NA43

Investigations of the Coherent Hard Photon Yields and other QED Processes for (50–300) GeV/c Electrons/Positrons in the Strong crystalline Fields of Diamond, Si, Ge and W Crystals

University of Aarhus, University of Florence/INFN, Strasbourg CNR, Turin-INFN, University of Witwatersrand Johannesburg, and Yerevan Physics Institute

A STATUS REPORT

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SUMMARY

The aim of this experiment is to measure the influence of strong fields on QED-processes like:
emission of coherent radiation, pair production and shower formation when multi-hundred GeV electrons/positrons and photons penetrate single crystals near axial/planar directions. The targets will be diamond, Si, Ge, and W crystals.

QED is a highly developed theory and has been investigated experimentally in great detail. In recent years it has become technically possible to investigate QED-processes in very strong electromagnetic fields of strengths around the characteristic strong field $E_0 = m^2 c^3 e / (e h) = 1.32 \times 10^{16}$ V/cm (the Schwinger field). The work of such a field over the electron Compton length equals the electron mass. The theoretical description of QED in such fields is beyond the framework of perturbation theory. Such strong fields are only obtained in laboratories for a) heavy ion collisions, b) interactions of multi-GeV electrons/positrons with extremely intense laser fields (tera Watt) and c) in oriented crystals. In fact, it turns out that crystals are unique for this type of experiments. The point is that the probabilities of processes in axial/planar fields are determined by the magnitude of these fields in the particle's rest frame. Hence, the strong field parameter $\chi$ is given by $\chi = \gamma E / E_0$, where $E_0$ is given above, $E$ being the local field from the crystal axis ($\sim 10^{11}$ V/cm) and $\gamma$ the Lorentz factor for the particle ($10^2$-$10^3$). Therefore, for multi-hundred GeV electrons/positrons $\chi$-values of one or more are possible. A real advantage of crystalline targets is that for incidences close to axial/planar directions the particle interacts with the strong field over macroscopic distances ($1 - 100 \mu m$), leading to strong coherence effects.

For incoming particle energy (increasing $\chi$) the strong crystalline fields have a dramatic influence on QED processes like the radiative energy loss turning from the classical $E^2$-dependence ($\chi<1$) to the quantum synchrotron law of $E^{2/3}$-dependence ($\chi>1$). As a general result for axial/planar directions we have obtained until now: a) Radiation emission is enhanced up to two orders of magnitude (Fig. 2) with photon multiplicities (Fig. 3) up to 10. Pair production (Fig. 6) is enhanced up to one order of magnitude. This leads to a very fast shower formation (Fig. 5) with radiation lengths along crystal directions that are shortened (10-50) times as compared to the Bethe-Heitler values. Beam cooling has very recently been found for the first time (Fig. 4).

For investigations of the predicted strong field effects the experimental setup used by NA43 in the $H_2$ beam of the North Hall is unique (cf. Fig. 1). The two drift chambers 40 m apart on the incident side give an angular resolution of 3-4 $\mu rad$. There are two positions for crystal mounting on high precision goniometers inside the dedicated vacuum chambers. In Vacuum Chamber I, one probes the crystal with $e^+/e^-$, in Vacuum Chamber II with photons. These may be tagged with the combination of DC3, Bend3 and DC4. Crystal II may be cooled to liquid nitrogen temperature. DC1-DC2-DC3 allows to measure the scattering taking place in crystal I. With $C (= \text{convertor})$ and SSD the average photon multiplicity is measured. Finally, the pair spectrometer, represented by Bend4, DC5 and DC&, is used to determine single photon energies.

The NA43 detector is therefore a multi-purpose setup in which many aspects of strong QED effects may be studied.

THE 1996 PROGRAM

For 1996, 3 weeks of beam time in the SPS $H_2$ beam line (North Hall) is expected. Out of this beam time 1 week is expected for setting up the experiment. The following two weeks will be used for:

1) Detailed investigations of pair production in diamond, Si, Ge, and W crystals.
2) Influence of Landau-Pomeranchuk and Chudakov effects on pair production.
A comparison of shower formation in Ge crystals for (50-300) GeV electrons and gamma rays.

Ad. 1) Ever since NA43 found a pronounced peak in the photon spectrum from 150 GeV electrons traversing a Ge crystal, it has been discussed what new physics could come out of strong crystalline fields. For a review, cf. Ref. 2, where also vacuum polarization is discussed. Theoretically, the strong field effects require solving the Dirac equation, which is very complicated due to the many quantum states ($\sim \gamma$). Therefore, most theoretical groups use approximations, like the constant field approximation. For testing of approximations, all groups ask for experimental results, like single photon spectra. NA43 showed clearly that the pronounced peaks at about 0.8 times the particle energy are due to multi photons. On the other hand, the enclosed paper on photon multiplicities concludes that a single photon spectrum requires crystals thinner than the coherence length, which will destroy the coherence effects. In order to investigate single-event QED processes in crystalline fields, we intend in the coming period to investigate in detail the pair production (PP). For PP the enhancements are only about 10 so that single event processes can be obtained in (0.5-5) mm thick crystals.

Ad. 2) For multi-GeV electrons and gamma rays the coherence lengths can be very large ($\sim \mu$m). This can lead to a strong reduction in yields if the multiple scattering angle $\theta$ along the coherence length is larger than $1/\gamma$. This, so-called Landau-Pomeranchuk effect has not been investigated in the (50-300) GeV but can strongly influence the energy loss. For lower energies, see Refs. 8 and 9.

The Chudakov effect concerns pair production from high energy photons. Due to the smallness of the angle $\theta = 4m_e^2/E_\gamma$ between the components of the $e^+e^-$ pair produced by $\gamma$-quanta of energy $E_\gamma$, the transverse distance $l(z)$ between the components remains very small, even at sufficiently large distances (z) from the production point. As a result of the interaction between the two fields from the pair ($e^+e^-$) certain effects take place, like the so-called Chudakov effect. Due to mutual screening of the fields from $e^+e^-$, the ionization energy loss in a detector decreases. This effect is only investigated experimentally in a few cases; on the other hand, it can influence the detection of showers in solid state detectors (SSD). For $E_\gamma = 100$ GeV, the pair is only expected to give full energy loss corresponding to two particles after - 5 mm in Si. Hence, the effect can be detected by introducing a thin conversion foil ($\sim 100 \mu$m W) in front of a SSD and measure energy loss as a function of foil distance to the SSD. Only emulsion experiments have been performed until now.

Ad. 3) Until now, the enhanced shower formation along crystalline axes/planes has mostly been investigated using electrons. For future applications it is of utmost importance also to investigate the optimum thicknesses of crystals for incident gamma rays in the energy region of (10-300) GeV.

Beam and beam time

For the investigations is needed electrons/positrons with energies up about 300 GeV. Requirements for beam intensity, diameter and angular divergence is fulfilled by the H$_2$ beam in the North Hall. The experimental setup is ready for installation any time in 1996. Three weeks of beam time is needed: for setting up 1 week and 2 weeks for data taking.
SOME PHYSICS BACKGROUND FOR NA43

Different areas of physics frequently benefit from symbiotic relationships, which is also the case for physics around NA43. The present case concerns QED-processes in very strong electric and magnetic fields. The theory of strong-field QED was developed by particle physicists (for a review, see Erber).\textsuperscript{12} In recent years the theory has turned out to be important for describing pulsars and “black holes”. The characteristic strong field (the Schwinger field) is given by:

$$E_0 = \frac{m^2 c^3}{eh}$$

The work of this field over a distance of the electron Compton wave length equals the electron mass

$$e \cdot \lambda \cdot E_0 = m c^2 \cdot E_0 = \frac{m^2 c^2}{eh}.$$ 

Such strong fields can only be found in heavy ion collisions and in the interaction of ultra-relativistic electrons with a) tera Watt laser, and b) crystalline targets.\textsuperscript{2} Crystal targets are, in fact, unique for such investigations since probabilities have to be calculated in the particle rest frame – being proportional to the Lorentz factor $\gamma$. Further on, in contrast to heavy ion collisions, the interaction length can be $\mu m$ or more for incidence along the crystal axes and planes. In such situations the quantum parameter determining the process is given by $\chi = \gamma \cdot E/E_0$, where $\gamma$ is the Lorentz factor for the particle and $E$ is the local field for which the Lindhard continuum potential can be used. Hence, for ultra-relativistic $e^+e^-$, $\chi$ is one or more. $\chi$ characterizes the influence of the quantum recoil during photon emission.

Coherence

When an electron/positron penetrates a single crystal close to axial/planar directions, it has a fair chance to scatter coherently on many atoms along its way. The coherence in scattering is carried on to radiation emission leading to strongly enhanced yields as compared to amorphous targets. For radiation emission, coherence lengths $l_{coh}$ for particle energies $E$ are given by

$$l_{coh} = \frac{2E(E - \hbar \omega)}{\hbar \omega mc^2} \cdot \frac{\hbar}{mc}$$

where $\omega$ is the photon energy. For pair production:

$$l_{coh} = \frac{E(\hbar \omega - E_e)}{\hbar \omega mc^2} \cdot \frac{\hbar}{mc}$$

Here $E_e$ is the energy of one of the pairs. Therefore, for multi-hundred GeV $e^+e^-$, $l_{coh}$ for radiation emission can typically be hundreds of $\mu$m. For pair production, also strong coherence effects come into play. For recent work, see Ref. 13.

The Landau-Pomeranchuk effect

Normally, the long coherence length leads to strongly enhanced radiation emission. On the other hand, the extremely long coherence lengths for large $\gamma$ values and especially for lower photon
energies, can lead to a reduction in yields. If the multiple scattering of the particle along the formation length for the photon is larger than \( \theta_{1,\gamma} = 1/\gamma \), the photon intensity decreases. The reason being that the emitted radiation intensity \( dI/d\omega \) is proportional to \( \gamma^2 |\Delta \beta|^2 \) as long as \( |\Delta \beta| < 2/\gamma \). Above this limit for multiple scattering, \( dI/d\omega \approx \ln \gamma \) for small \( \omega \). The frequency \( \omega_{\gamma,p} \), for which the intensity reduction sets in, is proportional to \( \gamma \) and the plasma frequency is \( \omega_p \). This effect was for the first time investigated by the Aarhus group. SLAC reported new results in 1995.

**Critical angles for strong field effects**

For penetration of ultra-relativistic particles through single crystals two characteristic angles come into play, namely the Lindhard channeling angle

\[
\psi = \sqrt{\frac{4Z_1Z_2e^2}{pvd}}
\]

and the so-called Baier-angle

\[
\theta_0 = \frac{U_0}{mc^2}
\]

where \( Z_1, p \) and \( v \) are, respectively the atomic number, momentum and velocity of the projectile. \( Z_2 \) and \( d \) are the atomic number and lattice constant of the crystal. \( U_0 \) is the characteristic potential of axes and planes (the continuum potential). For incident angles \( \theta \) to crystal axes/planes smaller than the Lindhard angle, a strong channeling effect appears, where negative particles are focussed around the nuclei and positive particles are pushed away. This leads to enhanced photon yields for channeled electrons and reduced yields for channeled positrons. For multi-GeV e⁺e⁻, the Lindhard angles are (20 - 100) μrad, whereas the Baier angle \( \theta_0 \) is (5 - 10) times larger and independent of particle energy. For incident angles \( \theta \approx \theta_0 \), the process can be described by the standard perturbation theory, whereas for incident angles \( \theta \ll \theta_0 \) the process can be described as originating from a constant field. Since the transverse distance traveled by the particle during the process is small compared to distances over which the potential varies significantly. For incident angle \( \theta \approx \theta_0 \), a full quantum description should be performed. This is extremely complicated and first-order corrections have been introduced by Baier et al.\(^5\)

**THE PRESENT SITUATION IN CRYSTALLINE FIELDS**

Different theoretical and experimental groups in USA, former USSR and Europe have investigated QED processes in crystalline fields. In general, it has been found that along axial directions the photon yields are enhanced two orders of magnitude as compared to amorphous targets. For pair production, the enhancement is 5 - 10 compared to the Bethe-Heitler yields. This leads to very fast developing showers in axial/planar directions with critical angles equal to the Baier angle, \( \theta_0 = U_0/mc^2 \). The fast shower formation is equivalent to (20 - 50) times shorter radiation lengths along such crystal directions. Leading to directional sensitive calorimeters with angular resolutions around 100 μrad for the planar cases. The overall agreement between theory and experiments is fair. (See Refs. 4, 7, and 15 for a review.)

For the experimental investigations, the CERN H₂ beam line and the NA43 detector have been unique. The beam is well focussed, ± 30 μrad, and contains both e⁺e⁻ and π⁺π⁻ in the energy region from ~ 50 GeV to 300 GeV. The NA43 detector is discussed above. Below are listed publications from the last years.
The 1994-1995 Program

The 1994 program covered four different subjects, namely:

a) measurements of the photon multiplicities for electrons and positrons traversing thin diamond and Si crystals – the most recent report is enclosed

b) enhanced shower formation in thick Ge crystals

c) enhanced pair production in W crystals, and

d) measurements of the polarization of emitted photons from electrons incident along planar directions; a feasibility study.

A few, typical results are shown in the enclosures.

ad a) Figures 2 and 3 show the dramatic radiation emission for 150 GeV e⁻ traversing a 1.5 mm thick diamond (Fig. 2). The photon spectra have been normalized to the Bethe-Heitler yields. Close to axial directions the emission yields are dramatically enhanced (~ 200 times), and the photon multiplicities are around 10 (Fig. 3). The channeling angle is only 25 μrad; it is therefore clear that the strong field effect is found for much larger incident angles than by Ψ₁, as predicted by Baier et al. 5-7 This strong radiation emission is expected to lead to radiation cooling, which is now being investigated through the 1994 data.

Radiation cooling has already in 1977 been predicted by Baryshevsky and Dubovskaya. 17 With reference to electron cooling it was suggested to let a beam of positive particles pass through a crystal and thereby come out with reduced emittance. This effect has never been found. But now NA43 found for the first time the effect for 150 GeV electrons. The beam cooling comes about due to emission of many photons along axial directions, leading to a reduction in transverse energy E⊥ with respect to the axis. Hereby, some of the incident electrons exit with reduced angles to the axis. The effect is found in 0-6 mm Si but not in 1.5 mm diamond (Fig. 4). The reason for this is unclear.

ad b) Figure 5 shows the very pronounced shower formation for 150 GeV e⁻ incident on a Ge crystal. The angular widths of the peaks correspond to angular resolutions of around 100 μrad. Figure 6a shows the pair production in a W crystal for different angles to the <100> axis in a 3 mm thick crystal. The abscissa show the photon energy and the yields have been normalized to the Bethe-Heitler yields. The effect is proposed by NA48 to be used as an efficient trigger for the $K_1 (\sim 4\gamma)$ decay, and members of NA48 joined the experiment. Figure 6b shows calculated yields from the Baier group. A large discrepancy is found close to axial directions, the reason is not understood.

ad d) Results from our feasibility study on polarization measurements, using the Cabbibo idea, 18, 19 are disclosed in Figure 7, where the conversion probability for parallel and orthogonal configurations of the two crystals is depicted. The difference of the two settings has been converted to a degree of polarization, but the statistics is too low to give the degree of polarization – especially for the high energy photons. On the other hand, the data show that the technique can be realized. In order to use the technique, further investigations of coherent pair production is needed.

The 1995 program covered:

a) single photon spectra

b) the Landau-Pomeranchuk effect

c) pair production in cooled Ir and W crystals

d) influence of strong crystalline fields on hadron production.

Only a few of the data have been analyzed until now. Preliminary results are obtained only for program b).
The pair spectrometer was used to measure a single photon spectrum for cases like Figures 2 and 3. Such spectra are important for comparisons with theory. We have tried to obtain single photon spectra using thin targets (~100 μm) but the effects are so strong that even in such thin targets multi-photon effects were obtained.

The interest in the Landau-Pomeranchuk (LP) effect has come up considerably during the last years caused by measurements of cosmic rays with energies in the $10^{20}$ eV region. These high energies are detected through air showers in which the LP effect has to be incorporated. The experimental investigation of this effect is very limited. As mentioned above, our group made the very first investigations in 1988 for electron/positron energies up to 20 GeV, both for random and axial directions. This year a SLAC group published more detailed measurements for amorphous foil and electron energies up to 25 GeV. This summer NA43 investigated the effect for $(70 - 240)$ GeV $e^-$ and found very pronounced reduction of photon yields for photon energies up to 30 GeV, see Figure 8a,b.

**FUTURE PLANS**

As mentioned above, the CERN SPS-H$_2$ beam line and the NA43 setup is unique world wide for measurements of penetration phenomena for particle/antiparticle beams incident on crystals with energies of $(50 - 300)$ GeV. The field has been extremely fruitful with more than 25 scientific papers during the last five years, out of which there are mainly Phys.Lett. B and Phys.Rev.Lett. Publications. In this connection it should be pointed out that the CERN allocation of beam time is only about 4 weeks per year.

The results obtained until now have motivated many theoretical groups to investigate the influence of strong fields on QED processes. Many theoreticians have realized that now for the first time it is possible experimentally to investigate QED in strong fields with high precision. In 1995 we were encouraged to organize an international workshop in Aarhus on Channeling and other coherent crystal effects at relativistic energies. More than 80 attendees from 14 countries participated. From the enclosed program it can be seen that there is a broad interest in the field for future NA43 investigations. The following subjects should be mentioned:

1) Influence of strong field effects on hadron production in crystals.
2) The strongly enhanced shower formation in crystals should be used to build a directional sensitive calorimeter for GeV-TeV γ rays. The angular resolution of $(0.1 - 0.5)$ mrad would be very interesting for high energy physics and astrophysics.
3) Measurements of spin rotation for charmed baryons using crystals.
4) More detailed polarization investigations – is it possible to produce circular polarized γ rays? Such effects are predicted by different groups, like our Armenian collaborators.

For NA43,

E. Uggerhøj
Spokesman
References


NA43 related publications the last 5 years
7) E. Uggerhøj: Radiation Emission and Shower Formation in Strong Crystalline Fields - Recent CERN Experiments Proc. from Int. Conf. on: Coherent Radiation Processes in
9


**NA43**

**Fig. 1**

**NA43 experimental setup.** Scintillators are designated by Sc, drift chambers by DC and deflection magnets by B. HeI etc. are Helium tanks (introduced to reduce the amount of material along the beam line) while C is a calibrated convertor and SSD the solid state detector.
150 GeV electrons on 1.5 mm Diamond around <100> axis

Figure 2a.

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FILE ENH32.ORG
c:/dumle9332/enh32.org, 13-Jan-1994
150 GeV electrons incident on <100> axis of 1.5 mm Diamond

Incident polar angle ranges wrt crystal axis:
- $\theta_{in} = 0-5\mu\text{rad}$
- $\theta_{in} = 5-10\mu\text{rad}$
- $\theta_{in} = 10-20\mu\text{rad}$

Figure 2b.
150 GeV electrons incident on <100> axis of 1.5 mm Diamond

Figure 3.
COOLING AND NO COOLING

150 GeV electrons incident on 
<110> -axis of 0.6 mm Silicon crystal

\[ \theta_r = \frac{\theta_{\text{out}}}{\theta_{\text{in}}} \]

\[ 50 < \theta_{\text{in}} < 100 \mu\text{rad} \] (wrt crystal axis)

- 3 < \( E_{\text{in}} \) < 25 GeV
- 25 < \( E_{\text{in}} \) < 57 GeV
- 57 < \( E_{\text{in}} \) < 90 GeV
- 90 < \( E_{\text{in}} \) < 111 GeV
- 111 < \( E_{\text{in}} \) < 150 GeV

150 GeV electrons incident on 
<100> -axis of 1.5 mm Diamond crystal

\[ \theta_r = \frac{\theta_{\text{out}}}{\theta_{\text{in}}} \]

\[ 50 < \theta_{\text{in}} < 100 \mu\text{rad} \] (wrt crystal axis)

- 3 < \( E_{\text{in}} \) < 25 GeV
- 25 < \( E_{\text{in}} \) < 57 GeV
- 57 < \( E_{\text{in}} \) < 90 GeV
- 90 < \( E_{\text{in}} \) < 111 GeV
- 111 < \( E_{\text{in}} \) < 150 GeV

Fig. 15: Experimental investigations of photon multiplicity & radiation.
Scanning of the 25 mm germanium crystal

Shower Formation for 150GeV electrons

Normalized counts [Arb. units]

Tilt angle [mrad]
Pair production for high energy photons incident on a 3 mm thick <100> W crystal. The yields are normalized to the Bethe-Heitler yields and shown for different incident angles to the <100> direction.

Figure 6a
Photon conversion probability on aligned diamond crystal

Parallel and orthogonal configurations: source; .3 mrad from axis (.5 mm diamond), analyser; 2.0 mrad from axis (1.5 mm diamond)

Random configuration: Source; 1 cm Al, analyser; 2 mrad from axis (1.5 mm diamond)

Figure 2 corresponds to Fig. 3.
Landau-Pomeranchuk-Migdal effect.

Electrons on 0.2mm W, random incidence

NOT CORRECTED FOR BACKGROUND RADIATION

Energy deposited in LG [GeV]

0.00 0.25 0.50 0.75 1.00 1.25
0 20 40 60 80 100 120 140 160

Enhancement

Fig 6a
Landau-Pomeranchuk-Migdal effect
Electrons incident along $<111>$-axis
of 0.2mm W crystal

NOT CORRECTED FOR BACKGROUND RADIATION

Energy deposited in LG [GeV]
Workshop on
CHANNELING AND OTHER COHERENT CRYSTAL EFFECTS
AT RELATIVISTIC ENERGY
July 10 – 14, 1995
University of Aarhus
Aarhus, Denmark

Topics will include:

- channeling, channeling radiation,
- coherent bremsstrahlung,
- pair production and transition radiation,
- accelerator and particle physics applications,
- heavy ions and related material questions.

ABSTRACTS SHOULD BE SENT BY E-MAIL TO E. UGGERHØJ BEFORE MAY 1

Organizers: R. Carrigan (Fermilab) and E. Uggerhøj (Aarhus)

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International Committee:

Organizing Committee:
MONDAY, JULY 10

MORNING: CHANNELING – RADIATION I

Chairman: John A. Davies
McMaster University, Ontario, Canada

930 - 945 Welcoming remarks - Aim of the Workshop
945 - 1030 L. Vestergaard Hau, Rowland Institute for Science, Cambridge MA, US:
Quantum channeling effects and annihilation in flight of channeled MeV positrons

1030 - 1100 COFFEE

1100 - 1145 Yu. V. Kononets, RRC Kurchatov Institute, Moscow, Russia:
Radiation emission from relativistic electrons/positrons

1145 - 1215 K.A. Ispirian, Yerevan Institute of Physics, Armenia:
Measurements of photon polarization using coherent e^+e^- photoproduction

1215 - 1400 LUNCH

AFTERNOON: RADIATION II

Chairman: A. Uguzzoni
University of Bologna and I.N.F.N., Bologna, Italy

1400 - 1445 A. Schäfer, Theoretische Physik, Frankfurt, Germany:
QED in strong fields (Invited talk)

1445 - 1515 E. Uggerhøj, Aarhus:
Recent experimental results from CERN (NA43).

1515 - 1545 COFFEE

1545 - 1615 M. Kh. Khokonov, Khabardino-Balkarian State University, Nalchik, Russia
Influence of electromagnetic radiation on the angular distributions of electrons in oriented crystals

1615 - 1645 B. L. Berman, George Washington University, Washington DC, US:
Channeling radiation for electrons and positrons

1645 - 1715 N. V. Laskin, Institute of Physics & Technology, Kharlov, Ukraine
Bremsstrahlung from a relativistic electron moving through a finite thickness crystal

1715 → Arrangement of POSTERS
Visit to the Aarhus Storage Ring facility ASTRID
TUESDAY, JULY 11

MORNING: PAIR PRODUCTION / SHOWER FORMATION

Chairman: Niels Lund
Danish Space Research Institute, Lyngby, Denmark

9:00 - 9:45  V.N. Baier, Budker Nuclear Physics Institute, Novosibirsk, Russia:
Electromagnetic showers in crystals at GeV energies

9:45 - 10:30  M. Merck, Max-Planck-Institut für Extraterrestrische Physik, Garchin, Germany:
Gamma-ray astronomy (Invited talk)

10:30 - 11:00  COFFEE

11:00 - 11:30  P. Sona, INFN, University of Firenze, Italy:
Enhanced shower formation in thick Ge crystals for 70-150 GeV electrons

11:30 - 12:00  V.I. Sergienko, N.P. Lebedev Physical Institute, Moscow, Russia:
Electromagnetic showers in aligned crystals

12:00 - 12:30  Y.P. Kunashenko, Nuclear Physics Institute, Tomsk, Russia:
Experimental and theoretical investigations of type B pair production in Si and Ge crystals

12:30 - 14:00  LUNCH

14:15 - 15:00  POSTER SESSION  -  COFFEE

AFTERNOON: BENDING

Chairman: R. Carrigan
Fermilab, Batavia, ILL, US

15:00 - 15:45  S.P. Møller, Aarhus:
Review of bending experiments

15:45 - 16:15  N. Doble, SL CERN, Geneva, Switzerland:
A novel application of bent crystal channeling to the production of simultaneous particle beams

16:15 - 16:45  A.M. Taratin, Joint Institute for Nuclear Research, Dubna, Russia:
Computer simulation of energy loss and deflection efficiency for high energy protons in a bent crystal

16:45 - 17:15  Yu. Chesnokov, Inst for High Energy Physics, Protvino, Russia:
Review of IHEP experiments for focusing and deflection 70 GeV proton beam with bent crystals

17:15 - 17:45  E.N. Tsyganov, SUNY, Albany NY, US:
Beam bending by high Z single crystals
WEDNESDAY, JULY 12

MORNING: PARAMETRIC X-RAYS – AND OTHER RADIATION SOURCES

Chairman: R. Avakian
Yerevan Physics Institute, Armenia

9:00 – 9:45  H. Nitta, Department of Physics, Koganei Tokyo, Japan:
Theory of parametric x-ray radiation

9:45 – 10:15  U. Nething, Forschungszentrum Rossendorf, Dresden, Germany:
Channeling radiation and parametric x-ray radiation at electron energies less
than 10 MeV

10:15 – 10:45  S.P. Fomin, Kharkov Institute of Physics and Technology, Kharkov, Ukraine:
Suppression effect of high energy electron radiation in a thin crystal

10:45 – 11:15  COFFEE

11:15 – 11:45  A.P. Potylitsin, Nuclear Physics Institute, Tomsk, Russia:
Experimental investigations of coherent bremsstrahlung in pyrolytic crystals

11:45 – 12:30  R. Ruth, SLAC, Stanford CA, US:
Futuristic accelerators

12:30 – LUNCH

AFTERNOON: OUTING

EVENING: WORKSHOP DINNER
THURSDAY, JULY 13

Chairman: P. Hansen
Niels Bohr Institute, Copenhagen, Denmark

MORNING: CRYSTAL APPLICATIONS IN PARTICLE PHYSICS

900 - 945 D. O. Riska, Department of Physics, University of Helsinki, Finland
Physics of charmed baryons and their magnetic moments (Invited talk)

945 - 1015 N. F. Shul’ga, Kharkov Institute of Physics & Technology, Kharkov, Ukraine:
Measurements of spin rotation using doughnut scattering

1015 - 1045 A. V. Khanzadeev, Petersburg Nuclear Physics Institute, Gatchina, Russia:
Experiment to observe the spin precession of channeled relativistic Σ⁺ hyperons

1045 - 1100 COFFEE

1100 - 1130 V. M. Samsonov, Petersburg Nuclear Physics Institute, Gatchina, Russia:
On the possibility of measuring charm baryon magnetic moment with channeling

1130 - 1200 P. Kasper, Fermilab, Batavia ILL, US:
Present and future high energy photo-production experiments

1200 - 1230 J. P. F. Sellschop, University of Witwatersrand, Johannesburg, South Africa:
Diamond - Characteristics and use long past, past and present

1230 - 1400 LUNCH

AFTERNOON: CRYSTAL EXTRACTION AND OTHER ACCELERATOR APPLICATIONS

Chairman: W. Herr
CERN, Geneva, Switzerland

1400 - 1500 K. Elsener and J. Klem, SL CERN, Geneva, Switzerland:
Extraction of high energy beams using single crystals

1500 - 1545 D. B. Cline, Physics Department, UCLA, CA, US:
A muon crystal collider concept

1545 - 1615 COFFEE

1615 - 1645 A. A. Asseev, Institute for High Energy Physics, Protvino, Russia:
One more possibility of using bent crystals for beam extraction from accelerators

1645 - 1715 J. Silva, College de France, Paris, France:
Crystal targets for positron production and axial channeling of relativistic electrons in crystals

1715 - 1745 C. T. Murphy, Fermilab, Batavia ILL, US:
Studies of bent crystal extraction at the Fermilab Tevatron

EVENING

POSTER SESSION
FRIDAY, JULY 14

MORNING: HEAVY IONS

Chairman: V.V. Okorokov
Institute of Theoretical and Experimental Physics, Moscow, Russia

9:00 - 9:30  J.U. Andersen, Aarhus:
Channeling of heavy ions

9:30 - 10:00  C. Scheidenberger, GSI Darmstadt, Germany:
Heavy ions experiments at GSI

10:00 - 10:30  A.H. Sørensen, Aarhus:
Calculations of energy loss for relativistic heavy ions

10:30 - 11:00  COFFEE

11:00 - 11:30  S. Datz, Oak Ridge National Laboratory, TN, US:
Complete energy loss of 33-TeV Pb ions in carbon

11:30 - 12:00  Y. Pivovarov, Nuclear Physics Institute, Tomsk, Russia:
On the resonant coherent excitation of heavy ions at relativistic energies

12:00 - 12:30  D. Dauvergne, Institut de Physique Nucléaire de Lyon, France:
Application of the radiative electron capture by channeled heavy ions to the
measurement of electron Compton profiles in a Si crystal

12:30 - 12:45  Concluding remarks - End of Workshop

12:45 -

LUNCH - END OF THE WORKSHOP

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Speakers are requested to reserve 5-10 minutes of the allocated time for discussions.
The talks will take place in the Auditorium of the Institute of Physics and Astronomy.

The Poster Session will be held in the Canteen on the 7th floor
Posters can remain posted during the whole Workshop.

On behalf of the Organizing Committee

Richard Carrigan  Erik Uggerhøj
Experimental Investigation of Photon Multiplicity and Radiation Cooling for 150 GeV Electrons/Positrons Traversing Diamond and Si Crystals

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Abstract

Detailed experimental investigations of photon multiplicities for 150 GeV electrons/positrons traversing thin diamond and Si crystals have been performed. Along axial directions up to 10 photons are emitted in 1.5 mm diamond for a radiative energy loss larger than 4 GeV. This corresponds to a mean free path for photon emission of about two orders of magnitude shorter than in an amorphous target. This is in agreement with an enhanced radiative energy loss of ~30 times that in amorphous targets. The strongly enhanced photon emission leads to radiation cooling which can result in particles exiting the crystal with a reduced angle to the axis. For incidences along planar directions the average multiplicity is still above one, even for the thinnest crystals used in the present experiment, so a single-photon spectrum can only be obtained for thicknesses \( \leq 50\mu m \), which, on the other hand, is comparable to the coherence lengths for GeV photons, leading to destruction of the coherent effects.
1. Introduction

Relativistic particles incident on crystalline targets in directions close to axial/planar directions will interact with the electromagnetic fields from the atomic rows/planes. The interaction length for GeV particles can be very large \(-\) mm. This means that the particles have a fair chance to scatter coherently on many atoms along their way. This coherence in scattering leads to strongly enhanced radiation emission \(-\) coherent bremsstrahlung. Channeling is another coherent process leading to a strong steering effect, different for positive and negative particles. Here the interaction with axes/planes can be described by a potential \(-\) the continuum potential \(-\) obtained by smearing the charges along the rows/planes of atoms. The corresponding electromagnetic fields are \(E \sim 10^{11} \text{Volts/cm}\) at a distance of \(0.05 - 0.1 \text{ Å}\) from the axis. In the GeV region it turns out that the continuum description can be used for incident angles much larger than the channeling angles (cf. Ref. 3 for a review). When the energy of the particles gets into the multi-Gev region, the photon emission causes a significant recoil. On the other hand, the pure motion of the particle still remains classical. For a general description of penetration phenomena at such energies a proper QED calculation has to be used; but this is very complicated. Fortunately, the Baier group has shown that the so-called constant field approximation (CFA) is a good approximation for small incident angles to crystal axes/planes. The critical angle \(\theta_0\) for this approximation is given by \(\theta_0 \equiv U/mc^2\). Here, \(U\) is the depth of the axial/planar potential and \(m\) the rest mass of the electron. For incident angles \(\theta \gg \theta_0\) the Born approximation is justified and for \(\theta \ll \theta_0\) the CFA is a good approximation. It should furthermore be pointed out that probabilities for QED processes in the electromagnetic fields from axes/planes are determined by the magnitude of these fields in the rest system for the incoming particle. Hence, the quantum parameter \(\chi\) is given by \(\chi = \gamma \cdot E/E_0\), where \(E_0 = 1.3 \cdot 10^{16} \text{V/cm}\) and \(\gamma = 10^5 - 10^6\). This means that crystalline targets are unique for investigating QED processes in strong fields because here large \(\chi\)-values \((\geq 1)\) can be easily obtained. Until now, the present CERN NA43 collaboration has investigated the influence of crystalline fields on radiation emission for \((50-240)\ \text{GeV}\) electrons and positrons traversing diamond, Si, Ge, and W crystals (cf. Refs. 5-8 for recent results). The radiation emission is, in general, enhanced dramatically for incidences close to axial/planar directions as compared to yields from amorphous targets of the same thickness. The enhancements are generally inverse proportional to the atomic numbers of the targets. The yields for diamond are two orders of magnitude larger than for amorphous targets.

2. Photon multiplicity and radiation cooling

The dramatic enhancements of radiation emission from multi-Gev electrons/positrons traversing single crystals have raised many questions both theoretically and experimentally, like a) How many photons are emitted during the passage? and b) What is the influence of this strong radiation on the angular distribution of the particles behind the crystal? After the emission of a photon, the transverse energy \(E_\perp = 1/2m\gamma v_\perp^2 + U(r)\) decreases. Here \(v_\perp\) is the transverse velocity. This so-called radiation cooling will counteract the multiple scattering. Furthermore, the reduction in \(E_\perp\) might result in an increase of the number of channeled particles from above-barrier particles. For electrons, such a situation can lead to dechanneling followed by 're-channeling'. This means that such particles spend a considerable time in the strong field from the atomic axis/plane, leading to strongly enhanced radiation emission and also enhanced multiple
scattering.

Several groups have studied theoretically the radiation cooling and multi-photon processes. The studies were firstly motivated by the observation of an unexpected peak in the photon spectrum from 150 GeV electrons incident on a Ge crystal. Different explanations were given at that time. Most theoretical papers related the peak to radiation cooling.\textsuperscript{10–13} Later on, experimental results\textsuperscript{5} clearly showed that the unexpected photon peak was due to multi photons detected as one photon. In sufficiently thin crystals the peak disappeared. These measurements brought up new calculations of radiation emission.\textsuperscript{4,14–18}

In general, the agreement between calculations and experimental results are reasonable. But basic issues still remain to be investigated, like: Photon multiplicity, the role of radiation cooling and multiple scattering, single photon spectra, influence of the Landau–Pomeranchuk effect, etc.

The present paper describes some new, experimental results (from the NA43 collaboration) with respect to photon multiplicities and radiation cooling.

3. Experimental

The experiment was performed in the North Area of the CERN SPS. The beam H2 is a tertiary one containing electrons, positrons or pions with energies ranging from 35 GeV to 300 GeV. The experimental arrangement is shown schematically in Fig. 1. A drift chamber (DC1) was placed 40 m in front of the target and another drift chamber (DC2) was placed immediately (15 cm) behind the target. In this arrangement the influence of multiple scattering on angular resolution is minimum on the incident side. A third drift chamber (DC3) is placed 20 m behind the target. Vacuum tubes, (10\textsuperscript{-2} torr) are used between the drift chambers. The angular resolution on incident and exit sides are 5 µrad or better due to the good position resolution (100 µm) of the drift chambers. Scintillation counters (SC1, SC2, SC3) were used to define the useful fraction of the beam. Bend 1 and Bend 2 remove the background from upstream material. By means of Bend 3 the beam was bent away from the photon detectors and into the dump. The lead–gass photon detector had a resolution of 7% (FWHM) at 150 GeV. Helium bags were introduced between Bend 3 and the photon detector to reduce the background. Inserted in the figure is shown the measured incident angular resolution of the beam with FWHM of 54 µrad and 96 µrad in the horizontal and vertical directions, respectively. By means of the drift chambers it is possible to select specific areas of the target crystals and thereby check the stability and the bending of the crystal both before and during the run. In the present experiment we used two (100) diamond crystals (0.5mm and 1.5 mm thick) and two (110) Si crystals (0.6 mm and 1.4 mm thick). The diamond crystals were synthetic ones, grown for the Johannesburg group. The Si crystals were produced from commercial high-grade intrinsic materials. The mounting of the crystals in the goniometer was performed by gluing them in one single point on a copper ring, which was mounted in the goniometer. The same technique has been used in our experiments the last years. The on–line alignment of the crystals was performed by finding planar directions and from the stereograms the axial direction was found and controlled. Both in on–line and off–line analysis planar and axial directions are defined as the ones giving maximal radiation emission. The accuracy of the axial setting is about 5 µrad. Figure 2a shows such an alignment scan for the 0.6 mm thick (110) Si crystal. Clearly, even higher–order planes give distinct signals.
Photon multiplicities were measured by a special detector arrangement installed in front of the lead–glass detector, which consists of a 1 mm thick lead converter followed by a 0.5 mm thick solid state detector (SSD) with an area of 600 mm. From the particle data book it is found that the probability of a photon converting to $e^+/e^-$ pairs is 13% in the 1 mm thick lead. For normalization and background subtraction we used photon spectra for incidence along random directions in the crystal. Single photon spectra were here assumed. From the lead–glass spectrum certain energy windows for emitted energy have been considered. The conversion probability for photons in this window gave the average photon multiplicity.

From the very good energy resolution of the SSD it is possible to discern between 1, 2, 3, ...... minimum ionizing particles (MIP). In Fig. 2b a typical SSD spectrum, used for multiplicity measurements, is depicted. Figure 2c shows random conversion probabilities (in %) with and without the 1.0 mm thick Pb–converter. The conversion without the 1.0 mm Pb comes from the mylar windows, air gaps, etc. The difference between the two conversion probabilities (14 %) is in a very good agreement with the theoretical value mentioned above. The thickness of the Pb–converter was chosen such that the preshower is linear dependent of the number of incident photons.

4. Results and discussion

In the following, the experimental radiation spectra are plotted as a function of photon energies normalized to the incident particle energy; all photon spectra being power spectra. The emitted radiation intensity is normalized to that from an equivalent amorphous target of the same thickness. When curves are drawn through data–points, it is only to guide the eye.

4.1 Radiation emission and multiplicity

4.1.1 Axial case

In the following we present experimental data for 150 GeV electrons and positrons incident on the 1.5 mm thick (100) diamond crystal together with the 0.6 mm thick and the 1.4 mm thick (110) Si crystal. Figs. 3, 5 and 7 show electron data while Figs. 4 and 6 give positron data. In the figures are firstly given the photon spectra for increasing incident angles to the axis. Secondly, the average multiplicities are given as a function of the emitted energy, and, finally, the total average photon multiplicities are shown as the function of incident polar angle to the axis.

The first general result is that for incidence close to axial direction every electron/positron emits many photons during passage of the crystal, even for an 0.6 mm thick Si crystal. Here it should be remembered that events, where the total radiated energy is less than 4 GeV, are not recorded. This is done in order to reduce dead–time during data taking and thereby increases the number of events with large energy loss. It is furthermore clear that the maximum number of photons per incident particle is obtained for maximum radiated energy. Normally, the number of photons emitted falls off for increasing photon energy. This is also the case for axial channeled electrons, but only for very thin crystals (cf. Ref. 5). These results show that the influence of strong crystalline fields on radiation emission is so dramatic, that, in order to investigate single–photon spectra, very thin crystals — 50 μm or less — have to be used. Such investigations are, unfortunately, very complicated to analyse because the background from drift chambers, vacuum windows, etc. corresponds to some hundred μm of Si.

In a later experiment we detected single photons using a pair spectrometer, but the
energy of the emitting particle cannot be measured.

Another general result is clear: Large multiplicities are obtained for incident angles much larger than the Lindhard channeling angles, \( \psi_1 \). For 150 GeV electrons on (100) diamond and (110) Si the critical channeling angles \( \psi_1 \) are 25 \( \mu \)rad and 37 \( \mu \)rad, respectively. From a comparison between the electron and positron data the strong steering effect inside the channeling region is clear: Here electrons are focused around the nuclei, giving rise to exceptionally high energy loss and multiplicities. For channeled positrons the steering effect pushes the positrons away from the nuclei, giving rise to a reduction in energy loss and multiplicities. For positrons, the maximum multiplicities occur for incident angles around 1.5 times the Lindhard angles — in good agreement with the general channeling picture for positive and negative particles (cf. Ref. 3 and references therein).

The large photon multiplicities (5–10) along the axial directions in diamond and Si correspond to a strongly reduced mean free path \( \lambda_f \) for photon emission. In a random direction the mean free path \( \lambda_f \) is given by

\[
\lambda_f \sim \frac{L_{\text{rad}}}{\ln E_0/\hbar \omega_{\text{min}}},
\]

where \( L_{\text{rad}} \) is the radiation length, \( E_0 \) the particle energy and \( \hbar \omega_{\text{min}} \) the minimum photon energy. For 150 GeV electrons \( \lambda_f \) is 3–4 cm in amorphous diamond and Si. Thus, along axial directions the average mean free path for photon emission is reduced by approximately two orders of magnitude in diamond and Si.

### 4.1.2 Planar case

In an earlier experiment we found, for the first time, a very pronounced high-energy photon peak for incidence along the \{110\} planes and 0.3 mrad to the (100) axis in diamond crystal. The same effect was found in Si-crystals. From calculations by Baier et al.\(^4\) it was predicted that the peak should mostly contain single photons. In Figs. 8 and 9 are shown results from such investigations for 150 GeV electrons incident on the 0.5 mm thick and the 1.5 mm thick (100) diamond crystal. Also shown in the figures are the photon spectra for different incident angle regions to the \{110\} plane (a) together with multiplicities for incidence parallel to the plane (b) and for scans across the plane (c). Clearly, in none of the cases do we obtain multiplicities around 1 (single photons) even for the high-energy photons. Like in the axial case, this is most likely due to crystal thickness, so that the number of lower energy photons is still enhanced to such an extent that a high-energy photon is accompanied by a low-energy one. This is even the case for 150 GeV positrons incident on the 1.5 mm thick diamond, as can be seen from Fig. 10. It is furthermore also clear that the photon spectra are strongly enhanced, generally for incident angles far outside the planar channeling angle, which in the present case is only 7 \( \mu \)rad. On the other hand, strong field effects are expected for incident angles larger than \( \theta_0 = U/mc^2 \), which for the present case is around 100 \( \mu \)rad.

For incident angles close to planar directions but away from the axial region, normal coherent bremsstrahlung is expected. Figure 11 depicts photon spectra (a) and the multiplicities (b) for 150 GeV electrons incident at different angle regions close to the \{110\} plane in the 1.5 mm thick diamond — but 10 mrad away from the (100) axis. Clearly, photon multiplicities of 4–5 are found in the high photon energy region — and only at incident angles larger than 50 mrad the multiplicity comes close to 1, i.e., single photons are emitted.
4.2 Energy loss

The energy loss for GeV electrons/positrons is practically all due to radiation emission. For 150 GeV electrons and positrons incident on the 0.6 mm thick [110] Si crystals and the 1.5 mm thick (100) diamond the radiative energy losses are shown in Fig. 12. For a comparison it should be mentioned that the radiative energy losses for amorphous diamond and Si of the same thicknesses are 2 GeV and 1 GeV, respectively. It is in general seen that inside the channeling regions positrons lose considerably less energy than electrons — most pronounced here for the Si-case. This difference between diamond and Si could be explained as being due to angular resolution. Outside the channeling region the energy loss in both cases is (25-30) times the amorphous values, showing the dramatic effect of the strong fields from the axis.

Experimentally, the evident difference between positrons and electrons shows that the angular resolution is much better than the channeling angle (25 μrad for diamond). The fact that the electron–positron curves do not coincide outside the channeling region for diamond can be explained by a normalization problem in this specific experiment. The positron beam was contaminated with non-radiating particles (protons).

It should furthermore again be pointed out that the Lindhard angles for channeling were calculated in connection with penetration of MeV ions. From the present results it can be seen that this classical picture of channeling holds for multi-hundred GeV electrons/positrons.

4.3 Radiation cooling

As mentioned above, radiative cooling has been discussed ever since the beginning of channeling radiation in the early eighties. With reference to electron cooling of ion beams it has been proposed just to pass a beam of positrons through a crystal in order to decrease the angular spread of the beam.

In the present experiment we have the first preliminary investigations of radiation cooling, which means — as mentioned above — that the transverse energy \( E_{\perp} = \frac{1}{2m}v_{\perp}^2 + U(r) \) is reduced due to photon emission. Because of energy conservation we have for the exit angle to the axis \( \theta_{\text{exit}} = (E_{\perp}/E)^{1/2} \). For GeV particles incident close to crystal axes, the most pronounced scattering effect is the doughnut scattering. From this effect a parallel beam of momentum \( \vec{p} \) will undergo correlated scatterings on the rows of atoms (strings). In the transverse plane only the momentum vectors \( \vec{p}_{\perp} \) are rotated. After a certain number of string collisions \( \vec{p}_{\perp} \) may be found in any direction. Hence, the net result is that the incident parallel beam appears as a ring-shaped (doughnut) distribution in the exit angle space with a radius being equal to the incident angle \( \theta_{\text{in}} \) to the axis. If \( E_{\perp} \) is reduced during the crystal passage, this will lead to smaller \( \theta_{\text{exit}} \). Multi scattering leads to a general smearing of the doughnut and increases in the transverse energy \( E_{\perp} \). In our experiment we have compared the doughnut scattering for 150 GeV/c electrons/positrons with \( \pi^- \). In this way it was possible to compare this type of scattering processes for radiating (leptons) and non-radiating particles, \( \pi^- \). The azimuthal equalization in the doughnut gives a qualitative measure of the number of string scatterings.

The doughnut scattering for 150 GeV electrons (A,C,D), positrons (E,F) and \( \pi^- \) (B) is shown in Fig. 13, where the incident angle regions are shown as well. In the figure, C) and E) the particles have radiated photon energies less than 70 GeV and D) and F) correspond to radiated energies above 70 GeV.

As a general result, it is seen that the degree of equalization in the doughnut is
larger for particles with large radiative energy levels, i.e., high photon multiplicities. A comparison between electrons and $\pi^-$ (figures A and B)) also indicates that radiation emission results in more particles exiting with small angles to the axis, radiation cooling.

In Fig. 14 is shown scans across the doughnuts (integrated in azimuth) for 150 GeV $\pi^-$ and electrons incident in three angle regions to the $(100)$ axis in the 1.5 mm diamond. By plotting the change in polar angles ($\theta_{\text{out}} - \theta_{\text{in}}$), the azimuthal scattering in doughnuts are eliminated. From the present curves it is clear that radiation emission leads to an increased probability for large scattering angles, especially for incidence in the channeling region. In this angle region the photon multiplicity (Fig. 3) for the present crystal is 8–10. The figures also demonstrate that particles, exiting with smaller angles to the $(100)$ axis than the incident ones, are obtained for incidence at $(2-3)\psi_1$. These particles are above barrier particles, which through radiation emission have lost transverse energy $E_T$ and finally become channeled just before exiting the crystal.

The exit scattering angle distributions for 150 GeV electrons incident on the 0.6 mm thick $(110)$ Si (a) and the 1.5 mm thick diamond is shown in Fig. 15. The plots show scattering distributions for different radiative energy loss. Two results come out clearly: Firstly, we obtain more particles exiting with reduced angles to the axes only for larger energy losses. Secondly, the cooling effect is more pronounced for the 0.6 mm thick Si than for the 1.5 mm thick diamond. These results indicate that there is an optimum crystal thickness for which one obtains maximum particles exiting along axial directions. In the diamond case, the radiative energy losses and photon multiplicities are two times higher than in the Si case.

The radiation cooling, as discussed by many theoretical groups\textsuperscript{14–18}, seems difficult to detect, especially because of the very strong doughnut effect. Further on, the cooling effects depend on crystal type and thickness. The radiation cooling for multi-GeV electrons/positrons might result both in reduced and increased exit scattering angle distributions. Detailed investigations of these effects will be published elsewhere.

5. Conclusion

From the present experimental investigations on photon multiplicities and radiation cooling it can be concluded that in a 1.5 mm thick diamond 150 GeV electrons emit up to 10 photons along axial directions for a total radiative energy loss larger than 4 GeV. This high multiplicity is found for incident directions much larger than the Lindhard channeling angles but fall off outside the angle $\theta_0 = U_0/mc^2$. This dramatic enhancement of radiation emission along crystalline directions means that, in order to obtain a true single photon spectrum, very thin crystals ($\leq 50\mu$m) have to be used. On the other hand, the random background from drift chambers, vacuum windows, etc. in a setup like NA43, corresponds to some hundred $\mu$m. Further on, the crystals should not be thinner than the coherence lengths, which for 1 GeV photons in our case is $\sim 50\mu$m. Therefore, to obtain single photon spectra, where the energy of the emitting particle is known, is very difficult experimentally. In strong crystalline electromagnetic fields the radiative energy loss is enhanced between one and two orders of magnitude. Outside the channeling region electrons and positrons give the same results. The strong doughnut scattering for GeV particles incident along axial directions complicates a true measurement of radiation cooling. In the present experiment, radiation cooling was detected either as a reduced exit angle distribution or as extraordinary large scattering
angles, depending on crystal type and thickness.

References

1 G. Diambrini Palazzi, Rev.Mod.Phys. 40 (1968) 611.


Figure Captions

Fig. 1: The experimental setup. Beam profiles for a typical electron run are inserted. The profiles are obtained on-line from position detection in the two drift chambers (DC1, DC2). The profiles vary somewhat for the different particles.

Fig. 2: a) Alignment of the 0.6 mm thick (110) Si crystal using radiation emission from 150 GeV electrons. b) Pulse height spectrum from the 0.5 mm thick solid-state detector placed just behind the Pb-converter for multi-photon detection. c) Photon conversion probability in the 1 mm thick lead and mylar windows (left) and mylar windows alone (right).

Fig. 3: Photon spectra (a) for 150 GeV electrons incident on the 1.5 mm (100) diamond crystal as a function of total radiated energy. The spectra are shown for increasing incident angle regions to the (100) axis. In (b) is shown the photon multiplicities for selected incident angle regions. The incident angle regions are given in the figures.

Fig. 4: Photon spectra (a) for 150 GeV positrons incident on the 1.5 mm thick diamond with increasing angles to the (100) axis. In (b), the multiplicity spectrum as function of radiated energy for (40–60) μrad incident angles to the axis is shown. The general average multiplicities as functions of polar angles to the axis are shown in (c).

Fig. 5: Same as Fig. 4 but for 150 GeV electrons incident on the (100) axis in the 0.6 mm thick Si crystal.

Fig. 6: Same as Fig. 4 but for 150 GeV positrons incident on the (110) axis in the 0.6 mm thick Si crystal.

Fig. 7: Same as Fig. 5 but for the 1.4 mm thick (110) Si crystal.

Fig. 8: Photon spectra (a) for 150 GeV electrons incident on the 0.5 mm thick (100) diamond. The incident directions are around the {110} plane but always at 0.3 mrad with respect to the (100) axis. In (b) is shown the photon multiplicity for incidence at ±10μrad to the {100} plane, and in (c) the average photon multiplicities for varying incident angle θ to the {110} plane.

Fig. 9: Same as Fig. 8 but for the 1.5 mm thick diamond crystal.

Fig. 10: Same as Fig. 9 but for 150 GeV positrons.

Fig. 11: Photon spectra (a) and photon multiplicities (b) for 150 GeV electrons incident at 10 mrad from the (100) axis in the 1.5 mm thick diamond crystal. The incident angle regions to the {110} plane are given in the figures.
Fig. 12: Radiative energy loss for 150 GeV electrons and positrons traversing the 0.6 mm (110) Si crystal (a) and the 1.5 mm (100) diamond. All curves are given as function of the incident angles to the respective axes.

Fig. 13: Exit angle distributions (doughnuts) for 150 GeV electrons (A,C,D), positrons (E,F) and π⁻ (B) traversing the 1.5 mm thick (100) diamond crystal. The incident angles are (50–60) μrad to the (100) axis.

Fig. 14: Polar scattering angles for 10 GeV π⁻ and electrons incident on the 1.5 mm diamond. Incident angle regions are given in the figure.

Fig. 15: Polar scattering angle distributions for 150 GeV electrons traversing the 0.6 mm thick (110) Si crystal (a) and the 1.5 mm thick (100) diamond. The incident angle regions are in both cases (50–100 μrad to the axes. The exit polar angles are normalized to the incident one. The different radiative energy losses are indicated on the curves.
Fig. 2.
Kirsebom et al.: Experimental investigations of photon multiplicity & radiation.
150 GeV electrons incident on \(<100>\) - axis of 1.5 mm Diamond

ENHANCEMENTS

PHOTON MULTIPLICITY

Fig. 3. Kirsebom et al.: Experimental investigations of photon multiplicity & radiation......
150 GeV positrons incident on <100> - axis of 1.5 mm Diamond

**Fig. 4.** Kuzelov et al.: Experimental investigations of photon multiplicity & radiation.
150 GeV electrons incident on <110> - axis of 0.6 mm Silicon crystal

**ENHANCEMENTS**

Incident polar angle ranges w.r.t crystal axis:
- • 0-10 μrad
- ○ 10-20 μrad
- □ 20-30 μrad
- ▼ 30-40 μrad
- ◇ 40-50 μrad
- ♦ 50-80 μrad

**PHOTON MULTIPLICITY VS INCIDENT POLAR ANGLE**

- □ $\theta_m = 0-20$ μrad
150 GeV positrons incident on <110> -axis of 0.6 mm Silicon crystal

ENHANCEMENTS

Incident polar angle ranges wrt crystal axis:

- 0-10 µrad
- 10-20 µrad
- 20-30 µrad
- 30-40 µrad
- 40-50 µrad
- 50-60 µrad

PHOTON MULTIPLICITY

θ\text{in} = 0-10 µrad

PHOTON MULTIPLICITY VS INCIDENT POLAR ANGLE

Radiated energy [GeV]

Fig. 6.
Kirsebom et al.: Experimental investigations of photon multiplicity & radiation...
150 GeV electrons incident on \(<110>\) - axis of 1.4 mm Silicon crystal

Incident polar angle ranges wrt crystal axis:
- 0-5 \(\mu\)rad
- 5-10 \(\mu\)rad
- 10-20 \(\mu\)rad
- 20-30 \(\mu\)rad
- 30-40 \(\mu\)rad
- 40-50 \(\mu\)rad
- 50-80 \(\mu\)rad

Radiated energy [GeV]

PHOTON MULTIPLICITY

\(\theta_{in} = 0-20 \, \mu\text{rad}\)

PHOTON MULTIPLICITY VS INCIDENT POLAR ANGLE

Fig. 7. Kirsebom et al.: Experimental investigations of photon multiplicity & radiation...
150 GeV electrons incident on
0.5 mm Diamond, 0.3 mrad off <100> - axis

ENHANCEMENTS

Incident angle ranges wrt {110} crystal plane:
- -5 to +5 µrad
- -10 to -20 µrad
- -30 to -40 µrad
- -60 to -85 µrad

Radiated energy [GeV]

PHOTON MULTIPLICITY

Radiated energy [GeV]

PHOTON MULTIPLICITY VS ANGLE WRT (110) - PLANE

θy, angle wrt plane [µrad]

Fig. 8.
Kirsebom et al.: Experimental investigations of photon multiplicity & radiation...
150 GeV electrons incident on
1.5 mm Diamond, 0.3 mrad off <100> - axis

Figure 9. Enhancements of radiated energy vs. photon multiplicity for various incident angles with respect to the (110) crystal plane.
150 GeV positrons incident on 1.5mm Diamond, 0.3 mrad off <100> - axis

ENHANCEMENTS

PHOTON MULTIPLICITY

PHOTON MULTIPLICITY VS ANGLE WRT {110} - PLANE

Fig. 10. Karsebon et al.: Experimental investigations of photon multiplicity & radiation...
150 GeV electrons incident on
1.5 mm Diamond, 10mrad off <100> - axis

Figure 11.
Kirsebom et al.: Experimental investigations of photon multiplicity & radiation....
Radiation yield on-axis, comparing $e^+$ and $e^-$

150 GeV on <110> - axis of 0.6 mm Silicon crystal

![Graph](image)

150 GeV on <100> - axis of 1.5 mm Diamond crystal

![Graph](image)
Doughnut scattering on 1.5 mm Diamond

Fig. 13.
Kisebom et al.: Experimental investigations of photon multiplicity & radiation.
COOLING/HEATING

150 GeV electrons and pions
incident on <100> axis of 1.5 mm Diamond

Incident polar angle
ranges wrt crystal axis:

- $\theta_{\text{in}} = 0-20$ $\mu\text{rad}$
- $\theta_{\text{in}} = 20-30$ $\mu\text{rad}$
- $\theta_{\text{in}} = 80-100$ $\mu\text{rad}$

Fig. 14.
Kirstem et al.: Experimental investigations of photon multiplicity & radiation......
COOLING AND NO COOLING

150 GeV electrons incident on
<110> -axis of 0.6 mm Silicon crystal

\[
\theta_f = \frac{\theta_{\text{out}}}{\theta_{\text{in}}}
\]

- \(50 < \theta_{\text{in}} < 100 \mu\text{rad (wrt crystal axis)}\)

\[
\begin{align*}
\text{dN}/\text{d}\theta_f & \quad \text{at} \\
0,0 & \quad 0,16 \\
0,04 & \quad 0,08 \\
0,08 & \quad 0,12 \\
0,12 & \quad 0,16 \\
0,16 & \quad 0,20
\end{align*}
\]

- \(3 < E_{\text{LO}} < 25 \text{ GeV}\)
- \(25 < E_{\text{LO}} < 57 \text{ GeV}\)
- \(57 < E_{\text{LO}} < 90 \text{ GeV}\)
- \(90 < E_{\text{LO}} < 111 \text{ GeV}\)
- \(111 < E_{\text{LO}} < 150 \text{ GeV}\)

150 GeV electrons incident on
<100> -axis of 1.5 mm Diamond crystal

\[
\theta_f = \frac{\theta_{\text{out}}}{\theta_{\text{in}}}
\]

\[
\begin{align*}
\text{dN}/\text{d}\theta_f & \quad \text{at} \\
0,0 & \quad 0,16 \\
0,04 & \quad 0,08 \\
0,08 & \quad 0,12 \\
0,12 & \quad 0,16 \\
0,16 & \quad 0,20
\end{align*}
\]

- \(3 < E_{\text{LO}} < 25 \text{ GeV}\)
- \(25 < E_{\text{LO}} < 57 \text{ GeV}\)
- \(57 < E_{\text{LO}} < 90 \text{ GeV}\)
- \(90 < E_{\text{LO}} < 111 \text{ GeV}\)
- \(111 < E_{\text{LO}} < 150 \text{ GeV}\)

Fig. 15. Experimental investigations of photon multiplicity A radiation...