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TRANSPORT OPTICS DESIGN AND MULTI-PARTICLE TRACKING FOR THE ILC POSITRON SOURCE*

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Abstract

Undulator-based positron source is adopted as the International Linear Collider baseline design. Complete optics to transport the positron beam having large angular divergence and large energy spread from a thin Ti target to the entrance of the 5 GeV damping ring injection line is developed. Start-to-end multi-particle tracking through the beamline is performed including the optical matching device, capture accelerator system, transport system, superconducting booster linac, spin rotators, and energy compressor. Positron capture efficiency of different schemes (immersed vs shielded target, and flux concentrator vs quarter wave transformation for the optics matching system) is compared. For the scheme of a shielded target and quarter wave transformation, the simulation shows that 15.1% of the positrons from the target are captured within the damping ring 6-D acceptance of $A_x + A_y \le 0.09$ m and $\Delta E \times \Delta z \le$ (±25MeV)×(±3.46cm), at the entrance of the damping ring injection line.

OVERVIEW

The undulator-based positron source is adopted as the International Linear Collider (ILC) baseline design, which uses a ~100-m-long helical undulator (K≈1, λ≈1 cm) placed at the 150 GeV point of the ILC electron main linac. The 150 GeV ILC electron beam passing through the undulator generates circularly polarized photons, which impinge on a Ti target with thickness of 0.4 radiation length and produce longitudinally polarized positrons. The generated positron beam will be first collected and accelerated to 125 MeV. Then a dogleg is used to separate positrons from electrons and photons. Positrons are accelerated to 400 MeV in the normal conducting pre-acceleration linac. The 400 MeV beam passes through a beamline to the electron main linac tunnel, along which the beam travels for 4.1-km. Then the positron beam is deflected from the electron main linac tunnel into the positron booster linac tunnel through a 462 m long beamline, and is transported through a 479 m of beamline up to the superconducting positron booster linac. After acceleration to 5 GeV, it is transported from the booster linac to the ring performing the spin rotations and energy compression, and finally is injected into the damping ring (DR) injection line [1]. The overall optics functions and geometry of the positron source except the beamline from the target to the capture accelerator system are shown in Figs. 1 and 2, respectively.

This paper is organized as follows: first, the optics for each part of the beamline is described; then, the start-to-end multi-particle tracking results are presented; and, finally, the results are summarized and future work is outlined.

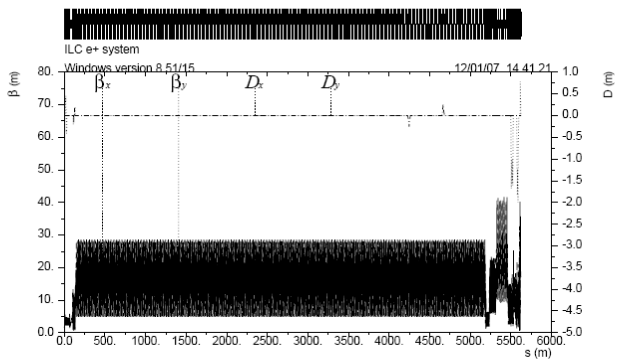

Figure 1: Overall optics of the positron source.

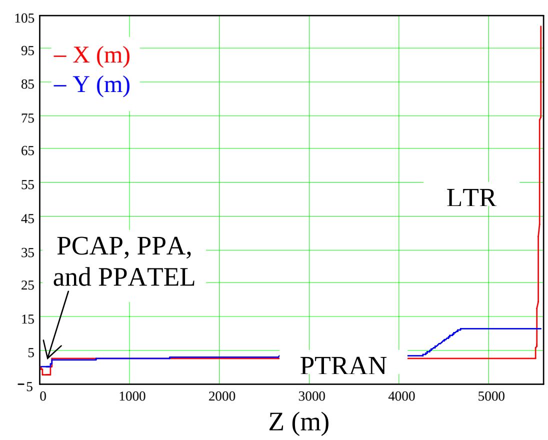

Figure 2: Overall geometry of the positron source.

START-TO-END OPTICS DEVELOPMENT

The positrons emerging from a thin Ti target are collected and accelerated in a beamline named as Optical Matching Device (OMD) and pre-acceleration capture system. The OMD is used to transform positrons characterized by small spot size and large divergence at the target into small angular divergence and large size to match the pre-acceleration capture system consisting of normal conducting L-band RF structures embedded in a solenoid. For the scheme of a shielded target and quarter

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wave transformation, the solenoid field on the target is shielded to a very small value in order to reduce eddy current created by the target spinning; then, the field sharply increases to ~1 T within ~2 cm, and then decreases to 0.5 T on the L-band structures. The distance from the target to the L-band structure is 20 cm. Parameter optimizations in the OMD and the capture cavities are described in detail in Ref. [2-3]. The positrons are accelerated to 125 MeV through the pre-acceleration capture system.

Optics of PCAP, PPA, and PPATEL

The positrons following the capture system are transported by the "Positron CAPture" beamline (PCAP), which separates positrons from electrons and photons by using an achromatic dogleg with a horizontal offset of 2.5 m. The collimators to scrape the positrons with large incoming angles and large energy errors are installed. The optics details can be found in [4].

The "Positron Pre-Accelerator" beamline (PPA) immediately downstream of the PCAP is used to accelerate positrons from 125 MeV to 400 MeV. It consists of the normal conducting L-band RF structures embedded in a constant solenoid field of 0.5 T. The MAD code does not have an element containing RF structure embedded in a solenoid, but one can use an approximate model in the MAD by longitudinally slicing both the RF structures and the solenoid, and alternating these slices for a smooth effect of both the RF and solenoid field. In this model, the solenoid field B_z in each slice is constant, but the solenoid strength $K_s = B_z/(B\rho)$, where $B\rho$ is the magnetic rigidity, varies from slice to slice with the beam energy. For an accurate model, the number of RF and solenoid slices must be sufficiently large. The optics calculation with this model does agree well with PARMELA calculation, which can directly model RF structures embedded in a solenoid. The accelerating gradient of the L-band structure in the PPA system is 8.0 MV/m, and about 34.6 m of the PPA length is required to accelerate the beam to 400 MeV.

The beamline named as "Positron Pre-Accelerator To the Electron main Linac tunnel" (PPATEL), is to transport the 400 MeV beam from the PPA to the electron main linac tunnel. It uses a horizontal and vertical achromatic dogleg to deflect the beam by 5 m and 2 m in the horizontal and vertical planes, respectively. As a result, the positron line at exit of the PPATEL is positioned 2 m high and exactly on top of the electron main linac beamline. The optics details can be found in Ref. [4].

Optics of 5 km Transport

In the ILC positron source baseline design, the Positron TRANsport (PTRAN) system was ~18 km long used to bring positrons from the electron main linac side to the positron main linac side bypassing the interaction point, from the end of the PPATEL to the entrance of the Trombone system used for path length adjustments. In September 2006, after the Vancouver Global Design Effort meeting, the ILC layout was changed to central DRs based complex, where the PTRAN system only needs about 5.03 km length and the Trombone system was removed. The PTRAN system has three sections: PTRANa – to deliver positrons on the top of the electron main linac for 4.09 km; PTRANb - to transfer positrons from the electron main linac tunnel to the positron booster linac tunnel through a 462 m of beamline; and PTRANc - to transport positrons through a 479 m of beamline up to the positron booster linac. The PTRAN system uses 16.8 m long FODO cells with 90° phase advance per cell and maximum β-function of ~28.5 m. The PTRANa follows the earth curvature as does the main linac tunnel. To simulate the beam to follow the curvature, presently a tiny vertical bend is used in each cell, whose bending angle is $16.8/(6378\times10^3) = 2.63$ μrad. It generates ~0.08 mm of dispersion along the PTRANa. Positron tracking shows that the small dispersion does not degrade the beam performance since the dispersion contribution to the beam size is negligible compared to the beam size due to the large emittance. In the real machine, no dispersion should be generated for that matter, which can be modeled by implementing the solution developed in Ref. [5]. The PTRANb – a vertical dogleg - is to provide 8 m of vertical offset to bring the positron beam from the electron main linac tunnel to the positron booster linac tunnel. On both ends of the PTRANb a double bend achromat is used to provide 19.0 mrad of the bending angle. Four quadrupoles are inserted in between the two bends so that the phase advance between the two bends is 180° and the dispersion is thus cancelled. 479 m of the PTRANc is to connect the positron booster linac with PTRANb. The detailed optics is described in Ref. [1].

Optics of the 5-GeV Superconducting Linac

The Positron BooSTeR linac (PBSTR) starts from the end of the PTRAN beamline and accelerates the beam from 400 MeV to 5 GeV through the superconducting L-band Cryo-modules. The PBSTR has three sections. The energy in the first section ranges from 400 MeV to 1083 MeV, and four non-standard-ILC-type cryomodules are used, each of which has six 9-cell cavities and six quadrupoles. Typical FODO cells are used, and the field strength of quadrupoles, $(\partial B/\partial x)\times L$, is in range of 0.88-2.0 T. In the second section, the beam energy increases from 1083 MeV to 2626 MeV, and six standard ILC-type cryomodules are used, each of which has eight 9-cell cavities and two quadrupoles. $(\partial B/\partial x)\times L$ is in the range of 0.62-1.3 T. Finally, the positrons are accelerated to 5 GeV using twelve standard ILC-type cryomodules, each of which has eight 9-cell cavities and one quadrupole. And $(\partial B/\partial x)\times L$ is in the range of 0.95-1.63 T.

Optics of the Linac-to-Ring System

The positron Linac-to-Ring (LTR) system, which extracts the positrons from the booster linac system and injects them into the DR injection line, has three main functions: the first is to rotate the electron spin vector to the vertical plane; the second is to manipulate the energy compression to accommodate more positrons within DR longitudinal acceptance; and the last is to collimate positrons in the energy tail to avoid beam loss in the DR. The longitudinal polarization of the positrons is generated at the target and preserved prior to the DR. In the DR, only positron spin directions parallel or anti-parallel to the magnet field – that is, transverse to the plane of the DR – will be preserved. The LTR system consists of bending magnets and solenoid that change the spin of the positrons first from the longitudinal to the horizontal plane and then from horizontal to vertical, parallel to the magnetic field of the DR. The spin precession with respect to the momentum vector caused by a bending angle, θ_{bend}, is given by $\theta_{spin\_bend} = \frac{E(GeV)}{0.44065} \cdot \theta_{bend}$, where E is the positron energy. Rotation of the spin vector in the horizontal plane by $n \cdot 90°$ (n is an odd integer) from the longitudinal direction requires a total bending angle of $\theta_{bend} = n \cdot 7.929°$ at 5 GeV. When a positron passes through a solenoid, its component of spin perpendicular to the solenoid field is rotated around the solenoid field axis. The spin rotation angle caused by a solenoid is given by: $\theta_{spin\_sole} \approx \frac{B_z \cdot L_{sole}}{B\rho}$, where B_z is the longitudinal solenoid magnetic field, L_{sole} is the solenoid length, $B\rho$ is the magnetic rigidity. For a 90° of spin rotation from the horizontal to the vertical plane at 5 GeV, a solenoid magnetic field integral of $B_z \times L_{sole}$ = 26.23 T.m is needed. Two 4.15-m-long superconducting solenoid with B_z=3.16 T are used.

The energy compression can be realized by properly manipulating the linac RF phase with a suitable transfer function, $R_{56} = \int \frac{D_x}{\rho} ds$ (D_x is the dispersion, and ρ is the bending radius), generated in bends. The first LTR arc consisting of four FODO cells with 8 bends is designed for the energy compression and the spin rotation [1]. A bending angle of $7\times$ 7.929°= 55.5° is chosen in the design. The nominal R_{56} is 86 cm but adjustable within the range of ±30cm. After the bunch decompression, an RF voltage of 180 MV provided by a 12-m-long superconducting linac is implemented to rotate the positrons in the longitudinal phase space to match the DR longitudinal acceptance. The remaining part of the LTR system includes an additional 34.5° horizontal-bending arc for energy collimation, and a matching section.

TRACKING WITH OPTIMIZATION OF ENERGY COMPRESSION

Multi-particle tracking from a thin Ti target to the entrance of the DR injection line has been performed. The tracking from the target to the capture cavities (125 MeV) is described in detail in Ref. [3]. The ELEGANT code [6] is then used to track the positron beam through the rest of the positron beamline including the PCAP, the PPA, the PPATEL, the PTRAN, the PBSTR, and finally the LTR system. Positron 6-D coordinates at the exit of the capture cavities are used as the input data in the ELEGANT code tracking. To accommodate more positrons within the DR 6-D acceptance of $A_x + A_y \le 0.09$ m and $\Delta E \times \Delta z \le$ (±25MeV)×(±3.46cm) [7], the energy compression has been fully optimized in the LTR before injecting into the DR injection line. For that purpose, the PBSTR upstream of the LTR runs booster linac RF phase off-crest to create a suitable correlated energy spread. For the scheme of a shielded target and quarter wave transformation, the tracking shows that 15.4% of positrons from the target can survive the transport through the complete beamline based on the physical apertures of the beam pipes [1]. Further studies show that 15.1% of positrons from the target, i.e. 98% of the survived positrons, can be captured within the DR 6-D acceptance.

Capture efficiency for various kinds of schemes, such as immersed vs non-immersed targets, flux concentrator (FC) vs quarter wave transformation (QW), is compared, as briefly presented in Table 1.

Table 1: Comparison of capture efficiency.

	5T target FC	0T target FC	0T target QW
Capture within DR 6-D acceptance	34.8%	22.8%	15.1%

SUMMARY AND FUTURE WORK

Start-to-end beam optics for the ILC positron source is developed; complete multi-particle tracking from a thin Ti target to the entrance of DR injection line is performed. For the scheme of a shielded target and quarter wave transformation, the tracking shows that 15.1% of positrons from the target are captured within DR 6-D acceptance at the entrance of the DR injection line. Looking towards the Engineering Design Report, more detail work is needed including: (1) beamline optics optimizations to meet the engineering design; (2) reducing the number of positrons reaching the DR outside of its acceptance by extensively optimizing both betatron and energy collimators; (3) start-to-end tracking as parameters of undulator and/or target are refined; (4) modeling of the activation in the 5-GeV collimators; (5) specification of component tolerances; and (6) defining tuning requirements.

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