**An Experimental Setup to Measure the Minimum Trigger Energy
for Magneto-Thermal Instability in Nb₃Sn Strands**

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Abstract

Magneto-thermal instability may affect high critical current density Nb₃Sn superconducting strands that can quench even though the transport current is low compared to the critical current with important implications in the design of next generation superconducting magnets. The instability is initiated by a small perturbation energy which is considerably lower than the Minimum Quench Energy (MQE). At CERN, a new experimental setup was developed to measure the smallest perturbation energy (Minimum Trigger Energy, MTE) which is able to trigger the magneto-thermal instability in superconducting Nb₃Sn-strands. The setup is based on Q-switched laser technology which is able to provide a localized perturbation in nano-second time scale. Using this technique the energy deposition into the strand is well defined and reliable. The laser is located outside the cryostat at room temperature. The beam is guided from room temperature on to the superconducting strand by using a UV-enhanced fused silica fibre. The strand is mounted on a VAMAS barrel. A part of the beam's energy is absorbed into the strand acting as the trigger energy for the magneto-thermal instability. In this paper the experimental setup and the calibration of the absorbed energy is presented.

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Abstract—Magneto-thermal instability may affect high critical current density Nb₃Sn superconducting strands that can quench even though the transport current is low compared to the critical current with important implications in the design of next generation superconducting magnets. The instability is initiated by a small perturbation energy which is considerably lower than the Minimum Quench Energy (MQE). At CERN, a new experimental setup was developed to measure the smallest perturbation energy (Minimum Trigger Energy, MTE) which is able to trigger the magneto-thermal instability in superconducting Nb₃Sn-strands. The setup is based on Q-switched laser technology which is able to provide a localized perturbation in nano-second time scale. Using this technique the energy deposition into the strand is well defined and reliable. The laser is located outside the cryostat at room temperature. The beam is guided from room temperature on to the superconducting strand by using a UV-enhanced fused silica fibre. The strand is mounted on a VAMAS barrel. A part of the beam's energy is absorbed into the strand acting as the trigger energy for the magneto-thermal instability. In this paper the experimental setup and the calibration of the absorbed energy is presented.

I. INTRODUCTION

MAGNETO-THERMAL instability is one of the major issues in high critical current Nb₃Sn superconducting strands even when the RRR (Residual Resistivity Ratio) is high ≥ 100 [1], [2]. The problem persists even when the effective filament size is reduced, which can cure a strand suffering from another type of instability, magnetization instability [3]. The magneto-thermal instability has been observed also in Nb₃Sn superconducting cables and magnets [4], [5]. From now on in this document, “the instability” refers particularly to the magneto-thermal instability.

The nature of the instability has been studied via finite element model in [1]. The publication shows how the quench current changes with respect to the magnitude of trigger energies. The trigger is a relatively small (compared to the minimum quench energy) and localized energy which is perturbing the current distribution in a strand. Before an instability is triggered, the current is distributed in the outer filaments of the strand while the inner filaments have no current at all due to the self field effect [2]. When the instability in a strand is triggered, a flux jump is generated, which is homogenizing the current distribution over the strand cross section. The change in the magnetic field will release more energy which in some

cases is able to quench the strand. The quench current of the strand is highly dependent on the trigger energy and in practice it plays a role especially at intermediate field region. The energy requirement increases towards higher magnetic fields as the critical current density decreases. At every magnetic field, below a certain current the instability hasn't got enough magnetic energy to quench the strand.

An experimental setup to measure the minimum trigger energy (MTE) is presented and its calibration is reported. The triggering method is based on Q-switched laser technology; a laser light pulse is guided via an optical fibre on the surface of the strand, which absorbs a part of the energy of the pulse. The absorbed energy is considered as the trigger energy for the instability. The calibration of the trigger energy is done at 4.2 K in two phases: 1) black body measurement and 2) absorptivity measurement. The black body measurement defines the overall energy which is guided through the fibre. The absorptivity measurement defines the energy which is absorbed by the strand.

There has been a study on thermal stability of NbTi strands based on laser technique [6]. However, an IR laser was used and the pulse widths were in the order of 10 μ s. Whereas, the setup described here is for magneto-thermal instability and it is based on UV laser with pulse width in the order of 1 ns which is smaller than the thermal diffusion time. For example, the characteristic thermal time constant in a 1 mm wide slab of copper is 1 μ s at 6 T [7]. Moreover, the IR light require a black coating for the strand in order to absorb the electromagnetic radiation, otherwise the absorptivity is poor [8]. In this document, high absorptivity of the intense UV and green light, without any coating on the strand, will be shown.

II. MEASUREMENT SETUP

The setup to study the instability is installed in a test station for measuring superconducting strands at the CERN. In the station, it is possible to supply 2000 A into a superconducting strand which is mounted on a VAMAS barrel and in a 12 T external magnetic field. The barrel is located in a cryostat which can be cooled down to 4.3 K or 1.9 K. An all-silica optical fibre with 100 μ m diameter [9] is installed in the cryostat to guide laserpulses from room temperature to the strand. Outside of the cryostat, the fibre is coupled to a UV laser which is able to send pulsed light at 355 nm or 532 nm wavelengths with 100 Hz repetition rate, pulse width

Figure 1. View of the experimental setup. The optical fibre is inside a metal tube which is covered by a heat shrink tube and both are fixed on the G10 structure by a metal clip. The alignment of the light beam is being checked with white LED light which is not harmful for eyes unlike the laser light. The sample in this figure is covered with Stycast[®] to overcome movement issues.

in the order of 1 ns. The energy of the laser is measured with a photodetector which is inside the laser, before the coupler. Half a meter of the fibre from the connector is outside of the cryostat and protected with a heat shrink tube and a metallic tube. Inside the cryostat, the fibre is protected with metallic tube and partly with a flexible heat shrink tube. The end of the fibre is fixed in the metallic tube with Stycast[®] glue. The metallic tube is fixed on the G10 structure of the sample holder to hold the end face of the fibre on the surface of the strand. Light is sent from the front face of the fibre to confirm the position (Fig. 1).

In order to calibrate the energy of the laser absorbed by the superconducting strand, an additional calibration setup is used. The calibration is based on a comparative heater method: the absorbed laser energy is transformed in heat which is measured in terms of risen temperature, the heat is calibrated with a known heat input by using an electric heater.

In the calibration setup an optical fibre, similar to the fibre described before, is used to guide laser pulses from room temperature into a vacuum chamber at 4.2 K. The chamber is immersed in liquid helium bath at atmospheric pressure in a cryostat (Fig. 2a). Inside the chamber a copper mass is thermally grounded to the walls of the chamber via four copper wires (Fig. 2b). There is a cavity in the copper mass which is acting as a black body [10]. The feedthrough for the fibre from the cryostat into the vacuum chamber is made of a stainless steel pipe filled with Stycast[®] glue. In the black body measurement, all the light is guided in the black body via the fibre by setting up the end face of it in the middle of the cavity (Fig. 2b). The end face is fed in through a 150 μm hole. In the absorptivity measurement, the end face is set up on the copper surface of the mass and a reflection screen is added around the fibre to absorb the reflected light (Fig. 2c). The reflection screen is insulated from the copper mass with an Ultem 2100 cap. The fibre is guided into the screen with a small stainless steel tube (Fig. 2d). Temperature sensors were

Figure 3. Heater calibration curve and 2 verification measurements. HTC and TC mean hydro-thermic and thermo cycle, respectively.

installed on the copper mass and on one of its grounding points and a heater of 100 Ω was installed in the middle of the mass.

The reflection screen is made of stainless steel tube and thermalized with a copper braid. The inner surface of the tube is polished to avoid light scattering. At room temperature, the optical reflectivity of stainless steel is in the order of 60% and 50% for 355 nm and 532 nm lights, respectively [11]. However, the reflectivity should not change drastically at cryogenic temperatures. For example in pure iron it doesn't show noticeable difference between room temperature and 4.2 K [12].

III. RESULTS AND DISCUSSION

A. Calibration

The heater calibration results at 4.2 K are given in Fig. 3. It shows the temperature difference between the copper mass as a function of heater power. The calibration is reproducible throughout the measurements even after a thermocycle or when the vacuum is broken and recreated (hydrothermic cycle).

The energy of the laser beam is partly lost due to coupling loss, micro and macrobending. The coupling loss consists of

Figure 2. The sketch of the calibration setup: a) *A* is the laser, *B* is the optical fibre, *C* is the radiation shielding and *D* is the vacuum chamber. b) *1* is the vacuum feedthrough; *2* is the thermal grounding via copper wires which are attached on the wall of the vacuum chamber by using a copper ferrule (the black rectangle is a temperature sensor); *3* is the copper mass with the heater (black circle), the temperature sensor (black rectangle) and the black body cavity (brown open circle); *4* is the unprotected optical fibre. c) *5* is the reflection screen. The head of it is represented in detail with the copper mass on the right hand side; *6* is the copper braid, *7* is the stainless steel tube, *8* is the fibre inside the tube, *9* is the Ultem 2100 cap between the screen and the copper mass; *10* is the black body cavity.

Figure 4. The black body measurement for 100 Hz repetition rate. The black line is a polynomial fit through the heater points. The other lines with points are calibrated laser data curves with 532 nm and 355 nm wavelengths. The laser calibration is done via fitting the points on the calibrated heater curve. The fit parameter is the energy efficiency from the laser to the cavity.

the intrinsic Fresnell loss and misalignment of the beam. Most of the losses originate from the misalignment when the fibre diameter is small. In theory the highest possible coupling efficiency is approximately 90%. The photodetector inside the laser is calibrated and the coupling efficiency is measured with an energy meter, EnergyMax[®] from Coherent. The measured coupling efficiency with 100 Hz repetition rate is 35% for 355 nm and linearly variable with respect to pulse energy between 26% and 32% for 532 nm. The active area of the energy meter is a disk. It is not taking into account the light which is scattered from the end face of the fibre with a high angle. The fibre has to have a small distance from the active area, which is otherwise destroyed due to the high intensity light. For this reason, the measured value might be slightly lower than in reality.

The beam power of the laser is measured at 4.2 K in the black body and absorptivity measurements for 100 Hz repetition rate, at 355 nm and 532 nm wavelengths with different laser output powers. The results for black body measurements are given in Fig. 4. In the figure, the laser measurements are calibrated with the heater calibration curve via fitting. Based on the fit, the energy efficiency from the

laser into the cavity is 33.5% for 355 nm, whereas it is 35% (coupling efficiency) in room temperature. Therefore, the cryogenic loss is $\approx 5.5\%$. For 532 nm the cryogenic loss is calculated to be $\approx 1.8\%$. The cryogenic losses have been measured to be 25% at 355 nm for this type of fibre in another experiment [9]. The cryogenic conditions were similar, however the fibre was more than two times longer and had four 30 mm diameter loops in liquid helium. Therefore the results are in line with this experiment. In the absorptivity measurement the analysis is done similarly, except the fit parameter is absorptivity since the power output at the end face of the fibre is known from the black body measurement. The absorptivities were 83% and 89% for 355 nm and 532 nm wavelengths. In literature the corresponding values are 60% and 40% [12]. The difference might be due to the high intensity ($\approx 0.4 \text{ GW/cm}^2$) of the light which might change the surface properties [13]. It has been reported that the reflectivity of an irradiated metal surface significantly decreases due to high intensity of laser pulses [14]. For copper, high intensity 532 nm light seems to be slightly more efficient than 355 nm. It has been shown in [13] that 532 nm outperforms 355 nm light in etching copper foils due to the nature of the plasma formed above the surface of the material. The high absorptivity is noteworthy, since the earlier studies with IR light in [6] required black coating on the strand in order to have 22% absorptivity. Another reason for the high absorptivity could be back reflections from the reflection screen, which might increase the measured absorptivity. However, it should not play a big role, since the screen is well polished to avoid scattering.

B. Proof of concept

The Fig. 5 shows the first characterization done with the new experimental setup to study the MTE. The sample is a 0.8 mm RRP superconducting strand with critical current density of 2951 A/mm^2 at 12 T, 4.3 K and RRR of 149. It is first measured with conventional techniques to characterize the strand, that are the VI and VH measurements [2]. This measurement revealed the I_c -surface and the quench curve for a certain

Figure 5. An example characterization with the new setup. (....) I_c -surface fit based on the critical current measurement, (●) critical current in VH measurement, (▼) quench current in VH measurement, (■) quench current in VI measurement with conventional sample holder, (○) quench current in a second VI measurement with the new setup, (▲) quench initiated (26 μ J/pulse) with the laser, (▲) quench initiation tried (26 μ J/pulse) with the laser but no quench.

perturbation spectrum. Based on the VH measurements, the strand did not suffer from magnetization instabilities. The second measurement is done after a thermocycle and with a different sample holder with respect to the first one. Based on the introductory statements, evidently the second measurement suffered from stronger perturbations, since the minimum of the spontaneous quench curve is shifted from 3 T to 8 T (the higher the field the higher the perturbation energy that triggers the magneto-thermal instability). After the second conventional measurement, the laser is configured to 92 μ J/pulse at 355 nm wavelength, which makes 26 μ J/pulse absorbed in the strand (absorbed pulse energy). The measurements were done in VI manner: in a constant magnetic field the current is ramped up at a certain value and after it the laser is used to trigger the instability of the strand. The laser is able to trigger the instability in a range from 9 T to 12 T which is the most extensive possible in this case since the instability is initiated at the minimum quench current in all the other fields by the natural perturbations acting on the strand. The laser is not able to quench the strand under the minimum quench curve. The curve is revealed by taking a union of all the quench current measurements.

IV. CONCLUSIONS

The new experiment to study the instability has been successfully set up. The validity has been demonstrated by characterizing a 0.8 mm superconducting RRP strand with high critical current density and high RRR. In this case, with absorbed pulse energy of 26 μ J/pulse and pulse width in the order of 1 ns, the laser is able to trigger the magneto-thermal instability at all possible magnetic fields. The setup is based on Q-switched laser technology, which provides a rapid and energetic pulse of light at 355 nm or 532 nm wavelengths. The 532 nm is more effective wavelength based on the calibration measurements. The cryogenic losses for

355 nm and 532 nm are 5.5% and 1.8%; absorptivities are 83% and 89%, respectively, without any surface treatment for the copper. The beam energy is delivered on the strand via an all-silica 100 μ m diameter core fibre. The absorbed energy is localized, well defined and can be adjusted to study extensively the MTE in the future by using the proposed setup.

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