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PROTOTYPE TEST OF ENERGY DOUBLER/SAVER BENDING MAGNET*

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Summary

An improved full scale bending magnet (E22-13) for the Energy Doubler was cooled down with a prototype satellite refrigerator and its characteristics were measured. We intentionally induced quenches on this magnet below 40 kG using a heater and the quench behavior was investigated from the viewpoint of system safety. The first self-induced quench of this horizontal magnet system occurred at about 41.7 kG. Due to high single phase pressure, we did not train the magnet to any higher field. The measurement of ac loss was done and the data showed some wire movement at about 20 kG. Transfer function was measured to be 9.81 (G/A). The magnetic field was measured using a harmonic coil. The field quality was found to be improved over the first full scale magnet (E22-1).

I. Introduction

Since the first 22-foot full scale bending magnet, E22-1, for the Energy Doubler was tested[1], production continued at a rate of 2 completed magnets per month. During that time, many improvements and changes were made in coil winding, coil support and the cryostat itself[2]. The first 6 magnets have round beam bores and the next 7 have elliptical ones. These magnets have two phase return pipes inside the coils. For the next version of the E22-14 series, the two phase pipes will be installed outside the coils to decrease the heat load on the single phase cryostat. During these developments, different types of collars were used to support the coils and some of the recent coils were wound with the keystoned cable consisting of selected high quality single strands. All of these coils were tested in a vertical dewar without final cryostats and iron yoke. Most of the coils can be trained to 40 kG without iron at 4.2 K in this test[3]. There is an azimuthal wire movement in the coil due to the electromagnetic force, as well as a radial movement[4], and efforts continue to make as tight a coil as possible. One of the production magnets, E22-13, was chosen for extensive testing. The data presented here are the ac loss, the field quality and the performance at quench.

II. Magnet Performance

The magnet, E22-13, was cooled down with the prototype Energy Doubler satellite refrigerator. The magnet on the test stand is shown in Fig. 1 with the satellite refrigerator in the background. The satellite refrigerator was recently put into operation[5]. There was no cryogenic pump in the system and a testing junction box connected to the magnet was directly hooked up to the refrigerator. The operational condition was not optimized due to shortage of time. It seems there was a thermal short between the shield line and the single phase line inside the junction box. This caused the incoming helium temperature to rise. Also, the heat exchange between the single phase helium (1 Ø) and the two phase helium (2 Ø) was not efficient, because there was a sheet of Mylar wrapped around the stainless tube between these two helium flows. Therefore, the operating temperatures of the helium was rather high. A typical set of temperatures and pressures is as follows:

1 Ø	inlet temperature	4.9 K
1 Ø	outlet temperature	5.05 K
1 Ø	pressure	12.5 psig
2 Ø	outlet temperature	4.5 K
2 Ø	pressure	5.2 psig

The shield line was cooled down with a cold He gas, which was branched from the turn-around end box. Its operating temperature was 62～63 K at the exit.

Quench Behavior

A 25 Ohm heater was installed on the surface of the superconductor cable just outside the magnet coil. With three-watt input to this resistor, quenches were induced intentionally at currents below real quench current. Quench behavior was studied using the CAMAC-PDP-11 system reported elsewhere[1]. Since then, we have modified the software to determine the upper limit of the coil temperature using actual current decay signal. Together with the information about temperature dependence of electric resistance and heat capacity of copper we can calculate the temperature of cable at the hottest point. At currents below 3000 amps, the induced quenches caused only minor perturbations except for a heated spot in the wire. Recovery was very rapid. Above 3000 amps, there were rapid changes with increasing current except for the temperature which leveled off. Pressure in the 1 Ø line, energy loss in the magnet, upper limit of magnet temperature and magnet resistance are plotted vs. current in Fig. 2. The pressure changes in the 1 Ø and 2 Ø helium lines for induced quenches at 4000 and 4130 amps and a natural quench at 4260 amps were recorded on a strip chart recorder. In each case, the maximum 1 Ø pressure is reached in about 0.6 second, then rapidly decreases. However, the pressure at the self-induced quench went up to 92 psia. The cryostat has not been designed so as to stand the pressure above 60 psia, so we did not train the magnet any further. The integrated dumped energy into the magnet reached the maximum at about 0.6 second. The resistance value reaches a maximum at 0.2 second and starts to decay at 0.7 second, indicating the coil is cooling down again. The magnet power supply was tripped at several currents and the resultant data was compared against that for quenches. The two sets of data were very similar at high current. This fact suggests that the trip at high currents (above 3500 A) induces a quench in the coil.

AC Loss

The ac loss is a major contribution to the heat load of a magnet. The ac loss as a function of ramp rate was measured and shown in Fig. 3. A substantial portion of this loss is due to hysteresis loss and is independent of the ramp rate. The ramp rate dependence of the loss was weak; somewhat less than for other magnets tested.

The ac loss as a function of maximum magnetic field was measured at ramp rate of 1.8 kG/s. The data are shown in Fig. 4 for two cases, starting zero field and 9 kG corresponding to 200 GeV injection. The curve starting from zero field shows an upward deviation from

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linearity above 20 kG, indicating there is mechanical movement of the coil. Some inelastic movement of single strands inside the cabled wire, of cables inside the coil, or of the coil as a whole, causes an extra energy loss at higher field. Measurements were made up to 41 kG, the projected loss from 4.5 kG to 45 kG is about 550 Joules/cycle for a ramp rate of about 50 GeV/sec. This results in a heat load of about 10 watts per magnet for the designed Doubler operation. This value includes the effect of the wire movement and will be reduced to 400 Joules/cycle with a solider coil. There is a droop at high field in the measured magnetization curve. This indicates there is still some coil deformation above 20 kG. The shape of the magnetization curve indicates a small iron saturation above 40 kG.

Field Quality

Various harmonic components (4 pole, 6 pole, 8 pole and 10 pole) were measured in the DC mode from low field up to above 40 kG, taking into account the history of excitation. Measurements were done in the central region and in the end portion, using a Morgan coil (1.0 inch diameter and one foot long).

This magnet has an elliptical beam bore and a round warm bore cryostat was put inside. It was difficult to put the measuring coil at the real center of the magnet coil, instead of at the center of the warm bore. The 4 pole component includes some errors from the higher order harmonics, especially from the 6 pole component. However, the off-centering of the coil has only a small effect on the 6 pole and the higher components.

Harmonic coefficients under DC operation are given in Table 1 for the 2-dimensional region and for the increasing field. The b_n terms are the normal components and the a_n terms are the skew ones. In this table, some corrections are made for the off-centering of the coil. The field quality is much improved compared with that of E22-1[1], but is still worse than the precision magnet, E5-1[6].

As shown in Fig. 5, the normal 6 pole component has a large hysteresis loop at low field, which comes from the magnetization of the superconductor itself. But, the values coming from construction errors do not depend on the excitation field. This fact suggests that the wire movement observed in the ac loss and the magnetization curves does not seriously affect the 6 pole components. The 6 pole component at the end portion over one foot long is also given in Table 1. As we expected, it is worse than in the central region by a factor of about five. However, over the whole magnet, the integral normal 6 pole component is $-3.75 \times 10^{-4}/\mathrm{cm}^2$ at 40 kG. Our magnet has a long straight section, so the end effect is diluted. But, the integral harmonics could be reduced more by modifying the end portion.

Conclusions

The magnetic performance of E22-13 magnet is improved compared with the first full scale bending magnet E22-1, as far as the field quality and maximum field are concerned. However, efforts should continue to make the system operate the magnet more safely, especially at quench time.

Acknowledgements

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References

1 R. Yamada et al: IEEE Trans. on Magnetics, Mag-13, No. 1, 86 (1976).

W.B. Fowler et al: IEEE Trans. on Magnetics, Mag-13, No. 1, 279 (1976).

2 The Energy Doubler: A Progress Report for the Energy Doubler/Saver, Collider Project, June 1976.

3 R.H. Flora: Private Communications.

4 A.V. Tollestrup et al: Contribution to this conference.

5 C. Rode et al: Contribution to this conference.

6 R. Yamada et al: Operation Test and Field Measurement of E5-1 Magnet (1) (1976), Fermilab Internal Report TM-667.

Table 1. Harmonic Coefficients at increasing field (D.C.) E22-13

	5	10	20	30	kG
Central Region					
b_1	-1.61	-1.04	-0.69	-0.38	$\times 10^{-4}$/cm
a_1	-4.79	-5.08	-5.16	-5.10	
b_2	-4.02	-2.98	-2.84	-2.73	$\times 10^{-4}/\mathrm{cm}^2$
a_2	-0.49	-0.48	-0.45	-0.43	
b_3	0.24	-0.28	-0.68	-1.13	$\times 10^{-5}/\mathrm{cm}^3$
a_3	-1.39	-1.60	-1.25	-1.22	
b_4	-7.63	-4.56	-4.59	-4.08	$\times 10^{-6}/\mathrm{cm}^4$
a_4	0.08	0.37	-1.51	-1.15	
End Region					
b_2	-15.3	-14.9	-14.9	-14.9	$\times 10^{-4}/\mathrm{cm}^2$
a_2	-1.61	-0.1	-0.1	-0.1	

$$B_z\ (z=0) = B_0\ (1 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + ..)$$

$$B_x\ (z=0) = B_0\ (\quad a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + ..)$$

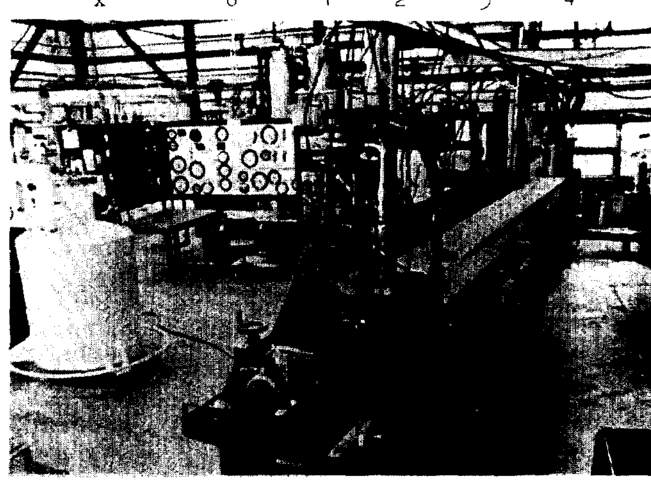

Fig. 1. E22-13 Magnet under test, using the prototype satellite refrigerator in the background.

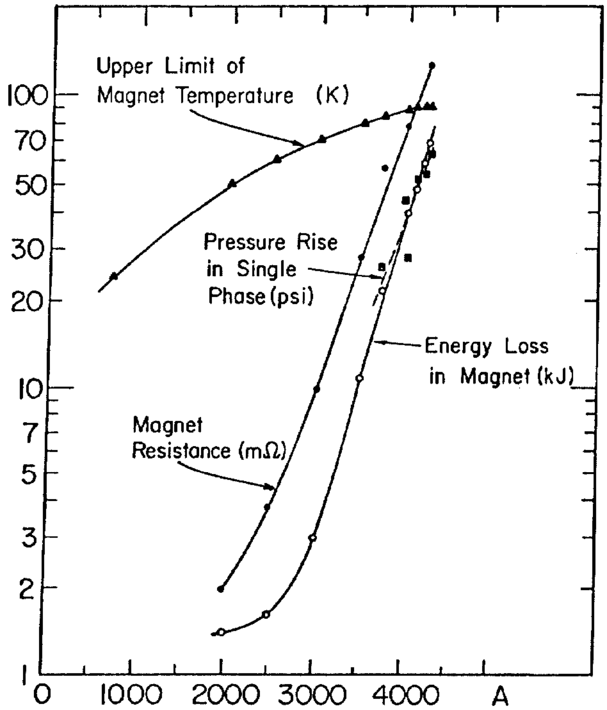

Fig. 2. Behavior of various parameters at quenches for E22-13 Magnet

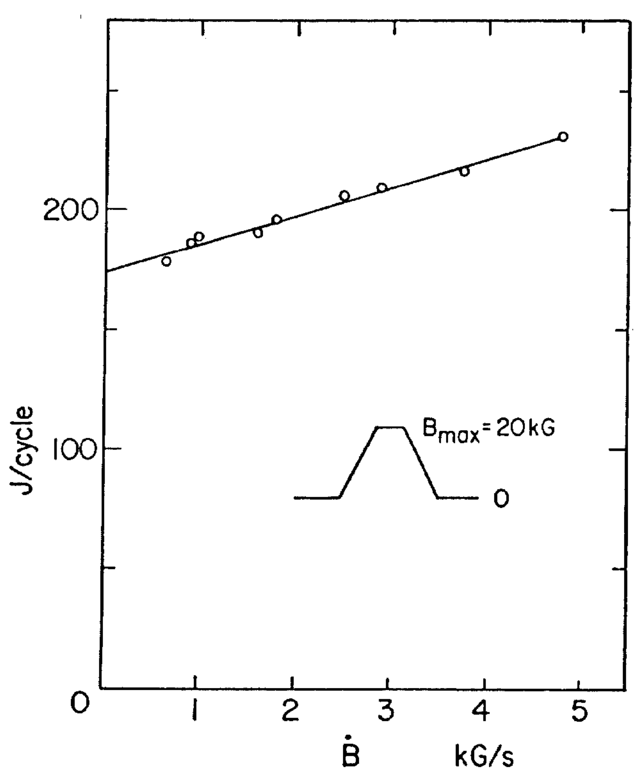

Fig. 3. Ramp rate dependence of ac loss for E22-13 Magnet

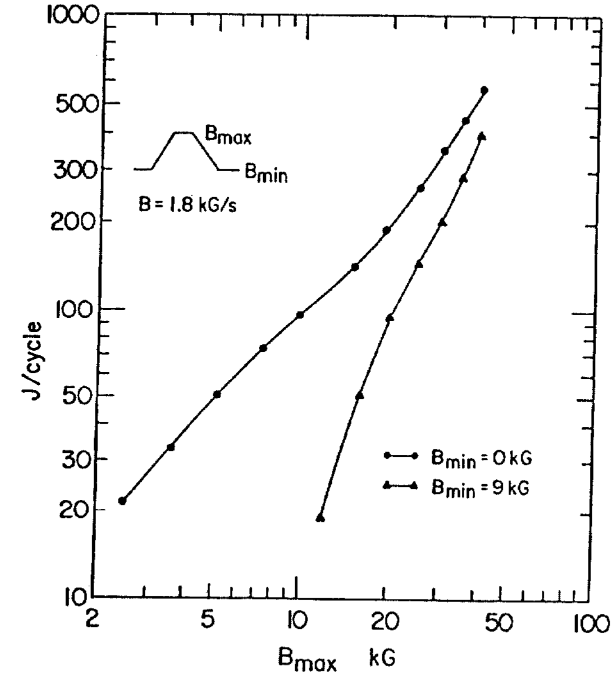

Fig. 4. Amplitude dependence of ac loss for E22-13 Magnet

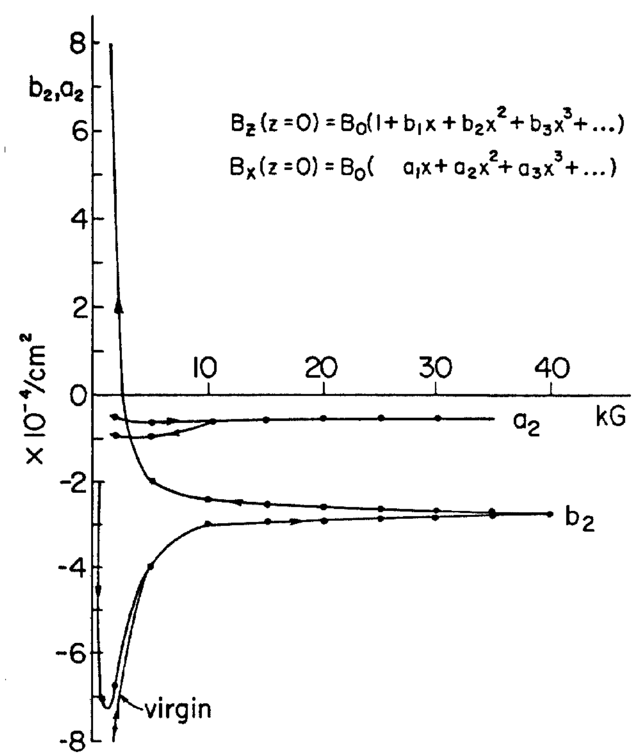

Fig. 5. The harmonic coefficients for the sextupole for E22-13 Magnet