IRRADIATION EFFECTS IN SUPERCONDUCTING SYNCHROTRON MAGNETS

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I. Introduction

Superconducting magnets being placed in an accelerator or used in fusion reactors are in general not exposed to high irradiation doses. Only in cases of disaster, such as missteering, or in cases of beam scraping, beam ejection, or if magnets are placed close to internal targets, or beam absorbers and septums, may appreciable irradiation doses be expected in magnets.

To determine the dose rates in synchrotron magnets, a 10^3 GeV proton synchrotron with 10^{13} ppp, at present being studied by the GESSS committee*, is taken as a model. The calculation of the dose rates at first collision at the magnet where maximum energy is absorbed is based on experimental data*, and on Monte Carlo calculation performed over the magnet volume*. The axially symmetric magnet coils are not protected by means of steel plates in the upstream and downstream faces. The dewar walls are thinner than one radiation length and we can expect that the scattered primary particle produces a primary collision only with the superconducting coil.

In this paper, we present methods of irradiation dose estimation in magnets, where we confine our attention to protons (estimated electron dose rates are discussed in literature*) and discuss briefly, endangered magnet areas. Also we discuss the properties of superconducting magnets when exposed to high irradiation dose rates.

II. Energy Loss by Collisions

The incident beam passing through an internal target or at extraction areas, passing through collimators or slits will produce secondaries. A fraction of the primary particles (say about 10 % of the proton beam) of the incident beam may collide with the magnet surfaces. The distribution of the deposited irradiation dose is shown for a dipole magnet with circular aperture in Fig. 1. The data given are extrapolated values measured at 20 GeV and adjusted to 1000 GeV protons. The incident beam distribution curve indicated by (0 cm) is assumed to have an exponential radial decay. The intensity distribution is given by* :

$$J(r,z) = 2 \times 10^9 \text{ rad } (1 - 0.04z) \times \exp(-(r - r_i)/r_0) \text{ for } r \geq r_i$$

and with z in m.

In lateral or axial magnet direction the beam intensity is reduced by less than 20 %. The incident intensity over the magnet having an axial length of several metres is completely absorbed by the active and inactive magnet material.

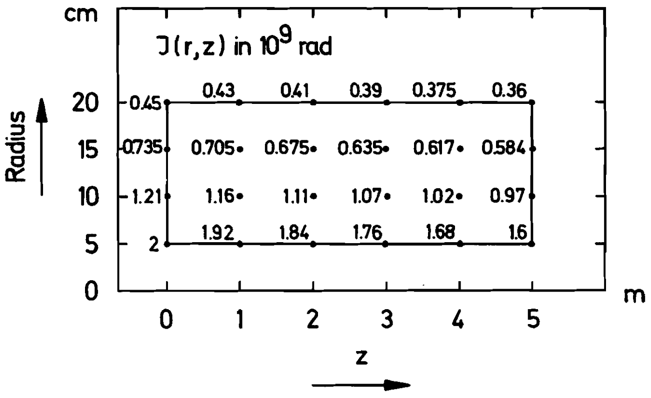

Figure 1
Irradiation dose distribution

Estimated secondary particles produced are 15 % thermal neutrons, 60 % fast neutrons, 15 % high energy particles (such as pions) and 10 % γ-rays. Among these secondaries the fast neutrons are the most dangerous. About one third of the energy of the primary particle is lost to the secondaries. The average secondary particle energy is thus : $E/3n$, where n is the average number of produced secondaries.

The average dose rate per year over the magnet due to primary particles is 2.4×10^{10} rads/year. This value is obtained for a beam energy of 1000 GeV and an intensity of 10^{13} ppp. The pulse duration is assumed 10 s with a 10 s pause between pulses. The maximum dose rate due to primary incident particles alone is 2.5×10^{11} rads/year assuming an 8000 hour machine operational schedule.

The cascade build-up occurs after one to three collision lengths and the distance increases logarithmically with the primary energy*. The maximum build-up occurs in our particular case about 80 cm downstream from the magnet face. The effective energy loss per ionising particle was estimated to be 3 MeV cm^2/g in the 1000 GeV accelerator.

The peak absorbed irradiation dose deposits in one cm^3 a heating power of 0.4 W (average magnet density ~ 5 g/cm^3). Assuming only a cooling surface of 0.8 cm^2 per cm^3 is exposed to liquid helium and the heat is transferred through this surface, then the heat flux to be removed is 0.5 W/cm^2. The average heat flux over the magnet produced by irradiation is about 0.06 W/cm^2 and thus not of prime concern.

Particles are lost in the accelerator and in the beam transport area in a variety of ways :

a) Injection, b) Beam Extraction, c) Beam collimation (Slits), d) Septum Magnets, e) Thick and Thin Targets, f) Scattering from residual gases.

One of the most dangerous but fortunately rare incidents in the accidental exposure of magnets to the full beam is due to missteering as a result of machine failure.

At the slow pulse rates a failure in this form is immediately apparent and the machine can be shut off after one pulse. The beam however is unfocused and it is hoped that the particle flux colliding with the magnet will be only a small fraction of the total flux (say about ∿1 %).

III. Irradiation Effects on Type II Superconductors

It is known that few physical properties of superconductors are changed due to defect production*. The critical current density, the critical temperature T_c, the lower and upper critical fields and hysteretic losses are primarily affected, when irradiated.

In NbTi and Nb_3Sn alloys the critical temperature is reduced, as is the upper critical field. The hysteretic losses are increased in general, but J_c does not change uniquely as a function of dose rate and must be studied in more detail. In composite conductors, due to the fact that the resistivity of the matrix material is substantially increased, the magnet becomes more unstable and fluxjump sensitive.

The mechanical properties of superconductors are also altered. As in the case of normal metals, superconductors undergo a transition from ductile to brittle condition (specifically NbTi), which in case of multifilament composite conductors can lead to filament breakage. The situation for Nb_3Sn is not yet clear; measurements on the mechanical properties of multifilament Nb_3Sn wires have not been performed.

Nb_3Sn irradiated* with fast neutrons ($E > 0.1$ MeV) have exhibited higher hysteretic losses with dose rates ($0.5 - 1.5 \times 10^{18}$n/cm^2). The critical current density of Nb_3Sn (10..... 100 μm) thin films* was enhanced 50 %, when irradiated at 50°C with 10^{18} fast neutrons per cm^2. Evaporated Nb_3Sn surfaces have shown the same general trend*.

The current density of diffusion layers of Nb_3Sn, irradiated up to a critical dose rate of 10^{17} particles per cm^2 with protons and deuterons of 1 - 3 MeV was enhanced by a factor of six*. Above this critical value the critical current density decreases. The enhancement in current carrying capacity is due to generation of clusters with dimensions of 10 - 100 Å which are comparable to the coherence length of Nb_3Sn (∿50 Å). The clusters are very effective pinning centres. Assuming the formation energy of a cluster is 20 keV, the maximum value of J_c is obtained at a cluster expansion of 75 Å and an optimum mean distance between clusters of 240 - 310 Å. Each cluster consists of about 200 - 500 Frenkel defects. The reduction of the critical current density at higher dose rates is probably due to cluster-overlapping. The current enhancement disappears at 700 - 800°C indicating that cluster formation is the prime source of the generation of pinning centres.

Coffey et al* have irradiated Nb_3Sn evaporated layers with 15 MeV deuterons up to a dose rate of 10^{17} d/cm^2. Probes with initially low critical currents exhibit at 5.7 K an enhancement, at 10.9 K a reduction of J_c. Nb_3Sn samples with initially high critical current showed always a reduction in J_c at any temperature and dose rate. The critical temperature of Nb_3Sn was reduced by 1 K (∿ 5 %) and the upper critical field H_{c2} was lowered by about 15 %.

Coldworked NbTi probes were irradiated with deuterons at temperatures below 30 K. It was found that J_c was in general reduced. Warming up to 300 K yielded a recovery of J_c to about 95 %.

Hassenzahl et al* irradiated NbTi composite conductors with 13 - 15 MeV protons. At dose rates of 10^{18} p/cm^2 and temperature of 400 K no appreciable reduction in J_c was noticed. At 77 K the reduction was 2 - 5 %. At 30 K the reduction in critical current was stronger at low fields (4T) than at higher fields (10T).

Irradiation tests with 51.5 MeV deuterons at room temperature by Maurer et al* have been performed on stabilized NbTi multicore conductors on the following geometries:

Conductors type A : Copper matrix, 1 mm diameter, 361 filaments with 26 μm indiv. fil. diameter.

Conductors type B : Copper matrix, 0.4 mm diameter, 61 filaments with 35 μm indiv. fil. diameter.

Results of type A : At a dose rate of $1.1 - 1.24 \times 10^{11}$ rads the take off current was reduced 15 - 22 %. After a single irradiation period no recovery to the original values was measured after 14 days exposition of the sample to room temperature. A second probe which was irradiated several times showed after the irradiation dose of 0.35×10^{11} rads a reduction of the critical current by about 10 %. After the sample was warmed up and exposed to room temperature for 10 days, it recovered 97 % of its initial I_c value. Further irradiation up to 1.24×10^{11} rads reduced I_c to values of about 78 % of its original value (see Fig. 2).

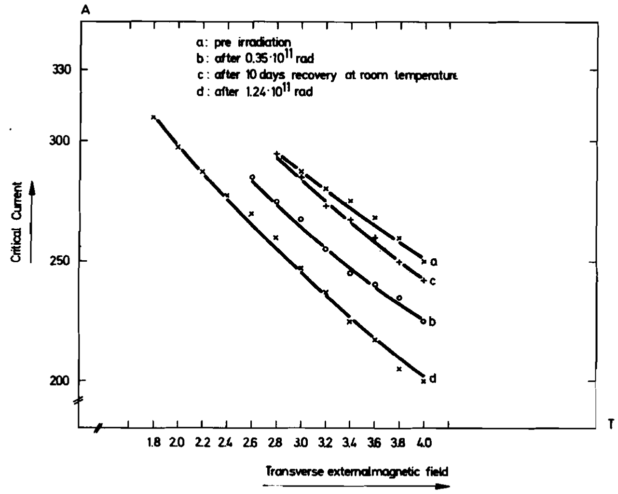

Figure 2

I_c(B)-characteristic

Results of type B : At dose rates of 10^{11} rads only a reduction of I_c and the take off current of about 5 % was measured. Fig. 3 shows the general trend of the (U-I)-curves, which is unchanged pre- and after irradiation. However, samples having a (U-I)-characteristic as in Fig. 4 exhibited at 1.6×10^{10} rads a reduction in the take-off and critical current of 5 %. The stabilisation characteristic of these samples is changed considerably. At the same magnetic field value the irradiation probes showed a degradation of about 20 %.

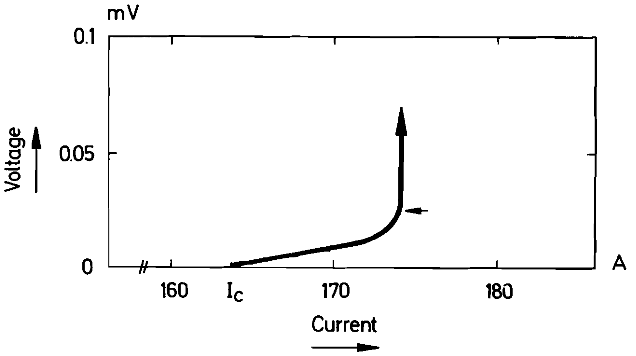

Figure 3

(U-I)-characteristic

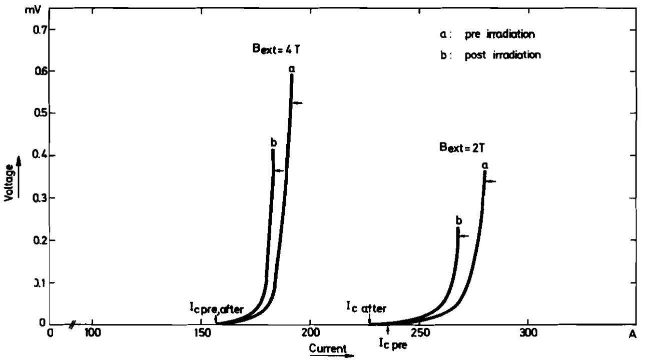

Figure 4

(U-I)-characteristic

IV. Irradiation Effects on Normal Metals

Copper, aluminium and cupronickel are widely used as matrix material in conjunction with superconductors in magnets. In pulsed magnets, the use of In-Sn and Ag-Sn alloys as impregnants is becoming increasingly attractive. It is interesting to note that the electrical properties of these solders are not affected by irradiation appreciably.

Room temperature irradiated high purity copper and aluminium show that the resistivity is increased by a factor 2. Irradiated samples at 77 K exhibit an increase in resistivity of a factor 5. Samples irradiated at temperatures below 10 K exhibited an increase of resistivity by a factor of at least 40.....50.

New measurements by Sassin* on high purity copper and aluminium tapes (RRR_{Cu} = 2800; RRR_{Al} = 1600) at 9 K with 2.8 MeV electrons show that the resistivity of copper was increased from $\rho_0 = 15.7 \times 10^{-9}$ Ohm·cm to $\rho_{irr} = 590 \times 10^{-9}$ Ohm·cm. This means that at a rate of 1.15×10^{20}e/cm^2 the copper resistivity was increased by a factor of 37.5. At the same dose rate the resistivity of aluminium was changed from $\rho_0 = 14.6 \times 10^{-9}$Ohm·cm to $\rho_{irr} = 578 \times 10^{-9}$ Ohm·cm, an increase of 39.6. The increase in resistivity per electron per unit area is thus :

$$\frac{\Delta\rho}{e^-/cm^2} = 5 \times 10^{-27} \text{ Ohm·cm}/e^-/cm^2$$

Newer measurements by Böning et al* show even larger increase in resistivity. Copper (RRR = 950) irradiated with fast neutrons (E > 0.1 MeV) shows that the resistivity was increased from 0.178×10^{-8} Ohm·cm to 13.56×10^{-8} Ohm·cm^2 (an increase by a factor of 76). Aluminium (RRR = 2160) irradiated showed that the resistivity changed from 2.08×10^{-7} Ohm·cm to 310×10^{-7} Ohm·cm at a dose rate of 1.5×10^{18}n/cm^2 (an increase in resistivity by a factor of 149).

The increase of resistivity in copper and aluminium can be explained by the generation of Frenkel pairs which change the scattering properties of conduction electrons. The mean free path of the electrons is generally reduced. The fact that the resistivity of copper and aluminium does change when irradiated has a profound effect on the stabilisation of superconducting magnets. However, the increase in temperature (up to 300 K) anneals the effect about 95 %. The irradiation imposed strain on the matrix material, in the magnet section exposed to the highest dose rates produces a material which is fluxjump sensitive. As the superconductor has also changed its current carrying capability, a region of instability is produced, which may endanger at high dose rates the safe performance of the magnet.

In Fig. 4, the short sample characteristic of 51.5 MeV deuterons irradiated (at room temperature) and not irradiated NbTi-copper composite is illustrated. After a dose of 1.6×10^{10} rads we have found a decrease of stability at transverse external fields of 4 T resp. 2 T. At 4 T, I_c is unchanged, but the take-off current decrease about 4 %.

The irradiation effects on cupronickel, which is widely used as a matrix material can be neglected. Irradiation effect on the metallic bond between superconductor and normal metal is also of concern. In the intermetallic layer between the superconductor and the normal metal matrix, which is composed of ternaries of Nb, Ti and Cu generally a high thermal and electrical resistivity is encountered. The bond is responsible for a somewhat lower thermal diffusivity from the superconductor to the matrix. The intermetallic diffusion layer between the superconductor and the matrix is increased, when the composite conductor is exposed to nuclear irradiation. Thus at an unchanged magnetic diffusivity the thermal diffusivity is futher reduced. At present, measurements on thermal diffusivity over the intermetallic barrier are nonexistant due to complexity of the problem.

V. Irradiation Effects on Magnet Insulations and Reinforcements

From a variety of thermoplastic and thermosetting materials only a few insulation materials are being considered for superconducting high energy magnets: glass fibre tapes with or without mica and impregnated or cast in epoxies*. If the coils are not impregnated in thermosettings, glass fibre tapes are recommended as interturn and interlayer insulations. Glass fibres have a radiation damage threshold which is higher than 10^{11} rads. They exhibit high compressive strength ($>3 \times 10^4$ kp/cm^2) and are adequate to prevent shorts between turns and layers.

If the coils are to be impregnated in appropriate thermosettings in order to prevent conductor movements and with it coil degradation, a variety of epoxies and epoxy Novalacs have been tested at low temperature irradiation environment. Glass fibre impregnated thermosettings have shown at 5×10^{15}n/cm^2 no apparent change at 4.2 K in mechanical and electrical properties. Slight embrittlement was encountered (rupture elongation changed from 8.1 % to 7.3 % at 4.2 K) when the samples were irradiated up to 10^{17}n/cm^2.

The mechanical properties of fibre glass reinforced thermosettings can be improved by an order of magnitude (in irradiation dose) if proper epoxy functional materials to make the glass fibre compatible to the resin is used in combination with the thermosettings and the glass fibre tapes are to be heated and chemically treated prior to impregnation.

VI. Irradiation Effects on Helium

Irradiation of liquid helium at 4.2 K with γ-rays, neutrons, protons, deuterons etc., yields helium contamination and production of radioactive isotopes such as

$${}^3_2\mathrm{He},\quad {}^3_1\mathrm{H},\quad {}^5_2\mathrm{He},\quad {}^5_3\mathrm{Li},\quad {}^6_3\mathrm{Li}\qquad \text{etc.,}$$

based on nuclear reactions. As these elements are partially unstable, and decay, they can contaminate the helium, which in a refrigerator system may lead to blocking of small passages. Fortunately, the amount of contaminants is small and not effective at present. Ionization effects lead to a higher boil off rate of the liquid.

Reference

* H. Brechna, W. Maurer: KFK Report 1468 and 1469 (1971). In this paper all pertinent references are given.