EXPERIMENTAL STUDIES OF POSITRON SOURCES USING MULTI-GEV CHANNELLED ELECTRONS AT CERN[a] AND KEK[b]

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Abstract: Enhancements of photon production by multi-GeV electrons moving along the axes of aligned crystals are used to generate high yields of positrons in the same crystals or in amorphous disks put after the crystals. The experiment WA103 used tungsten crystals oriented along their <111> axis, alone or followed by tungsten amorphous disks. The incident electron energy was chosen between 5 and 40 GeV and mainly used at 6 and 10 GeV. Photon as positron production enhanced by channeling and coherent bremsstrahlung have been measured with photon and positron detectors. The positron detector consisted in a drift chamber immersed in a magnetic field and presenting rather large momentum and horizontal angle acceptances of 150 MeV/c and 30°, respectively.The KEK experiment on the KEKB injector used 8 GeV incident electron beam and different kinds of crystals. Tungsten crystals and more recently Silicon and Diamond crystals have been used. The measurements concerned the positrons.The results gathered on both experiments are presented and commented.

Key words: Channeling, Coherent Bremsstrahlung, Crystals, Photons, Positrons, Drift Chamber

1. INTRODUCTION

Achievement of high luminosities at the interaction point of a e^+e^- linear collider requires high intensity and low emittance beams. Concerning the positrons, conventional sources use high intensity electron beams impinging on thick amorphous targets with high atomic number. As a consequence, a large energy deposition induces important heating problems leading to mechanical stresses and target failure. Moreover, multiple Coulomb scattering occurring in the thick target leads to large emittance positron beams.

The reduction of the overall target thickness is obtained through the generation of a high number of photons- much higher than with ordinary bremsstrahlung- which are, then, materialized in thin targets. These photon generators –hereafter called radiators- could be magnetic undulators, as first proposed by V.Balakin and A.Mikhailichenko [1] or "atomic" undulators like oriented crystals [2]. The latter has been studied theoretically and experimentally since many years [3, 4, 5, 6]. Proof of principle and experiments were ran out in Europe and Japan [7, 8, 9, 10, 11, 12] with different crystals and various incident electron energies.

We report here, on the experiment WA103 carried out at CERN on the X-5 transfer line of the SPS. The crystal chosen was tungsten and the incident energies were between 5 and 40 GeV with the main measurements at 6 and 10 GeV, which correspond to the chosen values for the incident energies of NLC (Next Linear Collider) and JLC (Japanese Linear Collider), respectively. The results gathered at KEK on the KEKB linac are also reported. They concern Tungsten, Silicon and Diamond crystals. Some emphasis will be put on the latters.

2. WA103 EXPERIMENT

2-1 Experimental set-up

The experiment WA103 is using tertiary electron beams of the SPS having energies between 5 and 40 GeV. The electrons, after passing through profile monitors (delay chambers) and trigger counters, impinge on targets installed on a goniometer. Photons as well as e+e- pairs are produced in the targets, come mainly in the forward direction and travel across the magnetic spectrometer made of a drift chamber and positron counters (see figure1).The photons and high energy electrons and positrons come out in the forward direction. The charged particles are swept by a second magnet (MBPL) while the photons reach the photon detector made of a preshower and a calorimeter.

The beam: the electron pulses of 3.2/5.2 seconds duration and with periods of 14.4/16.8 seconds have intensities of ~ 10^4 electrons/pulse. Two energies have been particularly used: 6 and 10 GeV. The channelling condition requires that the incident electron angle be smaller than $\Psi = \sqrt{(2U/E)}$, where U represents the depth of the potential well of an atomic row and E, the electron energy. At 10 GeV and for the <111> orientation of the tungsten crystal, this angle is 0.45 mrad. As crystal effects are lasting slightly above this critical angle, we gave to the trigger system, made of scintillation counters (see figure 1), an angular aperture of 0.75 mrad. The trigger selection is improved by the informations provided by the proportional delay chamber (off line selection).

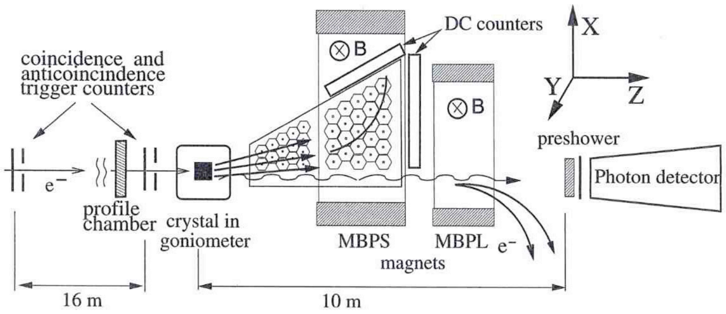

Figure 1 : WA 103 set-up

The targets: four kinds of targets have been used:

- 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,
- an amorphous disk 20 mm thick

The mosaic spread of the crystals was measured by γ-diffractometry and was less than 500 μrad.

Photon detector: the photon multiplicity is rather high ~ 200 γ/event at 10 GeV for a 8 mm crystal oriented on its <111> axis. The detector is made of:

- a preshower (0.2 Xo thick Copper disk and a scintillator) gives information on photon multiplicity. It is used for crystal alignment.
- a spaghetti calorimeter [13] with thin scintillation fibers gives the amount of radiated energy. Preshower and calorimeter are in close contact.

Positron detector: it consists in a drift chamber with hexagonal cells, filled with a gas mixture {He(90%);CH4(10%)} and positron scintillation counters. It presents two parts:

- the first part (DC_1) with a cell radius of 0.9 cm, located mainly outside the magnetic field. It allows the measurement of the exit angle.
- The second part (DC_2) with a cell radius of 1.6 cm is immersed in the magnetic field. It allows the measurement of the positron (electron) momentum. Two values of the magnetic field are used: 1 and 4 kGauss in order to investigate the whole momentum region of interest, up to 150 MeV/c.

The wires are parallel to the magnetic field. The available space in the bending magnet (MBPS) is restricted vertically to 6 cm. In order to avoid border effects of the metallic walls of the chamber, the useful part of the wires is limited to a central part of 3 cm defined by the dimensions of positron counters put on lateral and back sides of the chamber (see figure

1).That sets the angular acceptances, vertically to ± 1.5° and horizontally to 30°. The overall acceptance represents 6 % of 2π solid angle. Achieved coordinate resolution is about 500 μm leading to momentum and angle resolutions of 0.6 MeV/c and 0.25°, respectively.
Reconstruction; positron (electron) tracks are reconstructed in the drift chamber. Signals are coming from hitted wires ; each hit is represented by a circle centered on the hitted wire and which radius is proportional to the drift time. The reconstruction procedure assigns 3 parameters to each track : the e+ or e- trajectory, projected on the horizontal plane is parametrised as a circle with the 3 parameters: *r,*the circle radius; (xc, zc) the coordinates of the circle centre. A track is determined by a minimum of 3 hitted wires. To find a good compromise between the number of fake tracks (reconstructed but not real) and the lost tracks(real tracks not reconstructed) a minimum of 10 as number of hitted wires has been defined for the track selection. In these conditions a reconstruction efficiency of 80% has been verified for the worst case (amorphous target 20 mm thick and 10 GeV).

2-2 Results

Reconstructed trajectories: an example of reconstructed trajectory, is given on figure 2. It concerns a crystal 8 mm thick and an incident energy of 6 GeV.

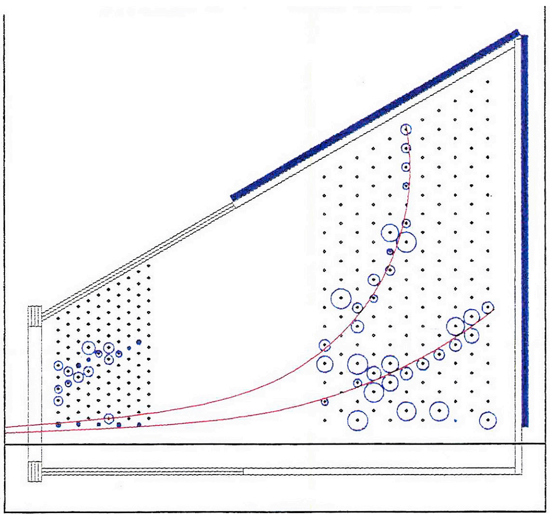

Figure 2: Reconstructed trajectories for 8 mm thick crystal and 6 GeV.

Photon measurement: the preshower gives the average photon multiplicity in a forward cone. On figure 3, we compare the measurements with the simulations for a 4 mm crystal and an incident energy of 6 GeV.

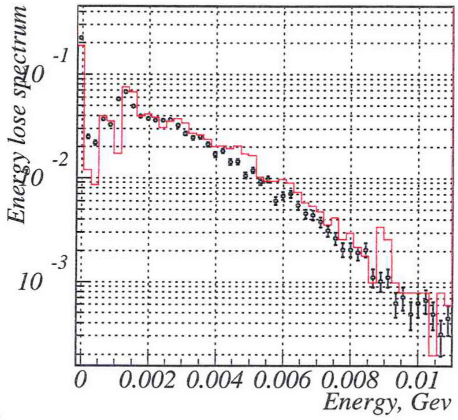

Figure 3: Signal from the preshower for 4 mm thick crystal and 6 GeV

Positron measurement: energy spectrum and angular distributions have been measured for all the targets and comparisons carried out between crystal and amorphous targets of the same thickness. In the latter case, the crystal was in full random orientation.

(a) amorphous target 20 mm thick; this measurement was important for two reasons:
- to test our reconstruction programme in the "worst case", i.e. with maximum occupancy in the chamber (at 10 GeV incident energy),
- to make valuable comparisons between simulations and experiment, particularly with GEANT and also to compare the simulations from GEANT to those of an original programme [14]

The results are conclusive as we can see on figure 4 where both kinds of simulations are compared to the experiment for the angular distribution in the "worst case".

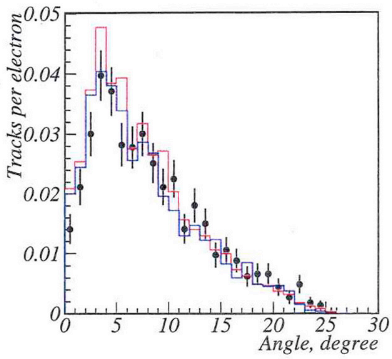

Figure 4: Angular distributions (simulations and experiment) for 20 mm crystal and 10 GeV Points: experiment. Histograms: simulations; blue: SGC, red: GEANT

The agreement is quite good.

(b) Crystal target 4 mm thick: simulation and measurement are compared for the crystal on axis and in random orientation. A significant enhancement is observed when the crystal is aligned on its <111> axis; this enhancement is slightly larger than 4 for an incident beam of 10 GeV, as can be seen on figure 5. For an incident energy of 6 GeV, the enhancement is slightly higher than 3.

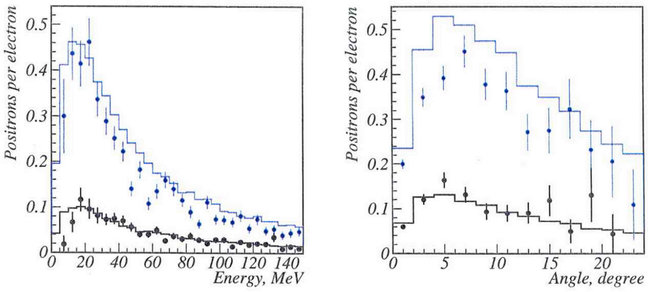

Figure 5: Positron energy and angular distributions for a 4 mm thick crystal and 10 GeV. Blue: crystal. Black: amorphous. Points: experiment; histogram: simulations

(c) Crystal 8 mm thick and compound target; at 10 GeV as incident energy, the observed enhancement in positron yield is slightly larger than 2 for an incident energy of 10 GeV.
Comparison of the 8 mm crystal target with a "compound" target made of a 4 mm crystal followed by a 4 mm amorphous disk shows very close results at 6 GeV (figure 6). This is showing that after 4 mm in the crystal, the processes are the same as in an amorphous medium The same observations can be made at 10 GeV incident electron energy.

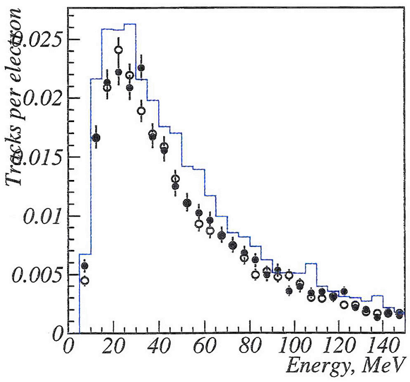

Figure 6: Positron energy distribution for 8 mm thick crystal and compound target at 6 GeV. Empty circles: compound target; filled circles: 8 mm crystal Histogram: simulations

(d) Distribution in transverse momentum: the transverse acceptance of the positron matching systems being defined by the maximum transverse momentum, it is interesting to consider the transverse momentum distribution of the measured positrons. This is illustrated on figure 7 corresponding to 8 mm crystal target with 10 GeV as incident energy. We can see that we have a peak around 3 MeV/c and a FWHM width of 6 MeV/c. Existing matching systems (adiabatic devices) are presenting such acceptances.

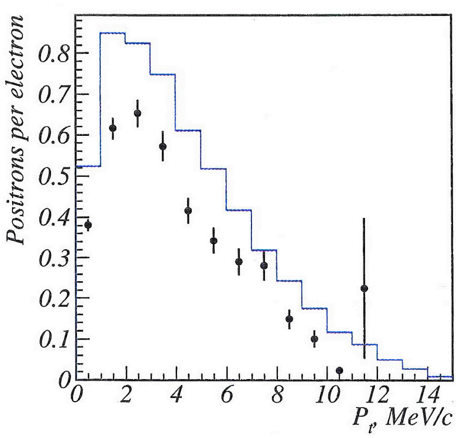

Figure 7: Transverse momentum distribution for 8 mm thick crystal and 10 GeV. Points: experiment; histogram: simulations

(e) Positron yields: given the maximum total and transverse momenta accepted by a matching system put after the positron target, we can determine the accepted positron yield. On table 1, we give the yields for the case of 8 mm crystal target and 10 GeV, electron energy.

	$5 < p_l < 25$	$5 < p_l < 30$	$5 < p_l < 40$
$p_t < 4$	1.16 ± 0.04	1.28 ± 0.04	1.43 ± 0.04
$p_t < 6$	1.66 ± 0.05	1.85 ± 0.05	2.13 ± 0.05
$p_t < 8$	2.11 ± 0.07	2.46 ± 0.08	2.90 ± 0.08
$p_t < 10$	2.31 ± 0.08	2.75 ± 0.08	3.32 ± 0.08
$p_t < 12$	2.40 ± 0.08	2.94 ± 0.09	3.67 ± 0.10

Table 1: Measured positron yields in (pl, pt)acceptance domains for the WA 103 experiment

(f) Enhancement of positron production with energy using oriented crystals. The possibility to rise the energy, for the incident electrons, up to 40 GeV (and more) allowed us to make a comparison of the positron yields - measured on the side positron counters – for the three incident energies: 10, 20 and 40 GeV. This can be seen on the rocking curves of figure 8.

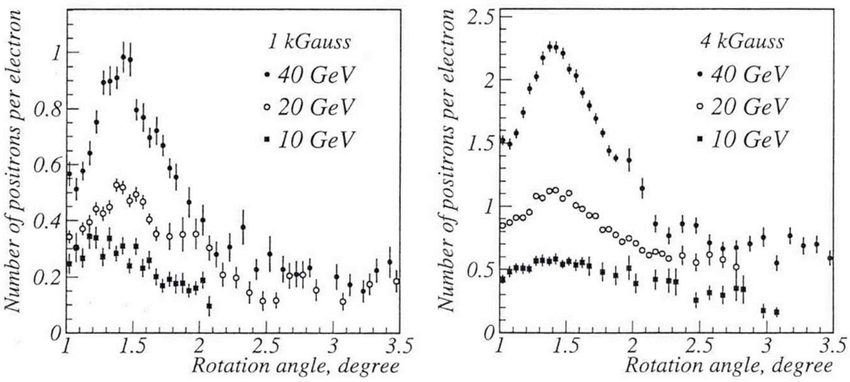

Figure 8: Rocking curves measured on the positron counters for 8 mm crystal and two values Of the magnetic field: 1 and 4 kGauss

3. KEK EXPERIMENT

3-1 Motivations

Tungsten crystal based positron sources have also been investigated at KEK [11]. The experimental set-up, with a different conception from that of CERN, allowed the measurement of positron yields for different kinds of crystals using an electron *beam* rather intense (~10^9 e-/bunch).
Intense photon generation by channelled electrons can be operated also in light crystals as shown in the first proposition [2]. Instead of using tungsten, lighter crystals as silicon or diamond may be used. Theoretical considerations by Baier, Katkov and Strakhovenko [3] showed the interest to use Diamond, for instance, to get a significative enhancement in the energy radiated and in the photon yield at optimum thickness. If , after these authors, we represent the *efficiency of radiation* as the ratio Lrad/Lch where Lrad and Lch are the radiation lengths of the amorphous material and of the oriented crystal, respectively, this ratio is of 8.4 for Silicon and 5.4 for tungsten at an energy of 10 GeV, close to the energies used in CERN and KEK. From the point of view of radiation resistance, Diamond would be more interesting than tungsten [15] On the other hand, promising results

were obtained at Yerevan with diamond crystals using a 4.5 Gev electron beam [16] Using the same experimental apparatus for all the targets, results have been obtained on tungsten, Silicon and Diamond crystals. Some emphasis will be put on the latters.

3-2 Experimental set-up

The experimental set-up, represented on figure 9, is comprising:

- a target holder in a goniometer,
- a magnetic spectrometer,
- collimators,
- two kinds of positron detectors: a lead-glass calorimeter and an acrylic Cherenkov counter.

The silicon and diamond crystals are oriented on their <110> axis and have different thicknesses. They are used alone or in combination with amorphous tungsten plates, with thicknesses from 3 to 15 mm with 3 mm steps installed on an horizontal moveable stage behind the crystal targets. The positrons emitted from the target in the forward direction are analysed for momenta up to 30 MeV/c by the 60° bending magnet. Collimators are installed before the detectors. The acceptance of the measuring system (from 1 to 9.10^{-4} MeV/c.sr, for momenta from 5 to 30 MeV/c) is rather small. No measurements on photons are foreseen.

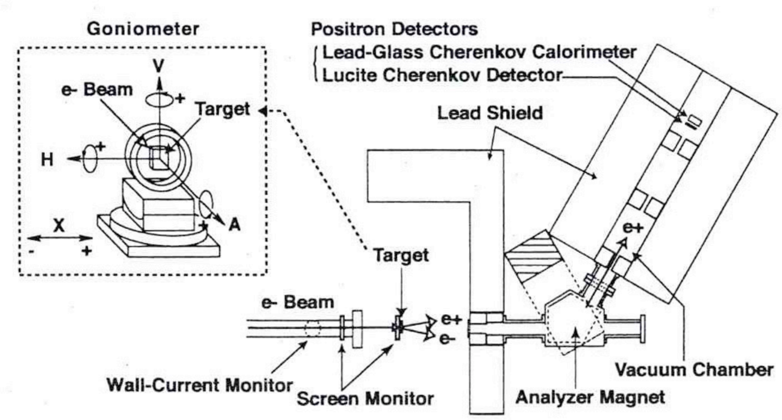

Figure 9: Channeling at KEK: the set-up

3-3 Results

3-3-1 Tungsten crystals

Experiments with 2.2, 5.3 and 9 mm thick tungsten crystals oriented on their <111> axis have been worked out using 4 and 8 GeV incident beams. The results show:

- rocking curves widths (FWHM), much larger than the channelling critical angle : crystal effects are present beyond the critical angle,
- positron yield enhancements (crystal/amorphous) for the same thickness going from 5 to 3 and 1.8 when the crystal thickness is increasing from 2.2 to 5.3 and 9 mm, at an incident energy of 8 GeV and for 20 MeV/c positrons. The enhancements are decreasing when the incident energy does. They decrease about 25 % when the energy decreases from 8 to 4 GeV.
- the enhancements in positron yield observed on tungsten crystals in KEK and CERN experiments are coherent between them, taking into account the scaling laws with incident energy and crystal thickness. Even if the angular acceptances of the two positron detectors are very different, the enhancements found remain coherent.
- the experimental results for tungsten crystals at CERN and KEK have been compared to simulations worked out by V.Strakhovenko [17]. Good agreement was found.

3-3-2 Silicon and Diamond crystals

Experiments with Silicon crystals having thicknesses of 9.9, 29.9 and 48.15 mm and Diamond 4.57 mm thick were carried out at KEK. Angular scanning has been performed for all the crystals. As an example, we show on figure 10, the scanning operated for 20 MeV/c positrons for the Diamond crystal and the 30 mm thick Silicon crystal. Peaks are indicating the <110> axis for both crystals [12].

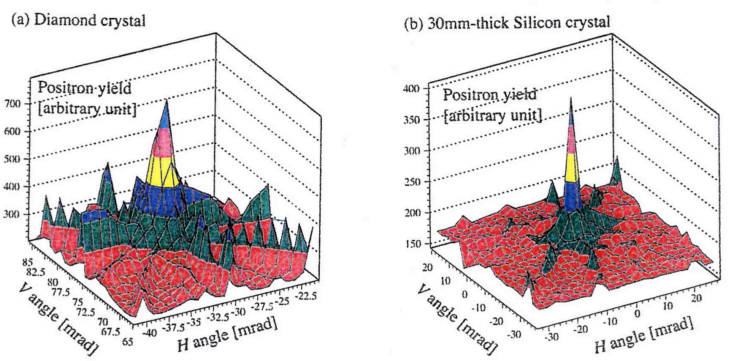

Figure 10: 2-D angular scanning for a 4.5 mm Diamond crystal (a) and a 30 mm Si crystal (b).

Mini peaks are corresponding to passage by planar orientation [12].
Rocking curves: examples of rocking curves obtained for 20 MeV/c positrons at 8 GeV are shown on figure 11. It is noticeable that the width FWHM is much larger than the channelling critical angle: 1.4 and 2.4 mrad for diamond and silicon, respectively, compared to $\Psi c = 0.13$ and 0.17 mrad, also respectively.

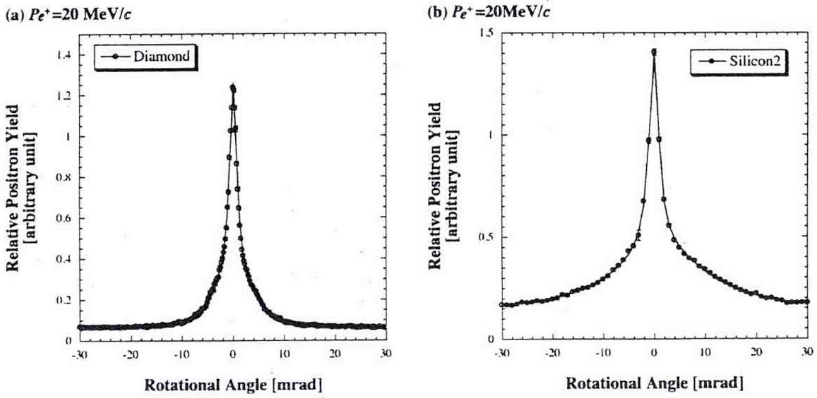

Figure 11: Rocking curves for the 4.5 mm Diamond and the 30 mm Si crystals

Enhancement in positron yield: the enhancement is measured on the rocking curve between the peak yield and the yield 50 mrad apart from the crystal axis. These enhancements are shown on figure 12 for both crystals which thickness is expressed in terms of Xo (123 mm for diamond, 93.6 mm for silicon) .

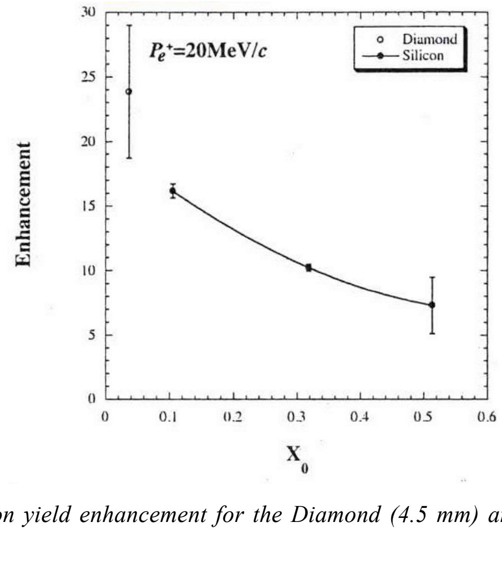

Figure 12: Positron yield enhancement for the Diamond (4.5 mm) and the Si (10, 30 and 50 mm) crystals

For *combined* targets associating crystals as radiators and amorphous tungsten as *converters,* we can observe a comparison for the enhancement between different crystals on figure 13; the total thickness (crystal +amorphous) is put on abscissa.. we can observe that for the light crystals the enhancement (with respect to Bethe-Heitler value) is larger than 1 but smaller than for the "heavy" crystal as tungsten.. The probable reason is that the positrons created by photons generated in light crystals have lower energy due to softer photons than in tungsten crystals (due to smaller potential well) and are more easily scattered and henceforth, less captured in the small acceptance detection system.

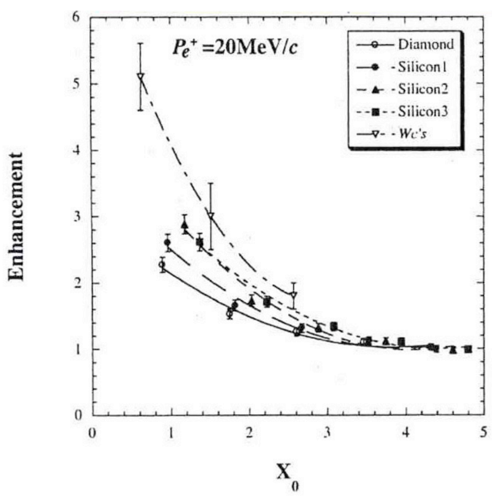

Figure 13: Positron yield enhancements for the combined targets of KEK.

4 SUMMARY AND CONCLUSIONS

4-1 Concerning the CERN experiment:

- A clear enhancement in *photon* and *positron* production is observed for all the crystals aligned on their <111> axis, when they are compared to amorphous targets of the same thickness. The enhancements are respectively slightly larger than 4 and 2 for 4 and 8 mm thick W crystal submitted to 10 GeV electron beam. At 6 GeV, the enhancements are slightly lower.
- Good agreement is found between the results of a 8 mm crystal and a "compound" target made of 4 mm crystal followed by 4 mm amorphous target. This result confirm that crystal effects are essentially present in the first millimetres of the crystal leading to a

separation between the *radiator* and the *converter*. Such assembling is interesting to limit the energy dissipation in the radiator, preserving high values of the potential well.

- A large number of *soft* photons is created due to channelling and coherent bremsstrahlung; these photons generate soft positrons, easily accepted by known matching systems which collect preferably positrons up to 30 MeV/c.
- A good agreement is found between simulations and experiment validating these simulations based on crystal processes and allowing further predictions.
- The data collected in this experiment allows 2-D reconstruction in the phase space (p_L,p_T) and positron yield determination in given acceptance domain in longitudinal and transverse momenta.

4-2 Concerning the KEK experiment

- The results on tungsten crystals are in coherence with those of CERN taking into account scaling laws for target thickness and incident energy. This is true though the acceptance of the two detection systems are quite different.
- The results on light crystals (Silicon and Diamond) show promising results. Real phase space of the produced positrons may be reached through modification of the positron detector towards a larger acceptance.
- Experimental results compared to simulations [17] are in good agreement within the experimental accuracy

4-3 Concerning both experiments

- Some complementaries are found between different thicknesses and different incident energies, concerning tungsten crystals.
- The KEK set-up is relatively simple and provides rapid indications on yields, enhancements,… The measurements being direct, the analysis is straightforward.
- However, the KEK apparatus, due to the very small acceptance does not give indications on the positron phase space.
- The CERN apparatus is conceived to proceed to track reconstruction which is a more complicated task and time demanding
- The large horizontal acceptance of the CERN detection system allows full reconstruction of the positron phase space and precise estimations of the yield in given acceptance conditions.

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5. REFERENCES

[1] V. Balakin, A. Mikhailichenko Preprint INP 79-85, Novosibirsk, 1979

[2] R. Chehab et al., Proceedings of IEEE PAC, March 1989, Chicago, IL

[3] V.N. Baier, V.M. Katkov, V.M. Strakhovenko Phys.Stat.Solid (b) **133** (1986) 583

[4] V.N. Baier, V.M. Katkov, V.M. Strakhovenko "Electromagnetic proceses at high energies in oriented single crystals" World Scientific Ed. Singapore, 1998

[5] J.F. Bak et al., Nucl.Phys.B **302** (1988) 525

[6] R. Medenwalt et al., Phys.Letters B **242** (1990) 517

[7] X. Artru et al., Nucl.Instr.and Meth. B **119** (1996) 246

[8] R. Chehab et al., Phys.Letters B **525** (2002) 41

[9] X. Artru et al., Nucl.Instr.and Meth.B **201** (2003) 243

[10] K. Yoshida et al., Phys.Rev.Letters **80** (1998) 1437

[11] T. Suwada et al., Phys.Rev. E **67** (2003) 016502

[12] M. Satoh et al., "Experimental study of positron production from silicon and diamond crystals by 8-GeV channeling electrons" To appear in Nucl.Instr.and Meth. B

[13] V. Bellini et al., Nucl.Instr.and Meth. A **386** (1997) 254

[14] V.M. Strakhovenko SGC (Shower Generation in Crystal).
See V.N. Baier, V.M. Katkov, V.M. Strakhovenko Nucl.Instr.meth. **B103** (1995) 147

[15] X. Artru, V.Baier, R. Chehab, A. Jejcic Nucl.Instr.and Meth. A **344** (1994) 443

[16] R. Avakian et al., Sov.Tech.Phys.Letters **14** (5) 2003

[17] V. Baier, V. Strakhovenko Phys.Rev Special Topics –AB **5** (2002) 121001