Design of a polarized positron source for linear colliders

T. Omori\textsuperscript{a,*}, T. Aoki\textsuperscript{b}, K. Dobashi\textsuperscript{c}, T. Hirose\textsuperscript{b,c}, Y. Kurihara\textsuperscript{a}, T. Okugi\textsuperscript{a}, I. Sakai\textsuperscript{d}, A. Tsunemi\textsuperscript{e}, J. Urakawa\textsuperscript{a}, M. Washio\textsuperscript{b}, K. Yokoya\textsuperscript{a}

\textsuperscript{a} KEK: High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki 305-0801, Japan
\textsuperscript{b} Advanced Research Institute for Science and Engineering of Waseda Univ., Tokyo 169-8555, Japan
\textsuperscript{c} Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji-shi, Tokyo 192, Japan
\textsuperscript{d} National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba-shi, Chiba 263-8555, Japan
\textsuperscript{e} Sumitomo Heavy Industries, 2-1-1 Yado, Tanashi-shi, Tokyo 188-8585, Japan

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Abstract

We propose a design of a polarized positron source for linear colliders. The design is based on electron–positron pair creation from polarized $\gamma$-rays which are produced by Compton scattering of circularly polarized laser light off a high-energy electron beam. Polarized positrons are created from those $\gamma$-rays incident on a thin conversion target. A future linear collider of the TeV-energy region requires an extraordinary large number of positrons ($\sim 1 \times 10^{10}$ positrons/bunch) in a multi-bunch time structure. To meet these requirements, our design employs a high-current, low-emittance electron beam of 5.8 GeV, 10 CO\textsubscript{2} lasers, and 200 laser–electron collision-points. At each collision point, a pair of specially designed parabolic mirrors is installed to achieve efficient head-on collisions. This system allows us to produce high-intensity polarized $\gamma$-rays, which effectively generate high-intensity polarized positrons with the magnitude of polarization greater than 50%.

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1. Introduction

It has been widely accepted that an electron–positron linear collider (LC) is an ideal machine to study particle physics, and is regarded as a next-generation accelerator in the energy frontier. Since an electron and a positron are not composite, the initial energy of an interaction is well defined and the signal-to-background ratio is substantially larger than that in hadron colliders. These advantages of an LC allow researchers to discover new particles and to conduct precise studies of their detailed properties as well. It is believed that an LC will play a role complementary to that of the hadron collider LHC being constructed at CERN; both LC and LHC will be necessary to accomplish a full understanding of physics at the energy frontier.

Polarized beams bring additional and effective advantages of an LC by choosing the chirality of...
the initial particles. At high energies where the electron (positron) mass is negligible, the helicity of an electron (positron) coincides with its chirality. Therefore, in a high-energy LC, we can control the chirality of the initial particles by using spin-polarized beams. The controllability of the initial chiralities will play a crucial role in physics studies at future LCs, because chirality is one of the essential quantities of elementary particles. Beam polarization can enhance certain types of interactions, and suppress backgrounds as well, leading to a powerful capability for the search for new particles. If a new particle is found, the beam polarization can also help us to solve any weak mixing of components of the new particle.

One of the significant features of LCs is that they can accelerate polarized beams without depolarization, because linear accelerators do not suffer from spin resonances, which usually exist in ring accelerators, that destroy polarization of beams. Polarized electrons can be produced through photoemission from semiconductor cathodes. In the 1990s there was significant progress in the development of semiconductor photocathodes [1–5]: newly developed photocathodes provided significantly higher degrees of polarization of 70–90% than previous ones with a polarization of 30–40%. This improvement made polarized electron beams more valuable in physics studies. Especially, an accurate measurement of $\sin^2 \theta_W$ by using a polarized electron beam in SLC provided an impressive example [6]. In future LCs of the TeV-energy region, polarized electron beams will play more important roles. For example, if we choose the right-hand polarization of electrons, we can suppress $W^- W^+$ pair production. This may be illustrated, in unitary gauge for example, as follows. $W^- W^+$ pair production occurs by annihilation through an intermediate vector boson, or by neutrino exchange. In the former case, the intermediate vector boson is very close, in high energy, to the $SU(2)_L$ eigenstate, $W_3$. In the latter case, left-handed neutrinos are solely allowed in the standard model (no right-handed neutrinos exist). In both cases, only left-handed electrons can be coupled with those particles which have left-handed chirality. Since $W^- W^+$ pair production is the most serious background in many physics studies, its suppression is of essential importance for clarifying new phenomena beyond the standard model.

If we accomplish in LC double-beam polarization in which both the electron and positron beams are polarized, the advantage of polarized beams is significantly enhanced [7–9]. Under a CP transformation, right-handed positrons are antiparticles of left-handed electrons, and thus only right-handed positrons couple to $W_3$ bosons and neutrinos. Therefore, in the processes where the weak interaction is involved, a left-handed positron beam and a right-handed electron beam play the same role.

The following are examples of the advantage of double-beam polarization. First, $W^- W^+$ pair production can be further suppressed when we use a left-handed polarized positron beam in addition to a right-handed polarized electron beam. Second, this combination of beam polarities increases the rate of electron–positron annihilations. At high energy, an electron and a positron which annihilate each other are always a combination of $e^- e^+$ or $e^- e^+$, because the annihilation occurs through a vector boson. When only the electron beam is polarized, positrons having helicities opposite to those of the electrons are automatically chosen. This means that half of the positrons having the same helicities as electrons have no chance to annihilate at all. If we choose the polarities of the electron and positron beams to be opposite, we can preclude the existence of positrons which have no chance to annihilate. Since in many cases new particles will be produced through vector bosons, the double-beam polarization will increase the production rate of new particles. Both the first and second points result in a significant improvement of the signal-to-background ratio in new-particle searches. Third,

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1 In this article, when the direction of the spin is parallel to the direction of the momentum, we call it right-handed. We use this definition not only for electrons and positrons, but also for photons. Caution: In the conventional definition used in optics, right/left handedness of circularly polarized photons is opposite to the definition used in this article.

2 Here we assume 100% polarization of both beams for simplicity.
double-beam polarization reduces the systematic error arising from polarization measurements of each beam [10,11]. Fourth, if we choose both electron and positron beams to be right-handed, the annihilation processes are significantly suppressed. Then, the interactions, for example, such as \( e_R^+ e_R^- \rightarrow \bar{e}_R^- \bar{e}_L^+ \bar{v}_e, \bar{e}_R^- e_L^+ q \bar{q}, e_R^+ W^+ e_e, \) can be observed without being subject to any backgrounds, where \( \bar{e}^- \), \( e^+ \), and \( \bar{e}^+ \) are a scalar electron, a scalar positron and a chargino, respectively. Finally, we mention an effect of transverse polarization [12] which is uniquely achieved only if both beams are polarized. Since the transversely polarized state is a linear combination of longitudinally polarized states, the effect of new physics can be observed through the interference between the initial states which have different combinations of longitudinal polarizations of the electron and positron.

Although the polarization of positron beams is very useful, as described above, technical progress has been rather slow. Since a positron is an antiparticle, and thus there are no positrons in material, we should create them. There are typically two methods to create high-intensity polarized positrons. One is to use \( \beta^+ \) decay of short-lifetime isotopes produced by an accelerator [13]. However, thus-generated positron beams are essentially DC, and hence are not appropriate for LCs. The other method is to use electron–positron pair creation from circularly polarized \( \gamma \)-rays. To obtain pulsed beams of circularly polarized \( \gamma \)-rays, Balakin and Michailichenko proposed to utilize a high-energy electron beam passing through a very long helical undulator [14]. This method imposes technically hard requirements on both an electron beam energy, i.e. \( \sim 150 \text{ GeV} \), and the length of the undulator, i.e. \( \sim 100 \text{ m} \). In 1995, we proposed a novel method in which Compton backscattering of a circularly polarized laser beam off a relativistic electron beam [15] generates polarized \( \gamma \)-rays which are incident on a conversion target to create polarized positrons. In our method, an electron beam of several GeV and CO2 laser beams are employed instead of a \( \sim 150 \text{ GeV} \) electron beam and a long undulator.

After the proposal was presented in 1995, we have pursued a conceptual design to meet the requirements of future LCs as well as experimental R/D at both BNL and KEK. At BNL, the development of a high-power multi-bunch CO2 laser is progressing [16]. Using a 0.6 GW CO2 laser and a 60 MeV electron beam of the BNL Accelerator Test Facility, we produced high-intensity X-rays of \( 2.8 \times 10^7 \) photons/bunch [17]. At KEK-ATF, we performed a \( \gamma \)-ray production experiment where a \( 2 \times 10^5 \) photons/bunch was observed [18]. In both experiments, specially designed off-axis parabolic mirrors were installed in the beam lines to achieve efficient head-on collisions. At the center of each mirror, there is a hole which allows both an electron beam and generated \( \gamma \)-rays to pass through the mirror. Regarding the conceptual design of a polarized positron source for LCs, we have been mainly concentrating on producing a large number of positrons required in LCs. To realize this requirement, in previous papers [19,20] we presented a design in which 40 high-power CO2 lasers are employed to make 40 laser beams collide on a high-intensity electron beam at 40 collision points (CPs). In this article, we propose a new version of the conceptual design, including the reuse of laser beams, and refocus of an electron beam. Hence, we can reduce both the number of lasers from 40 to 10 and the current of the electron beam by a factor of two, and furthermore we can increase the available length of the laser–electron collision region, which makes the design of laser focus systems much easier. These improvements eventually lead to enhance the number of generated positrons.

This paper is organized as follows. The basic idea of the proposed scheme is described in Chapter 2. The collision system of laser and electron beams is described in Chapter 3. In Chapter 4, positron production on the conversion target is presented. Positron capturing is described in Chapter 5. In Chapter 6, the power consumption of the proposed system is discussed in comparison with the total power of the LC. Possible options of the design are discussed in
Chapter 7. Finally, the summary and conclusions are given in Chapter 8.

2. Basic idea of the proposed scheme

For future LCs, a positron source is required to generate a large number of positrons of very short pulse duration. The short pulses, called bunches, are repeated in a complicated manner. In this article, we choose JLC [21] as an example. Fig. 1 shows the time structure of the JLC beam.

The repetition of RF pulses of the linear accelerator is 150 Hz. Each RF pulse contains 95 bunches at 2.8 ns intervals. A set of 95 bunches is called a train. Each bunch contains $1.1 \times 10^{10}$ positrons. The extremely high intensity and the complicated time structure make it difficult to design a polarized positron source for JLC.

Our proposed scheme for generating polarized positrons is based on two basic processes, namely backward Compton scattering of circularly polarized laser light and pair creation of polarized γ-rays. Fig. 2 shows the principle of the proposed positron source. Circularly polarized laser light generates polarized γ-rays through backward Compton scattering. Those γ-rays subsequently hit a thin target, and hence some of the γ-rays are converted into electron–positron pairs. If the circular polarization of the laser light is right-handed, both of Compton-scattered photons and pair-created positrons are left-handedly polarized in the high-energy part of the spectrum.

We choose a CO₂ laser with photon energy of 0.117 eV as a light source and an electron beam of 5.8 GeV. These choices have many advantages, as follows. The total cross-section of Compton scattering is large, i.e. 658 mb. The maximum energy of scattered γ-rays is 60 MeV for which the cross-section of electron–positron pair creation on the tungsten (W) target is also large, i.e. on the order of $10^3$ mb. The maximum energy of the created positrons is also 60 MeV; which is suitable (not too high) to capture positrons into a capture section consisting of a solenoidal magnetic field and RF acceleration. CO₂ lasers can be of very high power because they are able to have a large laser medium; also, CO₂ lasers have high
efficiency. Since the photon energy of a CO₂ laser is small, the number of photons in a pulse at fixed energy is one order larger than that of solid-state lasers. This results in a large probability for laser–electron collisions. Because the required energy of the electron beam is moderate, the size of the accelerator to provide the electron beam can be relatively small. Thus, the size of the whole facility stays reasonably compact. Because the energy of scattered γ-rays is much smaller than the energy of the electron beam, one electron can undergo multiple interactions with the laser photons, and thus enhance the number of scattered γ-rays.

The biggest challenge in designing a polarized positron source is that the source must generate a huge number of positrons. To satisfy this requirement, we employ multiple laser–electron CPs. The methods used to realize multiple CPs are the keys of the design. The overall scheme of the positron source is shown in Fig. 3. The positron source mainly consists of four parts: (i) an electron accelerator which provides a high-current, low-emittance electron beam for laser–electron collisions, (ii) a set of lasers, (iii) a multiple-collision system, and (iv) a system which captures created positrons and damps them.

The first key to realizing the multiple CPs is to introduce a parabolic mirror which has a hole at its center. As shown in Fig. 4, for one CP, a pair of parabolic mirrors are utilized in the electron beam line. The first mirror changes the direction of the laser propagation so that the laser and electron beams run on the same axis, but in opposite directions. The mirror also focuses the laser beam, and then two beams collide head-on at the laser focal point. After a collision, the laser beam is
extracted by the second mirror. Each mirror has a hole at the center along the electron beam axis, and thus the electron beam and back-scattered γ-rays pass through these holes. An axicon expander located in front of the first mirror deforms the laser lateral shape from Gaussian to doughnut-like in order to avoid any laser power loss in the hole of the mirrors. Because the focal length of a mirror is chosen to be 90 mm; the total length of the pair of mirrors is short, slightly over 200 mm. This compactness allows us to put many mirror pairs in an electron beam line, as can be seen in Figs. 3 and 5.

The second key for multiple CPs is to provide an electron beam with a very small emittance. In order to put many mirror pairs in an electron beam line, the beam must be tightly focused over a long distance. Hence, we require the normalized emittance to be $1.25 \times 10^{-6}$ rad-m in both the horizontal and vertical directions. The characteristics of the electron beam are as follows: the beam energy is 5.8 GeV, the time structure of the beam is the same as that of JLC, and each bunch of the beam contains $5 \times 10^{10}$ electrons. As shown in Fig. 3, the accelerator system which provides such a high-current, low-emittance beam consists of an RF-gun, a 3 GeV linac, a 3 GeV damping ring (DR), a bunch compressor (BC), and a 2.8 GeV linac. It is assumed that the electron beam generated by the RF-gun has a normalized emittance of $5 \times 10^{-6}$ rad-m. Then, the beam is accelerated up to 3 GeV by a S-band linac and damped by the DR which is operated in full coupling, so that the normalized emittance of the beam is reduced to $1.25 \times 10^{-6}$ rad-m in both the horizontal and vertical directions. The bunch compressor is located after the DR to compress the longitudinal beam size to be 1 mm in r.m.s. Then, the beam is again accelerated by the S-band linac up to 5.8 GeV.

3. Collision system of laser and electron beams

3.1. Collision system

A focus system which has $\beta^* = 3.6$ m is adopted to focus the electron beam to a small spot size. The small emittance and long β function maintain the electron beam to be well focused over a rather long distance. The electron spot size at the waist is 20 µm and the size at 2.1 m away from the waist point is still small, i.e. 23 µm. Because the length of the parabolic-mirror pair is roughly 200 mm, we can install 20 such pairs over a distance of ±2.1 m from the electron waist point, as shown in Fig. 5.
The thus-designed collision section (CS) has a total length of 5.2 m and contains 20 pieces of parabolic-mirror pairs and diagnosis systems for both the electron and laser beams. A single laser provides laser bunches for those 20 CPs through all 20 parabolic-mirror pairs. The laser beam first enters the mirror pair at the most-downstream position of the electron beam, and moves to the upstream mirror pair. Thus, the laser beam going from a pair to the next pair finally reaches the 20th mirror pair, which is located at the most-upstream position of the electron beam. If the laser beam has 114 bunches\(^6\) in a train, and if the distance and laser path length between adjacent collision points are properly arranged, it can be realized that all 95 bunches in the electron beam collide 20 times at the 20 collision points. A detailed discussion of the geometry of the collision sections is given later. The energy of each laser bunch is assumed to be 0.25 J. Therefore, one laser should provide a total photon energy of 28.5 J in a train. The bunch spacing of the laser beam should be the same as that of the electron beam, i.e. 2.8 ns. The details of the laser system are described in Section 3.4.

Because the number of \(\gamma\)-rays generated during 20 collisions, as described above, is not large enough to create the required number of positrons, the electron beam is refocused after the first collision section by a triplet, and put to the next collision section which equips another 20 mirror pairs for the next 20 collisions. The collisions in the second collision section take place in a similar manner as that in the first collision section. The space needed for a refocusing triplet is 1 m. In order to obtain the required intensity of \(\gamma\)-rays, we provide 10 laser systems in total for 10 collision sections, as shown in Fig. 6. The total length of 10 collision sections and 9 refocusing triplets is 61 m. The entire area for collisions is called the collision region (CR). Since each collision section has 20 collision points, there are 200 collision points in total. The energy of the electron beam decreases and the energy spread increases through collisions; for example, at the entrance of the refocusing triplet of the 10th collision section, the average energy of the electrons is 5.36 GeV and the

\[ E_e = 5.80 \text{ GeV} \]
\[ \Delta E/E = 0 \% \]

6 The number of bunches in a laser beam train, 114, is determined by \( N_l = N_e + (N_{CP} - 1) \), where \( N_l \) is the number of bunches in a train of the laser beam, \( N_e \) is the number of bunches in a train of the electron beam, and \( N_{CP} \) is the number of collision points in which a laser beam is provided by a single laser.
increase in the energy spread becomes 5.9% in r.m.s. However, since the beta function is longer than the distance between the waist point and the nearest quadrupole magnet in the triplet, the effect of chromaticity is negligible, even for such a large energy spread. At the waist point in the 10th collision section, the spot size of the electron beam is maintained to be the same magnitude as that in the first collision section, i.e., 20 μm. The total number of γ-rays generated during 200 collisions is $8.3 \times 10^{11}$ photons/bunch.

### 3.2. Laser path and collision timing

Fig. 7 illustrates a 3D schematic drawing of a laser beam path from the mirror pair to the next mirror pair. For the laser path from the exit of a mirror pair to the entrance of the next mirror pair, four flat mirrors are employed to transport the laser beam. We assume that the reflectivity of the mirror surface is 99.8%, which can be achieved in finishing a copper surface by gold plating and dielectric coating. One collision section has 120 mirrors in total, i.e., 40 parabolic mirrors and 80 flat mirrors. The average power loss caused by mirrors is 11% in one collision section. The continuous heat load on a mirror generated by laser light is calculated to be 8.6 W under the assumption that all of the loss of laser power (i.e., 0.2% of the total laser power) occurs through absorption at the mirror surface. Since the magnitude of heat generated on the mirror is rather small, it can be easily removed by installing liquid-cooling channels in the mirror.

Fig. 8 illustrates the relation for the bunch spacing of the electron beam, and the distance and laser path length between adjacent collision points. The distance between adjacent collision points should be $\frac{1}{2} cT$ to realize that collisions occur at all collision points, where $T$ is the bunch spacing and $c$ is the light velocity. In addition, the laser path length between adjacent collision points should be $\frac{3}{4} cT$. Therefore, the path length from the exit of a mirror pair to the entrance of the next mirror pair should be $\frac{3}{4} cT - 2f$, where $f$ is the focal length of the parabolic mirror ($f = 90$ mm).

Fig. 9 shows the time sequence of how collisions occur at all collision points in one collision section. As described above, and as shown in Figs. 7 and 8, in a collision section the laser beam travels a

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7The bunch spacing of the laser beam is the same as that of the electron beam.
longer distance than the electron beam. From one collision point to the next one, the electron beam travels \( \frac{1}{4}cT \), but the laser beam travels \( \frac{3}{4}cT \) along the cranking path, as illustrated in Fig. 9. The period of the crank corresponds to the sum of the following paths: the path from a collision point to the exit parabolic mirror, the path from the exit parabolic mirror to the entrance parabolic mirror of the next pair, and the path from the entrance parabolic mirror to the next CP.

3.3. Laser profile at the CPs

To avoid the loss of laser power on the holes of the parabolic mirrors, the laser beam is reformed by an axicon expander just before the entrance of the first mirror pair of a collision section, so that the lateral profile of the beam is transformed from Gaussian to a doughnut-like shape. The doughnut-like beam is expressed by

\[
I(r, t) = \begin{cases} 
\frac{P(t)}{2\pi\sigma_m^2} \left(1 - \frac{r_h}{r}\right) \exp\left(-\frac{(r - r_h)^2}{2\sigma_m^2}\right) & \text{for } r > r_h \\
0 & \text{for } r \leq r_h 
\end{cases}
\]

where \( \sigma_m \) is the r.m.s size of the Gaussian beam before entering the axicon expander and \( r_h \) is the radius of a hole defined by the axicon expander. We choose \( \sigma_m \) to be 4.0 mm and \( r_h \) to be 5.0 mm. Since the laser beam profile is doughnut-like, an interference pattern is created near to the focal point. This pattern is calculated by Kirchhoff integration; we take the result into account in a simulation of laser–electron collisions, which is described in Chapter 3.5. The lateral profiles of the

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**Fig. 8.** Relation for the bunch spacing of electrons, and the distance and the laser path length between adjacent CPs. In this article, we use \( 3 \times 10^8 \text{ m/s} \) as the light velocity for simplicity.

**Fig. 9.** Time sequence to show how collisions occur at all CPs in one collision section. For simplicity, in this figure the collision section has 5 CPs, while in the actual design 20 CPs are available for one collision section.
doughnut-shaped beam near the focal point are shown in Fig. 10.

The temporal profile of a laser bunch assumed in the collision simulation is shown in Fig. 11. The peak power density, $P$, at the focal point is calculated to be $2.9 \times 10^{19}$ W/m$^2$. We use the parameter $\xi$ to characterize the laser strength,

$$\xi = \frac{\lambda_L}{2\pi m} \sqrt{\mu_0 c P}$$

where $\lambda_L$ stands for the laser wavelength, $m$ the electron mass in eV/c$^2$, $c$ the velocity of light in m/s, and $\mu_0 = 4\pi \times 10^{-7}$. At the laser focal point, $\xi$ takes the maximum value of 0.35.

3.4. Laser system

Fig. 12 is a schematic design of a laser system. A long, ~400 ns, pulse with an energy of ~0.1 J, generated by a CO$_2$ oscillator (150 Hz), is sliced into 114 seed-bunches by Germanium (Ge)-plates [22], which have switching properties by reflection and transmission.

The reflectivity/transparency of the Ge-plates is controlled by a multi-bunch pico-second YLF laser. After slicing, the energies of the 114 seed bunches are equalized with an electro-optic (E-O) power modifier. Then, 114 seed bunches are
amplified by a preamplifier and a main amplifier. Finally, we obtain 114 bunches, each of which contains 0.25 J and has a bunch duration of ~10 ps. This short bunch width is necessary to match the laser-pulse length with a depth-of-focus of ~0.8 mm for the parabolic mirrors, which create the small spot size. To achieve such a short bunch width, the pressure of CO₂ gas in the amplifiers must be high (10 atm).

### 3.5. Collision simulation

A collision simulation is performed by using CAIN [23,24] under the assumption that the laser beams have 100% right-handed helicity at all collision points. The simulation takes into account the following items/effects:

- The temporal and spatial profiles of the electron beam with the design value of the beta function and emittance.
- The temporal and spatial profiles of the laser beam with the interference pattern caused by a doughnut-shape.
- Collisions at all 200 collision points are simulated sequentially by taking into account the recoils of electrons during Compton scattering. Therefore, after and during collisions, the electron energy decreases and its energy spread becomes larger.
- Non-linear QED effect in Compton scattering.
- Focusing of the electron beam at 10 focusing systems with the energies, energy spreads, and emittances of the beam at the corresponding points.

The result of the simulation shows that the electron-beam size at the waist point of the 10th collision section is maintained to be the same as that of the first collision section (20 μm in r.m.s. in both horizontal and vertical directions). This means that the emittance growth caused by beam collisions is negligible, and also that the effect of chromaticities is negligible even for a large energy spread caused by collisions.

**Fig. 13** shows the energy distributions of the γ-rays generated by a simulation of 200 collisions; the initial laser beams are assumed to have 100% right-handed polarization. In the figure, the solid line shows all γ-rays (SUM), and the dotted (L) and broken (R) lines correspond to those which have left-handed and right-handed helicities, respectively. The figure demonstrates that if we select γ-rays of higher energy, we obtain highly polarized γ-rays. The total number of γ-rays generated during 200 collisions is \(8.3 \times 10^{11}\) photons/bunch.

It should be noted that only those γ-rays which pass through the holes of the parabolic mirrors reach the conversion target. Actually, for
protecting the mirrors from the \(\gamma\)-rays, many collimators are put in the electron beam line (Fig. 14(a)). Since the radius of the doughnut-hole of the laser beam is 5 mm, we determined that both the radius of the mirror hole and that of the collimator are 4 mm. In the simulation, \(\gamma\)-rays which collide with collimators were thrown away. As a result, the number of \(\gamma\)-rays which reach the conversion target was reduced to 5.5 \(\times\) \(10^{11}\) photons/bunch. Fig. 14(b) shows the spectrum of the \(\gamma\)-rays which reach the target as well as all generated \(\gamma\)-rays (SUM). The \(\gamma\)-rays which reach the target are indicated separately for the left-handed ones (Lc), right-handed ones (Rc), and the total (SUMc). As shown in Fig. 13, most of the \(\gamma\)-rays in the high-energy side are left-handed and reach the target. As clarified in Section 4, such high-energy photons are also effective to generate highly polarized positrons. It is therefore concluded that the collimators work well not only for mirror protection, but also for polarized positron generation and the reduction of the heat load on the target.

4. Positron production

After the collision region, bending magnets are placed so as to throw away the electron beam (Fig. 15). The curvature should be small in order to suppress unwilling synchrotron radiation emitted from the electron beam. Because the conversion target is located after the bending section at a distance of 20 m from the collision region, the spot size of the \(\gamma\)-beam on the target is big enough to keep the thermal stress of the target at a tolerable level. The r.m.s. spot size of the \(\gamma\)-ray beam on the target is 3.0 mm in both the horizontal and vertical directions. The spot size of the created electrons and positrons at the exit of the target is 4.0 mm in r.m.s.\(^8\)

Fig. 16 shows a comparison of the positron production rate on tungsten with that on titanium as a function of the target thickness. As shown in the figure, the tungsten generates a larger number of positrons per \(\gamma\)-ray. Also, the tungsten has a larger number of captured positrons. The cross-section of pair creation is proportional to the square of the atomic number, and the ionization energy loss of a positron is, roughly speaking, proportional to the atomic number. Consequently, tungsten is superior to titanium with respect to the production and capture of positrons. On the other hand, in view of the tolerance against instantaneous thermal stress, titanium has an advantage because its heat capacity is larger than that of tungsten. When we consider a cylinder of the material with a radius of 4.0 mm and a length of one radiation length, a cylinder of titanium has about a 10-times larger heat capacity than that of tungsten. However, since we use a \(\gamma\)-ray beam (not an electron beam as usual) to produce positrons, the heat deposit on the target is considerably small. Thus, as shown below, the thermal stress of the tungsten target is maintained at a tolerable level, leading to choosing tungsten as the target material. The thickness of the target is determined

\(^8\)The positrons having relatively large longitudinal momentum are mainly collected in the capture system, which is described in Section 5. Then, if we see the positrons which longitudinal momentum is larger than 15 MeV/c, the spot size at the exit of the target is 1.9 mm in r.m.s.
to be 0.5 radiation length, because, as shown in Fig. 16, the number of captured positrons is saturated at around this value.

Fig. 16 illustrates the energy deposit and thermal stress on a tungsten target of 0.5 radiation length. The EGS [25] code is used to simulate pair creation. The energy deposit on the target by a train (95 bunches) of the γ-ray beam is estimated to be 10 J. Because the repetition rate of the trains is 150 Hz, the continuous heat load on the target is 1.5 kW, which is approximately 1/3 of that on the SLC positron target (5 kW) [26]. Since the heat load is rather small, any method is applicable to cool the target. If the target plate is rotating, the
small spot of the target heated by a hit of single train escapes from a hit of the next train. Hence, any heat given by all trains is distributed uniformly along a circumference on the target. Since 95 bunches in a train enter the target in a very short time-period of 260 ns, all bunches in a train practically hit the same spot. For simplicity, we assume that the initial temperature of the target is 1000 K and an area of 4.0 mm radius is uniformly heated up by a train, and the temperature rising of the area is described by a step function (Fig. 17(b)). Because the temperature rise is 80 K at the surface of the target exit, the temperature at the surface reaches 1080 K:

\[ \sigma_{\text{e/e}} = 4.0 \text{ mm} \]  
\([\text{at target exit}]\)

\[ \Delta T_{\text{train}} (at \text{ target exit}) = 80 \text{ K} \]

\[ \text{stress} \sim 180 \text{ MPa} \]

We modified the EGS code to include spin polarization of pair-produced positrons, which is described by the GRACE [27,28]. Eventually, the number of positrons which are emitted from the target is \( 6.9 \times 10^{10} \) positrons/bunch for which the energy distribution is shown in Fig. 18 as a function of the positron longitudinal momentum. The vertical axis of the figure is the number of positrons per MeV/c normalized by the total number of \( \gamma \)-rays on the target: the solid line (all positrons), the dotted and broken lines (left-handed and right-handed). As demonstrated in the figure, positrons collected from the high-energy part of the distribution are highly polarized.
5. Positron capturing

Fig. 19 shows a schematic design of the positron capturing system. Just after the conversion target, an L-band (1.428 GHz) accelerating structure is placed to collect positrons from the high-energy part of the spectrum. Both the accelerating structure and the conversion target are located inside the superconducting solenoid magnet for minimizing the number of positrons escaping in the lateral direction; this part is called the capture section. The length of the accelerating structure is 1.5 m and its accelerating gradient is 30 MeV/m, resulting in an energy gain of 45 MeV in the structure. The magnetic field of the solenoid is 6 T at the center. Since the L-band accelerating structure is set in the solenoidal magnet, the magnet with an iron return yoke (the yoke is not shown in Fig. 19) is rather large; its inner radius is 0.25 m and the length is 2.1 m. At both sides of the yoke, there are 50 mm radius beam holes. The conversion target is located at a position of 400 mm from the entrance of the solenoidal magnet. Then, the entrance of the accelerating structure is at a downstream position 150 mm from the target. The shape of the magnetic field calculated by the POISSON is used in positron tracking, which is described below. After the capture section, positrons are accelerated up to 1.98 GeV by a linear accelerator, and are cooled by a pre-damping ring.

An extensive simulation study for the capture section was conducted. Multiple scattering of positrons in the conversion target was taken into account using EGS. A simulation program based on Runge–Kutta method was developed to track positrons in the capture section. By including spin motion, we evaluated the depolarization caused by spin precession in the capture section. The parameters of the capture section and the thickness of the target were optimized in accordance with the result of the simulation study. After the capture section, we did not track the positrons, but simply considered the acceptances in the 1.98 GeV linac and pre-damping ring. These conditions were also maintained for positrons at the exit of the capture section. Various qualifications were applied to the linac and pre-damping ring:

(1) The 1.98 GeV linac has a time window which corresponds to ±20° of the L-band phase.
(2) The energy acceptance of the pre-damping ring is ±0.017 GeV, which corresponds to a
momentum selection of $77 \pm 17$ MeV/c at the exit of the capture section.

(3) The pre-damping ring has an acceptance of 0.06 rad-m in the normalized edge emittance.

Fig. 20 represents the positron momentum distributions (a) immediately after the target exit, and (b) at the exit of the capture section. The vertical axis of the figure is the number of positrons per MeV/c normalized by the total number of $\gamma$-rays on the target. In (a), the solid line shows all positrons emitted from the target, being identical with the solid line in Fig. 18. The solid line in (b) shows all positrons which, corresponding to 95% of the positrons emitted from the target, come out of the capture section. Then acceptance criteria 1–3 described above are applied to the positrons at the exit of the capture section. The dotted line in Fig. 20(b) shows the accepted positrons. If we trace those positrons back to the exit of the target, we obtain the dotted line in Fig. 20(a).

We obtained a capture efficiency of 18.0%, which is defined to be the number of accepted positrons (= positrons in the dotted lines in Fig. 20) divided by the total number of positrons at the exit of the target. The capture efficiency as a function of the positron longitudinal momentum at the target exit is shown in Fig. 21, which indicates that we can collect positrons with high momentum at the target exit by selecting both the phase of the accelerating field of the L-band structure and the central value of the positron momentum criteria. Consequently, the captured positrons have a polarization of 54%. When the number of positrons at the target exit is $6.9 \times 10^{10}$/bunch as described in Section 4, the number of accepted positrons is $1.2 \times 10^{10}$/bunch, which meets the requirement shown in Fig. 1.

6. Power consumption

The breakdown of the power consumption is estimated as follows. We assume that the total
power efficiency of the 3 and 2.8 GeV electron linacs, from the wall plug to the beam is 8%. Then, the required wall-plug power for the electron linacs is 8.3 MW. The 3-GeV electron DR consumes 2 MW, which is the sum of 0.8 MW for the bending and quadra-pole magnets, 0.5 MW for the wiggler magnets, and 0.7 MW for the RF power. The 10 CO₂ lasers require 1.1 MW, if the power efficiency from the wall plug to the beam is estimated to be 4%. The 1.98 GeV positron linac is estimated to consume 2.7 MW under the assumption that the total power efficiency of the positron linac is 2%. This efficiency is much lower than that of the 3 and 2.8 GeV electron linacs, because the current in the positron linac is far less than that of the electron linacs, leading to both low beam loading and low power efficiency in the positron linac. The 1.98 GeV positron pre-damping ring may require 3.7 MW, which is the sum of 1.7 MW for the bending and quadra-pole magnets and 2.0 MW for the RF power. The positron damping ring, which follows the pre-damping ring, consumes 4.1 MW, which is the sum of 1.5 MW for the bending and quadra-pole magnets, 1.6 MW for the wiggler magnets, and 1.0 MW for the RF power. Then, the total power consumption of the polarized positron source is approximately 22 MW.

7. Options

In this chapter, we discuss the possible options concerning the following points:

- Do not use the 3 GeV damping ring.
- Use non-coated copper parabolic mirrors which are more resistive against radiation damage.
- Use lenses to focus the laser beams instead of parabolic mirrors.

As listed in Table 1, the design described so far is option (a).

The role of the 3-GeV DR is to considerably reduce the emittance of the electron beam, so each collision section becomes relatively long. If we do not use the 3-GeV DR, we have a larger emittance of the electron beam and reduce the cost of the positron source. It is assumed that the normalized emittance of the beam obtained by the RF-gun is 5.0 × 10⁻⁶ rad-m, even if the 3-GeV DR is not employed. This value is four times larger than that of the DR. Therefore, in order to achieve the same spot size of the electron beam, we reduce the beta function of each collision section by a factor of four. This version of the design is shown as option (b) of Table 1. The number of CPs in each collision section is 10 in option (b), instead of 20 in option (a). Then, to recover the total number of γ-rays, we increase the number of collision sections to be 24; the corresponding number of collision points is 240, which is 20% larger than that in option (a). One laser is employed for each collision section. The total length of the collision region, which contains 24 collision sections and 23 refocusing triplets, is 97 m in option (b). This is approximately 50% longer than that in option (a). To make generated γ-rays pass through the longer collision region, the holes of mirrors and collimators are set to be larger than those in option (a). For this larger hole, an axicon expander with a larger beam hole \( r_h = 7.5 \text{ mm} \) is necessary, and we attain the luminosity in each collision point in option (b) to be slightly smaller than that in option (a).

In options (c) and (d), we consider designs in which non-coated copper mirrors with a reflectivity of 99.2% are utilized, because a bare copper surface has a higher resistance against radiation damage. In option (c), we again adopt a 3-GeV DR, like option (a), and adopt 10 collision sections, each of which has 20 collision points. However, since the reflectivity of the mirrors is lower than that in option (a), we introduce two lasers for each collision section in order to reduce the effect of power loss by the mirrors. Option (d) has no damping ring in electron acceleration like option (b). Therefore we employ 24 collision sections, each of which has 10 collision points. One laser is employed for each collision section. In both options (c) and (d), the average laser power loss by the mirrors is 18%. The continuous heat load on a mirror by laser light is 34 W, if all of the loss of laser power is caused by absorption at the

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10 The positron pre-damping ring dose not have wiggler magnets.
mirror surface. Though this value is four times larger than that in a mirror with a coating, the heat is still at a manageable level by installing liquid cooling channels in the mirror.

In option (e), lenses instead of copper parabolic mirrors are utilized for laser focusing. If the lenses are not damaged by both the radiation environment in the collision region and the high power of the laser beams, we can simplify the laser path in a collision section. Fig. 22 shows the laser path and distance between adjacent lenses, which should be \( \frac{1}{4}cT \) to realize that collisions occur at all collision points. Then, the focal length of the lens should be \( \frac{1}{4}cT \); i.e. 210 mm for \( c = 3 \times 10^8 \text{ m/s} \). This value is more than twice longer than that in the options using the parabolic mirrors. In order to keep the

<table>
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<tr>
<th>Options</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
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<td>( N_e^b \text{/bunch (generated)} (\times 10^{12}) )</td>
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<td>7.59</td>
<td>6.03</td>
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<td>( N_e^b \text{/bunch (on target)} (\times 10^{12}) )</td>
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<td>( N_e^b \text{/bunch (produced)} (\times 10^{10}) )</td>
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<td>( N_e^b \text{/bunch (captured)} (\times 10^{10}) )</td>
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<td>55.7</td>
<td>54.2</td>
<td>55.7</td>
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See text for abbreviations such as DR, CP, \( \sigma_{\text{os}}, \ r_b, \ \xi_{\text{max}}, \ \text{CR, CS, WPP}, \ etc. \)


laser spot size at the focal point as small as that of the parabolic-mirror focus, we choose the larger spot size of the Gaussian beam before entering the axicon expander, i.e., \( s_m \) to be 9 mm. The longer CP-to-CP distance gives rise to the total length of the collision region to be longer than those of options (a) and (c). In order to make generated \( \gamma \)-rays pass through the longer collision region, the holes of lenses are set to be larger than the holes of mirrors in option (a). This forces us to use the axicon expander which produces a rather large beam hole of \( r_h = 7.0 \text{ mm} \). Fig. 23 illustrates the time sequence of collisions occurring at all collision points in one collision section. This scheme of multiple collision points using lenses is basically the same as a scheme proposed by Miyahara [29]. It is noted that although Miyahara’s scheme employs a large solenoid coil to keep the electron beam size small, ours is to refocus the electron beam with quadra-pole magnets. In the figure, each lens is indicated as a single lens for simplicity; however, in the actual design, each “lens” will be a group of lenses to correct for any aberration and to adjust the focal point as well. Because we assume that the lenses are made from ZnSe with a dielectric multilayer coating, the laser power loss by a lens can be very small. Most of the loss by a lens is caused by diffused reflection, but not by absorption. The absorption in a ZnSe lens is about 0.05% for a lens with a thickness of 10 mm. Because the heat load caused by this absorption is considerably small, i.e. about 2 W, it could be cooled by liquid-cooling channels in the lens mount. When we use a group

![Diagram](image-url)
of lenses instead of a single lens, the room between the lenses can be used for gas cooling, which improves the uniformity of the temperature. Option (e) has a 3-GeV DR like options (a) and (c), and has 10 collision sections with 20 CPs in each. However, since the distance between a certain CP and the neighboring CP in option (e) is twice longer than that in option (a), the total length of the collision region is much longer in option (e).

An option which involves lenses for laser focusing and has no DR in electron acceleration can be considered, in principle. However, for this option, we should divide the collision region into 40 sections with refocusing triplets to keep the electron beam size sufficiently small. This results in a considerably long collision region and 40 lasers. Therefore, we consider that this option is not realistic, because the requirement of 40 lasers is too much. Note that when the bunch spacing of the JLC beam is 1.4 ns, instead of 2.8 ns being assumed in this article, this option is worth consideration. Due to the shorter bunch spacing, the distance between adjacent lenses is so short that one collision section has twice as many CPs. This gives rise to a decrease in the number of collision sections and lasers as well.

8. Summary and conclusions

A design of the polarized positron source for JLC was given based on backward laser-Compton scattering, in which circularly polarized laser light collides with an electron beam and generates polarized $\gamma$-rays. Those $\gamma$-rays subsequently hit a thin target and produce polarized positrons through electron–positron pair creation. In order to obtain a large number of positrons, the design requires a high-current and low-emittance electron beam, which can be prepared by combining an RF-gun, linacs, and a damping ring. The design demands 10 CO$_2$ lasers and 200 laser–electron collision points. At each collision point, there is a pair of 90° off-axis parabolic mirrors with holes at their centers to achieve efficient head-on collision as well as to transmit the electron beam and $\gamma$-rays. Positrons created by the $\gamma$-rays are captured by a combination of a high-gradient accelerating structure (L-band, 30 MeV/m) and a high-field superconducting solenoid (6 T). According to our simulation, $1.2 \times 10^{10}$ positrons/bunch and a magnitude of polarization of $\sim 54\%$ can be obtained. This number meets the requirement of JLC. The power consumption of the positron source is estimated to be 22 MW in total, which is about 10% of the power for all JLC facilities. Since a polarized positron beam will be very useful for collider physics, it is reasonable to allocate this amount of power to the polarized positron source.

Four additional options of the design were also discussed in the cases of using no damping ring in the electron acceleration, non-coated copper mirrors, and lenses to focus the laser beams. In most of the options, the number of produced positrons meets the JLC requirement, or is close to the requirement. The polarizations of the produced positrons are greater than 50% in all options. The choice of options depends on the results of hardware R/D, which is now progressing. The experimental program has been pursued in BNL using the 60-MeV electron beam in which high-brightness X-ray generation via laser-Compton scattering and the development of a high-power multi-bunch CO$_2$ laser are included [16,17]. A copper parabolic mirror with a hole at its center was actually used in this experiment, and was working well with no damage. At KEK, we have been pursuing the development of advanced technologies for polarized $\gamma$-ray generation using the 1.28-GeV electron beam of KEK-ATF. It is remarked that recently the polarization of short pulse $\gamma$-rays has been successfully measured, and we plan to take further steps to produce polarized positrons and to measure their polarization. An experiment to test the radiation hardness of the ZnSe lenses and the dielectric coating will be necessary for a further consideration of the option of using lenses.

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References