Quench Location in the LARP MQXFS1 prototype

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Abstract— The high luminosity upgrade project US LARP/HiLumi has successfully tested the first 1.5 m prototype quadrupole MQXFS1 at Fermilab' Magnet test facility. Several thermal cycles and test programs were performed, with different pre-load configurations. To localize and characterize quenches a quench antenna and voltage taps are used. The quench antenna was placed inside a warm bore of an anti-cryostat centered in the magnet. We varied the length between quench antenna segments from 1” to 6”, and shifted the location of the antenna to localize the quench origin along the various wedge and spacers transitions in the lead end of the magnet. We present results on the identified quench locations for the second and third thermal cycle in this paper.

Index Terms— Accelerator magnets, quench, quench propagation, training.

I. INTRODUCTION

T he LARP collaboration and CERN have developed the MQXF series Nb3Sn quadrupoles (150 mm aperture, 132.6 T/m gradient) for the LHC luminosity upgrade [1]. Among others, several short prototypes with a magnetic length of 1 m were designed [2,3]. An extensive testing campaign at FNAL for MQXFS1, the first prototype, was conducted to ensure it matches performance expectations [4–8]. Three different test cycles with varying axial and azimuthal pre-stress were conducted, testing new quench protection as well as quench training and memory and field quality studies. During these tests, the quench locations in the coils were recorded using voltage taps and a newly developed quench antenna. The goal was to identify potential weak spots in the magnet performance or mechanical design as well as to study the quench training and quench propagation.

A quench antenna is a device to localize quenches non-invasively and to measure their propagation dynamics. The antenna used for MQXFS1 is based on a design presented in [9] and is described in more detail in [10]. A quench is localized by detecting the gradient of the axial field component in the magnet bore arising from a normal zone formation in the superconducting cable. The antenna consists of two pairs of dipole-buckled pickup coils. Pairs are orthogonal to each other in the sensor’s x-y plane. A warm bore (“anti-cryostat”) with 130 mm inner diameter allows to place the antenna in the magnet bore. The antenna location in the warm bore can be adjusted, so varying coverage along the magnet bore (z-axis) is possible. The elements of the quench antenna are separated by spacers to detect time derivatives of dB/dx and dB/dy, as indicated in Fig. 1 with 2 cm accuracy, presented previously with a fixed spacer length of 6 inches. In this paper, we show

Fig. 1. (a) A sketch showing quench propagation in a Rutherford cable. The normal zone expands to the right causing “leakage” of the solenoidal field form the cable interior, as well as current redistribution near the normal zone boundary. Both effects can be simulated as a set of current loops building up along the cable length. When quench front passes along the antenna pickup coil (shown in dashed line) an inductive signal is generated.

(b) The transient inductive voltage calculated for a 25x25 mm-sized rectangular pickup loop placed at x0=55 mm from the quenching cable.

Fig 2. A photograph of the assembled antenna board (single element).
the results from extensive studies with varying spacer lengths and positioning of the antenna around the magnet center and the lead end region of the magnet.

II. QUENCH ANTENNA CONFIGURATIONS

A. Antenna configuration and functionality

The antenna was designed such that multiple elements can be stacked to cover different MQXF series magnets with magnetic lengths of 1, 4.2 and 7.15 meters. For this test, the antenna was equipped with 8 elements, each made from a 4-layer 0.6 mm-thick printed circuit board, and were 95 mm in diameter. As shown in Fig. 2, each board has two dipole-bucked pair of sectorial 90-degree wide flat coils that rotated by a 180 degree angle (coil pairs are denoted as “ab” and “cd”). The boards are connected by a flat ribbon cable for power supply and signals, a connector box allows to connect the antenna to the FNAL quench data acquisition system. For reduction of parasitic electromagnetic noise in the warm bore due to the magnet test facility, the entire flat ribbon cable is encased by a copper-mesh shield and the coil areas on boards were laminated at one side with a ground-terminated 0.1 mm-thick aluminum foil. The fully assembled antenna section is shown in Fig. 3 (top), using 6 inch spacers for an antenna length of 107.1 cm. This ensures full length coverage of the MQXFS1 magnet straight section (100.2 cm), with a small overlap to the coil ends. To center the quench antenna, the mechanical center of the magnet was used as shown in Fig. 4. Shown in the Fig. 3 (bottom left) is how the quench antenna location is fixed on the warm bore; a 4 inch tall plastic cone (in blue) is used to guide the magnetic probe and quench antenna into the warm bore, a dry nitrogen vent prevents ice buildup in the bore, two G10 half

Fig. 4. A schematic of the mechanical quench antenna centering. The magnet inside the FNAL test stand is at a depth of 116.285 inches w.r.t the mounting bracket that clamps the quench antenna in place. A comparison with the magnetic center shows a displacement of 0.345 inches.
sphere compress on the antenna rod fixing its location along the z-axis. A comparison between the mechanical and magnetic center shows a shift of 0.345 inch between the two. For the second set of measurements of the MQXFS1 magnet, the quench locations happened mostly in the lead end (LE) of the magnet, where only one antenna segment was located.

In order to help further localize the quench location, we decided to reduce the distance between antenna segments, and cover only the LE area. The shortened quench antenna with 5 segments at 1 inch distance, and three segments at 2 inch distance each, is shown in Fig 3 (right). Shown in Fig. 5 is the time evolution of the quench antenna location in the frame of the MQXFS1 magnet. After modifying the antenna length, the antenna was placed such that it was covering the LE of the MQXFS1 magnet. The quench antenna covered the turns inside and outside the middle pole spacer. Several quenches at this position were recorded. The quench location was mostly around the straight section wedge in coil 03 near the LE in a multi-turn segment. Examples for two quenches are shown in Fig. 8. As the wedge and pole spacer transition was a possible point of interest for quench origination, the antenna location was adjusted again to center one antenna segment over this transition. The observed signals indicated a quench location very close to the first segment’s xy plane. For that reason, we decided to set all segments to a 1 inch spacing and cover only the LE, with the center of the antenna at the wedge transition.

To further localize the quench origin, we tried to rotate the quench antenna 45 degrees, such that the dipole-bucks coil...
segment face parting plane (mid plane) between coils the instead of the pole, as indicated in Fig. 6; further analysis to study the effect is needed.

In Fig. 7 we overlay boxes of the various quench locations as indicated by the quench antenna segments. The number in the center associate the quench time (MM/DD HH:MM), quench antenna identification and the coil number. The boxes in the image are utilizing information obtained from the voltage taps; they indicated a quench origin near the pole and first wedge transition, where a change in materials could explain quench origins. For two quenches the location was in the lead end turn, yet it is not clear where, thus the larger rectangular box. The analysis for the third run is pending. Most quenches occurred in coil 03; overlaying the quenches and extending the boxes with a five percent shading creates a quench density map. Most quenches occur on the wedge and pole spacer transition.

III. CONCLUSION

We have extensively tested and modified a quench antenna developed for the MQXF magnet series for localizing quenches in high-field accelerator magnets. Thanks to the 2 cm resolution of the quench antenna and the voltage tap information we were able to identify the axial localization of quenches in the wedge to end-spacer transition area of the coils. While we were not able to distinguish between transition and non-transition side of the coils, the obtained data proved the working principle of the antenna and provided useful input for the future design and assembly of the MQXF magnet series.

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REFERENCES


