DOI: 10.1109/TASC.2021.3069047
FERMILAB-CONF-21-095-TD
(accepted)

TEST OF SUPERCONDUCTING WIRES AND RUTHERFORD CABLES WITH HIGH SPECIFIC HEAT

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***Abstract*— High-field accelerator magnets made of state-of-the-art Nb_3Sn Rutherford cables demonstrate relatively long trainings due to sudden heat depositions originated by thermo-mechanical perturbations in the magnet coils. Coil sensitivity to these perturbations can be reduced by increasing the specific heat, C_p, of major coil components - strands, or whole cable, or epoxy. The R&D on all these three approaches is in progress. This paper studies feasibility of increasing the C_p of Rutherford-type cables by using a thin composite Cu/Gd_2O_3 tape. The tape can be either wrapped around the cable, placed on the cable wide faces under the insulation, and/or inserted as a core. Cu/Gd_2O_3 ribbons with ~30% of Gd_2O_3 powder and two different thicknesses were produced by Hyper Tech Research, Inc. Wire and cable samples outfitted with these high-C_p ribbons, or tapes, were prepared and tested at FNAL for the Minimum Quench Energy (*MQE*). At 80%I_c, the *MQE* gain average over the tested magnetic field range of the NbTi cable with high-C_p tape on both sides was ~1.3. The *MQE* gain average of the NbTi wire wrapped with the high-C_p ribbon was 3.1.**

***Index Terms*— Rutherford cable, critical current, NbTi, Nb_3Sn, Minimum quench energy.**

I. INTRODUCTION

A major focus of Nb_3Sn high field accelerator magnets R&D for high energy physics (HEP) is on significantly reducing or eliminating their training by understanding its underlying physics mechanisms and demonstrating practical solutions [1]. In short models of Nb_3Sn accelerator magnets, the first quench (i.e., transition from superconducting to normal phase) generally occurs at 60–70% of the short sample limits and more than 20 quenches are required to reach the magnet nominal field [2]. Training duration is expected to further increase for full-scale magnets, since the number of quenches grows with magnet length, as observed for NbTi and Nb_3Sn accelerators magnets, and in superconducting undulators. Superconducting (SC) magnets quench when their temperature increases above the current sharing temperature of the composite superconductor over a large enough volume. The temperature increase ΔT is proportional to Q/C_p, where Q is the dissipated heat, and C_p is the volumetric heat capacity. Energy deposition that initiates quenches can emanate from a variety of sources (magnetic flux jumps, conductor motion, epoxy cracking, etc.). Other sources of magnet training are materials and material interfaces, such as insulation, impregnating material, and neighboring structural materials. All these sources contribute to a resulting "disturbance spectrum".

The idea to increase a superconductor's stability, often based on its Minimum Quench Energy, or *MQE*, by inserting high specific heat (high-C_p) elements in superconducting wires dates to 1960 [3]. In the mid-2000s, a considerable improvement in stability to pulsed disturbances was obtained for NbTi windings, when distributing large heat capacity substances on the conductor during winding [4], [5]. Tests were performed with both small NbTi coils made of wire and larger windings made of Rutherford cable. The *MQEs* of the mixed coils were several times higher, and thermal efficiency was greatest for temperature diffusion times much smaller than the disturbance pulse duration. More recently, Hypertech (Fig. 1, right) and Bruker-OST have attempted to introduce high-C_p elements in their Nb_3Sn wire design [6].

An alternate approach is to introduce high-C_p materials in the Rutherford cable itself. Hyper Tech recently produced a high-C_p ribbon by rolling down the Cu/Gd_2O_3 high-C_p tubes used for their wires. Samples of this tape of 10 mm width and two different thicknesses were used in this study with the following goals:

1. Measure the effect on stability of NbTi wires and NbTi Rutherford cables outfitted with the high-C_p tape by comparing their *MQE* at various magnetic fields with that of bare NbTi wires and standard NbTi Rutherford cables.
2. Look for relative correlations between wire and cable tests.

NbTi has a T_{c0} of 9.8 K and B_{c20} of 14.5 T, and was chosen for this first study since sample preparation is simpler than for Nb_3Sn, allowing for a faster turnaround of results.

A simple calculation shows that the reduction in engineering critical current density is about 10% for a Rutherford cable of 15 mm or larger width, made of 1 mm strands and wrapped with 100 μm thick high-C_p tape. It is about 20% for the high-C_p Nb_3Sn wire in Fig. 1 (right).

Demonstration of an approach to increase the C_p of SC magnets using new materials and technologies is very important both for particle accelerators and light sources. It would improve thermal stability and lead to much shorter magnet training, with substantial savings in machines' commissioning costs. The increase of cable C_p will slow down

The work is supported by Fermi Research Alliance, LLC, under contract Nos. DE-AC02-07CH11359 with the U.S. Department of Energy.

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both quench detection in the magnet and coil heating after a quench. Therefore, quench protection is not impacted. However, if this were not correct, the use of a separate high-C_p element such as this Hyper Tech tape in a Rutherford cable allows applying it only in the highest magnetic field regions, i.e. closest to the superconductor critical surface.

II. Experimental Methods

A. *Strand, Cable and High-C_p Ribbon Parameters*

Fig. 1, left, shows a picture of an Hyper Tech high-C_p ribbon produced with thicknesses of 89 µm and 64 µm for FNAL. Fig. 1, right, shows for reference an example of alternate approach, i.e. a Nb_3Sn wire with the seven most internal and the six corner subelements replaced with high-C_p Cu/Gd_2O_3 tubes [6], [7]. The ribbons were the first attempt of this kind by Hyper Tech, and they were obtained from Cu/Gd_2O_3 high-C_p tubes used for their wires. The tubes that were selected for this feasibility experiment had 30% Gd_2O_3 in volume as a reasonable estimate of what could be technologically achieved.

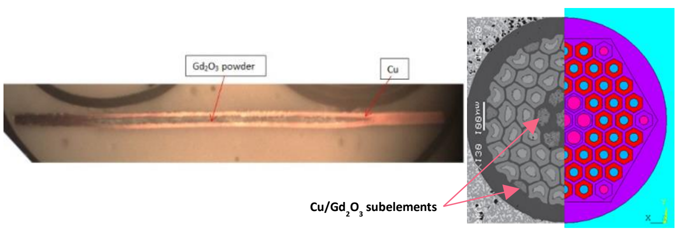

Fig. 1. Left: Cross section of Cu tape with Gd_2O_3 inside, 30% of the cross section is Gd_2O_3 (courtesy of Hypertech). Right: Hyper Tech Sn-in-Tube Nb_3Sn wire with 48 regular Nb-Sn subelements and 13 high-C_p ones made of Cu/Gd_2O_3 [6], [7].

The *MQE* of standard Rutherford cables and NbTi cables outfitted with the Hyper Tech tape were measured at FNAL in the experimental configuration described thereafter. Table I shows parameters of the NbTi and Nb_3Sn cables that were tested. The *MQE* of the NbTi wire extracted from NbTi cable ID1 and of an extracted NbTi wire outfitted with the high-C_p ribbon were also measured in the experimental configuration described in the following. The NbTi wire had a 0.8 mm diameter and 1.3:1 Cu-to-non-Cu ratio.

TABLE I
Tested Cable Parameters

Cable ID	Cable N x d, mm	Strand Type	Bare Cable t_{mid} x w, mm^2	Insul. Cable t_{mid} x w, mm^2	Lay angle, deg.
1	37 x 0.8	NbTi	1.490 x 15.52	1.743 x 15.76	16
2	40 x 0.7	Nb_3Sn	1.253 x 14.69	n/a	15

B. *Strand I_c and MQE Tests*

For both critical current, I_c, and *MQE* measurements, ~2 m long samples of NbTi wire are wound on grooved cylindrical Ti-alloy (Ti-6Al-4V) barrels and held in place by two removable Cu end rings.

Voltage–current (*V–I*) characteristics are measured in boiling He at 4.2 K, in a transverse magnetic field, in a cryostat from Oxford Superconducting Technologies (OST) with 15T/17T 64 mm cold aperture solenoid, 1875 A power supply, and 49 mm Variable Temperature Insert (VTI) for testing between 1.5 K to 300 K. In standard wire critical current, or I_c, measurements, three pairs of voltage taps are used. Two pairs are placed along the center of the spiral sample 50 cm and 75 cm apart, and one pair at the Cu leads to be used for quench protection. The I_c is determined from the *V–I* curve using an electrical field criterion of 0.1 µV/cm. Typical I_c measurement uncertainties are within ±1%. The measured I_c value is used when performing the *MQE* measurement at various normalized transport current ratios $I/I_c(B)$.

To measure the wire *MQE*, strain gauges are used as heaters. Strain gauges WK-09-125BT-350 from Micro-Measurements are glued to the samples using Stycast, with the gauge patterns (~4 mm in length and ~1.5 mm in width) centered on the wire (see Fig. 2, left). After curing of the Stycast, the instrumentation wires are soldered before sample and strain gauge get brushed with a thick layer (~1 mm) of Stycast. A 200 W BPO KEPCO 200-1 power supply provides the excitation voltage to the strain gauge. Using a LabView DAQ program, a 200 µs-long pulse output is generated from the power supply and the voltage across the strain gauge is measured. With the I_c of the sample first measured, a constant bias current below I_c is applied to the sample and heat pulses are fired using the strain gauge. A separate quench protection monitors the voltage across the sample and shuts down the power supply if the quench threshold is reached. By gradually increasing the pulse energy, the minimum energy that induces a quench is defined as the *MQE* of the sample. The measurement error is given by the difference between the *MQE* achieved value and the energy provided to the heater at the previous step, at which the sample was not quenching yet. For the wires in this study it was between -0.7% and -3.7%.

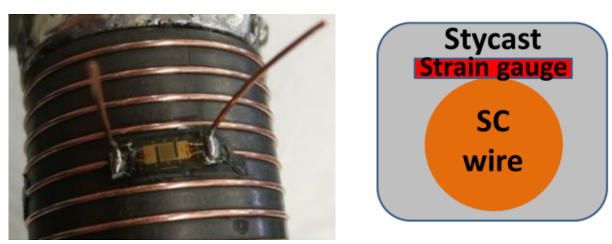

Fig. 2. Strain gauge used as heater mounted on wire (left) and experiment schematic, showing the strain gauge mounted on a SC wire (right).

To commission the *MQE* measurement system and achieve reproducibility, several SC wire samples were used [7]. For reproducibility, the most important factor is good thermal contact between the heater and the sample.

The NbTi extracted wire was tested bare and wrapped with the high-C_p ribbon after cutting it down to ~1 mm width, as shown in Fig. 3 for a different round specimen.

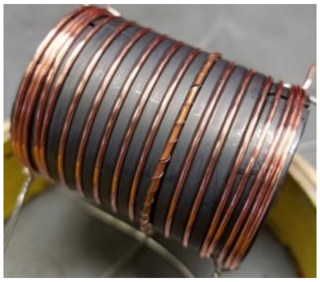

Fig. 3. NbTi superconducting wire sample wrapped with Hyper Tech high-C_p tape cut down to ~1 mm width, along half a turn of the specimen.

Fig. 4 shows as an example the specimen voltage signal during the *MQE* test of the bare sample of NbTi wire extracted from cable ID1 at 6 T and 90% of I_c (6T), with input pulse energy at the *MQE* value. In Fig. 4 the sample voltage rises sharply as soon as the quench develops, with a simultaneous drop of the sample current. This is due to the sample power supply, operated in constant current mode, whose current reduces to adjust to the larger resistive load seen by the test probe. In the subsequent sample heating stage, the current starts recovering based on the voltage limit of the power supply. The sample power supply then drives the current to zero when the voltage measured on the leads reaches a threshold value. The measured MQE for this NbTi wire was 888 μJ.

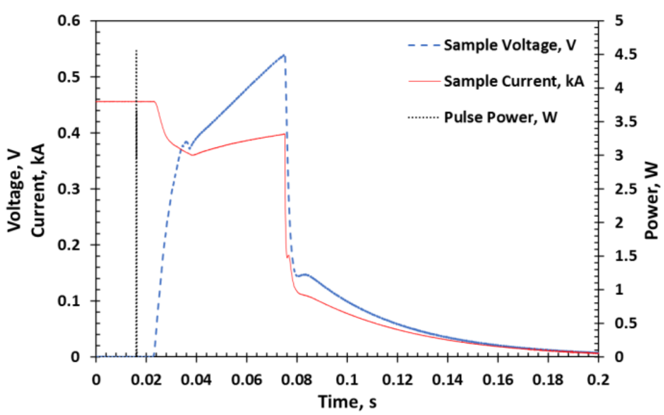

Fig. 4. Sample voltage signal obtained in the *MQE* test of the bare NbTi extracted wire at 6 T and 90% of I_c (6T) with input pulse energy at the *MQE* value. Pulse power and sample current are also shown.

Fig. 5 shows the specimen's resistance, or more accurately the sample voltage over current ratio, obtained in the *MQE* test of the bare NbTi wire at 6 T and 90% of I_c (6T). In Fig. 5, the initial increase of the resistance corresponds to quench development in the wire sample, whereas the subsequent increase of the resistance with lower slope corresponds to sample heating. The sharp peak in the *V/I* signal corresponds to the shut-down of the power supply. The resistance subsequently starts slowly decreasing due to sample cooling.

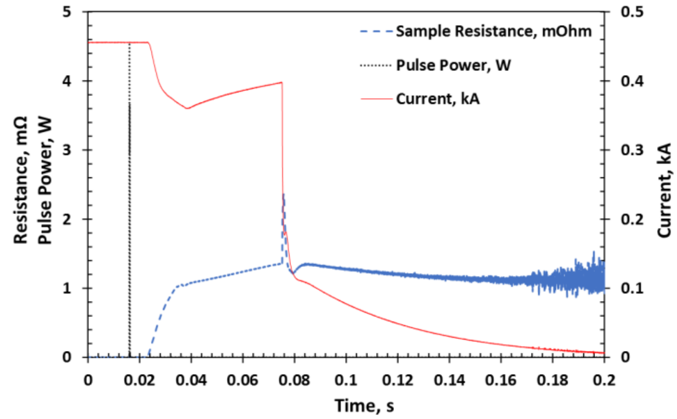

Fig. 5. Sample resistance, or more accurately sample voltage over current ratios obtained in the *MQE* test of the bare NbTi extracted wire at 6 T and 90% of I_c (6T). Pulse power and sample current are also shown.

C. Cable I_c and MQE Tests

Cable I_c measurements were performed at FNAL with a Rutherford cable test facility [8], [9] with bifilar sample and superconducting transformer that operates in a 14 T/16 T Teslatron system by Oxford Instruments. The primary power supply is 875 A at 5 V. The secondary winding is equipped with a heater to quench the current in the secondary before each primary new excitation step, and with a Rogowski coil to measure the secondary current. The integrated Rogowski signal, the primary current from the analogical output of the power supply, and the cable voltage signals are acquired with a NI DAQ card (NI 6289) connected to a Voltage Input Module (NI SCXI-1125) for signal conditioning. The secondary current is corrected from the linear contribution due to the primary stray field.

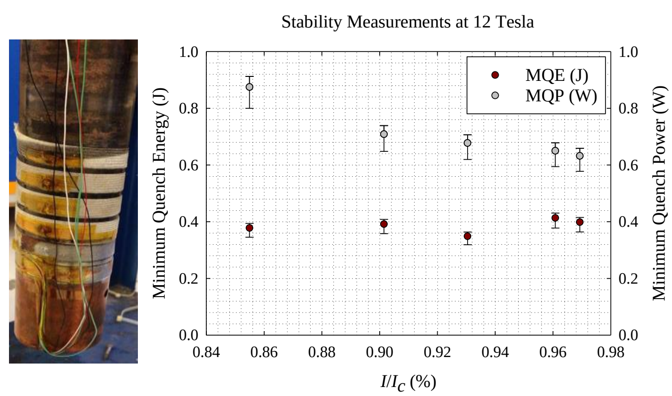

Fig. 6. Left: Picture of instrumented Nb_3Sn Rutherford bifilar cable sample ID2. Right: Minimum quench energy and power obtained for the 40-strand Nb_3Sn cable sample at 12 T and various transport currents (right) [10].

The feasibility of determining the *MQE* and Minimum Quench Power (*MQP*) of fully-excited Nb_3Sn Rutherford cables had also been shown [10] by using the SC transformer above for cable tests at magnetic fields up to 15 T and transport currents up to 30 kA. The spiral bifilar sample shown in Fig. 6 (left) on its holder was externally instrumented with a 350 Ω strain gauge as a heater. The sample was from cable

ID2 in Table I. Heater pulses of same duration and increasing amplitude were provided to the sample in a background field of 12 T, and in a range of transport current between 85% and 97% of the critical current I_c at 12 T, which was 12,373 A. Fig. 6 (right) shows the *MQE* and *MQP* obtained results.

A modified sample configuration and instrumentation was used instead to measure and compare stability of regular and high-C_p Rutherford cables. The experimental schematic of the insulated bifilar cable sample is shown in Fig. 7. Using a single specimen, the *MQE* can be measured for half a cable turn wrapped with high-C_p tape and for half a cable turn without the tape, as illustrated in the instrumentation schematic.

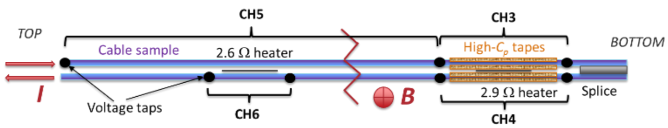

Fig. 7. Schematic of the instrumentation used for NbTi Rutherford cable tests.

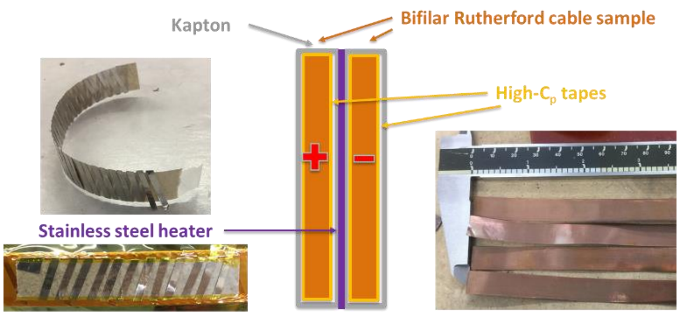

Fig. 8. Experimental schematic of SC bifilar cable sample.

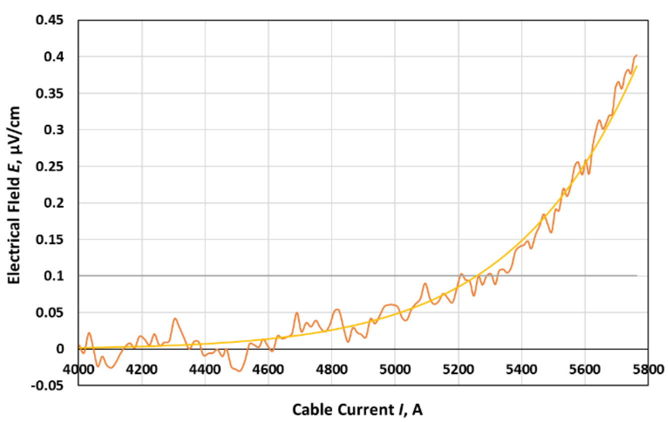

Fig. 9. NbTi cable's electrical field, *E*, vs. transport current, *I*, for cable test at 9 T. The I_c was determined using an electrical field criterion of 0.1 µV/cm.

For these experiments, the 89 µm thick Hypertech ribbon 10 mm wide was used, with a piece 0.115 m long placed on the bare side of each SC cable under their insulation. In both locations with and without the high-C_p tapes, a stainless-steel heater wrapped around mica tape and 14.5 mm wide was installed centrally between the insulated SC cables (see Fig. 8). The heater on the side without the tapes was 0.050 m long with a 4.2 K resistance of 2.6 Ω. The heater on the side with the tapes was 0.055 m long (i.e. half cable pitch length) with a 4.2 K resistance of 2.9 Ω. The distance between the voltage taps indicated in Fig. 7 was 0.135 m for CH3, 0.124 m for CH4, 0.700 m for CH5, and 0.075 m for CH6. The distance between the CH4 and CH6 voltage tap pairs was 0.140 m. Channel CH6 was used to measure the cable I_c, which was determined from the *V–I* curve using an electrical field criterion of 0.1 µV/cm, i.e. same as for the wire I_c tests. Fig. 9 shows an example of *V–I* curve and I_c evaluation for the NbTi cable at 9 T.

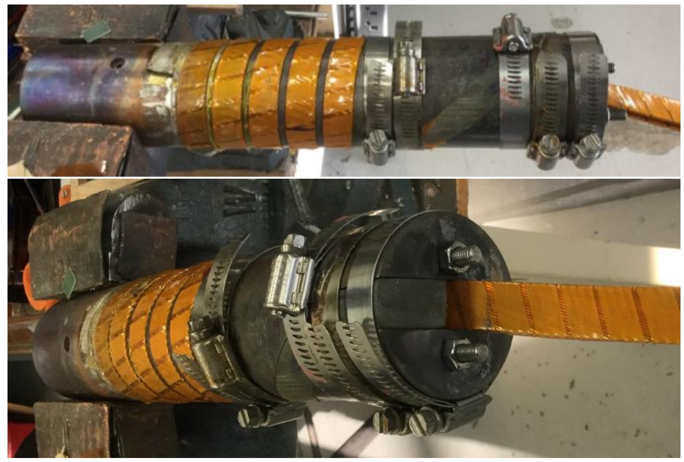

Fig. 10. NbTi cable sample assembly for *MQE* test of standard Rutherford cable and cable outfitted with high-C_p tape.

A 400 W BPO KEPCO 36-12 power supply provides the excitation voltage to the heaters. This is a high speed power amplifier that delivers dynamic voltages for test and simulation. Using a multifunction NI DAQ card (NI-6289), a voltage pulse output from the card is amplified by the BPO KEPKO amplifier to generate a ~15 W pulse on the heaters. A power pulse triggers the acquisition of the voltage signals on the heaters and cable. For the signals acquisition another NI DAQ card (NI-6289), paired with an NI SCXI-1125 signal conditioning module, are used. By gradually changing the pulse duration (i.e. pulse energy), the minimum energy that induces a quench is defined as the *MQE* of the sample. The measurement error is given by the difference between the *MQE* achieved value and the energy provided to the heater at the previous step, at which the sample was not quenching yet. For the cables in this study it was between -1.3% and -4.5%.

The NbTi cable assembly is shown in Fig. 10. The NbTi cable is insulated with Kapton, and the bifilar sample was spliced at the bottom. The pulse power used for testing this cable was 15 to 16 W, with pulse durations of 10 to 25 ms.

For reproducibility in the experiment with the high-C_p ribbon, the most important factor is control of the preload of the two aluminum half-tubes that encase and contain the cable sample. The preload determines the contact pressure between the high-C_p tapes and the bare cable faces. Fig. 11 shows examples of voltage signals obtained for channels CH3 and CH4 in the *MQE* test of the NbTi cable outfitted with the high-C_p ribbons, at 6 T and 47% of I_c (6T) for the three cases of input pulse energy lower than the *MQE* value (top), at the

MQE value (middle) and above the *MQE* value (bottom) of 0.34 J. As shown in Fig. 11 (top), at input energies inferior to the *MQE* value, the heat pulse is not sufficient to heat the cable sample above its T_c *(I, B)* and therefore no voltage signal develops. In Fig. 11 (middle) the input energy is sufficient to quench just one cable of the bifilar sample, presumably due to a better contact of the heater on the cable side of CH4. In Fig. 11 (bottom), the energy is sufficiently higher than the *MQE* for both cables to quench together. When analyzing the data, in 70-80% of all cases only one cable quenched at the measured *MQE* (vs. 20-30% of the cases in which both cables quenched at the *MQE*).

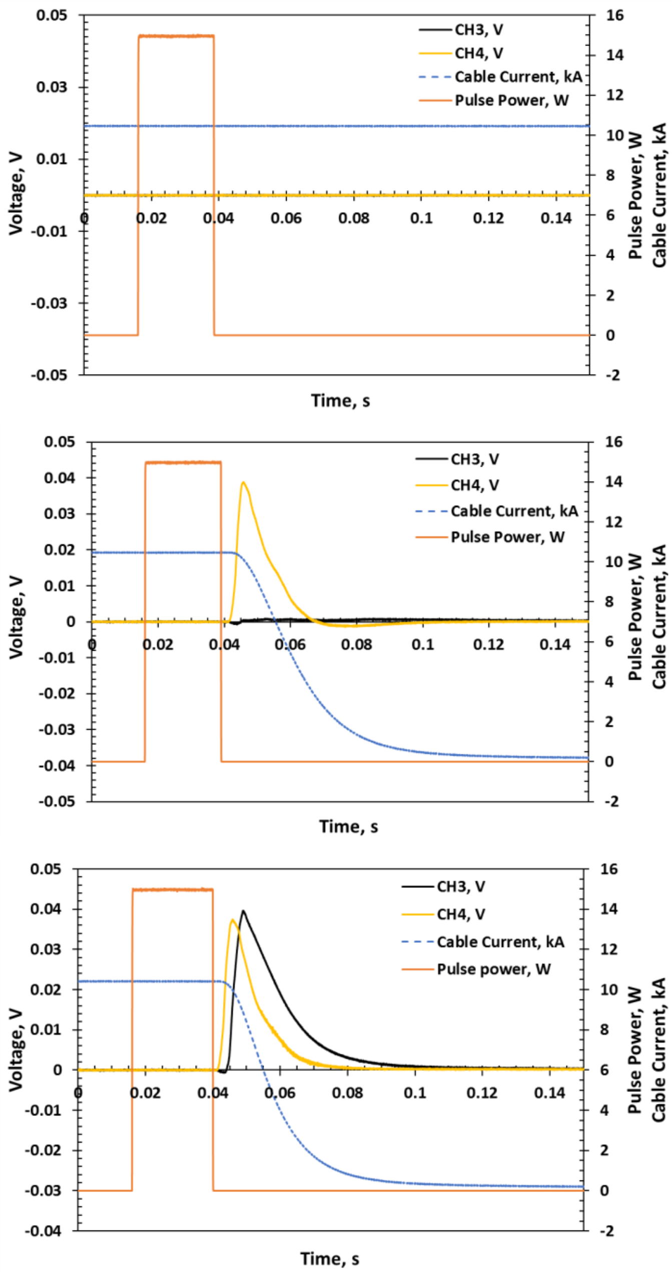

Fig. 11. Voltage signals obtained for channels CH3 and CH4 in the *MQE* test of the NbTi cable outfitted with the high-C_p ribbons at 6 T and 47% of I_c (6T) for the cases of input pulse energy lower than the *MQE* value (top), at the *MQE* value (middle) and above the *MQE* value (bottom) of 0.34 J. In the top plot both channels signals are at zero. At constant pulse power of ~15 W, the cable *MQE* is determined by the pulse duration.

Fig. 12 shows the sample voltage over sample current ratios obtained for voltage tap channels in the *MQE* test of the NbTi cable outfitted with the high-C_p ribbons at 6 T and 47% of I_c (6T). As is typical in quench events, the resistance grows first, then starts to recover, and then grows again. Before decaying, the resistance values present immediately after the quench correspond to an electrical resistivity of the Cu in the NbTi cable of 0.7 to $1.5 \cdot 10^{-10}$ Ω m, which is typical of oxygen-free high conductivity (OFHC) annealed Cu at zero magnetic field. Since the test was performed at 6 T, this means that there is a negative inductive component in the voltage signals that reduced the absolute value of the resistive component and that therefore cannot be neglected.

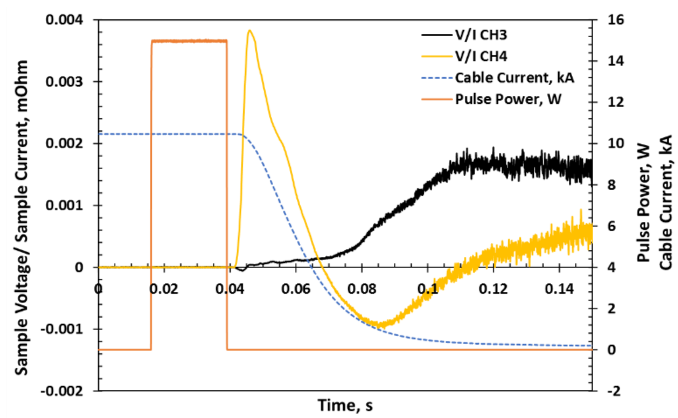

Fig. 12. Sample voltage over sample current ratios obtained for voltage tap channels in the *MQE* test of the NbTi cable at 6 T and 47% of I_c (6T).

III. Results and Discussion

MQE results at various magnetic fields for a bare and high-C_p tape-wrapped sample are shown in Fig. 13 as function of normalized transport current for the NbTi wire extracted from cable ID1. Fig. 14 shows the gain of wrapping a NbTi wire with high-C_p tape, or the *MQE* ratio between the *MQE* obtained with the ribbon and that without, as function of normalized transport current. The wire sample wrapped with high-C_p tape has *MQE* values between 1.5 and 4.6 times higher than the bare specimen. Such gain increases with the transport current, and is therefore maximum at the highest tested I_c% of 90%.

The NbTi cable's $I_c(B)$ was tested first as function of magnetic field for accurate computing of the normalized transport current $I/I_c(B)$. Fig. 15 plots the *MQE* results at various magnetic fields for NbTi Rutherford cable sample ID1 as function of normalized transport current, and Fig. 16 plots the gain of outfitting a NbTi cable with high-C_p tape, or the *MQE* ratio between the NbTi cable's *MQE* obtained with the ribbon and that without, as function of normalized transport current. It has to be noted that no self-field corrections were applied for the cable, hence the actual magnetic field value may be larger than shown in the plot legends. Conversely, the I_c at the indicated magnetic fields would be larger when applying self-field corrections, so that the normalized transport currents in the plots are overestimated, with more accurate *MQE* curves moving to the left. The NbTi cable *MQE* values in Fig. 15 are of the same order as those measured for the Nb_3Sn cable at 12 T in [10] and shown for convenience in Fig. 6. The steeper decrease in *MQE* at ~90%I_c with respect to the wire *MQE* reduction is a typical behavior of NbTi Rutherford cables, and indicate that at high currents a lower number of strands in the cable is needed to quench the cable [11]. It is also known that the level of current at which the step occurs depends on heat transfer to the helium. The greater the heat transfer, the higher the I_c% at which the step occurs, with such step moving beyond 1, i.e. not experimentally observable, with high heat transfer.

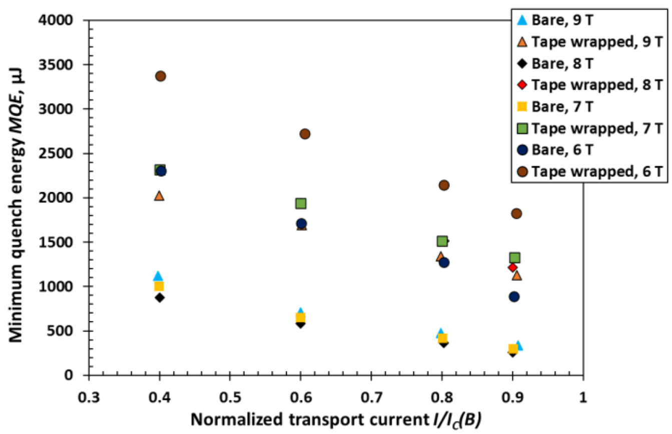

Fig. 13. *MQE* results at various magnetic fields for bare extracted NbTi wire and for NbTi wire sample wrapped with Hyper Tech high-C_p ribbon as function of normalized transport current in the sample.

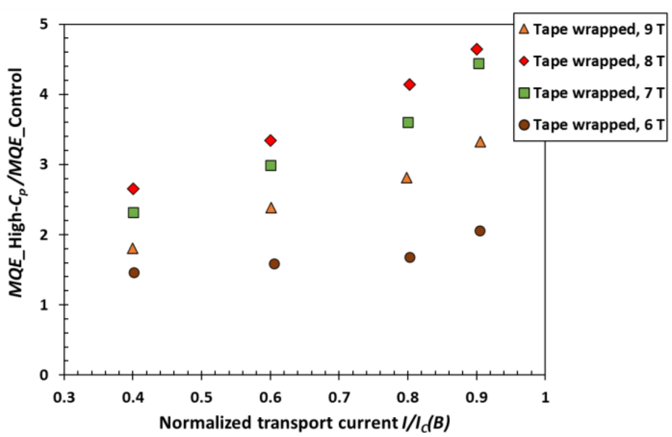

Fig. 14. Gain at various magnetic fields of wrapping the NbTi wire with the thin high-C_p tape, or the *MQE* ratio between the *MQE* obtained with the ribbon and that without, as function of normalized transport current.

As seen in Fig. 16, the NbTi cable sample outfitted with high-C_p tapes has *MQE* values between 1.1 and 2 times higher than the bare specimen. As in the case of the wire, such gain increases with transport current, reaching a maximum at the highest tested I_c% of about 90%. It is therefore important to perform *MQE* tests at the highest reachable I_c% values.

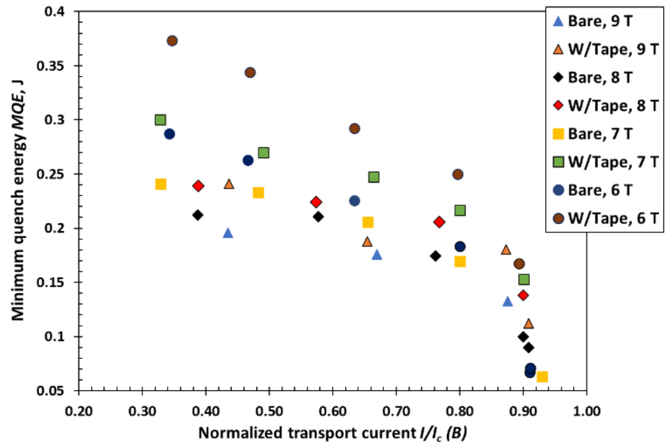

Fig. 15. *MQE* results at various magnetic fields for NbTi Rutherford cable sample ID1 as function of normalized transport current.

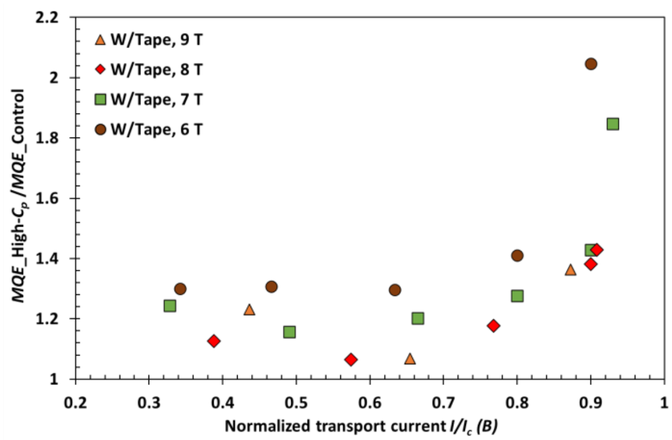

Fig. 16. Gain at various magnetic fields of outfitting a NbTi cable with high-C_p tape, or the *MQE* ratio between the NbTi cable's *MQE* obtained with the ribbon and that without, as function of normalized transport current.

It is also important to check whether this effect of gain enhancement is present in the case of localized disturbances as well. Indeed, the cable experiment in this study used a distributed perturbation, i.e. on the order of the characteristic thermal length, or $(kA/hp)^{1/2}$, where k is the conductor thermal conductivity, A its cross-section area, h the convective heat exchange coefficient and p the cooled perimeter [12], [13]. For Rutherford-type cables, the characteristic thermal length ranges from 3 mm to 2.5 cm with heat transfer coefficients h respectively from 1 W/(cm^{2}K), which may apply to Kapton insulated NbTi cable in boiling Helium, to 0.01 W/(cm^{2}K), which may apply to impregnated Nb_3Sn cable. The large heaters, 5 to 6 cm long, used for the NbTi cable, clearly produced a distributed disturbance.

The gain curves in Fig. 16 also indicate the presence of a minimum at all tested magnetic fields. The presence of such a minimum is less evident in the plots from Fig. 14 of the wire gain.

To check for magnetic field dependence, the NbTi wire and cable *MQE* and gain values when outfitted with the high-C_p tape can be plotted as function of magnetic field for measurements performed at given I_c% values. Fig. 17 and

Fig. 18 show the results at 80% I_c. There is a clear magnetic field dependence in the NbTi Rutherford cable tests, with the measured *MQE* decreasing at higher fields, which is consistent with the decreasing critical temperature margin. The dependence is there for wires too, albeit with less monotonic curves. The gain behavior of the wire and cable outfitted with high-C_p ribbon is particularly interesting. The wire gain in Fig. 18 ranges from 1.7 to 4.1 and shows a maximum at about 8 T, whereas the cable gain is nearly constant at a value of 1.2 to 1.4. The gain behavior of wire and cable at 90% I_c is very similar to that at 80% I_c (Fig. 19), with a maximum also at about 8 T, larger wire gain between 2.0 and 4.6, and larger cable gain between 1.4 and 2.0. It is possible that the cable behavior be due to current and heat redistribution effects among strands in the cable.

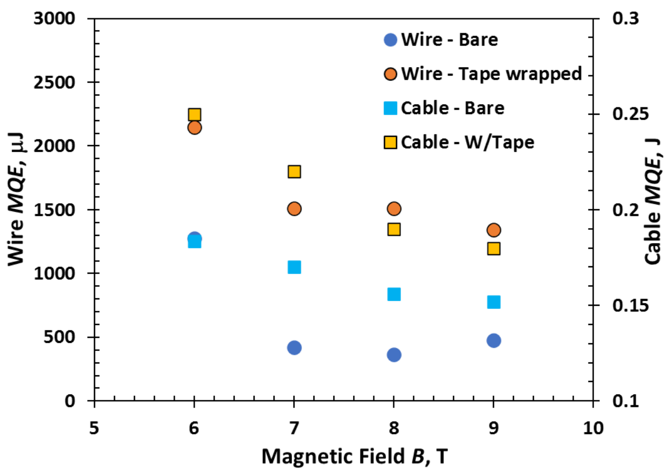

Fig. 17. Wire and cable *MQE* values as function of magnetic field for measurements performed at 80% I_c.

When looking for correlations between wire and cable tests, the NbTi wire wrapped with the Hyper Tech ribbon is a reasonable representation of the NbTi cable test with high-C_p tape. At 80%I_c, one can take the cable gain average over the tested magnetic field range of ~1.3 and compare it with the wire gain average of 3.1. The wrapped wire ratio is reduced to 2.3 to take into account the larger mass. The 130% relative increase is then reduced by 4 to represent the reduced volume of tape material for each wire in the Rutherford cable. This leads to an equivalent ratio for the cable of 1.3, which is consistent with the data. At 90%I_c, the wire gain average is 3.6. By repeating the same simple calculation, one obtains 1.4 as cable gain, which is again consistent with the data.

As a next step, to represent a Nb_3Sn cable test with high-C_p tape the high-C_p ribbon will be soldered to the SC wire, in the assumption that ribbon sintering to the bare cable faces will occur during coil reaction. Therefore, future Nb_3Sn cable test results with high-C_p tape on both sides will be compared with the wire outfitted with soldered tape. If a consistent correlation will be achieved, this will confirm sintering of the tape on the cable faces during high temperature reaction.

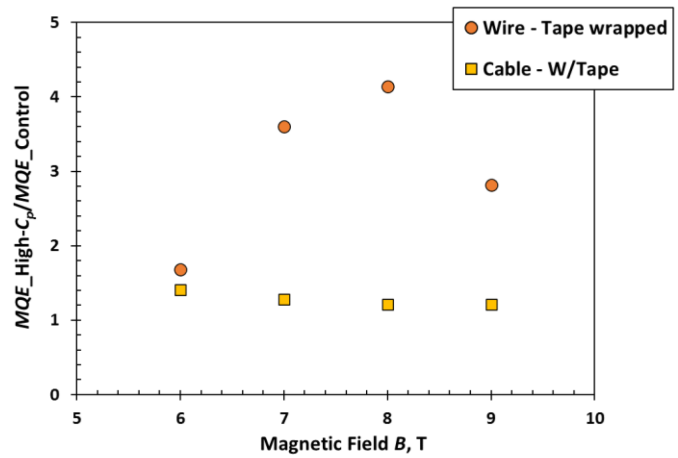

Fig. 18. Gain values of wire wrapped with high-C_p ribbon and of cable outfitted with it as function of magnetic field for measurements performed at 80% I_c.

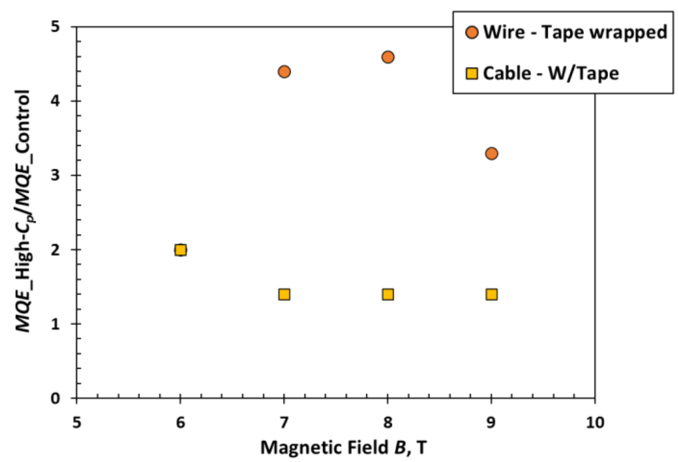

Fig. 19. Gain values of wire wrapped with high-C_p ribbon and of cable outfitted with it as function of magnetic field for measurements performed at 90% I_c.

IV. Summary

A major focus of Nb_3Sn accelerator magnets is on significantly reducing or eliminating training. Increasing the conductor specific heat will lead to shorter training with substantial savings in machines commissioning costs.

Samples of a Hyper Tech high-C_p Cu/Gd_2O_3 tape 10 mm wide and two different thicknesses 89 µm and 64 µm were used to measure and compare the Minimum Quench Energy (*MQE*) of NbTi wires and Rutherford cables both bare and outfitted with this tape. A large gain in *MQE* was found especially at high transport currents. The NbTi cable test results with high-C_p tape on both sides compares well with the wire wrapped with the ribbon.

This study looked at the effect of the Hyper Tech High-C_p ribbon for distributed disturbances on the NbTi Rutherford cable. Next, the experiment will be performed in a local perturbation configuration, with a heater covering a cable area smaller than the characteristic thermal length of the conductor.

Also, the Nb_3Sn cable test results with high-C_p tape on both sides will be compared with Nb_3Sn wire outfitted with tape soldered to it. If a consistent correlation will be achieved, this will confirm sintering of the tape on the cable faces during high temperature reaction. If so, we expect an *MQE* increase in the Nb_3Sn cable of at least 50% when also including a high-C_p tape as a core in the cable.

References

[1] U.S. Department of Energy, Office of Science, "The 2020 Updated Roadmaps for the U.S. Magnet Development Program," arXiv:2011.09539 [physics.acc-ph].

[2] Stoynev, S.E.; Riemer, K.; Zlobin, A.; Ambrosio, G.; Ferracin, P.; Sabbi, G.; Wanderer, P., "Analysis of Nb_3Sn accelerator magnet training," IEEE Trans. Appl. Sup. 2019, 29, 1–6, doi:10.1109/tasc.2019.2895554.

[3] Hancox, R., "Enthalpy stabilized superconducting magnets," IEEE Trans. Magn. 1968, 4, 486–488, doi:10.1109/tmag.1968.1066271.

[4] Alekseev, P.; Boev, A.; Keilin, V.; Kovalev, I.; Kruglov, S.; Lazukov, V.; Sadikov, I., "Experimental evidence of considerable stability increase in superconducting windings with extremely high specific heat substances," Cryogenics 2004, 44, 763–766, doi:10.1016/j.cryogenics.2004.03.004.

[5] Alekseev, P.; Boev, A.; Keilin, V.; Kovalev, I.; Kozub, S.; Kostrov, E.; Kruglov, S.; Lazukov, V.; Sadikov, I.; Shutova, D., "Influence of high heat capacity substances doping on quench currents of fast ramped superconducting oval windings," Cryogenics 2006, 46, 252–255, doi:10.1016/j.cryogenics.2005.07.005.

[6] Xu, X.; Li, P.; Zlobin, A.V.; Peng, X., "Improvement of stability of Nb_3Sn superconductors by introducing high specific heat substances," Supercond. Sci. Technol. 2018, 31, 03LT02, doi:10.1088/1361-6668/aaa5de.

[7] Barzi, E.; Berritta, F.; Turrioni, D.; Zlobin, A.V., "Heat Diffusion in High-C_p Nb_3Sn Composite Superconducting Wires," Instruments 2020, 4, 28.

[8] E. Barzi, N. Andreev, J. Brandt, C. Carmignani, M. Danuso, V. V. Kashikhin, V. S. Kashikhin, S. Mintchev, D. Mitchell, D. Turrioni, A. Rusy, and A. V. Zlobin, "Superconducting Transformer for Superconducting Cable Tests in a Magnetic Field," Advances in Cryogenic Engineering, V. 55, AIP, V. 1218, pp. 421-428 (2010).

[9] E. Barzi, N. Andreev, G. Apollinari, F. Bucciarelli, V. Lombardo, F. Nobrega, D. Turrioni, R. Yamada, and A. V. Zlobin, "Superconducting strand and cable development for the LHC upgrades and beyond," IEEE Trans. Appl. Sup., V. 23, No. 3, June 2013, article # 6001112.

[10] Christopher Kovacs, "Influence of Material Properties and Processing on Stability and Protectability in Superconducting Cables and Composites," PhD dissertation, Graduate Program in Material Science and Engineering, The Ohio State University, 2019.

[11] M. N. Wilson and R. Wolf, "Calculation of Minimum Quench Energies in Rutherford Cables", IEEE Trans. On Appl. Supercond., Vol. 7, no. 2, June 1997.

[12] Buznikov, N.A. and Pukhov, A.A., "Analytical method to calculate the quench energy of a superconductor carrying a transport current," Cryogenics 1996, 37, 7 547-553.

[13] Keilin, V.E. and Romanovsky, V.R. "The dimensionless analysis of the stability of composite superconductors with respect to thermal disturbances", Cryogenics (1982) 22 313-317.