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Quench Development at Supercritical Currents in Low n-value Superconductors

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***Abstract*—Superconducting magnets consisting of conductor having a low n-value can be operated shortly with overcritical currents without quenching the magnet. This applies also to epoxy impregnated coils. However, when sufficiently high disturbance occurs at a supercritical current a magnet quenches. Traditional approaches on minimum quench energy (MQE) do not consider the supercritical region. In this study we measured MQE at sub- and supercritical currents for MgB_2 and Bi-2223/Ag conductors having low n-values, i.e. below 15. A Finite Element Method model was compared with the measurement results and the differences in MQE between the sub- and supercritical regime were scrutinized.**

***Index Terms*—MgB_2, Bi-2223/Ag, HTS, stability, quench, measurements**

I. INTRODUCTION

MINIMUM quench energy, MQE, is the smallest disturbance that causes a quench. It was first introduced by Wilson in 1977. [1] However, the basis of the MQE concept was laid by Martinelli and Wipf in 1972 when they presented their theory on minimum propagating zones MPZs. [2] These theories form the basis of the transient stability studies for high n-value, i.e. above 25, Low Temperature Superconductors, LTS. [1] Stability studies for High Temperature Superconductors, HTS, are different since the margin between critical temperature and operational temperature is usually larger than with LTS. Therefore the loss of stability in HTS must be considered differently than in LTS. [3]

The stable operation point of the system is determined by the available cooling and the heat generation in the superconductor. Therefore the important quantity for systems using low n-value, i.e. below 15, superconductors is the thermal runaway current I_q after which a quench eventually occurs. When the operating current is greater than I_q, the system will inevitably leave the superconducting state due to excessive resistive heating in the system. [4] The low n-value however enables the possibility of overloading the system momentarily by allowing operation on currents greater than I_q. As with any superconducting system, the stability margin reduces when the operating current is increased. In this case the transient stability of the system becomes important and the study of MQEs is relevant.

The thermal runaway current is a system specific parameter and it is usually used to analyze a complete superconducting system. Therefore it is not feasible parameter to be used in a short sample characterization. Hence we used critical current I_c determined by an electric field criterion in this study. The same approach was taken also in [5] where quench propagation and onset at supercritical currents was studied experimentally for Bi-2223/Ag conductor. The results showed that short term operation on supercritical currents was possible.

Quench onset in MgB_2 conductors was studied in [8], [9] computationally and experimentally at sub-critical regime. The n-value in these studies varied from 10 to 50. Also in other publications reported n-values of MgB_2 conductors vary. In [6] low n-values were measured, whereas in [7] high ones were presented. In this paper, we contribute to the quench studies of MgB_2 at supercritical regime when n-value is below 10. We also tested our measurement system using a Bi-2223/Ag conductor.

In this paper we first present the setup used in our measurements. Then the computational model is presented after which both experimental and computational results are compared.

II. EXPERIMENT SETUP

The experiments were performed in a standard, cryocooler cooled, cryostat at self field. In the cryostat the temperature of the sample can be varied between 15-80 K. The sample under study was attached to a sample holder made from high purity copper and an insulating support shown in Fig. 1. This setup was chosen to a situation where heat is transfered only from the contacts soldered at the ends of the sample. The setup thus tries to reproduce the thermal environment a conductor experiences in an impregnated magnet.

For quench initiation we used a small surface mount resistor soldered directly onto the sample. The length of the solder joint was 1 mm and the width of the resistor was well below

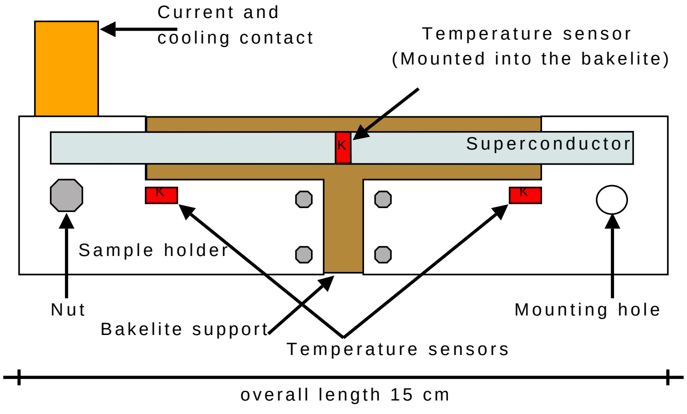

Fig. 1. Schematic of sample holder used in measurements.

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1 mm. The resistance of the heater increased notably during cool down and eventually settled to about $430\ \Omega$ at 20 K. This high resistance enabled us to use low excitation currents between 40-100 mA.

A more common setup used in MQE measurements is presented in [8]. We chose not to use the method presented in [8] since the needed excitation current is much higher than in our setup and therefore might interfere with the measurements performed near I_c. The low excitation is crucial, since the return current from the heater is passed through the superconducting sample and a too high excitation could interfere with the results when the superconductor is operating near I_c.

For the quench detection, we used a series of voltage taps shown in Fig. 2. The V_1 tap was placed across the heater and it was used to verify the operation of the heater by observing the presence of a normal conducting zone. The rest of the taps were used to distinguish propagating normal zones from shrinking ones. By studying the time differences in the rise times of the voltages we were able to distinguish propagating normal zones from the gradually rising resistive voltages due to the supercritical current operation.

The temperature of the sample before measurement was controlled by a temperature controller, the Cernox sensing elements of the controller were placed on the current contacts of the sample holder and at the center of the insulating support. During the measurement the temperature of the sample was not recored. If a quench had occurred during a measurement it could be detected, in addition to the detection from the measured voltages, from the very steep rise in the temperatures of the current contacts and the support after the measurement.

Each measurement cycle was begun by energizing the sample to the desired current with a very steep ramp,100-250 A/s, then after 500 ms the heater was excited with the desired amount of energy. For the protection of the sample, the transport current was cut one second after the quench initialization pulse resulting in total operation time of 1.5 seconds.

The studied MgB_2 tape had a stabilizing copper core and monel was used for the sheath. The width and the height of the tape were 3.6 and 0.65 mm respectively. The fill factors for superconductor and copper were 8.9% and 14.9% respectively. In the Bi-2223/Ag sample the filaments were embedded in a silver matrix and stainless-steel outer sheath was used for mechanical reinforcement. The width and height of the sample tape were 4.2 and 0.26 mm respectively. Fill factors of the tape were 65% and 35% for the superconductor and silver respectively.

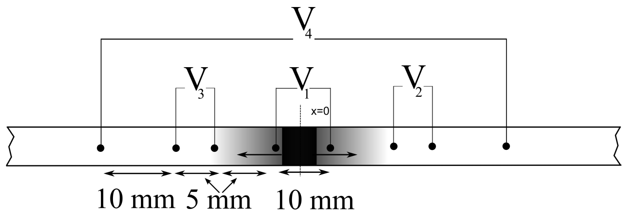

Fig. 2. Schematic figure of the sample and the placement of voltage taps

III. Computational Model

A 1D numerical model was used to obtain the computational results. The computational problem is characterized by the heat balance equation [10]

$$\frac{\partial}{\partial x}\lambda(T)\frac{\partial T}{\partial x}+Q(T)=C_\text{p}\frac{\partial T}{\partial t}, \tag{1}$$

where T is the temperature, Q the volumetric heat generation and C_p the volumetric specific heat. Finite Element Method (FEM) was used to solve (1). The heat generation Q present in the equation was computed from power-law [10]

$$Q(T)=\min\left\{\rho_\text{norm},\frac{E_\text{c}A}{I_\text{c}(T)}\left(\frac{I}{I_\text{c}(T)}\right)^{n-1}\right\}\left(\frac{I}{A}\right)^2, \tag{2}$$

where E_c is the electric field criterion $1\ \mu\text{V/cm}$ and I the operating current.

For quench detection the time derivative of the temperature was used. First a criterion for the derivative was chosen and a quench was detected when the derivative increased to a value greater than the chosen criterion. To provide a reference for determining MQE an initial computation without introduced disturbance energy was done. The time of the quench in the initial simulation is the the maximum operation time $t(T_\text{op},I_\text{op})_\text{op,max}$, where T_op and I_op are the temperature and current of a specific operation point. From the initial computation the desired operating time $t_\text{op,des.}$ was computed as

$$t_\text{op,des.}=\frac{1}{2}\cdot t_\text{op,max}. \tag{3}$$

Temperature and the time derivative of the temperature obtained from a computation for the MgB_2 conductor presented in the previous section operating at $T_\text{op}=22$ K and $I/I_\text{c}=0.95$, with annotations to clarify the introduced quantities $t_\text{op,max}$ and $t_\text{op,des.}$, are presented in Fig. 3.

For the quench criterion we used

$$\left.\frac{\partial T(t)}{\partial t}\right|_\text{x=0}\geq 10\text{ K/s for }T_\text{op}<30 \tag{4}$$

$$\left.\frac{\partial T(t)}{\partial t}\right|_\text{x=0}\geq 5\text{ K/s for }T_\text{op}\geq 30. \tag{5}$$

The $x=0$ in the criteria refer to a point defined in Fig. 2.

It was also determined that for practical purposes $t_\text{op,initial.}$ must be at least one second. If $t_\text{op,initial.}$ was determined to be less than 1 s for some operating current I_op MQE was marked to be zero.

When $t_\text{op,initial.}$ was found to be sufficient MQE for the case was computed using the condition

$$t(E_\text{dist})_\text{op}-t_\text{op,des.}=0, \tag{6}$$

where $t(E_\text{dist})_\text{op}$ is the time at which the condition (4) is fulfilled for a disturbance with energy E_dist.

IV. Results and comparison

In addition to the computation method described in the previous section we also used the operation time parameters of the experiments presented in section II. The values computed using a fixed operation time can then be compared directly to

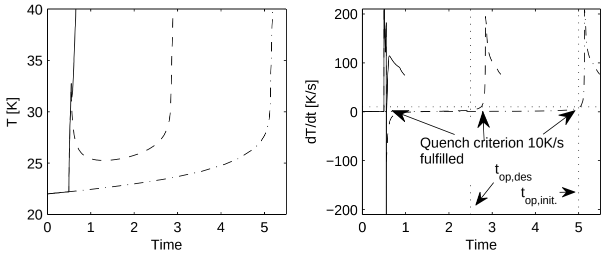

Fig. 3. Dot-dashed lines present temperature and its time derivative without disturbance. Dashed and solid lines present corresponding curves where disturbance is below MQE (40 mJ) and above MQE (40.5 mJ). Temperature is 22 K and $I = 0.95 I_c$.

the measured MQE values. The results using fixed operation time were in general smaller than those obtained using (3), in Fig. 4 a comparison between the two methods is presented for the MgB_2 conductor. For Fig. 4 the fixed operation time $t_{\text{op,fixed}} = 2$ seconds was chosen to provide a better view of the difference. Two n-values 7 and 14 were used to determine the effect of the n-value. As seen from Fig. 4 when the normalized current was increased MQE reduced more rapidly when fixed operation time was used. For example MQE at $1.022 I_c$ (300 A) was 27.8 mJ for the fixed case and 34.0 mJ for the other. The behavior can be explained by studying the inset showing the operation time and it is clear that the operation times decreased rapidly after $1.0 I_c$ was passed. These results indicate that the operation time is a crucial parameter when determining MQE for low n-value conductors operating near I_c.

We performed measurements in our measurement system at 22.5, 27 and 32 K for the MgB_2 sample. The results are illustrated in Fig. 5. The critical current of the sample was measured to be $I_c(T) = 747.39 - (20.62T)$ in this temperature regime. The n-value of the sample was 7 and temperature independent between 22-32 K. During the measurements the MQE was confirmed by performing several measurements using Up and Down method. The principle of the Up and Down method is presented in Table I. We used 1 mJ steps in our measurements and for each measurement the shape and size of the excitation pulse was confirmed using an oscilloscope. The accuracy of the MQE measurement was found to be around the 1 mJ step since we were able to see the sharp difference between quenching and recovery as illustrated in Table I for each measurement point. The determination if a quench had occurred was done by studying the time dependent voltages measured from the voltage taps. A quench had occurred when the voltage did not return to the noise level while the transport current was switched on. Fig. 6 illustrates the voltages present during a quench and a recovery.

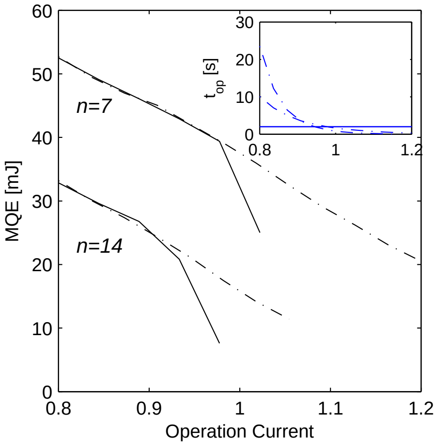

Fig. 4. MQE as function of I/I_c for MgB_2. Solid lines represent case where operation time is fixed to 2 s, dashed lines represent case where operation time is determined from (3). Inset shows operation times for variable time cases, solid line corresponds to $t_{\text{op,fixed}} = 2$ s.

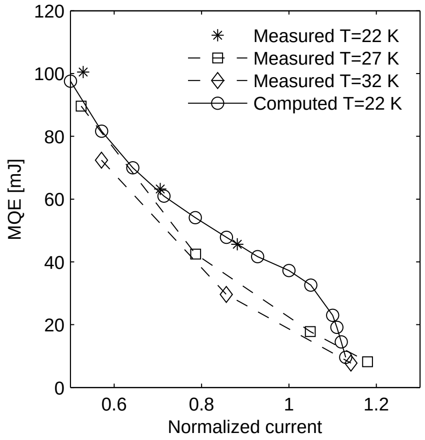

Fig. 5. Measured and computed MQE values for a multifilamentary MgB_2 tape. The dashed lines are only meant to be guides for eye.

TABLE I
UP AND DOWN TEST EXAMPLE. X = QUENCH, O = RECOVERY

101 mJ				x		x		x		x	
100 mJ			o		o		o		o		o
99 mJ		o									
98 mJ	o										
Energy/Pulse no.	1	2	3	4	5	6	7	8	9	10	11

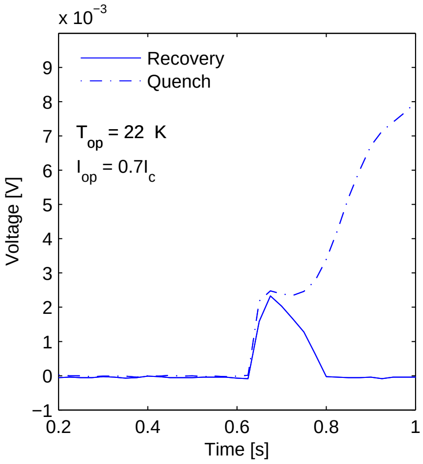

Fig. 6. Voltages measured across heater showing presence of non-propagating and propagating normal zones.

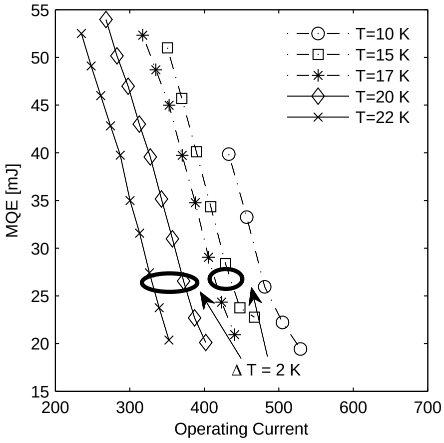

Fig. 7. Computed MQEs for several different temperatures for MgB_2.

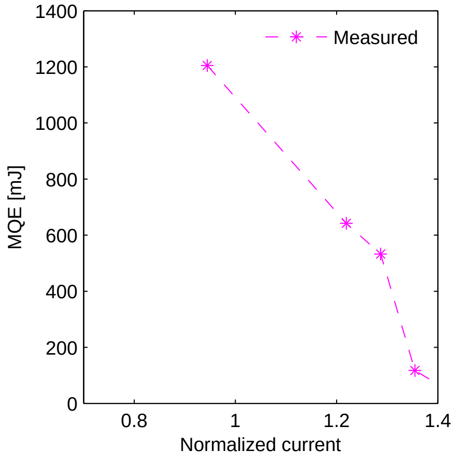

Fig. 8. Measured MQEs for Bi-2223/Ag tape at 78 K. The dashed line is only meant to be a guide for eye. Operation time used was 2.5 seconds.

In Fig. 5 the measured MQEs for the 22 K operation temperature case fit the computational data well. Also it can be seen that increasing the operation temperature and normalized operation current decrease the MQE.

Fig. 7 presents the results obtained from the computational model at operation temperatures 10, 15, 17, 20 and 22 K. The ellipses highlight that a 2 K increase in the temperature causes notably different reductions in the MQE. The explanation for these results is that the thermal properties of the stabilizing copper core of the tape change as the temperature changes. For example, the thermal conductivity of copper increases by about 47 % when temperature changes from 10 to 15 K. When T_{op} again increases to 20 K the change is only about 17 % and beyond $T_{\text{op}} = 23$ K the thermal conductivity starts to decrease.

The measurement system and procedures used with MgB_2 were also used for the Bi-2223/Ag conductor at 78 K. I_{c} of the conductor at this operation point was 122 A and the n-value 13. As expected the measured MQE were much higher than with MgB_2 and the step size for the up and down tests was increased to 5 mJ. The measured values for MQE at $t_{\text{op,fixed}} = 2$ s varied from 1.2 J at $0.94 I_{\text{c}}$ to 45 mJ at $1.35 I_{\text{c}}$. The results are illustrated in Fig. 8. The lack of material parameters prevented us from performing simulations for comparison.

V. CONCLUSIONS

We measured MQE for MgB_2 and Bi-2223/Ag tapes at sub- and supercritical currents. Also a computational model for determining MQE at supercritical currents was proposed. The MQE above I_{c} was found to be dependent on the required operation time along with temperature and current. Both measurements and simulations showed that with a low n-value conductor it is possible to operate at supercritical currents. Simulation results indicated that the operation time chosen has a significant effect on the MQE when the operation current approaches and passes the critical current.

The results obtained from the computations correlated well with measured results for MgB_2 at 22 K. For the Bi-2223/Ag conductor measurement results were obtained. MQE for the Bi-2223 operating at 78 K was about an order of magnitude higher than those obtained for the MgB_2 conductor.

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