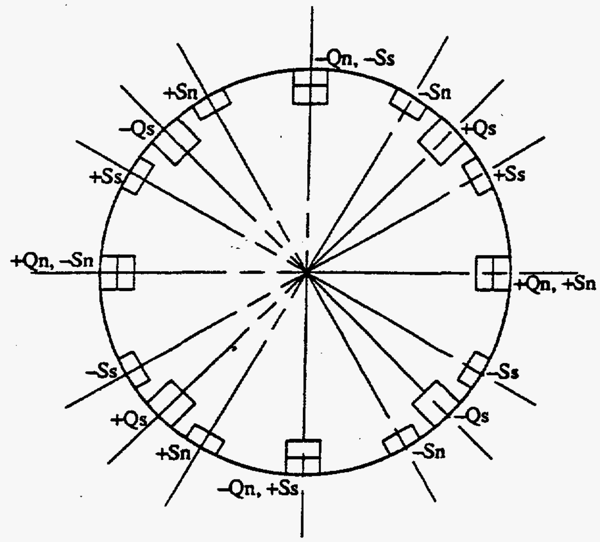

Fig. 1. Cross-sectional view of the quench antenna.

II. PRINCIPLE OF QUENCH ANTENNA FOR DIPOLE MAGNETS

A. Design Concepts and Fabrication

Figure 1 presents a cross-sectional view of the quench antenna. The coil assembly consists of four windings to which we shall refer as *normal* and *skew quadrupole windings* (Q_n and Q_s, respectively) and *normal* and *skew sextupole windings* (S_n and S_s, respectively). Each sextupole winding consists of three tangential coils wound in series. The three coils have an opening angle of $\pi/3$ and are rotated with respect to each other by $2\pi/3$. It was shown by Morgan [4], that such a winding configuration was primarily sensitive to the sextupole component of the magnetic field. Similarly, each quadrupole winding consists of two tangential coils wound in series. The two coils have an opening angle of $\pi/2$ and are rotated with respect to each other by π. Such a winding configuration is primarily sensitive to the quadrupole component of the magnetic field. The normal and skew windings are identical except that they are rotated with respect to each other by $\pi/4$ for the quadrupole windings and by $\pi/6$ for the sextupole windings.

The rationale behind choosing quadrupole and sextupole windings is that they are insensitive to the main component of the dipole field. Therefore, any fluctuations due to external dipole fields or changes in the magnet transport current are bucked out from the signals. The same idea can be applied to develop a quench antenna for quadrupole magnets. There, the suitable windings would be a normal and a skew sextupole winding, and a normal and a skew octupole winding.

The quench antenna coils have eight turns and use a 0.1 mm copper wire coated with polyester. They are wound into 1-mm-wide grooves milled along the length of a thick-walled, glass reinforced epoxy tube. The tube is 1 m long and has an outer diameter of 25 mm. All the coils of a given winding have the same radius and length, but the radius and length are slightly different for each winding. The average radii of Q_n, Q_s, S_n, and S_s are 11.0 mm, 10.4 mm, 12.2 mm, and 11.6 mm, respectively, while their lengths are 964 mm, 966 mm, 960 mm, and 962 mm, respectively.

B. Data Reduction

The field distortions picked-up by the quench antenna are believed to be caused by current redistribution in the quenching turns of the magnet coil. However, very little is known about how this redistribution takes place and how it is related to the propagating thermal front. In this paper, we shall limit ourselves to a simple model, whose main merits are that it leads to reasonable interpretations of the data and to quench start localizations which are consistent with those derived from the voltage tap data (when available).

Let (O,x,y,z) designate a Cartesian coordinate system such that the z-axis is parallel to the quench antenna axis and O is at the quench antenna center. We assume that the field distortions picked-up by the quench antenna can be described as produced by a current line parallel to the z-axis moving along the direction of the x-y plane. Let $\mathrm{a}(t) = a(t)\, e^{i\alpha(t)}$ designate the position of the current line in the complex x-y plane at time t, and let $\mathbf{v}(t) = v(t)\, e^{i\beta(t)}$ designate its velocity. The field, $\mathbf{B}$, produced by such a current line is parallel to the x-y plane and is given by

$$\mathbf{B}(x,y,t) = B_y + i\,B_x = -\frac{\mu_0 I}{2\pi}\sum_{n=0}^{+\infty}\frac{(x+iy)^n}{\mathrm{a}(t)^{n+1}}\;,\quad \text{for } \sqrt{x^2+y^2} < a, \tag{1}$$

where I is the current line intensity. The time derivative of $\mathbf{B}$ is simply

$$\frac{d\mathbf{B}(x,y,t)}{dt} = \frac{\mu_0 I}{2\pi}\sum_{n=0}^{+\infty}\frac{(n+1)\mathbf{v}(t)(x+iy)^n}{\mathrm{a}(t)^{n+2}}\;. \tag{2}$$

Let us now consider a tangential coil of opening angle δ oriented with an angle θ with respect to the x-axis. From the general expression for the flux penetrating a tangential coil [5], it can be shown that the voltage, V, induced by the time-dependent field $\mathbf{B}$ is given by

$$V(t) = -NL\,\frac{\mu_0 I v(t)}{\pi}\sum_{n=0}^{+\infty}\frac{R^{n+1}}{a(t)^{n+2}}\sin(n+1)\frac{\delta}{2}\,\sin[(n+2)\alpha(t)-\beta(t)+(n+1)\theta]\;, \tag{3}$$

where N, L, and R designate the number of turns, the length, and the radius of the tangential coil.

By using Eq. (3), it is now possible to derive the voltages induced by the moving current line in the various windings of the quench antenna. Let us, for instance, carry out the calculations for the winding Q_n of figure 1. This winding consists of two tangential coils of opening angle $\pi/2$ oriented with angles $\pi/4$ and $5\pi/4$ with respect to the x-axis. The voltage V_{qn} induced in this winding is thus

$$V_{qn}(t) = -N_{qn}L_{qn}\,\frac{\mu_0 I v(t)}{\pi}\sum_{n=0}^{+\infty}\frac{R_{qn}^{\,n+1}}{a(t)^{n+2}}\sin(n+1)\frac{\pi}{4}\left\{\sin\left[(n+2)\alpha(t)-\beta(t)+(n+1)\frac{\pi}{4}\right] + \sin\left[(n+2)\alpha(t)-\beta(t)+(n+1)\frac{5\pi}{4}\right]\right\}, \tag{4}$$

where N_{qn}, L_{qn}, and R_{qn} designate the number of turns, the length, and the radius of the normal quadrupole winding. If we limit the series to its first non-zero term, we get

$$V_{qn}(t) \approx -\frac{2N_{qn}L_{qn}R_{qn}^2\mu_0 I v(t)}{\pi a(t)^3}\cos[3\alpha(t)-\beta(t)] \tag{5a}$$

Similarly, for the other windings, we have

$$V_{qs}(t) \approx -\frac{2N_{qs}L_{qs}R_{qs}^2\mu_0 I v(t)}{\pi a(t)^3}\sin[3\alpha(t)-\beta(t)] \tag{5b}$$

$$V_{sn}(t) \approx -\frac{3N_{sn}L_{sn}R_{sn}^3\mu_0 I v(t)}{\pi a(t)^4}\cos[4\alpha(t)-\beta(t)] \tag{5c}$$

and

$$V_{ss}(t) \approx -\frac{3N_{ss}L_{ss}R_{ss}^3\mu_0 I v(t)}{\pi a(t)^4}\sin[4\alpha(t)-\beta(t)] \tag{5d}$$

where the subscripts qs, sn, and ss used for the voltage, V, the number of turns N, the length, L, and the radius, R, refer to the skew quadrupole, the normal sextupole and the skew sextupole windings, respectively.

The unknown variables of the Eqs. (5a) through (5b) are: the radius, a, the azimuth, α, the product $d\Gamma/dt = Iv$, and the angle, β. We thus have four unknowns and four equations, and we can undertake to solve the above system. (Note that this explains why four different windings are needed.)

By combining Eqs. (5a) and (5b), on one hand, and Eqs. (5c) and (5d), on the other hand, it is easy to establish that the angles α and β are the solutions of the system

$$3\alpha(t)-\beta(t) = \arctan\left[\frac{N_{qn}L_{qn}R_{qn}^2}{N_{qs}L_{qs}R_{qs}^2}\,\frac{V_{qs}(t)}{V_{qn}(t)}\right], \tag{6a}$$

$$4\alpha(t)-\beta(t) = \arctan\left[\frac{N_{sn}L_{sn}R_{sn}^3}{N_{ss}L_{ss}R_{ss}^3}\,\frac{V_{ss}(t)}{V_{sn}(t)}\right]. \tag{6b}$$

From the well known identity $\sin^2 x + \cos^2 x = 1$, it can be shown that the radius a is given by

$$a(t) = \frac{\sqrt{\left[\frac{V_{qn}(t)}{2N_{qn}L_{qn}R_{qn}^2}\right]^2 + \left[\frac{V_{qs}(t)}{2N_{qs}L_{qs}R_{qs}^2}\right]^2}}{\sqrt{\left[\frac{V_{sn}(t)}{3N_{sn}L_{sn}R_{sn}^3}\right]^2 + \left[\frac{V_{ss}(t)}{3N_{ss}L_{ss}R_{ss}^3}\right]^2}} \quad (7)$$

Finally, having determined α, β, and a, it is easy to calculate the coefficient $d\Gamma/dt$. From Eq. (5a) we get

$$\frac{d\Gamma(t)}{dt} = \frac{-\pi a(t)^3 V_{qn}(t)}{2N_{qn}L_{qn}R_{qn}^2\mu_0\cos[3\alpha(t)-\beta(t)]} \quad (8)$$

The coefficient Γ, which has the dimension of [A.m], can be interpreted as the magnetic strength of the moving current line.

In summary, we have shown that, if the signals picked-up by the quench antenna are assumed to be caused by the motion of a current line, the location of the current line and the parameters of its motion can be derived from Eqs. (6) through (8).

III. MEASUREMENT RESULTS

The measurements presented here were performed on 5-cm-aperture, 15-m-long SSC dipole magnet prototype DCA318. The design features and the cold test results of this magnet have been presented elsewhere [6-8]. This prototype was instrumented with about 55 voltage taps, primarily located on turns 12 through 19 of the inner coils. (The turns are counted starting from the midplane of the two-layer, four-coil assembly. The two inner-layer coils have 19 turns.)

Figure 2 displays the measurement set-up. It includes a pickup coil array consisting of four mole coil assemblies, from which only the quadrupole bucking winding is used, and of one quench antenna. The mole coil assemblies are 1 m in length and are located at intervals of 2.6 m; they are numbered from C1 to C4, starting form the magnet *non-lead end.* (The *lead end* is the magnet end where the current leads are located; the *non-lead end* is the opposite end.) The quench antenna is located between mole C1 and C2, next to mole C1.

The pickup coil array is inserted in the magnet beam tube so that the axial center of the four mole coil assemblies coincides with the magnet center. The normal quadrupole winding of the quench antenna is at an angle of –7.5 degree with respect to the midplane of the magnet coil assembly. The quadrupole windings of the four mole coil assemblies are oriented in the same direction and are at an angle of –21 degree with respect to Q_n. During test, the magnet beam tube is sealed and evacuated. It was verified that the presence of the pickup coil array did not affect the magnet quench performance.

The data acquisition system used for the measurements presented here includes isolation amplifiers with a gain of 10 and a 10-kHz low-pass filter, and a 12-channel, open-reel, analog tape recorder with a dynamic range of 10 kHz.

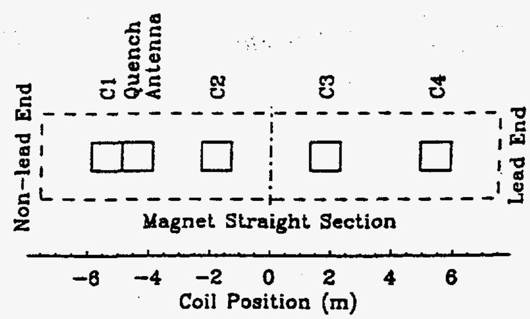

Fig. 2. Measurement set-up.

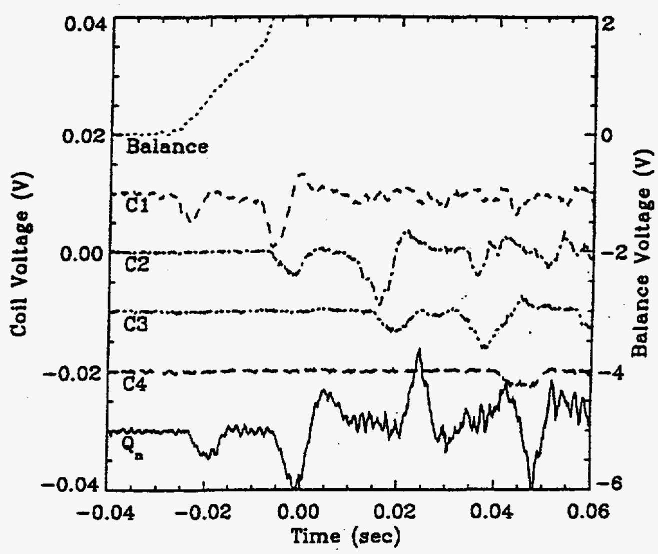

Fig. 3. Example of signals from quadrupole windings of mole coil assemblies and quench antenna for a quench at 6150 A. To clarify the presentation, the traces are shifted along the vertical axis.

Figure 3 shows an example of measured signals for a quench at 6150 A. The current was ramped from zero to quench at a ramp rate of 100 A/s while the magnet was at a nominal temperature of 3.5 K. Analysis of the voltage tap data indicates that the quench originated between turn 1 and turn 12 of the upper inner coil. In figure 3, curves C1 through C4 correspond to the signals from the mole coil assemblies. Curve Q_n corresponds to the normal quadrupole winding of the quench antenna, while the so-called *balance* voltage corresponds to the voltage difference between the upper and lower magnet coils.

Curve C1 and the balance voltage appear to take-off first and almost simultaneously. They are followed by the quench antenna signal and curves C2 through C4, successively. Note that the time interval between the take-offs of curves C2 and C3 and that between the take-offs of curves C3 and C4 are roughly the same. A simple interpretation of these data is that the quench originated within the axial location of mole C1 and propagated at a nearly constant velocity towards the magnet lead end. Assuming a constant propagation velocity, and knowing the positions of the pickup coils with respect to the magnet, it is then possible to determine the axial localization of the quench start. For the quench considered here, the estimate is 1.5 m from the magnet non-lead end.

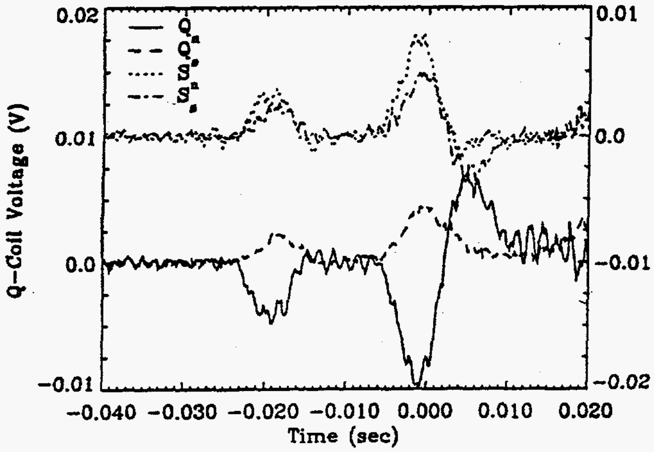

Fig. 4. Quench antenna signals during a quench at 6150 A. Offsets due to isolation amplifiers were subtracted.

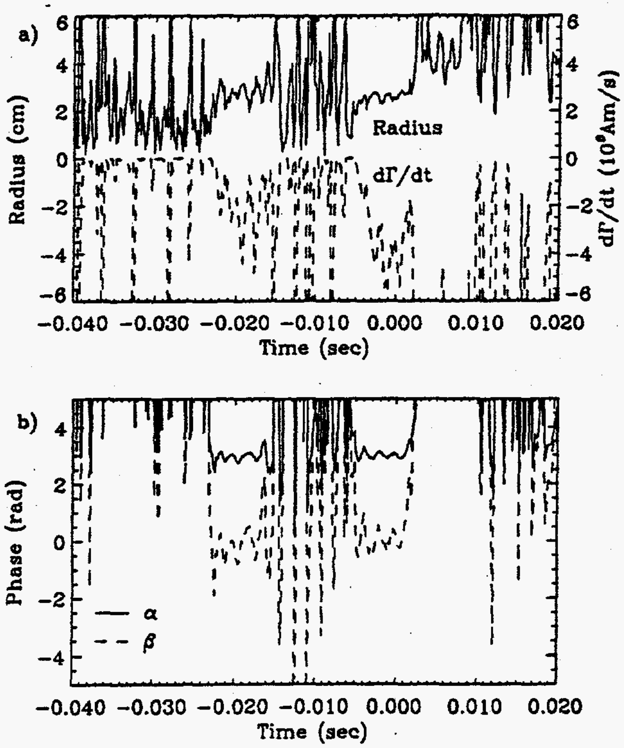

Fig. 5. Calculated parameters of the moving current line during a quench at 6150 A: (a) radius, a, and coefficient, $d\Gamma/dt$, and (b) angles α and β.

Figure 4 presents the signals from the four quench antenna windings during the same quench as in figure 3. The four signals appear to rise at the same time, but their amplitudes and signs are different. It also appears that, after 5 to 10 ms, the four signals die out and start rising again after a time interval of the order of 10 ms. The origin of these two peaks, which are also observed in the curves C1 through C4 of figure 3, is not yet clearly understood. A possible explanation is that the first peak corresponds the propagation of the quench along the quenching turn, while the second peak corresponds to the delayed propagation along the adjacent turn.

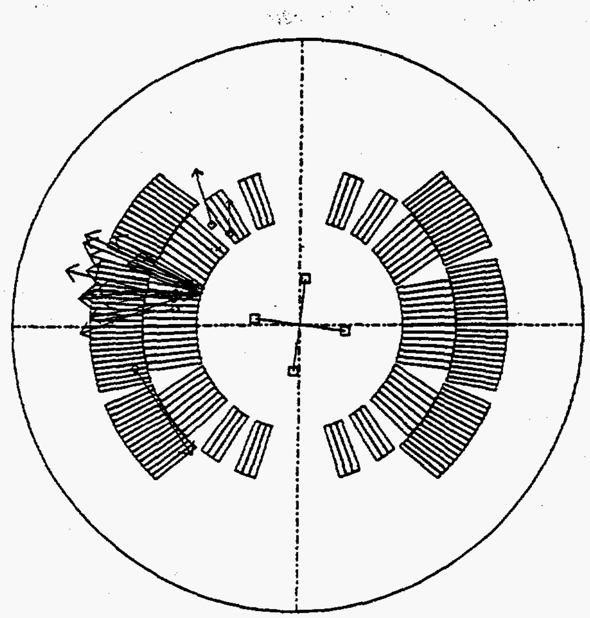

Fig. 6. Location and time derivative of the magnetic strength of the current line for selected data samples corresponding to the first voltage peaks of figure 4.

Figure 5(a) presents a plot of the calculated a and $d\Gamma/dt$ as a function of time for the voltage data of figure 4, while figure 5(b) presents a similar plot for the calculated α and β. It appears, that for times between –25 ms and –15 ms and larger than –6 ms the otherwise large noise on the calculated parameters is greatly reduced. These time intervals correspond to the voltage peaks of figure 4 when actual signals are picked-up by the coils. On average during the first peak, the current line radius and angle can be estimated to be 2.8 cm and 2.95 radian, respectively. (The angle is quoted with respect to the normal quadrupole winding.)

A more visual presentation of the calculated parameters is given in figure 6 which displays the localization of the current line (a) and the direction of its motion (Iv) with respect to the magnet coil assembly viewed from the lead end. Each of the points and arrows of figure 6 correspond to an average over 10 successive data samples; only the data from the first voltage peak of figure 4 are used. The points of figure 6 appear to be clustered at the inner edge of turn 6 of the upper inner coil, while the arrows appear to be directed outwardly. In our model, this means that the current line is moving from the inner edge to the outer edge of turn 6. Turn 6 is thus likely to be the turn where the quench originated.

There are no constraints in Eqs. (6) through (8) which force the current line to be located within the magnet coil. The fact that the calculated current-line locations are clustered, and, for the most part, fall within the same coil turn, tells us that the model we have developed yields consistent and physical results. The fact that the current line appears to move from the inner edge to the outer edge of the cable is more delicate to interpret. A possible explanation is that the quench originated at the cable inner edge, where the field is the highest, and that it forced the transport current to redistribute itself towards the cable outer edge, where the field is lower.

Note, however, that this interpretation is to be taken with caution since the model we developed is very crude and does not take into account the twisting of the cable or the propagation of the quench.

IV. CONCLUSION

We developed and tested a stationary quench antenna consisting of two quadrupole and two sextupole windings. This coil configuration appears to be adequate for determining the azimuthal localization of the quench start in dipole magnets. An array of four quench antennae is now under construction at KEK, which will replace the existing mole coil assemblies and which will enable us to simultaneously monitor the azimuthal and axial development of the quench.

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