Quench Propagation Ignition using Single-Mode Diode Laser

F. Trillaud, F. Ayela, A. Devred, M. Fratini, D. Leboeuf and P. Tixador

***Abstract*— The stability of NbTi-based multifilamentary composite wires subjected to local heat disturbances of short durations is studied in pool boiling helium conditions. A new type of heater is being developed to characterize the superconducting to normal state transition. It relies on a single-mode Diode Laser with an optical fiber illuminating the wire surface. This first paper focuses mainly on the feasibility of this new heater technology and eventually discusses the difficulties related to it. A small overview of Diode Lasers and optical fibers revolving around our application is given. Then, we describe the experimental setup, and present some recorded voltage traces of transition and recovery processes. In addition, we present also some energy and Normal Zone Propagation Velocity data and we outline ameliorations that will be done to the system.**

***Index Terms*— quench energy, quench propagation velocity, single-Mode Diode Laser, superconducting wires.**

I. INTRODUCTION

THE stability of superconducting wires is a necessary task in order to design safe and reliable superconducting magnets. These magnets are subjected to premature quenches caused by local releases of energy [1]. To simulate these quench precursors and quantify the minimum energies triggering quenches, various heater technologies, based on graphite pastes [2], inductive coils [3] or coated tips [4], have been explored for more than thirty years. Although some of these technologies were improved to a far extent, the reproducibility of results has always been subjected to criticism. The reason of this is related to the nature of heat exchanges involving helium coolant along with the non-controlled physical contact between heaters and samples, which is difficult to overcome for most of the techniques. Consequently, it makes the assessment of the genuine minimum energy necessary to trigger a full transition from the superconducting state to the normal resistive state a very delicate task. In order to reduce the number of uncertainties, we turned our attention toward a new system, which has the advantage of freeing the sample from any physical contacts with the heater. It is a fibered single-mode Diode Laser. The commercial and industrial use of these Lasers have been increasing within the past decade. From the first attempts in the 1960's till nowadays, constant improvements have led to their remarkable optical characteristics conjugated with miniaturization, toughness and reliability. Their small ratio of size versus optical power, their small electrical power consumption and their ease of operation make them very competitive compared to other Lasers and useful for a broad range of new technological applications [5]. They are easily adaptable to various experimental configurations at a low cost with an available average output optical power, which can range from less than 1 W for single Diode Lasers up to 50 W for powerful Diode Bars [6].

Despite these advantages, very few studies in the characterization of superconductors use Diode Laser. The present study, which relies on the interaction between the Laser beam and the metallic surface of superconducting multifilamentary composite wires, is based on the work on superconducting thin films carried out in the 1990's by F. Ayela at CNRS-CRTBT/Grenoble [7].

II. PRESENTATION OF THE SINGLE-MODE DIODE LASER AND ITS COUPLED OPTICAL FIBER

A. Single-mode diode Laser

A single-mode Diode Laser (supplied by Spectra-physics) of ∼1.2 W, pre-coupled with an anti-reflection coated optical fiber of ∼30 cm long, was used as a pulsed heater. Phenomenologically, the beam light strikes locally the surface of the superconducting multifilamentary composite wire. Due to electromagnetic field shielding, mesoscopic currents develop generating heat inside a thin layer at the periphery of its metallic stabilizer. Consequently, the temperature of the metal increases creating a normal zone in the bundle of superconducting filaments, which can expand or shrink on the balance between dissipated energy and cooling conditions. Table I summarizes the essential characteristics of the Diode Laser implemented in our experiment.

A Diode Laser driver PCL-7410 (DEO) operated in single-shot mode with pulse widths varying from less than 10 μs to more than 1 ms provided current to the Diode Laser.

B. Output optical power versus current characteristic

The output optical power versus current curve is an important characteristic of any Diode Laser. The actual threshold current is 0.289 A and the slope efficiency, which is the slope of the output optical power versus current characteristic, is 0.776 W/A (Figure 1). The steepness of this slope yields

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TABLE I

SALIENT PARAMETERS OF THE SINGLE-MODE DIODE LASER AT 293 K.

Maximum continuous output power (W)	1.35
Maximum current (A)	2
Threshold current (A)	0.289
Numerical aperture	0.06
Peak wavelength (nm)	807.4

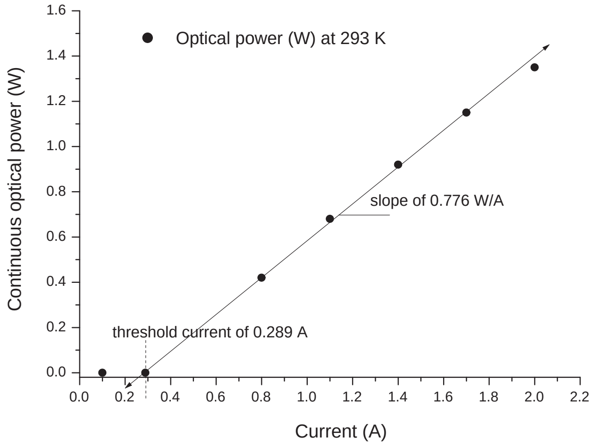


Fig. 1. Output optical power (CW) versus total electrical current (A) of the single-mode diode Laser (manufacturer data at 293 K).

information on the quality of the Diode Laser. A steeper slope with a low threshold current guarantees a better overall efficiency. Mainly, it is a calibration curve, which is temperature dependent.

C. Temperature dependency

The emission wavelength depends on the temperature of the Diode Laser. A typical sensitivity factor is -0.3 nm/K. In the experimental conditions, the Diode Laser is at room temperature. At lower temperatures, the slope of the output optical power versus current characteristic gets usually steeper and the threshold current decreases slightly, increasing efficiency. Thereby, in continuous mode operation, it is necessary to stabilize the temperature to maintain the beam quality.

In this experiment, no temperature control has been installed yet. However, the temperature variations were measured with a thermal sensor PT-110 (Lakeshore) glued with Stycast® 2850FT on the OFHC copper shell of the diode. For further discussions, we introduce the term of Minimum Pulsed Energy (MPE) to refer to the minimum output optical energy, which is necessary to trigger a quench at a given transport current. The MPE, for a pulse width of 1 ms, was recorded on different days as a function of the Diode Laser temperature. The diode temperature changed over time according to room temperature, but, there does not appear to be a clear correlation with the MPE. The erratic data are more likely due to the motion of the sample during the different tries (see section V). For long run experiments, a temperature regulation will be implemented.

TABLE II

FEW CHARACTERISTICS OF NBTI SUPERCONDUCTING WIRE.

Diameter (mm)	0.8223
Ratio Cu/Sc	1.96
RRR	194
J_c at 7 T, 4.2 K (A/mm^2)	1720

D. Optical fiber

An extra silica-silica optical fiber (SEDI, France) protected by a Teflon® sheath was connected through a connector (standard SC) to the one pre-coupled to the Diode Laser. Therefore, the Laser beam is guided along 2.024 m from the source located at room temperature to the sample at the bottom of the cryostat. The inner diameter of its core is 100 μm, which corresponds to a multi-mode optical fiber [8]. Its tip is made up of Ultem® 1000R into which is glued a hollow metallic needle (inner diameter of 300 μm). The cladding, corresponding to the outer silica sheath of the wave guide, is glued to the metallic needle so as to rigidify the whole assembly. It ensures as much as possible the control of the lightened area by maintaining still the tip of the fiber.

III. NBTI SAMPLE

A. Characteristics and environmental conditions

Thermo-electrical characterizations were carried on a NbTi-based superconducting multifilamentary composite wire supplied by Alstom/MSA. This sample was cooled down to 4.2 K in saturated liquid helium and placed in a DC transverse background magnetic field of 5 T, 6 T, and 7 T. Table II summaries the salient parameters of this wire.

B. Absorptivity of the copper stabilizer

For very short time pulses below 200 μs, the maximum achievable optical output power of the Diode Laser is not large enough to trigger the full transition of the sample. Indeed, the copper stabilizer of the NbTi wire has a poor optical absorptivity in the infrared region, so that the main part of the optical energy is reflected. Using classical electromagnetic theory [9], the coefficient of absorption for a copper with a Residual Resistivity Ratio (RRR) of 194 can be estimated to be of the order of 1%. Hence, there might be a large discrepancy between the optical energy delivered by the Diode Laser and the actual energy absorbed by the wire, which needs to be calibrated. In order to do so, we are planning a separate experiment with a bolometer. We are also studying various surface treatment that may be applied to the wire to improve its absorptivity. To avoid any misinterpretations of the data, we only report here optical energies as delivered by the Diode Laser without trying to convert then into actual energies absorbed by the wire.

IV. EXPERIMENTAL SETUP

The NbTi wire sample is stretched on a U-shaped sample holder made up of G-10. It is pushed inward into the pit of a V-shaped groove by two lugs. Two additional G-10 pieces screwed on the sample holder allow the sample to be positioned in front of the tip of the optical fiber. The two extremities of the wire, tinned with Indium-tin, are soldered onto two copper bus bars. The active zone of measurement perpendicular to the background magnetic field extends over 76 mm of the sample out of 500 mm. The heated zone located in the center of the active zone occupies at most 4×10^{-6} m^2. Three pairs of voltage taps with common taps are soldered to the sample. Voltage drop V1, across the heated zone, gives information on the evolution of normal zone during transitions and recoveries. Voltage drops V2 and V3, further down the sample, are used to assess Normal Zone Propagation Velocities. All the voltage drops were recorded by a digital oscilloscope, Yokogawa DL709. All the data were uploaded on PC through GPIB and RS232 using Labview® software.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

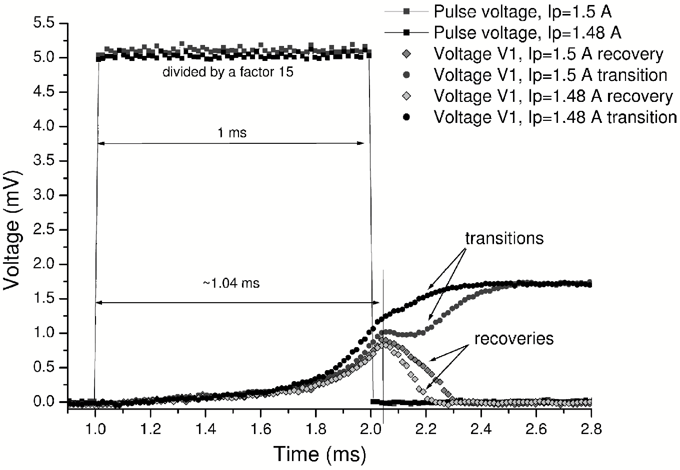
A. *Example of voltage traces*

Here are given some voltage traces at 7 T for a wire transport current of 230 A corresponding to 85% of the critical current, I_c. Figure 2(a) shows a series of current pulses of 1 ms duration, which led to transitions and recoveries. As it appears, if the energy absorbed by the wire is too small, the normal zone does not propagate and the wire goes back to the superconducting state (two bottom curves). However, when the deposited energy reaches or exceeds the Minimum Quench Energy (MQE), the normal zone propagates and the wire switches to normal resistive state (two top curves). This swinging behavior is certainly due to the change in the cooling conditions at the surface of the sample. In this case, the quench decision time, which is the time to reach the MPZ, is estimated around 1.04 ms.

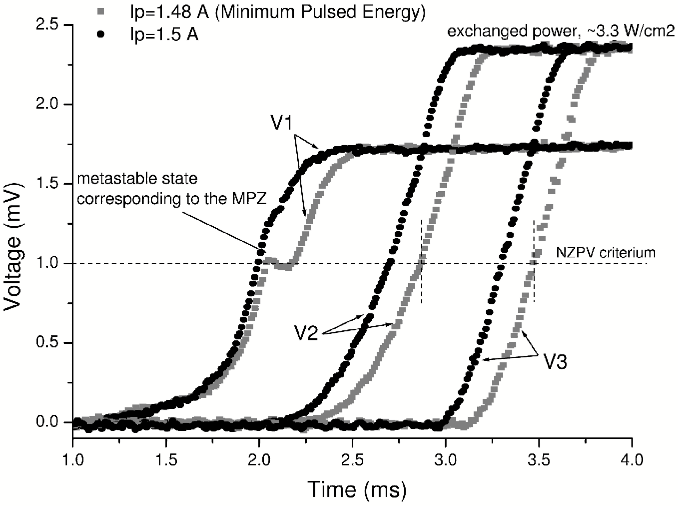
In addition, Figure 2(b) gives details on transitions. The two transitions have been recorded at different Pulsed Energies. Closer to the Minimum Quench Energy, the behavior of the wire becomes metastable. There is a kink on one of the voltage traces (V1), which is likely to correspond to the Minimum Propagating Zone, MPZ (see next section V-B). The MPZ estimated from these data is around 3 mm. Afterward, the voltage trace reaches a plateau, which corresponds to a full transition and at which the exchanged power with helium is estimated to be around 3.3 W/cm^2. In these conditions, the helium coolant is certainly in the film boiling regime [10].

B. *Normal Zone Propagation Velocity, NZPV*

Figure 3(a) reports estimated Normal Zone Propagation Velocities. The results obtained are consistent with those found in the literature [4]. When the Pulsed Energy gives raise to a normal zone inside the superconducting wire, this zone may grow or shrink and disappear. It is necessary to reach a critical size, called the Minimum Propagating Zone, to trigger a quench. If this condition is achieved, the normal zone grows along the wire at a constant speed. However, to assess accurately this velocity, it is necessary to record voltage rises away from the heated zone since thermal diffusion process corresponding to the metastable creation of the MPZ does not represent a propagating phenomenon. The NZPV is assessed by measuring the time delay between the voltage drops V2 and V3 for a voltage criterion of 0.001 V. The NZPV is related to the ratio of heat generation and cooling conditions. Heat generation due to the redistribution of current in the copper matrix increases as the square of the transport current whereas the cooling capacity tends to decrease with the increase of the exchanged power. Indeed, the heat coefficient, which is enhanced in the transient state, decreases following the changes in the helium cooling regime [10]. So, it is expected that the NZPV increases as a function of transport current as illustrated Figure 3(a).



(a) Accumulated transitions and recoveries.



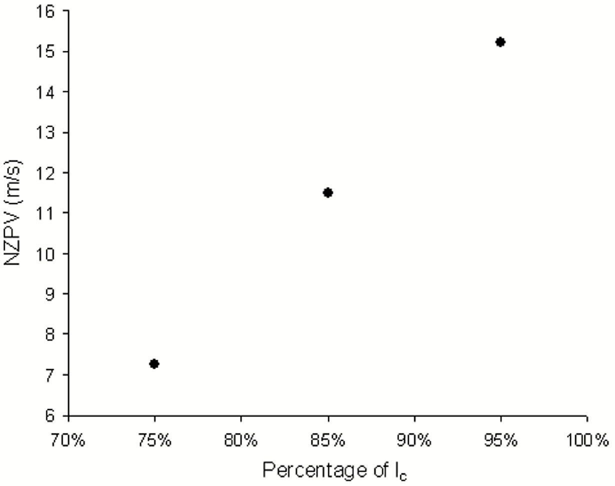
(b) Details on transitions.

Fig. 2. Figure (a) gives examples of transitions and recoveries at the metastable equilibrium at two close Quench Energies for 7 T, 4.2 K and 264 A (85%I_c). Figure (b) shows, through voltage rises V2 and V3, the propagation of the normal zone along the sample in the case of a full transition.

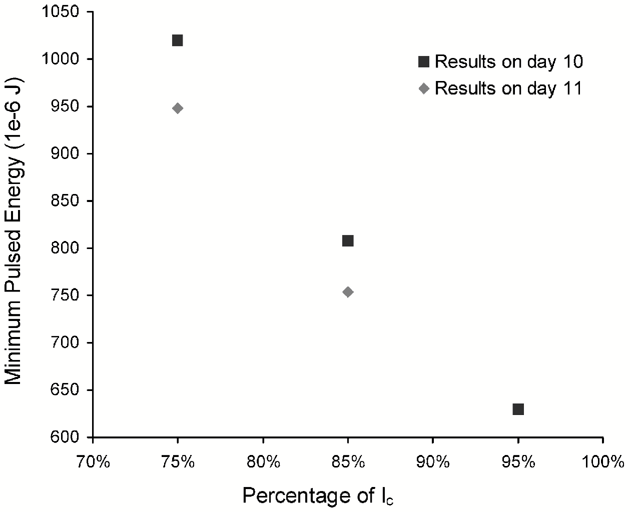
C. Minimum Pulsed Energy

Figure 3(b) presents a summary plot of Minimum Pulsed Energies (deduced from the optical power delivered by the Diode Laser) as a function of fractions of short sample critical currents. Two sets of data recorded on two different days are reported. The data follow the expected trend [4]. Indeed, the minimum amount of absorbed optical energy inducing a quench is expected to decrease as we get closer to the critical current. Following the considerations on NZPV, it is similarly related to the balance between heat generation and cooling. Heat generation increases quickly with the increase in transport current and takes the relay of the deposited energy to drive the wire to its full transition. However, even if the tendency is respected, there appears to be some discrepancy between the two data sets. Although the reproducibility of the measurements is quite good on a single day (better than 90%), it drops to ∼48% over the all series of measurement (obtained over 15 days of measurements).

We are in the process on investigating its origin, which is likely to be mechanical. So, despite the tight maintaining of the sample in its groove, it may still move under thermal cycling. An amelioration of the fixation of the sample and a better absorptivity of the sample may improve the overall reproducibility.



(a) Normal Zone Propagation Velocity versus the percentage of critical current.



(b) Minimum Pulsed Energy versus the percentage of critical current, bare data.

Fig. 3. Evolution of the propagation velocity and the Minimum Pulsed Energy versus the percentage of critical current at 7 T and 4.2 K. While the NZPV increases with increasing transport current because of a larger heat generation inside the copper stabilizer of the wire, the Minimum Pulsed Energy decreases for the same reason.

VI. CONCLUSION

In view of the preliminary results presented here, the feasibility of the Diode Laser heater has been proven. In spite of the issue of mechanical maintaining of the sample and the necessity to improve and quantify the absorptivity of the copper stabilizer, repeatable quenches and recoveries have been recorded. The quantification of the coefficient of absorption of the copper matrix can be achieved by the use of a bolometer conjugated with quasi-adiabatic environmental conditions. In addition, studies will be carried out to enhance the absorptivity by oxidized the copper surface of the wire sample.

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