This article has been accepted for publication in IEEE Transactions on Applied Superconductivity. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TASC.2024.3513943

4072679

Laser-Induced Quench Study of the Magneto-Thermal Stability of Nb_3Sn Wires

J. H. Kuczynska, S. C. Hopkins, C. Senatore, T. Boutboul

***Abstract*— In the pursuit of developing 14+ T Nb_3Sn magnets for a future energy-frontier circular collider, there is a growing demand for wires with enhanced critical current density (J_c), larger diameters, and lower copper-to-non-copper ratios. These requirements pose significant challenges to maintaining magnetothermal stability of the superconducting wires.**

This paper explores the technical aspects of non-traditional measurements of the Minimum Quench Energy (MQE) triggered by an ultra-violet pulsed laser. The advantage of a pulsed laser as opposed to the more commonly used resistive heaters is the speed: the laser deposits the energy in nanoseconds, significantly faster than the characteristic time of temperature diffusion in the samples tested. Methods for calibration of the energy absorbed by the wire are also discussed.

The stability of internal tin and powder-in-tube Nb_3Sn wire designs, originally specified for the requirements of the quadrupole (MQXF) magnets for the High Luminosity upgrade of the Large Hadron Collider, was evaluated under applied magnetic fields ranging from 5 T to 15 T and at both 1.9 K and 4.2 K. Notable trends were observed in the energy required to induce a quench at a constant current level as a function of the magnetic field. These trends persisted even as the superconductor approached current levels where premature quenches occur. Results suggest that the superconductor applied in the MQXF magnets cannot be quenched at the operating point by the energy available in this study, with a considerable margin.

***Index Terms*—Critical Current, Critical Current Measurement, Nb_3Sn Wire, Stability, Minimum Quench Energy (MQE)**

I. Introduction

PROPOSED 14+ T Nb_3Sn magnet designs for a future energy-frontier circular collider often call for wires with higher non-copper critical current density (J_c) and larger diameter [1]. While advancing Nb_3Sn superconducting wire technology to its performance limits, high-performing wire designs prove challenging for magnetothermal stability.

Copper, present as a stabilizer in most multifilamentary superconducting wires, contributes to stability in proportion to its quantity and quality. Both factors are influenced by efforts to increase J_c and engineering current density (J_e, defined as the critical current per unit cross-sectional area of a conductor, including stabilizing materials) in Nb_3Sn wires. Common strategies to maximize high-field J_c include increasing the Sn content in Nb_3Sn precursors in the wire design, or increasing the temperature or duration of the final heat treatment (HT) plateau. Both strategies maximize the rate of Nb_3Sn formation, the superconducting volume fraction and B_{c2} (perhaps at the expense of grain coarsening). However, these modifications can result in Sn leak across the diffusion barrier which can compromise the purity of the matrix copper and its stabilizing effect [2], as quantified by the Residual Resistivity Ratio (RRR) [3].

The magnetization of the superconductor is proportional to the effective diameter (d_{eff}) and to J_c, and elevated magnetization heightens the risk of magnetic instabilities, particularly problematic at low fields where J_c is high [4]. Producing a proven wire design at larger diameter naturally increases d_{eff}. Reducing the filament/sub-element size to compensate for the increase of d_{eff} can compromise J_c in Restacked Rod Process (RRP®) wires [5], and eventually increases the proportion of non-copper area occupied by diffusion barriers in any distributed barrier design.

Additionally, in response to the design requirements of high-field coils for graded magnets [6], there is a trend towards reducing the copper-to-non-copper (Cu:nonCu) ratio in novel wire designs. This reduction limits copper's ability to redistribute temperature and current during perturbations, thereby increasing the risk of premature quenches.

In summary, efforts to increase J_c in Nb_3Sn superconductors often come with a risk of instability. Magneto-thermal instabilities can lead to premature quenches, occurring at currents well below the critical current, which limits the coil performance. Two primary mechanisms responsible for these instabilities are flux jumps and magnetization instability. Flux jumps arise from rapid redistribution of current and can be triggered by self-field instability (originating from transport current, e.g. current ramp), while magnetization instability arises from persistent currents [3][7]. A deeper understanding of how wire design characteristics influence stability could provide valuable insights for developing high-performance, stable Nb_3Sn superconductors.

A common method for characterizing the stability of superconductors is the Minimum Quench Energy (MQE), defined as the minimum energy pulse of small extent and short duration required to initiate a quench. In the present study, MQE is estimated using a single pulse from an ultra-violet (UV) laser, the same one employed by Takala *et al.* [8]. The primary advantage of using a laser over traditionally used resistive

Footnote with the date of paper submission for review, populated by IEEE.

J. H. Kuczynska is with University of Geneva, 1205 Geneva, Switzerland; and with the Technology Department, CERN, 1211 Geneva, Switzerland (e-mail: joanna.kuczynska@cern.ch)

S. C. Hopkins and T. Boutboul are with the Technology Department, CERN, 1211 Geneva, Switzerland (e-mail: simon.hopkins@cern.ch).

C. Senatore is with Department of Applied Physics, University of Geneva, 1205 Geneva, Switzerland (e-mail: carmine.senatore@unige.ch).

This article has been accepted for publication in IEEE Transactions on Applied Superconductivity. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TASC.2024.3513943

4072679

heaters [9][10] is its superior speed. A UV laser employed in this study deposits the energy within 1.8 nanosecond, significantly faster than the characteristic time of temperature diffusion in the samples tested [7]. A related study on the MQE of Nb_3Sn wires using a laser was conducted by Breschi *et al.* [11]. In that study, a single-mode diode laser was used for energy deposition, with pulse durations ranging from 15 µs to 2 ms, which are significantly longer than those used in the current investigation.

This is the first systematic stability study to employ a UV laser, leveraging copper's high absorption rate at this wavelength. The laser pulses are significantly faster than in the study of Breschi *et al.* [11], bringing the test conditions closer to adiabatic. For the first time, an in-situ calibration method is proposed to evaluate the energy absorbed, as opposed to previous studies, which simply reported emitted energy, referred to simulations, or used calibration setups substantially different from the actual experimental conditions.

II. Experimental Setup

A standard V-I measurement station is utilized for testing at 4.2 K and 1.9 K [12]. The superconducting sample is placed in the bore of a solenoid to apply an external magnetic field up to 15 T. The sample current leads can supply up to 2000 A. Quench detection is facilitated using a pair of voltage taps positioned 60 cm apart along the approximately 1 m length of the sample. An additional pair of voltage taps is positioned at the points of current injection, specifically on the copper rings to which the superconducting wire is soldered over the length of 3-4 cm, about 90 cm apart.

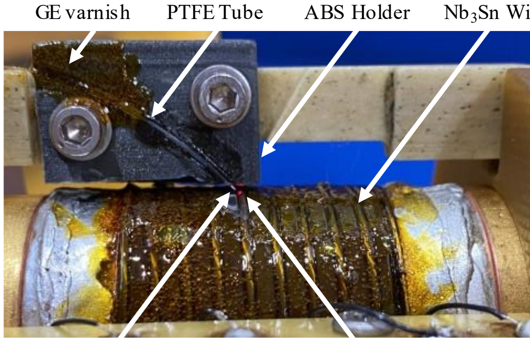


Fig. 1. Superconducting sample with optical fiber for laser-induced quench study.

The superconducting wire is wound onto an ITER-type barrel made of Ti-6Al-4V (VAMAS) and coated with GE varnish to minimize movement during the V-I tests. The GE varnish is subsequently removed from the deposition point using isopropanol. Laser energy is applied to the sample surface via the cleaved end of an optical fiber, which is 4 m in length. The fiber is secured in place with GE varnish inside a PTFE tube with a 254 µm internal diameter. This PTFE tube is held in an Acrylonitrile Butadiene Styrene (ABS) holder, which is mounted on the G10 arm of the sample holder. The ABS holder permits a 2 mm adjustment of the fiber's position relative to the sample.

Initially, the fiber was positioned as close as possible to the sample to maximize the deposited energy. However, after the first few cooldowns, a decrease in transmitted energy was observed, likely due to degradation of the fiber cleave. This degradation may have been caused by slight movements of the sample pressing against the fixed fiber, resulting in mechanical damage. To address this issue, the fiber was installed at a fixed distance from the sample surface. Currently, the fiber is consistently positioned with a 0.3 mm gap from the sample surface to avoid such issues.

Laser energy is transmitted to the sample region within the cryostat via a 200 µm core diameter optical fiber. Some energy loss occurs due to coupling inefficiencies between the fiber and the laser head, as well as along the fiber's length. The energy at both the laser head output and the fiber end at room temperature (RT) is measured with an EnergyMax energy meter from Coherent.

The laser energy is adjustable through an attenuator mounted on the laser head, which provides twelve discrete energy levels. However, only ten of these levels are used in practice, as the three highest levels are within 1 µJ to 3 µJ of each other.

TABLE I
Typical Average Laser Energy and Transmitted Energy at the End of the Fiber

Attenuation Level	Laser energy, µJ	Fiber End Energy, µJ	% transmitted
1	120.3 ±0.2	91.3 ±0.1	76
4	104.5 ±0.1	81.3 ±0.3	78
5	93.1 ±0.9	71.4 ±0.5	77
6	78.0 ±0.4	60.5 ±0.1	77
7	61.4 ±0.1	47.8 ±0.1	78
8	45.1 ±0.1	35.1 ±0.8	78
9	29.5 ±0.5	23.6 ±0.7	80
10	17.5 ±0.5	14.0 ±0.5	80
11	7.9 ±0.3	6.1 ±0.4	78
12	2.6 ±0.2	2.2 ±0.0	83

The typical energies at the laser head and transmitted through the fiber at various attenuation levels, averaged over 100 pulses at a frequency of 1 Hz, were measured in air at RT and are detailed in Table I. The energies of single pulses with lower repetition rates were found to lie within a similar range. The energy measured at the laser head remains consistent during the measurement campaign for a given temperature level, typically with a standard deviation of around 0.7 µJ. Complete set of measurements per temperature level lasts up to 8 hours. In rare cases, the deviation can reach as high as 2 µJ. However, day-to-day variations in laser energy of up to ±5% can occur. To account for these fluctuations, the laser energy at each attenuation level is measured throughout the measurement campaign whenever possible and the average value for that specific campaign is reported.

This article has been accepted for publication in IEEE Transactions on Applied Superconductivity. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TASC.2024.3513943

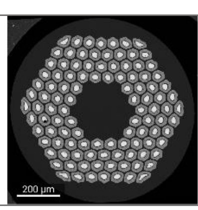
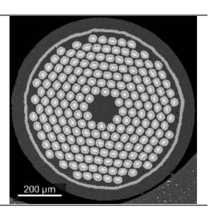
In this experiment, an average of 78% of the laser energy was transmitted through the fiber at RT. In the work by E. Takala [8], approximately 35% of the laser energy was transmitted at RT. This discrepancy may be attributed to the different fiber core diameters used: 200 µm in the present study compared to 100 µm used previously. Additionally, the laser operating parameters were adjusted in the current study to increase the single-pulse energy (from 92 µJ as reported by E. Takala to 120 µJ ± 5%) and to enhance pulse-to-pulse stability.

The energy measured at the end of the fiber at RT should not be considered as the MQE. While calibration efforts are ongoing, with further details on the concept, progress, and preliminary observations provided in Section IV, the energy measured at the end of the fiber at RT, corresponding to the attenuation level used during the laser quenching experiment, will be reported as Fiber End Energy. Although this is not the absolute value of energy that ultimately induces a quench, it represents the highest possible energy delivered to the sample. This measure allows for comparative analysis of the MQE as it varies with current levels and magnetic field strengths.

III. Measurement Procedure

A constant external magnetic field, ranging from 5 T to 15 T, is applied to the superconducting sample. For each field strength, the current is ramped at a rate of 8 A/s until the sample transitions to the normal conducting state. The critical current (I_c) at each field is determined using a criterion of 0.1 µV/cm. Subsequently, the current is ramped to a chosen value and kept constant, and within 5-10 seconds of reaching this level, a single laser pulse with the minimum available energy is applied. If this pulse induces a quench, the Fiber End Energy for that current level at the specified magnetic field is recorded. If quenching does not occur, a quench is forced, and the same test sequence (current ramp and laser pulse) is repeated at the same current with incrementally increasing laser pulse energy until a quench is achieved. The sample is deliberately quenched after a laser pulse that did not induce a quench, ensuring that the previous pulses of lower energy did not affect the final MQE value.

TABLE II
Characteristics of the Tested Wires

Wire Type	RRP®	BB-PIT
Layout	108/127	192
Diameter (mm)	0.85	0.85
RRR	291	199
Cu:nonCu	1.227	1.137
Last Plateau of HT	665°C, 50 h	645°C, 200 h
D_{eff} (µm)	59.0	-
I_c at B_p = 12 T and 4.2 K (A)	768	646
Backscattered electron micrographs		

The quench energy is typically determined at current values corresponding to reference levels of approximately 100%, 90%, 80% of I_c, proceeding in further decrements of 10%. In cases where a significant change in quench energy is observed within a 10% variation of I_c, the decrement is reduced to 5%. The current is then progressively decreased until quenching is no longer achievable with the maximum laser energy at that field. This procedure is systematically repeated across the magnetic field range from 6 T to 15 T, at intervals of 1.5 T. Measurements are conducted at temperatures of 4.2 K and 1.9 K. Table II provides an overview of the characteristics of the samples tested.

IV. Method Validation

A. Repeatability of the MQE measurements

The measurement sequence was chosen to verify repeatability over time. Each measurement campaign started with a full characterization at 12 T. After measurements at other fields, tests were periodically repeated at 12 T; characterization was performed at both 4.2 K and 1.9 K; and the campaign concluded with repeated tests at 4.2 K and 12 T.

All data reported in this article were confirmed to be repeatable, i.e. results at 12 T were consistent throughout the measurement campaign. However, in many other trials, shifts in quench energy towards higher values were observed during a single measurement campaign: i.e. the energy that previously induced a quench at a certain magnetic field and current level was no longer sufficient, and one level higher was necessary. These shifts did not occur at a fixed field, after a temperature change or after a certain number of pulses or integrated energy were delivered, so the cause is unclear. However, shifts did seem to occur at a consistent stage of the measurement campaign across multiple trials with the same sample (but exposing a different point on the sample to laser illumination for each trial). In most cases, a single energy shift of around one energy level occurred during tests at 4.2 K, whilst after testing at 1.9 K a larger energy shift was often observed. The causes of these offsets, and methods for controlling them, remain under study.

B. Calibration

In this article, the Fiber End Energy is reported. For relative comparisons of different wire types and characteristics, in principle this measure is sufficient. However, calibration of the energy absorbed by the wire would be required to determine the absolute MQE.

The concept of the calibration is to measure the temperature increase in response to a laser pulse train. Calibration of a similar system by E. Takala [8] found that approximately 28% of the laser energy (or 80% of the Fiber End Energy in his experiment) was absorbed by the superconducting wire and reported as MQE. This calibration was conducted in vacuum at 4.2 K, using a black body measurement, where laser energy was deposited at a frequency of 100 Hz inside of a copper cavity over approximately 2 minutes until a stable increase in temperature, relative to the thermal ground, was established. The procedure was repeated with a heater, requiring 1 hour to reach a stable temperature. The temperature increase was recorded for different power levels of the heater and laser to

This article has been accepted for publication in IEEE Transactions on Applied Superconductivity. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TASC.2024.3513943

develop a calibration curve. The laser measurements were then calibrated against the heater calibration curve through fitting, with the energy absorptivity of copper being the fitting parameter.

As noted earlier, fiber coupling inefficiencies are lower in this study than in Takala's case, and the Fiber End Energy is approximately 78% of the laser energy. Assuming the same energy absorption of the found in Takala's calibration, 20% of the Fiber End Energy would be subtracted to obtain the absolute MQE. To verify this, a new calibration approach has been proposed, using a setup closely replicating the conditions during the MQE measurement. To achieve this, a piece of copper wire with a 0.7 mm diameter was glued above a temperature sensor with Loctite® Stycast. Cernox® from Lake Shore Cryotronics was employed as a temperature sensor, as shown in Fig. 2. The copper wire was clamped over the sensor for 24 hours after gluing to ensure good contact. To minimize heat loss through conduction, the copper wire is limited to a short length and a special VAMAS barrel made of the Ultem® was employed. Ultem®, a thermoplastic polyimide, has a low thermal conductivity typically around 0.22 W/m·K. To ensure that the energy is not deposited directly at the surface of the Cernox®, the surface is carefully covered on the laser energy deposition side of the wire. This calibration setup on the VAMAS barrel was placed in the same sample holder used for the MQE measurements and the calibration was conducted in the same V-I measurement station in liquid helium at 4.2 K.

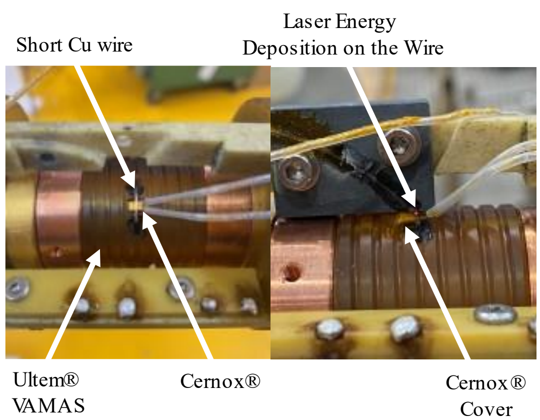


Fig. 2. Calibration setup with a short copper wire installed over a Cernox® temperature sensor.

It was demonstrated that a laser pulse train at maximum energy and a frequency of 1 kHz could induce a sustained temperature increase (ΔT) in the copper wire over the duration of the pulse train. The observed ΔT reached up to 70 mK relative to the baseline temperature before the pulse train, compared to the reported accuracy of the Cernox® sensor at 4.2 K, ± 5 mK. The temperature read-out is acquired at 50 kHz sampling rate.

However, calibration efforts have not been fully completed due to unresolved issues with repeatability across multiple ΔT measurements within a single cooldown. Similar repeatability challenges encountered in the laser-induced quench study, as discussed in the previous section, may shed light on the underlying effects that hinder consistency. These issues may be even more pronounced during calibration, where a 1 kHz pulse frequency is used, in contrast to single pulse application for the MQE measurement. The completion of the calibration is left for future work, and in this article, only the Fiber End Energy is reported.

V. Results

An energy shift affecting repeatability, as discussed in Section IV, did not occur during the data collection for the results presented in this section.

A. RRP® 108/127 wire

Restacked Rod Process (RRP®) wire with 108/127 layout was tested at 4.2 K and 1.9 K. This wire was procured for the quadrupole (MQXF) magnets for the High Luminosity upgrade of the Large Hadron Collider (HL-LHC project) [13]. The results of the measurements at 1.9 K and 4.2 K are presented in Fig. 3 and Fig. 4, respectively. The magnetic field plotted on the x-axis in Fig. 3, Fig. 4 and Fig. 5 has been adjusted to account for the sample's self-field. Markers indicate the lowest Fiber End Energy that was sufficient to induce the quench. The quench energy was studied across a magnetic field range of 6 T to 15 T, with increments of 1.5 T, and an additional data point at 5 T for the 4.2 K condition.

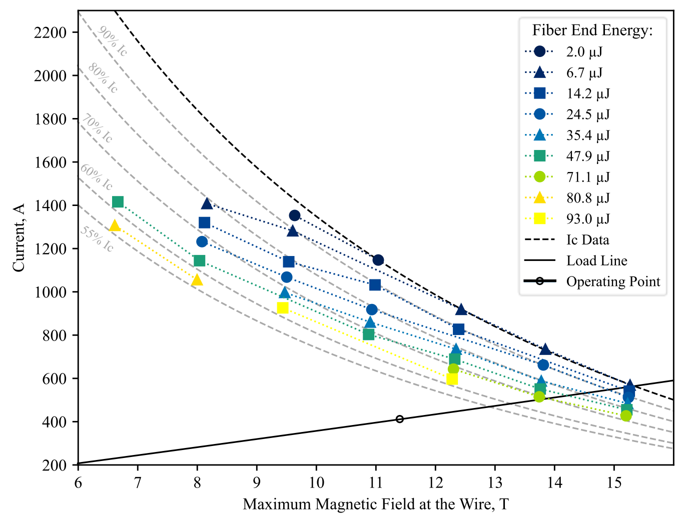


Fig. 3. Summary of laser-induced quench energy tests for RRP® wire at 1.9 K, with markers indicating the lowest Fiber End Energy (see section IV, subsection B) sufficient to induce a quench at each magnetic field and current level. Premature quenches occurred at as low as 1494 A at 6 T, so the test range was limited to 1500 A. The operating point of the MQXF magnet is indicated [15]. The percentage of the I_c, plotted in light grey, serves as a visual guide. The Fiber End Energy reported in the legend is the energy measured at the fiber output at room temperature. A previous calibration [7] suggested the absolute MQE would be 80% of this value (see section IV).

Fig. 3 shows that the operating point for the MQXF magnet is significantly below the conditions at which the maximum available laser energy was sufficient to induce a quench. Another notable observation at low magnetic fields is that, even

This article has been accepted for publication in IEEE Transactions on Applied Superconductivity. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TASC.2024.3513943

as the current approaches the value at which premature quenches would occur without a laser pulse, I_{max}, the Fiber End Energy required to induce a quench scales with the I_c and remains relatively high. Intuitively one might expect that, near I_{max}, a small laser energy would be sufficient to induce a quench. However, at 1.9 K and 6 T, where I_{max} is 58.7% of I_c, Fiber End Energies up to ~35 µJ do not trigger a quench even at 55.6% of I_c.

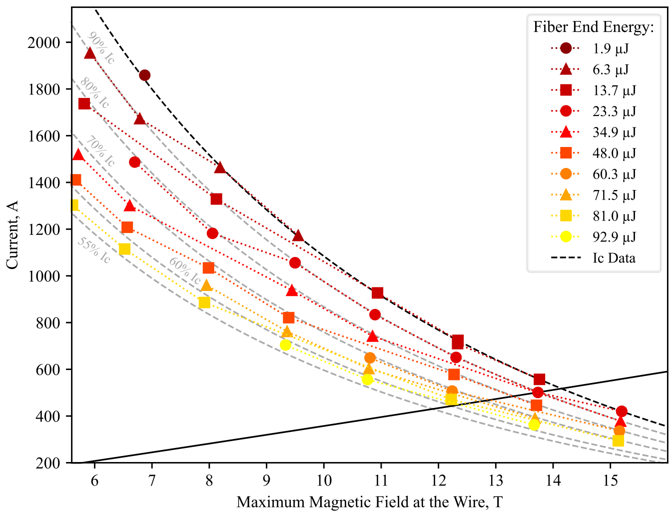


Fig. 4. Summary of laser-induced quench energy tests for RRP® wire at 4.2 K, with markers indicating the lowest Fiber End Energy sufficient to induce a quench at each magnetic field and current level.

It is consistent across both temperature levels that, at a constant percentage of I_c, the energy required to induce a quench decreases as the magnetic field decreases.

The energy required to induce a quench at four selected magnetic field levels was compared between 1.9 K and 4.2 K and plotted against the normalized current in Fig. 6. The quench energy at 1.9 K increases above that at 4.2 K for low normalized current (I/I_c), with the crossover occurring at lower normalized currents in lower magnetic fields. A similar crossover between 1.9 K and 4.2 K behavior has been observed previously, e.g. at ~$I/I_c = 0.8$ by A. K. Ghosh *et al*. for a 1.065 mm diameter Nb-Ti wire [9] and attributed to "superfluid enhancement" of MQE at 1.9 K [9][14]. The magnitude of this enhancement and the value of I/I_c below which it is significant has been found empirically and by modelling to be strongly dependent on cooling conditions, and in conditions approaching adiabatic little enhancement is expected [9][14]. For very short pulse durations, one might expect behavior closer to pseudo-adiabatic, so a full explanation of this behavior in the present test conditions for Nb_3Sn wire samples will require further study.

B. BB PIT 192 wire

Bundle Barrier (BB) Powder In Tube (PIT) wire with 192 filaments was tested at 4.2 K. The results are presented in Fig. 5, which demonstrate similarities to those obtained for RRP® wire at 4.2 K. This wire was specified for the same application [16] as the previously described RRP® 108/127, therefore, it is not surprising that they exhibit similar behavior. In both cases, for a given percentage of the Ic, the quench energy decreases along with the magnetic field (i.e. the energy needed to quench the sample at any chosen fraction of Ic is lower at 6 T than 15 T for both types of the wires). However, it can be seen that the maximal energy available (90.2 µJ) was only sufficient to quench the sample down to 60% of Ic in the case of BB-PIT wire, while in the case of MQXF, 81.0 µJ was sufficient to quench the sample below 60% of Ic. The quench energies intersect the MQXF magnet load line at lower magnetic fields for BB-PIT than RRP®, but this is due to a lower $I_c(B)$ rather than poorer stability.

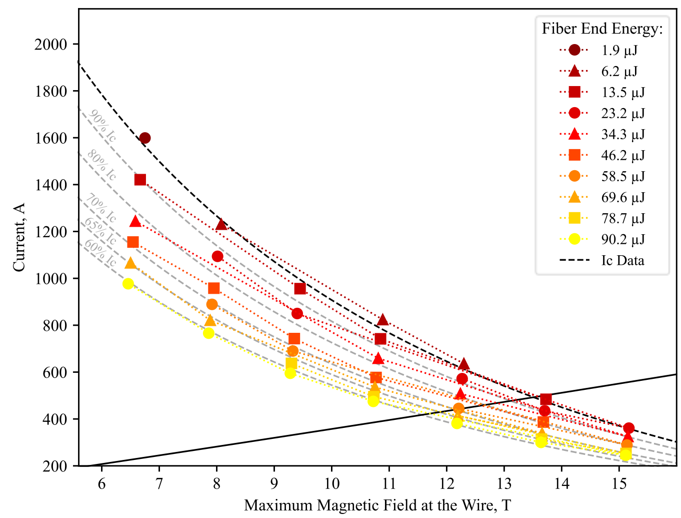


Fig. 5. Summary of laser-induced quench energy tests for BB-PIT wire at 4.2 K, with markers indicating the lowest Fiber End Energy sufficient to induce a quench at each magnetic field and current level.

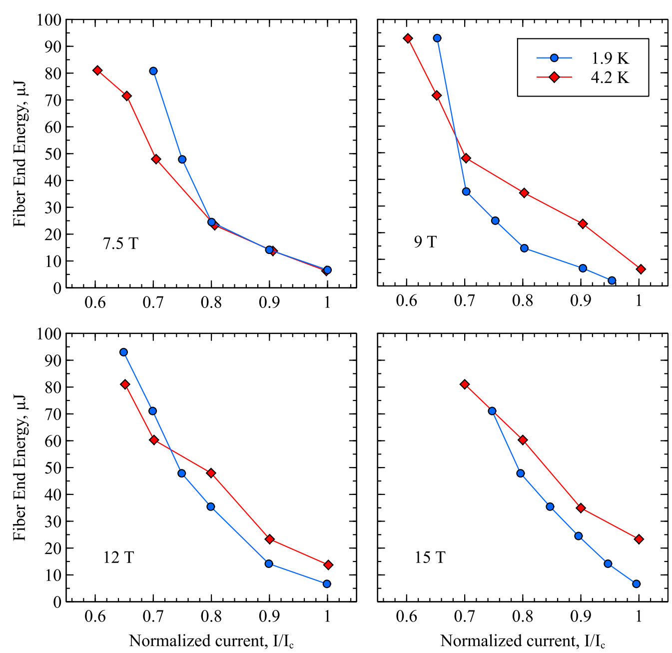


Fig. 6. The energy required to induce a quench of the RRP® wire vs. normalized current at 1.9 K and 4.2 K at selected magnetic field levels.

4072679

VI. Conclusion and Outlook

A new experimental configuration for laser-induced MQE measurement has been successfully established. The energy deliverable by the laser to the superconducting wire has been demonstrated to be adequate for initiating quenches down to 55% of the I_c for Nb_3Sn wires of interest for accelerator magnet applications. Furthermore, this method has been applied to characterize two different wire designs, including into a field-current range (at 1.9 K) at which the samples naturally experience premature quenches below I_c. A feasible calibration concept reflecting the final experimental conditions has been established and should be finalized smoothly with recent insights. Additionally, once the practice of positioning a Cernox® sensor below the sample is well-established, the measurement of the ΔT for each tested sample can be utilized as a reference for the energy absorbed. This will help confirm or correct direct comparisons of quench energies between different samples.

The first results reported in this paper reveal interesting aspects of stability for further exploration, *e.g.* the dependence of quench energy on normalised current in proximity to I_{max}, and differences in those trends at 1.9 K and 4.2 K, and as a function of magnetic field. Once the repeatability limitations discussed in Section IV are resolved, a larger sample size for analysis can be obtained more efficiently. This will facilitate the characterization and comparison of stability for wires with varying RRR, Cu:nonCu ratios, wire layouts, states (virgin wire compared to strands extracted from cables), and heat treatments.

References

[1] S. Hopkins, “Design Optimization, Cabling and Stability of Large-Diameter High J_c Nb_3Sn Wires,” in *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, Aug. 2023, Art no. 6000609, doi: 10.1109/TASC.2023.3254497.

[2] P. Li, “The Effect of Heat Treatment on the Stability of Nb_3Sn RRP-150/169 Strands,” in *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, June 2017, Art no. 6000805, doi: 10.1109/TASC.2017.2662938.

[3] B. Bordini, “Impact of the Residual Resistivity Ratio on the Stability of Nb_3Sn Magnets,” in *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, June 2012, Art no. 4705804, doi: 10.1109/TASC.2011.2180693.

[4] A. K. Ghosh, “Investigation of Instability in High J_c Nb_3Sn Strands”, BNL, US, rep. BNL-219093-2020-TECH, Jan. 2005.

[5] M. B. Field, "Optimizing Nb_3Sn Conductors for High Field Applications," in *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1-5, June 2014, Art no. 6001105, doi: 10.1109/TASC.2013.2285314.

[6] E. Rochepault, "The Use of Grading in Nb_3Sn High-Field Block-Coil Dipoles," in *IEEE Trans. Appl. Supercond.*, vol. 31, no. 4, pp. 1-10, June 2021, Art no. 4001510, doi: 10.1109/TASC.2021.3061246

[7] M. N. Wilson, Superconducting Magnets, U.K.: Oxford University Press, 1983, ch. 7.4

[8] E. Takala, “An Experimental Setup to Measure the Minimum Trigger Energy for Magnetothermal Instability in Nb_3Sn Strands,” in *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, June 2012, Art no. 6000704, doi: 10.1109/TASC.2011.2174555.

[9] A. K. Ghosh, “Minimum Quench Energy Measurements on Single Strands for LHC Main Magnet,” in *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 252-256, June 1999, doi: 10.1109/77.783284.

[10] E. Barzi, "Minimum Quench Energy of Nb_3Sn Wires with High Specific Heat Tape," in *IEEE Trans. Appl. Supercond*., vol. 32, no. 6, Sept. 2022, Art no. 6001105, doi: 10.1109/TASC.2022.3159774.

[11] M. Breschi, "Stability of Nb_3Sn Superconducting Wires: The Role of the Normal Matrix," in *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 1305-1308, June 2008, doi: 10.1109/TASC.2008.920608.

[12] T. Boutboul, “Critical Current Test Facilities for LHC Superconducting NbTi Cable Strands,”, CERN, Geneva, Switzerland, LHC Project Report 520, 2001.

[13] L. D. Cooley, "Conductor Specification and Validation for High-Luminosity LHC Quadrupole Magnets," in *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1-5, June 2017, Art no. 6000505, doi: 10.1109/TASC.2017.2648738.

[14] P. Bauer, “Stability of Superconducting Strands for Accelerator Magnets” Ph.D. dissertation, Phys., Tech. Univ., Vienna, 2000.

[15] S. Stoynev et al., "Effect of CLIQ on Training of HL-LHC Quadrupole Magnets," in *IEEE Trans. Appl. Supercond*., vol. 34, no. 5, pp. 1-6, Aug. 2024, Art no. 4900606, doi: 10.1109/TASC.2023.3341871

[16] B. Bordini *et al*., "The Bundle-Barrier PIT Wire Developed for the HiLumi LHC Project," in *IEEE Trans. Appl. Supercond*., vol. 27, no. 4, pp. 1-6, June 2017, Art no. 6000706, doi: 10.1109/TASC.2016.2640760