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Critical current density of Nb_3Sn wires after irradiation with 65MeV and 24GeV protons

T. Spina, C. Scheuerlein, D. Richter, L. Bottura, A. Ballarino, R. Flükiger
CERN, TE-MSC, Geneva, Switzerland

tiziana.spina@cern.ch, christian.scheurlein@cern.ch, david.richter@cern.ch, luca.bottura@cern.ch, amalia.ballarino@cern.ch, rene.flukiger@cern.ch

Abstract. Industrial Nb_3Sn wires with Ti and Ta additives (RRP process) and with Ta additives (PIT process) with a diameter of 1 mm have been irradiated at room temperature with protons of 65 MeV and of 24 GeV at various fluences up to 1×10^{21} p/m^2. A steady increase of J_c vs. fluence was observed for all the wires up to the highest fluence. The observed increase of J_c at 4.2K in all wires was quite similar in spite of the very different proton energies. With increasing fluence, the radiation induced pinning force was found to increase, the enhancement J_c/J_{co} after 5.04×10^{20} p/m^2 reaching 1.4 for Ta and 1.8 for Ti alloyed wires at 10T. The present results were quantitatively analysed by assuming a radiation induced point pinning mechanism in addition to grain boundary pinning. The results are compared with those of an ongoing neutron irradiation study undertaken on the same Nb_3Sn wires in collaboration with the Atominstitut Vienna. Proton irradiation was found to produce considerably higher damage than neutron irradiation.

1. Introduction

The High Luminosity Large Hadron Collider upgrade (HL-LHC) aims at reaching an integrated luminosity of 3000 fb^{-1} with a peak luminosity of 5×10^{34} cm^{-2}s^{-1}. The present NbTi inner triplet in the interaction regions will be replaced by larger aperture quadrupoles based on Nb_3Sn conductors [1]. RRP or PIT Nb_3Sn wires will be used, the requirement for the critical current density being $J_{c(non\text{-}Cu)}$ = 1500 A/mm^2 at 4.2 K and 15 T. The radiation issue is very complex, the quadrupoles being simultaneously exposed to various high energy radiation sources [2]. The aim of the present work is to study the effect of proton irradiation on current carrying capability of RRP and PIT Nb_3Sn wires with Ti and Ta additives during the LHC lifetime. At the same time, the effect of neutron irradiation on the same wires was studied at the Atominstitut Vienna in the frame of a collaboration.

2. Experimental

2.1. *Proton energies, proton irradiated Nb_3Sn wires and the two facilities (IRRAD1 and UCL)*

The maximum radiation load acting on the quadrupole Q2a over the whole operation time has recently been calculated by F. Cerutti at CERN [2]. At the inner winding of the Q2a quadrupole, where the maximum damage is expected, the radiation spectrum will consist of photons, electrons, protons and pions, with energies ranging from 0.1 MeV to 10^3 GeV (with maxima around 1GeV for electrons and positrons and around 200 MeV for protons and pions) and neutrons with an energy peak value around 1 MeV. The maximum fluence at 3000 fb^{-1}, calculated for the case without W shielding, is: $\sim1.5\times10^{21}$ neutrons m^{-2}, $\sim 2\times10^{20}$ protons m^{-2} and ~ 2×10^{20} pions m^{-2} [2]. The present room temperature proton irradiation study was performed at two different energy values: 65 MeV and 24 GeV at the Université Catholique de Louvain-La-Neuve (UCL) and at CERN (IRRAD1) respectively. The corresponding proton fluxes were 8×10^{13} p/m²s at IRRAD1 and 2×10^{16} p/m²s at the UCL. The set-up for irradiation facilities has been described in detail by Otto et al. [3]. The proton fluences were chosen based on earlier works at proton energies E ≤ 3 MeV [4, 5]. However the present proton energies being substantially higher, work at higher fluences has still to be undertaken to reach the maximum of J_c/J_{c0}. Three types of Nb_3Sn industrial multifilamentary wires with a length of approximately 5 mm and a mass of ~ 20 mg were irradiated up to 1×10^{21} p/m²: two RRP (or Restacked Rod Process) wires from Oxford Superconducting Technology (Ta alloyed, billet #7419, and Ti alloyed, billet #11976) and a PIT wire from Bruker EAS (Ta alloyed, billet #0904). These wires have been characterized in a recent article (Flükiger et al. [6]).

2.2. *Measurements*

The magnetic moment of the Nb_3Sn wires was measured in a Vibrating Sample Magnetometer (VSM) at 4.2K. The measurements, performed in He gas flow, were accomplished by sweeping the applied field perpendicular to the wire axis, between 0 and 10.5 T with steps of 250 mT while increasing and decreasing the field (rate of 500 mT/min for each step). The temperature was measured by means of three Cernox thermometers. The values of J_c were determined from magnetization under the assumption that each sub-element can be treated as an independent superconducting hollow cylinder, as recently reported by Baumgartner et al. [7]. A conventional AC magnetic susceptometer (2 mT and 40.8 Hz) was used to determine the variation of the critical temperature T_c vs. proton fluence.

3. Results and discussion

The experimental values of T_c after proton irradiation are reported in table 1. The observed decrease of T_c due to proton irradiation is higher with respect to that obtained after neutron irradiation [6].

Table 1. Variation of T_c after proton irradiation for the RRP Ti alloyed (#11976) and PIT Ta alloyed (#0904) wires at 24GeV and 65MeV respectively.

Φt (p/m²)	T_c(K) #11976	T_c(K) #0904
1.08×10^{20}	16.90	-------
2.00×10^{20}	-------	17.10
5.04×10^{20}	16.85	-------
1.00×10^{21}	-------	16.95

---- no data available for these fluences

The variation of the ratio $J_c(\phi t)/J_{c0}$ (J_{c0} is the unirradiated value) with proton fluence at different energies is shown in figure 1.

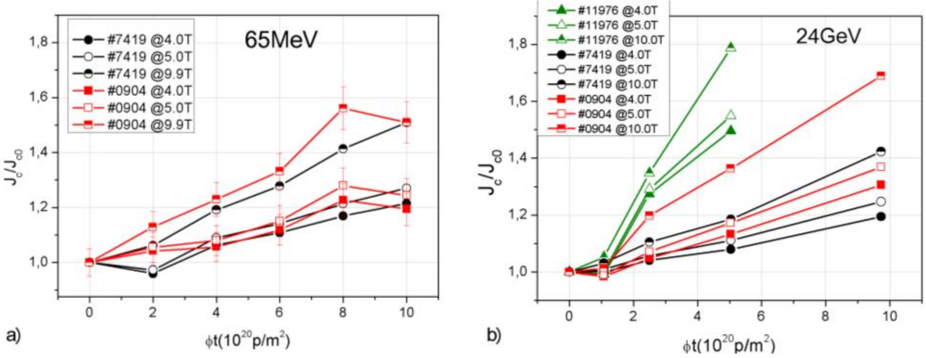

Figure 1 Enhancement of the critical current density with fluence after 65 MeV (a) and 24 GeV (b) proton irradiation. The small decrease of J_c/J_{c0} up to 2×10^{20} p/m² was discussed by Brown et al. [10]

Up to the maximum applied fluence, J_c/J_{c0} of all irradiated wires was found to increase with fluence, the enhancement being more important at higher magnetic fields. The small decrease of J_c/J_{c0} at low fluences (discussed earlier by Brown et al. [10]) was not observed in all wires. The present results allow two main observations: (a) The enhancement of J_c in all wires is quite similar, in spite of the very different proton energies. This could be explained on the basis of the PHITS calculation of Fukahori et al. [8] on Cu, our wire diameter being small with respect to the proton penetration depth at these energies, (b) Both Ta alloyed wires exhibit a similar enhancement, regardless of the fabrication technique. The nature of the additive seems to be important, J_c/J_{c0} of the Ti alloyed wire (#11976) exhibiting a larger enhancement than the Ta alloyed wires #7419 and #0904: at the fluence 5×10^{20} p/m^2 and 10 T, the ratio J_c/J_{c0} reaches 1.8, while both Ta alloyed wires reach values between 1.2 and 1.4. The variation of J_c/J_{c0} for the Ta alloyed PIT wire irradiated at 65 MeV (figure 1b) seems to indicate a peak around 8×10^{20} p/m^2, within the error bar. A conclusive answer is expected after ongoing irradiations at higher fluences.

3.1. Contribution of radiation induced defects to the volume pinning force

As shown in figure 2, the enhancement of J_c for the irradiated wires is higher at small reduced fields b thus reflecting enhanced pinning after irradiation. This behaviour is not affected by the uncertainty in the extrapolated $B_{c2(Kramer)}$ (see table 2).

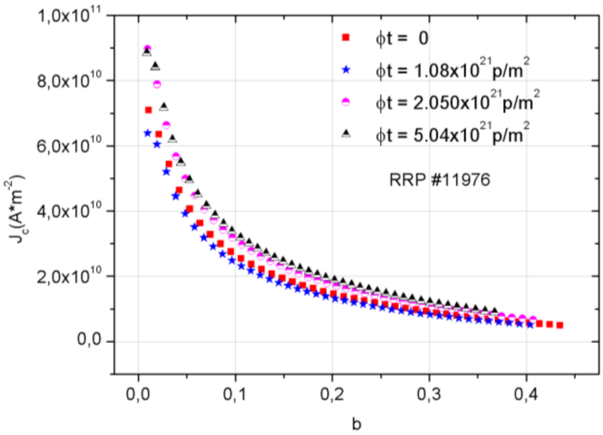

Figure 2 Behaviour of J_c vs. b for various fluences for RRP Ti alloyed (#11976) wires at 24 GeV.

Table 2 B_{c2} values calculated with the Kramer extrapolation and scaling fields B_{c2}* (fitting parameter) at 4.2 K for RRP Ti alloyed wires (#11976) at 24GeV. These values are only indicative, the highest applied field being 10 T.

ϕt (10^{20}p/m^2)	**$B(4.2K)_{c2(Kramer)}$ (T)**	**$B^*(4.2K)_{c2}$ (T)**
1.08	25.9	26.2
2.5	25.7	25.8
5.04	28.5	28.2

As proposed by various authors, the enhancement of J_c after irradiation with neutrons [7,9,10,11] or protons [4,5,12] is attributed to the radiation induced nanosize defect clusters acting as new pinning centers. Küpfer et al. [11] proposed a two-mechanism model which was recently improved by Baumgartner [13]: $f(b) = \alpha\, b^{p_1}(1-b)^{q_1} + \beta\, b^{p_2}(1-b)^{q_2}$, with $\alpha + \beta = 1$ and $b = B/B^*_{c2}$ (B^*_{c2} is a scaling field parameter, see table 2). The first contribution is due to grain boundary pinning and does not change after irradiation (p_1, q_1 are fixed at the values found for unirradiated wires), while the second contribution is due to defect clusters, various combination of the fitting parameters yielding values close to $p_2 = 1$ and $q_2 = 2$, thus suggesting point defects. The two contributions of the volume pinning force are shown in figure 3. For the RRP Ta alloyed wire at 24 GeV the field $(b_{max})_{Defect\ Cluster}$ increases from 0.17 (unirradiated) to 0.24 for 1×10^{21} p/m^2, while $(b_{max})_{Grain\ Boundairies}$ remains unchanged at ~ 0.17.

3.2. Comparison between the damage caused by neutrons and by protons

The enhancement of radiation induced pinning force can be represented by the variation of the factor β in the formula given above for the normalized pinning force *f(b)* (figure 4).

Comparing the present results with neutron irradiation data obtained on the same wires by Baumgartner [13], it follows that for the same fluence, the damage produced by proton irradiation is considerably higher than the damage due to neutron irradiation. The same value of β (for example 0.5) obtained after proton fluences between 4 and 8×10^{20} p/m^2 (figure 4), is obtained after a neutron fluence of ~1×10^{22} n/m^2 [13], i.e. a factor > 10 higher.

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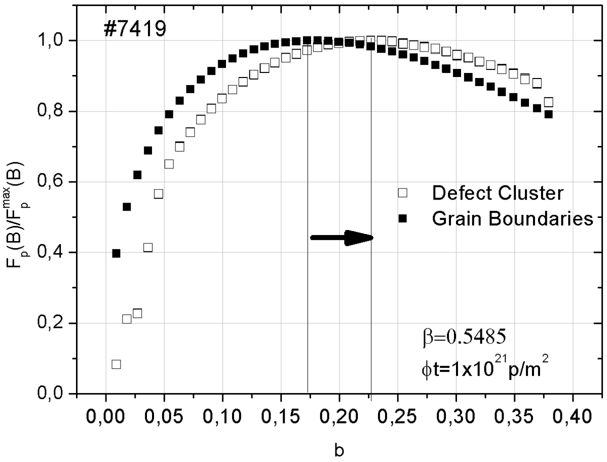

Figure 3 Volume pinning force vs. reduced field *b* for Ta alloyed wire #7419 irradiated with 65 MeV protons at $1{\times}10^{21}$ p/cm^2.

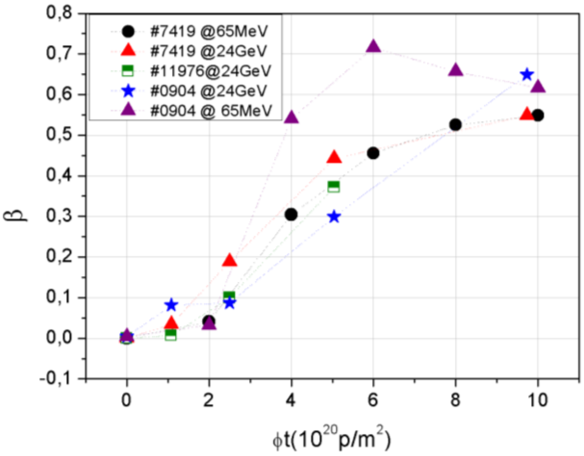

Figure 4 Increase of the proton radiation induced pinning force term *β* with fluence. (*β* uncertainty: ~ 10%)

Conclusion

Ternary alloyed RRP and PIT Nb$_3$Sn wires with high J_c values have been irradiated at the UCL and IRRAD1 reactors up to $\phi t = 1\times\ 10^{21}$p/m^2. The enhancement of J_c/J_{c0} in all irradiated wires is quite similar, in spite of the very different proton energies. Both Ta alloyed wires (RRP and PIT) exhibit a similar enhancement regardless of the fabrication technique, while J_c/J_{c0} of the Ti alloyed wire exhibits a stronger increase than the Ta alloyed wires. With the present fluences the expected maximum in J_c/J_{c0} was not yet achieved. The variation of J_c after proton irradiation was quantitatively analysed by assuming a radiation induced point pinning mechanism in addition to grain boundary pinning. A comparison with the results obtained on the same wires after neutron irradiation [6,13] shows that proton irradiation causes the same damage at fluences being one order of magnitude lower.

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