# HTS Quadrupole for FRIB - Design, Construction and Test Results

Ramesh Gupta, Michael Anerella, John Cozzolino, Piyush Joshi, William Sampson, Peter Wanderer and Al Zeller

***Abstract*— This paper presents the outcome of significant magnet R&D that was started over a decade ago towards solving one of the most critical issues in the design of the Facility for Rare Isotope Beams (FRIB) and resulted in the successful demonstration of a full size prototype HTS quadrupole for the fragment separator region. This magnet will be subjected to unprecedented radiation and heat loads. An HTS quadrupole, with more than a 12 K margin over the nominal 38 K operating temperature, provides a unique solution. After briefly presenting the design and construction, the test results will be discussed in more detail. An advanced quench protection system was able to protect the magnet against an accident which caused thermal run away (or quench) is also discussed. The magnet uses a significant amount of HTS from two leading manufacturers. The successful demonstration should encourage the use of HTS magnets where one must deal with a large amount of radiation and/or energy deposition.**

***Index Terms*—FRIB, HTS, HTS magnets, Quadrupole, Superferric.**

## I. Introduction

HTS quadrupole magnets are now part of the baseline design of the FRIB [1], [2] fragment separator region. HTS magnets provide a unique solution [3]-[12] to the large radiation (~10 MGy per year) dose and heat loads (over 200 Watts). Compared to a conventional low temperature superconducting magnet operating at ~4 K, the second generation design, built with second generation (2G) superconductor and operating at ~38 K, can remove large heat loads more efficiently. With large temperature margin, HTS magnets are also robust against large local and global heat loads. Earlier radiation damage studies performed have shown that the Rare Earth, Barium, Copper Oxide (ReBCO) conductor is highly radiation tolerant [9] with a lifetime of over 10 years even in an FRIB environment. To demonstrate that more than one vendor can satisfy the project requirements, coils from two HTS manufacturers, SuperPower (SP) [13] and American Superconductor Corporation (ASC) [14], were built as a part of technology demonstration. The second generation magnet follows work after the successful demonstration of the first generation design which was built with the first generation HTS, Bismuth strontium calcium copper oxide (Bi2223), supplied by American Superconductor Corporation, and designed to operate at 30 K.

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## II. Design

The overall magnet design is guided by unprecedented heat load and radiation tolerance requirements [3], [7]. All magnet parts can withstand this high radiation for over ten years, with most, including turn-to-turn insulation, being metallic. The warm iron design minimizes the heat loads on the superconducting coils. The magnetic design with a contour plot superimposed on the conductor and the iron (part of the iron removed for clarity) is shown in Fig. 1.

The main components of the mechanical structure [11] are the stainless steel clamps around the coil and the stainless steel plates in the ends. By virtue of these components, the coils are self-supporting against Lorentz forces. Cooling is provided by helium gas flowing through the holes in the support structure with special piping which cools both the body and the ends of the magnet. The mechanical structure, with cryostat over the coil and exiting leads, is shown in Fig. 2. The magnet is designed to be remotely serviceable so that the coils, if damaged during the operation, can be replaced without humans entering the high radiation environment (see Fig. 3).

TABLE I: Design Parameters of the HTS Quadrupole

| Parameter | Value |
|---|---|
| Pole Radius | 110 mm |
| Design Gradient | 15 T/m |
| Magnetic Length | 600 mm |
| Coil Overall Length | 680 mm |
| Yoke Length | 546 mm |
| Yoke Outer Diameter | 720 mm |
| Overall Magnet Length | ~880 mm |
| HTS Conductor Type | Second Generation (2G) |
| Conductor Vendors | Two (SuperPower and ASC) |
| Conductor width, SP | 12.1 mm ± 0.1 mm |
| Conductor thickness, SP | 0.1 mm ± 0.015 mm |
| Cu stabilizer thickness SP | ~0.04 mm |
| Conductor width, ASC | 12.1 mm ± 0.2 mm |
| Conductor thickness, ASC | 0.28 mm ± 0.02 mm |
| Cu stabilizer thickness ASC | ~0.1 mm |
| Stainless Steel Insulation Size | 12.4 mm X 0.025 mm |
| Number of Coils | 8 (4 with SP and 4 with ASC) |
| Coil Width (for each layer) | 12.5 mm |
| Coil Height (small, large) | 27 mm (SP), 40 mm (ASC) |
| Number of Turns (nominal) | 220 (SP), 125 (ASC) |
| Field parallel @design (maximum) | ~1.9 T |
| Field perpendicular @design (max) | ~1.6 T |
| Minimum $I_c$ @2T, 40 K (spec) | 400 A (in any direction) |
| Minimum $I_c$ @2T, 50 K (expected) | 280 A (in any direction) |
| Operating Current (2 power supplies) | ~210 A (SP), ~310 (ASC) |
| Stored Energy | ~40 kJ |
| Inductance | 0.45 H (SP), ~1.2 (ASC) |
| Operating Temperature | ~38 K (nominal) |
| Design Heat Load on HTS coils | 5 kW/m$^3$ |

The magnetic and the mechanical designs have been described in more detail previously [10], [11] with the major parameters shown in Table 1. The conductor from ASC is a 4-ply tape with two HTS tapes soldered together. Since the thickness and properties of the two conductors are significantly different from each other, the coil design also had to be different. The magnet in the present state therefore requires two power supplies.

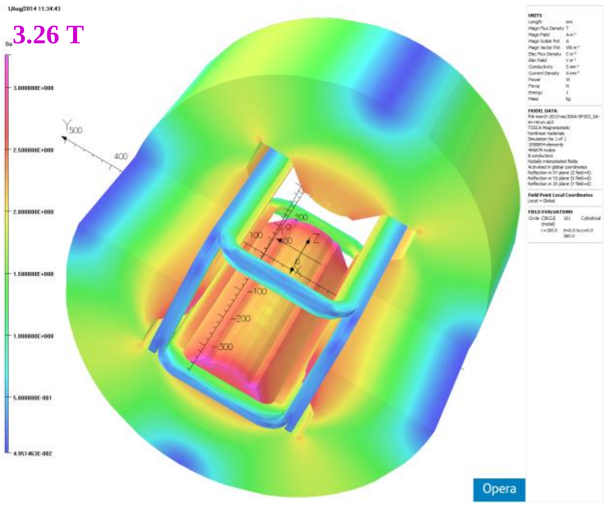


Fig. 1. Magnetic design with field contours superimposed on iron and coil.

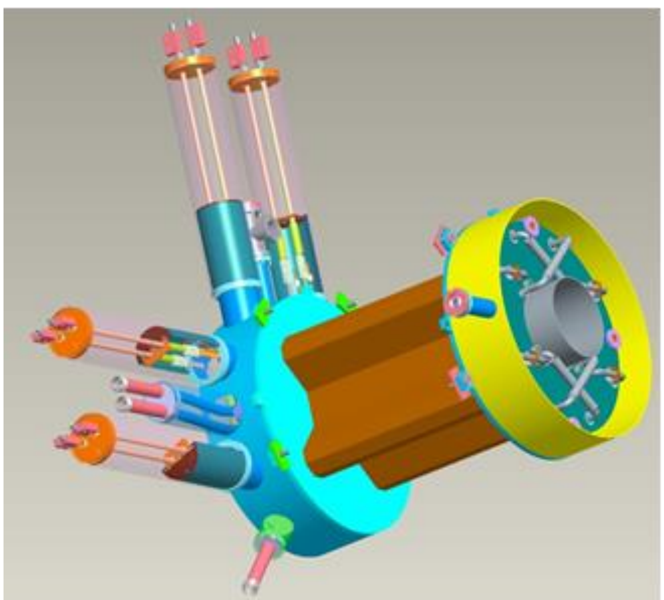

Fig. 2. Mechanical design with cryostat and Leads (yoke hidden for clarity).

## III. Construction

The coils were co-wound using a computer controlled coil winder (Fig. 4) with ~12 mm HTS tape and slightly wider stainless steel tape serving as turn-to-turn insulation. A number of voltage taps were installed for initial coil testing which were removed for the final magnet assembly. Each of the smaller four coils was made with approximately 330 meters of ~12 mm wide SuperPower tape and each of the larger coils was made with approximately 220 meters of ~12 mm wide ASC double tape (2 X 200 = 440 meters of single tape). The configuration of double tape was such that the superconductor was facing out. One coil made with ASC tape did not need splicing as the conductor was delivered in sufficient length. All other coils needed one or two splices.

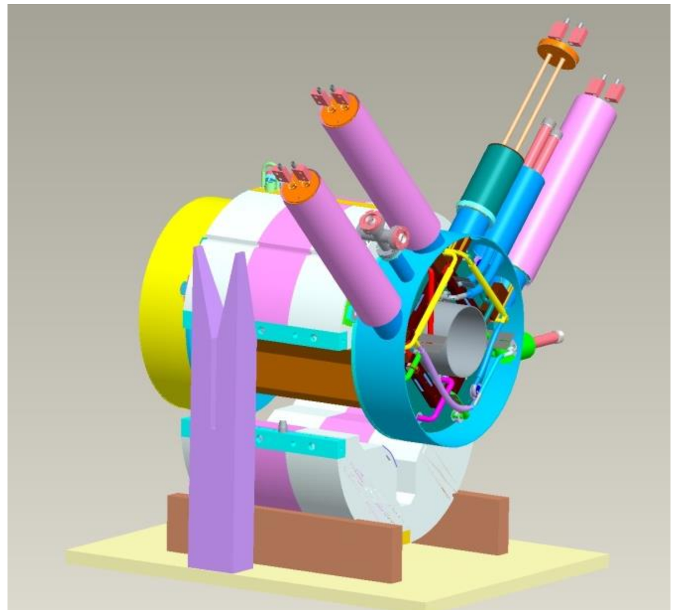

Fig. 3. A remotely serviceable magnet design.

Fig. 4. A racetrack FRIB coil being wound on computer controlled coil winder.

Assembling eight coils in the special support structure was an involved task. Eight practice pancake coils were wound with stainless steel tape for the trial assembly. Coils assembled in the support structure (including end plates) are shown in Fig. 5. The coils in this structure were tested at 77 K before the structure was installed in the iron yoke (see Fig. 6) for a cold iron test. For the warm iron test, the cryostat will have to be installed around the coil (see Fig. 2).


Fig. 5. Coils in support structure consisting of clamps and end plates.

Fig. 6. Fully assembled FRIB quadrupole with support structure and iron yoke (cryostat for warm iron test is not yet installed).

## IV. Quench Protection

In HTS magnets, quench protection has been a major area of concern [15]. In medium field magnets, such as this, it is a relatively less demanding issue. However, one requires a fully reliable system for use in an accelerator. This has been and continues to be a major area of R&D on FRIB magnets. HTS coils have low quench propagation velocities compared to typical LTS coils. However, the use of stainless steel tape as insulation has a major advantage as it aids in distributing energy faster after the quench. A key part of the program has been the development of advanced quench protection electronics [15], as shown in Fig. 7. It allows the detection of the pre-quench phase after which the energy is extracted quickly, well before the conductor can be damaged. This will be discussed in more details in the next section.

## V. Test Results

Even though the magnet will be operated at ~38 K, testing at 77 K with liquid nitrogen plays an important role as it provides a low cost critical quality assurance test of each coil. First we discuss tests at 77 K with liquid nitrogen and then tests at a range of temperatures in a gaseous helium environment.

### *A. Testing at liquid nitrogen temperature*

Each coil was tested at 77 K. Individual coil tests were performed with a very simple vessel of Styrofoam which can be filled with atmospheric-pressure liquid nitrogen, as shown in Fig. 8. Fig. 9 shows the cryostat for testing coils in a support structure at 77 K (Fig. 5). It consists of a stainless steel container placed inside a wooden box with space in between filled with insulating foam.

Fig. 9 shows eight leads of four double pancakes which, with two power supplies, allowed the testing of each double pancake either individually or in a variety of configurations.

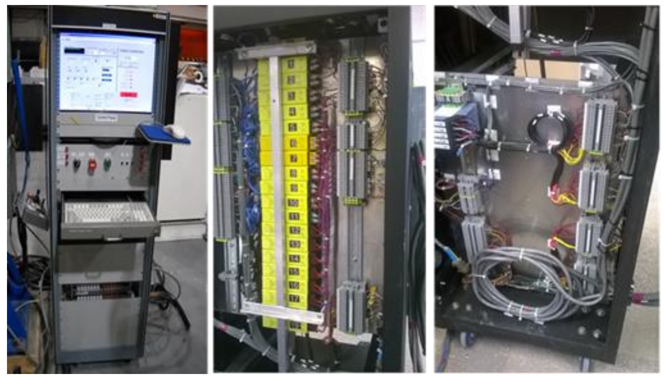

Fig. 7. Elements of advanced quench protection electronics developed at BNL for testing HTS magnets.

Fig. 8. Simple vessel made with Styrofoam for testing individual FRIB coils at 77 K in liquid nitrogen.

Fig. 10 summarizes the performance of each single pancake in the double pancake structure. The current in ASC coils is divided by two to account for the two tape configurations. Even though the test current was usually limited by one of the two single pancakes, we were able to see the onset of resistive voltage in all pancakes. A large number of voltage taps helped in analyzing the performance and locating the area of concern in detail. One coil (SP coil 3) stand outs in performance. Initial linear onset of the voltage was attributed to the splice joint and later non-linear rise to the conductor in one region of the coil.


Fig. 9. A cryostat made of a stainless steel container installed inside a wooden frame, filled with insulating foam in between.

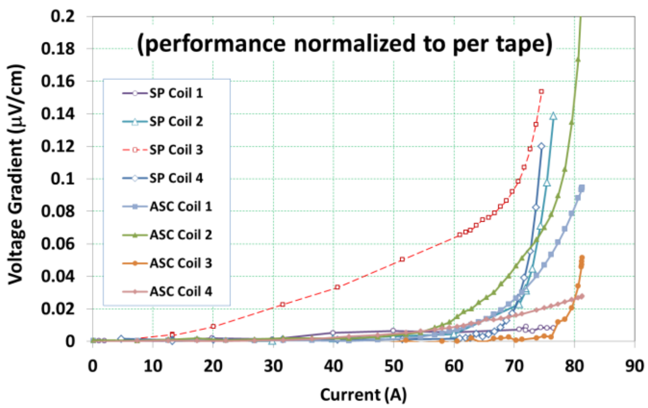


Fig. 10. Measured voltage gradient as a function of current in eight pancake coils. The current in ASC coils is divided by two to normalize the plot to single pancakes.

## *B. Testing with helium gas*

The magnet was installed in the vertical test facility (see Fig. 11) to perform the lower temperature testing. Initial tests were performed at 77 K in liquid nitrogen, and then at ~65 K after reducing the temperature by pumping on the nitrogen. In later tests, a certain amount of liquid helium was injected at the bottom of the dewar and then the magnet was allowed to reach an equilibrium temperature with no additional liquid helium injected. Since the whole magnet (coil and iron) is cooled by helium gas, this test corresponds to a cold iron configuration (rather than warm iron configuration, as in the machine design). Nevertheless, this provides a critical test of HTS coils at the design field. The test setup had eight leads brought out which allowed independent powering of each double pancake coil or powering them in a variety of coupled configurations. Two power supplies were used during this test to allow different current and ramp rates for the coils made with the conductors from the two vendors. A significant system of diagnostics (about hundred voltage taps, eight temperature sensors, etc.) was installed to monitor the performance in detail. Most of the diagnostics will be removed after the final test.

An extensive testing program (which included energy deposition experiments utilizing the heaters installed between two single pancakes of the double pancake coil) was carried out in two separate test runs. The performance of each double pancake coil (either when powered alone or when powered with others) was measured at various temperatures. Generally, there was little impact on the critical current of individual coils, either when powered alone or when powered with other coils. In this paper we summarize selected test results.

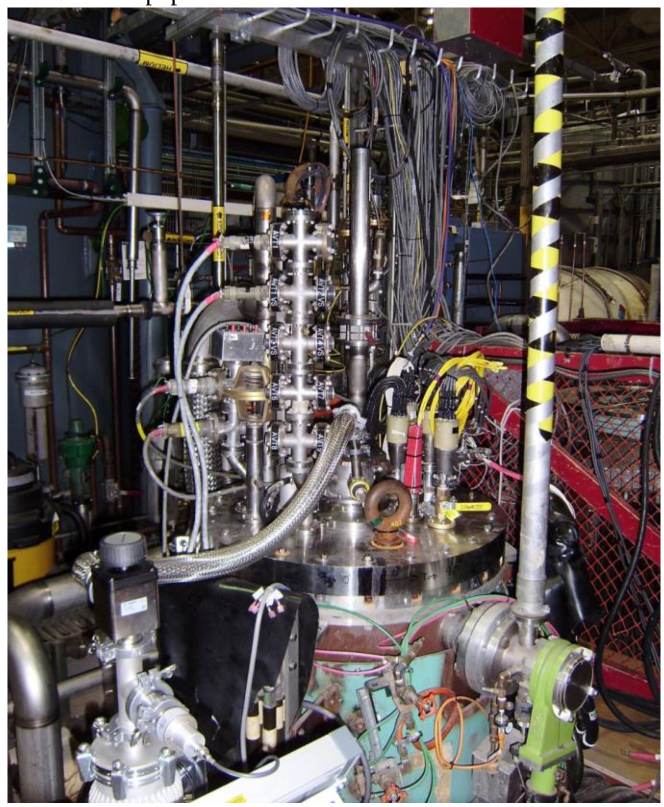

Fig. 11. FRIB HTS quadrupole installed in vertical test facilities with a significant diagnostics instrumentation.

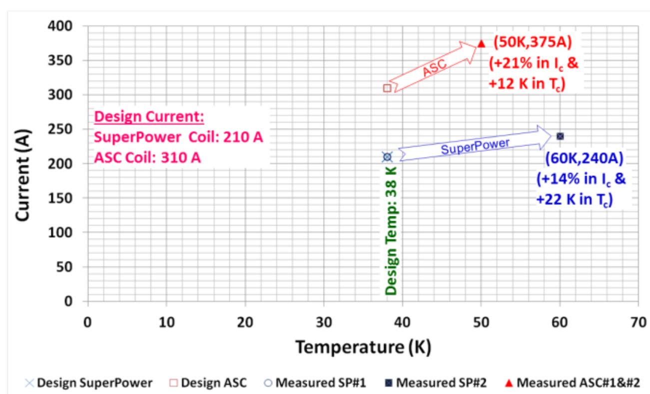


Fig. 12. Test points for coils made with conductor from SuperPower and ASC showing a significant operating margin both in current and in temperature.

The operating temperature is 38 K; the design current for coils made with SuperPower conductor is 210 A and for coils made with ASC is 310 A. The coils made with conductor from the two different manufacturers are expected to have different temperature and/or current margins. Fig. 12 shows one test point for each when the two coils are operated well beyond the design value. With 240 A at 60 K, coils made with

SuperPower HTS had 14% margin in current and 22 K temperature. With 375 A (limited by test setup and not the coil) at 50 K, coils made with ASC conductor had over 22% margin in current and 12 K in temperature. Such high operating temperatures and also such large temperature margins are only possible with HTS.

A balance has to be made between the desire to prove that the magnet can survive various failure modes on a test bench and has sufficient safety margin and the desire to use this particular magnet in the machine. The rest of the discussion in this section is to address the above issues, to understand the behavior of HTS coil before, during and after the quench and to demonstrate that the quench protection system is able to protect the coil in the event of an accident.

Fig. 13 shows the ramping of all coils in the nominal quadrupole configuration at approximately 67 K. One can see the inductive voltage on the coil during the ramp. The quench protection system software is able to distinguish between the inductive and resistive voltage at the level of 1 mV (for example by taking the difference between similar coils and/or by subtracting computed inductive voltages) and protect the magnet by shutting down the power supply and extracting the energy. However, during this particular current ramp, we let the resistive voltage rise first to about 15 mV and then to about 50 mV (see Fig. 13), both well above the quench detection threshold of about 1 mV. Most of this voltage appeared in the section of the coil that was previously identified during 77 K test. The resistive voltage continued to rise but did not cause a run-away situation (or quench) and eventually leveled off at about 120 mV. After this test, the coils showed no sign of degradation. Even though these tests were done at approximately half of the design field, the fact that the magnet safely operated in what we call “a semi-resistive region”, with resistive voltage more than two orders of magnitude over the quench detection voltage is reassuring.

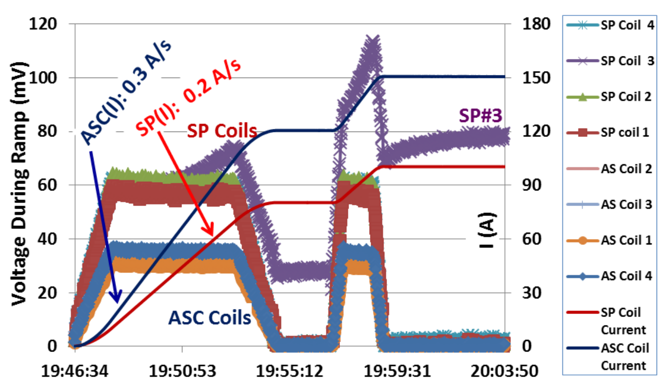


Fig. 13. Ramp and hold of the FRIB HTS magnet (with all coils powered in nominal quadrupole configuration) at a temperature of ~67 K.

Another potentially fatal event occurred not according to the test plan but by accident. A vacuum leak developed which caused the temperature rise to ~57 K which is well beyond the design operating temperature of 38 K. At that time, the coils made with SuperPower HTS were being ramped up (see Fig. 14) and the system was able to detect a quench at the millivolt level (by taking the difference between the two pancakes), shut-off the power supply and extract the energy with later tests showing no degradation in the performance of the coil. Such unexpected events or accidents could happen during real operation and the ability of the system to protect the magnet against them increases the level of confidence in the technology. It may be noted that at ~185 A, coils with SuperPower HTS were close to their design current of 210 A. Fig. 14 also shows the voltage across the coil in the slow data logger (recording at one point per second) before, during and after the event (the ringing is related to the power supply which the system was able to handle). The actual event (exceeding the quench detection threshold with difference criterion), which was captured in the fast data logger (recording at one point per millisecond), is not presented here. These signals can be compared with those observed in conventional low temperature superconductors.

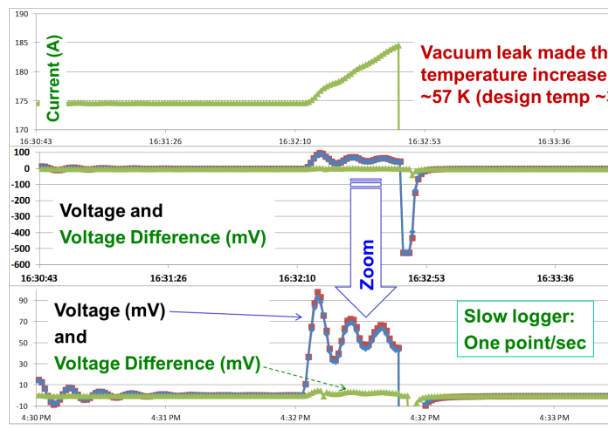


Fig. 14. Current and voltage signals of an event when the quench protection system detected a quench in coils during the ramp at mV level (difference voltage) and protected the coil made with SuperPower HTS. The increase in temperature was caused by an accidental vacuum leak.

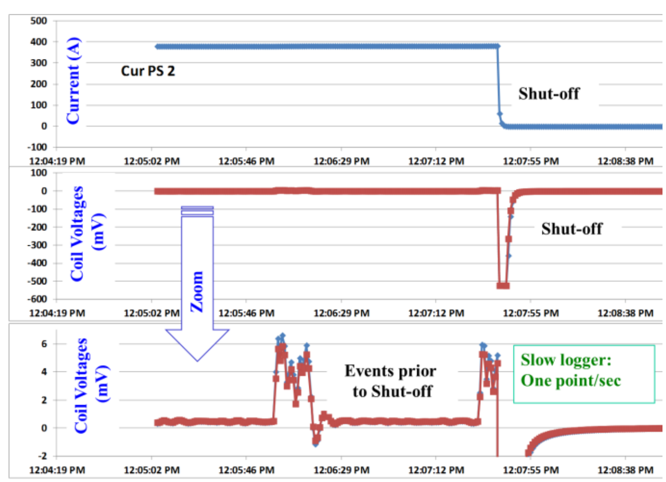


Fig. 15. Current and voltage signals of an event in slow data logger when quench protection system detected a quench at the mV level when the current was held constant at 382 A in the coils made with ASC HTS (design current 310 A). The dewar temperature was at ~50 K.

Fig. 15 (slow data logger, one point/second) and Fig. 16 (fast data logger, one point per/ms) show an event in which the current was held constant at 382 A in the ASC coils at ~50 K (design current is 310 A at 38 K) and the quench protection system detected a quench (as per the criterion set), shut-off the power supply and extracted the energy. One can see activities in the slow data logger 1 to 2 seconds before the shut-off and the actual event in the fast data logger (see difference voltage in Fig. 16) at approximately 40 to 60 milliseconds before the shut-off. These may be the signals of flux jumps, as also seen in conventional low temperature superconductor coils. Since the difference voltage had decreased to a safer level (see Fig. 16, 70 milliseconds onwards), the magnet would have continued to operate safely (as was the likely in the previous case recorded in the slow data logger in Fig. 15), however, the quench protection system correctly acted as per the criteria set. Part of the stored energy was extracted and part was absorbed by the coil. It is good to know that it did not cause any damage.

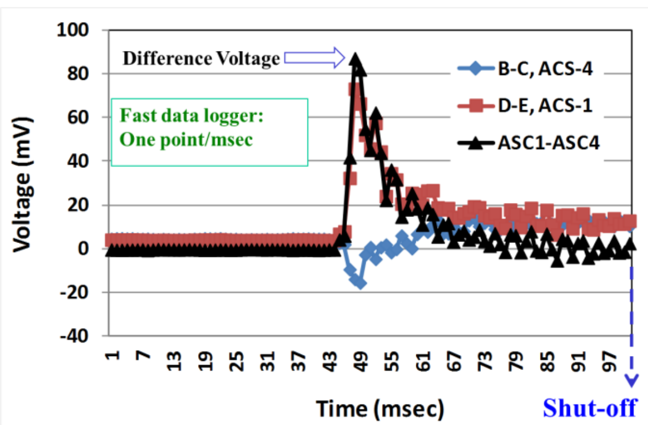


Fig. 16. Current and voltage signals of an event in the fast data logger when the quench protection system detected a quench (based on difference voltage) at mV level when the current was held constant at 382 A.

## VI. Future Work

Having demonstrated that the basic HTS magnet design and the radiation resistant technologies developed are suitable for the fragment separator region of FRIB, the next major task is to build a cryostat and demonstrate the magnet performance with warm iron operation based on the design already developed. The heat load to be removed at ~38 K is much lower in the warm iron design. Since the test environment is different in a warm iron test (where the coils are cooled by conduction from the support structure) than from the cold iron test (where a small amount of helium gas is present into the dewar environment), a new set of tests would need to be carried out. A similar study was performed in the first generation HTS quadrupole [8] also.

The magnet, as to be delivered to FRIB, must be compatible with the design of their remote handling tooling. The design will be carefully examined and required features will be incorporated.

The lower performing coil (SP coil #3) may be replaced. Even though it meets the design specifications now, it might get degraded over time.

We also continue to perform quench and other failure mode studies in separate coils which are not part of this magnet and hence may be allowed to be damaged to determine the operating limits.

## VII. Conclusion

HTS magnets provide a unique solution to the unprecedented radiation and heat loads anticipated in the magnets in the fragment separator region of FRIB. A successful demonstration of the radiation tolerant superconducting magnet design that can also withstand large energy deposition represents a significant advancement in magnet technology that can be used in a variety of future applications. The magnet has used a significant amount of conductor (~9 km of 4 mm HTS tape equivalent) from two leading conductor manufacturers. With a measured temperature margin of well over 10 K, it would provide a robust operation margin against local and global thermal excursions. A variety of tests were performed over a wide range of temperatures. The quench protection system was able to protect the coils in all cases, including a case when during current ramping, the temperature rose unexpectedly due to an insulating vacuum failure. The next phase of the program involves building a cryostat to demonstrate this design in a warm iron configuration.

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