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DAMAGE TO STABILIZING MATERIALS BY 400 GeV PROTONS

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ABSTRACT

A study of the radiation induced resistivity resulting from 400-GeV protons was made. The pulsed beam of the Fermi National Accelerator Laboratory was used with an intensity of 6×10^{12} protons per pulse at 400 GeV with a slow spill of approximately 1 sec. The instantaneous irradiation rate on the sample is 1.5×10^{13} p/cm^2/sec. The resistivity of copper increased linearly with proton fluence at a rate of approximately 3.6×10^{-25} $\Omega\cdot$cm/p/cm^2. Subsequently isochronal annealing was performed. Following the first room temperature anneal, 16% of the induced resistivity was still present. Subsequent irradiations of the same sample indicate that this residual resistivity increases with each irradiation with a tendency to saturate at a higher resistivity. The annealing results and the effects of repeated irradiations will be discussed in detail.

I. INTRODUCTION

The use of superconducting magnets in high energy proton accelerators requires a knowledge of the radiation damage resulting from stray particles and accidental losses. A study of the radiation-induced resistivity is the first step in this process. Two parameters have been studied: a) the resistivity increase at < 10 K as a function of the integrated 400 GeV proton flux and b) the fraction of the resistivity increase remaining following a room temperature anneal. This second parameter was investigated in terms of limiting the long term detrimental effects of this resistivity increase on the performance and lifetime of superconducting magnets. This was first proposed for fusion reactor magnet systems[1] but is applicable to particle accelerators as well.

II. SAMPLE PREPARATION

The target is in the shape of a small coil 5 cm long and 1.0 mm in diameter of 0.25 mm diameter copper wire. The purity is given as 4N total impurities and 5N metallic impurities alone.[2] The wire is wound uninsulated around an Al_2O_3 form and annealed at 908 C and 10^{-5} vacuum for one hour. Following the anneal, a CuO film is allowed to form on the wire as it cools in air. The turn to turn resistance on point contact has been measured at 500 kΩ which is adequate for this sample. The primary insulation is provided by the physical separation of the turns. The alumina coil form is then removed and replaced with a cylindrical heater which is used during the annealing process. The heater coil and the sample, both clean and oxidized, are shown in Fig. 1. The sample to be irradiated is then inserted in the target chamber and the final assembly is shown in Fig. 2.

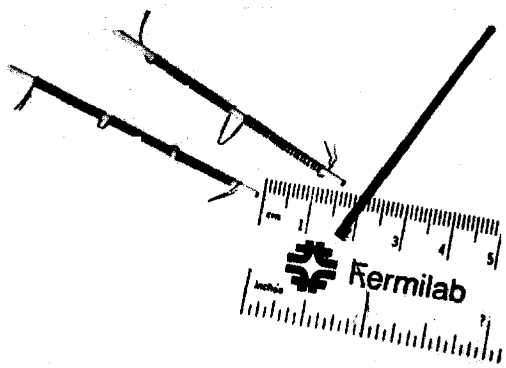

Fig. 1. The heater coil and the sample, oxidized and clean (counterclockwise from scale) before assembly into target chamber.

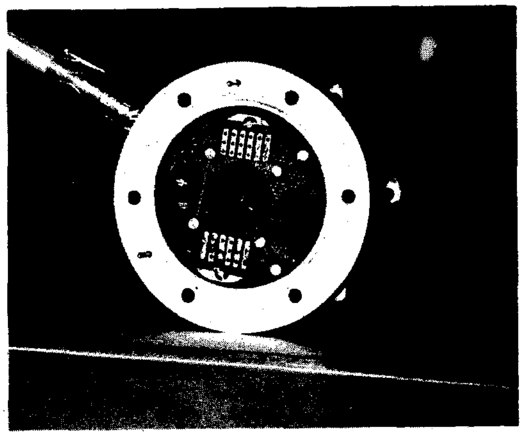

Fig. 2. The target chamber with target and heater coil before installation in refrigerator.

The completely installed sample has a resistivity ratio of 2500 uncorrected for size effect. The bulk resistivity ratio is calculated to be 3400. The resistance is measured using a current of 200 mA and a voltage sensitivity of 10^{-8} V. Each resistivity data point is the result of 10 separate measurements.

The refrigeration for the target is provided by a modified CTI 504 refrigerator with a 5 watt capacity. The target chamber is kept filled with liquid helium during the irradiation providing maximum heat transfer with the sample. The annealing sequence is accomplished by emptying the target chamber of liquid and applying current to the central heater. The temperature during the anneal is regulated by the phonon resistivity of the sample.

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III. RADIATION SOURCE

A pulsed 400 GeV proton beam at Fermi National Accelerator Laboratory is used for the irradiation. The target is aligned such that the beam is incident parallel to the coil axis. The beam profile is a slightly elliptical Gaussian distribution with a vertical width at half maximum (WHM) of ~4 mm, and a horizontal WHM of ~8 mm. At the beginning of each run, the target position is adjusted to the beam position by maximizing the beam-target nuclear interactions as registered by a gas filled loss monitor located near the target. The signal of the loss monitor minus the background losses is also proportional to the proton flux at the sample and is integrated and recorded during the run. The constant of proportionality is determined by activation analysis of the sample itself using the isotopes Mn^{52} and Na^{24}. The production cross sections for protons at 400 GeV on copper are 4.9 mb and 4.0 mb for Mn^{52} and Na^{24} respectively.[3]

For a given run, relatively stable beam conditions are necessary and can be obtained. However, the actual beam characteristics from run to run vary over a broad range of operating conditions. These conditions include intensities of $1.-6. \times 10^{12}$ protons per pulse, 0.4 to 2.0 second spill times and 11 to 16 sec machine cycles. Under most conditions the proton flux at the sample is $\sim 1.5\times10^{13}$ p/cm^2/sec. This proton flux corresponds to a beam heating slightly less than that required for departure from nucleate boiling thus maintaining a temperature less than 5 K. Irregularities in the spill structure occasionally causes a higher instantaneous proton flux to occur and temperatures near 20 K result from the transition to film boiling. The particular run, from which the data of Figs. 3 and 4 was taken, was devoid of any temperature spikes. In this case the irradiation temperature was less than 10 K, the minimum detectable temperature spike.

IV. RESISTIVITY RATE MEASUREMENTS

The results of the resistivity $\Delta\rho_{total}$ as a function of proton fluences ϕt are shown in Fig. 3 and reveals a linear dose dependance. This linear dependance can be more clearly seen from a plot of the derivative $d\rho/d\phi t$ versus ρ (Fig. 4). The rate remains constant at a value of $3.6\pm0.2\times10^{-25}$ $\Omega\cdot$cm/p/cm^2 after a slightly higher rate at low dose. It is expected that at higher doses this rate will decrease and has been interpreted by Horak and Blewitt[4] to be due to overlapping recombination volumes following the form

$$\frac{d\rho}{d\phi t} = A(1-B\rho)^2 \qquad (1)$$

where A and B are constants determined by the material and irradiation rate. Good agreement with neutron damage has been found using this model. The constant B derived from these earlier works would predict a decrease of 1-2% for a resistivity change of $10^{-8}\Omega\cdot$cm. This change is not within the present accuracy of the experiment and the effect of overlapping recombination volumes cannot be seen. The higher initial rate below $2\times10^{-9}\Omega\cdot$cm has been seen in other irradiations on copper and studied extensively in gold.[5] Several explanations have been proposed. In our case it seems possible that the nonaddivity of the resistivity contribution from Frenkel pairs with the resistivity contribution due to dislocations and the size effect is the cause of this deviation. The actual defect production rate is believed to be constant but this effect has not been studied sufficiently to make a definite determination of its origin.

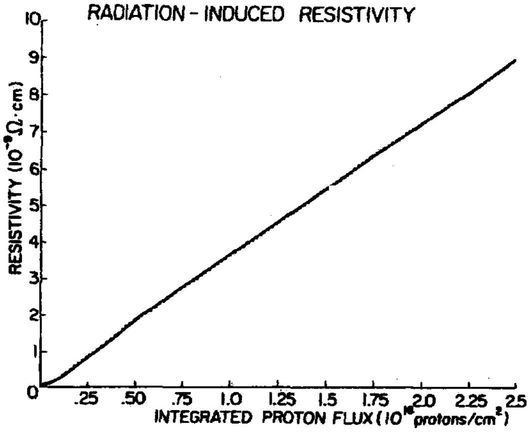

Fig. 3. The resistivity increase as a function of integrated proton flux for an irradiation temperature of less than 10 K. Each data point is the average of 10 individual measurements.

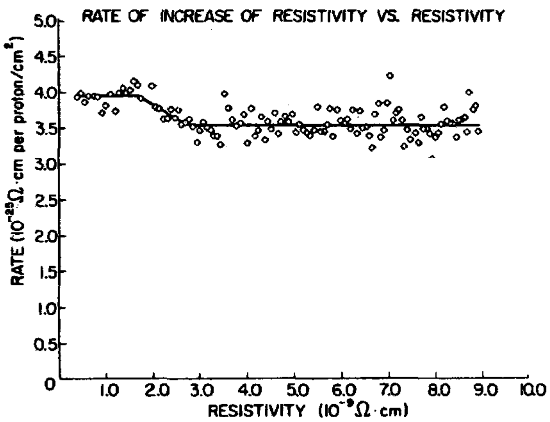

Fig. 4. The rate of increase of the resistivity as a function of the total radiation-induced resistivity charge (same run as Fig. 3).

IV. MINIMIZATION OF THE RESISTIVITY INCREASE

For the long-term operation of a superconducting magnet, a resistivity increase of $10^{-8}\Omega$ cm becomes unacceptable in terms of stability and quench protection. One method of reducing this degradation is by annealing the magnet at a temperature high enough for the recombination of interstitials and vacancies to take place. Room temperature (~300 K) is a convenient annealing temperature since no extra heaters are required and no special construction materials are needed. Unfortunately complete recovery in copper occurs only above 600 K. We have attempted to study the residual resistivity remaining at 300 K after several irradiation/anneal cycles.

The cycle has been to irradiate to $\sim 10^{-8}\Omega$ cm, anneal at 298 K for 10 minutes and repeat the cycle several times. Two features of this sequence are important: 1) the derivative $d\rho/d\phi t$ remained the same for all four irradiations and was not affected by the defects remaining from earlier irradiations. It might be expected that the residual defects would act as sinks enhancing spontaneous recombination but no detectable effect was measured at the low doses investigated;
2) the residual resistivity $\Delta\rho_{298}$ does not increase linearly with dose $\Delta\rho_{total}$ which indicates interactions between the residual defects. The model chosen to describe this interaction considers three types of defect configurations remaining after 298 K annealing:

a) Trapped single vacancies.
b) Vacancy clusters or vacancy loops formed in the collapsed denuded zone of a displacement cascade.
c) Interstitial loops formed as the result of interstitial migration.

These configurations have been studied using electron microscopy after neutron irradiation.[6,7] The contribution of defects a) and b) to the residual resistivity can be expected to increase linearly with dose. The saturation concentration will only be attained at much higher doses than could be allowed in a magnet system. However, dislocation loops are due to the free migration of interstitials. These loops are known to grow in size but saturate in concentration. As the composite defect grows, the resistivity per interstitial decreases. As a first approximation, the resistivity of a loop was taken to be proportional to the dislocation line length and therefore would increase only as $\Delta\rho_{total}^{1/2}$. It is expected that this model would be true for infinitely long dislocations. It ignores the perturbation of the strain field caused by the circular geometry. The contribution to the resistivity by the dislocation core would be less affected. These assumptions lead to a form for $\Delta\rho_{298}$ as shown

$$\Delta\rho_{298} = 0.071\Delta\rho_{total} + 0.265\,(\Delta\rho_{total})^{1/2} \qquad (2)$$

This form agrees quite well with the data as can be seen in Fig. 5.

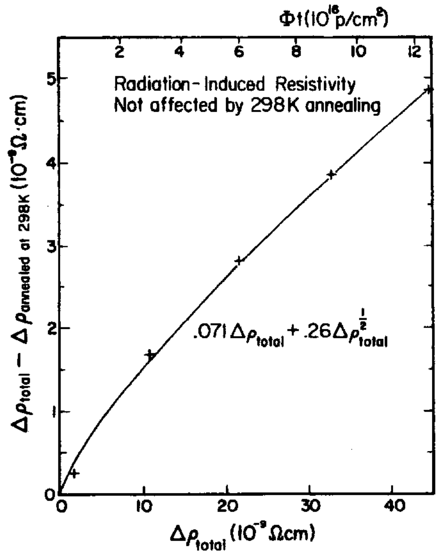

Fig. 5. Residual resistivity remaining after repeated irradiations followed by 298 K anneals for 10 minutes. The total resistivity $\Delta\rho_{total}$ has been corrected for annealing during the irradiations resulting from temperature spikes.

V. CONCLUSIONS

A 400 GeV proton flux increases the resistivity of copper at a rate of $3.6\pm0.2\times10^{-25}\,\Omega\cdot cm/p/cm^2$. Following room temperature annealing, some residual resistivity remains. The residual resistivity is well described by a model which considers vacancies in clusters, and interstitial dislocation loops resulting from interstitial migration.

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