Quench Behavior of $YBa_2Cu_3O_7$ Coated Conductor With AC Transport Current

Guo Min Zhang, David J. Knoll, Doan N. Nguyen, Pamidi V. P. S. S. Sastry, Xiaorong Wang, *Student Member, IEEE*, and Justin Schwartz, *Fellow, IEEE*

***Abstract*—Alternating current (ac) loss and quench behavior measurements were performed on a $YBa_2Cu_3O_x$ coated conductor at 45 K. The minimum quench energies (MQEs) and the quench propagation velocities were measured as a function of transport current and frequency. AC losses were measured at the corresponding temperature and frequencies to quantify the internal thermal load during ac quench measurements. It was found that the direct current (dc) and ac quench behavior are similar, but that the MQE for dc experiments is higher than the corresponding ac cases. This difference is not seen in the normal zone propagation velocity data, indicating that the difference in MQE is minimal if the ac losses are included in the energy calculation. The ac experiments show that the MQE and propagation velocity varies weakly with frequency.**

***Index Terms*—Alternating current (ac) quench, AC losses, minimum quench energy (MQE), normal zone propagation velocity, $YBa_2Cu_3O_7$ tape.**

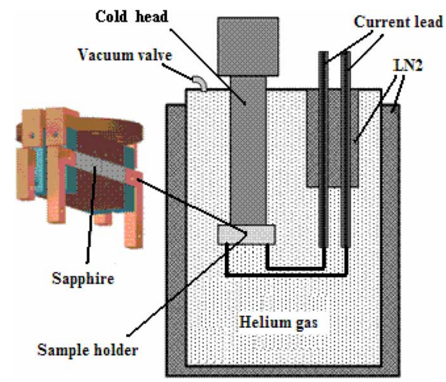

Fig. 1. Experimental setup. The sample holder is mounted on the cold head. The sample is placed on the sapphire strip with its ends soldered on the current conjunctions of the sample holder. The arrangement of the voltage taps, temperature sensors, and heater is shown in Fig. 2.

I. Introduction

THE significant progress in the commercialization of high-temperature superconductor (HTS) based on $YBa_2Cu_3O_x$ (YBCO) coated conductors may enable power application of HTS materials in the near future [1]. For practical applications, understanding quench behavior is essential for protecting HTS-based devices. Under typical operating conditions, the conductor will carry alternating (ac) currents, so ac losses are unavoidable and studying the quench behavior of HTS conductors with ac transport current is essential. To date, quench studies of HTS conductors have focused on direct current (dc) experiments [2]–[10] and no results have been reported on the quench behavior of YBCO coated conductors with an ac transport current.

In this work, the quench behavior of a YBCO coated conductor with ac and dc transport currents is reported. The minimum quench energies (MQEs) and the normal zone propagation velocities are reported for different dc and ac transport currents at 45 K. The frequency of the ac transport current is varied from 50 to 400 Hz. AC losses are measured at the corresponding frequencies and temperature to analyze the background conditions of ac quench.

II. Experimental Approach

Cu-stabilized YBCO coated conductor was obtained from American Superconductor Corporation. The conductor architecture was a 75-μm-thick NiW substrate, 225-nm-thick Y_2O_3/YSZ/CeO_2 buffer layers, a 0.8-μm-thick YBCO layer, a 3-μm-thick silver layer, and a 5- to 10-μm-thick layer of solder. The conductor cross section was 10 mm $\times$ 0.15 mm. For more details about the conductor see [11]. For these experiments, samples were cut to 15-cm lengths.

The experimental setup is shown in Fig. 1. The sample is cooled via sapphire using a GM cryocooler. Critical current, ac losses, and quench behavior are all measured on this experimental system. The arrangement of the voltage taps and temperature sensors is shown in Fig. 2. The distance between voltage taps for critical current and ac loss measurements was 5 cm, while for quench propagation measurements the distance between voltage taps was 0.9 cm. Voltage taps were attached using low temperature solder.

A Lakeshore 340 temperature controller was used to control the temperature. Helium gas was used to ensure temperature uniformity along the sample. The cryostat was first pumped

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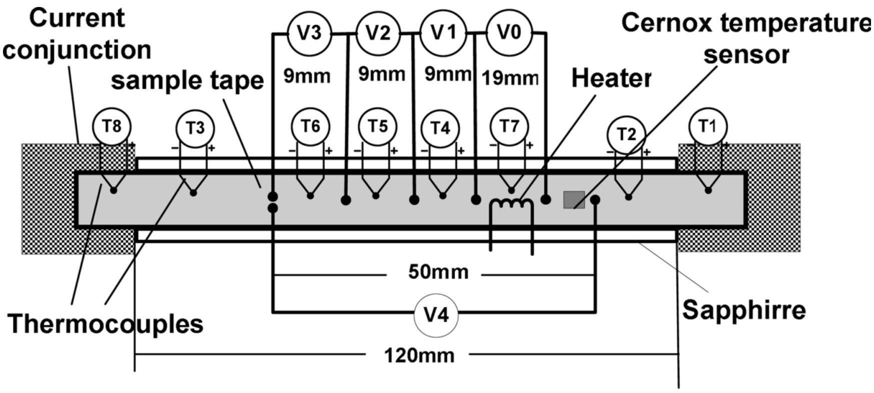

Fig. 2. Schematic of the sample, mounted on the sample holder, with the arrangement of the voltage taps, temperature sensors, and heater.

to a vacuum of about 10^{-6} mbar, then filled with helium gas ($\sim 10^{-3}$ mbar) and cooled. For a fixed temperature, the temperature fluctuation is controlled to less than 0.2 K. To protect the sample from damage, temperature protection limits were set during all the measurements.

The critical current (I_c) of the sample was measured using a 1-μV/cm electric field criterion. To quantify the steady-state heat load in the sample during ac quench measurements, ac losses were first measured using the electrical method [11] as a function of transport current with the transport current operating with frequencies of 50, 200, and 400 Hz. To avoid temperature rise during ac loss measurements, ac losses were first measured at one current, then stopped until the temperature re-equilibrated at 45 K, and then measured at the next current. For (ac) $I < 70\% I_c$, the temperature remained constant during loss measurements, and for $I > 70\% I_c$, the temperature rise was less than 0.5 K. Thus, we consider the data to be at 45 K. A compensation coil was adjusted for each frequency of ac transport current.

For quench measurements, a resistive heater (5.93 Ω at 45 K) was attached to the sample and a current pulse to the heater was used to create a local normal zone in the sample. Before initiating the normal zone, a steady-state transport current (ac or dc) was established in the sample. The normal zone collapse or propagation was observed through measurements of the temperature and voltage as a function of time along the sample. Four digital multimeters were used to measure the voltage signals. Eight thermocouples and one cernox temperature sensor were used to measure the temperatures. Detailed experimental procedures for studying the quench behavior can be found in [10]. For AC quench measurements, the voltage loops were made as small as possible to diminish the inductive voltage signals. Measurements of ac and dc quench behavior were first made at a transport current equal to 50% I_c (root-mean-square (rms) value for ac quenching, i.e., peak value 70.7% I_c). AC quenching was measured at frequencies of 50, 100, 200, 300, and 400 Hz. DC quench measurements were made at transport currents equal to 56% $I_c, 60\% I_c, 64\% I_c$ and 70% I_c.

III. Results and Discussion

The self-field critical current at 45 K was 505 A. After the initial ac and dc quench measurements at 50% I_c (rms value for ac quenching) were completed, the critical current was degraded to 409 A. This degradation influenced the values of transport current selected for the subsequent dc quench measurements.

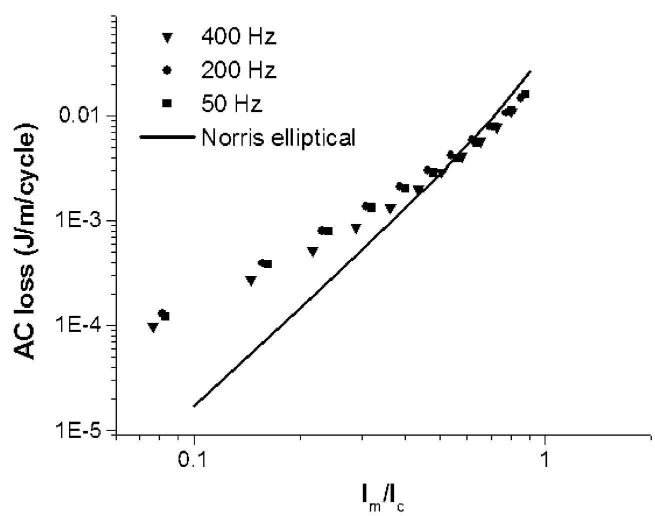

Fig. 3. AC losses of YBCO coated conductor as a function of normalized transport current (I_m/I_c) at 45 K for transport current frequencies of 50, 200, and 400 Hz.

Fig. 3 shows the ac losses at 45 K as a function of peak current ratio I_m/I_c for transport current frequencies of 50, 200, and 400 Hz. The solid line is the ac loss calculated for 50-Hz transport current using Norris' elliptical formula [13]

$$P = \frac{I_c^2 \mu_0}{\pi}\{(1-\Gamma)\ln(1-\Gamma) + (2-\Gamma)\Gamma/2\} \qquad (1)$$

where $\Gamma = I_m/I_c$ and I_m is the peak current.

It can be seen that the measured loss for (I_m/I_c) less than ~ 0.5 are much higher than those calculated, and the slopes of the loss curves are lower. This is caused by the contributions of ferromagnetic (and eddy current loss) in the NiW substrate. Similar to the measurements conducted by Duckworth *et al.* [14], [15], the results also show that the contribution of ferromagnetic loss is significant for peak current ratio (I_m/I_c) below ~ 0.4. The detailed studies on temperature and frequency dependence of ac transport losses in YBCO tape and a comparison with the loss behavior of BSCCO tape were published previously [16], [17].

AC and DC quench behavior was studied at 50% I_c (252.5 A, rms value for ac quenching) after the ac loss measurements. Results from the ac and dc quenches are compared in Fig. 4(a).

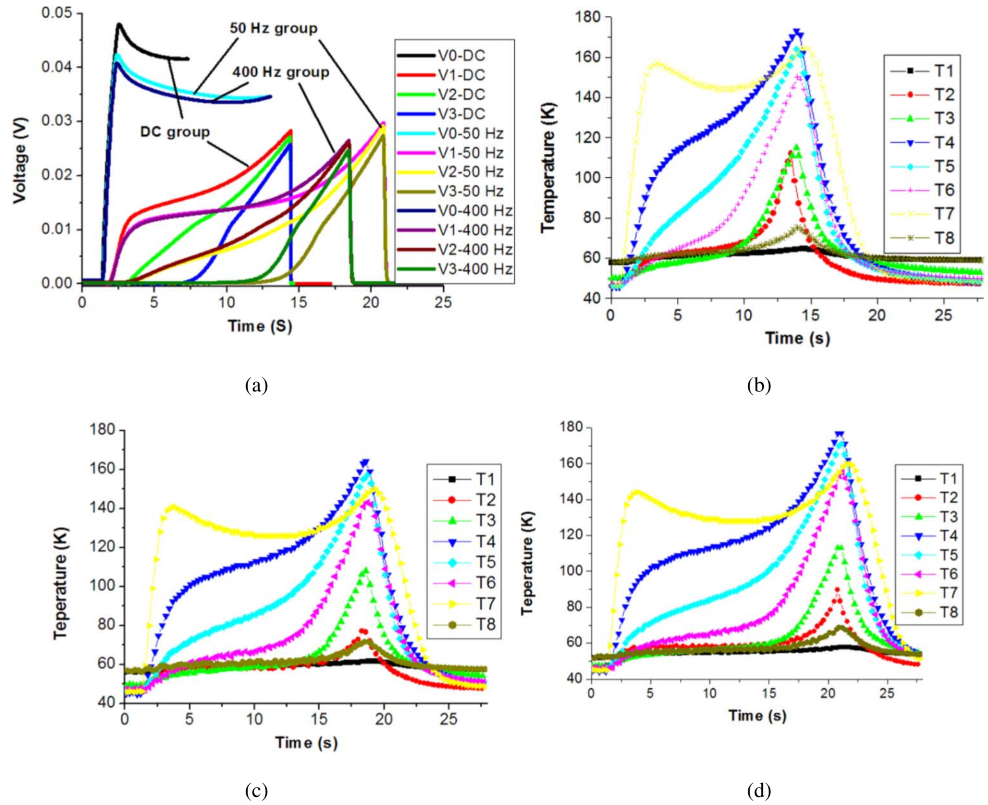

Fig. 4. (a) Quench behavior of the YBCO coated conductor at 45 K, with a transport current of 50%I_c. Voltage-time data is shown for a dc experiment and for ac experiments at 50 and 400 Hz. The curves are for different locations along the conductor. (AC transport currents are in rms value). (b) Temperature profiles of dc quench at 45 K. (c) Temperature profiles of ac quench at 45 K, 400-Hz current. (d) Temperature profiles of ac quench at 45 K, 50-Hz current.

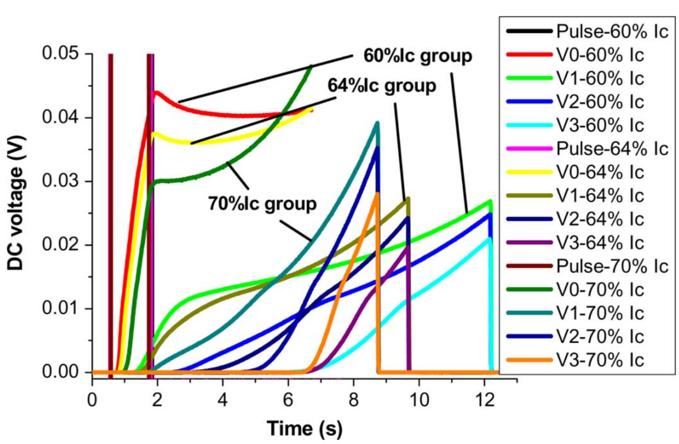

Fig. 5. Comparison of dc quench behavior of YBCO coated conductor at 45 K for different fractions of I_c

Shown are the voltage versus time traces for four voltage tap locations for the dc, 50- and 400-Hz experiments. It is seen that the ac and dc quench curves are similar for a fixed value of normalized transport current, except that the dc voltage curves increase more quickly than the ac curves. This trend continues as the frequency changes; comparing the 50- and 400-Hz data shows that the higher frequency curves rise more quickly. These results are in concert with the temperature profiles along the sample given by Fig. 4(b), (c), and (d). The difference in temperature rise time seen in Fig. 4(a)–(d) is caused by the difference of MQE (discussed below) results and ac losses. In the dc experiments, a greater amount of heat is localized in the conductor from the heater, so the temperature spikes quickly. Although the heater energy decreases with increasing frequency, ac loss increases with increasing frequency. The ac losses in the sample is conceptually similar to lowering the heat capacity of the sample, thus the resulting temperature spike is lessened and delayed with decreasing frequency.

Subsequent to the ac and dc measurements at 50% I_c, dc quench behavior as a function of fraction of I_c was measured. Note that I_c was reduced to 409 A due to damage after the initial quench measurements. Results for dc quenching as a function of fraction of I_c are shown in Fig. 5. As seen elsewhere with other YBCO coated conductor architectures, the quench voltages increase more rapidly as the fraction of I_c increases [10].

The MQE was determined for all quench experiments using the minimum heater pulse voltage (V) that causes a quench, the duration of the heater pulse (t), and the heater resistance (R) : MQE $= V^2t/R$. Using this approach, the calculated MQE is an overestimate because an unknown amount of heat is absorbed by the stycast used to glue the heater to the tape and because some of the heat is removed by the He gas. The calculated MQEs at 45 K as a function of normalized transport current (I/I_c) and frequency are shown in Figs. 6 and 7. Fig. 6 shows that the MQE decreases sharply—by about 20%—when comparing the dc and ac experiments, but that the frequency dependence in the ac experiments is very weak. In comparing these curves, it is important to note that the energy from the heater is

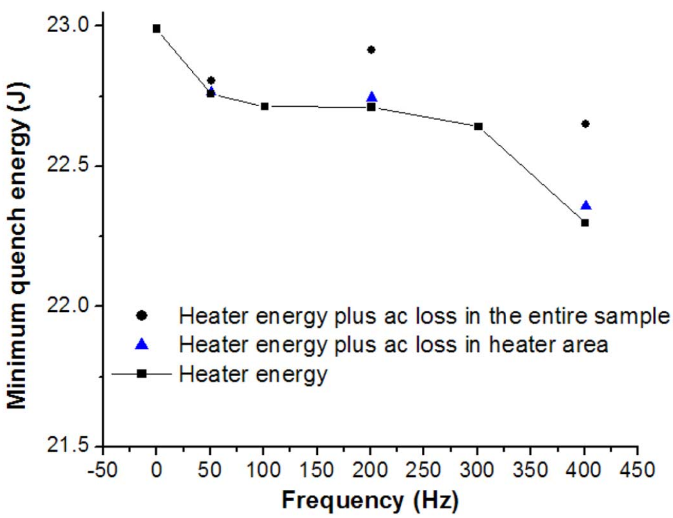

Fig. 6. MQE of YBCO coated conductors as a function of the transport current frequency at 45 K, 50% I_c ($I_c = 505$ A).

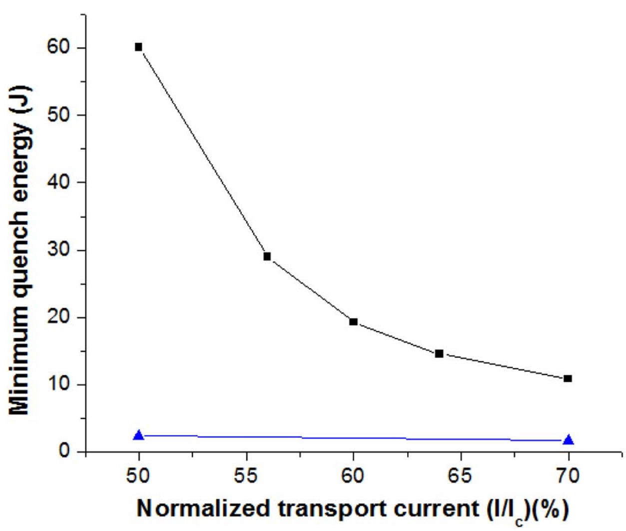

Fig. 7. MQE of YBCO coated conductors reported here (upper curve) at 45 K ($I_c = 409$ A) and reported previously at 58 K [4]. The large difference between the curves is primarily due to the presence of significant cooling in the experiments reported here.

localized in a small region of the conductor while the ac losses are distributed throughout the sample. Thus, it is difficult to determine the contribution of ac loss to the MQE. Fig. 6 shows the ac quench data in three ways: the heater energy only, the heater energy plus ac losses from within the heater section (0.02 m), obtained by integrating the data shown in Fig. 3 over the heat pulse duration (950 ms), and the heater energy plus the ac losses within the entire sample length (0.12 m), obtained from a similar integral. These calculations show that the addition of ac losses does not fully account for the MQE difference between the dc and ac cases. Thus, the distribution of ac losses along the length of the conductor must be considered when evaluating the contribution of ac losses to the MQE. This requires further study.

Fig. 7 shows that the dc MQE decreases with increasing normalized current I/I_c. In this figure, the 45 K data is the new data reported here and the 58 K data is from previously published work on another sample measured in vacuum with conduction cooling at the sample ends [4]. The dramatic difference

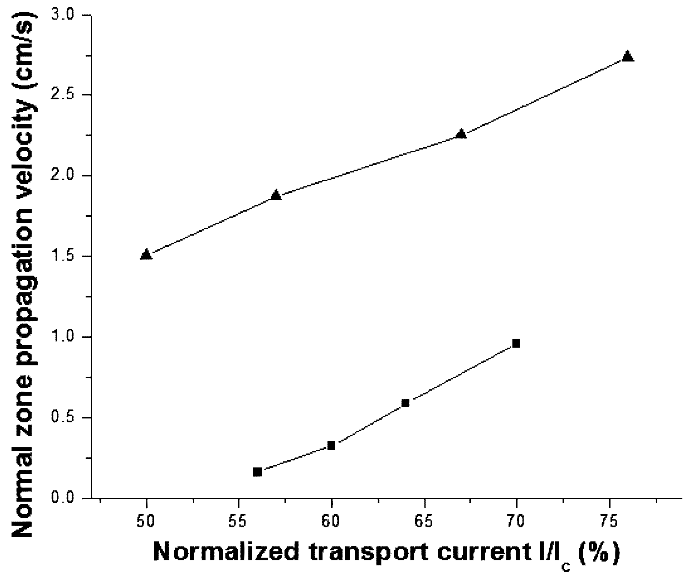

Fig. 8. Normal zone propagation velocity YBCO coated conductor as a function of the normalized transport current 45 K (lower curve; $I_c = 409$ A; this work) and 58 K (upper curve, from [4]).

between the two curves shows the effectiveness of the cooling in this experiment. There is cooling on both sides of the sample (through the sapphire and convection cooling to the helium gas in the cryostat). As a result, the MQE is more than an order of magnitude greater than in the nearly adiabatic case reported previously. Note that dc MQEs at 50% I_c in Figs. 6 and 7 are not the same. The 23.02 J in Fig. 6 was measured before the sample degraded ($I_c = 505$ A), while the 66.09 J in Fig. 7 was measured after the sample degraded ($I_c = 409$ A).

The normal zone propagation velocities during quenching are determined from the voltage-time data like that in Figs. 4(a) and 5 using the distance between voltage taps divided by the time required for a predetermined voltage level to be reached at those taps. This is described in detail in [10]. Figs. 8 and 9 plot the normal zone propagation velocities as a function of normalized current (I/I_c) for dc quenching and frequency for ac quenching, respectively. Fig. 8 shows that, consistent with previous experiments, the normal zone propagation velocity increases with increasing transport current. Comparing the new data reported here at 45 K with previously reported conduction cooling results at 58 K, it is clear that the improved cooling in this experiment has a significant effect on reducing the quench propagation. The rough order of magnitude difference cannot be accounted for merely by the difference in temperature. Figs. 7 and 8 are also consistent with past results; as the MQE increases, the propagation velocity decreases.

Fig. 9 shows the normal zone propagation velocity versus frequency. At first glance, this data appears to indicate that the propagation is faster for the dc quenching than the ac quenching, but the difference is within experimental error and thus in fact the propagation velocity is considered to be frequency independent. This is in contrast with what would be expected based upon the MQE data in Fig. 6 and the relationship between MQE and propagation velocity described above. In this case, however, the lack of correlation with MQE is related to the difference between dc and ac quenching. The MQE reported in Fig. 6 is the heater energy, but the propagation velocity is determined by the total heat into the conductor, i.e., the heater energy plus the ac

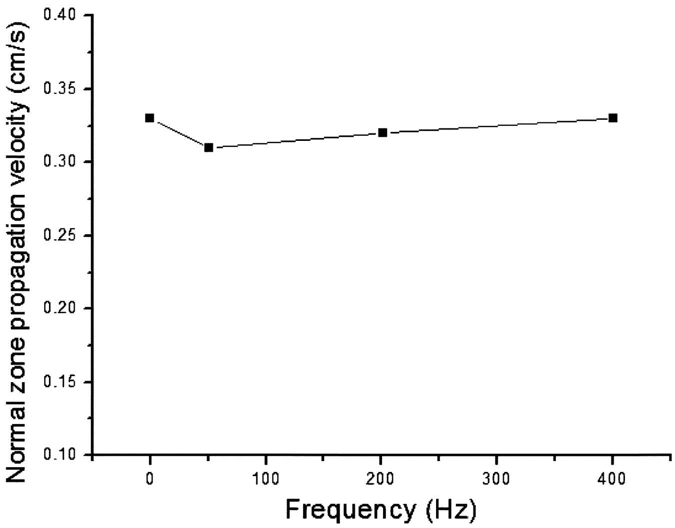

Fig. 9. Normal zone propagation velocity of YBCO coated conductor as a function of the transport current frequency at 45 K ($I_c = 505$ A).

losses, and the energy distribution. Thus, while the MQE data shows a difference between dc and ac behavior, the propagation velocity data indicates that the difference is negligible when considering the ac loss energy and distribution as well.

IV. Conclusion

Measurements of critical current, ac losses, and dc and ac quench behavior of a Cu-stabilized YBCO coated conductor were performed at 45 K as a function of fraction of critical current and transport current frequency. Results show that the dc and ac quench behavior are similar, but that the MQE for dc experiments is higher than the corresponding ac cases. This difference is not seen in the normal zone propagation velocity data, indicating that the difference in MQE is minimal if the ac losses are included in the energy calculation. The role of the heat distribution (localized for the heat pulse but distributed for the ac losses) also must be factored in if the differences between dc and ac experiments are to be better understood. The ac experiments show that the MQE and propagation velocity vary weakly with frequency.

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