A SPIN ROTATOR FOR THE COMPACT LINEAR COLLIDER

A. Latina, N. Solyak, Fermilab, Batavia, IL, USA
D. Schulte, CERN, Geneva, Switzerland

Abstract

Polarized positron and electron beams are ideal for searching for new physics at the Compact Linear Collider (CLIC). In order to properly orient and preserve the polarization of the beam at the interaction point, the beam polarization must be manipulated by a spin rotator along the beam line. In this paper a spin rotator design for the CLIC is presented and its integration into the CLIC ring to main linac transport system is discussed.

INTRODUCTION

Spin manipulation is necessary in four locations at the Compact Linear Collider, two per each side of the machine. Electrons and positrons, originating from the source polarized in the longitudinal direction, have to be rotated into the vertical direction by means of a spin manipulator before the injection in the damping rings, where their orientation must be parallel to the rotation axis of the ring. Subsequently, after the damping rings, another spin manipulator is necessary to set the spin vector to any desired direction. A spin rotator system must meet several design criteria:

- the rotator must be flexible so that longitudinal IP spin orientation can be restored for various collider energies
- the system must not significantly dilute the transverse emittance
- the net momentum compaction must be small, such that energy fluctuations do not become longitudinal position fluctuations
- the rotator should be located such that total spin diffusion due to energy spread is held to a reasonably small level
- the system should be short, simple and as robust as possible

A few different implementations of such a spin manipulator are explored in Ref. [1]. In this paper we chose the solenoid solution.

Spin Precession

The precession motion for the magnetic moment of an accelerating relativistic particle is given by the solution of the Thomas-BMT equation, which is described in Ref. [2]. Fundamental quantities in spin dynamics are: spin precession, $\phi_s = G\,\gamma_0\,\alpha$, mean polarization

$$< P_z >= P_0 e^{\frac{-(G\gamma_0\alpha\sigma_\delta)^2}{2}}$$

relative depolarization, $1 - \frac{< P_z >}{P_0}$, where $G \approx 0.0011614$ is the anomalous momentum of the electron, α is the bending angle, γ_0 is the relativistic factor and σ_δ is the beam energy spread.

Spin Rotator Location

The best location for the spin rotator, according to the criteria previously listed, is at the exit of the damping rings, before the first bunch compressor. In this location the energy spread is small enough to limit spin depolarization, and the beam energy is small enough to keep the beam rigidity relatively low.

CLIC RTML LAYOUT

The current layout of the CLIC RTML (see Fig. 1) presents an asymmetry between the electron and the positron lines in the early stages of the machine, i.e. in the region between the booster linac and the injection in the second stage of bunch compression. In this region the electrons travel parallel-wise to their main linac, whereas the positrons travel anti-parallel-wise to their respective linac. The direction of the arcs for the electrons have been chosen to provide zero bend angle (instead of 360 degrees).

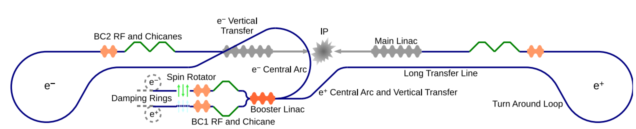

Figure 1: Conceptual layout of the RTML showing the main components

Since the spin precession and depolarization depend on the total bending angle, the difference between the two beamlines reflects in the total spin precession and depolarization experienced by the electrons and by the positrons along their way to the IP. The electrons, that travel parallel to the main linac, do not experience any total bending angle. On the other hand, the positrons experience a turnaround by 180 degrees between the booster linac and the injection in the second bunch compressor. In this region the beam energy is 9 GeV and the energy spread is 0.33%. One can calculate that the total positron spin depolarization is therefore 2.2%.

More details about the RTML design can be found in Ref. [3], in the proceedings of this conference.

BEAMLINE DESCRIPTION

Following Ref. [1] and [4], dipoles and solenoids constitute the base for this spin rotator. Vertical dipole fields are utilized for rotating the spin around the vertical (y) direction. Solenoids are utilized for rotating the spin vector around the longitudinal direction (z). The spin rotator must be able to transform an incoming vertical spin from the damping ring, into any arbitrary orientation. A rotator with such a flexibility can be obtained by putting a bending section between two solenoid pairs, each equipped with a coupling correction device, called reflector. The actual layout of the whole spin rotator is shown in Fig. 2.

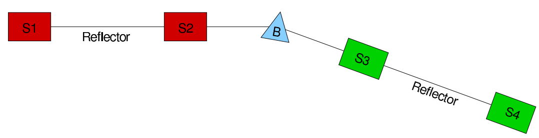

Figure 2: Schematic layout of the spin rotator, showing the solenoids, the reflectors and the bending magnets

Lattice

The reflector beamline (between solenoids) is built with four FODO cells each with 90° degrees phase advance in x and 45° in y. The bend section is a simple achromatic arc containing six horizontal bend magnets and three FODO lattice with 90° phase advance in x and y. Since this section must rotate the spin by 90 degrees around the vertical axis, the net horizontal bend angle, at 2.86 GeV, is 13.87 degrees. The peak horizontal dispersion is 1 m and the total R_{56} is 60 mm. The solenoids must be capable of providing a maximum of ± 45 degrees spin rotation each. Assuming 2.6 meters long solenoids (like in the ILC, see Ref. [4]), the maximum required field strength is 2.9 T. There are also a four quadrupole beta matching section between the first solenoid pair segment and the arc, and another matching section between the arc and the second solenoid pair segment. The final optics functions are shown if Fig. 3. The total length of this spin rotator is 134 m.

Longitudinal Phase Space

The rotator system has very little impact on the performance of the following bunch compressor. The longitudinal transfer matrix of the first bunch compressor, not including the spin rotator, is:

$$R_{\rm BC} = \begin{pmatrix} 1 + fR_{56} & R_{56} \\ f & 1 \end{pmatrix}.$$

In case of full compression, i.e. when the RF parameters contained in f are chosen so that $1 + fR_{56} = 0$, adding the spin rotator changes the total transfer matrix $R_{\rm TOT} = R_{\rm BC} \cdot R_{\rm ROT}$, as follows

$$\begin{pmatrix} 1 + fR_{56} & R_{56} \\ f & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \alpha \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & R_{56} \\ f & 1 + \alpha f \end{pmatrix}.$$

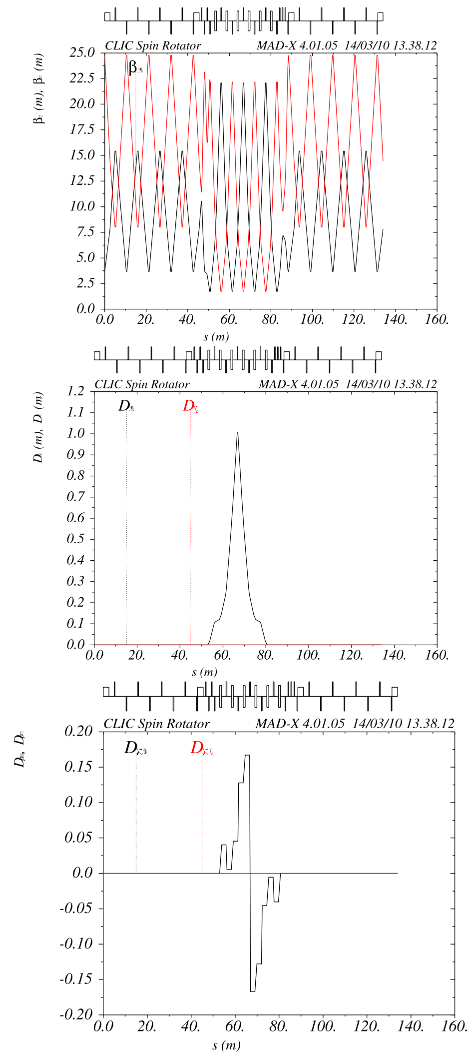

Figure 3: Twiss functions, dispersion and optics of the proposed spin rotator

The bunch length after compression is unchanged by the rotator and the energy spread after compression is even slightly smaller ($\alpha f < 0$):

$$\sigma_{z,f} = \sigma_{\delta,i} R_{56}, \quad \sigma_{\delta,f} = \sqrt{\sigma_{z,i}^2 f^2 + \sigma_{\delta,i}^2 \left(1 + \alpha f\right)}.$$

In the CLIC case the first stage of bunch compression does not fully compress, therefore the total transfer matrix $R_{\rm BC} \cdot R_{\rm ROT}$, is

$$\begin{pmatrix} 1 + fR_{56} & R_{56} + \alpha\left(1 + fR_{56}\right) \\ f & 1 + \alpha f \end{pmatrix}.$$

This implies that the rotator has an impact also on the compression factor

$$\sigma_{z,f} = \sigma_{\delta,i} \left[R_{56} + \alpha\left(1 + fR_{56}\right)\right]$$

$$\sigma_{\delta,f} = \sqrt{\sigma_{z,i}^2 f^2 + \sigma_{\delta,i}^2 \left(1 + \alpha f\right)}.$$

This problem can be solved replacing the achromatic bending section with an isochronous arc.

Table 1: Summary table with beam and rotator parameters for a spin rotator located before bc1 and before bc2

quantity	before bc1$^{(*)}$	before bc2	unit	remarks
beam energy	2.86	9	GeV	
beam energy spread	0.13	0.33	%	
total bending angle	0 (π)	0	rad	in the RTML
spin depolarization	0 (2.2)	0	%	bds excluded
spin precession	0 (10.2)	0	turns	" "
solenoid field	2.9	9.1	T	L=2.6 m
bending angle	13.9	4.4	deg	L=1 m
bending magnet	0.38	0.38	T	" "
R_{56}	60.0	6.0	mm	can be zeroed using an isochronous arc
$\Delta\gamma\epsilon_x$ by ISR	0.7	0.003	%	negligible
total length	134.0	longer	m	scales with the energy

$^{(*)}$ in parenthesis the numbers for the positrons.

Emittance Growth Induced by Synchrotron Radiation Emission

The effect of incoherent synchrotron radiation emission on the emittance growth can be estimated using the following formula[5, 6]:

$$\Delta\gamma\epsilon = 4 \times 10^{-8} E^6 \text{ [GeV] } I_5 \text{ [m}^{-1}\text{]},$$

where

$$I_5 = \frac{4L}{|\rho|^3} \cdot \frac{\eta^2 + (\eta\alpha + \eta'\beta)^2}{\beta}.$$

For a 2.86 GeV beam energy, assuming $L = 1$ m, $\rho = 24.8$ m, average dispersion and its derivative $\eta = 0.3$ m, $\eta' = 0.15$ rad, horizontal twiss $\alpha = \pm 3.5$ and $\beta = 22.5$ m, and horizontal emittance $\gamma\epsilon = 0.68$ μm, the total emittance growth induced by synchrotron radiation emission is:

$$\frac{\Delta\gamma\epsilon}{\gamma\epsilon} = 0.7\%.$$

ALTERNATIVE LAYOUT

An alternative layout for the downstream positron spin rotator has been considered, in order to avoid the 2.2% spin depolarization due to the 180 degrees turnaround previously described. An alternative location for the positron spin rotator might be right before the second stage of bunch compressor. In this configuration the spin rotator would be located where the beam has 9 GeV energy and 0.33% energy spread. The disadvantages of this solutions are the following: (1) the beam magnetic rigidity $B\rho$ is larger, therefore the magnetic strength of all magnets would need to be increased; (2) the system would be considerably longer, as the optics functions scale with the beam energy. For instance, the required solenoid magnetic strength would be 9.1 T. Tab. 1 compares the two layouts.

CONCLUSIONS

The Compact Linear Collider will require four spin manipulators, two per each side of the machine: one at the injection of the damping rings, one at their extraction, before the first stage of bunch compressor. A solenoid based design has been chosen for all of them, because this design is flexible, compact and allows to achieve arbitrary spin orientations at the IP. The system presents a momentum compaction that might impact the performances of the following bunch compressor. This can be corrected by replacing the achromatic bending section with an isochronous arc. This should also shorten the line by a few meters.

Alternative locations have been considered for the downstream positron spin rotator, such as right before the second stage of compression, at 9 GeV. Although this solution would guarantee no spin depolarization for the positrons in their motion from the spin rotator all the way to the end of the main linac, this alternative solution does not seem desirable for two reasons: (1) the magnetic rigidity is larger, and this would imply larger magnetic strengths both for the solenoids and for the bends; (2) the system would likely be longer due to the scaling of the optics functions with the energy.

REFERENCES

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