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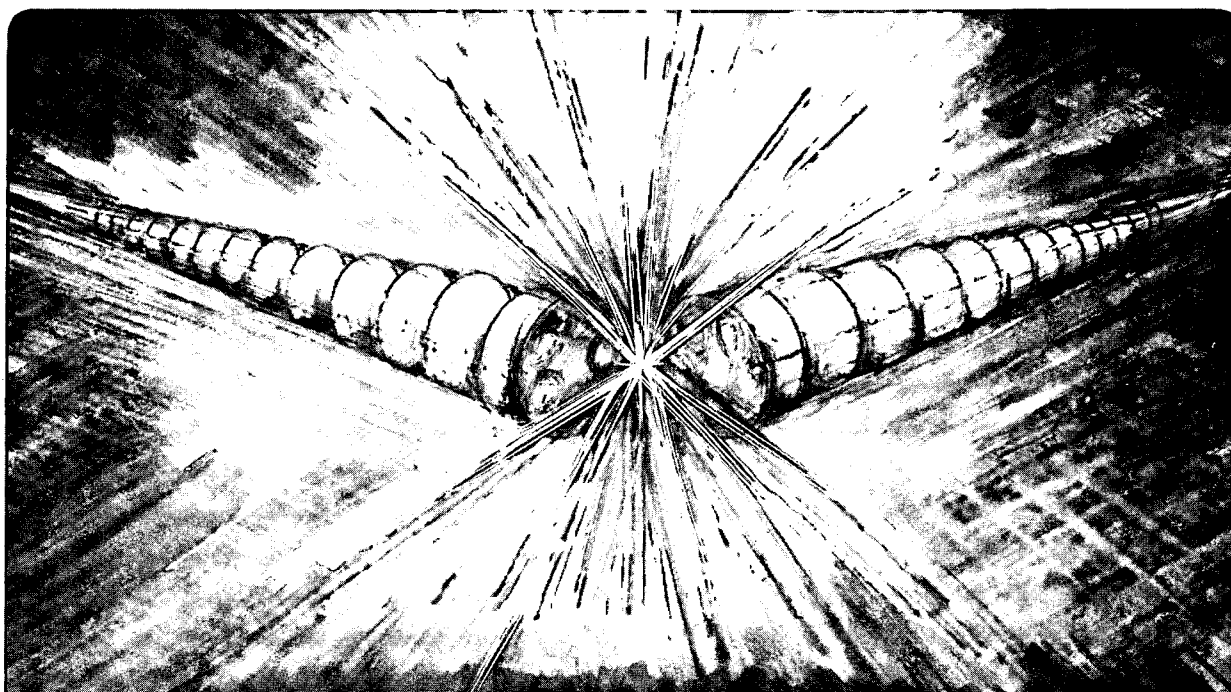
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Quench Antenna and Fast-Motion Investigations During Training of a 7T Dipole

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Abstract- Equipment was installed to detect fast conductor motion and quench propagation in a 1 meter long super-conducting dipole magnet. 1) The fast-motion antenna, centered within the bore of the magnet, used three long dipole coils, mounted end-to-end to span the magnet length. Coil signals were nulled against a neighbor to produce low-ripple signals that were sensitive to local flux changes. A low-microphonic signal was used as an event trigger. 2) Nulling improvements were made for the magnet's coil-imbalance signals for improved cross-correlation information. 3) A quench-propagation antenna was installed to observe current redistribution during quench propagation. It consisted of quadrupole/sextupole coil sets distributed at three axial locations within the bore of the magnet. Signals were interpreted in terms of the radius, angle, orientation, and rate of change of an equivalent dipole. The magnet was cooled to 1.8K to maximize the number of events.

Twenty-four fast-motion events occurred before the first quench. The signals were correlated with the magnet-coil imbalance signals. The quench-propagation antenna was installed for all subsequent quenches. Ramp-rate triggered quenches produced adequate signals for analysis, but pole-turn quenches yielded such small signals that angular localization of a quench was not precise.

I. INTRODUCTION

There has been wide speculation that some of the quenching of a superconducting magnet is triggered by small motions of the current-carrying conductor. In the presence of a strong magnetic field, sufficiently large motions can be expected to generate enough heat to overcome local cooling capabilities, raising the local temperature, hence "quenching" the super-conducting state. Such conductor motions should produce small changes in the local magnetic field, and therefore be observable nearby. Should such motions be visible, localizable, and smaller than needed to quench the magnet, one would be able to provide magnet designers and builders with "magnet training" information unavailable from the analysis of the quench-origins. Correlating such signals with voltage-tap evidence would strengthen our confidence in their interpretation.

There is a similar desire to acquire reliable quench-origin localization capability for coil regions that are not monitored by voltage-taps. This has motivated an interest in using the magnetic evidence of quench propagation [1]-[3] as a means of locating quench-origins. Comparison to voltage-tap data is desired to establish the limits of credibility for this technique.

II. SYSTEM DESCRIPTION

A fast-motion (F-M) antenna was constructed of three dipole coils (30 cm long, 20 turn), mounted coplanar and end-to-end inside a thin-walled stainless steel tube. The tube was sized for insertion into the 50 mm "warm-bore" tube at LBL's Magnet Test Facility and was installed such that the coils spanned the length of the 1 meter magnet.. Each coil's signal was nulled against a neighbor in a manner to simultaneously remove most of the residual power supply ripple and provide differential axial sensitivity. Each nulled signal was amplified by a differential derivative (ac) amplifier (G = 1 @ 16 Hz). All fast-motion antenna signals were passively integrated (RC = 0.1 ms) before entering the 8212A's.

A low-microphonic, fast-motion event-trigger-signal was constructed by nulling the middle coil against a microphonically-nulled average of the two end-coil signals. The resulting signal was amplified by a dc amplifier (G = 134), sent to a window trigger generator, and recorded on a LeCroy 9410 dual oscilloscope operating in the differential mode. The trigger pulse was used to generate a "stop-trigger", which automatically paused magnet ramping when an event was detected, and stopped the slow digitizer (2-LeCroy 8212A's: 64 chn, 1024 pts/chn @ 5 kHz).

The quench-propagation antenna consisted of three diagnostic-coil-sets as in [3]. Every set was 127 mm long, and separated by 310 mm, thereby producing a total span of 1.0 meter. The middle coil-set was positioned near the middle of the magnet, thereby allowing a diagnostic set near each end (Fig. 1). Each coil-set consisted of ten, 5-turn coils: two quadrupole-connected pairs (one pair rotated azimuthally 45 degrees relative to the other) and two sextupole triplets (one triplet shifted 30 degrees relative to the other). The

resulting twelve signals was amplified by a differential amplifiers (G=134).

The magnet chosen for the test was a 1 meter, four coil (2-layer, 1.1 Tesla/kA) dipole magnet which had previously exhibited poor training and poor training-retention (thereby increasing the likelihood of many "training" events). It had been stored at 300K for nearly 1 year in an uncontrolled He environment.

The magnet was equipped with pole-turn voltage-taps (five for each of its four coils, allowing accurate (<5 mm) quench localization for pole-turn quenches (the usual location for training quenches). A voltage tap at each inter-coil splice permitted the observation of coil-coil imbalances. In a manner similar to the fast-motion antenna, differential imbalance signals were constructed by resistively nulling a coil's voltage against a comparable neighbor prior to amplification. Magnet-end grounding constrained this to two signals: Top-Bottom (half-dipole), and Outer-Inner (lower half-dipole). As with the antenna signals, each signal was amplified near its source by a differential amplifier whose output was delivered via shielded twisted-pair to the 8212A's described above, where the signals were sampled and stored until down-loading for storage and viewing.

III. OPERATION

The magnet was immersed in 1 Atm liquid helium, which was cooled to 1.8K to maximize the number of training events. Each antenna was operated at 300K, so it could be inserted and rotated at will. Current ramping began with the fast-motion (F-M) antenna installed and rotated for maximum (PS) ripple amplitude (each coil's axis parallel to the dipole field). Ramping toward the first quench was slow (1A/s), in order to reduce the possibility of missing any fast-motion events. The ramp was automatically paused at each event large enough to exceed the window-trigger threshold. A Polaroid picture of the oscilloscope display (Fig. 1) was recorded, along with the value of the magnet current. The slow digitizer data was down-loaded and stored for later analysis and viewing. Ramping was resumed when more data was desired (with the exception of event #23, where the ramping was restarted from zero). The F-M antenna was removed after the first quench (event # 24).
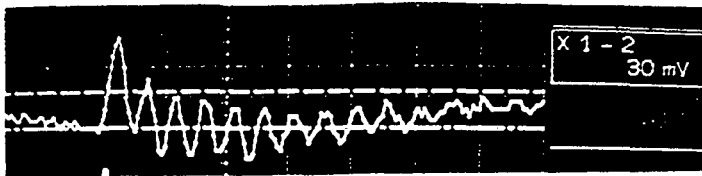

Fig. 1. Fast-Motion Event-trigger (0.5 ms/div, 50 mV/div @ G=134). The ringing was not expected. The significance of the amplitude and frequency requires further study.

The quench-propagation antenna was then installed and oriented relative to gravity. Two "training" (16A/sec) ramp-

rate quenches were recorded as examples of inner-layer pole-turn quenches (one "upper", and one "lower"). Experimentation was terminated after three "ramp-rate" (250A/sec) quenches were recorded in an attempt to observe non-pole-turn quenches. The data was analyzed according to the prescription set forth in [3] (the prescription having been "warm-checked" with a small dipole coil prior to antenna insertion).

IV. OBSERVATIONS

We observed twenty-four fast-motion events (Fig. 2) prior to the first quench. The current at which the events were observed generally increased smoothly except for three instances: 1) Each time we raised the trigger level significantly, we observed a jump in the current at which the trigger event occurred. 2) A small fall-back (#23) was observed the one time we re-started the ramp from zero. 3) The first quench (#24) occurred incrementally higher. Subsequent training quench events (the last three points) showed roughly the same "training" rate.
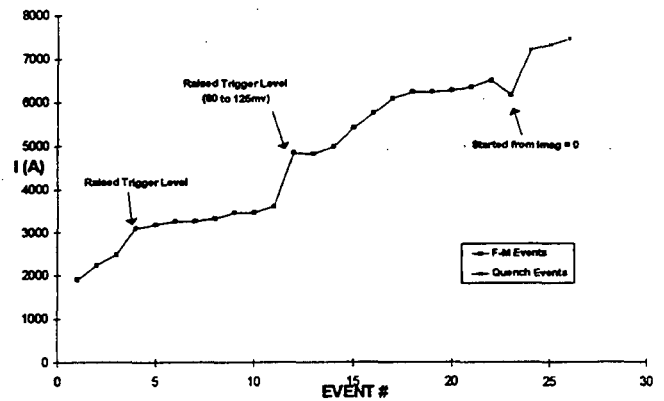

Fig. 2. Training curve: Magnet Current (A) vs. Training Event #. Considerable "training" occurred before the first quench (#24). Restarting the ramp from I=0 (#23) showed only a small fall-back.
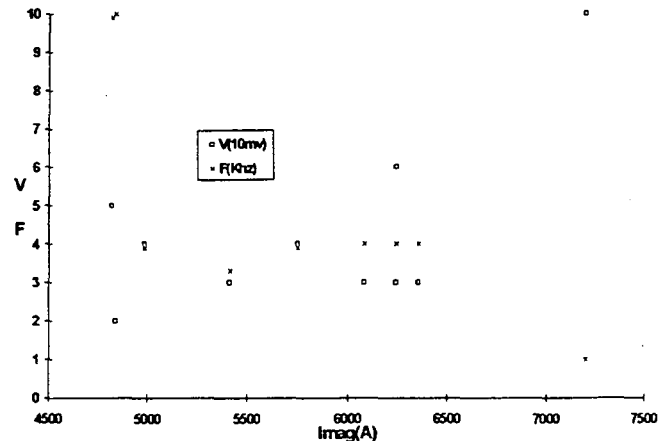

Fig. 3. Fast-Motion: Amplitude & Freq. vs. Magnet Current. The amplitude had little dependence on the B-field, while the frequency decreased. The last point is the only antenna-confirmed, Fast-Motion event observed after quench-initiation.

2

Neither the amplitude, nor the ring frequency of the F-M antenna signal correlated well with the magnetic field (Fig.3). The last F-M antenna point is unique in that it has the lowest frequency, the largest amplitude and started 50 ms after quench-initiation.

Axial differentiation of the F-M antenna signals was easily deducible (Fig. 4), and the imbalance transients were coincident with magnet-coil-imbalance transients (Fig. 5).
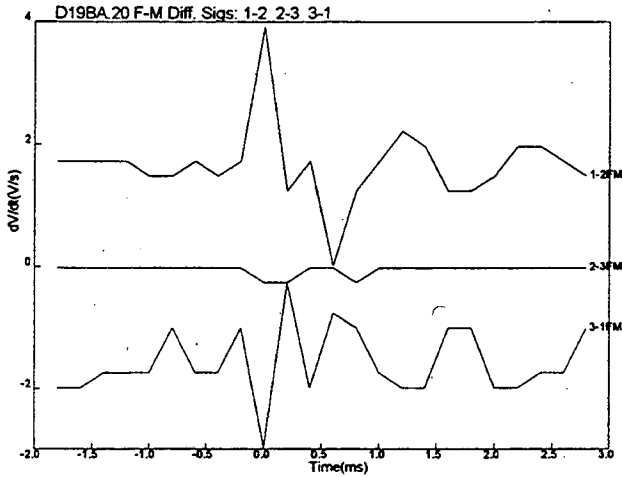

Fig. 4. Fast-Motion: Axial localization is visible from the difference signals of coils #1 (feed-end), #2 (middle), and #3 (return-end). Signal 2-3 is quiet, while 1-2 is a rough inverse of 3-1. Hence, the signal-source is within region #1.

Fig. 5. Fast Motion: The antenna-imbalance (1-2) onset was coincident with one or more magnet-coil-imbalances (both imbalances in this example, same event as Fig. 5).

Fig. 6. 1st quench (#24): The largest fast-motion transient produced the stop-trigger (t = 0) but occurred 17 ms after quench-initiation (BIFs @ t = -17 ms.). A smaller one was coincident with quench onset.

Three "training" (16A/s) inner-pole-turn quenches, and three "ramp-rate-triggered" (250A/s) non-pole-turn quenches were examined. Fast coil-imbalance transients were observed for all quenches (Table 1). Every training quench showed a transient 0-2 ms prior to quench origination, with activity often occurring well after quench onset. For example, we observed our largest fast-motion event 17 ms after the first quench's onset (Fig. 6). No fast-motion activity was observed prior to any of the ramp-rate-triggered quenches.
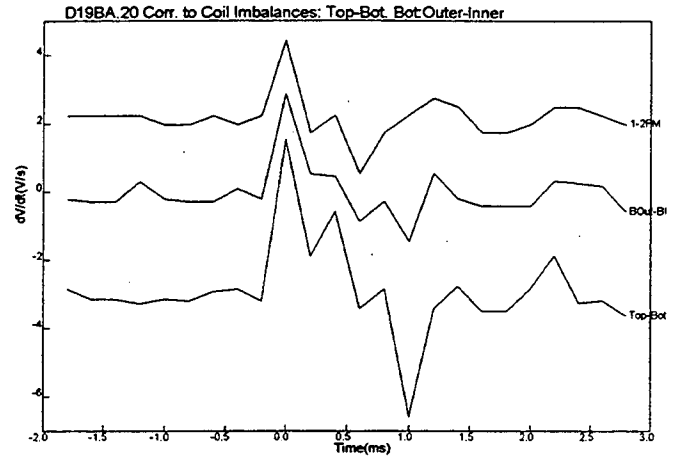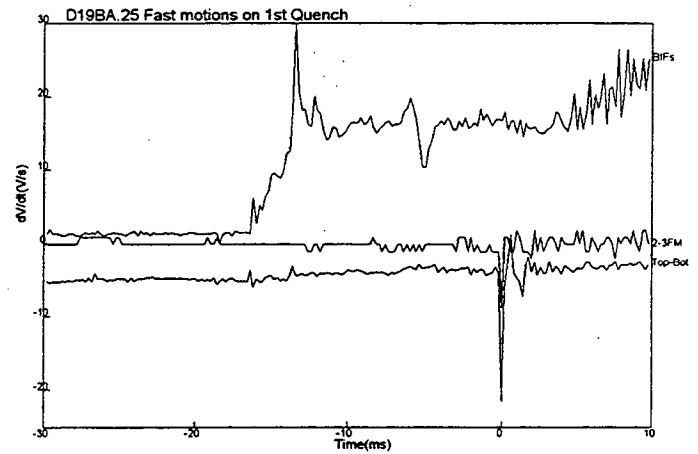
The Quench-Propagation antenna was in place for every quench except the first one, but decent S/N ratios were observed only for the inner-multi-turn quench [TABLE II].

TABLE 1

QUENCH SUMMARY: RAMP-RATE, QUENCH ORIGIN, TIME OF FAST-TRANSIENTS, (FT'S) INFERRED RADIUS AND ANGLE OF QUENCH-PROPAGATION.

Q #	Ramp-rate (A/s)	Quench Origin[a]	FT-1 t(ms)[b]	FT-2 t(ms)[b]	FT-3 t(ms)[b]	FT-4 t(ms)[b]	FT-5 t(ms)[b]	Radius (cm)	Angle (Deg)[c]	V-Tap Angle
1	16	BIFs	-2	-1	0	+3	+17	N/A.	N/A.	N/A.
2	16	BIFs	-2.3	-2	-1.5	+1.4	+42	2.5	-100	-100
3	16	BIFs	-0.5	0	+0.5	+18	-----	2.5	-100	-100
4	250	TIMt	+7	+12	-----	-----	-----	2.6	51.1	> 0
5	250	BOMt	+2	+3	+4	+5	-----	0	+106,-14	< 0
6	250	BOMt	+0.5	+1.5	+2	+2.5	+3	0	13	< 0

[a]Location of the voltage-tap segment, whose derivative signal first stays out of the noise (B = Bottom, T = Top, I = Inner, O = Outer, Fs = Feed-side, Rs = Return-side, Mt = Multi-turn.
[b]Time of fast transient magnet-coil-imbalances relative to quench propagation onset (+/- 0.2 ms, see Fig. 6 for an example).
[c]Angle is from right-hand horizontal midplane, (+)= clockwise, (-)= ccw, viewed from the return end.

Unfortunately, the locations inferred for such a quench could not be checked in detail because of the lack of voltage-taps in this region of the coil. The other quenches produced signals very close to the digital noise of the system (2.4 mV, at the 8212A's input). The uncertainty in the angle is therefore very high for such quenches (because the denominator for the angular relationships in [3] crosses zero). Outer layer quenches gave an r = 0 prediction because the quadrupole signals were so much smaller than the sextupole signals. The noisy angle predictions resulted from the small normal sextupole signal. An angle-drift was observed to be caused by drift in the skew-sextupole signal.

TABLE II
SUMMARY OF QUENCH ANTENNA UNCERTAINTIES

Q#	Q-org. Layer	Q-org. Region	Signal (mV)	S/N Ratio	Error (deg)
2	Inner	Pole	0.1	.25	90
3	Inner	Pole	0.1	.25	90
4	Inner	M-Turn	.2	8	5
5	Outer	M-Turn	0.2	1	60
6	Outer	M-Turn	0.2	1	60

V. DISCUSSION

The ability to observe and axially localize evidence for fast conductor motion significantly increases the amount of information that is available during magnet training and qualification. The jumps in the training curve (Fig. 2) observed when the trigger-level was raised, suggests that there is a range of fast-motion signal amplitudes that can be examined. This is supported by the evidence of fast-motion at the start of the first quench that did not trigger the stop-trigger generator. New questions are raised about the ultimate axial resolution of a disturbance, its length, and its azimuthal location. The frequency variations are interesting. Does the ringing frequency indicate something about the strain state of the conductor, or is it more indicative of the location of the disturbance within the magnet?

The technique of local nulling and amplification before transmission greatly improves the visibility of fast-motion events on the magnet imbalance signals. This allows a layer-by-layer differential localization of a fast motion. Such a decomposition is most straight-forward when the coil voltages are referenced to the center of a 2-layer magnet. It will be interesting to determine whether the magnet imbalance signals reveal the same frequency as the Fast-Motion antenna?

The quench-propagation antenna was not very useful for the training quenches because the observed signals were too small. This is believed to indicate that the current distribution in the normal state and the super-conducting

state were not sufficiently different for the inner pole turn in this magnet. This result was disappointing, because we had hoped to correlate the antenna's deduced quench-origins with locations deduced from the signals from the voltage-taps on the pole-turns.

The erroneous radial prediction (r = 0) and the noisy predicted angles for the outer-layer quenches suggests that this technique has limited validity for any outer layer quenches. This result was also disappointing in view of our upcoming 4-layer Nb3Sn magnet, where non-pole-turn, non-first-layer quenches are very likely, and the need for quench information is amplified by the high cost of the magnet.

VI. CONCLUSIONS

Fast motion antenna imbalances in the magnet bore were easy to observe. Many imbalance events were observed prior to the first quench. The signals were coincident with imbalances that were visible in the magnet coil voltages. All fast-transient imbalances are believed to be caused by small, local conductor motions. As such, they provide a means to locate such conductor motions. Those that occur before quench propagation are especially interesting. The problems and questions encountered during this experiment suggest at least three improvements: 1) faster digitization of the coil imbalances (to adequately record the ringing that might exist), 2) more coils (for better axial localization), and 3) a long quadrupole-sextupole coil-set (to locate the azimuth of any disturbance).

The quench propagation antenna was quite good at pointing to a quench-origin, as long as the location was not a pole-turn (where the signal was too small) and not an outer layer quench (where the inferred location was not reliable, presumably because of image currents).

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