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Radiation Damage Study of a Monocrystalline Tungsten Positron Converter

X. Artru[1], R. Kirsch[1], R. Chehab[2], B. Johnson[3], P. Keppler[4], J. Major[4],
L. Rinolfi [5], A. Jejcic [6]

Abstract

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[1]IPN, Lyon, France, [2]LAL, Orsay, France, [3]SSRL, Stanford, USA,
[4]MPI, Stuttgart, Germany, [5]CERN, Geneva, [6]IPN, Orsay, France

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X. Artru, R. Kirsch, IPN, Lyon, France; R. Chehab, LAL, Orsay, France;
B. Johnson, SSRL, Stanford, USA; P. Keppler, J. Major, MPI, Stuttgart, Germany;
L. Rinolfi, CERN, Geneva, Switzerland*; A. Jejcic, IPN, Orsay, France.

Abstract

The exploitation of the enhancement of positron sources by channeling effects, in particular for Linear Colliders (LC), relies on the long term resistance of the crystal to radiation damages. Such damages have been tested on a 0.3 mm thick tungsten monocrystal exposed during 6 months to the 30 Gev incident electron beam of the SLAC Linear Collider (SLC). The crystal was placed in the converter region, orientated in a random direction and received an integrated flux of e^- (fluence) of $2.10^{18} e^-/mm^2$. The crystal was analyzed before and after irradiation by X and γ diffractometry. No damages were observed, the mosaic spread remained unchanged during irradiation (0.4 mrad FWHM). Implications for use of orientated crystal as converter for positron sources of future LC are discussed.

1 INTRODUCTION

The use of orientated crystals in positron sources is motivated by the enhanced gamma radiation along the crystallographic axes or planes and the corresponding enhancement in pair production [1, 3]. Their use in linear colliders (LC), where high beam intensities are required with rather large repetition frequencies, depends essentially on their long-term resistance to radiation damages. Estimation as well as experiments have been concerned with this problem. Most of the previous experimental tests were dealing with silicon crystals to be used as extraction devices in circular proton accelerators [4, 5]. The damage threshold for such crystals has been determined at BNL with a 28 GeV proton beam: it appeared at a fluence of 4.5×10^{20} p/cm^2 [4]. At CERN, reduction by 30% of deflection efficiencies of irradiated silicon bent crystals with 2.4×10^{20} p/cm^2 are also reported [6]. Compared to electrons, protons give rise to additional nuclear interactions. Furthermore, Coulomb scattering of the beam particles on the nuclei, which is the main source of damage, depends on the atomic number Z of the target. Therefore, it seems worthwhile to perform a test with an electron beam and a tungsten crystal, corresponding more closely to the proposed converter. Moreover, an experiment in linear collider conditions should make this test as close as possible to the actual working conditions of a LC. This test has been done on the SLC site with a 30 Gev electron beam and a thin tungsten crystal during the first six months of 1996. In the present paper after a theoretical introduction, the experiment and the results concerning the crystal analysis will be presented. Some pratical conclusions will also be derived.

2 THEORETICAL ESTIMATIONS

The main processes occuring during irradiation by fast charged particles are:

- elastic collisions with the nuclei of the crystal,
- excitation of the electronic layers of the atoms,
- nuclear transformations.

For electron beam and small thickness we can ignore the 3rd process. The second one only heat the crystal without producing defects. Only the first process is harmful and we study it briefly below. If the recoil energy T=Q^2/2M (Q= Transfer momentum, M= mass of the nucleus) is above some threshold E_d, about 25 eV for Tungsten, the nucleus is dislodged from its lattice site [2]. For T larger than about 2 E_d, the primary nucleus can initiate a cascade of displacements among the neighbouring atoms. The average number of displaced atoms per primary collision is [2]:

$$< n >= 1 + 0.5 \ln(L_c/2E_d) \qquad (1)$$

where L_c=Ax1 keV , A being the atomic mass of the nucleus. In order to evaluate the damage threshold in terms of integrated fluxes (fluences) we have to introduce the characteristic fluences:

- F_o, corresponding to one primary displacement per atom: $F_o=1/\sigma_d$, where σ_d, primary displacement cross section, is given by [2]:

$$\sigma_d = \frac{Z^2}{A \times E_d} \times 1.43 \times 10^{-22} cm^2 \qquad (2)$$

- $F_1= F_o/< n >$ for which there is on the average one displacement (primary or secondary) per atom. Concerning tungsten, we can get [2]:
- $F_o> 0.82\times10^{22}$ cm^{-2} and $F_1> 0.17\times10^{22}$ cm^{-2}.

The degradation of channeling properties occurs when the fraction of dislodged atoms reaches a critical

* At SLAC, during the tests.

value, f_c. Then, the critical fluence can be estimated as:

- $F_c = F_1 \times f_c$

For f_c=0.01, we obtain $F_c = 10^{20}$ cm^{-2}. Such values are comparable to those obtained by V. Biryukov et al. [7].

3 THE TEST AT SLC

3.1 Analysis of the samples prior to exposure

Three samples of tungsten monocrystals, with (111) faces, were grown at the Max-Planck Institute in Stuttgart. Two of them (C1 and C2) were 0.3 mm thick; the third one (C3) was 1 mm thick. They were characterized by γ-diffractometry at Stuttgart and with an X-ray analysis at SSRL (Stanford) after chemical cleaning.

3.1.1 X-ray analysis

X-ray diffraction rocking curves and topographs, exposed photographs of the diffracted beam, of the W(222) reflection were taken. The rocking curve FWHM and the topograph quality were used as relative measurements of mechanical strain in the sample induced by its mounting. A highly collimated (E=8.048 keV) X-ray beam has been used. A W sample was positioned in the beam in a standard $\theta - 2\theta$ geometry. The rocking curves were produced by scanning theta (i.e. the sample) with a step size of 0.00125 degree through the W (222) reflection. The topographs reveal approximately 50% of the area exposed to X-rays were diffracted into 2θ for sample C1 and approximately 70% for sample C2. The narrower rocking curves (See Figure 1, for C2) and topographs indicating a larger diffraction area for sample C2 suggests it has significantly less mechanically induced strain than sample C1. For that reason, C2 was installed on the SLC line.

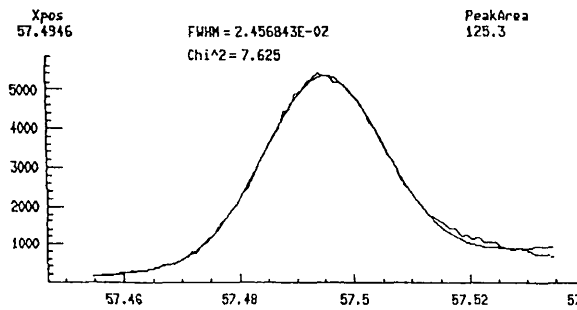

Figure 1: Rocking curve for C_2. Abscissa in degree.

3.1.2 γ-ray diffractometry

The Stuttgart γ-diffractometer set-up (Figure 2) is based on the radioactive γ-radiation source ^{137} Cs. This source provides us with monoenergetic γ radiation of an energy of 661.7 keV corresponding to a photon wavelength of 0.0187 $\AA$. The radiation of the source is collimated. The beam size (vertically 5mm and horizontally adjustable between 0.5 mm and 1.0 mm) is defined by the last collimator in front of the sample, 5 m downstream of the source. The sample is mounted on a goniometer that can be adjusted by means of a computer-controlled stepping motor. The rotation steps of the sample can be as small as 0.001 degree. The sample can also be moved in directions perpendicular to that of the beam. The radiation detector is situated 5 m downstream of the sample. This is a BGO crystal, optically coupled to a photomultiplier tube. The horizontal position of the detector is adjustable in a direction perpendicular to that of the beam. Exactly in the beam position, a narrow laser beam makes an accurate adjustment of the sample with the detector. The FWHM of the resolution function of the γ-diffractometer is about 0.011 degree. The results of the γ-diffractometer measurements provide us with volume averaged quantities for the beam spot size through the entire thickness of the sample, in contrast to the results obtained from traditional X-ray equipments where only the near-surface regions can be studied. The rocking curve method provides us with the real mosaic-distribution function directly, independently of any model considerations.

The γ-Diffractometry results showed, for the same crystal, a rather good mosaicity (0.02 to 0.03 degree FWHM). That corresponds to the smaller FWHM value obtained by X-rays (0.0245 degree).

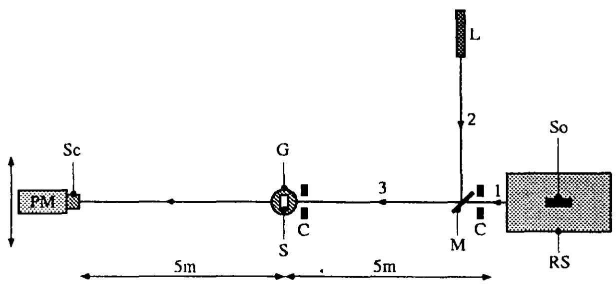

Figure 2: The Stuttgart γ -diffractometer set-up. So: ^{137}Cs radioactive source, RS: radiation shield, C: collimators, L: laser light source, M: mirror, G: goniometer, S: sample, Sc: BGO scintillator, PM: photomultiplier, 1: γ beam, 2: laser light, 3: γ beam and laser light.

3.2 The experimental set-up

The C2 tungsten crystal was installed in the converter region, in front of the SLC positron source. In order to avoid degradation of the incident beam and hence of the positron yield, a limitation on the crystal thickness was considered; a 0.3 mm thickness appeared to be the maximum tolerable value. Henceforth, the 1 mm thick crystal has not been installed. The diameter of the beam pipe is 25 mm. There is an aluminium window of 0.6 mm thickness situated 50 cm upstream of the e^+ target. The C2 crystal has a diameter of about 10 mm. It is held between two thin metallic rings. On the exit side of the crystal an aluminium screen is fixed and allows vizualisation of the electron beam spot hitting the crystal. The ensemble is mounted in the air, directly on the beam pipe. A camera is installed behind a shielding a few metres apart from the ensemble holding the crystal and the screen. The incident beam has an energy of 29.5 GeV and the total spot area on the crystal is estimated to be 6.2 mm^2. Two current transformers (TORO175 and TORO376) are used to measure the electron beam intensity. Beam position monitors are installed close to the beam current transformers. The aluminium oxide screen downstream of C2 is graduated and allows control of the beam spot on the C2 crystal (See Figure 3).

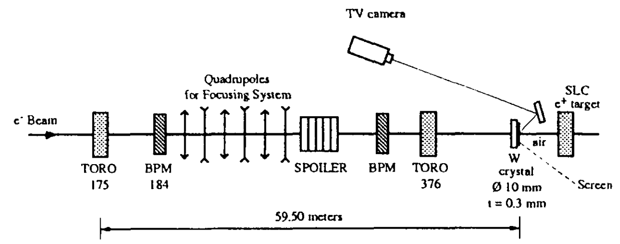

Figure 3: The SLC experimental set-up

3.3 *Irradiation*

The C2 crystal was kept in the primary electron beam between January and June 1996. At the end of this irradiation period and after one day of shutdown the radiation level was 1rad/h at 2 cm from the crystal. During the first month the electron beam repetition rate was 10 Hz and 30 Hz with an average intensity of $2.5\times 10^{10}e^-/pulse$. For the remaining period, the repetition rate was 100 Hz on the average. At the end of the irradiation period, the integrated intensity was $1.2\times 10^{19}e^-$. Therefore, the total electron flux experienced by the sample C2 is, for the total irradiated area, $2\times 10^{18}e^-$ /mm^2.

3.4 *Analysis by γ-diffractometry*

The results of the analysis are represented on Figure 4, for the irradiated part of the crystal. Mosaic distribution of the non irradiated part showed similar results as on figure 4. In both cases, FWHM values are almost identical (0.03 degree) and equal to the value obtained on the sample before irradiation. Moreover, this value corresponds, almost, to the usual mosaicity of the tungsten crystals after crystal growth.

4 SUMMARY AND CONCLUSIONS

The test of radiation damage made with the SLC electron beam at a comparable fluence as in the BNL test showed no detectable damage on the irradiated sample. Such a fluence corresponds to about a hundred hours of working conditions of LC projects as the CLIC or NLC. Some preliminary conclusions can, then, be drawn:

- use of monocrystals as positron sources with the known operating conditions of the LC projects (CLIC, NLC, JLC) does not present any precluding condition related to radiation damage.
- to go further than this encouraging result it should be highly desirable to repeat such test at much higher fluence in order to determine the threshold level.

Furthermore, the annealing process, which has not be taken into consideration, is expected to improve the crystal target lifetime in case of damage.

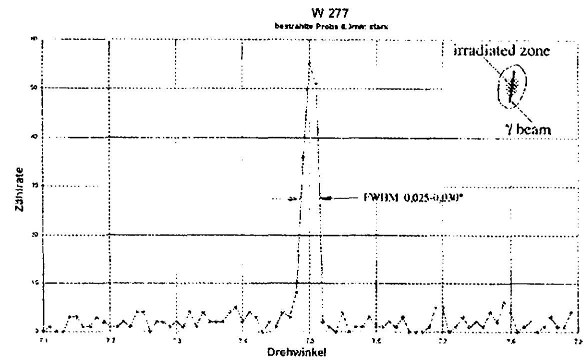

Figure 4: Mosaic distribution function of sample C2 obtained by γ-diffractometry. The γ beam is on the irradiated zone.

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