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SIMULATION OF FUSION REACTOR CONDITIONS FOR
SUPERCONDUCTING MAGNET MATERIALS*

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ABSTRACT

We report on a comprehensive study of neutron irradiation induced changes of critical current densities in a variety of NbTi- and some Nb₃Sn-superconductors with Ti-additions as well as of changes in normal state resistivity of the copper stabilizer at 8 T. The samples were irradiated at 5 K and subjected to room temperature annealing cycles after each irradiation step. The results on NbTi show, in general, small degradations of j_c , which do not exceed 20% over the life time fluence at the magnet location. Contrary to the low-field data we find a rather uniform radiation response of different materials at high fields. The results on (NbTi)₃Sn show the usual increase of critical current densities with neutron fluence followed by a sharp decrease of j_c . However, the peak of j_c is shifted to much lower fluences in the alloyed samples as compared to pure Nb₃Sn. Finally, results on the resistivity change of "magnet" copper are presented which indicate that a considerable increase of resistivity ($\sim 60\%$ at 8 T) cannot be avoided under reasonable operating conditions of the magnet.

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1. Introduction

The radiation environment at the magnet location has been evaluated for various fusion reactor designs (cf., e.g., [1],[2] and references therein). Considering the damage mechanisms in the superconductor and the stabilizing material, it is appropriate to characterize the radiation environment by the fast neutron flux density or, integrated over the plant lifetime, by the fast neutron fluence. Assuming a total operation period of 30 years, neutron fluences of 5.68 and $1.61 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$) have been calculated for the MARS and STARFIRE designs, respectively. Of course, the damage will be introduced at the operating temperature of the magnet ($\leq 5 \text{ K}$), but occasional warm-ups to room temperature will occur during maintenance.

Hence, in order to provide reliable information on the performance changes of magnet components, the following procedure should be adopted: irradiate the samples at low temperatures with a neutron spectrum, which is similar to the one expected at the magnet location, up to a certain neutron fluence; measure the change of relevant sample properties in situ and/or after an annealing cycle to room temperature; continue the irradiation program and the measuring cycles up to neutron fluences well into the 10^{22} m^{-2} ($E > 0.1 \text{ MeV}$) fluence range.

The results to be presented in the following sections meet these requirements in nearly every respect; only the in situ measurements of critical current densities and stabilizer resistance were prevented by the large number of samples to be investigated. The irradiations were made at the spallation neutron source IPNS at

Argonne National Laboratory and the measurements taken after room temperature annealing cycles in magnetic fields up to 11 T.

2. Materials

The superconductors investigated in the present study comprise a broad variety of metallurgically different monofilamentary NbTi-conductors, some commercial multifilamentary NbTi-conductors as well as several multifilamentary $(\text{NbTi})_3\text{Sn}$ -conductors with Ti-additions of 0.8 and 1.5 wt % Ti, respectively. A detailed description of the single core conductors has been given elsewhere [3,1]. The main metallurgical variation parameters are the Ti-concentration (42, 49, 54 wt % Ti) and the final thermomechanical treatment (320-430°C, 0-91% final cold work). Among the multifilamentary NbTi conductors special emphasis will be paid to the conductor S-300-1, which was used for the construction of the Swiss LCT-coil (manufacturer: BBC Brown Boveri & Cie., 46.5 wt % Ti, 330 filaments of 17 μm diameter, Cu: superconductor = 1.2 : 1). The A15 conductors with Ti-additions, on which much interest has focused recently [4] because of the increase of the upper critical field H_{c2} achieved by adding small amounts of a third component, contain approximately 10.000 filaments of small size ($\sim 1.3 \times 5 \mu\text{m}^2$), the bronze to niobium ratio is 3 : 1.

All samples were prepared to meet the stringent space requirements in the irradiation facility; they were cut into straight pieces of 47 mm length and polished to remove the oxide layer from the copper stabilizer. Thin potential leads were soldered onto each sample

prior to the irradiation program, the gauge length for the critical current and copper resistance measurements was chosen to be 20 mm.

3. Results:

3.1 NbTi-superconductors

Previous results on the same materials, which were obtained in fields up to 6 T following reactor neutron irradiation at ambient and liquid nitrogen temperatures [3,5], revealed a rather general correlation between the radiation response of critical current densities and the metallurgical condition of the conductors prior to irradiation. These data showed firstly, that the radiation-induced degradation of critical current densities was, in general, smaller than the improvements of J_c achievable by appropriate thermomechanical treatments prior to irradiation, and secondly that, for a given thermomechanical treatment, conductors with higher Ti-contents were less sensitive to radiation damage because of the increasing predominance of precipitate pinning. Both of these aspects were confirmed by the present study involving 5 K irradiation and an annealing cycle prior to the J_c -measurements; an example of this data referring to three conductors of identical thermomechanical treatment, but different Ti-contents, is shown in the upper part of Fig.1, where the change of critical current densities at 5 T is plotted versus the fast neutron fluence.

However, if we compare the data on the same samples at higher fields (≥ 7 T), this characteristic dependence of the J_c -degradation with neutron fluence on the metallurgical starting conditions is no longer

observed. Instead we find a rather uniform radiation response of the samples in a certain external field, as long as the upper critical fields H_{c2} of the conductors are comparable (cf. Fig. 1, lower section). This result strongly suggests that the changes of J_c with neutron fluence are governed at high fields by changes of H_{c2} and/or the elastic constants of the flux line lattice.

In order to clarify this interesting new effect, a program was set up to determine H_{c2} of all the materials prior to irradiation and after the last irradiation step ($\sim 3 \times 10^{22} \text{ m}^{-2}$, $E > 0.1 \text{ MeV}$) as accurately as possible. Experimentally H_{c2} is defined from critical current measurements using a $0.1 \mu\text{Vcm}^{-1}$ -criterion either by direct observation ($B \leq 11.2 \text{ T}$) or by extrapolating the square-root of the pinning force to zero [6]. The results available so far (Table 1) show that in all cases H_{c2} decreases with neutron fluence. An explanation of this result is not available yet, but we propose that the decrease of H_{c2} is related to the known small decreases of T_c in NbTi-superconductors [3]. An experimental verification of this hypothesis is under way.

Based on this data a straightforward application of current flux pinning models, e.g. [7,8], can be used to estimate the effect of the H_{c2} -reduction on the change of critical current densities. Neglecting all other possible changes of material parameters (such as κ , H_c , c_{IJ} , ...) and retaining only the measured change of H_{c2} , both of the models mentioned above yield the following relation for the fractional change of J_c :

$$\frac{J_c}{J_{c0}} = \frac{H_{c20}}{H_{c2}} \left(\frac{H_{c2} - B}{H_{c20} - B} \right)^2 \quad (1)$$

An evaluation of Eq.(1) at 8 T and using the results of Table 1 reproduces the trend of data correctly, but overestimates the actual magnitude of J_c/J_{c0} by about 5 %. Further work and a more detailed analysis will be needed, in order to fully discuss the radiation response of these materials at high fields.

To conclude this section, the results on the conductor S-300-1, which was used for the construction of the Swiss LCT-magnet, are presented in Fig. 2. The data show a smooth variation of J_c with neutron fluence and a tendency to level off in the fluence range of interest for fusion reactor applications. The critical current densities degrade to 0.86 at 8 T and to 0.88 at 5 T, which is clearly not a problem from the applied point of view. Further work on the change of H_{c2} and T_c of this conductor is still under way.

3.2 (NbTi)₃Sn-superconductors

Four of these advanced conductors [4] were included in the present study and irradiated up to a fluence of $\sim 1 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$); again room temperature annealing cycles were made following 5 K-irradiations to ~ 0.5 and $1 \times 10^{22} \text{ m}^{-2}$, respectively. The Ti-contents of the conductors were 0.8 and 1.5 wt % Ti, the final reaction temperatures 625 and 700°C, respectively. The preirradiation results on H_{c2} [9] show clear correlations of this quantity with material parameters (0.8 wt %, 625°C : 22.0 T, 700°C : 22.5 T; 1.5 wt %, 625°C : 21.0 T, 700°C : 21.5 T) and a significant enhancement of H_{c2} as compared to pure Nb_3Sn .

The observed change of critical current densities with neutron fluence differs considerably from all the results obtained previously on pure A 15 compounds. As an example we show data on the 1.5 wt % conductor (625°C , $\mu_0 H_{c2} = 21.0 \text{ T}$) in Fig.3 and compare them with earlier work on pure Nb_3Sn [10]. It will be noted, that the usual increase of critical current densities followed by a rather sharp decrease is observed again, but the maximum enhancement of J_c occurs at a neutron fluence which is lower by a factor of almost 6 compared to pure Nb_3Sn . No significant enhancement of J_c is found with a conductor of the same composition (reaction temperature: 700°C instead of 625°C) and a considerable decrease of J_c occurs even at the lowest fluence in the conductor with the highest critical field H_{c2} (0.8 wt % Ti, 700°C).

Although no additional information on the change of material parameters, especially H_{c2} , with neutron fluence is available yet, it is tempting to explain these results in terms of the disorder-induced variation of H_{c2} in Nb_3Sn . It is generally accepted that the increase of critical current densities is caused by an increase of H_{c2} via the radiation induced increase of normal-state-resistivity. Direct measurements of H_{c2} as a function of neutron fluence were made on a monofilamentary Nb_3Sn -conductor recently [11] and demonstrated excellent correlations between the increase and subsequent decrease of H_{c2} and J_c with neutron fluence (in fact, the maximum enhancement of H_{c2} by about 12 % occurs at the same fluence of $2 \times 10^{22} \text{ m}^{-2}$ as the peak in J_c). If we assume, that the increase of H_{c2} in the unirradiated ternary superconductor is caused partly (or completely)

by the same mechanism, i.e. preirradiation disorder introduced by alloying the third component, an (almost) immediate decrease of critical current densities with neutron fluence is to be expected. This conclusion is also supported by the observations mentioned above, viz. that for a given Ti-concentration the critical current densities degrade faster in the material with a higher preirradiation value of H_{c2} .

In summary, it should be pointed out, that according to the present experimental evidence the addition of small amounts of a ternary component to Nb_3Sn -superconductors significantly degrades the radiation resistance of these materials and, hence, counteracts the desired effect of an H_{c2} -enhancement on the achievable critical current densities in an intolerable way.

3.3 Copper stabilizer

On all the NbTi-conductors discussed in section 3.1 additional experiments on the resistivity ratios (10 K) of the copper stabilizer were made in zero field. As mentioned before, all these conductors were irradiated at 5 K and subjected to a room temperature annealing cycle after each irradiation step and prior to the resistivity measurements. The results display a very uniform behavior: those materials, which were subjected to final cold work as the last preparation step, showed resistivity ratios around 60 [$\rho(10\text{ K}) \sim 0.30\text{ n}\Omega\text{m}$], which remained constant in the course of the irradiation program. On the other hand, those materials subjected to a final heat treatment, usually applied to commercial conductors for magnet construction, showed initial

resistivity ratios around 120 [$\rho(10\text{ K}) \sim 0.15\text{ n}\Omega\text{m}$], but degraded continuously towards the "cold work limit" of 60.

Based on recent work [12] on similar "magnet" copper, which established the applicability of a Kohler plot over a rather wide range of starting resistivities and irradiation/annealing conditions, the data of our experiments can be converted to show the fractional increase of stabilizer resistivity with neutron fluence at high fields, e.g. 8 T. (It should be borne in mind, however, that this representation is typical of copper only in this resistivity range and not universal because of the known deviations from Matthiessen's rule, e.g. [13]). The results of this evaluation are shown in Fig.4. It will be noted that the inclusion of magnetoresistivity drastically reduces the amount of resistivity increase with fluence because of the decrease of magnetoresistivity with increasing zero-field resistivity.

Since the data presented so far refer to the post-annealing conditions only, the crucial question on the resistivity increase at 8 T prior to the annealing cycle has still to be answered. Fortunately, in situ 5 K-irradiation and annealing experiments on comparable magnet copper [$\rho(4.2\text{ K}) \sim 0.16\text{ n}\Omega\text{m}$] were made in the low fluence range [14] and the measurements taken in fields up to 6.5 T. Perfect agreement between these data and our own results is found in the overlapping fluence range. We, therefore, believe that the extrapolation shown for the Swiss LCT-conductor by the dashed line in Fig. 5 represents a reasonable approximation to the actual operating conditions of a fusion magnet, if we assume a lifetime fluence of $4 \times 10^{22}\text{ m}^{-2}$ ($E > 0.1\text{ MeV}$) over 30 years

and plant shut-downs (annealing cycles) after 2,6,9,12.5,15,20 and 25 years of operation. Although extrapolation errors should be allowed for, it is fairly obvious that present design limits for the permissible resistivity increase of the stabilizer at 8 T (25 %) cannot be reconciled with a reasonable operating schedule of a fusion plant.

4. Conclusions

The results on the change of material parameters of superconducting magnet components, which were obtained under conditions similar to the actual requirements in a fusion reactor, may be summarized as follows.

- 1) The radiation-induced decrease of critical current densities in NbTi-superconductors is small and certainly not a problem from the applied point of view. At high fields (≥ 7 T) the fractional change of J_c is rather independent of sample metallurgy, which indicates a predominant influence of the upper critical field H_{c2} on the magnitude of J_c . Initial results on the change of H_{c2} in irradiated samples, which show a decrease of this quantity as a function of neutron fluence, are well suited to explain the observed J_c -degradation in a qualitative way.
- 2) The results on $(\text{NbTi})_3\text{Sn}$ -superconductors are characterized by significant degradations of critical current densities already in the 10^{21}m^{-2} fluence range. From a comparison with pure Nb_3Sn and additional H_{c2} -measurements of the unirradiated samples, we conclude that some preirradiation disorder is introduced by the alloying of

a third component. The prospects for a successful application of these materials in fusion reactors seem doubtful in view of the present experimental evidence.

3) The radiation-induced increase of stabilizer resistivity is found to exceed present design limits for operation at 8 T considerably.

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Table 1: Upper critical fields H_{c2} of some NbTi-superconductors

Sample				$\mu_0 H_{c2}$ (T)	
				unirradiated	$\sim 3 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$)
# 13	42 wt%Ti,	350°C,	71%f.c.w.	11.70	11.32
# 14	49 wt%Ti,	350°C,	71%f.c.w.	11.36	11.18
# 15	54 wt%Ti,	350°C,	71%f.c.w.	10.78	10.52
# 31	42 wt%Ti,	400°C,	91%f.c.w.	11.83	11.39
# 32	49 wt%Ti,	400°C,	91%f.c.w.	11.75	11.32
# 33	54 wt%Ti,	400°C,	91%f.c.w.	10.94	10.65

Figure Captions

Fig.1: Change of critical current densities with fast neutron fluence ($E > 0.1$ MeV) at 5 and 8 T.

13,14,15 : 42,49,54 wt%Ti; annealing temperature: 350°C, final cold work : 71%

Fig.2: Change of critical current densities with fast neutron fluence ($E > 0.1$ MeV) at 5 and 8 T.

Conductor S-300-1 (used for the Swiss LCT-magnet)

Fig.3: Change of critical current densities with fast neutron fluence. The scaling is not completely accurate, because differences in damage energy cross-sections resulting from different radiation sources are not taken into account. Low temperature irradiations of an alloyed conductor are compared to ambient temperature irradiations of pure Nb₃Sn [10].

Fig.4: Fractional increase of stabilizer (copper) resistivity with fast neutron fluence ($E > 0.1$ MeV) normalized to the preirradiation values at B=0 and 8 T, respectively. Multifilamentary NbTi-superconductors; stabilizer resistivity ratios prior to irradiation: ~60(#34), ~120 (#35,36).

Fig.5: Complete simulation cycle for the change of stabilizer resistivity with neutron fluence ($E > 0.1$ MeV) over the plant lifetime. Conductor #36: Swiss LCT-conductor. The in situ low fluence data of Ref.14 are used to extrapolate the present postannealing data to a fluence of $4 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1$ MeV).