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Laboratoire de l'Accélérateur Linéaire

STUDY OF A POSITRON SOURCE GENERATED

BY PHOTONS FROM

ULTRARELATIVISTIC CHANNELED PARTICLES

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Abstract

Radiation by channeled electrons in Germanium and Silicon crystals along the <110> axis is studied as a very promising photon source of small angular divergence for positron generation in amorphous targets. Radiation rates for different crystal lengths - from some tenths of mm to 10 mm - and two electron incident energies, 5 and 20 GeV, are considered and a comparison between the two crystals is presented. Thermic behaviour of the crystal under incidence of bunches of 10^{10} electrons is also examined. The corresponding positron yields for tungsten amorphous converters - of 0.5 and 1 X_0 thickness - are calculated considering the case of a Germanium photon generator. Assuming a large acceptance optical matching system as the adiabatic device of the SLC, accepted positrons are evaluated and positron yields larger than 1 e^+/e^- are obtained.

Introduction

In recent years, there has been increasing interest in the use of high intensity positron beams in storage and collider rings. With the advent of linear colliders such as SLC or others presently under study, more stringent conditions are imposed on positron intensity and emittance. Positron beam intensity and emittance are strongly related to the methods of production and collection.

Electromagnetic interaction of an electron beam with the atoms of a thick converter is the main process used in existing positron sources. The maximization of the luminosity, required for a linear collider, leads to increase the incident electron intensity, energy and repetition rate and hence the converter thickness. But thermic and radiation problems limit the incident electron beam power and rotating targets are somewhat difficult to handle.

Instead of using very high power electron beams on thick targets we could use photons to create positrons by pair production in the target. Photons may be generated by undulatory radiation of high energy electron beams. A solution using a long helical undulator has been already proposed for the VLEPP project [1].

Rather than using a long undulator we can use the radiation emitted by channeled electrons in oriented crystals. A study of this kind of source is presented here : the method has been already reported very recently by one of us (FC) [2].
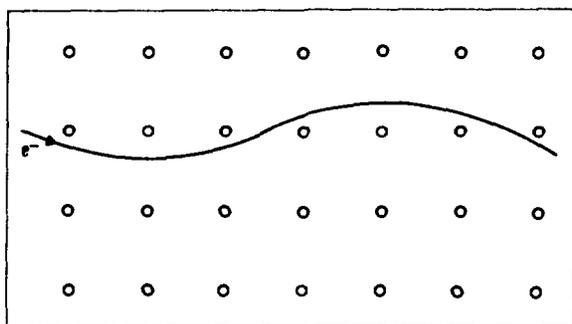

Figure 1 : Electron channeling in a crystal. This drawing is considerably exagerated. Oscillations of channeled particles occur with wavelengths of thousands of lattice spacings

Radiation in oriented crystals

An electron incoming on a crystal at small angle relative to an atomic string (Fig. 1), instead of being incoherently scattered by individual atoms, feels only the *average crystalline potential* (Linhard) in the longitudinal direction

$$\bar{V}(x,y) = \frac{1}{L}\int_0^L V(x,y,z)\, dz, \qquad (1)$$

L being the crystal thickness. Its longitudinal motion is then uniform while its transverse motion is governed by the non relativistic hamiltonian

$$H_T = \frac{P_T^2}{2E} + \bar{V}(x,y) \qquad (2)$$

and the corresponding *transverse energy* E_T is conserved. $E = m\gamma$ in the total electron energy.

$\bar{V}(x,y)$ has deep wells at the string locations. *Channeled electrons*, which are in bound states ($E_T < 0$) in such wells describe helicoïdal trajectories around the corresponding strings. *Above barrier electrons* which have $E_T > 0$, scatter from well to well.

Instead of incoherent Bremsstrahlung, channeled electrons emit the *Kumakhov radiation* [3] analogous to the radiation of a magnetic undulator, but with much larger intensity and shorter wavelengths, due to the strength of the Linhard field ($\sim 10^2 - 10^3$ Volt/Å $\sim 3.10^3 - 3.10^4$ Tesla) and to the short period ($\sim 1\,\mu$m) of the oscillations. Above barrier electrons also radiate strongly (coherent Bremsstrahlung). As in synchrotron radiation, there is a cutoff frequency given by

$$\frac{\hbar\,\omega_c}{E - \hbar\,\omega_c} = \frac{\gamma e\,\mathcal{E}\hbar}{m^2 c^3} \qquad (3)$$

where $\mathcal{E}$ is the maximum electric field. For 5, 10 and 20 GeV electrons, we get 0.4, 1.4 and 5 GeV respectively for ω_c.

To evaluate the radiation rate, we have built a computer simulation program [4] which calculates the electron trajectories and the photon emission probabilities in oriented crystals. This program uses the semi-classical Baïer-Katkov formula for radiation in a nonuniform field [5] and takes also into account multiple scattering.

Some Results from the Simulation Code of the Channeling

- The simulations have been done with the following initial conditions :
  - gaussian angular distribution with $\sigma = 20\,\mu$rad centered along the <110> axis of Germanium and Silicon crystals,
  - in each case 4000 incident electrons were treated,
  - crystal temperature : 300°K,
  - electron beam energies : 5 and 20 GeV,
  - the crystal is a disk of 4 cm diameter, different thicknesses up to 10 mm are considered. The heat is removed by a water cooled circuit around the crystal disk.

Cumulated Photon Yield

Figure 2 shows the total number of photons -regardless of their energy- for Silicon and Germanium as a function of crystal thickness. At small thickness, Germanium is more efficient due to the stronger electric field, but it saturates sooner than Silicon. This saturation indeed results partly from the decrease of the remaining electron energy and partly from dechanneling effects.
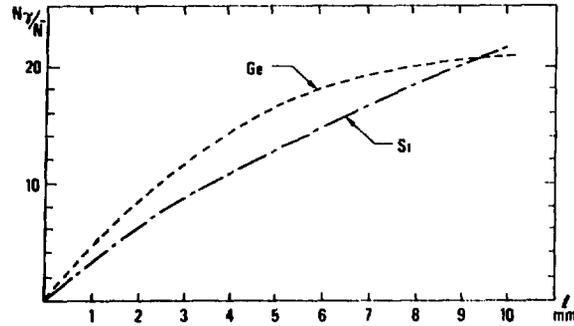

Figure 2 : Cumulated number of photons generated by 20 GeV electrons

Figure 3 compares the photon yields from 5 and 20 GeV electrons for Germanium.
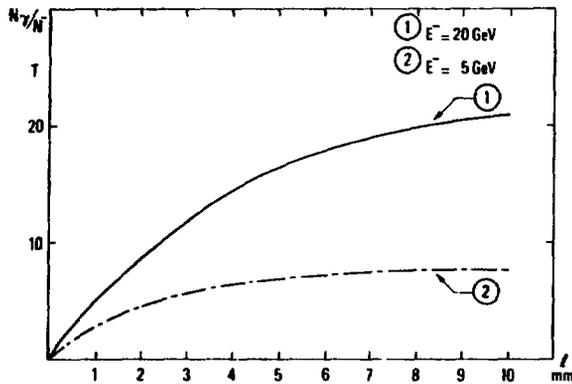

Figure 3 : Cumulated number of photons generated by 5 and 20 GeV electrons in Germanium

Photon Spectra

Figure 4 shows the photon spectra $dN\gamma/d(\log_{10} E\gamma)$ per electron at fixed electron energy ($E^- = 20$ GeV) for a crystal thickness of 1 cm, which roughly corresponds to equivalent cumulated photon yields for both crystals (see Fig. 2). Germanium gives a harder spectrum, due its stronger electric field, but this effect is attenuated by the stronger damping of the electron energy during propagation in the crystal.

Figure 5 compares the photon spectra at 5 and 20 GeV for 1 cm Germanium. Both the number and the average energy of the photons grow with electron energy. On the basis of eq. 3, one should expect the photon energies at maximum in curves 1 and 2 to be roughly in the ratio 16:1. This ratio is however only ~ 4:1 due to damping of the electron energy inside the crystal.
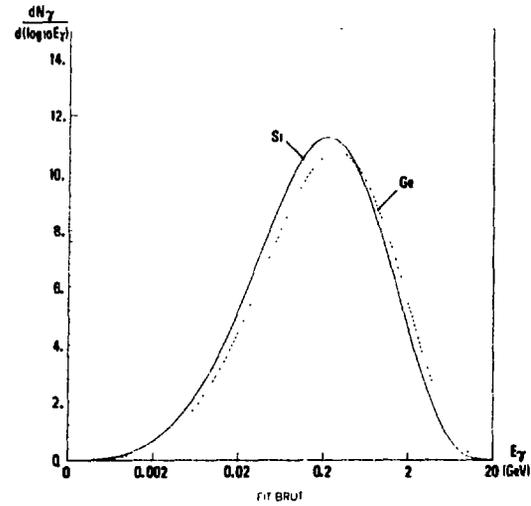

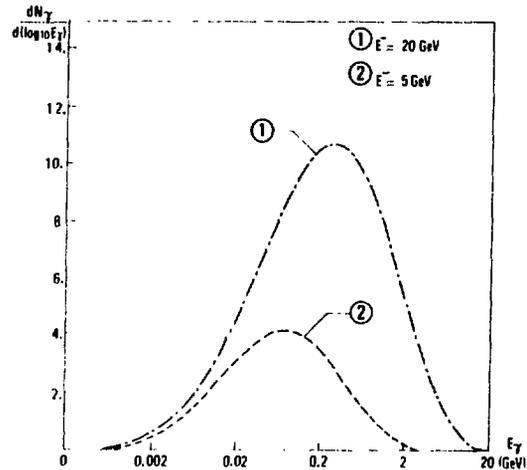Figure 4 : Photon spectrum obtained with 20 GeV electrons

Figure 5 : Photon spectrum at 5 and 20 GeV for Germanium
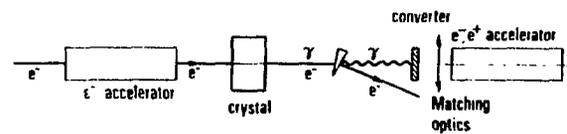
Conversion and Collection

Figure 6 : Layout of a positron source using channeling

At the exit face of the crystal photons are directed on an amorphous tungsten converter whereas the electrons are deflected, as shown on figure 6. Photon conversion into pairs has been simulated with EGS code [6] and positron distributions in energy, radius and angle have been obtained using three converter thicknesses : 0.5, 1 and 2 X_0.

Figure 7 shows the variation of the total e$^+$ yield with photon incident energy for two target thickness values.
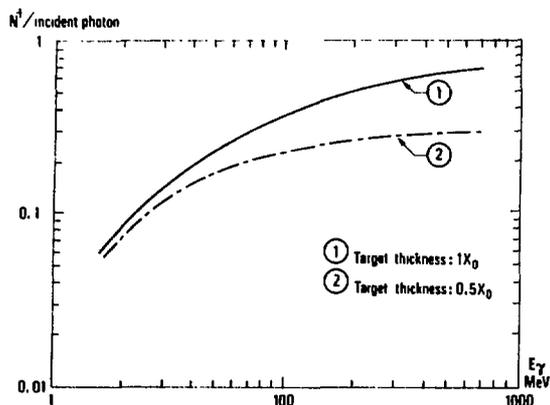

Figure 7 : Variation of the total yield with incident photon energy

A certain amount A(Eγ) of the positrons is captured by matching optics before being accelerated. A SLC-like collection system [7] using an adiabatically tapered magnetic lens is chosen. The following acceptance has then been assumed :

5 MeV $\leq$ E$^+$ $\leq$ 20 MeV

r $\leq$ 2.5 mm

θ $\leq$ 25° (corresponding to the accepted P$_T$ of the "central" value of 9 MeV)

The overall efficiency (number of collected positrons per incident electron) is expressed by :

$$N^+ = \int_{E_\gamma^m}^{E_\gamma^M} A\,(E_\gamma)\ g\,(E_\gamma)\ \frac{dN}{dE_\gamma}\,(E_\gamma)\,dE_\gamma$$

where A (E$_\gamma$) is the acceptance function derived from EGS
g (E$_\gamma$) is the total positron yield variation with incident photon energy
$\frac{dN}{dE_\gamma}$ is the photon spectrum
E$_\gamma^m$ and E$_\gamma^M$ are the photon energy boundary values.

This efficiency is presented, for photon energies from 10 MeV to 2 GeV, radiator thickness of 1 cm and electron incident energy of 20 GeV, in table 1.

Table 1

Converter thickness	Ge radiator	Si radiator
0.5 X$_0$	0.5	0.6
1 X$_0$	1.2	1.3

A comparison restricted to 10 MeV $\leq$ E$_\gamma$ $\leq$ 200 MeV has been made with a 2 X$_0$ converter and did not show significant changes with the 1 X$_0$ results for both crystals. Some remarks can be inferred from these results :
- A positron yield larger than one positron per incident electron is attainable using 20 GeV electron beam on 1 cm radiator and 1 X$_0$ converter thickness.
- Silicon seems slightly more interesting than Germanium for the simulated conditions. Such a difference should be confirmed if we choose a thicker crystal.

Thermal Consideration

The electron beam going through the crystal will lose some of its energy by ionization and cause radiation damage. We are dealing here only with the resulting temperature rise and mechanical stress associated with the temperature gradient. We assume that the crystal is brazed to a water cooled jacket in vacuum and that the heat conduction is isotropic in the crystal. We consider a 2 mm diameter electron beam of 10^{10} particles/bunch with a repetition rate of 1.8 kHz. Assuming an energy deposition rates of 7 MeV cm^{-1} and 3.6 MeV cm^{-1} in Ge and Si respectively, the steady state temperature difference between the axis and the cooling jacket is of 17° and 8° for Germanium and Silicon respectively. Pulse temperature rise is less than one degree for both types of crystal. Considering the stress, which is the most harmful effect in pulsed regime, the maximum value is much lower than 10^3 PSI for both crystals.

Energy deposition of the photon beam in the amorphous tungsten converter is evaluated for 0.5 and 1. X$_0$ thickness ; it exhibits a plateau of 1.4 and 7 MeV respectively per incident photon i.e. 30 and 140 MeV respectively per incident electron of 20 GeV on 1 cm crystal. These values represent less than 0.3 Joule/bunch and about 500 watts for the average power (N = 10^{10}, f = 1.8 kHz).

This is about 50 times lower than the power dissipated by an equivalent beam of 33 GeV in a 6 X$_0$ classical converter [8].

Summary and Conclusion

The use of channeling radiation to generate positrons in a converter offer at first sight a very promising way to obtain high intensity positron sources, provided the crystal resistance to radiation be successfully tested. Thermal behaviour of the whole system -radiator and converter- presents more interesting features than that of classical positron sources. The photon spectrum obtained with channeling is much broader than with a helical undulator and contains a long high energy tail. Although these high energy photons are less efficient from the positron collection point of view, this contribute significantly -the thicker the converter- to positron generation. At equivalent positron yields, the channeling solution presents a more compact facility.

Theoretical investigations using different crystals and channeling axis are under way. Experiments using the 1.5 GeV electron beam of the Linear Accelerator of Orsay are planned for preliminary measurements of channeling radiation and radiation resistance of the crystal.

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