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Experimental study of a crystal positron source ☆

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Abstract

Tungsten crystals oriented on their ⟨111⟩ axis, were submitted to 6 and 10 GeV electron beams on the SPS-CERN transfer lines. The crystals, 4 and 8 mm thick, used alone or associated to 4 mm thick amorphous disk, were studied as positron sources. The emerging positrons were detected by a Drift Chamber partially immersed in a magnetic field, where their trajectories were reconstructed providing the energy spectrum and the angular distribution. Significant enhancements were observed for the crystal source when compared to the amorphous one of the same thickness. The gain was larger than 3 and 2 for the 4 mm and 8 mm targets, respectively. The presented results look very promising for e^+e^- linear colliders.

Keywords: Channeling; Positrons; Crystals; Drift chamber

1. Introduction

In order to achieve high luminosities at the interaction point of a linear collider, very powerful positron sources with high intensity and low emittance are required. Conventional sources, using positron generation with a high intensity electron beam impinging on a thick amorphous target with high Z, could be optimised for that purpose [1,2] as demonstrated with the SLAC Linear Collider (SLC). However, the large energy deposition in thick targets induces serious heating problems leading to mechanical stresses and tar-

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get failure; moreover, multiple scattering contributes to positron emittance worsening.

The target thickness can be substantially reduced if we start with photons produced by some independent device—hereafter called *radiator*—instead of obtaining them via bremsstrahlung from electrons in the target itself. Evidently, lower emittance and energy deposition would be provided by a thinner target. The gain may be especially large if the spectrum of the radiator is concentrated within the interval of some tens of MeV in contrast with the broad bremsstrahlung spectrum. This photon energy interval seems to be the most efficient in producing positrons of energies acceptable by the existing accelerator matching systems.

The radiator could be a magnetic undulator as proposed, first, for the VLEPP project [3] and considered now for the superconducting linear collider TESLA [4]. Note that the electron beam used in such undulators should be of rather high energy ($E >$ 200 GeV) in order to generate photons of some tens of MeV. This is because the period of the undulator cannot be done small enough ($\sim$ 1 cm for currently used devices).

An alternative way consists in replacing the magnetic undulator by an aligned single crystal. Here the characteristic period of motion in the collective field of the atomic strings or planes is typically of the micrometer size. Then electrons of only a few GeV can produce the photons in the interesting range. When aligned to some axial or planar direction, the incoming electron or photon interacts coherently with a set of the ordered atoms. This leads to the significant enhancement of the rates of the basic QED processes (radiation and pair production) as compared to the amorphous medium where they are due to the interaction with individual atoms. The physics of these phenomena has been well understood, calculated and proved experimentally (see, e.g., [5] and [6]). Here axial alignment will be considered. Then the coherent pair production occurs in the strong field of atomic strings if the photon energy is above a threshold of about 20 GeV for a tungsten crystal. In our case the incident electron energies of a few GeV are assumed. We shall be, therefore, below the threshold energy for the coherent pair production and only ordinary Bethe–Heitler pair production occurs. Nevertheless, the positron source using a crystal will have a greater efficiency, due to the more efficient production of intermediate photons [7]. For our conditions, we have the enhancement of the spectrum in the interesting range of photon energies as well as of the total intensity of the emitted radiation. The latter leads to shortening of the radiation length. For example, when 5 GeV electrons are aligned with $\langle 111 \rangle$ axis of a tungsten crystal, the radiation length is 3.5 times shorter [8] than for the amorphous tungsten.

Crystal radiators can be used as a part of a compound target. Such a solution using Si and Ge radiators followed by an amorphous tungsten converter, was described, first, in [9]. One may also use an all-crystal target. In this case the initial part plays the role of the radiator. For the energies under consideration, the remaining part of the crystal target works as an amorphous one. Strictly speaking, we do not have two quite separated parts, the radiator and the photon-to-positron converter, as in the magnetic undulator solution. However, the main advantages (lower energy deposition, lower multiple scattering) are still present, due to the enhancements mentioned above. Owing to the reduction of the radiation length, the optimal thickness of a crystal radiator turns out to be smaller than X_0, whereas for an amorphous radiator this thickness is of several X_0.

Detailed theoretical investigation of the shower formation in a crystal have been performed in Refs. [8, 10] where spectral and angular distributions of photons and positrons as well as the energy deposition have been calculated. In these papers, the dependence of the shower characteristics on the target thickness and the kind of the crystal have been obtained in a wide range of the initial electron energy. Note that the event generator used for simulation in our experiment is based on formulas given in [8].

A first experimental investigation of the problem was concerning the study of a tungsten crystal axially oriented on its $\langle 111 \rangle$ axis and working as a photon generator when submitted to an incident electron beam of 1 to 2 GeV [11,12]. Such experiment was undertaken at Orsay in 1992–1993. The results showed photon generation enhancement on the crystal axis, with respect to the random position by a factor 2, using a 2 GeV beam. Later, a japanese team realised an experiment in Tokyo at 1.2 GeV and reported enhancements in photon and positron production with a W crystal [13]. These experiments were continued at KEK at different energies (3 and 8 GeV) [14] and confirmed the gain brought by this method. Very recently, an experiment (WA103) has been carried out at CERN by our collaboration aiming to measure the characteristics of the positron beam generated in a crystal target [15,16]. We are presenting, hereafter, the preliminary results obtained in this experiment. Some indications resulting from a test made at SLAC on the radiation resistance of the crystal will also be presented.

2. The experimental set-up

The experiment used tertiary electron beams of the SPS having energies between 5 and 40 GeV. The electrons after passing through profile monitors (delay chambers) and counters impinge on the targets. Photons as well as e^+e^- pairs are produced in these targets. These particles come mainly in the forward direction and travel across the magnetic spectrometer consisting of the drift chamber and positron counters inserted between the poles of a magnet. The photons and most energetic charged particles leave the spectrometer nearly in the forward direction. Then, the charged ones are swept by a second magnet while the photons reach the photon detector made of preshower and calorimeter.

2.1. The set-up (see Fig. 1)

The beam. The SPS tertiary electron beam is made of almost 99% of electrons. The number of electrons was of some thousands in a burst.

The trigger. The channeling condition requires that the incident electron angle on the target be smaller than the Lindhard critical angle $\Psi = \sqrt{2.U/E}$, where U represents the potential well depth of an atomic row and E the incident energy. In order to fulfill it, we installed a trigger system made of scintillation counters for which the vetos had holes of 20 and 3 mm separated by a distance of 16 meters. The trigger selection is improved by the informations provided by the delay chamber (off line). The informations allow a better definition of the incident trajectory. For 10 GeV and $\langle 111 \rangle$ axis of the tungsten crystal the critical angle is of 0.45 mrad. Taking into account the presence of crystal effects at angles larger than the critical angle, the acceptance angle for the trigger has been set to 0.75 mrad. In these conditions, the trigger efficiency is about 1%.

Targets. Four kinds of W targets have been installed on a 0.001 degree precision goniometer:

- a 4 mm thick crystal;
- a 8 mm thick crystal;
- a compound target made of 4 mm crystal followed by 4 mm thick amorphous disk;
- a 20 mm thick amorphous disk. This disk was used to check the reconstruction efficiency with a similar number of positrons as for the 8 mm crystal.

The mosaic spreads of the crystals measured by γ-diffractometry are less than 0.5 mrad.

The positron detector. The drift Chamber is made of hexagonal cells filled with a gas mixture He(90%); CH4(10%) and presents two parts:

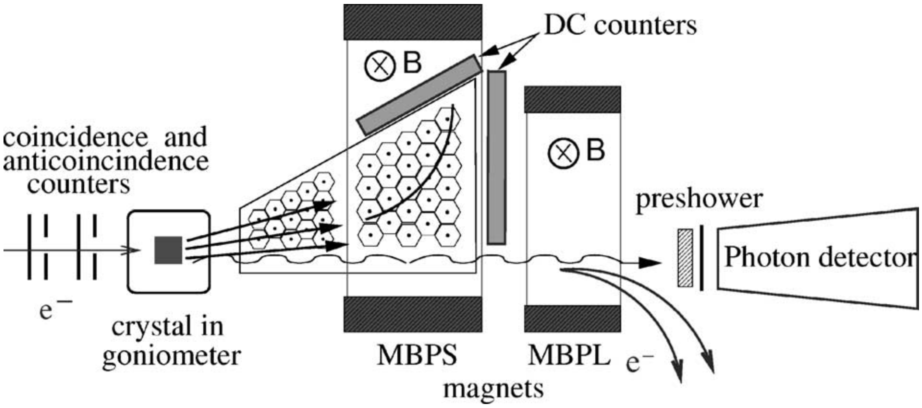


Fig. 1. The experimental set-up.

- the first part, with a cell radius of 0.9 cm is mainly outside the magnetic field of the bending magnet. It allows the measurement of the exit angle of the positron;
- the second part, with a cell radius of 1.6 cm, is submitted to the magnetic field. It allows the measurement of the positron momentum. Two values of the magnetic field were used: 1 and 4 kGauss, in order to investigate the whole energy region of interest, from 5 to 100 MeV.

Signal and field wires are short (6 cm) and made of gold-plated tungsten and titanium, respectively. The drift chamber exhibits 21 layers and the resolution is of 300 micrometers. The maximum horizontal angle being accepted is 30 degrees. The limited vertical size sets the vertical acceptance of the chamber to $\pm 1.5°$. The choice of Helium provides a small multiple scattering. Counters are placed on two sides of the drift chamber. The first one is on the lateral side of the chamber and the other on the front side. Low energy positrons are more likely bent towards the side positron counter for the two values of the magnetic field, considered. The signal provided by the side counter gives a rather good indication on the low energy positron yield.

The electronics. For drift time measurements, the electronics detects the leading edge of the signal coming from the sense wire and digitize the time with 3 ns resolution. Front end electronics is made of preamplifier, shaper and ECL discriminator. The TDC (Time to Digital converter) has a scale range of 1.5 microseconds. A common stop is used.

The photon detector. Photon multiplicity is rather high: about 200 photons/event for a 8 mm thick crystal oriented along its $\langle 111 \rangle$ axis. The photon detector is made of:

- a preshower made of copper disks (0.2 X_0 thick) and scintillators. The copper disks, 3 and 6 cms diameter, have been used successively to look at the number of photons and to their angular distribution;
- a "spaghetti" calorimeter with thin scintillation fibers, giving the amount of radiated energy [17].

3. The reconstruction procedure [18]

A template method for the track reconstruction was chosen. Sets of reference tracks corresponding to positrons and electrons with energies $E_i^\pm$ from 5 MeV to 150 MeV (step 1 MeV) and angles $\theta_k^\pm$ from $-5°$ to $35°$ (step $0.5°$) originated from the target center were calculated using GEANT for both values of magnetic field. The trajectories in the DC were parametrised by 9-degree polynomial $y(x)$ and the coefficients were stored in the database. For each event the reconstruction program makes the maps of the functions L_0 and L_2 representing the distance between the simulated reference tracks of known initial angle and energy and the hited wires of the DC. It calculates the values L_0 and L_2 for each track of positron or electron with energy $E_i^\pm$ and angle $\theta_k^\pm$ using the following formulae:

$$L_0\left(E_i^\pm, \theta_k^\pm\right) = \frac{1}{N_1 + N_2} \sum_n^{N_1+N_2} \exp\left(-\frac{|d_n - r_n|}{\lambda}\right), \tag{1}$$

$$L_2\left(E_i^\pm, \theta_k^\pm\right) = \frac{1}{N_2} \sum_n^{N_2} \exp\left(-\frac{|d_n - r_n|}{\lambda}\right), \tag{2}$$

where indexes 1 and 2 mean DC1 (part of the DC outside of the magnetic pole) or DC2 (part of the DC inside of the magnetic pole), N—number of hited wires, $\lambda = 1$ cm—coefficient characterizing the dimension of the DC cells, d_n—distance between the track $(E_i^\pm, \theta_k^\pm)$ and the nth wire, r_n—the radius calculated from TDC value of the nth wire. The values L_0 are used for the tracks with $\theta_k^\pm > \theta_{\lim} = 5°$ and L_2—for others. For tracks with $\theta_k^\pm < \theta_{\lim}$, the information from the DC1 is difficult to use due to its acceptance. Peaks on the maps $L_{0/2}(E_i^\pm, \theta_k^\pm)$ correspond to the real tracks and, therefore, the local maxima are taken for the further analysis as candidates for the good tracks, which should satisfy also to number and quality of the hited wires, which belong to them. The search of the good tracks starts from the largest local maximum.

4. The results

The experimental results presented here for a 10 GeV incident electron beam were obtained using the following procedure:

- Selection criteria, taking into account cuts on reconstructed track angle and energy and on the presence

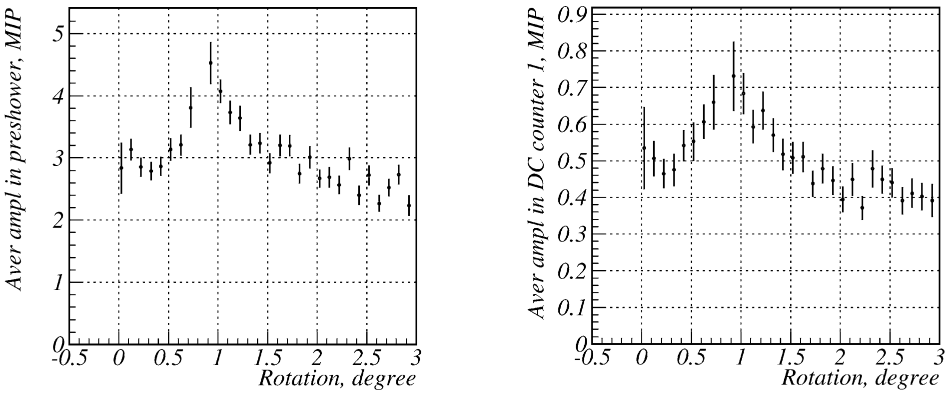
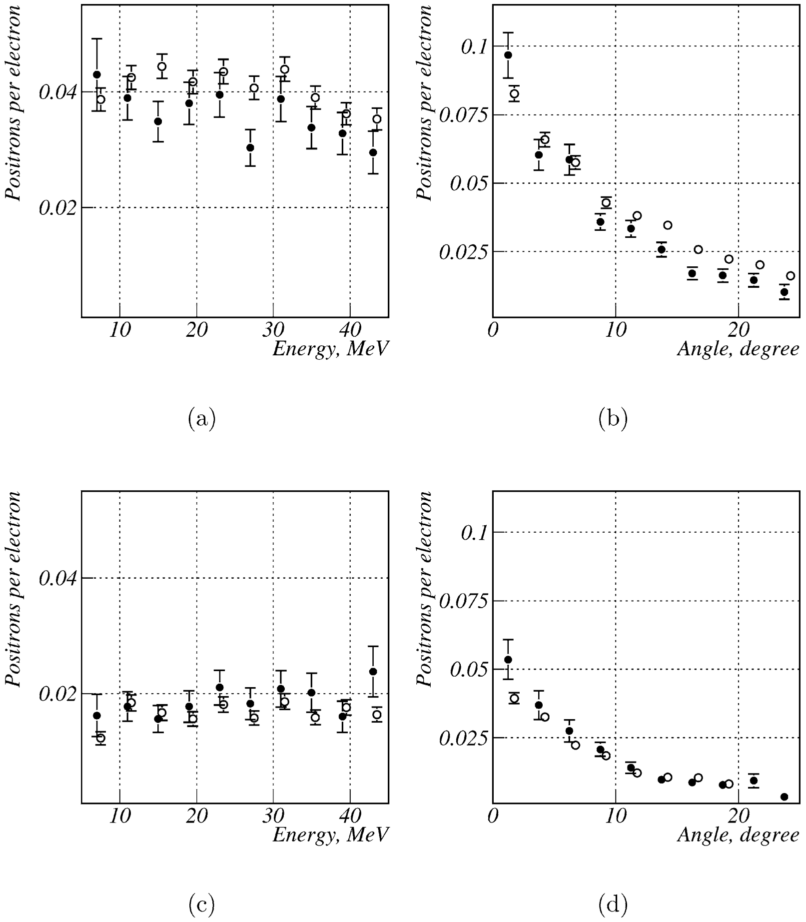


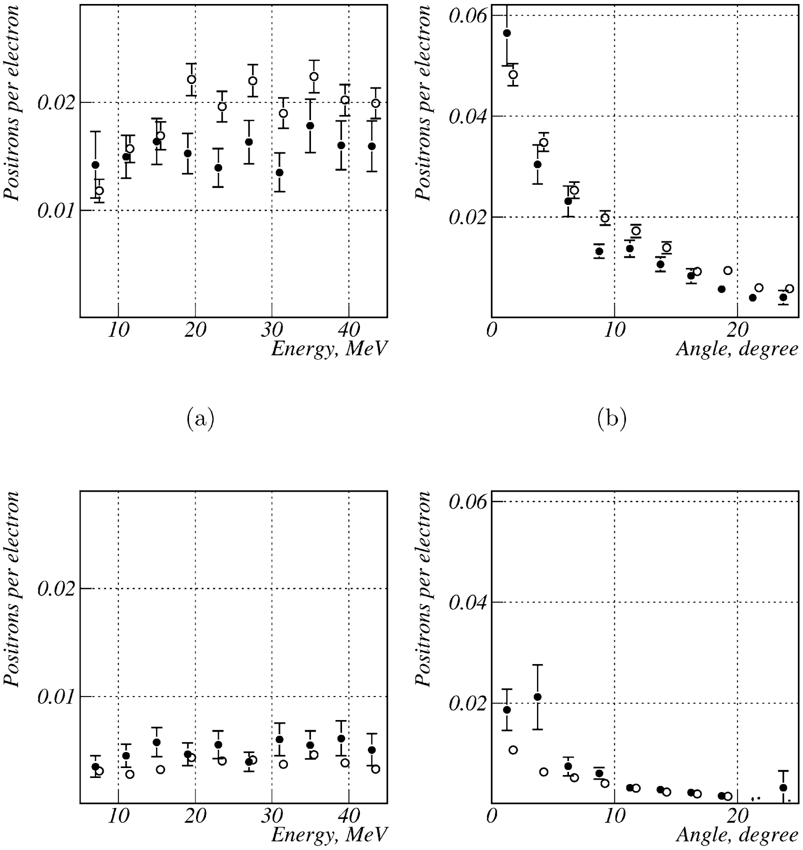
Fig. 2. Rocking curves for the Preshower (photons) and DC1 counter (positrons).



(a) (b)

(c) (d)

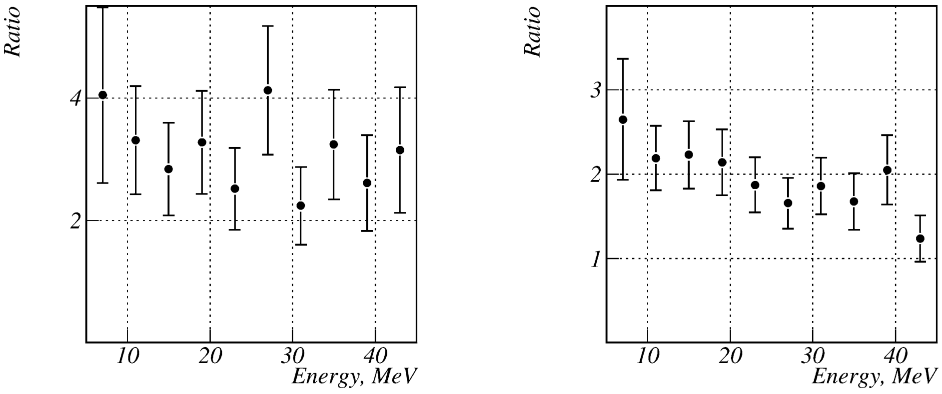
Fig. 3. Energy and horizontal angular distributions. 8 mm crystal (a), (b) and amorphous (c), (d) targets: simulation (open circles) and experiment (black points).



(a) (b)

(c) (d)

Fig. 4. Energy and horizontal angular distributions. 4 mm crystal (a), (b) and amorphous (c), (d) targets: simulation (open circles) and experiment (black points).



(a) (b)

Fig. 5. Ratio crystal/amorphous for 4 (a) and 8 mm (b) targets.

of a signal in the positron counters, were applied to the reconstructed events.
- Positron registration efficiency was determined using the simulations. Such efficiency value is needed to evaluate the actual yield at the target exit.

The simulation programme used involves two parts:

- An event generator [8] taking into account the crystal effects in the target.
- A full description of the detector using GEANT code configuration. The results on positrons presented hereafter are, henceforth, taking into account the reconstruction efficiency. They correspond to the limited angular acceptance described above.

Enhancement in photon production. On the $\langle 111 \rangle$ axis of the tungsten crystal, the ultrarelativistic electrons radiate more photons than by conventional bremsstrahlung. The preshower provides the relative photon multiplicity with respect to the crystal orientation. Correspondingly, the positron yield is enhanced on $\langle 111 \rangle$ axis orientation. We report on Fig. 2, the associated rocking curves for the preshower and the positron counter placed on the lateral side of the drift chamber.

Enhancement in positron production. The energy spectra and horizontal angular distributions are presented on Fig. 3 for crystal and amorphous targets 8 mm thick. Simulations and experimental data are presented on the same picture. A good agreement is noticeable between them. If we compare the crystal and amorphous targets an enhancement slightly larger than a factor 2 is obtained for the oriented crystal. We precise that the amorphous target corresponds to the crystal in random orientation.

The same kind of presentation is operated on Fig. 4 for the 4 mm targets. The enhancement for the 4 mm crystal with respect to the amorphous target of the same thickness, is larger than 3. The dependence of the enhancement on positron energy is shown on Fig. 5 for both crystals.

5. Some specific features of the crystal sources

5.1. Effect of the heating on the crystal source performances

As recalled in the introduction and confirmed by the experimental results, the thickness of a crystal converter is much less than the equivalent amorphous converter giving the same number of produced positrons. That is why, the energy deposited in crystal converters is less than in equivalent amorphous converters. However, this deposited energy leads to heating which could affect the crystal performance. The following calculations have been done:

- the energy deposited in the crystal has been calculated as for an amorphous target;
- the crystal heating has been calculated taking into account the actual intensity which can be expected in a linear collider configuration. The case of JLC (10 GeV; $5 \times 10^{11}\,e^-$/pulse) was chosen for a 8 mm tungsten crystal and for the compound target (4 mm crystal followed by 4 mm amorphous). The deposited energy per pulse was about 37 Joules;
- the increase of the thermal vibration amplitude in the crystal has been calculated and, correspondingly, the diminution of the crystal potential well depth. The positron yield has, then, been calculated with the modified characteristics of the crystal.

In these conditions, the heating effect led to the lowering of the positron yield by an amount of 15–20%, for the 8 mm crystal, and of 10%, for the compound target when the temperature grows from the ambient to 600 degrees Celsius [19].

5.2. Radiation damage

The radiation damage in the crystal, caused mainly by Coulomb scattering of the electron beam on the nuclei, has been evaluated and an experiment has been worked out at SLAC [20]. A tungsten crystal, 0.3 mm thick and orientated in a random direction, was placed in the converter region of SLC. It received, during six months, an integrated flux of e^- (fluence) of $2 \times 10^{18}\,e^-/\text{mm}^2$. The crystal has been analysed before and after irradiation by X and γ diffractometry. No damages were observed; the mosaic spread (0.4 mrad) remained unchanged. Further tests with higher fluences, in order to determine the damage threshold, are under discussion.

6. Summary and conclusions

The preliminary results on positron production using axially oriented tungsten crystals, with incident electron beams of 10 GeV, show an enhancement in photon and positron yields with respect to amorphous targets of the same thickness. They are in good agreement with the simulations. More precisely, they show enhancements, for the positron yields, which are larger than 3 for 4 mm targets and more than 2 for 8 mm targets. A large number of low energy positrons is obtained with the crystals: that gives additional interest to this process as low energy positrons (some MeV to some tens of MeV) are more likely captured by the known positron matching systems. These results are very promising for a high intensity positron source. A complete analysis of the data gathered during the runs for the 6 and 10 GeV incident energies is underway.

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