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A Possible Design for the NLC e^+ Source*

H. Braun
Paul Scherrer Institut, CH-5232 Villigen
J. Clendenin, S. Ecklund, A. Kulikov
Stanford Linear Accelerator Center, Stanford University, Stanford CA 94309
R. Pitthan†
European Laboratory for Particle Physics - CERN, SL Division, CH-1211 Geneva 23

Abstract

The Next Linear Collider (NLC) currently under investigation at SLAC requires a Positron source with a flux of about 8.6×10^{13} particles per second, 14.4 times more than the SLC source.

Based on the SLC experience, a source for NLC is proposed that can be realized with present accelerator technology. It consists of a 7 GeV S-band electron linac, a solid moving target, a 1.8 GeV L-band positron accelerator and a pre-damping ring with a large acceptance. The pre-damping ring performs positron accumulation and the matching of the positron source emittance to the NLC main damping ring acceptance.

The scheme and parameters of the NLC positron source are given and the expected source performance is computed.

1 DESIGN GOALS

In table 1 the required parameters of the NLC e^+ beam at the injection into the damping ring are given. For comparison, the SLC design parameters are also given.

Table 1: NLC and SLC e^+ parameters at damping ring injection. The emittance is normalized to $\gamma = 1$.

	NLC	SLC
Repetition rate [Hz]	360	120
Number of bunches per RF pulse	10	1
Bunch spacing [m]	0.214	-
Number of particles per bunch	$2.4 \cdot 10^{10}$	$5 \cdot 10^{10}$
Accepted emittance [m]	0.003	0.01
Energy [GeV]	1.8	1.2

Most of the parameters can be found in references [1,2, 3]. The NLC design requires a 14.4 times higher e^+ flux in a considerably smaller transverse phase-space area. To achieve such a brightness with a source based on the same principles as the SLC source, major changes in the source parameters are necessary.

2 CONVERTER TARGET

The number and phase space distribution of the positrons depends on the intensity and energy of the initial electron beam, as well as on the target geometry and material. The SLC target is a moving disk, 2.1 cm thick, made from W75Re25 alloy. This material combines good mechanical properties with a high Z, thus allowing high electron beam power and good conversion efficiencies [4].

The scaling of the positron yield and the optimum target length with electron energy was investigated for W75Re25 targets with the program EGS4 [5], for electron energies between 0.3 and 30 GeV. The target lengths that give the highest yields obtained from these computations can be approximated with:

$$l_{opt} = 1.1 \cdot \log E + 3.9 , \tag{1}$$

where E is the incident electron energy in GeV and l_{opt} is the target length in units of the radiation length.

The analysis of the EGS4 results shows that the shape of the energy and transverse momentum distribution of the positrons emerging from the target is almost independent of the initial electron energy, if the target length is close to the values given by equation 1. The energy spectrum of the positrons with transverse momenta smaller than a given value P_r can be approximated with

$$\frac{1}{N_-}\frac{dN_+}{dE_+} \simeq E_-(0.57-0.056\log E_-)\, E_+^{-1.75}\frac{P_r^2}{P_r+2.5}, \tag{2}$$

where E_- is the initial electron energy in GeV, N_- is the initial number of electrons, E_+ is the total positron energy in MeV, N_+ is the number of positrons and P_r is the maximum transverse positron momentum in units of MeV/c. Although the radial positron distribution at the target exit has some weak dependence on E_- and E_+, the fraction of positrons contained in a circle of radius r is for $r > 1$ mm reasonably well approximated with

$$\frac{1}{N_+}\int_0^r \frac{dN_+}{dr}\, dr \simeq 1 - \exp\left(-\frac{r}{r_m}\right)\left(\frac{r}{r_m}+1\right) , \tag{3}$$

where $r_m = 0.5$ mm. However this is only valid if the initial electron beam size is negligible; otherwise, both contributions have to be convoluted.

The most serious limitation for the intensity and energy of the incident electron beam pulses is target damage by thermal stress. From measurements with W75Re25 targets [7], one gets the limit

$$\rho = \frac{N_-E_-}{\pi\sigma^2} \; < \; 2 \cdot 10^{12}\frac{\mathrm{GeV}}{\mathrm{mm}^2} , \tag{4}$$

where ρ is the energy area density per linac pulse, N_- is the number of electrons per pulse and σ is the rms radius of the e^- beam.

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†Permanent address: SLAC, Stanford CA 94309

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3 SCALING SLC TO NLC

The number of positrons is roughly proportional to the accepted transverse momentum P_r times the initial beam power (compare equation 2)

$$N_+ \sim P_r\, N_-\, E_- \,. \tag{5}$$

$N_- E_-$ can be substituted by ρ and σ giving

$$N_+ \sim P_r\, \sigma^2\, \rho \,.$$

ρ is limited by equation 4. To get a good efficiency, one has to go close to this limit.

One limit for the accepted P_r is the damping ring acceptance ε. If σ is equal or larger than the natural spread of the shower, one gets the relation

$$P_r \sim \frac{\varepsilon}{\sigma}\,;$$

hence

$$N_+ \sim \varepsilon\, \sigma\, \rho \,. \tag{6}$$

The present NLC design requires five times more positrons per RF pulse than the SLC, but has only one third of the damping ring acceptance. Since there is only a little headroom in the current ρ value of SLC, σ would have to increase by a factor 15. But this requires a factor $15^2 = 225$ in beam pulse energy compared to the SLC production beam. The beam power would be about 23 MW, which seems to be prohibitive anyway.

To get more reasonable parameters, one has to increase either ρ or ε or both of them. ρ could perhaps be increased by using a liquid target. Liquid targets have already been used for positron production [8] and were also considered for linear colliders [9], however it remains to be proven that such a device could deal with the requirements of NLC. Here we restrict ourselves to the possibility of increasing the acceptance.

The acceptance of the positron system could be considerably increased by a pre-damping ring [1]. Such a ring would be located between the positron accelerator and the main damping ring, operating at the same energy as the latter. The equilibrium emittance of such a ring could be rather high, thus allowing small tune values and low sextupole fields, therefore providing a large dynamic aperture. The time structure of the bunches would reflect the time structure in the main damping ring. A reasonable design goal for such a ring is an acceptance of about 0.025 m, giving a gain of 2.5 compared to SLC, provided the acceptance of the positron capture system is improved by the same factor.

Another factor of two in the number of positrons could be gained by doubling the repetition rate of the production linac to 720 Hz. In this case the positrons of every second linac pulse would have to be stacked in RF-buckets already containing particles, since the injection rate into the main damping ring has to stay at 360 Hz.

Since the pre-damping ring as well as the main damping ring would operate with ten batches of ten bunches [3], the minimum storage time for a positron is 13.9 ms. The pre-damping ring has to reduce the emittance from 0.025 m to 0.003 m (see table 1). To do this in less than 13.9 ms the damping time has to be smaller than 6.6 ms, which should be achievable with a 1.8 GeV ring. The time between the injection of the first and the second linac pulse into a damping ring batch is 12.5ms, which is determined by the stacking scheme. Therefore the positrons of the first pulse are already strongly damped when the second pulse is injected. Thus a good injection efficiency can be expected.

Equation 6 shows that this scheme gains a factor of 5 compared to SLC (2 for stacking and 2.5 for emittance), retaining the same σ and ρ values as the SLC. It will be more than sufficient to meet the NLC demand of a number of positrons per RF pulse 4.8 times higher than SLC.

The product of the pulse charge and the particle energy of the production linac has to be about the same as the SLC scavenger beam value of $150 \cdot 10^{10}$ particle $\cdot$ GeV. However, since this linac would be dedicated to positron production, the pulse charge can be much higher. The limit is presumably given by the energy spread due to beam loading. If the beam pulse is short compared to the filling time of the waveguide, the beam loading is given by

$$\frac{\Delta E}{E} = \frac{\pi\, \nu\, r\, n\, e}{Q\, E}\,,$$

with ν the RF frequency, r the shunt impedance, n the number of particles per RF pulse, Q the quality factor of the waveguide, and E the accelerating field strength. Typical values for a S-band accelerator are $\nu = 2.85\,\mathrm{GHz}$, $r = 60\,\mathrm{M\Omega/m}$, $Q = 14000$ and $E = 15\,\mathrm{MV/m}$. Assuming that a total energy spread of 10% can be handled, one gets a maximum particle number of $2.44 \cdot 10^{11}$ per pulse. Thus the energy of the electrons can be lowered to 6.14 GeV. In the following, a 7 Gev Linac will be assumed.

With this scheme the overall conversion efficiency including the transmission losses through the rings has to be 0.5 positrons per targeting electron.

4 CAPTURE SYSTEM

The enlarged acceptance obtained with the pre-damping ring can only be utilized if the capture system downstream of the target has at least the same acceptance.

A positron capture system for accelerators consists of a magnetic matching system following the conversion target and an accelerating RF-waveguide with an aperture radius r_2 embedded in a long solenoid magnet with a constant longitudinal magnetic field B_2.

The acceptance of the waveguide normalized to $\gamma = 1$ is given by[1]

$$\varepsilon = \frac{e}{2m\,c}\, r_2^2\, B_2 \,. \tag{7}$$

It is independent of the particle energy. r_2 is constrained by the RF wavelength λ. For a SLAC-type waveguide geometry, the limit is

$$r_2 < 0.0786\,\lambda \,. \tag{8}$$

Thus if the acceptance of the system has to be increased one has the choice either to go to a higher B_2 field or to lower the RF frequency. In the NLC case it is for several

[1]Throughout this section all dimensions are in SI units, e and m denote the electron charge and mass, c the velocity of light.

reasons of advantage to reduce the RF frequency. A considerable increase of B_2 compared to SLC would require a superconducting solenoid, which is difficult to maintain at the high radiation levels of the positron source. On the other hand, a lower frequency reduces the energy spread due to beam loading and due to dephasing in the matching system. To stay compatible with the time structure of the damping ring, the only possible choice is an L-band Linac with $\nu = 1.43\,\mathrm{GHz}$.

The matching of the positrons emerging from the target to the waveguide could be done with a flux concentrator (FC) similar to the one used at SLC [10]. The ideal shape of the longitudinal field of such a device is [6]

$$B = \frac{B_1}{1 + g\,z},$$

where B_1 is the magnetic field at the target, z is the longitudinal coordinate with $z = 0$ at the target exit face and g is a parameter that can be adjusted with the FC geometry. The accepted transverse momenta P_r and radial displacements r of an FC are

$$P_r \leq \sqrt{\frac{m\,c\,e}{2}}\,\sqrt{\varepsilon\,B_1} \quad \text{and} \quad r \leq \sqrt{\frac{2m\,c}{e}}\,\sqrt{\frac{\varepsilon}{B_1}}, \tag{9}$$

with ε given by equation 7. Equation 9 is only valid for positron energies

$$E_+ \lesssim \frac{e}{2}\,\frac{B_1}{g} \tag{10}$$

because of the breakdown of the adiabatic approximation at higher energies [6,11], while for low energies the transverse momentum acceptance decreases due to particle dephasing, which is caused by the different path lengths of the positrons in the FC:

$$P_r < m\,c\sqrt{\frac{\dfrac{\delta\varphi\,g\,\lambda\,\gamma^2}{\pi} - \dfrac{B_1}{B_2} + 1}{\log B_1 - \log B_2}}, \tag{11}$$

where $\delta\varphi$ is the maximum acceptable dephasing angle and γ is the relativistic factor.

Using equations 2,3, 9,10 and 11, the yield of positrons for the proposed source can be estimated. It was found that an FC with $B_1 = 10\,\mathrm{T}$ and $g = 100\,\mathrm{m}^{-1}$ is a good compromise between technical feasibility and a good yield. With these parameters a yield of 2.6 positrons per targeting electron is estimated. This is more than one would expect by scaling the SLC yield with equation 5. The main reason is the enhanced acceptance of low energy positrons due to the lower sensitivity of the L-band linac to dephasing.

The estimated yield is a factor 5 higher than the required one. However, the injection and extraction process for the two rings will cause some beam losses which are difficult to predict, and the operational experience with SLC has shown that a comfortable overhead in positron production is desirable.

A summary of the source parameters in comparison with the SLC source is given in table 2. The number of particles per pulse for the positron linac are the values estimated with the given formulas and not the design values for the damping ring (compare table 1). In the SLC case this is close to the measured values [12].

Table 2: Parameters of the NLC and SLC positron source

	Electron Linac		Positron Linac	
	NLC	SLC	NLC	SLC
Repetition rate [Hz]	720	120	720	120
Energy [GeV]	7	30	1.8	1.2
RF frequency [GHz]	2.85	2.85	1.43	2.85
Bunches per RF pulse	10	1	10	1
Bunch spacing [m]	0.214	-	0.214	-
Particles per pulse [10^{10}]	24.4	5	63.4	13.5

Converter and FC		
	NLC	SLC
Pulse energy on target [J]	275	240
Beam power on target [kW]	198	29
Target length (r.l.)	6	6
B_1 [T]	10	7
B_2 [T]	0.5	0.5
g value of tapered field [1/m]	100	40

Pre-damping ring parameters	
Wall acceptance [m]	0.025
Transverse damping times [ms]	≤6.6
Energy [GeV]	1.8
RF frequency [GHz]	1.43
Circumference	Same as damping ring
Time structure of bunches	Same as damping ring
Injection rate [Hz]	720
Extraction rate [Hz]	360

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