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Irradiation Effects in NbTi Multicore Superconductors

Abstract

Irradiation effects in some NbTi multicore superconductors are reported. Critical and take off current changes due to 50 MeV deuteron irradiation at room temperature are investigated. The voltage current characteristic in the resistive region is altered. The measured characteristic is compared with some existing models, and a new empirical formula describing the voltage current dependence in the resistive region is given. The irradiation influence on maximum dissipated power and on stability is investigated.

Bestrahlungseffekte in NbTi Vielkernsupraleitern

Zusammenfassung

Es wird über Bestrahlungseffekte in einigen NbTi Vielkernsupraleitern berichtet. Die Änderungen des kritischen und des "take off" Stromes aufgrund von 50 MeV Deuteronenbestrahlung bei Zimmertemperatur werden untersucht. Die bei Bestrahlung geänderte, gemessene Strom-Spannungscharakteristik im Widerstandsbereich wird mit einigen existierenden Modellen verglichen, und eine neue empirische Formel zu ihrer Beschreibung wird angegeben. Der Einfluß der Bestrahlung auf die maximal verbrauchte Leistung im Widerstandsbereich und auf die Stabilität wird untersucht.

1. Introduction

Superconducting magnets being placed in an accelerator or used in fusion devices are in general not exposed to high irradiation doses. Only in cases of disaster, such as misteering, or in cases of beam ejection, or if magnets are placed close to internal targets or beam absorbers appreciable irradiation doses may be expected in magnets. In the case of the 1000 GeV proton synchrotron studied by the GESSS commitee[1] the estimated dose[2] is about 2.4×10^{10} rads (1 rad = 100 erg/g) per year averaged over the entire magnet and the maximum dose is expected to reach 2.5×10^{11} rads per year at the magnet upstream face, adjacent to the bore.

In the case of NbTi magnets we expect an irradiation influence on the superconducting properties. It is well known, that few physical properties of superconductors are changed due to defect production, when they are exposed to nuclear particle irradiation. The critical current density, the critical temperature, the lower and upper critical fields, hysteretic losses, the resistivity in the normal state and the resistive state of the superconductor are affected due to irradiation. Measurements of Coffey et al.[3] on coldworked NbTi samples irradiated with 15 MeV deuterons at 30 K show a decrease of current density with increasing dose and a recovery effect, and a little decrease in the critical temperature ($\sim$ - 0.2 K) at a dose of 10^{17} d/cm^2 and a decrease of the upper critical field of about 11%. Proton irradiation of NbTi multicore wires at 13 - 15 MeV at 400 K, 77 K and 30 K by Hassenzahl et al.[4] show a decrease in critical current, too. The same behaviour in critical current is found at room temperature irradiation with 50 MeV deuterons of stabilized NbTi multicore wires by Brechna and Maurer.[2,5]

In this paper, changes in critical and take off current, in the voltage current characteristic in the resistive region and the influence on maximum dissipated power are reported.

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2. Samples and irradiation procedure

Two kinds of superconducting multicore wires are investigated. The first one, type A, is a NbTi multifilament wire, 1 mm in diameter, with copper matrix, 361 filaments, each of about 26 µm in diameter, and a copper-superconductor ratio of 3:1. The second one has 0.4 mm in diameter, 61 filaments, each of about 35 µm in diameter and a copper-superconductor ratio of 1.4:1.

Pre irradiation the voltage current characteristic at 4.2 K is measured in dependence of a transverse external magnetic field B. Then the short samples are irradiated by 50 MeV deuterons at room temperature in the Karlsruhe isochroncyclotron with average beam currents of 0.2 - 1.8 µA. Sample B has reached in one run a dose of 1.6×10^{10} rads, while sample A has received at the first run a dose of 3.55×10^{10} rads. After irradiation the voltage current measurement is repeated at 4.2 K to find the changes in the superconducting characteristic due to irradiation. Sample A is moreover irradiated several times up to a total dose of 1.24×10^{11} rads to study saturation effects. A detailed description of the irradiation procedure is given in reference 5.

3. Results

3.1 Critical and take off current

Sample A shows after 3.55×10^{10} rads a decrease in critical current I_c and in take off current I_t of about 10% in the magnetic field region of 3 T to 4 T (see Fig. 1), while sample B shows after 1.6×10^{10} rads a decrease of about 5% for field values of 1 T to 4 T. The current field dependence of sample B obeys the Kim- Anderson model[6,7] $I_c = \alpha/(B + B_o)$, where α is a structure constant and B_o is the bulk critical field. The agreement of the model with experimental data is very good in the given field region with $\alpha = 944$ AT and $B_o = 1.98$ T pre irradiation and $\alpha = 856$ AT and $B_o \doteq 1.78$ T after irradiation, but fails for fields smaller than 1 T. The further irradiations of sample A up to a dose of 1.24×10^{11} rads show a saturation effect in the critical current changes $\Delta I_c = I_{c\ pre} - I_{c\ after}$. After 3.55×10^{10} rads ΔI_c per deuteron per cm^2 is 1.6×10^{-16} A/(d/cm^2) and after 1.24×10^{11} rads this value is equal to 1.0×10^{-16} A/(d/cm^2). The change in the ratio of take off to critical current I_t/I_c (1.6 for sample A and 1.2 for sample B due to the different copper-superconductor ratios) due to irradiation is not important as seen in Fig. 2 and 3.

3.2 Resistive region

The resistive state of a superconductor is a nonequilibrium state created by the transport current in the sample. Due to the transport current we have a gradient in magnetic induction, i.e. the flux line density is not uniform and the flux line is subjected to a driving force. In technical multicore wires we have lattice defects of various kinds, which are effective pinning centres and so we have the possibility to sustain a nonuniform flux line density. If the pinning force is overcome by the driving force, we have the critical (resistive) state with flux creep and flux flow, which effects an electric field in transport current direction. This electric field is proportional to the magnetic field induction.[6] At a fixed external magnetic field B, we measure the voltage in current direction as a function of current I increasing with a time rate of 2 A/s. No detectable voltage appears until I exceeds the critical current I_c. The voltage increases rapidly with ascending current for $I > I_c$ and has a jump at the take off current I_t from the take off voltage V_t to the voltage V_n, which indicates that the superconductor is now in the normal state.

The voltage current characteristic for the both investigated types of superconducting wires pre and after irradiation vs the ratio of transport current I to critical current I_c is shown in Fig. 2 and 3 for some external magnetic fields. For the same I/I_c value we have after irradiation a smaller voltage than pre irradiation.

Some models exist describing the V-I characteristic in the resistive state of a superconductor. A linear dependence is predicted by Kim et al.[6] and Bardeen and Stephen[8] in the case of a pure superconductor, while Sherrill and Payne[9] have fitted the V-I dependence by a nonlinear characteristic

$$V = (\pi a^2 R_n/\Phi_o)\, BI_c(i - 1)^2/(i - \beta) \quad \text{for } i = I/I_c \text{ and } \beta < 1$$

where a is the radius of the normal core associated with the fluxon, R_n is the resistance per square of the sample in the normal state, $\Phi_o = 2 \times 10^{-7}$ Gcm^2 is the flux quantum and the dimensionless parameter β is given by the ratio of the coherence length to the mean free path of a fluxon between pinning centres. For stabilized superconducting multicore wires the V-I characteristic is given by Stekly and Zar[10]

$$V = \rho I_c/A\ x(i - 1)/(1 - \alpha i) \qquad \text{with } \alpha = \rho I_c{}^2/(hPA(T_c - T_b))$$

where the conductor is considered as a parallel network with current sharing. V is the voltage per unit conductor length, ρ and A are resistivity per unit length, resp. cross sectional area of the copper matrix, h is the heat transfer per unit surface area per unit temperature rise from the conductor to the bath at the temperature T_b, P is the perimeter of the conductor and T_c is the critical temperature in the field B. A refined consideration by Sychev and Altov[11] yields:

$$V = \rho I_c/A\ x(i - 1)/(1 - \alpha i + x)$$

where x is the ratio of the copper resistance ρ/A per unit length to the resistance of the superconducting portion of the composite conductor in the resistive state.

In our measurements we expected a behaviour as predicted by Stekly and Zar. Plotting (i - 1)/V as a function of i a linear dependence is not seen overall, but we have two regions with approximately linear dependence, where the first is the flux creep and the second is the flux jump region. As seen from Fig. 2 and 3 nuclear irradiation effects very strongly the flux creep region. Due to collisions of irradiation particles with lattice atoms, the defect structure, produced by cold working, is distorted and therefore sensitive for flux creep. With increasing current the flux motion is amplificated ending in flux flow and the transition in the normal state at V_t. Due to irradiation V_t decreases about 40% compared with the initial values as seen in Fig. 4 in the case of sample B, where we have plotted V_t vs magnetic field. The expected linear dependence is seen with except of small magnetic fields. The radiation induced V_t decrease shows that the flux flow region is influenced in such a way, that the jump to normal state occurs at smaller V_t values.

Due to failing of the above models in describing our V-I characteristic for stabilized multicore wires, we have fitted empirically our experimental data by

$$V = I_c i^3 (i - 1) \times (A_1 (i - 1) - A_2 \sin(2\pi A_3 (i - 1)/(i_t - 1)))$$

where A_k $(k = 1,2,3)$ are constants. Up to now we are not sucessfull to calculate the V-I characteristic from first principles and therefore we have not a physical interpretation of the constants. A dimension consideration shows however that A_1 and A_2 are resistances and A_3 is dimensionless. In the case of sample A we have determined for example these constants at 4 T and get $A_1 = 2.2$ µΩ, $A_2 = 0.2$ µΩ, $A_3 = 1$ pre irradiation and $A_1 = 1.64$ µΩ, $A_2 = 0.276$ µΩ and $A_3 = 0.817$ after a dose of 3.55×10^{10} rads (see Fig. 2). Comparing these values we have a decrease in A_1 of about 25% due to irradiation and in A_3 of about 18%, while A_2 is increased by about 38%.

The dissipated power in the resistive region is given by integration of V(I) over I from I_c to I_t. Using the empirically found formula we get

$$\begin{aligned} P = {} & I_c^2 A_1 \beta^3 \alpha^3 (\beta^3 \alpha^3/6 + 3\beta^2 \alpha^2/5 + 3\beta\alpha/4 + 1/3) \\ & - I_c^2 A_2 \alpha^2 (\sin\beta \times (4\beta\alpha^3(\beta^2 - 6) + 9\alpha^2(\beta^2 - 2) + 6\beta\alpha + 1) \\ & - \cos\beta \times (\alpha^3(\beta^4 - 12\beta^2 + 24) + 3\beta\alpha^2(\beta^2 - 6) + 3\alpha(\beta^2 - 2) + \beta) \\ & + 6\alpha (4\alpha - 1)) \end{aligned}$$

with $\beta = 2\pi A_3$ and $\alpha = (i_t - 1)/\beta$. Pre irradiation we get 36.7 mW and after irradiation 28.6 mW; this is a decrease of about 22%. To obtain the dissipated energy in the resistive region, we have to multiply with time (76.5 s pre and 72.5 s after irradiation) and get E_{diss} = 2.81 Ws pre and 2.08 Ws after irradiation; this is a decrease of about 26%. Due to irradiation we found a decreasing maximum dissipated energy, resp. power and so decreasing stability.

4. Conclusion

Due to irradiation, we have observed some changes in the superconducting characteristic of NbTi multicore wires. First, the critical current in an external magnetic field decreases, but shows a saturation effect, the same is seen for the take off current. Second, the take off voltage, linear dependent on magnetic field with except of small fields, decreases strongly. Also, the dissipated power, resp. energy in the resistive state decreases very strongly, which yields decreasing stability of such a wire, i.e. the wire goes earlier into the normal state due to radiation induced sensivity of flux creep and flux jump.

To extent the measurements to low temperatures, we have constructed in our institute an irradiation cryostat which allows cold irradiation at 4.2 K and also measurements at this temperature.

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Figures

Fig. 1: Take off and critical current for sample A pre irradiation and after 3.55×10^{10} rads vs transverse external magnetic field.

Fig. 2: Voltage current characteristic for sample A pre irradiation and after 3.55×10^{10} rads at 4 T.

Fig. 3: Voltage current characteristic for sample B pre irradiation and after 1.6×10^{10} rads at 1.6 T, 2.0 T and 3.6 T.

Fig. 4: Take off voltage vs transverse external magnetic field for sample B pre irradiation and after 1.6×10^{10} rads.

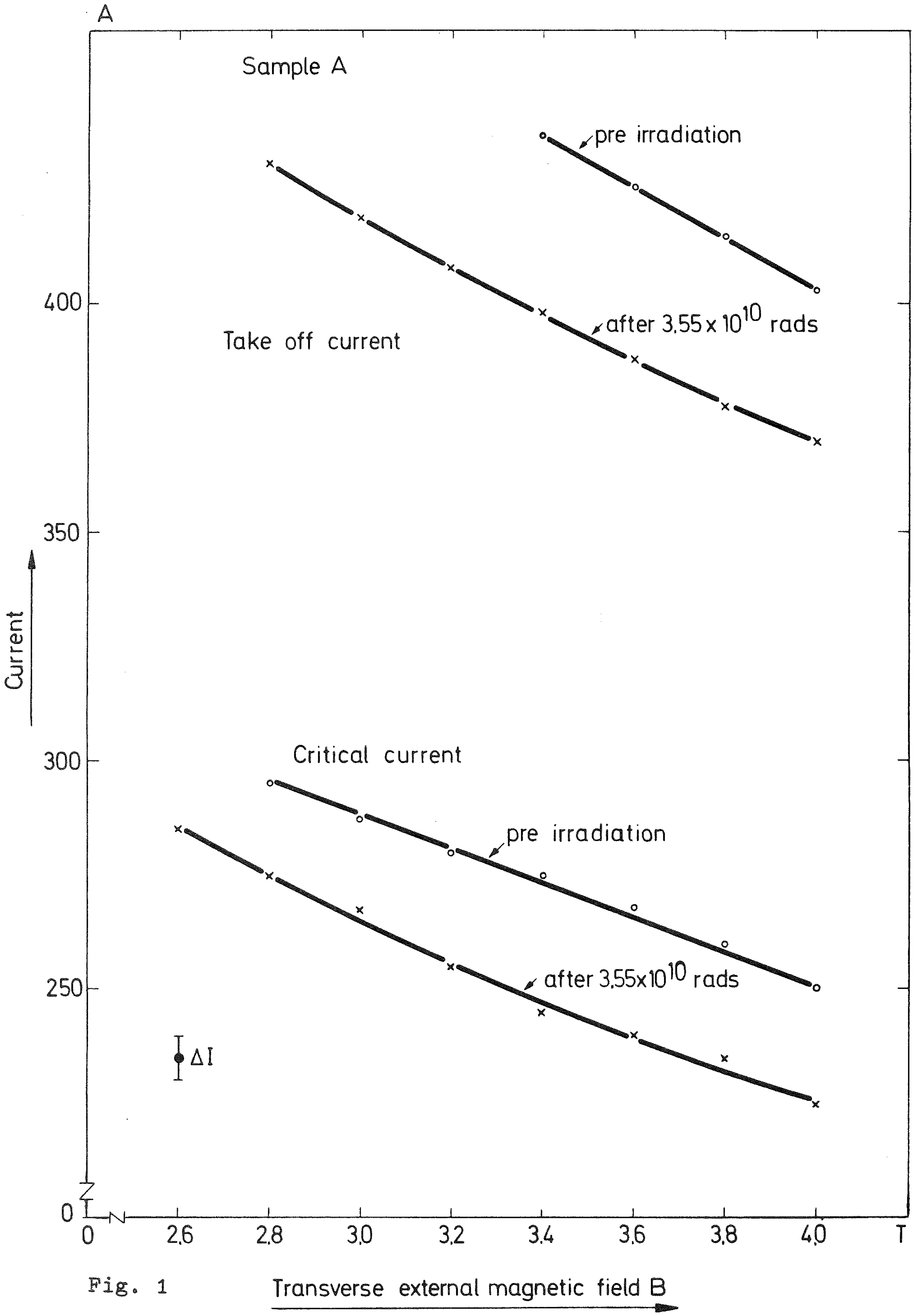

A
Sample A
pre irradiation
after 3,55 x 10^{10} rads
Take off current
Critical current
pre irradiation
after 3,55x10^{10} rads
ΔI
Current
400
350
300
250
0
0
2,6
2,8
3,0
3,2
3,4
3,6
3,8
4,0
T
Transverse external magnetic field B

Fig. 1

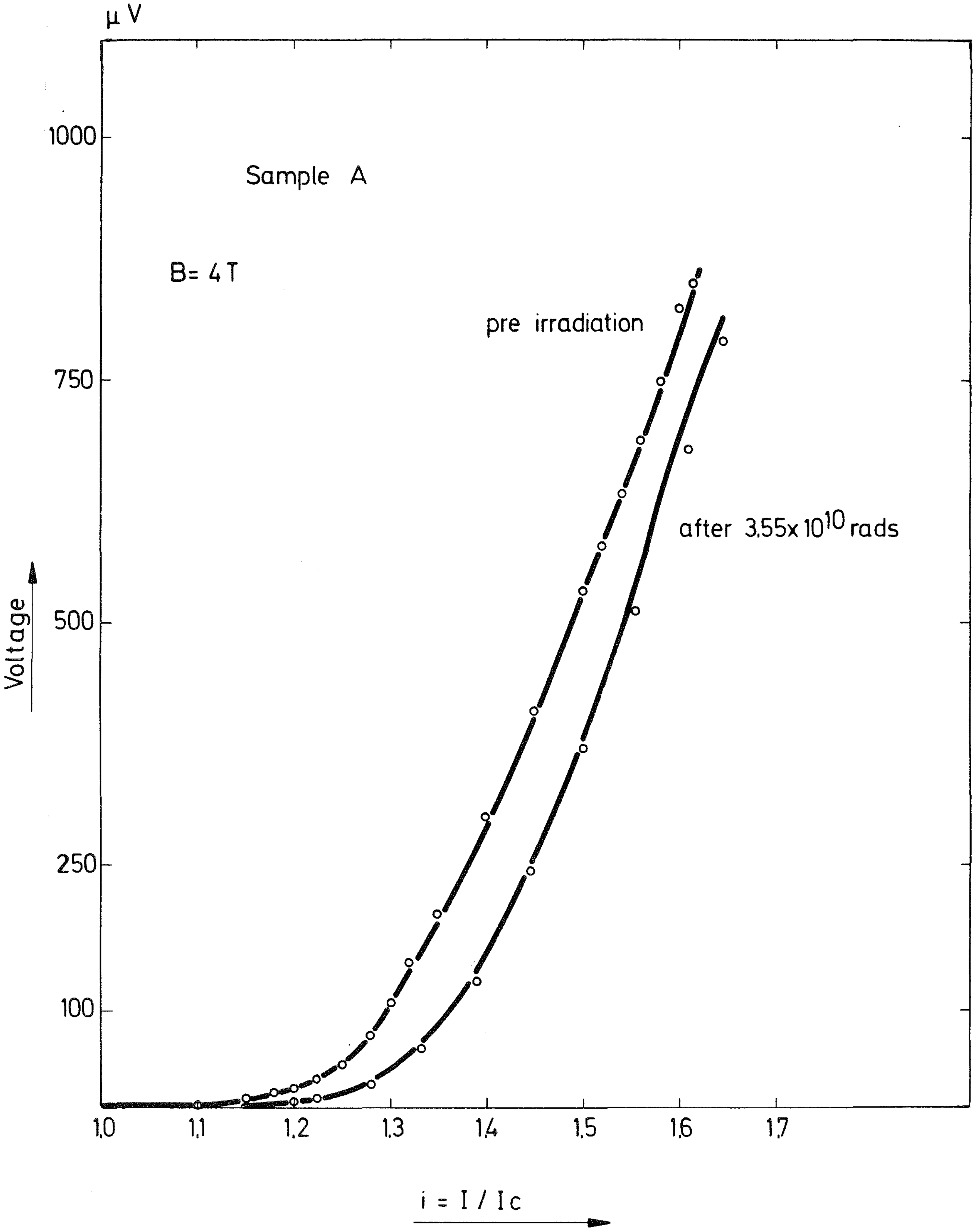

μ V
1000
750
500
250
100
Voltage
Sample A
B= 4 T
pre irradiation
after 3,55x10^10 rads
1,0
1,1
1,2
1,3
1,4
1,5
1,6
1,7
i = I / Ic

Fig. 2

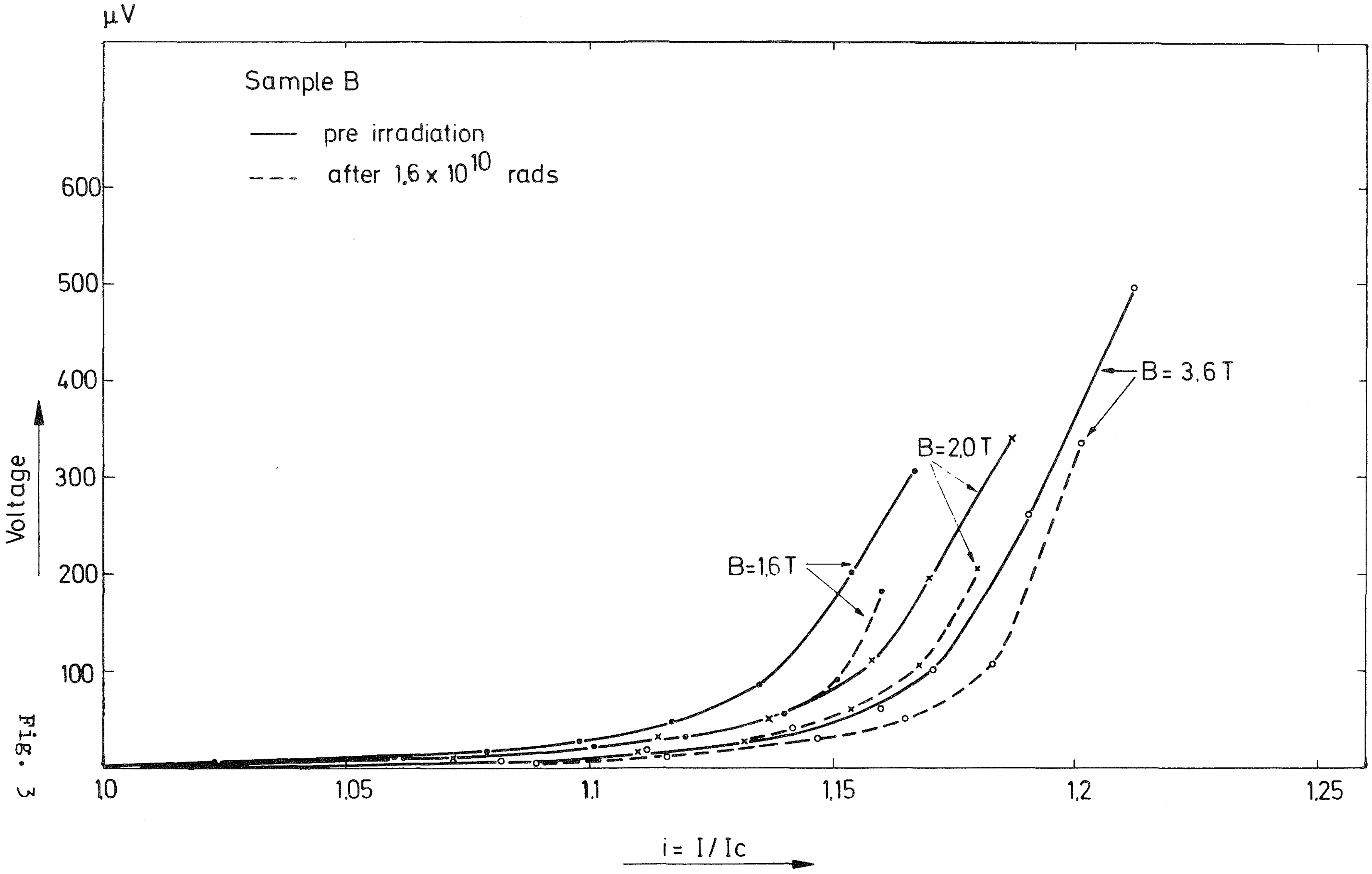
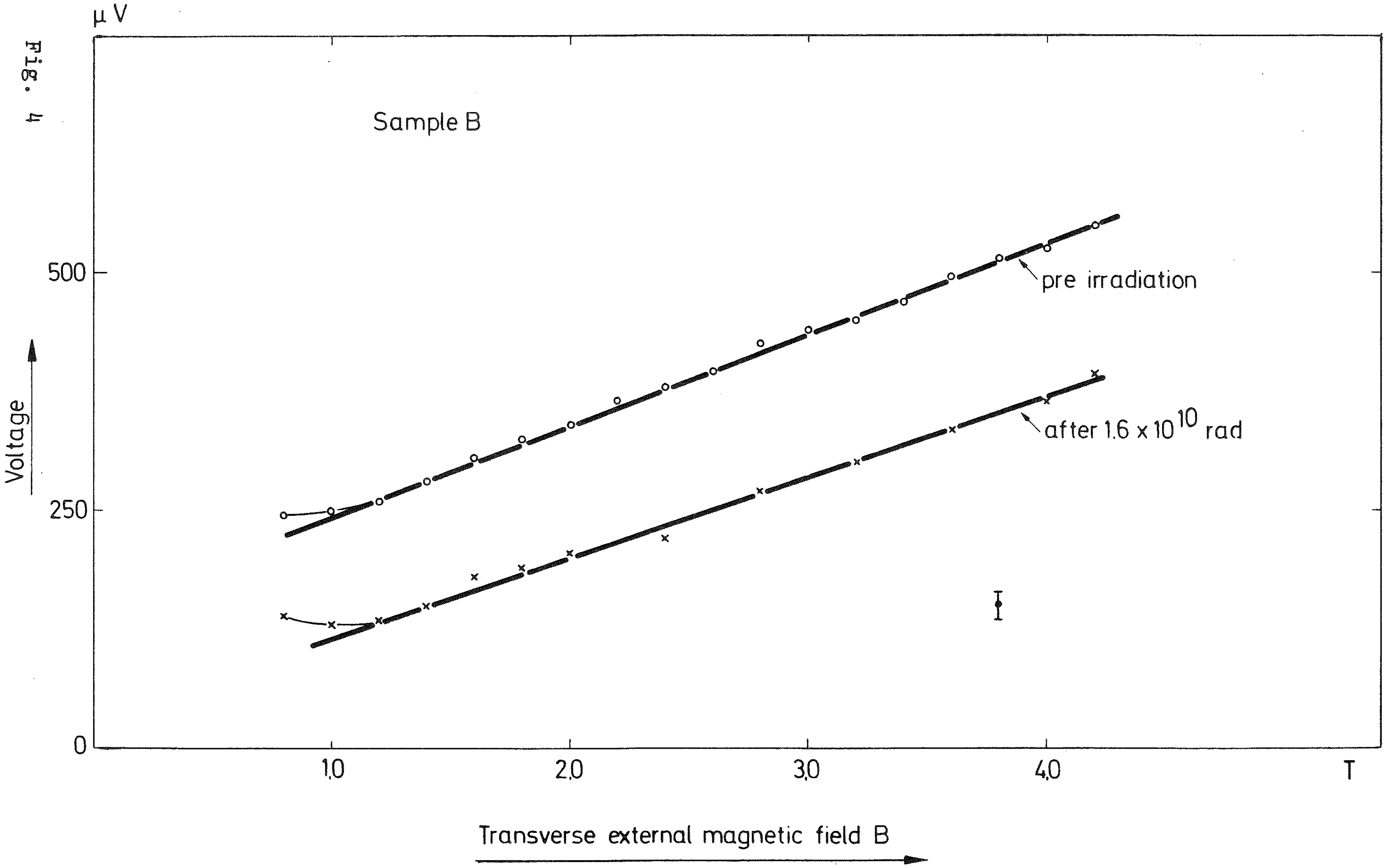

μV
Sample B
pre irradiation
after 1,6 x 10^10 rads
600
500
400
300
200
100
Voltage
1,0
1,05
1,1
1,15
1,2
1,25
i = I / Ic
B = 3,6 T
B=2,0 T
B=1,6 T

Fig. 3

Fig. 4


µ V
Sample B
Voltage
500
250
0
1,0
2,0
3,0
4,0
T
pre irradiation
after 1.6 x 10^10 rad
Transverse external magnetic field B