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A High Intensity Positron Source for Linear Colliders

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Abstract

A high intensity positron source for linear colliders is proposed, which is able to deliver $3.6 * 10^{12}$ positrons per bunch train. The 250 GeV electron beam after the interaction point is used as a primary beam. In a wiggler high energy photons are emitted which will be converted into positrons in a thin target. Thermal load problems are reduced, because it is possible to use a target of low Z material with high heat capacity.
Source parameters (i.e. energy spectrum, source area) are estimated and preliminary target parameters as well as suitable target materials are given.

Introduction

The DESY/THD linear collider study requires a positron production rate of $3.6 * 10^{12}$ positrons per bunch train with a repititon rate of 50 Hz. This is a factor of 70 more than the present SLC source ($5 * 10^{10}$ positrons per bunch with 120 Hz rep. rate), which is up to now the positron source with the highest intensity.
At SLAC a 33 GeV electron beam strikes a 6 radiation lengths thick target of high Z material (W–Re–alloy). Per incident electron more than 50 positrons are generated [1] from which only one is captured, accelerated and transmitted into the damping ring, so that the over all efficiency e^+/e^- is ~ 1.
Numerical calculations show that a maximum temperature of 720 °C will be reached, if $7 * 10^{10}$ electrons strike the rotating target; nearly 8 kw thermal energy would be deposited in this case (120 Hz rep. rate). Due to stress estimations the maximum allowable intensity is limited to $5.3 * 10^{10}$ electrons per pulse [2].
In this paper a scheme is investigated, which is based on a proposal of Balakin and Mikhailichenko for the production of polarized positrons [3]. Our emphasis, however, is more on high e^+ intensities rather than polarization.
The principal layout of the source is shown in Fig. 1. The 250 Gev electron beam is used after the collision as a primary beam. After passing a special optics section the beam travels through a wiggler or undulator section. Here photons of 0 - 30 MeV are emitted which will be converted into electron-positron-pairs in a thin target, while the primary electrons are extracted with a dipole magnet.

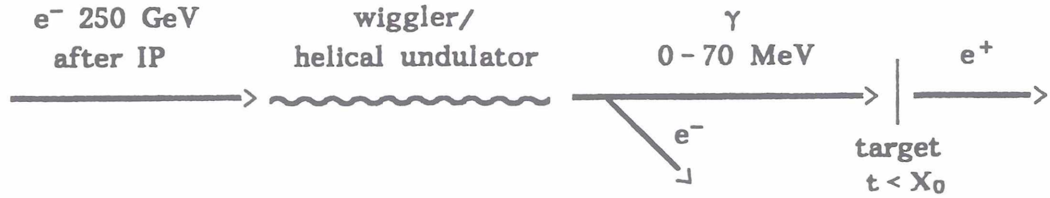

Fig. 1 Principal layout of the proposed positron source.

Putting the main emphasis on high intensity results in two major differences to the design of ref. [3]:
As we can accept a broad spectrum of photons because polarization is not important, we propose to use a permanent magnet wiggler (instead of an undulator) only about 50 m long which will be easier and less expensive to build. Secondly, using low Z target material with high specific heat capacity will substantially reduce thermal load problems.

Preparation of the disrupted beam to drive the undulator or wiggler

It is proposed to use the disrupted high energy electron beam after collision to generate the undulator or wiggler radiation. The beam has to pass the final focus quadrupole magnets of the oncoming beam to avoid mechanical damage as well as an intolerably high background in the detector anyway. It requires, however, some additional optical effort to match the disrupted beam to the undulator or wiggler (U/W) requirements. We will first consider these requirements and then show how to realize them.
The desired beam properties in the U/W section are governed by the requirement of being able to adjust the U/W radiation spot size on the conversion target over a range of 1−3 mm in diameter to optimize positron capture efficiency vs. thermal stress in the target. In addition, it is desirable to keep the transverse rms beam size in the U/W section below about 2 mm to reduce the costs of fabrication.
There are two contributions to the radiation spot size which add up more or less quadratically, namely the beam parameters in the U/W section and the opening angle α of the synchrotron radiation. Let's consider a U/W length of L = 50 m plus about 20 m for beam separation from the target. The rms spot size due to α is approximately:

$$\sigma_{SR} \approx \alpha \; (L/2 + D)$$

Since the opening angle of undulator radiation is approximately $1/\gamma$, we get in that case:

$$\sigma_{SR} \approx 1/\gamma \; (L/2 + D) \approx 0.1 \text{ mm}$$

which is negligible.
In the case of a wiggler with period length λ we get:

$$\alpha \approx \frac{q\,B}{p} * \frac{\lambda}{4} + \frac{1}{\gamma}$$

i.e

$$\sigma_{SR} \approx \frac{0.3}{8} * \frac{B[\,T\,] * (L + 2D)\,[\,m\,]}{E\,[\,GeV\,]} * \lambda \approx 0.024 * \lambda$$

Here, the wiggler is assumed to consist of sections of alternating constant magnetic field $B = \pm\ 1.76$ T. To achieve $\sigma_{SR} < 0.5$ mm, λ must not be larger than 21 mm, which sounds feasible on the basis of permanent magnet technology (at least for gap height smaller than 5 mm).
The minimum electron beam size contribution to the spot size σ_e^* is attained if the beam is focussed such that it would converge to a beam waist on the target if it were not deflected shortly before hitting the target (a larger spot size is always feasible by simply defocusing the beam).
For sake of cost minimization we also want a small rms beam size $\sigma_e(U/W)$ in the U/W section. Let us assume:

$$\sigma_e^*(x,y) = 0.5 \text{ mm} \qquad \sigma_{ey}(U/W) \leq 1 \text{ mm}$$
$$\sigma_{ex}(U/W) \leq 2 \text{ mm}$$

Then, the minimum tolerable β-function on the target is about:

$$\beta_y^* \approx (L+D) * \sigma_e^* / \sigma_{ey}(U/W) = 35 \text{ m}$$
$$\beta_x^* = 18 \text{ m}$$

The maximum β value inside the U/W device is then:

$$\beta_y(U/W) = \frac{(L+D)^2}{\beta^*} + \beta^* = 175 \text{ m}$$
$$\beta_x(U/W) = 290 \text{ m}$$

The maximum tolerable emittance of the disrupted beam is thus:

$$\hat{\varepsilon}_y = \frac{(\sigma_e(U/W))^2}{\beta(U/W)} = 5.7 * 10^{-9} \text{m} \qquad (1)$$
$$\hat{\varepsilon}_x = 1.4 * 10^{-8} \text{m}$$

The emittance of the disrupted beam can be estimated on the basis of the work of Yokoya and Chen [4]. For DESY/THD parameters we get:

$$\varepsilon_y^* \approx 40 \text{ nm} * 0.3 \text{ mrad} \approx 1 * 10^{-11} \text{ radm}$$
$$\varepsilon_x^* \approx 300 \text{ nm} * 0.6 \text{ mrad} \approx 2 * 10^{-10} \text{ rad m}$$

(values for most of the other collider studies are similar). The emittance just after the collision is therefore not a problem.
The only complication arises from the large energy spread of the disrupted beam due to the beamstrahlung. It has been calculated using formulae of ref. [4]. Fig. 2 shows the integrated energy spectrum $\int_0^{E/E_0} \Psi \, d(E/E_0)$ of the disrupted beam for various collider parameter sets.

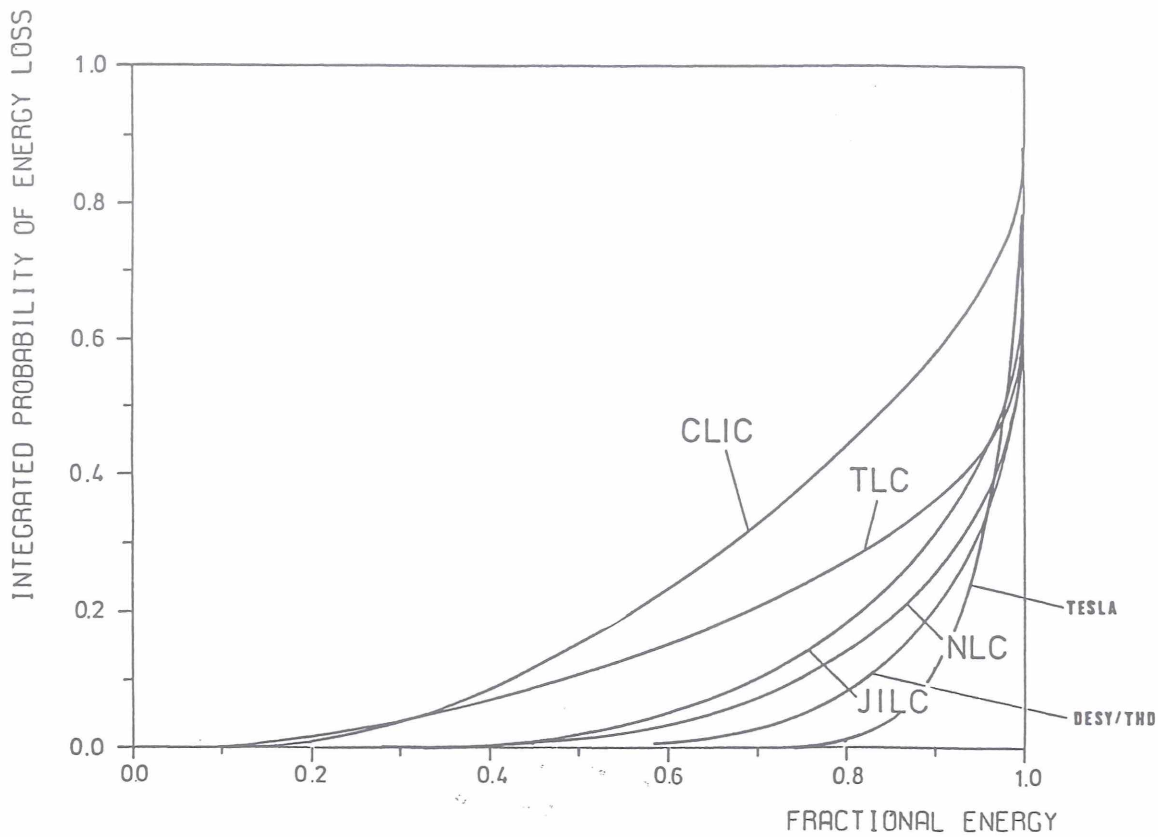

Fig. 2 Energy spectrum of the disrupted beam, integrated between 0 and E/E_0, i.e. the lines represent the probability that the fractional energy is smaller than E/E_0. Parameter sets from various collider studies have been used.

For DESY/THD parameters it is seen that 10% of the electrons lose more than 20% of the initial energy.
A perfectly matched β function for the disrupted beam at the interaction point would be:

$$\beta^*_{x,match} \approx \frac{\sigma_x^2(IP)}{\varepsilon_x^*} \approx 1 \text{ mm}$$

(An analogous reasoning yields $\beta_y^* \approx 0.1$ mm). These tiny β^* values would necessarily lead to huge beta values in the first beamline lenses. This gives huge local chromaticities which, in turn can be compensated only within a narrow energy bandwidth. According to R. Brinkmann's refined sextupole scheme for broadband chromaticity compensation [5], we may expect about 1% energy bandwidth for a transport line starting with our tiny β^* values. On the other hand, a bandwidth of ± 10% has been shown to be feasible for a disrupted beam transport line if one is allowed to start with $\beta^*=2$ m [6]. We conclude that it might be a safe estimate to use a <u>mismatched</u> beta of

$$\beta^*_{mis} = 4 \text{ cm}$$

and assume a bandwidth of ± 3%. With this beta value, the effective emittance of the disrupted beam at the interaction point is :

$$\varepsilon^*_{y,eff} \approx \Theta_y^2 * \beta^*_{y,mis} \approx (0.3\ \text{mrad})^2 * 0.04\ \text{m} \approx 3.6 * 10^{-9}\ \text{m}$$
$$\varepsilon^*_{x,eff} \approx \Theta_x^2 * \beta^*_{x,mis} \approx (0.57\,\text{mrad})^2 * 0.04\ \text{m} \approx 1.3 * 10^{-8}\ \text{m}$$

which meets the requirements of eq. 1. Note that Θ is the maximum disruption angle of particles, i.e. the estimate is very conservative. Fig. 2 shows that we can expect to contain about 70% of the disrupted beam within our ± 3% bandwidth. All of these paticles will not exceed a beamsize of ± 1 mm vertically and ± 2 mm horizontally in the U/W section, as desired.

The Target

The heating of the target is mainly determined by the ionisation loss of the charged particles which is approximatly 2 $\frac{\text{MeV cm}^2}{\text{g}}$ per particle.
In a target of thickness t the energy loss due to ionisation is:

$$\triangle E\ [\,J\,] = 2 * 10^6 \left[\frac{\text{eV cm}^2}{\text{g}}\right] * \rho \left[\frac{\text{g}}{\text{cm}^3}\right] * t\ [\,\text{cm}\,] * 1.6 * 10^{-19} \qquad (2)$$

In order to get N positrons, 2 * N * n particles (electrons and positrons) have to emerge from the target. The factor n descibes the overproduction, which is neccesary to compensate the limited efficiency of the capture optics. Hence the temperature rise in the target can be estimated at :

$$\triangle T\ [\,K\,] = \frac{2 * N * n * 2 * 10^6 * 1.6 * 10^{-19} * \cancel{\rho} * \cancel{t}}{c * \cancel{\rho} * A * \cancel{t}} \qquad (3)$$

c = heat capacity $\left[\frac{\text{J}}{\text{g K}}\right]$

A = source area $[\,\text{cm}^2\,]$

There are three more or less free parameters, which determine the temperature:

- the heat capacity of the target c
- the efficiency of the capture optics 1/n
- the source area A

These parameters will be disscused below, and at the end of the paper we will be able to specify preliminary target parameters as well as suitable target materials.

- **heat capacity**

From the Dulong-Petit rule we know that light materials with low Z have, in general, a high heat capacity. There are, however, two reasons that forbid low Z material in a conventional target:

Firstly the positron yield of a thick, low Z target is lower than that of a high Z one. To understand that consider a reference particle of 10 MeV. Neglegting bremsstrahlung and measuring the target thickness in units of radiation length X_0, one finds from eq. 2 the maximum depths from which the particle can reach the end of the target:

$$t_{Escape} / X_0 = \frac{10}{2 * \rho * X_0}$$

Material	Z	t_{Escape} / X_0
W	74	0.74
Cu	29	0.39
Al	13	0.21

Tab. 1 Escape depth for a reference particle of 10 MeV for different materials

As seen from table 1 low energy particles can emerge out of a thicker layer (in X_0 units) in high Z materials. Since a conventional conversion target requires many radiation lengths for full development of the electromagnetic cascade, this means a considerable loss of conversion efficiency for low Z material. If, however, a target thickness $t < X_0$ is envisaged anyway, this disadvantage is not an issue any more.

The second disadvantage of low Z materials follows from multiple scattering theory :

According to ref. [9] the rms-scattering angle for a charged particle traversing a medium is:

$$\Theta_{rms} = \frac{19.2\ [\mathrm{MeV}]}{\beta c\, p\, [\mathrm{MeV/c}]} * \sqrt{\frac{t}{X_0}} \left[1 + 0.2 \ln\left(t/X_0 \right) \right] \qquad (4)$$

which is independent of the material. But the rms-displacement of a particle at the end of the target due to multiple scattering is:

$$y_{rms} = \frac{1}{\sqrt{3}} * \Theta_{rms} * t \qquad (5)$$

(The positrons are produced inside the target, therfore the mean path-length is only half the target thickness.)

Since a low Z target requires a greater geometrical thickness to be equivalent to a high Z target (in terms of e^+ production rate, i.e. in terms of t/X_0), y_{rms} will be larger for a low Z material. The positron phase space density has to be as high as possible, due to the limited acceptance of the positron capture optics. However, the source area is not limited due to multiple scattering but due to the maximum allowable particle density in the target, which is limited by thermal load problems.

- efficiency of the capture optics

The efficiency of the capture optics depends on numerous parameters which are not yet known in detail. There are some general rules, however. Since the scattering angle Θ_{rms} and the source radius y_{rms} depend on $1/E$ it will be easier to catch the high energy particles of the positron spectrum than the low ones.

So we first try to estimate the positron spectrum for different undulator parameters and also for a wiggier, which would be much easier and less expensive to build.

The photon spectrum of an undulator is determined by the magnetic field B and the wavelength λ of the undulator. Introducing the parameter:

$$K = \frac{e}{m_0 * c * 2\pi} * B * \lambda$$

$$= 0.934 * B[T] * \lambda[cm]$$

we find for the first harmonic of the radiation of a helical undulator in forward direction :

$$\omega_1 = \frac{4\pi * \gamma^2 * c}{(1+K^2) * \lambda}$$

According to B. Kincaid [7] the photon number spectrum for a one meter helical undulator integrated over all solid angles is (SI-units):

$$\frac{dNph}{dE}\left[\frac{1}{m * MeV}\right] = \frac{10^9 * e^3 * 4\pi\varepsilon_0}{\hbar} * \frac{K^2}{\gamma^2} *$$

$$* \sum_{n=1}^{\infty}\left(J'_n(x)^2 + \left(\frac{\alpha_n}{K} - \frac{n}{x}\right)^2 J_n(x)^2 \right) \qquad (6)$$

the sum has to be evaluated only for

$$\alpha_n^2 = \left[n * \frac{\omega_1(1+K^2)}{\omega} - 1 - K^2 \right] \geq 0$$

$$x = 2 * K * \frac{\omega}{\omega_1(1+K^2)} * \alpha_n$$

In Fig. 3 the photon spectrum for different K-values is plotted.

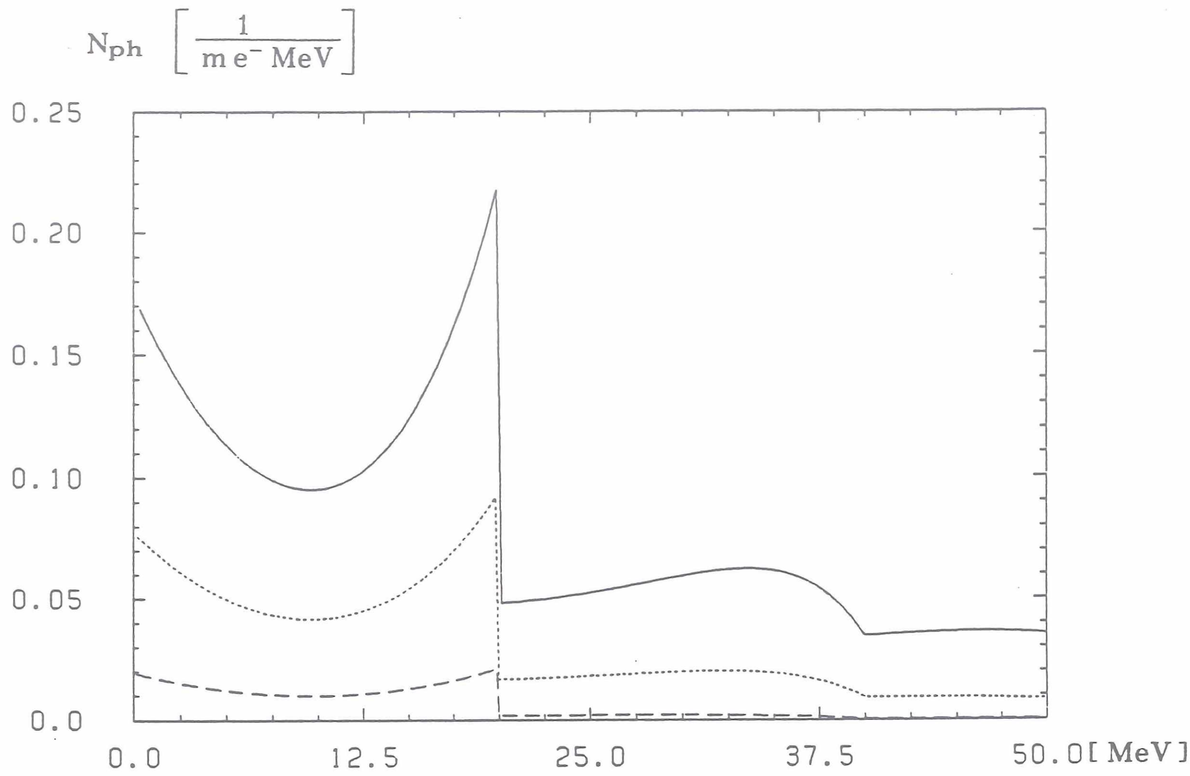

Fig. 3 Photon number spectrum of a 1 m helical Undulator for $K = 0.5$ ---, $K = 1$ ····· and $K = 1.5$ ——; $E_1 = 20$ MeV

Substituting $\frac{\omega}{\omega_1(1+K^2)} = \frac{E}{E_1(1+K^2)} = r$ one finds:

$$\frac{d N_{ph}}{d r} = \frac{10^9 * e^3 * 4\pi\varepsilon_0}{\hbar} * \frac{K^2}{\gamma^2} * E_1 * (1+K^2) *$$

$$* \sum_{n=1}^{\infty} \left(J'_n(\bar{x})^2 + \left(\frac{\bar{\alpha}_n}{K} - \frac{n}{\bar{x}} \right)^2 J_n(\bar{x})^2 \right)$$

It follows that N_{ph} is

- independent of γ for a fixed λ $\left(E_1 = \frac{4\pi * \gamma^2 * c * \hbar}{(1+K^2) * \lambda} \right)$
- linear in E_1

The sum depends only weakly on K, therefore we derived from our results the approximated formula for the total photon production (Fig. 6):

$$N_{phtot}\left[\frac{1}{m\,e^-}\right] = \int_0^{\infty} \frac{N_{ph}}{dE}\, dE \simeq 10^3 * (14.36 - 2.78 * K) * K^2 * (1+K^2) * \frac{E_1\,[eV]}{\gamma^2}$$

$$\simeq (3.56 - 0.69 * K) * K^2 / \lambda\,[cm] \qquad (7)$$

for $0 < K \leq 3$

The positron production by one photon of energy E in a thin target ($t < X_0$) can be approximated by the linear expression:

$$N = \bar{\sigma}(E)\left[\frac{cm^2}{g}\right] * \rho * \left[\frac{g}{cm^3}\right] * X_0\,[\,cm\,] * \left({}^{t}/_{X_0}\right)$$

with the limit:

$$N_{E \to \infty} = \frac{7}{9} * \left({}^{t}/_{X_0}\right)$$

$\bar{\sigma}(E)$ is the total cross section for pair production multiplied by N_A / A.
(N_A = Avogadro's number, A = atomic weight)
In order to take the cross section into consideration, the photon spectrum has been multiplied by the function:

$$S(E) = 0 \qquad \text{for} \qquad E \leq 1.6 \text{ MeV}$$
$$S(E) = 0.14 * \ln(1.5 * E\,[\text{MeV}]) - 0.117$$
$$S(E) = 7/9 \qquad \text{for} \qquad E \geq 400 \text{ MeV}$$

Fig. 4 shows a comparison of $S(E)$ with $\bar{\sigma}(E) * \rho * X_0$ of tungsten and copper.

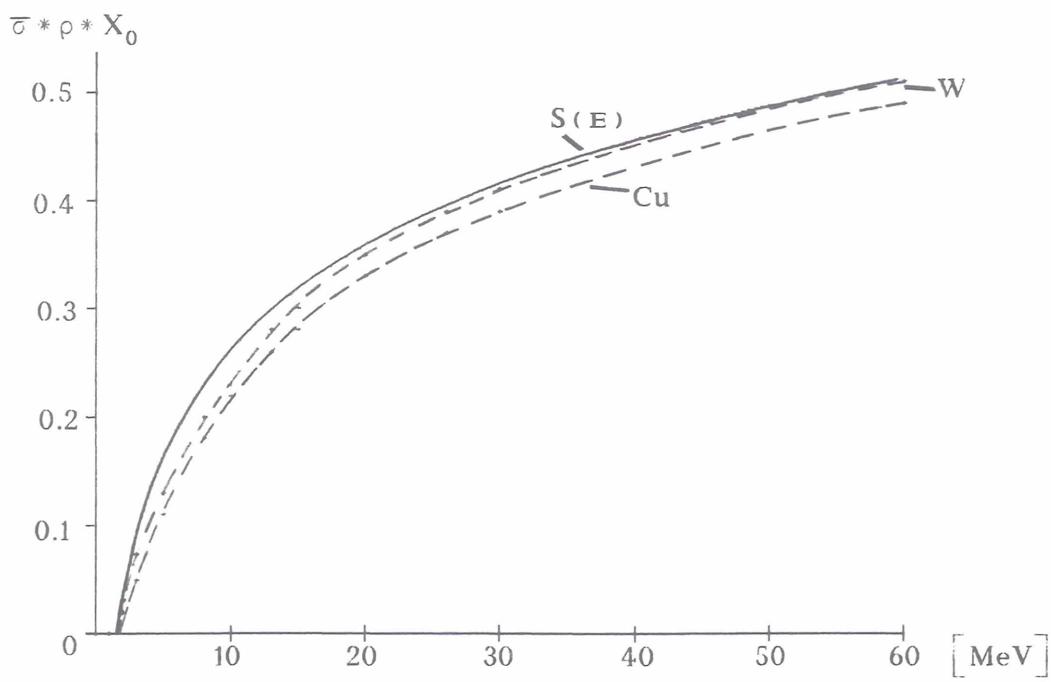

Fig. 4 Comparison of the approximate pair production cross section $S(E)$ with $\bar{\sigma}(E) * \rho * X_0$ of W and Cu (data for W and Cu from [8])

Assuming that positrons produced by photons with energy E_γ are equally distributed over the energy range from 0 to E_γ, which is a good approximation only for $E_\gamma > 10$ MeV, one finds the positron spectrum by:

$$\frac{dN_{e^+}(E_0)}{dE} = \int_{E_0}^{\infty} \frac{N_{ph}}{dE} * \frac{1}{E} * S(E)\; dE * \frac{t}{X_0}$$

Fig. 5 shows the resulting positron spectrum for two different photon spectra, namley for the undulator spectrum, eq. 6, with B = 1.76 T, λ = 0.9 cm, K = 1.5 (solid line, energy of first harmonic E_1 = 20 MeV) and for the well known wiggler spectrum at B = 1.76 T. The wiggler is assumed to consist of sections of constant magnetic field only.

The wiggler produces more low energy positrons, which are difficult to catch but contribute to the thermal stress of the target. The difference is however amazingly small and it might be possible to use a wiggler.

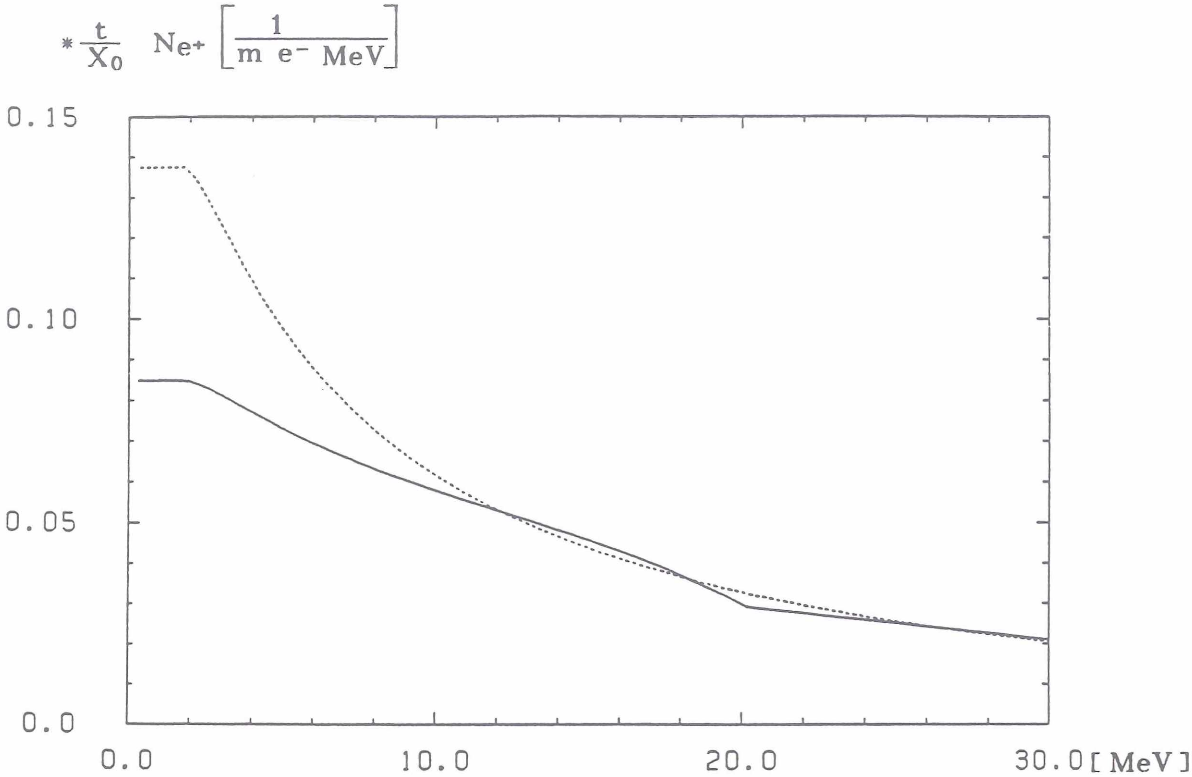

Fig. 5 Estimated positron spectra for a wiggler with B = 1.76 T (dashed line) and an helical undulator with B = 1.76 T, λ = 0.9 cm (solid line) at 250 GeV

The total amount of positrons from the undulator is 2.27 $\frac{e^+}{m\ e^-} * \frac{t}{X_0}$, of which 49% are in the energy range between 2 and 20 MeV (the energy acceptance of the SLC-source). The respective numbers for the wiggler are 2.3 $\frac{e^+}{m\ e^-} * \frac{t}{X_0}$ and 51% respectively.

In Fig. 6 the dependence of the positron production on the parameter K for a helical undulator is plotted. The energy of the first harmonic is fixed to E_1 = 20 MeV.

The three lines show the total photon production $N_{phtot} = \int_0^\infty \frac{N_{ph}}{dE}\, dE$, the total positron production $N_{e^+tot} = \int_0^\infty \frac{N_{e^+}}{dE}\, dE$ and the positron production in the energy range from 2 to 20 MeV $N_{e^+} = \int_2^{20} \frac{N_{e^+}}{dE}\, dE$.

While the three lines rise with higher K-values the conversion efficiency N_{e^+tot}/N_{phtot} and even so the ratio of the positron production in the

rang 2 - 20 MeV to the total positron production falls.
To get a good impression of the influence of different K-values on the positron spectrum the length L of the undulator has been varied, so that the amount of positrons in the range between 2 and 20 MeV is the same for the three cases plotted in Fig. 7.
The positron spectra indicate that at low K-values there are too many low energy positrons, while at high K-values there are too many high energy positrons above 20 MeV. Therefore the capture efficiency will be the best at medium K-values even though the highest production is at high K-values.
Fig. 8 and Fig. 9 show plots for the variation of the energy of the first harmonic E_1 with fixed K-value: $K = 1$.
Following the same reasoning as before the highest capture efficiency will be at medium energys while the maximum production is at high energys.

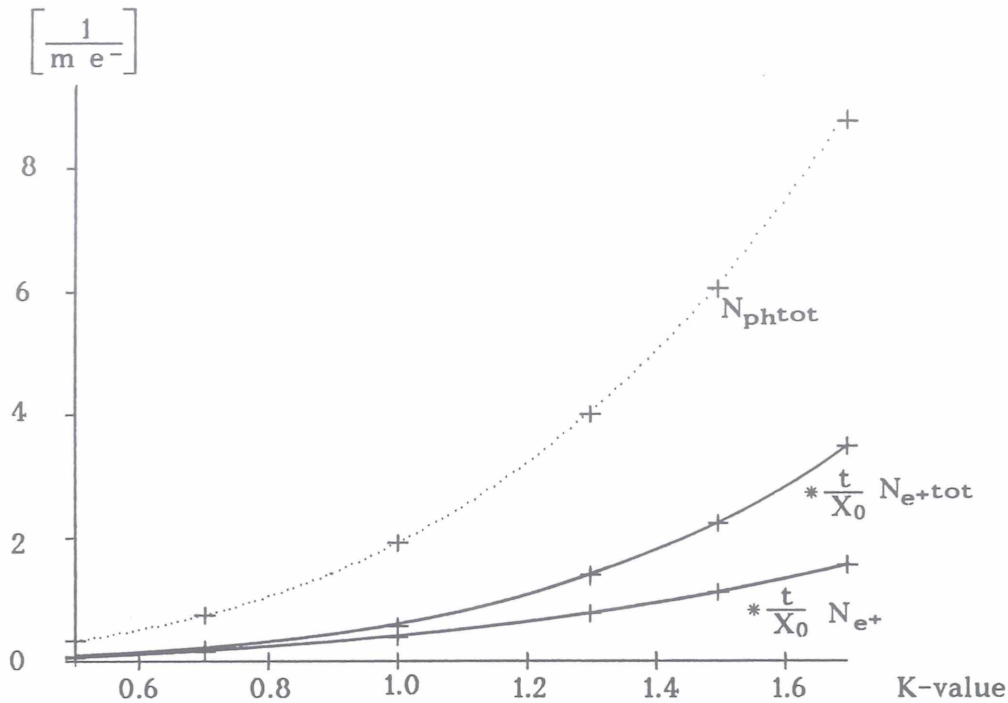

Fig. 6 Dependence of e^+-production rate on the Parameter K,
$E_1 = 20$ MeV , E = 250 GeV; ····· Approximation eq. 7

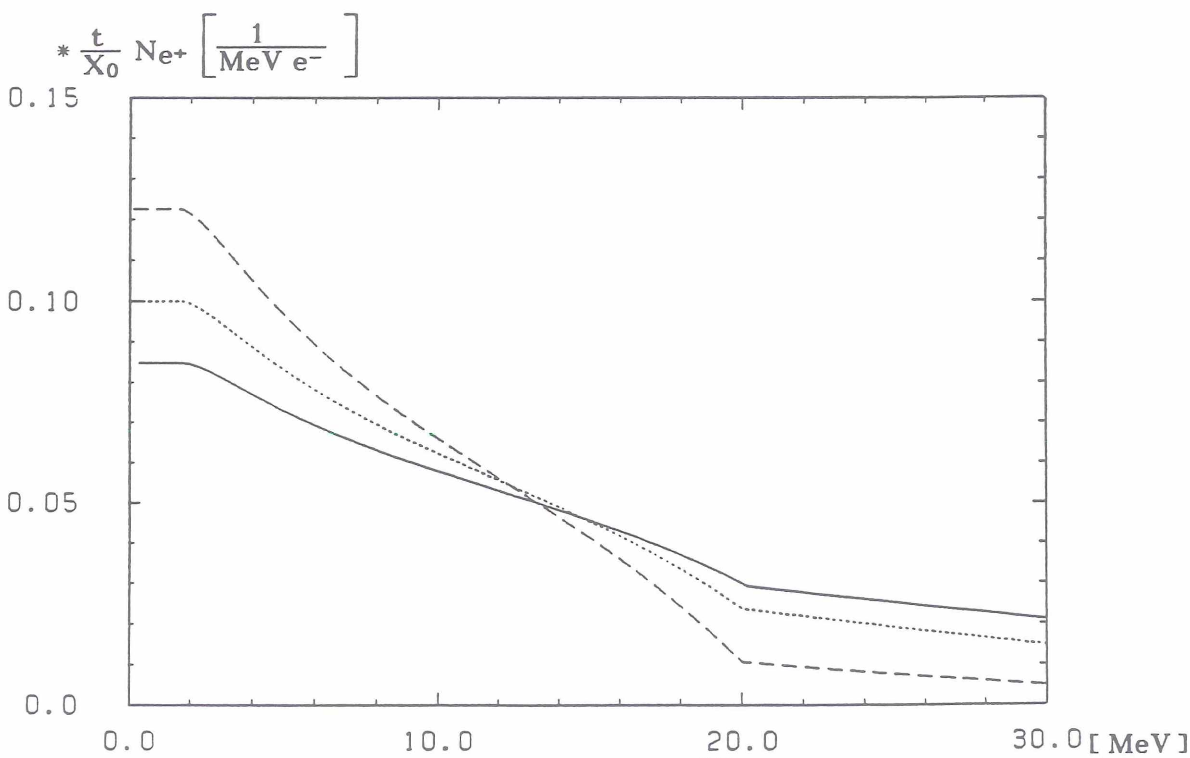

Fig. 7 Positron spectra for K = 0.5, L = 17.3 m -----
K = 1.0, L = 2.9 m ········
K = 1.5, L = 1.0 m ——
(E_1 = 20 MeV, E = 250 Gev)

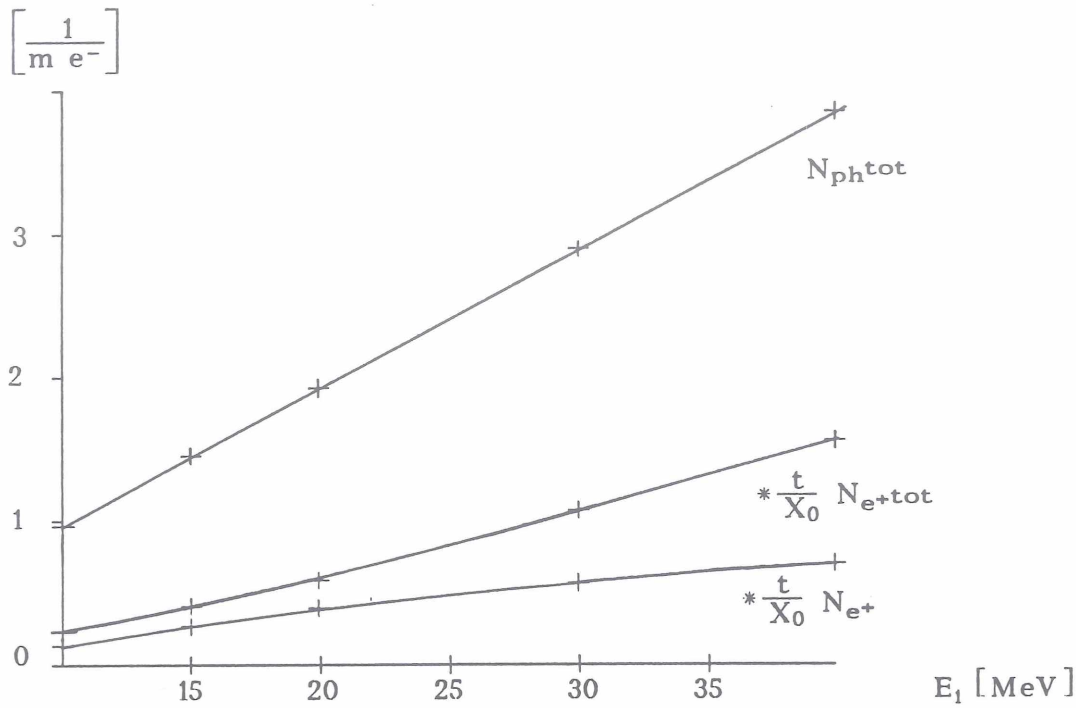

Fig. 8 Dependence of e^+-production rate on the first harmonic energy $E_1 \sim 1/\lambda$, $K=1$, $E=250$ GeV

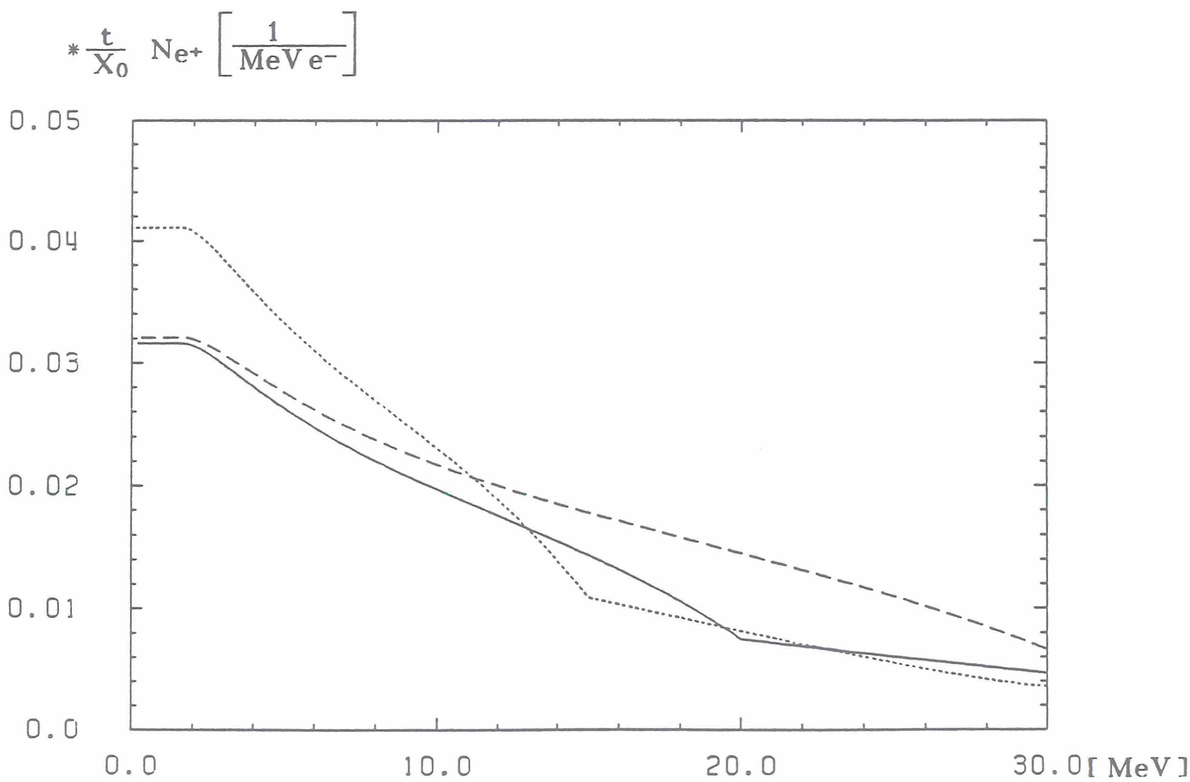

Fig. 9 Positron spectra for $E_1 = 15$ MeV, $L = 1.4$ m ········

$E_1 = 20$ MeV, $L = 1.0$ m ———

$E_1 = 30$ MeV, $L = 0.7$ m -----

($K=1$, $E=250$ GeV)

An important property of a positron production scheme which uses the electron beam after collision is the dependence of the production rate on the energy of the electrons, because the collision energy may be reduced due to requirements of the experiments or even increased by an upgrading.

The photon production of an undulator with fixed λ and B is independent of γ; the same is valid for a wiggler. This is due to the fact, that the radiation power, the mean photon energy and the energy of the first harmonics all increase with γ^2.
Of course this variation of the mean photon energy influences the positron production. Fig. 10 shows the dependence of the positron production on γ for an undulator with $K = 1.5$ ($B = 1.76$ T, $\lambda = 0.9$ cm) and a wiggler with $B = 1.76$ T.

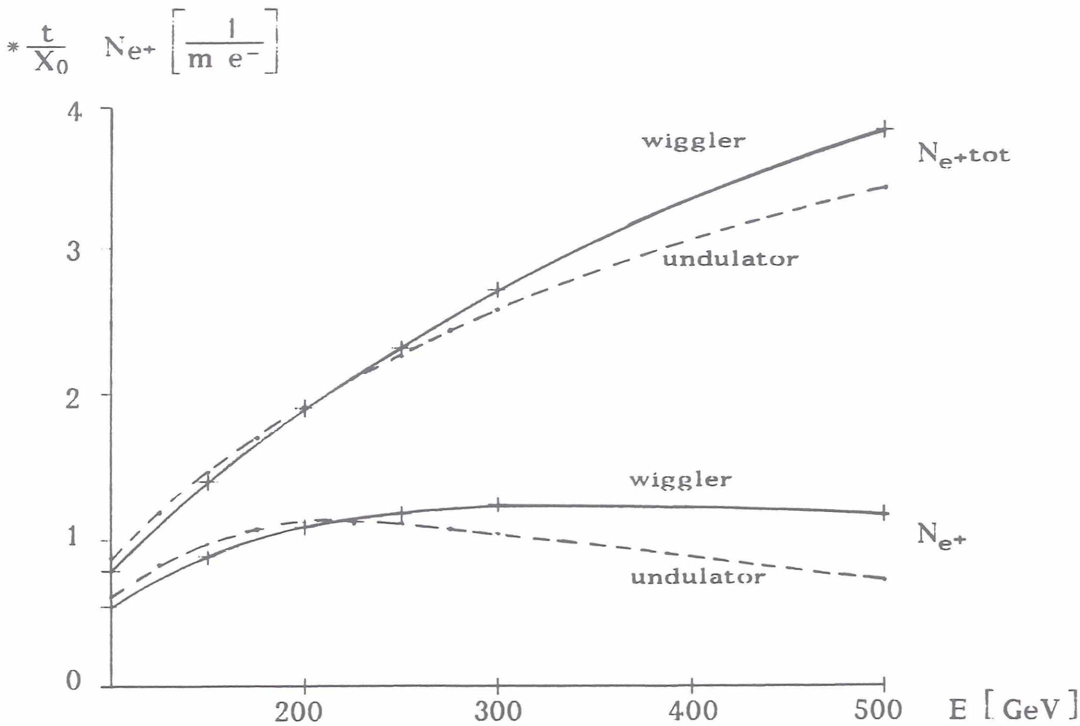

Fig. 10 Dependence of e^{+-} production on γ for an undulator ($K = 1.5$, $B = 1.76$ T, $\lambda = 0.9$ cm) and an wiggler ($B = 1.76$ T)

Corresponding positron spectra are plotted in Fig. 5 for a 250 GeV, in Fig. 11 for a 200 GeV and in Fig. 12 for a 300 GeV electron beam.
The behaviour of the undulator spectra is a little better but even so the wiggler seems to be useful for a γ-variation over a considerable range.

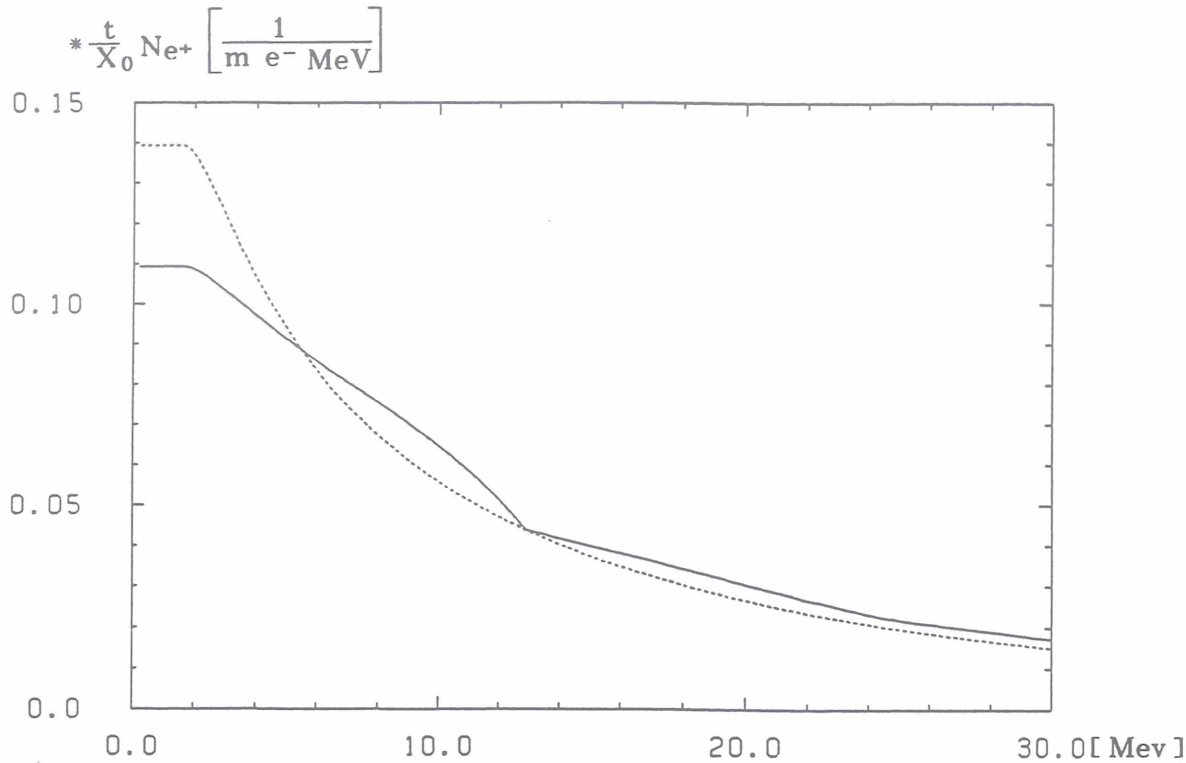

Fig. 11 Estimated positron spectra for a wiggler with B = 1.76 T (dashed line) and an undulator with B = 1.76 T, λ = 0.9 cm (solid line) at 200 GeV

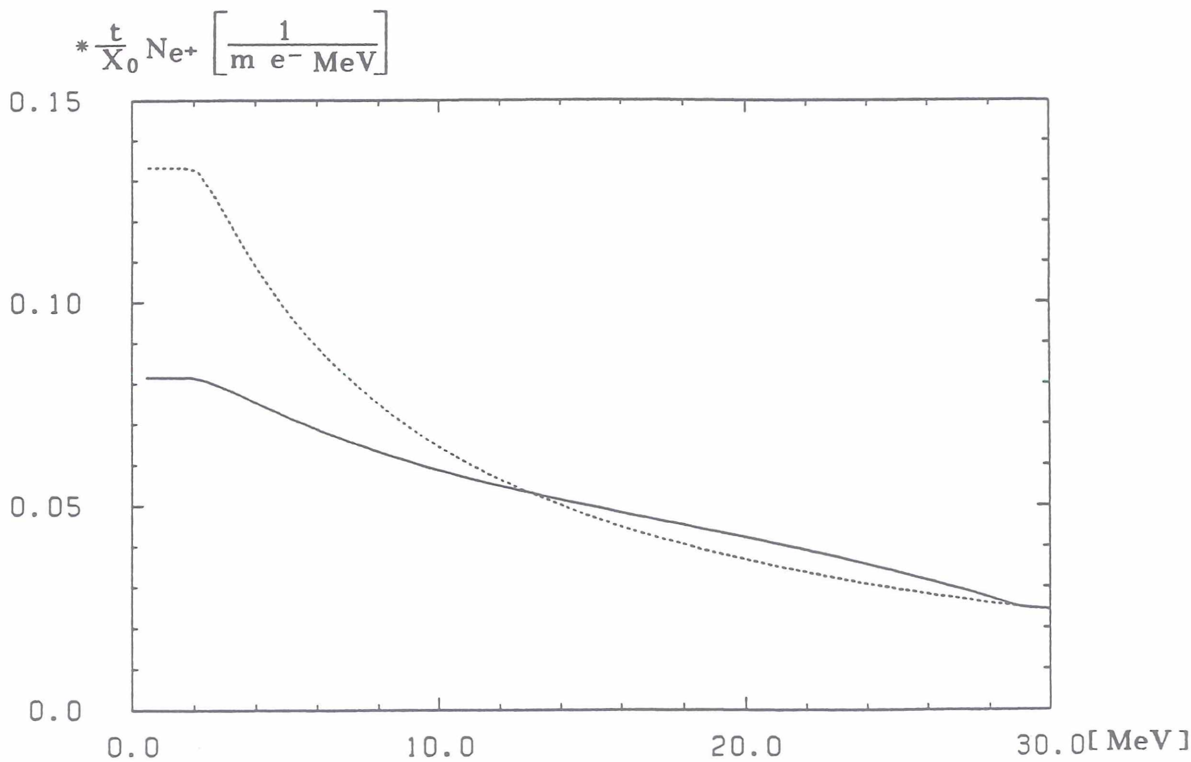

Fig. 12 Estimated positron spectra for a wiggler with B = 1.76 T (dashed line) and an undulator with B = 1.76 T, λ = 0.9 cm (solid line) at 300 GeV

- **source emittance considerations**

Considering target heating and thermal stress a large source area is required. However, the source area is limited by the acceptance in the capture optics. For an adiabatic focusing device the source radius and angle are given by [10,11]:

$$r_{max} = \sqrt{\frac{B_f}{B_i}} * R \qquad \Theta_{max} = \frac{e * c}{2 * E} * \sqrt{B_f\, B_i} * R$$

where B_f and B_i are the final and initial fields of the device respectively and R is the aperture radius. R is quite small because after the flux-concentrator follows a high gradient, i.e. high impedance accelerating structure to minimize bunch-lengthening due to particles with different velocities and due to particles with different transvere momenta.
Common parameters for a adiabatic focusing device are:

$$B_f = 0.4\ \text{T}; \qquad B_i = 6.0\ \text{T}; \qquad R = 10\ \text{mm}$$

with this values we obtain:

$$r_{max} = 2.6\ \text{mm}; \qquad \Theta_{max} = \frac{4.64}{E\,[\,\text{MeV}\,]}$$

If we consider a target of thickness $t = 0.2\,X_0$ we find for the rms-scattering angle (eq. 4):

$$\Theta_{rms} = \frac{3.28}{E\,[\,\text{MeV}\,]}$$

As these fomulae allow approximative estimates only (especially for the low energy part of the positron spectrum), we conclude that much more detailed numerical simulations are required to get an accurate prediction of the attainable capture efficiency, as well as for the optimum target thickness.
For the optimisation of the target thickness two ways have to be taken into consideration:
First, with a thinner target we obtain smaller angles and therefore a higher capture efficiency. This may lead in the same yield at lower temperature.
Secondly we can profit from the smaller angles of a thinner target by lowering the initial field of the flux-concentrator B_i and increasing the source area to lower the temperature.
In any case, since the rms-scattering angle (eq. 4) doesn't depend on the target material, but on the target thickness in units of radiation length only, we can conclude, that the angular divergence of positrons in our $0.2\,X_0$ target will be small compared to conventional multi-X_0 targets.
Thus, taking the capture efficiency of the present operating SLAC target into account, we conclude that 6% capture efficiency is a safe preliminary estimate for our design.

Conclusions

Both a wiggler ($B = 1.76$ T) and a helical undulator ($K = 1.5$, $B = 1.76$ T, $\lambda = 0.9$ cm) of 50 m length produce approximately $115 * \frac{t}{X_0}$ positrons per incident electron over the whole energy range. Assuming a capture efficiency of 6%, a target of 0.2 radiation length will produce enough positrons for a yield of 1.3 e^+/e^- (which is necessary to compensate the particle loss of the primary beam in the matching optics).
As high Z material is no longer necessary, it is possible to choose between numerous materials with a wide variety of material constants. For example in a ceramic target of Al_2O_3 ($X_0 \simeq 7.2$ cm) a 10 MeV particle would reach a rms-distance from the center (eq. 5) of:

$$y_{rms} = 1.4 \text{ mm}$$

(The radiation length of a compound can be estimated by: $1/X_0 = \sum_i \frac{f_i}{X_{0i}}$ [9] where f_i is the fraction by mass of atoms type i, radiation length X_{0i}. With $f_{Al} = 0.51$, $X_{0AL} = 24.01$ g/cm^2 [9], $f_O = 0.49$, $X_{0O_2} = 30.0$ g/cm^2 [9] and $\rho\, Al_2O_3 = 3.9$ g/cm^3 [12] we obtain $X_{0Al_2O_3} \simeq 7.2$ cm.)
With the assumption that all particles emerge from the area $A = \pi * (0.15 \text{ cm})^2$ the maximum temperature rise can be estimated at (eq. 3):

$$\Delta T_{max} = 720\,^0\mathrm{C}$$

$$N = 3.6 * 10^{12}\ e^+$$
$$n = 1/0.05$$
$$c = 0.9 \text{ J/gK at } 20\,^0\mathrm{C} \text{ [12]}$$

The heat capacity of this material is a factor of 7 higher than that of tungsten. The particle density in the target rises linearly from the entrance of the γ-beam to the target end. Therefore the mean temperature rise is $\Delta T_{mean} = 360^0$C. Thus, an amount of 128 J thermal energy is deposited in the target per pulse and, with 50 Hz rep. rate, we obtain for the mean power deposited in the target 6.4 kw.

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