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Positron sources using channeling: A promising device for linear colliders

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Summary. — The need of intense and bright positron sources for linear colliders has urged the researches on polarized and unpolarized positrons. For 20 years, continuous theoretical and experimental investigations on unpolarized positron sources using axially channelled electrons in aligned monocrystals have pointed to efficient solutions concerning not only the source intensity, but also the minimization of the deposited energy. Simulations using the channelling programme of V. Strakhovenko associated to GEANT4, provided a description of such sources composed of tungsten crystals as photon radiators and amorphous tungsten as converters, the so-called hybrid source; the incident electron energies are taken between 5 and 10 GeV. Here, some applications are shown for CLIC, for which this source is the baseline, and also for ILC. The simulations are also concerning the test at KEK of such hybrid source, with a sweeping magnet separating the crystal radiator and an amorphous converter. Future developments on the simulation programme are also reported. The main issues for such sources are also analyzed.

PACS 29.20.Ej – Linear accelerators.
PACS 29.25.-t – Particle sources and targets.
PACS 61.80.-x – Physical radiation effects, radiation damage.
PACS 61.85.+p – Channeling phenomena (blocking, energy loss, etc.).

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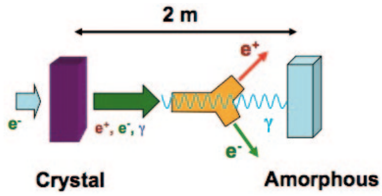

Fig. 1. – The hybrid target scheme.

1. – Introduction

There are strong requirements for high intensity, low-emittance positron beams for future linear colliders. In order to reach such goal, intense incident electron beams on positron converters have first been considered. Such choice has heavy consequences on the accelerator wakefields and, more importantly, as far as the parameters of CLIC and ILC are concerned, leads to inadmissibly large deposited power and energy density, causing serious thermal and radioactivity problems.

In conventional positron sources, e^-e^+ pairs are produced by bremsstrahlung photons emitted by incident electrons in an amorphous target which serves also as a converter. However, it is known (see, *e.g.*, [1]) that axially aligned crystals are much better radiators than the amorphous ones. For example, the effective radiation length for 8 GeV electron beam aligned with the $\langle 111 \rangle$ axis of a tungsten crystal is of 0.61 mm only (cf. with 3.5 mm for the amorphous tungsten). Another important feature of the crystal radiator is a substantial increase in the number of relatively soft photons, which leads to the enhancement of the positron yield as compared with the amorphous radiator. The idea of substituting, in a positron source, an axially aligned crystal target with an amorphous one was presented more than twenty years ago [2]. Experimental confirmation of the promising positron yields expected with this method has been worked out at CERN in experiment WA 103 [3-5] and in KEK [6, 7]. Tungsten crystals with all the shower processes (radiation and pair production) as well as combined targets with a crystal radiator (W, Si, Ge, C(d)) and amorphous converter were studied and experimented. Further progress is related to the idea of separating the crystal radiator from the amorphous converter by some distance allowing the use of a sweeping magnet in between to get off the charged particle coming from the crystal. With only photons impinging on the amophous target, it is possible to strongly reduce the energy deposition in the converter leading to a reasonable amount of deposited power and also to a peak energy deposition density (PEDD) below the limit (35 J/g, for the tungsten) providing a long-term stable work of the source. This choice led to a new kind of a positron source, named the *hybrid target*.

2. – The hybrid target

A typical scheme for the hybrid target is presented in fig. 1. The crystal radiator is a thin tungsten crystal with a thickness between 1 and 2 mm. Such value resulted to be optimum for incident electron beams of some GeV. Only the photons are impinging on the amorphous converter. Transverse incident beam dimensions as the distance radiator-converter are chosen in order to keep a high enough accepted yield and to lower the PEDD in the converter.

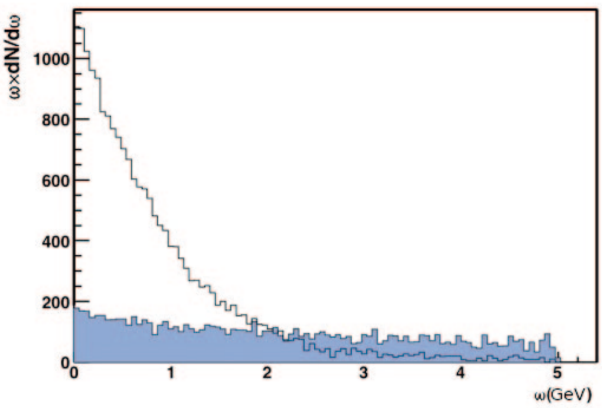

Fig. 2. – Photon energy spectrum for a 5 GeV electron beam and 1.4 mm target. In dark, the distribution associated to the bremsstrahlung photons.

3. – The problem of PEDD

After the breaking of the SLC positron target, analyses and tests have been carried out at SLAC, LLNL and LANL in order to find out the critical issues for the positron amorphous target. Critical energy density as well as timescales of the different phenomena occurring when an intense energetic pulse is impinging on a solid target have been determined [8, 9]. It appeared that:

– the tolerable value of PEDD for tungsten targets is about 35 J/g;

– the timescale associated with the thermal shock wave is about some μs.

However, much deeper studies need to be developed in order to get even more precision on these values. Nevertheless, these results are helpful as a starting basis for target preservation.

4. – Simulation results

The simulations have been worked out using a) a dedicated simulation program for crystal-assisted radiation under quasi-channeling at axial alignment provided by V. Strakhovenko and b) GEANT4 which takes into account all the shower processes. In this code we have also introduced electric and magnetic fields to calculate the accepted yields in the matching systems.

4·1. *The case of CLIC* [10-12]. – We consider an incident energy of 5 GeV, a crystal thickness of 1.4 mm, a converter thickness of 10 mm and a distance radiator-converter of 2 meters.

It is interesting to observe the photon spectrum provided by the crystal radiator and to compare it to that of an amorphous converter of the same thickness: that would be the case when the crystal is in random orientation with respect to the beam direction. We can see in fig. 2, for which the vertical axis has been scaled in $\omega \mathrm{d}N/\mathrm{d}\omega$, that the bremsstrahlung has an almost constant behavior due to its $1/\omega$ shape. Moreover, the crystal radiator is presenting much more soft photons than the amorphous. The total and

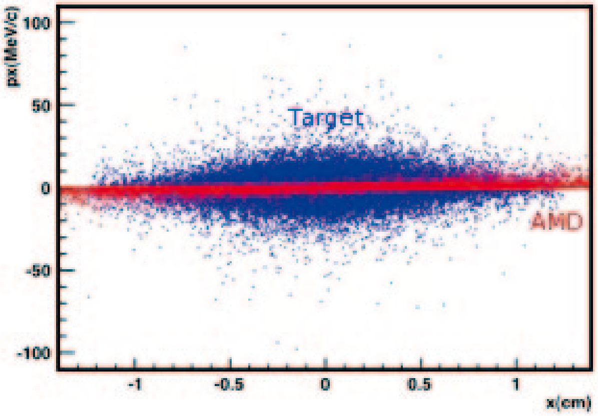

Fig. 3. – The positron beam emittance at the target and at the end of the AMD.

accepted yields have been determined. The accepted yield is depending on the Optical Matching Device (OMD) chosen. Here, we use the so-called *Adiabatic Matching Device* which has an axial magnetic field tapering adiabatically (with conservation of the action integral) from a maximum value (6 tesla) to a minimum value (0.5 tesla) on a length L for which we considered two values: 20 and 50 cm. The positron pre-accelerator after the OMD is a 2 GHz structure. In such conditions, the total yield at the converter is about 8 e^+/e^- and the accepted yield with that matching system is of 2.2 e^+/e^-. After 200 MeV acceleration that yield is about 0.8 e^+/e^-.

Concerning the PEDD, we calculated the quantity in the crystal and in the amorphous converter considering an incident electron beam of $2.34 \cdot 10^{12}$ e^-/pulse (with 50 Hz repetition) and an incident electron beam size of 2.5 mm rms radius. We obtained a PEDD of 1.15 GeV/cm^3/e^- in the amorphous and 0.35 GeV/cm^3/e^- in the crystal. That brings with the CLIC intensity 22 J/g in the amorphous and 6.8 J/g in the crystal. These values are well below the limit of 35 J/g. Henceforth, only one target system is needed. Such result led to the choice of the hybrid target as the baseline solution.

We present in fig. 3 the positron beam emittance at the target and at the end of the matching system (AMD). In fig. 4 the energy deposition density in the amorphous converter is shown. The elementary volume is 0.25 mm^3 leading to a maximum of deposited energy density of 1.15 GeV/cm^3/e^-.

4˙2. *The case of ILC* [13]. – The very high pulse intensity ($5 \cdot 10^{13}$ e^-/pulse) foreseen for ILC precludes the use of a solid target in the beam. If we want to use a hybrid target, we have two choices:

a) to use a multiple target system or b) to transform the nominal ILC pulse before the target into a series of micropulses with much less charge in each of them and with a separation between them allowing enough relaxation time for the thermal shock wave and easy stacking in the Damping Ring. The latter choice is kept. Two different ways (fig. 5) to realize it are considered: the 300 Hz solution with 20 pulses of 0.99 μs separated by 3.3 ms proposed by T. Omori (KEK) shown on fig. 5a and the 45 kHz solution with 44 pulses of 22.14 μs separated by 11 μs proposed by A. Variola (LAL) shown in fig. 5b.

We have chosen the following parameters for the ILC hybrid source: a target thickness of 1 mm for the crystal and 8 mm for the amorphous; an electron incident energy of 10 GeV and a distance of 2 meters between the radiator and the converter.

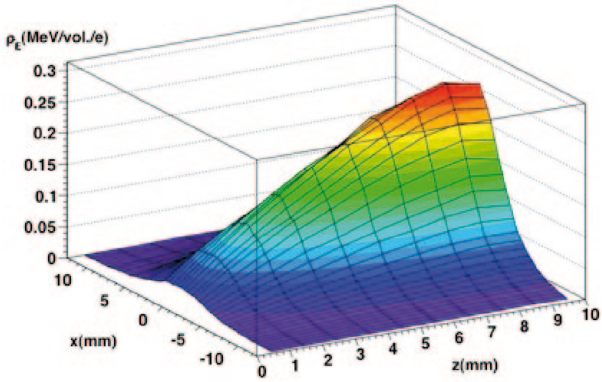

Fig. 4. – Energy deposition density in the 10 mm thick amorphous converter.

The results of the simulations have given the following values:

– Yield, 13.4 e^+/e^- at the converter exit and 4.7 e^+/e^- at the end of the matching device (the same as for CLIC); after 150 MeV acceleration in an *L*-band structure (1.3 GHz) the accepted yield is about 2.9 e^+/e^-.

– PEDD, the simulated values for the PEDD give, for an incident electron beam size of 2.5 mm rms radius, 44 J/g for the 300 Hz solution and 20 J/g for the 45 kHz solution. In fig. 6, the energy deposition density per incident e^- in $GeV/cm^3/e^-$ is shown.

4·3. *Test of a hybrid source at KEK* [14]. – Simulations have been made for the tests of a hybrid positron source on KEKB linac. The characteristics of the test were the following: an incident electron energy of 8 GeV with rms beam sizes of $\sigma_x = 0.26$ mm, $\sigma_y = 0.91$ mm, a W crystal thickness of 1 mm, an amorphous W thickness of 8 mm and a distance radiator-converter of 3.4 meters.

Results on the emitted photons at the crystal exit and on the positrons at the converter exit are represented in fig. 7. The photon energy distribution at the crystal exit is represented in fig. 7a, the total number of photons above 2 MeV is 17 γ/e^-. The positron energy distribution is represented on fig. 7b. The total yield is 9.9 e^+/e^-. Both results come from V. Strakhovenko's crystal simulations.

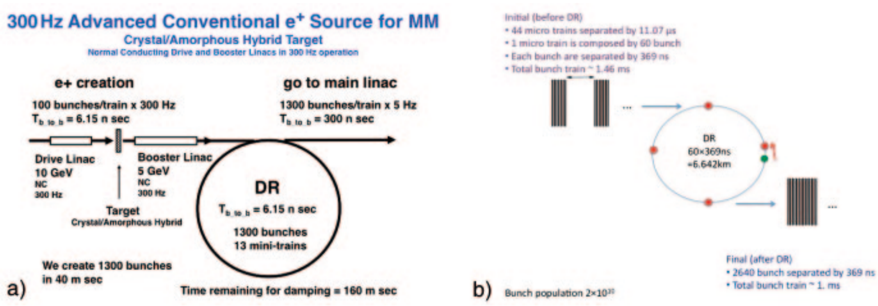

Fig. 5. – Transformation of ILC pulse: (a) 300 Hz solution, (b) 45 kHz solution.

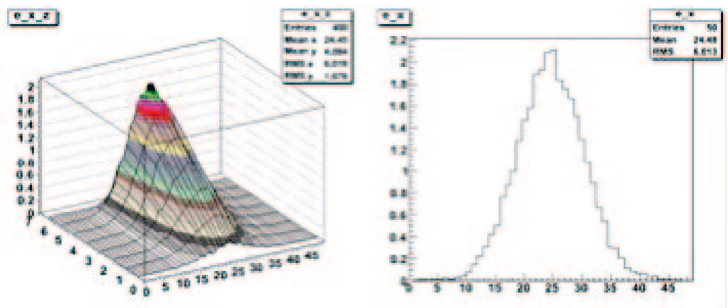

Fig. 6. – Energy deposition density in the 8 mm converter for ILC: vertical scale in $\mathrm{GeV/cm^3/e^-}$. On the left side, the density in the plane (x, y); on the right side, a cut at the exit of the target.

5. – Recent developments on the simulation program

A simulation code, in Fortran (FOT), describing crystal effects was written in the 1980's [15] and used to simulate the first proposal [2]. This code has been often successfully tested. However, though very precise, this program was extremely time consuming. In order to simulate a very large number of cases for our experiment WA 103 at CERN, we used another program written by V. Strakhovenko (VMS). With the goal of adding new functionalities to the simulation program, FOT was first converted into C++ and used as an event generator for GEANT4 also written in C++. This new package (G4Fot) has been compared to Strakhovenko's program and showed satisfactory agreement. We present in fig. 8 the compared results in photon energy distribution for the two programs.

6. – The main issues for the hybrid source

One of the main issues for the e^+ source is related to the beam power deposition and target breakdowns. The intense scattering of the charged shower components on the atoms of both targets may affect the qualities of the hybrid source.

Concerning the crystal target, radiation damages are occurring by elastic collisions of the shower components on the nuclei. If the recoil energy $T = Q^2/M$ (Q, transfer momentum and M, nucleus mass) is above some threshold E_d (about 25 eV for W), the nucleus is dislodged from its lattice. For T larger than $2E_\mathrm{d}$, the primary nucleus can

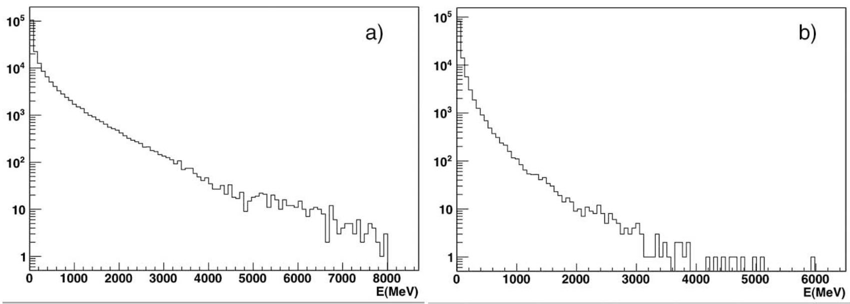

Fig. 7. – Photon (a) and positron (b) energy distributions for the hybrid source test.

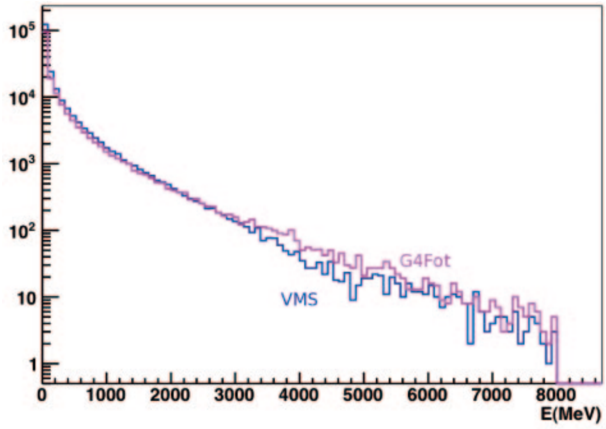

Fig. 8. – Comparison of the two programs for photon energy distribution, the corresponding simulation programs are indicated near to the curves.

initiate a cascade of displacements among neighbouring nuclei. An evaluation has been done for incident electron beams and different crystals (W, Si, Ge, C(d)-diamond) [16]. The maximum fluence was found between 10^{19} and 10^{21} particles/cm^2. An experiment done at SLAC in 1996 on the SLC target location, with a thin W crystal, showed that a fluence of $2 \cdot 10^{20}\,e^-/cm^2$ did not affect the nominal mosaic spread [17]. For CLIC, the fluence is $4 \cdot 10^{14}\,e^-/cm^2/s$ for a 2.5 mm rms beam radius. So, it needs 140 hours to reach the fluence measured at SLAC. If we assume that the critical fluence would be an order of magnitude higher, it represents a thousand working hours. Annealing can be used to eventually recover the crystal qualities.

Heating of the crystal makes the thermal vibration amplitude larger and affecting, henceforth, the available potential on the axis. This potential has been parameterized [18] and simulations have been done for rather thick crystals [19]. As the temperature is increasing in the crystal, the available potential decreases and the same happens for the photon yield. This effect is limited for thin crystal targets. For instance, for CLIC, the deposited energy in the crystal is rather low (12.5 MeV/e^- for a 1.4 mm crystal with a 5 GeV beam) that gives less than 0.25 kW deposited and consequences on the yield are not expected.

The instantaneous and inhomogeneous energy deposition density in the converter is leading to intolerable mechanical stresses; such density should be less than 35 J/g, in the case of tungsten [9]. For instance, for the parameters chosen for CLIC, the PEDD in the crystal is less than 7 J/g, which represents 20% of the maximum limit. As far as the amorphous target is concerned, a large amount of power is deposited. Two are the expected consequences: i) on the average heating for which an appropriate cooling system is to be designed; ii) on the instantaneous heating.

7. – Conclusions

The hybrid positron source using channeling presents promising features:

– the accepted yield is within the required values for CLIC and ILC;

– the amount of total deposited power and PEDD in the crystal radiator and in the amorphous converter provides a long-term stable work of the positron source.

Such a system has already been chosen for the CLIC baseline source; for ILC, a pulse length modification is needed to lower the amount of e^-/pulse and hence, the thermal shock wave. Now, two schemes are under study.

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