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Experimental study of a positron source using channeling

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Abstract

Many simulations have predicted that the yield of positrons, resulting from the interaction of fast electrons in a solid target, increases if the target is a crystal oriented with a major axis parallel to the electron beam. Tests made at Orsay and Tokyo confirmed these expectations. The experiment associated to this proposal concerns the determination of the main characteristics (emittance, energy spread) of a crystal positron source which could replace advantageously the conventional positron converters foreseen in some linear collider projects. The informations expected from this experiment will allow consistent predictions concerning the behaviour of such positron sources.

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[1] Spokesman
[2] Contactman

1 Introduction

The use of a crystal target as a converter instead of an amorphous one presents a very promising alternative way for the production of positron beams [1]. The regular atomic structure of the crystal provides conditions for various kinds of collective and coherent effects. One of them is electron channeling along the crystal axis. If the incident high energy electron has an angle, with respect to the crystal atomic chains, smaller than the Lindhard angle,

$$\Psi_c = \sqrt{\frac{2U}{Eo}} \tag{1}$$

where U represents the potential well for the chosen crystal axis and Eo is the incident electron energy, the trajectory is quasi periodic around the atomic string, and looks like in a magnetic wiggler. In tungsten, U $\sim 10^3$eV and $\Psi_c \sim 0.5$ mrad. At angles larger than the Lindhard angle, but typically smaller than one degree, crystal effects are still present due to coherent interactions with the successive atoms of the same row and with neighbouring atomic rows/planes (coherent bremsstrahlung). In both cases the electrons radiate a larger number of soft photons than in an amorphous target. These photons are converted into electron-positron pairs following the standard way (for photon energies above several GeV, coherent effects may also be at work). A crystal target has a series of advantages over a conventional one: the positron yield per initial electron is significantly increased. Alternatively, for the same positron yield it is possible to use an incident electron beam of lower energy and/or a thinner target, which decreases the thermal effects [2].
This proposal concerns an experimental determination of the characteristics (emittance, energy distribution) of a crystal positron source; such an investigation is necessary prior to the choice of a crystal target as a positron source for a linear collider. The principle of this experiment has been approved by the Scientific Council of LAL, in december 96. Final approval of the projet, with financial support, followed the obtention of external support for the russian and ukrainian participants (INTAS Contract).

2 Present situation

The method of positron production through materialization of the intense flux of photons generated in a crystal under channeling conditions has been proposed, for the first time at the 1989 Particle Accelerator Conference (Chicago, March 1989), by some of the participants. Since that time theoretical investigations and intensive simulations with high statistics (using parallel computers) have been worked out and different kinds of crystals with various orientations were considered. Up to now, two experiments have been devoted to crystal converters:

(a) A "proof of principle" experiment, at 2 GeV incident energy with a 1 mm tungsten crystal oriented along its $< 111 >$ axis, has been conducted at the Orsay linear accelerator by part of the team members of this project. The data gathered in this experiment confirmed the theoretical predictions and simulations showing an enhancement factor, between 2 and 3, for the photon yield (see figure 1) [3].

(b) Recently, experiments with tungsten crystals oriented along their $< 100 >$ axis have been undertaken at the Tokyo University with a 1.2 GeV electron beam. The yields for the photons as for the collected positrons showed enhancement factors larger than 2 with respect to the amorphous targets of the same thickness. Analysis of the results showed that most of the photons were generated by coherent bremsstrahlung [4]. The specific measurements on the positron yield brought additionnal confirmation of the interest in using crystals as converters.

These two experiments have been operated at relatively low energy (≤ 2 GeV). On the other hand crystal effects are more effective at higher energies, therefore it is necessary to make an experiment at significantly higher energy. More generally, if experimental results confirmed the theoretical expectations on photon generation and pair production in crystals no experimental data concerning the needed description of the transverse phase space, in shower developments, is available.

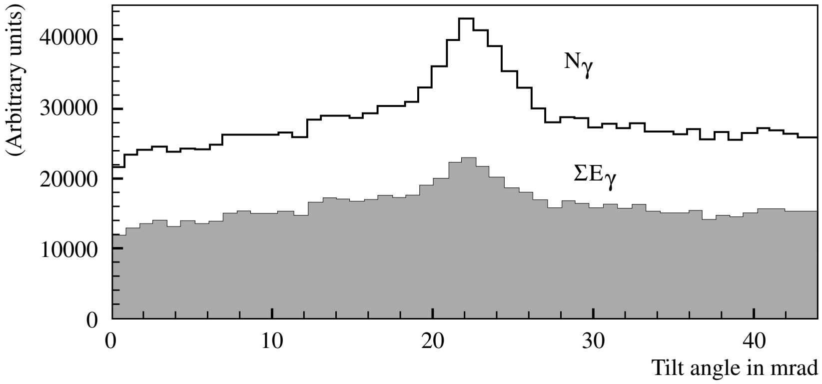

Figure 1: *Photon yield and radiated energy from a 1mm thick tungsten crystal versus tilt angle between* $< 111 >$ *axis and electron beam for an incident energy of 2 GeV (Arbitrary units) [3].*

Henceforth, a precise determination of the positron beam emittance from a crystal target is needed. Such information, when provided by our experiment, will allow the optimization of the matching system (magnetic lenses put after the converter and before the accelerator to match the positron emittance to the accelerator acceptance). Similarly, the actual energy spectrum will be measured by our apparatus, allowing to set the energy acceptance limits of the future matching system in which the positrons should be captured. The proposed experiment will lead to a relevant description of this kind of sources which are very promising for the future linear colliders.

3 Experimental programme

3.1 The programme

The experiment foreseen in the SPS transfer lines (CERN) will use tertiary electron beams produced after two targets: the first one is a Beryllium target 400 mm thick on which the impinging 450 GeV protons create pions (90%) and electrons (10%). The second one is a lead target 4 mm thick from which an almost pure electron beam is coming out. The electrons arrive to the hall from the transfer line of the SPS with an energy of 10 GeV, pass through beam profile monitors and collimating counters and impinge on the crystal target, mounted on a goniometer. Photons as well as e^+e^- pairs are produced in this target. Secondary particles from the target come in the forward direction mainly, and enter partially in the magnetic spectrometer, consisting of the drift chamber and positron counters inserted between the poles of a spectrometer magnet MBPS (1 meter long) (see figure 2). The most energetic photons and charged particles come out nearly in the forward direction. The charged particles are swept by a second magnet of the type MBPS or MBPL (2 meters long), after which the photons reach a detector called the Forward Photon Detector: when wide open this one will nearly measure the total photon energy; when tightly collimated it will measure single photon energy spectra, at various exit angles.

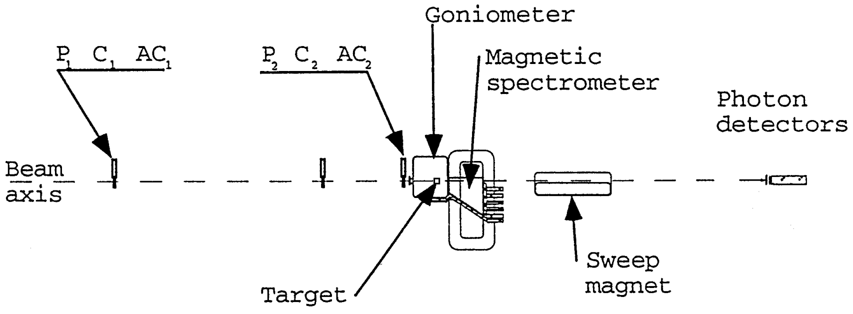

Figure 2: *Set-up lay-out.* C_1C_2 *- coincidence counters, fixing the beam particles;* AC_1, AC_2 *- anticoincidence counters for the beam collimation;* P_1P_2 *- the beam profile monitors.*

Additionally, the forward photon detector will be useful to optimise the crystal orientation. Secondary charged particles (electrons and positrons) of not too high energy coming from the target enter the magnetic spectrometer which consists in a Drift Chamber and positron counters in the field of the first magnet (see figure 3).

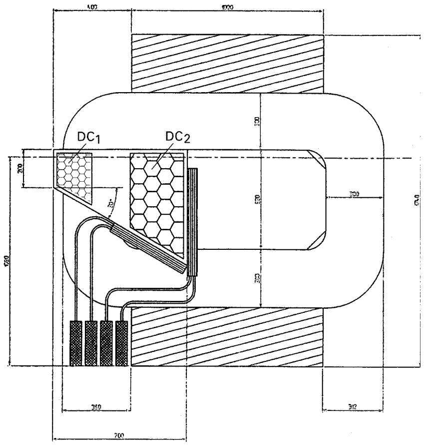

Figure 3: *The magnetic spectrometer.*

Being asymmetrical, this spectrometer will be dedicated to measure the positrons (instead of the electrons). The Drift Chamber is wired vertically, parallel to the magnetic field. The chamber consists of two independent parts DC1 and DC2 residing in common gas volume. DC1 is placed before the magnetic field, whereas DC2 is in the region of uniform magnetic field. The vertex and exit angle of the charged particles coming from the target are to be measured by DC1, while DC2 measures the particle momenta. To be able to cover all momenta range of interest two experimental runs with different magnetic field strengths in the first magnet, of 1.0 and 4.0 kGauss should be carried out. The data gathered by the Drift Chamber will lead to the knowledge of the phase space associated to the crystal assisted positron sources. That should determine the usable positron yield after any matching system, given the energy acceptance and transverse phase space admittance of the latter. Conversely, an optimization of the matching system could derive from those informations.

The parameters of the experiment have been considered fo an incident electron energy of 10 GeV. This energy corresponds to the maximum energy foreseen in the Linear Collider projects for the electron linac dedicated to positron production. An extension to higher incident energies, in our experiment, where enhancement of pair production is expected, represents an interesting opportunity to get a quantitative verification. A measurement at 40 GeV can be considered without any changement in the set-up. We present, on figure 4, the variation of the positron yield with the incident energy, using the targets of our experiment. For the sake of comparison, the total yield as the accepted yield in usual linear collider conditions are represented.

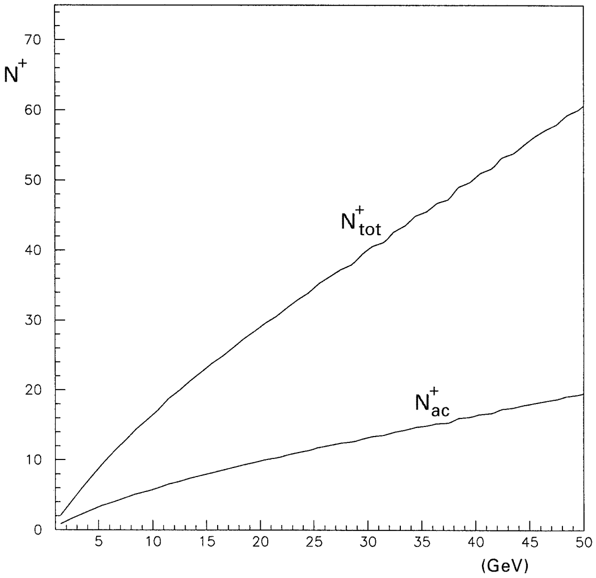

Figure 4: *Total and accepted positron yields vs incident electron energy for an hybrid target 0.4 cm* $< 111 >$ *+ 0.4 cm (amorphous).*

3.2 The simulations

In the simulations the main interaction processes are taken into account [1]. The distributions of the number of electrons and positrons coming from the 8 mm crystal target, per incident electron, are shown on figure 5. The average numbers of positrons and electrons are respectively 18 and 22 , i.e., 40 charged particles per event. In the Drift Chamber the histograms of the number of charged tracks is shown on figure 6. The mean number of tracks in DC1 is about 5, 90% of the events having less than 10 tracks. The distribution of tracks in DC2 depends on the magnetic field strength. The track multiplicity distributions for 1 and 4 kGauss are shown on figures 6b, 6c. On the average the number of tracks expected in DC2 is also about 5 per incident electron. From the histograms of the sum of the lengths of all tracks we have derived the number of hit wires, which is about 100 per event, in the whole chamber.

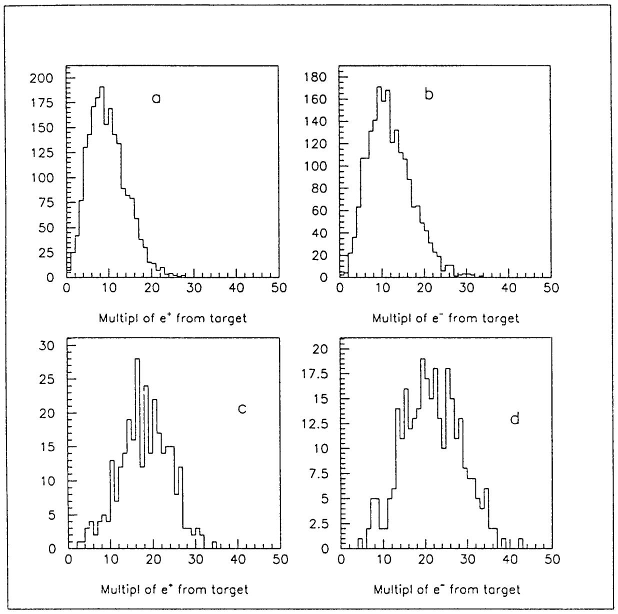

Figure 5: *Multiplicity for* e^+/e^- *coming from the target per incident* e^- : $a - e^+$ *from an amorphous target, b-*e^- *from an amorphous target,* $c - e^+$ *from a crystal target,* $d - e^-$ *from a crystal target.*

4 The experimental set-up

4.1 The incident beam

The channeling experiment will be located on the transfer lines X5/X7 of the SPS. The available number of electrons is of $5.10^3 - 10^4$ per burst of 2.5 seconds with a repetition rate of 14.4 seconds. Beam emittance corresponds to 6 mm radius and 0.5 mrad divergence at the reference focus. The electron profile is monitored with standard multiwire proportionnal chambers (MWPC). However, to satisfy the requirement on channeling condition, the electron beam divergence should be less than the Lindhard angle: $\theta o \sim 0.5$ mrad at 10 GeV. Plastic scintillation counters with 2 mm diameter holes in their center and separated by 5 meters, acting as collimators, ensure a beam divergence of about 0.4 mrad. Two coincidence counters are placed before the collimating anticoincidence counters. As a matter of fact, crystal effects extend to more than 2-3 critical angles. Therefore a wider collimator with larger aperture, for instance up to 1.2 mrad or 3 times the critical angle, can

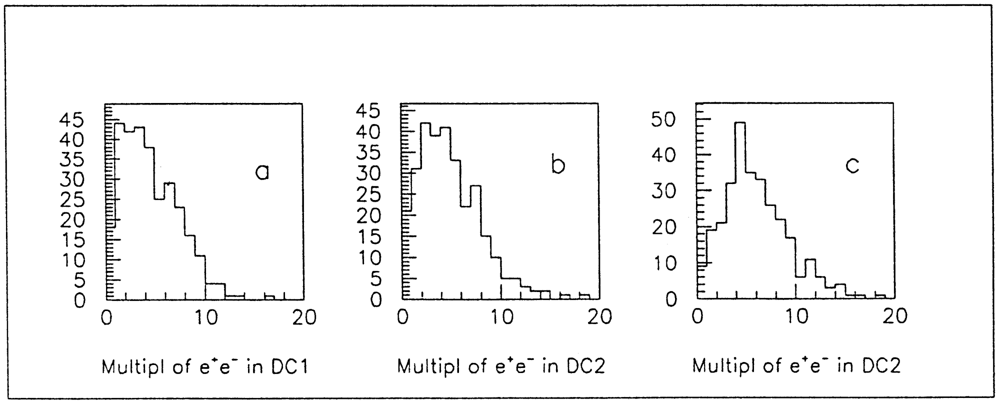

Figure 6: *Charged track multiplicity in drift chambers; a -DC1; b - DC2, B=1kGauss; c - DC2, B=4kGauss.*

be considered. It could be made of two 6 mm collimators located 5 meters apart. Many of these elements are already present on the SPS transfer lines.

4.2 The Targets

Two tungsten targets will be exposed to the beam: one "all crystal", 8 mm thick and the other "hybrid" with a 4 mm crystal followed by a 4 mm amorphous. Both targets should have a diameter of 7–8 mm in transverse dimension. The mosaic spread of the crystals will be controlled by gamma – diffractometry; it must be less than half of Lindhard angle (0.2 mrad for a 10 GeV incident electron beam). These crystals will be provided by march 99 by the Max-Planck Institute fur Metallforschung (Stuttgart). These two targets will be placed on a precision two-axis goniometer (with angular accuracy of 0.001 degree). By translation of the goniometer one can switch from one target to the other or let the direct beam go through.

4.3 The Magnets

Two magnets are used in the Set-up. A magnet for the spectrometer creates a vertical magnetic field in the region of the drift chamber; that allows the determination of the particle momentum by measuring the track curvature. A sweeping magnet, placed behind the spectrometer magnet, will deflect the high energy charged particles from forward direction in order to provide clean condition for registration of the photons.

The magnet for the spectrometer, which is available from the CERN equipment and suitable for the experiment , is of the type MBPS. We require a maximum magnetic field of 0.4 Tesla in the volume defined by an horizontal aperture of 42 cm, with a length of 100 cm along the beam and a gap of 14 cm.

The sweeping magnet, which is also available, is of the same type: MBPS or MBPL.

Its characteristics are suited to deflect the charged particles with momenta of 10 GeV from the photon detectors located at a distance of about 5 m from the magnet. At higher energy, 40 GeV, corresponding to a foreseen extension, the particles should also be deflected away from the photon detector. The requested strength is therefore: BL= 1.8 Tesla-meter.

4.4 The positron detector

We have chosen a positron detector consisting of a drift chamber partially inserted in a magnetic field and positron counters (scintillators) located on two exit faces of the Drift Chamber and defining the working region (with a good resolution) [5]. In order to reduce the influence of multiple scattering the chamber is filled with helium, like the goniometer chamber.A thin mylar foil is separating the two vessels. At the field of 0.1 Tesla, positron tracks with momenta from 5 to 20 MeV can be registered. The same track geometry can be obtained for positron momenta from 20 to 80 MeV at the field of 0.4 Tesla. Hence, using only two values of magnetic field, one could cover an interesting momentum range. All the wires are oriented along the magnetic field. Their length is $\sim$ 6 cm while the "working" length is $\sim$ 4 cm as defined by the vertical size of positron counters, located outside the drift chamber. The two parts of the Drift Chamber (DC1 and DC2) have a similar hexagonal structure with a cell radius of 1 cm in DC1 and 1.5 cm in DC2. Anode wires are made of gold-plated tungsten with diameter of 20 μm. Field shaping wires are made of titanium with diameter of 100 μm. The total number of signal wires is about 400. The total number of field shaping and guard wires is 900. The gas mixture consisting of He with 10% CH_4 is chosen in order to minimize the multiple scattering. The coordinates of the track are measured by drift time with an expected coordinate resolution better than 200 μm.

4.5 The positron counters

Placed on two exit faces of the Drift Chamber, they define the useful solid angle and serve also for the generation of the "start" signal as for the fast control of the positron yield.

4.6 Detector Resolution

The results of the calculations could be summarized as follows: a calculated resolution of 2.8% on a positron momentum of 30 MeV/c can be obtained using a magnetic field of 1 kGauss. The corresponding coordinate resolution is of 0.5 mm. For a 16 points/track curve the resolution on positron emittance is better than 0.5 mm x MeV/c. Obviously the resolution can be improved with a larger number of points per track; a value of 30 points can be reached easily.

4.7 Acceptance of the detection system

Due to the restriction on the useful aperture of the detector, so as to keep a good resolution, an acceptance of 3% is expected. That corresponds to an approximative rate of one hundred positrons in the burst which can be registered by the positron detector.

4.8 Electronics

A set of standard CAMAC modules is sufficient for our experimental purpose. The maximum number of analog to digital channels over all the detection system which is considered is the following: 400 TDC for the Drift Chamber, 10 ADC for the counters and calorimeters. The first level (fast) trigger is based on several controlled coincidence schemes. The second level trigger is based on software.

4.9 The Forward Photon Detector

The photon multiplicity is expected to be about 50 per incident electron. To observe these photons from each event and measure their integrated intensity (total energy) we will use a Forward Photon Detector (FPD), made of NaI crystals (11x11x45 cm^3). This detector will also serve for crystal alignment. The single photon spectrum will be measured using a sharp collimation of the direct photon beam so as to reduce the probability of a two-photon pile-up to 1%. The corresponding angular aperture of the collimator should then be less than 2 mrad. The total photonic energy is obtained with a cone of 10 mrad half aperture.

5 Requested conditions

5.1 Requested beam time

The requested beam time on the X5 or X7 transfer lines of the SPS West Hall is of six weeks divided in two parts:

- a week devoted to the beam studies, comprising the calibration of the detectors,
- five weeks of data taking mainly on the nominal energy of 10 GeV for the e- secondary beam with a verification at 40 GeV; these five weeks should not be consecutive but separated by some days in between.

Both X5 and X7 are suitable for our experiment, but the X7 line is already equipped with two pairs of filament scanners (FISC) that allows to measure directly the beam divergence. The preferred period of the year for our experiment is between april and august 2000.

5.2 Requested Manpower from CERN

Technical help from CERN should be greatly appreciated on the following items:

- installation on the beam line,
- magnetic field measurements on the MBPS/MBPL magnets used in our experiment,
- use of the standard beam monitors in order to control the beam qualities.

6 Division of tasks

- LAL-Orsay has been involved since many years in Accelerator Physics and for one of the partipants (R.C.) in positron source research and development (LAL and LEP positron sources).

The tasks allocated to LAL team are:

- general coordination of the project,
- work on detector lay-out in connection with IPN-Lyon, CERN and BINP,
- beam optics,
- acquisition electronics,

- care on goniometer installation,
- analysis of the results.

The persons involved are: Robert Chehab, Christophe Sylvia and a PhD student in the near future. Technical divisions (Mechanics and Electronics) are involved in the new realizations or modifications on existing apparatus.

- IPN-Lyon has a very large experience on channeling. The physicists involved in this project participated to many important experiences in the field, in particular at CERN.

The tasks allocated to this team are:

- general conception of the experiment,
- control of the goniometer,
- supervision of the acquisition,
- analysis of the results.

The persons involved are: Xavier Artru, Michel Chevallier, Robert Kirsch, Jean-Claude Poizat, Joseph Remillieux, Denis Dauvergne, Philippe Lautesse.

- IPN-Orsay: Alain Jejcic has contributed since the beginning to the simulations on crystal targets. His contribution is expected on this field.
- BINP-Novosibirsk involves:

- the theoretical group headed by Vladimir Baier (with V. Katkov and V. Strakhovenko) they will participate in the analysis of the results,
- the experimental group headed by Serguei Serednyakov (with A. Bukin, T. Dimova, V. Druzhinin, M. Dubrovin, V. Golubev, V. Shary). Possible participation of young physicists (M. Achasov, A. Vasiljev, K. Beloborodov and A. Zakharov) will be considered. This group has been working on SND experiment on VEPP-2M and has a large and interesting experience on Particle Detectors.

The tasks allocated are:

- set-up performance simulation,
- design and construction of the Drift Chamber,
- test of the Drift Chamber with the first stage of the Electronics provided by LAL-Orsay,
- preparation of the Data Acquisition System,
- analysis of the results.

- KIPT-Kharkov has a long experience in channeling experiments. Among the participants, Nikolai Maslov was the first to propose the method which will be used in this experiment; such method has been tested with success in Kharkov and Tokyo. The task of this group concerns the photon detection: Forward Photon Detector and photon collimation. The participants are: Nikolai Maslov, Vasilij Kulibaba, Georgij Bochek, Alexandre Starodubtsev.

- NPI-Tomsk has also experience in channeling. The three participants (A. Potylitsin, I. Vnukov and A. Bogdanov) will work on the photon detection in association with the KIPT group.
- The Max-Planck Institute fur Metallforschung team (J. Major, P. Keppler, X. Hanes and O. Kormann) will provide the monocrystals manufacturing and tests. The high quality of their tungsten crystals represents a guarantee for this project.

7 Remarks on the radiation damages

The use of crystals as positron converters in linear colliders, where high intensity beams are required, depends for a large part on their long-term resistance to radiation damages. Estimation as well as experiments have been concerned with this problem. A damage test has been operated on a tungsten crystal submitted to the SLC beam, upstream of the positron converter. A 30 GeV electron beam irradiated the crystal during a six-month exposure. The total fluence represented 2.10^{18} e^-/mm^2, corresponding to a hundred hours of working conditions of a collider like the Japanese Linear Collider. After analysis by Gamma-Diffractometry (at MPI-Stuttgart), no damage was found [6].

8 Conclusions

Many simulations have predicted the enhancement of the positron yield in crystal targets due to the high rate of photons produced by a high energy electron in channeling conditions. A proof of principle, done at Orsay 5 years ago confirmed these predictions for a 2 GeV electron beam. Tests made in Japan, at 1.2 GeV, brought more direct confirmation on this effect. The experiment foreseen at CERN with a 10 GeV electron beam and with a crystal of appropriate thickness should bring a necessary knowledge of the positron beam phase space created in a crystal. These informations are necessary prior to propose this promising source for use in a linear collider.

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