A Full-length Quench Antenna for MQXFA Production Series Quadrupole Magnet Testing

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Abstract—The MQXFA production series quadrupoles being built for the Hi-Lumi (HL) LHC upgrade by the US Accelerator Upgrade Project (US-HL-LHC AUP) will have very limited instrumentation for characterizing quench events that occur during magnet training and performance validation testing. In order to understand the origin of the quenches, and whether they have some implication for ongoing magnet fabrication, it was decided to build a full-length Quench Antenna (QA) with axial resolution of 50mm to be employed during cold testing in the anti-cryostat used for magnetic measurements. The goal is to have fine-resolution, full-length coverage detection of quench events axially, as well as to have azimuthal resolution on the order of the cable width (about 1 degree for the cross-section), in a device that can be used both for vertical and horizontal testing. To achieve this, a 5 m long QA with 128 channels of high-speed data acquisition has been designed and fabricated. The cylindrical antenna features an array of 12 full-length, dipole- and quadrupole-bucked coils positioned radially in the QA interior for azimuthal localization, and over 100 individual channels of short, high-sensitivity, antennas etched as flexible PCB circuits (which also buck dipole and quadrupole fields) wrapped circumferentially on the cylinder exterior in steps of 50 mm along the magnet length for axial detection. This paper discusses the design, construction and analysis of the MQXFA QA, and first results from using the antenna during quench testing in the production magnets.

I. INTRODUCTION

As part of the US-HiLumi Accelerator Upgrade Project (AUP), Fermilab, together with BNL and LBNL are fabricating 20 4.5 m-long Nb3Sn superconducting magnets to be used in the interaction regions of the LHC. These magnets are undergoing vertical test at Brookhaven to verify performance specifications before being sent to Fermilab for incorporation, pair-wise as a cold-mass, into cryogenic vessels, where they will be tested once again horizontally in their final configuration. Since these are production magnets, a minimum of diagnostic voltage taps used to characterize quench events are included during assembly, as these add risk and substantial time to fabrication and test schedules, and, if the production run is going well, in principle would not need to be employed. However, quenches are not uncommon as part of normal quench training procedures, and information on the details of quench events could be used to understand something about the fabrication process and even provide feed-back which could improve it. With the twin goals of minimizing impact on magnet construction and yet fully capturing quench information, a full-length quench antenna that can be placed in the anti-cryostat used for magnetic measurements has been fabricated at Fermilab for characterization of quenches during the vertical cold magnet testing at BNL. The quench antenna design which achieves complete 4.5 m axial coverage with fine resolution (~50 mm in straight section and 25 mm resolution in the ends), no dead zones, and which also has azimuthal localization capabilities, is described in detail herein, along with presentation of first results.

II. MEASUREMENT APPROACH

A quench developing in a superconducting magnet causes distortion in the local magnetic field because of current redistributions and/or motions in the cable. These small changes in field can be detected by a stationary wire pick-up loop of suitable sensitivity. Such a loop, or an array of such loops, is typically referred to as a ‘quench antenna’ (QA) [1]. Besides the quench induced changes, power supply ripple or fluctuations can cause substantial field changes which can obscure the QA signal, and so the effects of these field fluctuations need to be suppressed, or ‘bucked’ (as is typical in magnetic measurement probes [2]), as much as possible by using a combination of loops that yield a net low sensitivity to
quadrupole and dipole fields (DQ-bucked antennas). In order to achieve full coverage for the MQXFA magnets, two types of induction-sensitive QA are employed in a single device: quench antennas along the axis (referred to as Z-antennas, or ZQA) and antennas distributed azimuthally (so-called theta-antennas or TQA). The DQ-bucked ZQA are made with short axial extent so that they provide local detection of quenches with high resolution. Sensitivity to quenches throughout the magnet is then achieved by having a large number of ZQA distributed along the length. In order to also determine the angular position of the MQXFA quenches, DQ-bucked TQA are radially positioned within the interior of the quench antenna cylinder. These are full-length in order to limit the total number of channels of data acquisition.

For the Z-antennas, bucking is achieved by a sextupole-symmetric pattern of loops etched onto a flexible Printed Circuit Board (PCB). The sensitivity of the pattern to the quench event will depend on the angular position of the quench, and since the alternating 6-fold loop pattern will have regions in theta where the sensitivity is at or near zero, panels overlap by half the width and length of the loops to insure there are no gaps in sensitivity.

The bucking for the theta-antennas is accomplished with a radial configuration which suppresses the low order fields [2].

A quench event can be modelled as the appearance of a current line representing a new and shifted location of current within the magnet cable cross-section because of the development of a resistive zone, or more precisely, as that plus an oppositely signed current line that similarly represents the absence of current where it once flowed. This pair of current lines can be taken as causing the change in the field from the quench event, and, knowing the geometry of a wire loop in the vicinity, can be used to calculate the induced voltage observed in the loop (Fig. 1).

The field from a current line can be found from Ampere’s law

\[ B(z) = \frac{\mu_0 I}{2\pi \times (z - a)} \]

where here the \( z \) and \( a \) are complex positions in the coordinate cross-section of Fig. 1. The resultant voltage on the antenna can be found by applying Faraday’s law with the above B field over all lengths of wire \( L_j \) within the antenna which see the quench at their respective positions \( z_j \):

\[ V = \sum_{j=1}^{N_{\text{wires}}} -1 \times L_j \frac{\mu_0}{2\pi} \frac{dI}{dt} \ln(z_j \times (-1)^j) - a) \]

Assuming a radial current re-distribution distance of 1 mm (neighboring strand), and finding \( dI/dt \sim 2e5 \) A/s from the ~500 A current expected in a strand at high field with 1-2 milliseconds observed redistribution time, the voltage excursion expected can be found for various antenna designs. For the as-built ZQA, the voltage expected from a quench event would be on the order of 40mV, and for the TQA, about 100 µV.

### III. Design

The quench antenna (QA) has a 4.8 m active length and 5.2 m overall length, to provide full quench detection coverage for the 4.5 m long MQXFA04 magnet with 4.2 m straight section. The 12 TQA are distributed in theta every 30 degrees in the QA interior, underneath the circumferentially wrapped ZQA, and extend the full 4.8 m active length of the probe. With this length, making rigid or flexible printed circuits with high density becomes very costly. Instead, we made the full-length TQA out of ribbon cable with small circuit boards at each end to create the DQ-bucked circuit from the 25 mm-wide, 40 conductor cable (Fig. 2). IDC (Insulation Displacement Connectors)-type connectors are used to minimize soldering. The 40 wires become 4 separate loops with 10 wires (5 turns) each, and are connected so as to buck dipole and quad fields.

![Fig. 2. A model of the 3D-printed ‘spiders’ used to support the ribbon cables and connectors that comprise the Theta Quench Antennas.](image)

To compensate for the weak sensitivity of these few turns, the TQA channels are outfitted with 1000x gain amplifiers (based on AD8221BR) included on the lead end PCB which makes-up the circuit of each TQA. These are located inside the QA, upstream of the external cables and readout electronics.

The ribbon cables of the TQA are sandwiched in lightweight plastic stiffener and supported along the QA length every 150 mm in 3D-printed ‘spiders’. The spider supports are aligned and glued onto the 33 mm OD central carbon-fiber core which bears the mechanical load of the assembly. The spiders also have areas which serve as conduit for the cabling of all channels. A view of the partially assembled QA, with TQA and amplifiers visible, is shown in Fig. 5.

The ZQA are 6-fold symmetric as wrapped around the TQA to form a ~300 mm circumference cylinder. The sextupole configuration bucked dipole and quadrupole. There are 6 independent circuits, each going across the width of the flexible printed circuit panels. Each of the circuits in turn has 6 sets of ‘racetrack’ windings connected in series with alternating...
chirality, with 132 turns (66 per layer) on each track. Each track is 100 mm long and 50 mm wide, for a total panel size of 600 mm x 300 mm. The panel thickness is 0.2 mm (Fig. 3).

The overlapping of panels mentioned in Section II is by half their width and length in the body region of the QA, resulting in ZQA resolution of 50 mm, when the quench angle is such that the signal appears on both overlapped panels, or, if the quench is exactly at one of the minima, resolution of 100 mm. A length of 0.5 m at each end of the QA has higher density of ZQA with resolution 25 mm nominal (50 mm worst-case). This assures that the fine resolution extends into both ends of the magnet if the QA is placed within 0.15 m of magnet center. A view of the panel overlapping is shown in Fig. 4.

Given the overlap throughout, and double density in the ends for finer resolution, a total of 20 of the ZQA panels were needed to cover the 4.8 m QA, extending from Z= -2300 mm to Z= +2500 mm as positioned in the MQXFA04 magnet.

The signals are brought out on individually-shielded twisted pair cables, with shielding extending all the way to the data acquisition system. Data acquisition consists of a rack with 128 channels of 16-bit resolution, simultaneously sampled, National Instruments ADCs running at 100 kHz sampling frequency.

The TQA, over-wrapped by the ZQA, are enclosed within a carbon-fiber tube with 98 mm OD and 95 mm ID, which comfortably can be placed within the 103 mm ID anti-cryostat used during cryogenic testing of MQXFA for magnetic measurements. A swivel hoist ring is placed at the top of the antenna for craning it into position vertically. The overall weight of the quench antenna is less than 20 kg.

A polypropylene tube also runs the full length of the antenna so that warm-up gas can be delivered to the bottom of the anti-cryostat. The partially assembled QA is shown in Fig. 5.

First quench tests on MQXFA04 were conducted in August 2020 with the Quench Antenna installed. The results of the quench testing are presented elsewhere at this conference [3]. A total of 8 quenches occurred in MQXFA04, 6 of which have recorded QA data. The quench is detected at "t=0" and some number of "pre-quench" ADC samples are saved in the circular data buffer. For 5 out of 6 quenches, the pre-quench data extend back in time to -0.1 s. The last quench, Quench #8, had pre-quench data going back to -0.5 s.

IV. RESULTS

Fig. 6. Raw ZQA Voltage signals, Quench #1 (60Hz filtered)
Sample raw data are shown in Fig. 6 for Quench #1. Note that signal names represent their location relative to the start of the QA, thus "Z1500" is 1500 mm from the start of the active portion of the QA.

The data of Fig. 6 are unfiltered except for 60 Hz multiples. At first, more extensive filtering was applied to suppress the apparent noise and make the quenching segment stand out. However, in examining the signals at the end of the antenna, it was found that ZQA which extended past the end of the antenna showed very little noise, though these had the longest cables of the QA. This suggested that the "noise" seen in the other axial antenna channels was actually induced voltage signal being picked up from current redistribution/vibrational motion during excitation.

Representing the data in a surface plot (Fig. 7) allows for the first time a view of flux redistribution events along the entire magnet as a function of time. It is noted that there are several regions in $z$ that have high activity during more than one quench, and that the quenchs observed in this magnet are located in these same areas.

Fig. 8 shows data from Quench 2, which has moved to center, where some activity was seen in Quench 1. The region where Quench 1 occurred now has low activity, evidencing these measured voltages are not merely noisier signals.

The voltages can also be integrated to show accumulated flux over time, which can be a more salient quench indicator, with the voltage offset being removed from the QA voltage before integration by averaging the first 50% of the signal (Fig. 9).

Both the voltage and flux ZQA results provide clear localization of activity for all the quenches of MQXFA04, as represented by the quenches included here, with localizations within the designed 25-50 mm resolution for all 6 recorded quenches. The data also show evidence of quench propagation within the magnet (see Fig. 10).
Theta antennas (TQA) also detect some activity in all quenches. Analysis is still ongoing to compare this with partial voltage tap data and determine angular position and resolution.

The TQA data have been further filtered to help extract the weak, amplified signal. An example is shown in Fig. 11 for Quench #6; note that with 1000 gain amplification, the TQA signal size of Fig. 11 is on the order of the ZQA signal of Fig. 9. The angular variation at the time slice where the quench occurs (~ -10 ms) is similar to the calculated expectation from the simple model of Section II, as shown in Fig. 12.

Note also that the angular offset of the ZQA can additionally provide some azimuthal location information. The relative sensitivity to one angular position of antenna relative to its overlapping neighbor, shifted by 30 degrees, would indicate a maximum that is closer in angle to the position of the first.

Quench locations of MQXFA04 are summarized in Table I.

V. Conclusion

In summary, it appears that the Z quench antennas have very low noise and high sensitivity – allowing simultaneous measurements of current redistributions as a function of time over the entire magnet - and thus offering a new window on quench development and current redistribution events. The theta antennas also find angular location of quench, but owing to noise and signal size, may be more limited in angular resolution.

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References