KERNFORSCHUNGSZENTRUM

KARLSRUHE

September 1971

KFK 1468

Institut für Experimentelle Kernphysik

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Irradiation Effects in Superconducting Synchrotron Magnets*

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* Paper partially presented at the VIIIth International Conference on High Energy Accelerators CERN, Geneva, September 20-24, 1971.

Abstract

Synchrotron magnets placed at some distances downstream or upstream from septum magnets and targets are exposed to nuclear irradiation. In the paper an estimate of the dose rate, pattern and distribution of scattered particles, and neutrons is presented. The effect of irradiation on superconducting composits, on matrix materials, on insulation, on magnet stability, and increase in ohmic losses is given. Generation of defects, effect on defect-clusters are calculated as a function of energy levels. The paper describes performance problems of superconducting magnets, being exposed to an irradiation environment.

Zusammenfassung

Synchrotronmagnete in einiger Entfernung vor und hinter Septummagneten und Targets sind der Nuklearstrahlung ausgesetzt. In diesem Bericht werden Abschätzungen der Dosisraten und der Verteilung der gestreuten geladenen Teilchen und Neutronen angegeben. Es wird über Bestrahlungseffekte auf supraleitende Vielkernleiter, Matrixmaterialien und Isolationen berichtet. Außerdem wird über die Zunahme des elektrischen Widerstandes und über Magnetstabilität bei Bestrahlung berichtet. Defekterzeugung als Funktion der Energie wird berechnet, und der Effekt auf Defektcluster wird behandelt. Der Bericht beschreibt Performance Probleme supraleitender Magnete, die der Nuklearbestrahlung ausgesetzt sind.

I. Introduction

Superconducting pulsed magnets to be used in high energy accelerators are being developed by a number of laboratories in Europe [1] and the U.S. [2].

The aim of a very intensive study is either to upgrade existing high energy accelerators which have been in operation since a number of years [3,4] or to build new high energy accelerators in the $\leq 10^3$ GeV range, which is only realistic if high field synchrotron magnets with dipole fields in the range of 5 T are employed [5].

The superconducting magnets being placed in the ring of 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, pulse duration of 10 sec and a pause between pulses of 10 sec, at present being studied by the GESSS committee [6], 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 [7,8], and on Monte Carlo calculations performed over the magnet volume [9].

The present dipole magnets have a cos θ current density distribution, and we have assumed axial coil symmetry.

The 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 colliding with the cryostate wall will produce a primary collision directly with the superconducting coil.

We have assumed in our calculations that 10 % of the beam particles are absorbed by the internal target. According to measurements by Citron et al. [8] one may expect an exponential decay of the absorbed irradiation energy in the radial direction (from the inner to the outer diameter) and nearly constant energy deposition in the magnet axial length.

The estimate of the production of fast neutrons, which are the most dangerous secondaries are based on the data that for proton energies of E > 30 GeV the number of secondaries will be: $n \simeq 1.7 \times E^{1/4}$.

A Monte Carlo calculation provides the production of neutrons over the magnet volume. As the magnets have an axial length of about five meters, we can assume that practically all the scattered beam energy is absorbed in the magnet. The calculated expected dose rates (at 10 % beam loss due to the internal target) for proton energies in the range of 1000 GeV is about 2.4×10^{10} rads per year averaged over the entire magnet, which has an inner bore radius of 0.05 m, an outer coil radius of 0.2 m. The maximum dose rate is expected to reach 2.5×10^{11} rads per year at the magnet upstream face, adjacent to the bore. In the most endangered coil section a heat flux due to mere proton irradiation of ~0.5 W/cm^2 into the helium may be expected!

For the unperturbed machine operation, or in over the major parts of the accelerator beam losses are very small. It is of course not possible to give exact dose rates expected in superconducting synchrotron magnets, but we may expect that beam losses in the order of 0.1 % or less may be encountered. The maximum dose rate at upstream face is about 10^9 rads per year and one may expect a heat flux of ~ 0.5 mW/cm^2 from the conductor to the helium bath, which is equivalent to less than 0.1 K temperature rise.

Other effects of irradiation on magnet components (superconductor, matrix materials, insulation) depend on the type and the energy of particles and on production of secondaries. Irradiation effects with low energy deuterons are reported on superconducting type II materials by Coffey et al. [10], and electron irradiation effects by Brechna [11]. Dose rates up to 10^9 rads increase the critical current at 4.2 K only for NbZr and Nb_3Sn compositions. NbTi alloys have not shown an improvement in critical current density enhancement.

At low energy deposition (~ keV) in superconductors vortices are moved and point defects either produced or moved within the lattice. At MeV energy levels point defects or defect clusters or lattice deformation are observed.

At energy levels in the GeV range, provided the superconductor is not destroyed through heating, defect clusters are either produced, or moved and changed.

The irradiation effects on superconductors have two distinct influences which in general work together. At low dose rates per hour, where the heating of the sample is unimportant, the mere ionization effects tend to soften grain boundaries, as observed in a metal tempering process, thus defects can move more readily within the lattice, producing a different composition of pinning cites, which for Nb_3Sn has been more favorable resulting in enhancement of J_c. The increase of J_c however yields also a more unstable performance and the tendency towards fluxjumps.

Irradiation effects on matrix materials are also of interest. High purity aluminum and copper used for stabilization as a matrix material are work hardened by irradiation: The resistivity of aluminum (RRR ≈ 2000) is increased by a factor of ~ 120 at 4.2 K, the resistivity of copper (RRR ≈ 1000) by about 60.

The irradiation tests were performed on thin specimen [12,13] irradiated with 1.4 - 2.8 MeV electrons. A high resistivity matrix material such as cupronickel which is also frequently used in combination with copper did not change at dose rates up to about 10^{12} rads, when exposed to electron irradiation.

The effect of electron irradiation, gammas and fast neutrons on a few insulation materials were reported by Brechna [14]. The particle energies used to irradiate samples were about 15 MeV. The effect of irradiation on insulation materials is in general polymerization and thus increase in yield strength at low dose rates. The materials however become brittle and crush sensitive and being under constant or intermittant load, will not be able to support magnetomechanical strain. The most promising material tested so far are glass fibre reinforced epoxies, where the ratio of organic to inorganic materials will be about 40/60 % by weight. The mechanical performance of most epoxies can be improved by a factor of at least 3, by adding epoxy functional materials to the epoxies, which improve the bond between inorganic and organic materials. Few of the glass filament-thermosetting materials tested at cryogenic temperature did withstand irradiation damage ($\leq$ 25 %) at doses of $\leq 10^{12}$ rads.

The ionization effects on irradiated metals and superconductors are annealed to a large extend if warmed up to liquid nitrogen temperature or higher. Copper recovers its preirradiated properties more than 90 % of its original value if warmed up to room temperature. At 77.3^{o} K the increase in resistivity is about a factor 6 compared to preirradiated values when irradiated with 4.7×10^{11} rads.

NbTi alloys recover also preirradiated current carrying capacity, if warmed up appreciably above their critical temperature.

Damage introduced to insulation materials by irradiation are permanent and do not cure when warmed up.

The thermal effects on irradiated samples or magnets are of concern. As mentioned, at a yearly dose rates of ~2.5×10^{11} rads a heat flux of ~0.5 W/cm^2 can be generated at the most endangered magnet areas. This heat must be removed entirely by the coolant through a refrigeration system. This may proof to be the limiting factor in the magnet performance, specifically if the superconducting coils are impregnated with thermosetting material, and thus the heat generated must be removed by convection and heat transfer.

In this paper we present methods of estimation irradiation dose rates in magnets, where we confine our attention to protons (estimated electron dose rates in magnets are discussed in literature [11]) and report briefly an endangered magnet areas. Also we discuss production of defects and 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 for 1000 GeV protons. The secondary particles generated by the primaries within the magnet will propagate by subsequent interactions. The cascade developes within the magnet in longitudinal and radial directions. The incident beam distribution curve indicated by (0 cm) is assumed to have an exponential radial decay. The intensity distribution is given by:

$$J(r,z) = 2 \times 10^9 \text{rads } (1-0.04\ z)\cdot\exp[-(r-r_i)/r_o]$$

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. 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. The average number of secondaries n, produced in a collision is approximated by the relation [15]:

$$n \approx 1.7 \cdot E^{1/4} \text{ for } E > 30 \text{ GeV}$$

$$n \approx 0.85 \cdot E^{1/2} \text{ for } 3 < E < 30 \text{ GeV}$$

$$n \approx \frac{5}{9}E - 0.17 \text{ for } E < 3 \text{ GeV}$$

The data have been obtained empirically.

About one third of the energy of the primary particle is lost to the secondaries. The average secondary particle energy is thus: E/3n.

Using these approximation, the beam intensity in the magnet as a function of radial and axial distance is calculated. The average dose rate per year over the magnet due to primary particles (assumed 10 % of the particles are lost in the internal target) 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 seconds with a 10 second 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.

It is seen [9] that the cascade build up occurs after one to three collision lengths and the build up length 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.

During normal operation and not at ejection or extraction areas of the accelerator we estimated the beam loss to be less than 0.1 %. The absorbed beam energy by the synchrotron magnets will be 4 mW per cm^3 corresponding to a heat flux of 5 mW per cm^2. The average heat flux for the entire coil is less than 0.6 mW/cm^2.

Assuming heat due to irradiation is generated in a ring with a cross section of area of 1×1 cm^2, then the temperature rise in the centre of the ring assuming symmetric cooling conditions is given by:

$$\Delta T \approx \dot{q}\left[\frac{1}{2k}\left(\frac{a}{2}\right)^2 + \frac{a}{2h}\right]$$

where $\dot{q}$ is the dissipated power per unit volume, k the heat conductivity and h the heat transfer coefficient, a is the width of the ring perpendicular to the direction of the heat flow. For a coil impregnated with a thermosetting filled with inorganic materials k is about 3×10^{-3} W/cm K, and h is in a coil 3 W/cm^2 K and a is equal to 1 cm, thus we have temperature rise against the bulk liquid helium of 1/6 K. It may be pointed out, that in case of 10 % beam loss the temperature in the ring would be ~10 K which is above the transition temperature of superconductor.

At a power deposition of 0.4 W/cm^3 (most severe case at the extraction area) the coil temperature will increase to 22.5 K per sec, if we ignore thermal conduction and heat transfer to helium at the first instance. However even this temperature rise will lead to a full quench of the magnet as the conductor cannot be cooled down to prevent heat expansion.

At 0.1 % beam loss the power deposited in one cm^3 of coil (at the most endangered area of the upstream surface) is 4 mW, corresponding at first instance to a temperature rise of 0.2 K per sec again not counting heat conduction and heat transfer.

Particles are lost in the accelerator and in the beam transport area by 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

Most particles are lost in the septum magnets located in the beam extraction areas, which have efficiencies of maybe 50 %. If the length of the collimator and slit is adequate, the beam fraction lost will be absorbed fully in the collimator and only muons may penetrate the surfaces at low energies and are of less concern to the magnet operation.

Scattering from residual gases in the vacuum vessel will also produce secondaries. Lewin [15] has estimated the number of secondaries produced in a vacuum of p torr from the source strength given by:

$$125\ N\ p \cdot n/R \quad \text{particles /cm sec}$$

with: N the number of incident protons, R the radial distance and n the number of secondaries.

One of the most dangerous but fortunately rare incidents is the accidental exposure of magnets to the full beam, 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 (~1 %).

III. Defectproduction

Sufficiently high recoil energy transferred to the lattice atoms of a solid body by collision with the irradiated particles generates lattice displacements. In high energy radiation the recoil energy may be sufficient to trigger a displacement cascade. The number of displaced atoms is a function of the energy transmitted to the lattice. The recoil energy depends also on the particle itself. Irradiation with light particles such as electrons with an energy of a few MeV, produced statistically distributed Frenkel pairs. Heavy particles (protons, deuterons and neutrons) are able to trigger a displacement cascade.

Irradiation with electrons produces in the lattice atoms nuclear scattering. The differential cross-section of the electron-nuclear scattering is expressed by [16]:

$$d\sigma = \pi T_m (1-\beta^2) \left(\frac{Z\ e^2}{m_e c^2 \beta^2}\right)^2 \left[1-\beta^2 \frac{T}{T_m} + \pi Z \beta \alpha \left\{\left(\frac{T}{T_m}\right)^{\frac{1}{2}} - \left(\frac{T}{T_m}\right)\right\}\right] \frac{dT}{T^2} \qquad (1)$$

with $T_m = \frac{2}{Mc^2} (E + 2m_e\ c^2)E$

and E = the incident energy of the electron

m_e = the electron mass

$\beta = v/c$; $\alpha = \frac{e^2}{hc}$

Z = atomic number of irradiated nucleus, M = its mass

T = the kinetic energy transmitted to the nucleus

T_m = the maximum kinetic energy transmitted to the nucleus.

If T_d is the threshold energy for a displacement and $P_d(T)$ the probability that during the transfer of the kinetic energy T to a nucleus this nucleus is displaced permanently, we can write for the cross-section of the displaced atom:

$$d\sigma_d = P_d(T)d\sigma \quad \text{with} \quad P_d(T) = \begin{cases} 0 \text{ for } T < T_d \\ 1 \text{ for } T \geq T_d \end{cases}$$

The integration of (1) in the boundaries T_d to T_m gives the total displacement cross-section:

$$\sigma_{d,tot} = T_m(1-\beta^2)\left(\frac{Ze^2}{m_e c^2 \beta^2}\right)^2 \left[\frac{1}{T_d} - \frac{1}{T_m} - \beta^2 \frac{1}{T_m} \cdot \ln\left(\frac{T_m}{T_d}\right) + \pi Z \beta \alpha \left\{ \frac{2}{\sqrt{T_m}}\left(\frac{1}{\sqrt{T_d}} - \frac{1}{\sqrt{T_m}}\right) - \frac{1}{T_m} \ln\left(\frac{T_m}{T_d}\right)\right\}\right] \tag{2}$$

For example:

1 MeV electrons on copper $T_m \cong 68$ eV
51,5 MeV electrons on copper $T_m \cong 90$ keV

Numbers for T_d and resistivity change of various metals are given in table I [17]. The numbers are obtained from electron irradiation experiments.

Table I

Metals	T_d(eV)	$\Delta\rho_o$(μΩ cm per 1 % i-v pairs)
Al	32	3.4
Cu	22 - 23 - 25	1.3 - 2.5
Ag	28	1.4
Fe	24	12.5 - 20.0
Ti	29	42

In case of 51,5 MeV electrons on copper we have $T_m >> T_d$, $\beta \approx 1$ which indicates that $E >> m_e c^2$. In this approximation we can write for ($Z \leq 40$)

$$\sigma_{d,tot} = \pi \cdot T_m \cdot \frac{Z^2 e^4}{E^2} \cdot \frac{1}{T_d} \tag{3}$$

which gives for the above case:

$$\underline{\sigma_{d,tot} = 74 \text{ barns}}$$

<u>Defectproduction with deuterons or protons:</u>

For charged heavy particles Rutherford's scattering is dominant [16]:

$$d = \frac{\pi}{4} b^2 T_m \cdot \frac{dT}{T^2} \tag{4}$$

with

$$b = \frac{|Z_1 Z_2 \cdot e^2|}{\mu \cdot \frac{v^2}{2}}$$

$$\mu = \frac{m \cdot M}{m+M}$$

and

$$T_m = \frac{4mM}{(m+M)^2} E_1 \tag{5}$$

which is the classical impact equation.

E_1 is the incident particle energy of the heavy particle. The total displacement cross-section is analogous to the above section on electrons:

$$\sigma_{d,tot} = \pi Z_1^2 Z_2^2 e^4 \frac{m}{M} \cdot \frac{1}{E_1} \left(\frac{1}{T_d} - \frac{1}{T_m}\right) \tag{6}$$

For 51,5 MeV deuterons on copper one has $T_m \cong 6{,}1$ MeV $T_d = 25$ eV and thus:

$$\underline{\sigma_{d,tot} = 1450 \text{ barns}}$$

For 51,5 MeV protons on copper with $T_m \approx 3$ MeV one obtains:

$$\underline{\sigma_{d,tot} = 716 \text{ barns}}$$

Comparing the total displacement cross-sections one sees that deuterons with an energy of 51,5 MeV are 20 times more effective to produce defects than electrons and about a factor of 2 more effective than protons with the same energy.

If $T > T_d$, then the displacement cascade including primary particles consists of $\bar{\nu}$ Frenkel-defects, where

$$\bar{\nu} = 0.12 + 0.56 \cdot \ln\left(\frac{T_m}{T_d}\right) \qquad (7)$$

If n indicates the total number of lattice atoms per unit length, which are displaced by one deuteron (or proton) of constant energy E_1, then

$$n_{tot} = N_A \cdot \sigma_{d,tot} \cdot \bar{\nu} \qquad (8)$$

In (8) $N_A = \frac{L\rho}{A}$ indicates the number of lattice atoms per cm^3.

For 51,5 MeV deuterons on copper $n_{tot} = 816\ cm^{-1}$ and $\bar{\nu} = 7.05$.

Cluster production by irradiation with heavy particles is shown to be effective by irradiation of Nb_3Sn diffusion layers with 1, 2 and 3 MeV protons and 3 MeV deuterons [18]. A 6fold enhancement in the critical current density J_c is found up to a critical dose rate. Exceeding this dose the critical current density in the superconductor is again reduced. This J_c enhancement is due to formation of pinning centres by the displaced atoms having a minimum formation energy of about 20 keV. The minimum size of clusters becoming effective pinning centres is about 75 Å , with a calculated optimal distance between clusters of 240 Å to 310 Å. At a normalized particle flux of 2.5×10^{16} cm^{-2} MeV^{-1} we have a normalized optimal density of 2.5 - 3.2×10^{16} cm^{-3} MeV^{-1}. Each of these clusters consists of 200 - 500 Frenkel pairs at assumed mean displacement energies of 20 to 50 eV in Nb_3Sn.

Defect Production with Neutrons

Ultrapure copper foils (99.999 %) irradiated with neutrons have shown that Frenkel pairs and defect clusters are produced [19]. Their density and distribution could be observed under an electronmicroscope. Copper irradiated with 1.8×10^{17} fast neutrons/cm^2 ($E_n > 0.1$ MeV) at 4.2 K shows the following defect density:

$$n(100\ \text{Å}) \cong 10^{13}\ cm^{-3}$$
$$n(200\ \text{Å}) \cong 10^{12}\ cm^{-3}$$

The relation between defect density and cluster diameter is given by:

$$n(d) = n(0) \exp(- \frac{d}{d_o}) \qquad (9)$$

Enhancement of the neutron dose by a factor 5 (9×10^{17} n/cm^2) has given an increase in defect density by a factor 50.

To obtain the displacement cross-section for neutrons, numerical calculations are applied in general. A very simplified approximation gives [17]:

$$\frac{d\sigma}{dT} \begin{cases} = \frac{\sigma_e}{T_{max}} & \text{for } T \leq T_{max} \\ = 0 & \text{for } T > T_{max} \end{cases} \qquad (10)$$

where σ_e is the measured elastic scattering cross-section.

For $T \leq T_{max}$ the total displacement cross-section is given by:

$$\sigma_{d,tot} = \int \frac{\sigma_e(T)}{T_{max}} \, dT$$

As neutrons have no charge an excitation of the nucleus is possible. The new nucleons are most unstable, thus the emission of charged particles, secondary neutrons or γ's is possible. The inelastic scattering as the elastic scattering are approximately isotropic.

IV. Irradiation Effects on Type II Superconductors

It is known that few physical properties of type II superconductors are changed due to defect production, when exposed to nuclear irradiation. The critical current density J_c, the critical temperature T_c, the lower and upper critical fields H_{c1} and H_{c2} 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 [20] with fast neutrons (E > 0.1 MeV) have exhibited higher hysteretic losses with dose rates (0.5 - 1.5×10^{18} n/cm^2). The critical current density of Nb_3Sn (10 ... 100 µm) thin films [21] 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 [22].

The current density of Nb_3Sn diffusion layers, 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 [18]. Above this 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 clusters 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 clusteroverlapping. 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 [10] have irradiated Nb_3Sn evaporated layers with 15 MeV deuterons up to a dose rate of 10^{17} d/cm^2. Nb_3Sn 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 the specimen to 300 K yielded a recovery of J_c to about 95 %.

Hassenzahl et al.[23] 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 (4 T) than at higher fields (10 T).

Irradiation tests with 51,5 MeV deuterons at room temperature by Maurer et al. [24] have been performed on stabilized NbTi multicore conductors on the following geometries:

<u>Samples type A:</u> Copper matrix, 1 mm diameter; 361 filaments with 26 µm indiv. fil. diam.

<u>Samples type B:</u> Copper matrix, 0.4 mm diameter; 61 filaments with 35 µm indiv. fil. diam.

Results of <u>samples type A:</u> At a dose rate of 1.1 - 1.24 × 10^{11} rads the take off current was reduced 10 - 14 % at transverse fields of 2.5 - 4 T. The critical 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 a dose rate 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 about 78 % of its original value (see Fig. 2).

<u>Results of samples type B:</u> 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 stabilization characteristic of these samples is changed considerably. At the same magnetic field value the irradiated probes showed a degradation of about 20 %.

V. Irradiation Effects on Normal Metals

Copper, aluminum 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.

Mechanical properties of copper are known to change, when exposed to nuclear irradiation. At 10^{20} n/cm^2 the yield strength of OFHC copper has increased 5 fold at 4.2 K, its tensile strength about 1.9 fold. The high material yield strength which indicate embrittlement are due to strain hardening. The change in electrical properties are somewhat related to the change in mechanical properties. The resistivity of copper and aluminum are changed considerable, when exposed to nuclear irradiation (see table I). The increase in resistivity is temperature dependent.

Room temperature irradiated high purity copper and aluminum 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 [12] on high purity copper and aluminum tapes (RRR_{Cu} = 2800; RRR_{Al} = 1600) at 9 K with 2.8 MeV electrons show that the resistivity of copper was increased from $\rho_o = 15.7 \times 10^{-9}$ 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 aluminum was changed from $\rho_o = 14.6 \times 10^{-9}$ 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:

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

Newer measurements by Böning et al. [13] 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 at a dose rate of 2.52×10^{18} n/cm^2 (an increase by a factor of 76). Aluminum (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 1.05×10^{18} n/cm^2 (an increase in resistivity by a factor of 149).

The increase of resistivity in copper and aluminum can be explained by the generation of new 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 aluminum does change when irradiated has a profound effect on the stabilization of superconducting magnets. However, the increase in temperature (up to 300 K) anneals the effect to about 95 % of its original value. The irradiation imposed strain on 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 deuteron 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 decreases about 4 %, while at 2 T, the critical current and 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 further reduced. At present, measurements on thermal diffusivity over the intermetallic barrier are nonexistant due to the complexity of the problem.

The effect of neutron irradiation on nonmagnetic steels is not reported recently. However it is expected that at dose rates of $\geq 10^{17}$ n/cm^2 at 4.2 K no significant changes in yield and tensile strength is to be expected.

VI. Irradiation Effects on Magnet Insulations and Magnet Reinforcement

From a variety of thermoplastic and thermosetting materials only a few insulation materials are being considered for superconducting high energy magnets, such as glass fibre tapes with or without mica and impregnated or cast in a variety of epoxies [14]. 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 (> 3×10^{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.

VII. 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 based on nuclear reactions [11].

Ionization lead to a higher boil off rate of the liquid. In table II, we have written the most important reactions with Q values:

Table II

γ-irradiation:

$^{4}_{2}He + \gamma$	$\rightarrow$	$^{3}_{2}He + n$	- 20.577 MeV
	$\rightarrow$	$^{3}_{1}H + p$	- 19.813 MeV
	$\rightarrow$	$d + d$	- 23.845 MeV
	$\rightarrow$	$d + n + p$	- 26.07 MeV

n-irradiation:

$^{4}_{2}He + n$	$\rightarrow$	$^{5}_{2}He + \gamma$	- 0.957 MeV
	$\rightarrow$	$^{3}_{1}H + d$	- 17.588 MeV
	$\rightarrow$	$^{4}_{2}He + n$	± 0
	$\rightarrow$	$^{3}_{2}He + n + n$	- 20.577 MeV
	$\rightarrow$	$^{3}_{1}H + n + p$	- 19.813 MeV

p-irradiation:

$^{4}_{2}He + p$	$\rightarrow$	$^{5}_{3}Li + \gamma$	- 1.967 MeV
	$\rightarrow$	$^{3}_{2}He + d$	- 18.352 MeV
	$\rightarrow$	$^{4}_{2}He + p$	± 0

$$\rightarrow \; {}^{3}_{2}He + n + p \qquad - 20.577 \text{ MeV}$$

$$\rightarrow \; {}^{3}_{1}H + p + p \qquad - 19.813 \text{ MeV}$$

<u>d-irradiation:</u>

$${}^{4}_{2}He + d \;\rightarrow\; {}^{4}_{2}He + d \qquad \pm\, 0$$

$$\rightarrow \; {}^{5}_{2}He + p \qquad - 3.182 \text{ MeV}$$

$$\rightarrow \; {}^{5}_{3}Li + n \qquad - 4.192 \text{ MeV}$$

$$\rightarrow \; {}^{3}_{2}He + {}^{3}_{1}H \qquad - 14.320 \text{ MeV}$$

$$\rightarrow \; {}^{6}_{3}Li + \gamma \qquad - 1.471 \text{ MeV}$$

$$\rightarrow \; {}^{4}_{3}He + n + p \qquad - 2.225 \text{ MeV}$$

Irradiation leads to the production of new elements such as ${}^{3}_{2}He$, ${}^{3}_{1}H$, ${}^{5}_{2}He$, ${}^{5}_{3}Li$, ${}^{6}_{3}Li$ etc.

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 are small and not effective at present.

References

1 P.F. Smith: Particle Accelerators, Vol. 1, 151 (1970)

2 W.B. Sampson et al.: Particle Accelerators, Vol. 1, 173 (1970)

3 G. Bronca et al.: Proceedings Third Int. Magnet Conf. Hamburg 1970 (to be published)

4 P.F. Smith: Proceedings Second Int. Magnet Conf. Oxford, 594 (1967)

5 F. Arendt et al.: KFK-Bericht 1316 (1970)

6 GESSS Report: To be presented at the VIIIth Int. Conf. on High Energy Acc. (1971)

7 M. Van der Voorde: CERN ISR-MAG/68-28

8 A. Citron, L. Hoffmann, C. Passow, W.R. Nelson, M. Whitehead: Nucl. Instr. Meth. 32, 48 (1965)

9 K. Goebel, J. Ranft: CERN 70-16, J. Ranft: CERN 64-47

10 H.T. Coffey, E.L. Keller, A. Patterson, S.H. Autler: Phys. Rev. 155, 355 (1967)

11 H. Brechna: SLAC-PUB 469, (1968)

12 W. Sassin: Jül-586-FN (1969)

13 K. Böning, B. Lengeler, J.M. Welter, H. Wenzl: in Int. Conf. on Vacancies and Interstitials in Metals, p. 405 (1968)

14 H. Brechna: SLAC-40 (1965)

15 J.D. Lewin: RHEL/R 119, (1969)

16 F. Seitz, J.S. Koehler: Solid State Physics 2, 305 (1956)

17 M.W. Thompson: Defects and Radiation Damage in Metals Cambridge, Univ. Press (1969)

18 K. Wohlleben: Zeits. f. Angew. Physik 27, 92 (1969)

19 M. Rühle, J.C. Crump III: phys. stat. sol. (a) 2, 257 (1970)

20 P.S. Swartz, H.R. Hart jr., R.L. Fleischer: Appl. Phys. Lett. 4, 71 (1964)

21 J.P. McEvoy jr., R.F. Decell, R.L. Novak: Appl. Phys. Lett. 4, 43 (1964)

22 G.W. Cullen, R.L. Novak: Journal of Appl. Phys. 37, 3348 (1966)

23 W.V. Hassenzahl, J.D. Rogers, W.C. Armstrong: Proc. of the 1971 Particle Accel. Conf. (1971)

24 W. Maurer, H. Brechna: KFK-Report 1469

Figures

Fig. 1: Irradiation dose distribution for a dipole magnet with circular aperture

Fig. 2: Critical current versus transverse external magnetic field for a superconductor multicore wire.
(Cu matrix, 1 mm diameter, 361 filaments with 26 μm individual filament diameter).
Irradiation with 51.5 MeV deuterons at room temperature.
curve a: pre-irradiation;
curve b: after $0.35 \cdot 10^{11}$ rads;
curve c: after 10 days recovery at room temperature;
curve d: after $1.24 \cdot 10^{11}$ rads.

Fig. 3: Voltage-current characteristic for a superconductor multicore wire (Cu matrix, 0.4 mm diameter, 61 filaments with 35 μm individual filament diameter)

Fig. 4: Voltage-current characteristic for B_{ext} = 4 T and 2 T.
(Multicore wire with Cu matrix, 0.4 mm diameter, 61 filaments with 35 μm individual filament diameter)
curve a: pre-irradiation
curve b: post-irradiation (1.6×10^{10} rads)

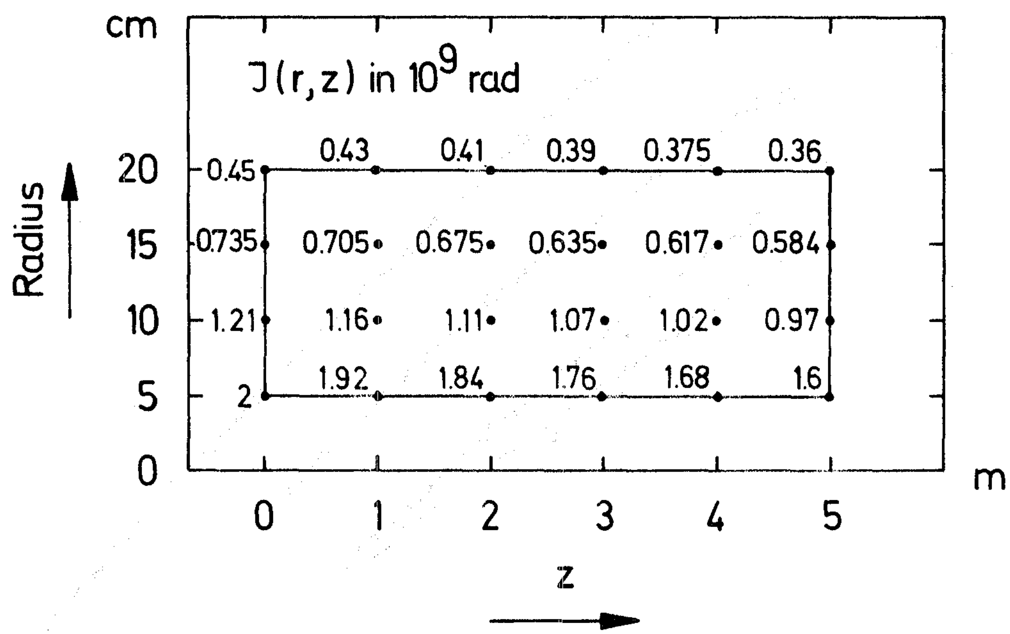
cm
J (r, z) in 10^9 rad
Radius
20
15
10
5
0
0.45
0.43
0.41
0.39
0.375
0.36
0.735
0.705
0.675
0.635
0.617
0.584
1.21
1.16
1.11
1.07
1.02
0.97
2
1.92
1.84
1.76
1.68
1.6
0
1
2
3
4
5
m
z

Fig. 1

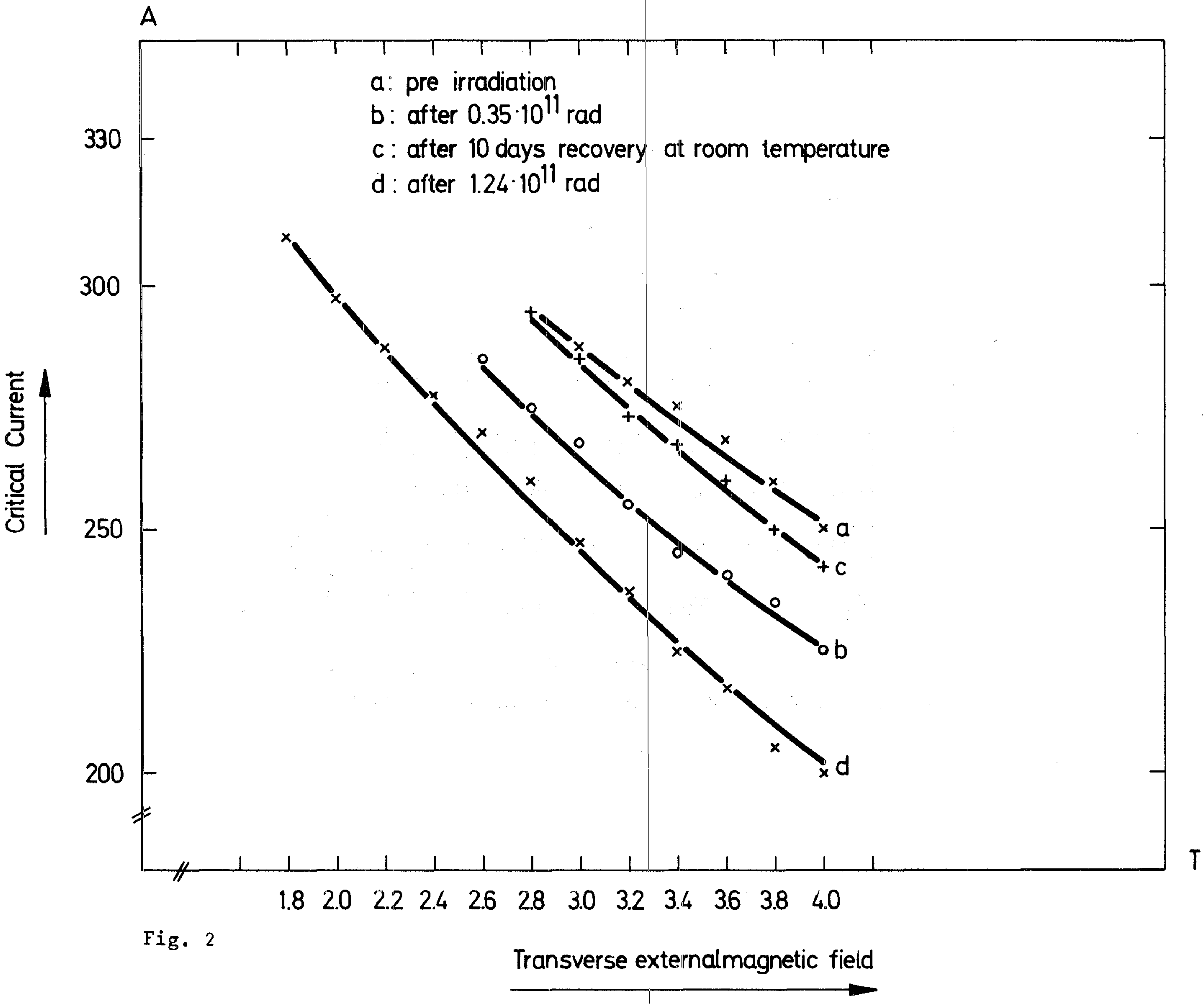
A
a: pre irradiation
b: after 0.35·10^11 rad
c: after 10 days recovery at room temperature
d: after 1.24·10^11 rad
330
300
250
200
Critical Current
a
c
b
d
T
1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0
Transverse external magnetic field

Fig. 2

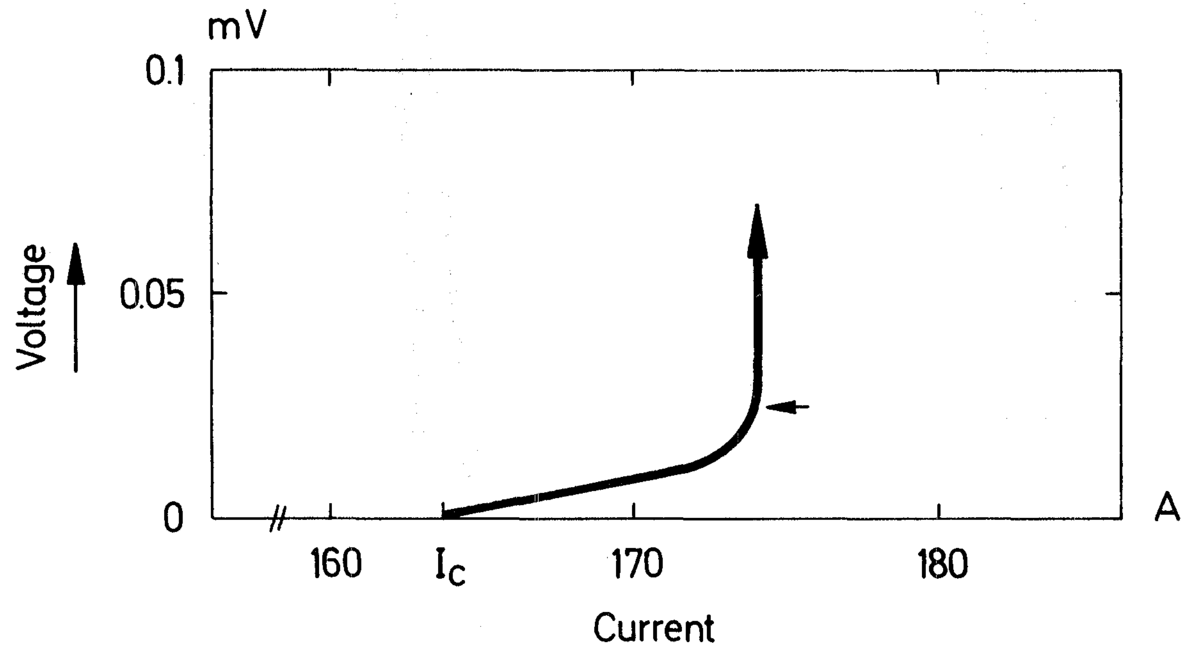

Fig. 3

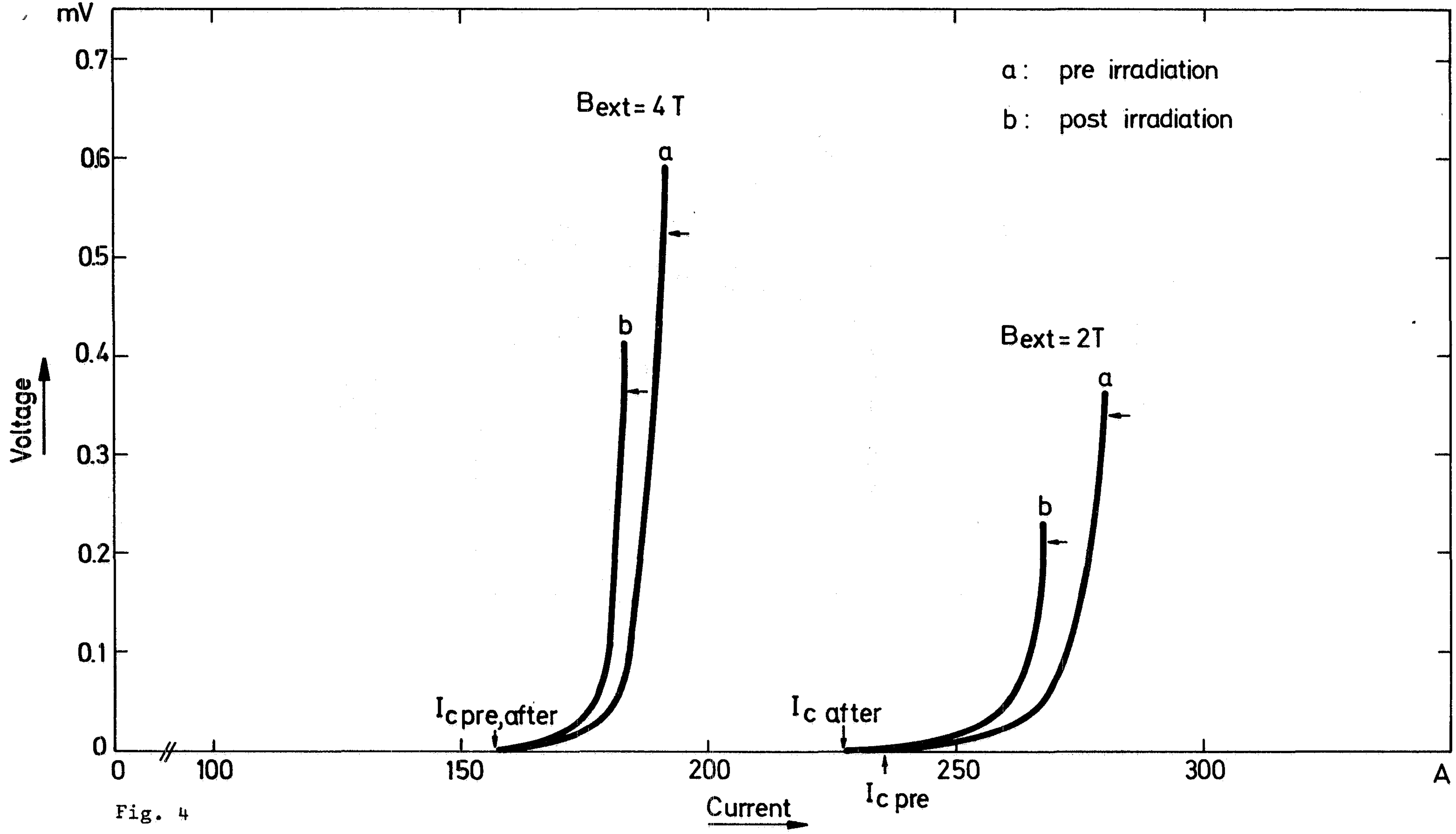
mV
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Voltage
a : pre irradiation
b : post irradiation
Bext = 4 T
Bext = 2T
a
b
Ic pre,after
Ic after
Ic pre
0
100
150
200
250
300
A
Current

Fig. 4