IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

RADIATION DAMAGE LIMITATIONS FOR THE FERMILAB ENERGY DOUBLER/SAVER

P. A. Sanger
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

Abstract

One important factor determining the lifetime of particle accelerators using superconducting magnets is the accumulated radiation damage of the magnet components. Using existing damage studies and a measured correlation between the radiation levels with the beam-off and the beam-on, a reasonable assessment of magnet lifetimes can be made. On the basis of this assessment it is expected that damage to the magnet conductor will not limit the magnet performance. The proper choice of polymeric materials used in the magnet is necessary to avoid frequent refurbishing of the magnets.

Introduction

The use of superconducting magnets in high energy proton accelerators subjects these magnets to damaging proton fluxes as a result of beam scraping and other accidental beam losses. The degradation of the critical current of the NbTi superconductor and the increase of the electrical resistivity of the stabilizer surrounding the superconductor have recently been completed.[1,2] These studies, along with the existing data on the radiation resistance of polymers, provide the necessary information to evaluate the long term performance of the Fermilab Energy Doubler/Saver. This evaluation also requires a prediction of the expected proton fluxes to be seen by the magnets. Previous studies have relied on Monte Carlo calculations to predict heat loads and particle fluxes at the magnet. However, the difficulty in applying these calculations to long term radiation damage lies with the uncertainty of estimating the probability of the occurrence of the specific accident case described by the calculation. The approach adopted in this study has been to measure losses that are typical of the present Fermilab synchrotron, to correlated beam-off activation levels to proton fluxes and doses with the beam on, and to use established scaling factors to predict probably radiation levels of the 1000 GeV Fermilab Energy Doubler/Saver.

Measurement

A typical radiation survey of the Main Ring is shown in Fig. 1. This survey illustrates several features having important implications to a radiation damage evaluation. In general it is evident that beam losses are highly nonuniform. The two major loss points in Main Ring of the accelerator are the Transfer Hall (A-0) where beam injection and extraction occur, and the beam abort target located at D-0. These areas exhibit radiation levels an order of magnitude higher than the rest of the ring and are not typical of the accelerator as a whole. Other high loss areas are distributed around the Main Ring as a result of small internal obstacles in the system and oscillations of the beam. Most of the accelerator however has relatively low activation levels.

It is expected that the activation levels measured with the beam off reflects the proton flux and dose levels during operation. The constants of proportionality remain to be determined. To obtain this correlation, one area of the accelerator located in A Sector was selected for detailed study using copper activation foils and hydrogen gas dosimeters. Detectors were placed at the top of the vacuum tube 2 in. from the beam between each magnet in the selected zone. During the period of July 29, 1976 to October 28, 1976, a total of 3.9×10^{18} protons were accelerated and distributed in time as shown in Fig. 2. The accumulated activation during this period was measured using the Mn^{54} isotope

*Operated by Universities Research Association Inc. under contract with the United States Energy Research & Development Administration.

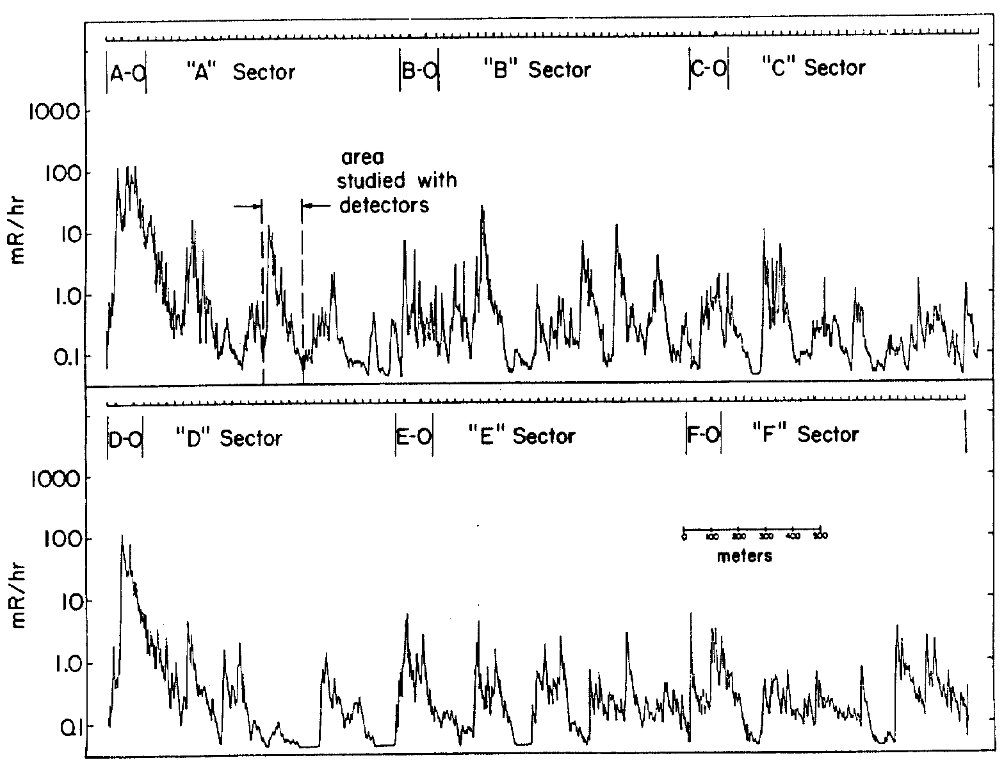

Fig. 1 Radiation survey of Main Ring one-half hour after beam turned off.

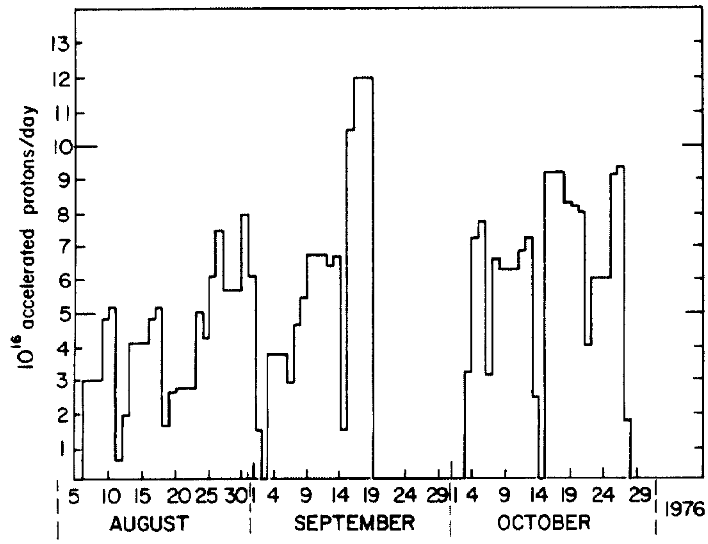

Fig. 2 Acceleration irradiation history for the period of August 6 through October 28, 1976.

production in copper with a cross section of 12.1 millibarns and corrected for decay during irradiation. The radiation dose was determined from the amount of hydrogen gas released from polyethylene by the dose. This method of dosimetry was chosen because the gas evolution can be easily related to mechanical property degradation of polymeric components. The minimum detectable dose using this type of dosimeter was 5×10^5 rads which is adequate for this study.

The integrated proton flux lost into the magnets and the corresponding dose are shown normalized to 10^{19} proton accelerated in Fig. 3. The radiation survey

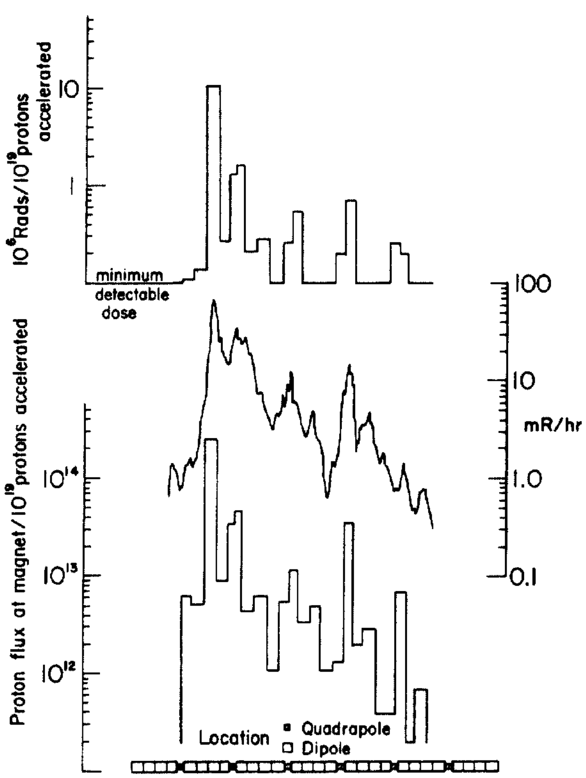

Fig. 3 Dose radiation survey and particle fluxes in A Sector for period of operation of Fig. 2.

of the area following the measuring period is also shown. As expected the radiation survey does exhibit the same general behavior as the detectors even though it is more sensitive to the most recent losses in that area as opposed to the detectors which measure an integrated dose over three months. For an activity of 1 mR/hr, $3\pm1\times10^{12}$ p/cm^2 per 10^{19} accelerated proton and $1\pm.3\times10^5$ rads per 10^{19} accelerated proton was measured.

Discussion

In order to make reasonable assessments of component lifetimes, it is necessary to determine the component properties that are critical to operation of the system. Those components important to superconducting magnet performance can be divided into three general areas: 1) conductor properties such as critical current and stabilizer conductivity; 2) electrical and thermal insulators such as Teflon, Mylar, Kapton and polyvinylchloride; and 3) structural materials such as fiberglass reinforced epoxy and mineral filled epoxy. Table I reviews the general radiation limits for these components based on the data presently available. The

TABLE I

MATERIAL	DOSE LIMIT	REF.	LIMIT CRITERION
CONDUCTOR			
NbTi Superconductor @ 40 kG	1.5×10^{18} p/cm^2	1	7% irrecoverable reduction
Cu Stabilizer Resistivity	6.3×10^{17} p/cm^2	2	2×10^{-8} Ωcm irrecoverable increase
	2.3×10^{16} p/cm^2	2	2×10^{-8} Ωcm 90% recoverable by 300 K anneal
POLYMERIC INSULATORS (Electrical & Thermal)			
Teflon®	.3 Mrads	4	50% reduction in elongation
Formvar®	~130 Mrads	5	50% reduction in elongation
PVC	~150 Mrads	4	50% reduction in elongation
Mylar® (Superinsulation)	~400 Mrads	4	75% reduction in elongation
Kapton®	6,000 Mrads	6	50% reduction in elongation
STRUCTURAL POLYMERICS			
Fiberglass Reinforced Epoxy	30,000 Mrads	7	50% reduction in elongation
Mineral Filled Epoxy	5,000 Mrads	7	50% reduction in elongation

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limits for the polymeric materials are for room temperature irradiations. It is expected that the radiation resistance at cryogenic temperatures will be slightly better[3] but until more complete studies have been undertaken the more pessimistic values have been adopted. For all the polymeric components, except the superinsulation, a 50% reduction in elongation has been chosen as the limit of reliability since differential thermal contractions during cooldown require substantial flexibility of the components. A more lenient limit of 75% reduction in elongation has been prescribed for the superinsulation where the mechanical requirements are much less stringent.

The radiation survey D(θ) as shown in Fig. 1 is not in a form readily integrated into a radiation damage assessment of the accelerator as a whole. A more useful function would be $F(D_O)$, the fraction of the accelerator with radiation levels greater than or equal to a dose level D_O. This can be expressed as

$$F(D_O) = \frac{1}{2\pi}\int_0^{2\pi} \alpha[D(\theta)-D_O]\; d\theta \qquad (1)$$

where $\alpha = 1$ if $D(\theta) \geq D_O$
$\alpha = 0$ if $D(\theta) < D_O$

Using this function the percentage of the accelerator in which damaged magnets will exist can be determined.

One additional function would be helpful in this assessment. The simple percentage of the accelerator affected by a damaging dose is not representative of the actual increase in operating cost incurred by the radiation induced degradation. Suppose that 10% of the accelerator receives doses greater than a level established as critical. A much smaller fraction of the accelerator may be operating at 10 times the critical dose and will therefore have to be replaced 10 times within the lifetime of the accelerator. The function $F_R(D)$ which accounts for these replacements in terms of a fraction of the accelerator can be calculated from $F(D_O)$.

$$F_R(D_c) = \sum_{i=1}^{\infty} i\left[F[iD_c]-F[(i+1)D_c]\right] \qquad (2)$$

where D_c = critical level and
i = number of times the magnet is replaced.

But $\sum_{i=1}^{\infty} iF[(i+1)D_c] = \sum_{i=2}^{\infty}(i-1)F[iD_c] = \sum_{i=1}^{\infty}(i=1)F[iD_c]$.

$$F_R(D_c) = \sum_{i=1}^{\infty} F[iD_c] \qquad (3)$$

Both $F(D)$ and $F_R(D)$ are shown in Fig. 4 as a function of the percentage of the accelerator magnets affected and replaced respectively.

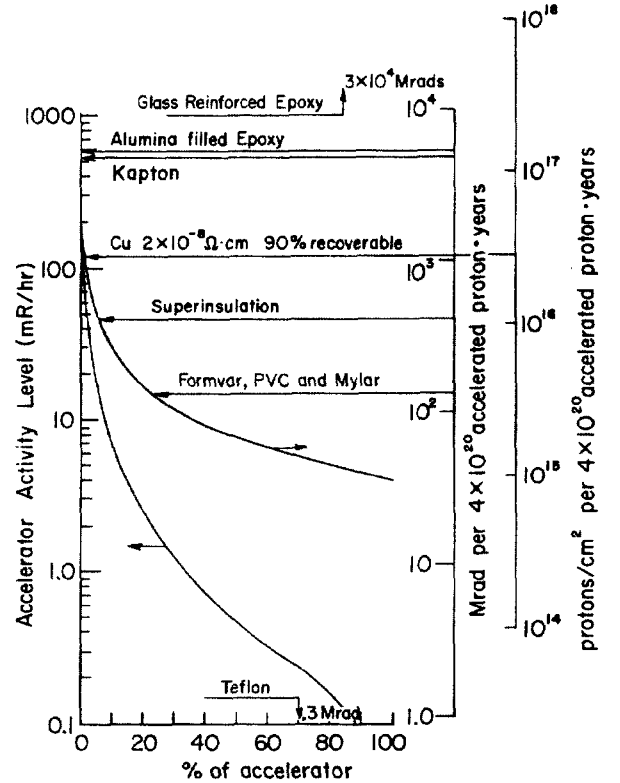

Fig. 4 Anticipated material property degradation for the Energy Doubler/Saver based on present accelerator operation.

Conclusions

A realistic assessment of the radiation damage occurring in the Fermilab Energy Doubler/Saver can be made using existing damage studies and the correlation of the residual activation measured with the beam off and the actual proton fluxes and dose levels during accelerator operation. A ten year lifetime at 1000 GeV and an average intensity of 4×10^{19} protons accelerated per year has been assumed. Due to the proximity of the Energy Doubler/Saver magnets to the existing accelerator magnets, a magnet in either system will see activation levels of both rings. In addition, the activation density of 1000 GeV protons will be substantially higher than that of a 400 GeV proton.[8] These two combined factors leads one to expect activation and dose levels twice as high as those measured. It was also assumed that operation at 1000 GeV will result in approximately the same percentage of lost particles. The right hand scales of Fig. 4 have been obtained using these operating conditions and the appropriate correlation factors. The reliable performance limits of Table I are also indicated. The conclusions obtained from Fig. 4 are:

1. The traditional electrical insulators would require 20% replacements with some areas such as A-0 and D-0 requiring replacement once a year.

2. The thermal radiation insulation would become unreliable in 2% of the accelerator with reinstallation in high loss areas after 2-1/2 years.

3. The disadvantages of 1 and 2 above can be avoided simply by the use of Kapton as electrical insulation and as the primary component of superinsulation instead of Mylar.

4. Increases in electrical resistivity will occur but no degradation of performance will remain following a room temperature warm-up.

5. No degradation of the critical current of the superconductor or the mineral filled or glass reinforced epoxy is expected.

Acknowledgements

I would like to thank Jay Baldwin for counting the activation foils, Jim McCrary who aided in the installation of the detectors and Ernie Ioriatti who helped analyze to hydrogen gas dosimeters. The many helpful discussions with Sam Baker were appreciated.

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