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Positron Production for Particle Accelerators

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Abstract

An introduction on positron production for particle accelerators is given describing the typical layout of the components. Basic considerations for the choice of the target and the positron focusing system are reviewed. The positron production in the LEP Injector Linac (LIL) is described as example.

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1. Introduction

The scope of this paper is to give an introduction to positron production for particle accelerators. More details can be found in various review papers ¹⁻²⁻³]. Positron beams are required in circular and linear colliders for particle physics. Some synchrotron radiation facilities operate or have operated with positron beams because a higher brightness can be obtained with positrons than with electrons.

The typical layout is shown in Fig. 1. A high-intensity electron beam of a few hundred MeV strikes a metal target. The electro-magnetic showers generate a mixture of secondary positrons and electrons having an energy up to a few tens of MeV. The secondary particle distribution is strongly peaked in the forward direction. A focusing system after the target maximizes the solid angle of collection of secondaries and guides them to the first accelerating section. Solenoids on the first accelerating sections and quadrupoles on the sections further downstream provide continued focusing. The beam transfer at the end of the accelerator separates positrons and electrons. The required energy resolution is given by a slit at a point in the transfer line where the dispersion function is large and where the beam has a horizontal focus. Table I gives a sample of positron sources in operation.

Table I, Positron sources in operation

	E_e (GeV)	E_p (GeV)	Used for
LAL/Orsay	1	1	SR
LNF/INFN/Frascati	0.09	0.30	SR + HEP
DESY/Hamburg	0.30	0.45	HEP + SR
KEK/Tsukuba-gun	0.20	2.5	HEP + SR
BEPC/Beijing	0.34	1.4	HEP + SR
CERN/LIL/Geneva	0.20	0.60	HEP
SLAC/SLC/Stanford	33	50	HEP

The table gives the primary electron energy (E_e), the final secondary positron energy (E_p). The abbreviation SR stands for synchrotron radiation, HEP means High-Energy Physics.

The most sophisticated source is the SLC system where more than one positron is collected per primary electron ⁴⁻⁵]. In the other systems, the yield is of the order of 2×10^{-2} when normalized to a primary energy of 1 GeV.

In order to illustrate the basic principles we shall use in the following as an example the positron production system of the LEP Injector Linac (LIL) ⁶], which is typical for medium energy linacs. The design concept ⁷] of this system is based on focusing with a short, pulsed solenoid after the target as proposed and first implemented at DESY ⁸], a very similar system is used at Frascati ⁹].

2. Target and source emittance

The secondary positrons are generated by the photons decaying into e^+/e^- pairs in the target. The photons are created mainly by Bremsstrahlung, the dominant process which makes the primary electrons lose energy in the target.

Since both cross-sections scale with $(Z + f(Z))^2$, materials with a high atomic number Z are used for the target. As the radial dimension of the shower is proportional to the radiation length (L_{rad}), materials with a small L_{rad} are preferred. The target should also withstand the thermal and mechanical stress induced by the energy deposition; hence, a material like W or Ta is usually chosen.

Fig. 2 shows the number of positrons as a function of target length for W and for a primary electron energy of 200 MeV ⁷]. This example was calculated with the Monte-Carlo program EGS ¹⁰]. The result agrees with measurements at DESY where the positron output current of the linac was measured as a function of target length for a primary energy of 200, 250 and 300 MeV ⁸]. The optimum target length ($t = 2 L_{rad}$) does not vary in this range. However, the optimum target length increases for appreciably higher primary energies. It is $t = 3 L_{rad}$ for a primary energy of 1 GeV ³], $t = 6 L_{rad}$ for 33 GeV ⁵].

Fig. 3 gives the positron spectrum in the range of interest for a lead target of $t = 2 L_{\text{rad}}$ and for a primary energy of 200 MeV. It comprises positrons of all angles and radial positions at the end of the target. It is derived from the standard tables (KDF9 results) obtained by Monte-Carlo calculations¹¹. Linear interpolation between 100 and 500 MeV primary energy was used. Since the tables give the positron yield including all positrons having an energy larger than a certain cut-off energy E_{p1} , the spectrum was obtained by numerical differentiation forming dN/dE_{p1} . Fig. 3 also gives the electron spectrum exhibiting a maximum around a kinetic energy of 8 MeV. The positron spectrum shows no maximum but a rise towards lower energies. This rise is only of limited use as positrons of too low an energy have a too large spread in the time of flight between target and accelerating section which creates an unacceptable energy spread as explained below. Note the difference in yield between electrons and positrons. If all lengths are normalized to L_{rad} the differences between the tabulated values for lead and copper are small. Since Z of tungsten is only 13% below of lead, we can use the values for lead also for tungsten targets.

The positron yield of a lead target at small angles has been measured. The relevant results for our example have been obtained for a lead target at zero angle with primary electrons between 55 and 220 MeV¹². The angular acceptance was 4×10^{-3} sr and the lowest measured positron energy was 7 MeV. The results show a relatively flat maximum around one tenth of the primary energy. For 220 MeV primary electrons, the maximum positron production occurs at 19 MeV; the yield drops to 87% at 7 MeV and is at 50% of the maximum at 70 MeV.

This does not agree very well with the result from the tables which however comprises all angles. We prefer to use the experimental values and assume a fairly constant positron yield between 5 and 15 MeV given by

$$\frac{1}{N_e} \frac{\partial^2 N_p}{\partial \Omega_p \partial E_p} = 0.24 \times 10^{-3} \left(1 - \frac{25}{E_e}\right) E_e \quad (1)$$

where the energies are in MeV and the solid angle in sr. Note that positrons from all radial positions of the source were accepted in this experiment. Here E_p is the energy of the secondary positrons after the target before acceleration.

Fig. 4 shows the fraction of secondary particles (positrons and electrons) at all angles inside a given radius at the end of a lead target with $t = 2 L_{\text{rad}}$ for 200 MeV primary electrons. The values are taken from the KDF9 computations ¹¹]. All secondaries with an energy above the cut-off energy E_1 , being the parameter of the curves, are included. The primary beam has vanishing radius and divergence. If the energy dependence of the radial distribution were strong, a discernible variation with E_1 would be expected as about 35% of the secondaries come from $5 \text{ MeV} < E < 15 \text{ MeV}$ ¹¹]. Since there is hardly a variation, we conclude that the radial distribution does not vary with energy in this range. Fig. 4 shows that a Gaussian with $\sigma_1 = 0.19 L_{\text{rad}}$ fits quite well. For tungsten, therefore, $\sigma_1 = 0.7 \text{ mm}$.

The primary, high-intensity beam is focused to have a r.m.s. radius of $\sigma_2 = 0.5 \text{ mm}$ in LIL ¹³]. Adding quadratically these two contributions gives a r.m.s. source radius of

$$r_0 = 0.8 \text{ mm}$$

at the downstream end of the target, which is a typical value.

The angular distribution of the secondary particles, again obtained by interpolation from the standard tables ¹¹], shows a weak dependence on the secondary energy in the range of interest. Measurements with positrons at 8.4 MeV and 16 MeV exhibit also this weak energy dependence ¹⁴]. These data are approximated within $\pm 20\%$ by

$$\frac{dN_p}{d\Omega} \sim \exp(-\theta/\theta_0) \quad (2)$$

where $\theta_0 = 0.35 \text{ rad}$ and θ is the angle between the trajectory and linac axis.

These distributions, tabulated or measured, do not give the real density in phase space

$$\frac{1}{N_e} \times \frac{\partial^3 N_p(r, \theta, E_p)}{\partial r \partial \Omega_p \partial E_p}$$

but projected distribution where integration over one or two variables has been performed. It is commonly assumed that the angular and radial distribution are independent though this is not proven.

3. Linac acceptance and effective yield

If the linac admittance at the target is $r_1 \theta_1 \pi$ (see Fig. 5) the yield per impinging electron becomes

$$n_p = \left[\frac{1}{N_e} \frac{\partial^2 N_p}{\partial E_p \partial \Omega_p} \right] \cdot \Delta E_m \cdot \Delta \Omega_1 \cdot G(\theta_1) \cdot F(r_1) \quad (3)$$

The first term is given by (1). ΔE_m is the energy band over which the solid angle $\Delta \Omega_1 = \pi \theta_1^2$ is approximately constant; $\Delta \Omega_1$ drops to zero outside. The function $G(\theta_1)$ takes into account the drop of production at larger angles

$$G(\theta_1) = \frac{1}{\pi \theta_1^2} \int_0^{\theta_1} \frac{\partial N}{\partial \Omega_p} 2\pi \theta d\theta$$

with (2)

$$G(\theta_1) = 2 (\theta_0 / \theta_1)^2 \left[1 - \left(\frac{\theta_1}{\theta_0} + 1 \right) \exp(-\theta_1 / \theta_0) \right] \quad (4)$$

Since we accept only particles coming from $r < r_1$, the term

$$F(r_1) = 1 - \exp(-r_1^2 / 2 r_0^2)$$

must be added. Next we have to define r_1 , θ_1 and ΔE_m .

The first accelerating sections downstream of the target are equipped with solenoids providing a longitudinal magnetic field B_2 for particle focusing. Fig. 5 shows the two particles (P_1 , P_2) defining the accepted phase space. The maximum possible radius (P_1), $r_2 = 8$ mm for LIL, is given by the iris radius of the accelerating structure minus a margin (1 mm) for misalignment. The maximum transverse momenta have particles (P_2) spiraling with a radius $r_2/2$ between the axis and the iris. This defines the largest angle θ_2 . In terms of B_2 and the longitudinal particle momentum p_m

$$\theta_2 = \frac{e B_2 r_2}{2 p_m}$$

For LIL, $B_2 = 0.3$ T and $p_m = 8.5$ MeV/c give $\theta_2 = 2.4^\circ$. The invariant admittance becomes

$$\beta\gamma A_2 = \beta\gamma r_2 \theta_2 \pi = \frac{e B_2 r_2^2}{2 m_0 c} \pi \quad (6)$$

Since this is independent of energy, the focusing is achromatic, which is the main reason why solenoid focusing is chosen after the target where the relative energy spread is very high. For LIL

$$\beta\gamma A_2 = 5.6 \times 10^{-3} \pi \text{ rad.m}$$

yielding at the end of the linac at 600 MeV the nominal positron emittance

$$A = 4.8 \times 10^{-6} \pi \text{ rad.m.}$$

Obviously, the linac admittance at target exit

$$A_1 = r_1 \theta_1 \pi$$

must be equal to A_2 though the ellipse aspect ratios will be very different (see Fig. 5). A matching system has to transform the admittance ellipse at the target end into the ellipse at the section input. The most practical system is a small, pulsed solenoid right after the target ^{8]} providing a field of $B_1 = 1.5$ T over a few cm. Fig. 6 shows the LIL target plus pulsed solenoid designed by R. Bertolotto and D.J. Warner. The nominal peak current is 5 kA.

The radial extension of the admittance ellipse at the target is approximately given by ^{3]}

$$r_1 = r_2 (B_2/B_1) \quad (7)$$

The maximum angle becomes by virtue of (6)

$$\theta_1 = \frac{eB_2}{2p} \frac{r_2^2}{r_1} \quad (8)$$

Unfortunately, this system has a good angular acceptance only over a limited band of positron energies centered around E_m ^{1]}

$$\Delta E_m = (4/\pi) (B_2/B_1) E_m \quad (9)$$

The detailed calculations ^{8-9]} show that $\Delta Q(E)$ is a bell-shaped curve with ΔE_m as FWHH. The choice of E_m is a compromise: the higher E_m , the larger ΔE_m but the solid angle accepted is decreased according to (8); if E_m is too low, the velocity spread of the positrons leads to our increased final energy spread apart from loss due to a smaller ΔE_m . Although particles

emerging with larger angles are accepted, their time of flight becomes too long compared to the time of flight of the on-axis particles; also $G(\theta_1)$ will drop. For LIL $E_m = 8$ MeV was chosen implying $\Delta E_m = 2$ MeV.

Expressing the focusing of the pulsed solenoid by the particle rotation, it can be seen that the positrons have to make a rotation by 180° around the linac axis in the short lens. The effective length at the solenoid field is then fixed. For a peak field of $B_1 = 1.5$ T the FWHH of the bell-shaped field curve is supposed to be 36 mm ¹].

The problem is now to maximize the yield n_p by properly choosing r_1 ; the angle θ_1 is determined by the boundary condition $A_1 = A_2$. Fig. 7 shows a plot of $n_p(r_1)$ in LIL for three values of E_m . Unfortunately, r_1 cannot be made smaller than the minimum value given by the maximum technically feasible field B_1 . For $B_1 = 1.5$ T, $r_1 = 1.6$ mm and for $E_m = 8$ MeV

$$n_p = 6.8 \times 10^{-3}$$

which is 20% lower than the optimum.

For illustration, further parameters at the nominal values are given. From (8)

$$\begin{aligned}\theta_1 &= 12^\circ \\ \Delta\Omega_1 &= 0.15 \text{ sr}\end{aligned}$$

The reduction factors taking into account the drop in source brightness are

$$F(r_1) \cdot G(\theta_1) = 0.87 \times 0.66 = 0.57$$

Using (1) yields for the first term for 200 MeV primary electrons

$$0.042 \text{ sr}^{-1} \cdot \text{MeV}^{-1}.$$

The formulae (7) and (9) are only approximative as they are valid for a target immersed in field B_1 . In our matching system, eddy currents prevent the field penetration into the target and therefore focusing by the rising field immediately after the target occurs, which is neglected in (7) and (9).

A more precise estimate needs particle tracking from the target through the effective magnetic fields to the entrance of the first accelerating section ⁸⁻⁹]. Tracking also determines the precise value of E_m which is given by the geometry and the magnetic fields B_1 and B_2 .

The principle of the tracking is to establish contours of accepted phase space at the target exit as a function of positron energy and of the relative position in the bunch. Adding up the number of particles found inside these contours taking into account the electron time distribution produces the effective yield.

These numerical computations take into account the time lag of particles emerging with large angles from the target with respect to small angle particles; the former have a longer path to the section than the latter. A further time lag is brought about by the energy spread of the positrons which produces a velocity spread as $\beta = v/c$ is not yet sufficiently close to 1, if E_m is chosen too low. This effect is negligible at $E = 8$ MeV ($\Delta t = 1$ ps) but the time lag becomes 3 ps at $E_m = 3$ MeV which corresponds to 3° in S-band RF-phase. Adding to this the time distribution of the primary bunch (bunch length typically 20 ps) produces the time distribution of the positrons as they arrive at the accelerating section. This time distribution creates an energy spread due to the sinusoidal accelerating voltage as not all particles will have the same time position relative to the crest of the accelerating electric field. Introducing a limit on the energy spread of the positrons at the end of the linac will introduce a further cut in the yield. Typical reduction factors are between 10% and 25% ⁹]. Thus, for LIL, a yield of

$$N_p/N_e = 5 \times 10^{-3}$$

was expected for $\Delta E/E < \pm 1\%$ at the end of the linac ⁶].

At present, LIL operates at $E_e = 215$ MeV and with lower fields, $B_1 = 0.8$ T and $B_2 = 0.26$ T, for technical reasons. Also the pulsed coil is shorter; it is only 28 mm long instead of 32 mm. These parameters give $E_m = 7$ MeV implying $\Delta E_m = 3$ MeV, $\Delta\Omega_1 = 0.05$ sr, $G(\theta_1) = 0.8$ and $F(r_1) \approx 1$ leading to a calculated $n_p = 5 \times 10^{-3}$ which agrees with the measured value at the end

of the linac. If $\Delta E/E \leq \pm 1\%$ is imposed, the measured n_p drops to about 4×10^{-3} .

For completeness, it should be mentioned that other matching systems between target and linac have been conceived and operated in various laboratories. One of the earlier systems used a d.c. lens instead of the pulsed lens to create a high solenoidal field over a short distance after the target ¹⁻²]. Also a tapered solenoid has been used as matching device where the field decreases adiabatically after the target ¹⁵⁻¹⁶]. The advantage of the adiabatic system is a large energy acceptance ($\Delta E_m \approx E_m$), which however cannot be fully exploited as the time-lag problems become severe ²⁻³]. All these d.c. systems are very bulky and not very practical because maintenance is difficult and power consumption is high. The SLC conversion system, being very performing but also elaborate, makes also use of a pulsed adiabatic system, where a flux concentrator provides a peak field of 4 T right after the target ⁴].

At this point it is interesting to compare the LIL yield figures with the yields obtained elsewhere. In order to facilitate comparison we scale according to (1) and normalize to 200 MeV primary energy.

Table II, Positron yields n_p normalized to $E_e = 200$ MeV

	$n_p \times 10^3$	E_e (GeV)	
SLAC	1.8	7	(typical) Adiabatic system used
	3.5	7	(peak) for SPEAR and PEP ¹⁷]
SLAC	13	33	Adiabatic, pulsed system for SLC ⁴]
LAL	5.8	1	Adiabatic system ¹⁶]
DESY	5	0.3	in $\pm 0.5\%$; pulsed lens ⁸]
LNF	5	0.09	Pulsed lens ¹⁸]

It can be seen that the expected yield of LIL (5×10^{-3}) is well within the range of known performances.

Finally, we cast a glance on the focusing downstream of the long solenoids.

In order to lower cost and power consumption, focusing by quadrupoles using the alternating gradient principle (FODO) is used in longer linacs after the first sections equipped with solenoids ¹⁹⁻²⁰]. Since the quadrupole spacing is proportional to momentum, the finite length of the quadrupoles gives the lower energy limit at which this principle can be applied. In LIL, quadrupole focusing starts after the first two accelerating sections where the beam has about 0.1 GeV. At this energy, the relative energy spread between particles having the same position relative to the accelerating field is already reduced. This implies a smaller total relative spread so that the chromaticity of the quadrupole focusing can be tolerated. Obviously, the invariant admittance of the FODO array must at least be equal to the admittance of the sections with the solenoids. The matching in both transverse planes of the two focusing systems is done by a few quadrupoles between solenoids and the FODO.

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Figure Captions

Fig. 1 Principle of positron generation. Linac stands for linear accelerator.

Fig. 2 Number of positrons versus target thickness in W for 200 MeV primary electrons.

Fig. 3 Spectrum of positrons generated in a lead target of 2 radiation lengths by primary electrons of 200 MeV (full line). Spectrum of electrons (dashed line). Both results are from Monte-Carlo calculations.

Fig. 4 Fraction of secondary particles inside a give radius at end of lead target $t = 2 L_{\text{rad}}$ for 200 MeV primary electrons for different cut-off energies. Result of Monte-Carlo calculations. Full line: Gaussian with $\sigma = 0.19 L_{\text{rad}}$.

Fig. 5 Schematic comparison of target emittance and linac admittance.

Fig. 6 LIL converter target and pulsed lens

1 - water-cooled copper cylinder, 2 - target,
3 - pulsed solenoid, 7 - collimator.

Fig. 7 Calculated number of positrons in LIL per primary electron versus radial acceptance at the target for three different energies of operation of the pulsed matching system. The energy of the primary electron is 200 MeV.

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Fig.1

Fig.2

Fig. 3

Fig. 4

Target emittance

Linac admittance

Fig. 5

Convertisseur $e^- \rightarrow e^+$

Fig. 6

Fig. 7