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**RAMP RATE TESTING OF AN HTS HIGH GRADIENT
MAGNETIC SEPARATION MAGNET**

M. A. Daugherty, E. W. Roth, D. E. Daney, D. D. Hill and F. C. Prenger

Los Alamos National Laboratory
Los Alamos, NM 87545 USA**ABSTRACT**

We report on the ramp rate testing of a prototype high temperature superconducting (HTS) high gradient magnetic separation (HGMS) magnet. HGMS magnets are ramped from full field to zero field to clean the separation matrix. The time spent ramping the magnet is unavailable for processing and must therefore be kept to a minimum. Existing commercial low temperature superconducting HGMS magnets are immersed in a liquid helium bath and are designed to ramp from zero to full current in one minute. The HTS magnet in our system is conductively cooled and operates in a vacuum at a temperature of approximately 30 K.

Heat generated during ramping is not as readily removed from the conductively cooled magnet as a bath cooled magnet. To verify that the conductive cooling can adequately remove heat generated during ramping we recorded magnet temperatures and voltages while ramping at rates of up to 4.8 A/second. The magnet can accommodate ramps from zero to 100 A (1.6 Tesla) in 21 seconds with no degradation in performance. The average magnet temperature rises a maximum of 1 K during ramping. Using temperatures recorded during ramps we have made rough estimates of the ac losses generated in the magnet.

INTRODUCTION

High gradient magnetic separation uses large magnetic field gradients to separate ferromagnetic and paramagnetic particles from solids, liquids or gases. Fifty-nine elements have paramagnetic properties in some form and are thus candidates for HGMS. HGMS separators are built around a high-field solenoid magnet, the bore of which contains a fine-structured, ferromagnetic matrix - typically magnetic stainless steel wool. The design of our HTS HGMS system is shown schematically in figure 1 and has been discussed in two earlier papers.^{1,2}

The matrix locally distorts the magnetic field and creates large field gradients, which trap contaminants on the matrix surface. As separation continues the contaminants build up on the matrix. Periodically the magnetic field must be turned off to clean the matrix and remove the accumulated contaminants. Then the magnet is turned on and separation resumes. In commercial magnetic separation systems the cycle times are typically on the order of twenty minutes of separation, one minute to ramp the field down, five minutes to flush the matrix, and one minute to ramp back up to the operating field.³ Approximately seven minutes out of every twenty-seven are therefore not available for processing.

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Minimizing magnet ramping time is therefore an important issue in the design of HGMS systems.⁴

Existing low temperature superconducting HGMS systems operate with the magnet immersed in a bath of liquid helium.^{4,5,6} The heat generated during ramping is relatively efficiently removed by convection of the liquid helium, ensuring approximately uniform magnet temperatures. In a system such as ours, which operates in a vacuum, the heat must be removed by conduction to the magnet bore tube and mounting plate. Significant temperature gradients may therefore arise between the outer sections of the magnet and the cooling surfaces at the inner bore and magnet bottom plate. If these temperature gradients are too large the superconductor will warm up and dissipate more energy after the ramp to full current than can be removed by conduction and the magnet will quench.

On the positive side the HTS material allows us to operate with a significant margin between the magnet operating temperature and the critical temperature of the superconductor. We also benefit from the much larger heat capacities of the magnet material at the magnet operating temperature, which greatly reduce the temperature rise for a given heat input. This work was carried out in order to examine the net outcome of these competing considerations and determine if this conductively cooled HTS magnet system is capable of ramping on the time scale required for industrial HGMS systems.

Figure 1. Schematic of the HTS high gradient magnetic separation system.

EXPERIMENTAL PROCEDURE

The HTS magnet temperature was measured by three silicon diodes located at the top, middle and bottom of the magnet. The reported magnet temperature is the average of the readings from the three diodes. The response of the diodes is affected by the magnet field generated during a ramp, so the temperatures before and after the ramp, when the magnetic field was zero, were used to estimate the ac losses. The magnet voltage was measured by voltage taps located on the magnet terminals. The magnet current was measured using a 100 m Ω shunt resistor.

Prior to the start of a ramp the initial magnet temperature was set using a heater wound on the thermal link between the second stage of the cryocooler and the magnet cooling plate. Initial temperatures were varied from approximately 22 K to 41 K. After the magnet temperatures had stabilized a programmable power supply was used to ramp the magnet up to the maximum current desired at rates varying from 0.6 A/s to 4.8 A/s. Magnet current, voltage and temperature were measured before, during and after the ramp. Data from a representative ramp are shown in figure 2.

Figure 2. Time history of one magnet ramp cycle at 1.8 A/s showing average magnet temperature, magnet voltage and magnet current .

The magnet temperature, shown in figure 2a, peaks soon after the current ramp ends. The slight time delay between the end of the ramp and the peak magnet temperature is attributed to the time for the heat generated within the windings to conduct out to the diodes, which are located on the external surface of the magnet. The magnet voltage is shown in figure 2b and the current in figure 2c. Using the measured voltage of approximately 375 mV and the ramp rate of 1.8 A/s the magnet inductance is estimated to be 0.2 H. At the conclusion of a ramp the magnet temperatures were allowed to return to the initial temperature prior to the start of the next ramp.

RESULTS

Magnet temperature, current and voltage were the primary quantities of interest measured in these experiments. To calculate the losses we used an energy balance given by:

$$\dot{Q} = C_p M \frac{dT}{dt} \quad (1)$$

Where $\dot{Q}$ is the heat being generated in the magnet due to losses, C_p is the temperature dependent specific heat of the magnet, M the total mass of the magnet and dT/dt the magnet's average rate of change of temperature. M was calculated from the dimensions and a materials list taken from the engineering drawing of the magnet assembly. While the determination of the magnet mass is believed to be accurate to within approximately 5 percent, the magnet is thermally coupled to the current leads, whose mass was not used in the calculation. This introduces a source of uncertainty because while the thermometers measured the magnet temperature, the magnet was thermally coupled to the rest of the system making accounting for the total relevant thermal mass difficult. dT/dt was approximated by taking the maximum average temperature change during a ramp cycle and dividing by the total elapsed time of the ramp cycle. These measurements and loss calculations were performed at various values of magnet temperature, current ramp rate, and peak current as indicated in the following figures.

Figure 3 shows the maximum average temperature rise of the magnet during the ramp cycle at various starting temperatures and ramp rates. The figure indicates the temperature rise increases with the faster ramp rate as expected but decreases at higher starting temperatures because of the higher heat capacity of the magnet. Note in all cases the temperature rise is less than one kelvin.

Figure 3. Average magnet temperature rise versus initial magnet temperature for various ramp rates.

Figure 4 shows the average power dissipated in the magnet during the ramp cycle at various starting temperatures and ramp rates. The figure shows increased dissipation at the higher ramp rates as expected. There does not appear to be much variation of dissipation with temperature. The average power dissipated is shown again in figure 5 as a function of ramp rate. The losses appear to scale with ramp rate to the 1.25 power.

Figure 6 shows the average power dissipated in the magnet as a function of peak current, which is equivalent to peak magnetic field. The ramp rate and starting temperature are fixed at 1.5 A/s and 30.5 K respectively. A peak current of 100 A corresponds to a peak magnetic field of 1.67 T. The data shows the average losses are independent of the peak current.

Figure 4. Ramping loss versus initial magnet temperature for various ramp rates.

Figure 5. Ramping loss versus ramp rate for various initial temperatures.

Figure 6. Ramping loss versus peak current (peak magnetic field) at a ramp rate of 1.5 A/s.

As we discussed in the introduction commercial magnetic separators typically operate at full current for approximately twenty minutes, ramp down in one minute, dwell at zero current for five minutes to clean the matrix, and finally ramp back up to full current in one minute. In order to determine if this HTS magnet could tolerate such an operating cycle we allowed the magnet temperature to stabilize at full current, ramped down to zero current in one minute, held at zero current for one minute, and ramped back up to full current in one minute.

The results, shown in figure 7, clearly indicate the magnet survived the ramp and is beginning to cool back down. The cooling rate after the ramp is not sufficient for the magnet to reach its initial temperature in twenty minutes with this operating cycle. Note, however, that the dwell time at zero current here was only one minute as opposed to five minutes for a commercial separation cycle. The magnet recovery time can be improved by using a larger capacity cooler or improving the internal thermal conductivity of the magnet.

Figure 7. Time history of a magnet ramp cycle at 1.8 A/s to simulate a typical high gradient magnetic separation system matrix cleaning cycle.

CONCLUSIONS

We have examined the response of a prototype HTS high gradient magnetic separation system magnet to ramps between zero current and a current of 100 A. Ramp rates were varied from 0.6 A/s to 4.8 A/s and the initial magnet temperature was varied from approximately 22 K to 41 K. The largest measured temperature rise during a ramp from zero current to full current and back to zero current was 0.9 K. Measured magnet temperature rises were used to estimate ac losses during a ramp cycle. At a ramp rate of 4.8 A/s losses were estimated to be approximately 11 W. Ramping losses were found to be largely independent of operating temperature in the range from 22 K to 41 K. Losses appear to scale with ramp rate to the 1.25 power in this same temperature range. Losses appear to be independent of peak magnetic field at a temperature of 30.5 K and a ramp rate of 1.5 A/s.

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