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# A Spin Rotator for the ILC

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**Abstract**

A spin rotator featuring a zero total horizontal orbit deflection is presented. This rotator utilizes three bends, two solenoid pairs and two correction devices. These correctors, named reflectors, are mandatory for removing the cross plane coupling introduced by the solenoids. We show how the solenoids should be set up to achieve longitudinal IP polarization taking into account non-zero crossing angles at the interaction region and a linac following the curvature of the earth.

# 1 Introduction

The physics return from the investment in the linear collider would be maximized by providing polarized electron and positron beams [1].
In order to ensure a well-defined extracted polarization vector, the spin vectors have to be aligned parallel to the rotation axis of the damping ring, the vertical direction [2]. Thus, the electrons originating from the source polarized by about 80% in the longitudinal direction have to be rotated into the vertical direction by means of a spin manipulator. Candidates for such a device are explored in Emma's paper [3].
After the damping ring another pair of spin rotators is required for restoring the longitudinal polarization. Additionally, it should be possible to align the spins in any direction at the IP to extract orientation-dependant portions of the cross sections. Furthermore, the effect of the non-zero crossing angles at the IP on the spin transport has to be compensated and investigated as well. Since the current layout of the linear collider features two interaction regions, two spin rotators, stacked side by side, will be required after beam extraction from the damping ring (see Figure 1) if quasi-simultaneous running of both IRs in parallel is required. Finally, we have investigated whether a successful and reliable spin manipulation is feasible even if the Linac follows the curvature of the earth.

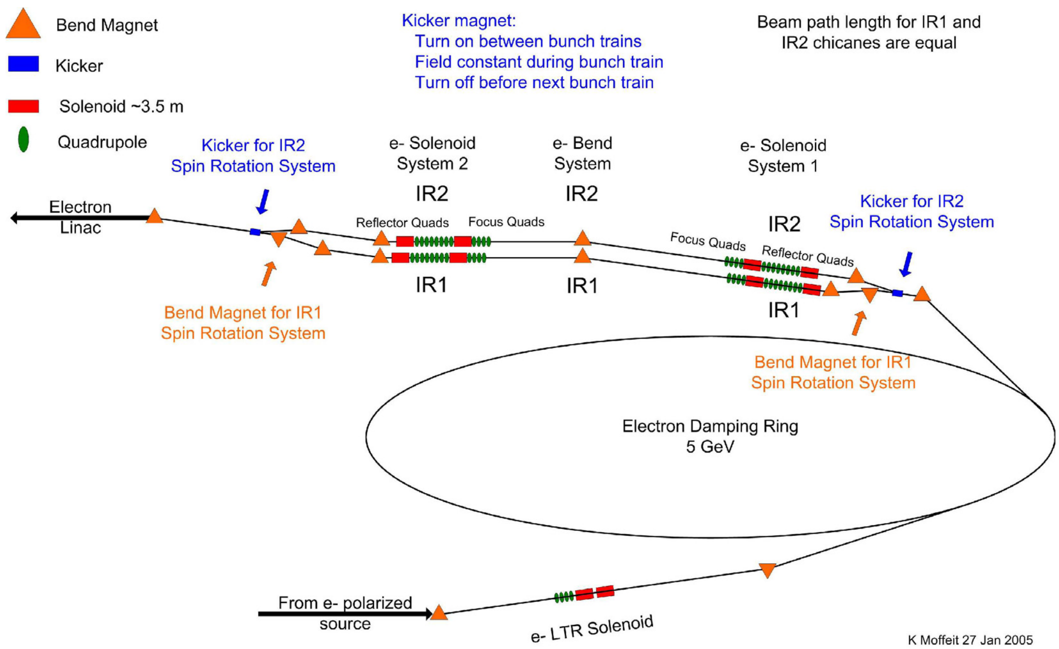



Figure 1: Possible layout of the source to ring to Linac section of the ILC [1].

# 2 Spin rotator design issues

The requirements for a candidate for the current layout of the ILC are:

- Flexible design: Longitudinal IP spin orientation has to be achieved. Additionally, the option to adjust the spin vector in any direction is desired.

- The rotator must not significantly dilute the transverse emittances ($\frac{\Delta\epsilon_y}{\epsilon_y} < 2\%$) by transverse coupling.

- The system should be short ($\lessapprox 100\,\mathrm{m}$) and as stable as possible.

- The emittance dilution caused by synchrotron radiation must be negligible.

- Two rotators should be stackable side by side, each catering for one interaction point (IP).

# 3 Rotator optics

Following Emma's work [3], dipoles and solenoids are used as building blocks for the 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 ($z$).
A spin rotator considered as a candidate for the ILC must be able to transform an incoming vertical spin, from the damping ring, into any arbitrary orientation. A rotator with such a flexibility may be obtained by putting a bending section between two solenoid pairs, each equipped with a corrector device described above.
In this paper, the original layout is augmented by an additional bending section at each end. Such a system preserves the straight geometry of the surrounding beam line. Two such systems can be arranged in parallel to accommodate concurrent runnings of the two IRs (each requiring a different spin rotator), if so required [4].
All dipoles rotate spins around the $y$-axis, the center arc by -90° and the outer ones by 45°.
The actual layout of the whole spin rotator is shown in Figure 2(b).
In addition to the optical components mentioned earlier, matching sections are added, which adapt the $\beta$ functions to the values required. The rotator has to match the external boundary conditions and the focusing effects of the solenoids have to be annulled, as well.

### 3.0.1 Solutions for straight Linac and zero crossing angle

When the solenoids are excited (see Figure 2(b)), the projected transverse emittance dilutions are: $\frac{\Delta\epsilon_x}{\epsilon_x^i} = 1.8‰$ and $\frac{\Delta\epsilon_y}{\epsilon_y^i} = 7.4‰$, respectively.
To achieve an acceptable beam transport with a relative transverse emittance dilution of less than 2% when the solenoids are off, the settings of the matching quadrupoles have to change considerably.
A viable solution is depicted in Figure 2(a). The projected emittance dilution reaches the values $\frac{\Delta\epsilon_x}{\epsilon_x^i} = 1.5‰$ and $\frac{\Delta\epsilon_y}{\epsilon_y^i} = 7.6‰$. Both of these values are acceptable. By

comparing Figures 2(a) and 2(b), it can be seen how differently the rotator works for the off- and for the on-mode.

### 3.0.2 Solutions for non-zero crossing angles at the IP

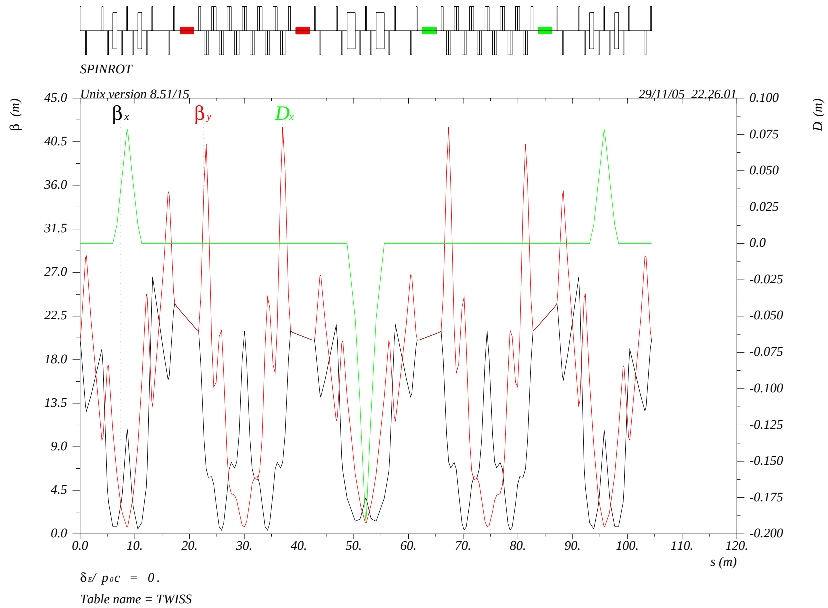
Deflecting the beam by an angle $\theta_b$ at the IP causes spin precession. Since the relativistic factor $\gamma = 978473.58$ is so large for a beam energy of 500 GeV, a deflection of the beam by $\theta_b = 10$ mrad, causes a precession of 11.35 rad.
A setup which provides longitudinal IP polarization for these parameters is shown in Figure 3. The respective relative emittance dilutions are: $\frac{\Delta\epsilon_x}{\epsilon_x^i} = 9.6‰$ and $\frac{\Delta\epsilon_y}{\epsilon_y^i} = 6.7‰$.

### 3.0.3 Solutions for curved linac

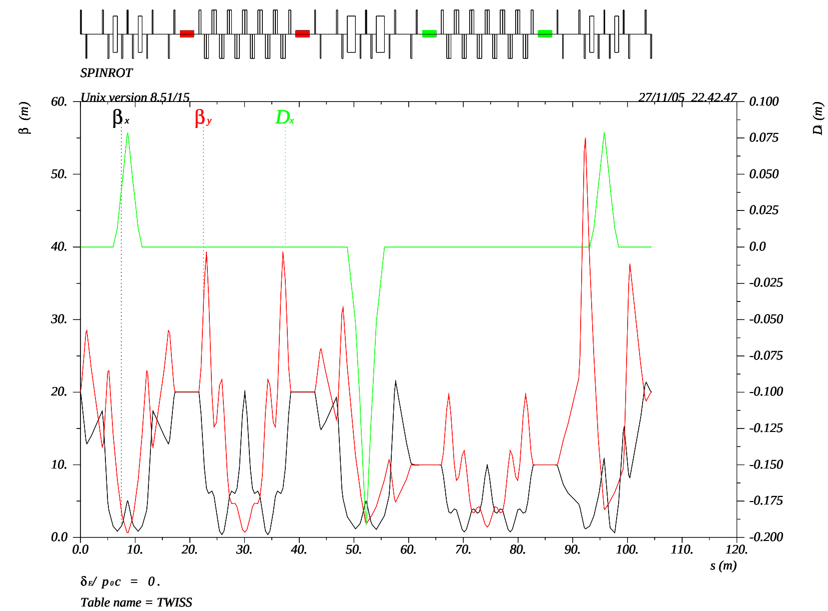
If the main Linac follows the surface of the earth, the spin transport is affected by effective dipole fields determined by the curvature of the earth. These small dipoles cause a precession of the spin. Additionally, the constant acceleration imposed by RF fields in the Linac changes the relativistic factor $\gamma(s)$.
Assuming a length of 20 km for the Linac, a maximum beam energy $\hat{E}$ of 500 GeV, an initial energy $E_0$ of 5 GeV, a radius of the earth $\rho = 6000$ km and an electron rest energy of 511 keV, the total spin precession angle $\psi_s$ becomes 109.5°. The projected transverse emittance dilutions are: $\frac{\Delta\epsilon_x}{\epsilon_x^i} = 4.5‰$ and $\frac{\Delta\epsilon_y}{\epsilon_y^i} = 1.6‰$, respectively. For the layout see Figure 4.

## 4 Spin rotator performance

In this section, the performance of spin rotators manipulating an ingoing vertical spin into the longitudinal direction at the exit of the rotator is investigated. Special attention is given to the influence of energy errors and measures for mitigating chromaticity-related emittance dilution.
The previous studies show how the large solenoid coupling can be avoided by judiciously designing a correction facility.
Unfortunately, this cancellation works perfectly only if the relative momentum error $\delta_p = \Delta p/p$ is zero (ignoring geometric aberrations). Below we elucidate how momentum errors affect the beam transport from start to end of the whole corrector. Cancelling cross-plane coupling over a range comparable to the momentum spread is highly desirable. Furthermore, the total relative emittance dilution caused by geometric and chromatic aberrations should remain below 2%.
To investigate these matters, the system described in the Tesla TDR [5] was set-up for appropriate spin transport by exciting the solenoids as explained earlier. The calculations were done with the help of MAD8 [6]. The emittance dilution obtained is excessive (see Table 1). This system employing three FODO cells per corrector unit is not a suitable candidate for the ILC.




(a) Solenoids off




(b) Solenoids on

Figure 2: Comparison of the beta-functions for two of the imaging modes of a spin rotator utilizing six FODO cells per corrector unit. In the top panel both solenoids are off. In the lower panel both solenoids are excited.

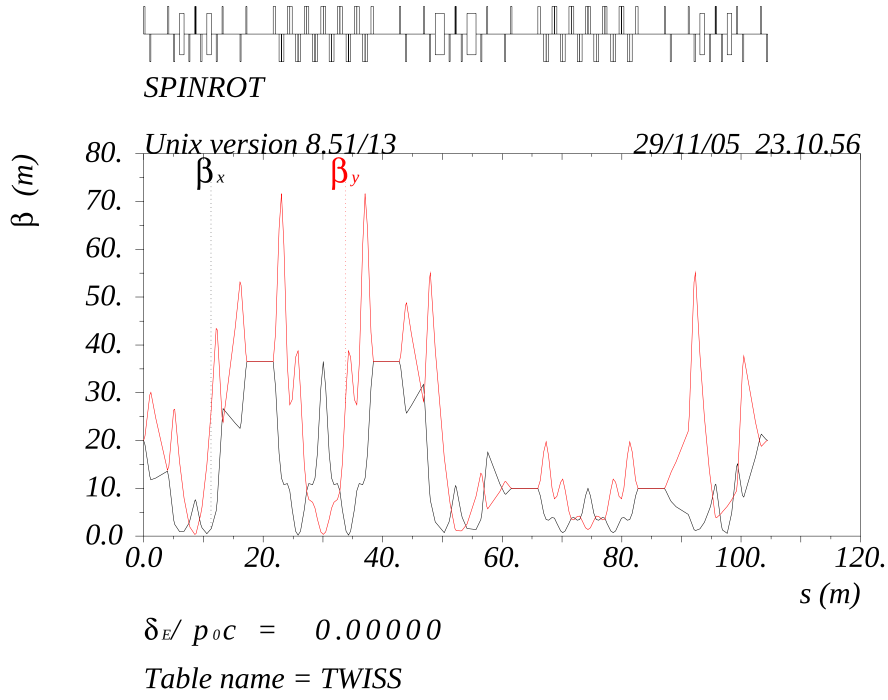



Figure 3: Beta functions of a spin rotator adjusted for longitudinal IP polarization taking a crossing angle of $2 \times 10\,$mrad into account.

| number of FODO cells per reflector | $\frac{\Delta(\gamma\epsilon_x)}{\gamma\epsilon_x^i}$ | $\frac{\Delta(\gamma\epsilon_y)}{\gamma\epsilon_y^i}$ |
|---|---|---|
| three (Tesla TDR) | 3.5‰ | 8.3% |
| four | 1.7‰ | 7.4‰ |
| six | 1.8‰ | 2.4‰ |

Table 1: Emittance dilution for spin rotators. A relative momentum spread $\delta_p = 1.3$‰ is assumed.

For the solution investigated, $\beta$-functions with vanishing slope ($\alpha_x = \alpha_y = 0$), at the beginning and at the end of the reflector unit are favorable for obtaining low emittance transport. Changing distances between matching quadrupoles, arranging four quadrupoles into two doublets helps in getting more appropriate matches. In addition to adjusting some other distances, increasing the number of FODO cells per reflector lowers the vertical emittance increase considerably (see Table 1). The reduced phase advance per FODO cell mitigates chromaticity related effects; thereby reducing the emittance dilution.

The reduction of emittance dilution for a system comprising four FODO cells per reflector (phase advances $\mu_x = 90°$ and $\mu_y = 45°$) and for six cells ($\mu_x = 60°$ and $\mu_y = 30°$) is shown in Table 1, as well. The projected emittances are achieved by calculating the moments of the final particle distribution.

The dependence of the transverse projected emittances on the relative momentum spread

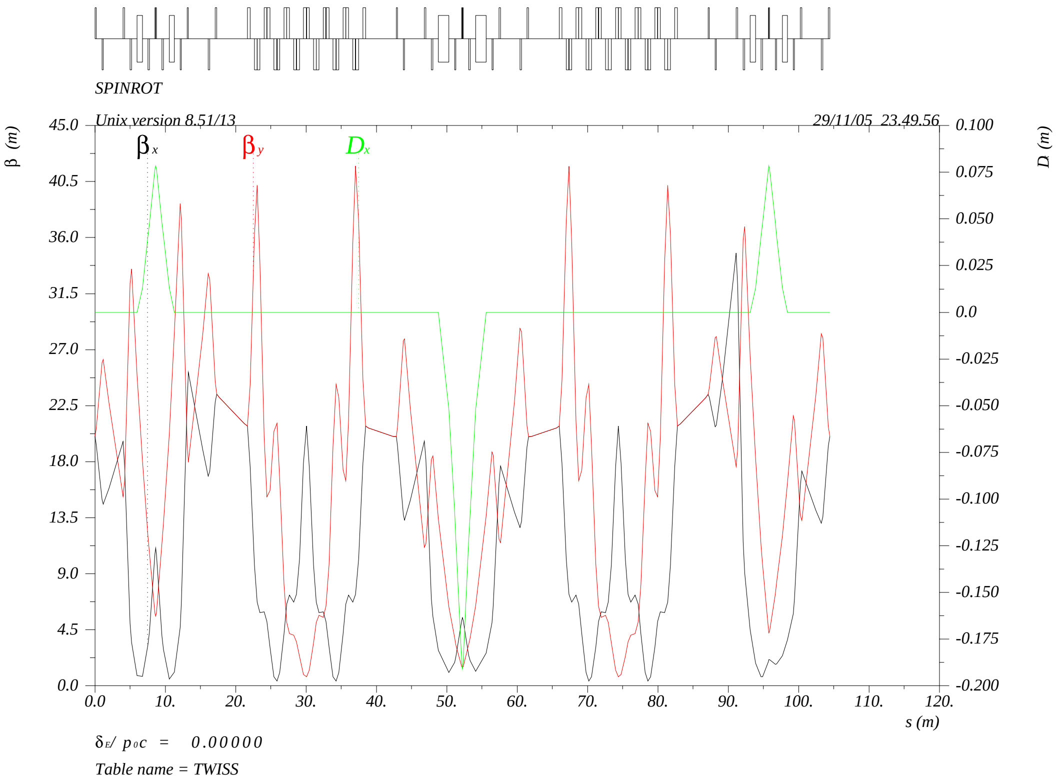



Figure 4: Beta functions of a spin rotator set-up for longitudinal IP polarization considering a Linac following the curvature of the earth.

$\delta_p$ is shown in Figure 5.
For on-energy particles, the transverse emittance dilutions are zero for all data sets depicted in Figure 5. This shows that the corrector is adjusted appropriately.
The emittance dilution is caused by chromatic effects. Since the transverse emittance dilution scales roughly with $\delta_p^2$ in the region shown in Figure 5, the relative momentum spread $\delta_p$ has to be small. Otherwise, a sufficient suppression of cross-plane coupling for off-energy particles is not viable.

# 5 Conclusion

The results presented in this document show that this spin rotator is a suitable candidate for a spin rotator meeting all the requirements of the ILC. Further details can be found in [7].


# Acknowledgment

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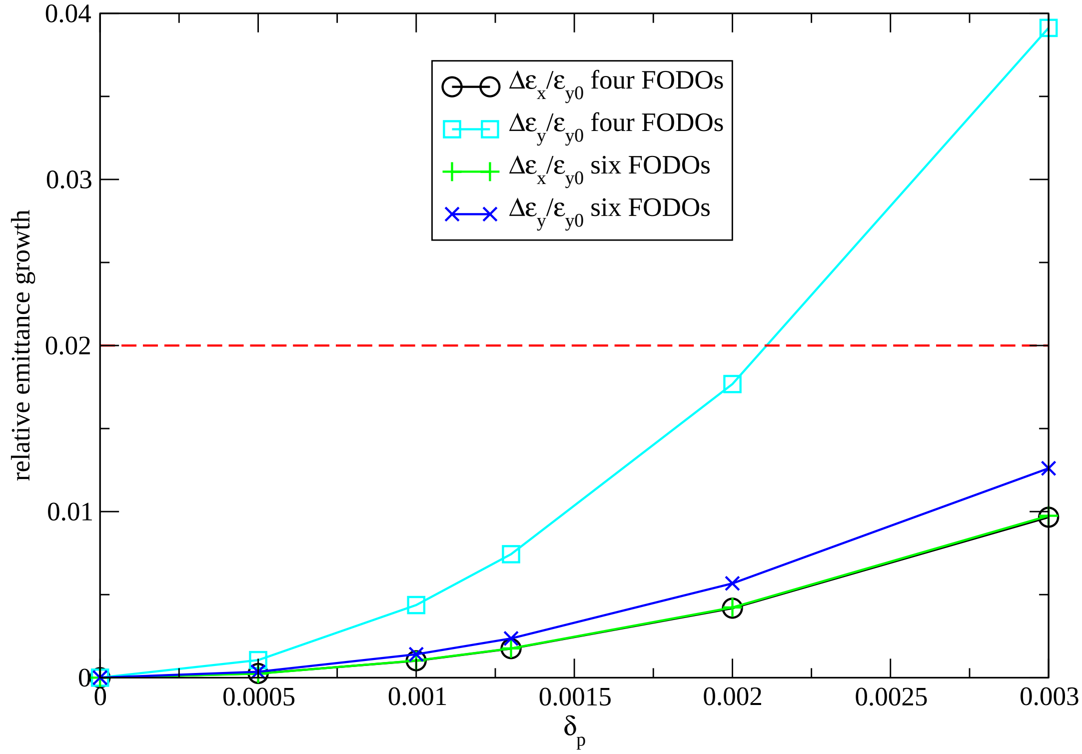


Figure 5: Vertical emittance dilution as a function of the relative momentum spread $\delta_p$.

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