A Spin rotator for the ILC

Peter Schmid

FLC

- Spin transport at the linear collider
- Spin rotator design requirements
- Outline of the system
- Solenoid settings required
- Results of stability studies
- Analysis for a Linac following the curvature of the earth
- Analysis for non-zero crossing angles

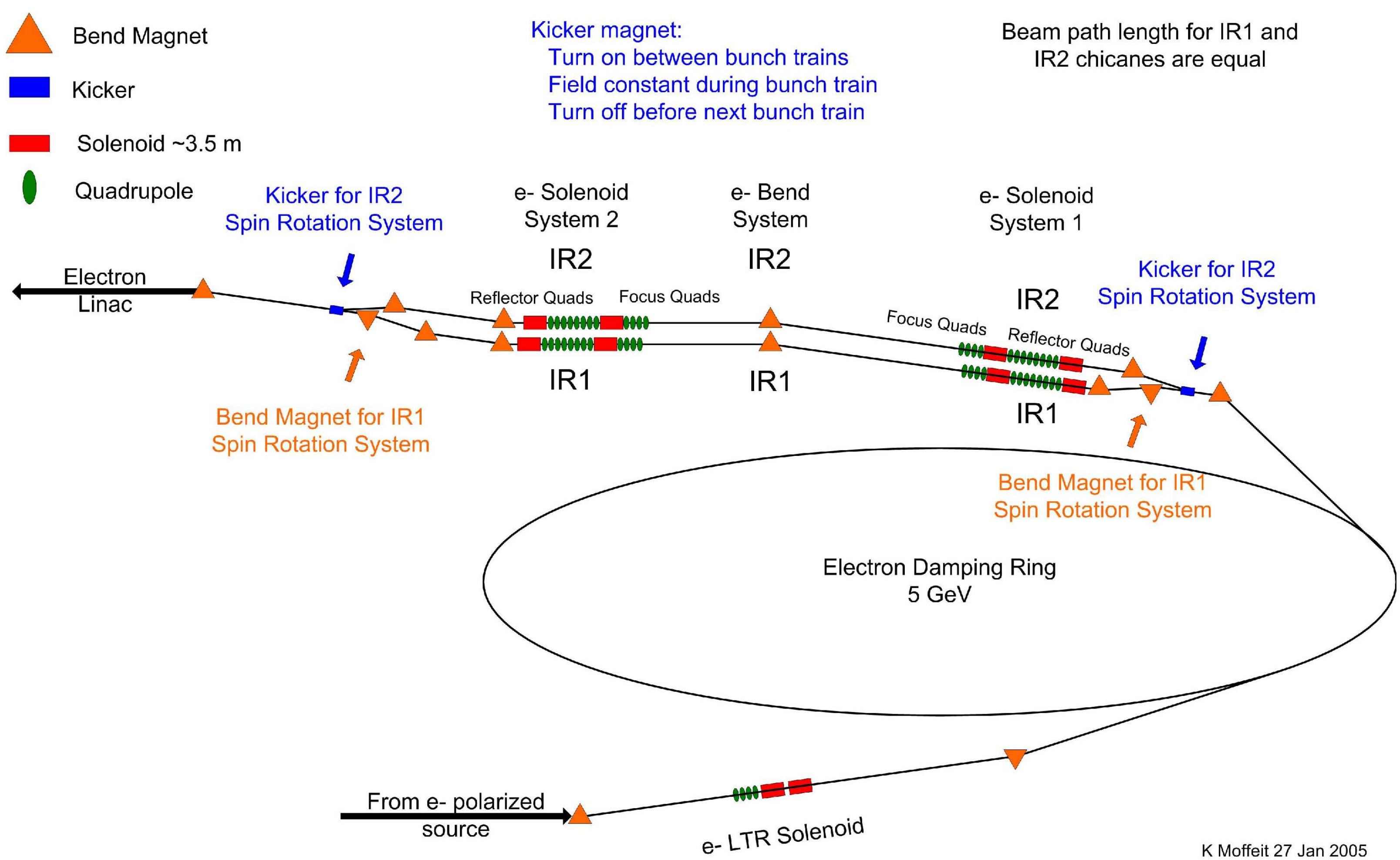
Introduction

- Polarized electrons are a requirement for the ILC; polarized positrons are very desirable.
  $\longrightarrow$ cross-sections increase
- Currently there are two interaction regions (IR).
- Running the two IRs (almost) concurrently is a plus, e.g. by alternating each train.
- The beams at the IRs are not parallel, the crossing angles are $2 \times 1\,\mathrm{mrad}$ and $2 \times 10\,\mathrm{mrad}$, respectively.
- Both helicities have to be provided for positron and electrons at the IRs considering the crossing angles.

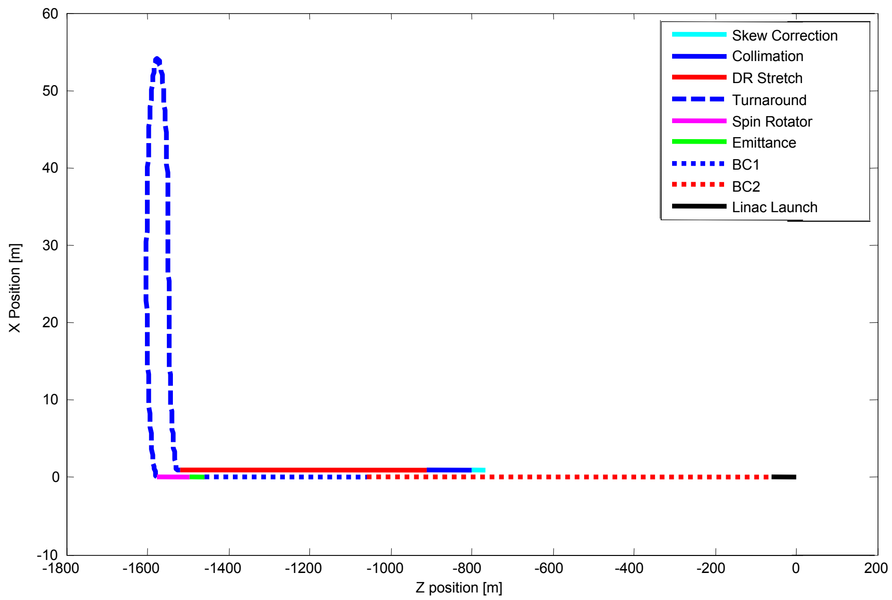
Spin transport considering two IRs

- Since the IPs are not parallel, the spins must be aligned differently for each of the IRs at the entrance of the linac to achieve longitudinal polarization.
  $\longrightarrow$ Two parallel rotator lines are required, which have to be stackable side by side.
- Solenoids and horizontal bends are utilized, minimizing the vertical emittance dilution in comparison to chicane based systems.
- The path length in both rotators has to be identical within the electron bunch length.

Spin transport for electrons



Current layout of the RTML



- nominal $\delta_p = 1.3 \times 10^{-3}$
- initial emittances: $\epsilon_x = 1 \times 10^{-9}\mathrm{m}$, $\epsilon_y = 1 \times 10^{-12}\mathrm{m}$
- beam energy is $5\,\mathrm{GeV}$

- The spin rotator is integrated in the turnaround.
- Only a single polarization can be provided for both IRs.
- Quasi-simultaneous running of the two IRs is not an option.

Spin rotator design requirements

- Flexible design: Longitudinal IP spin orientation has to be achieved. Additionally, the option to adjust spin polarization in any direction is desired.
- The rotator must not significantly dilute the transverse emittances ($\frac{\Delta\epsilon_y}{\epsilon_y} < 2\%$).
- Emittance increase caused by synchrotron radiation should be negligible at $5\,\mathrm{GeV}$ beam energy.
- The system should be short ($\lessapprox 100\,\mathrm{m}$) and as stable as possible.
- The dilation factor must be small, otherwise energy fluctuations are transferred into longitudinal position fluctuations comparable to the bunch length.

Spin-rotating building blocks

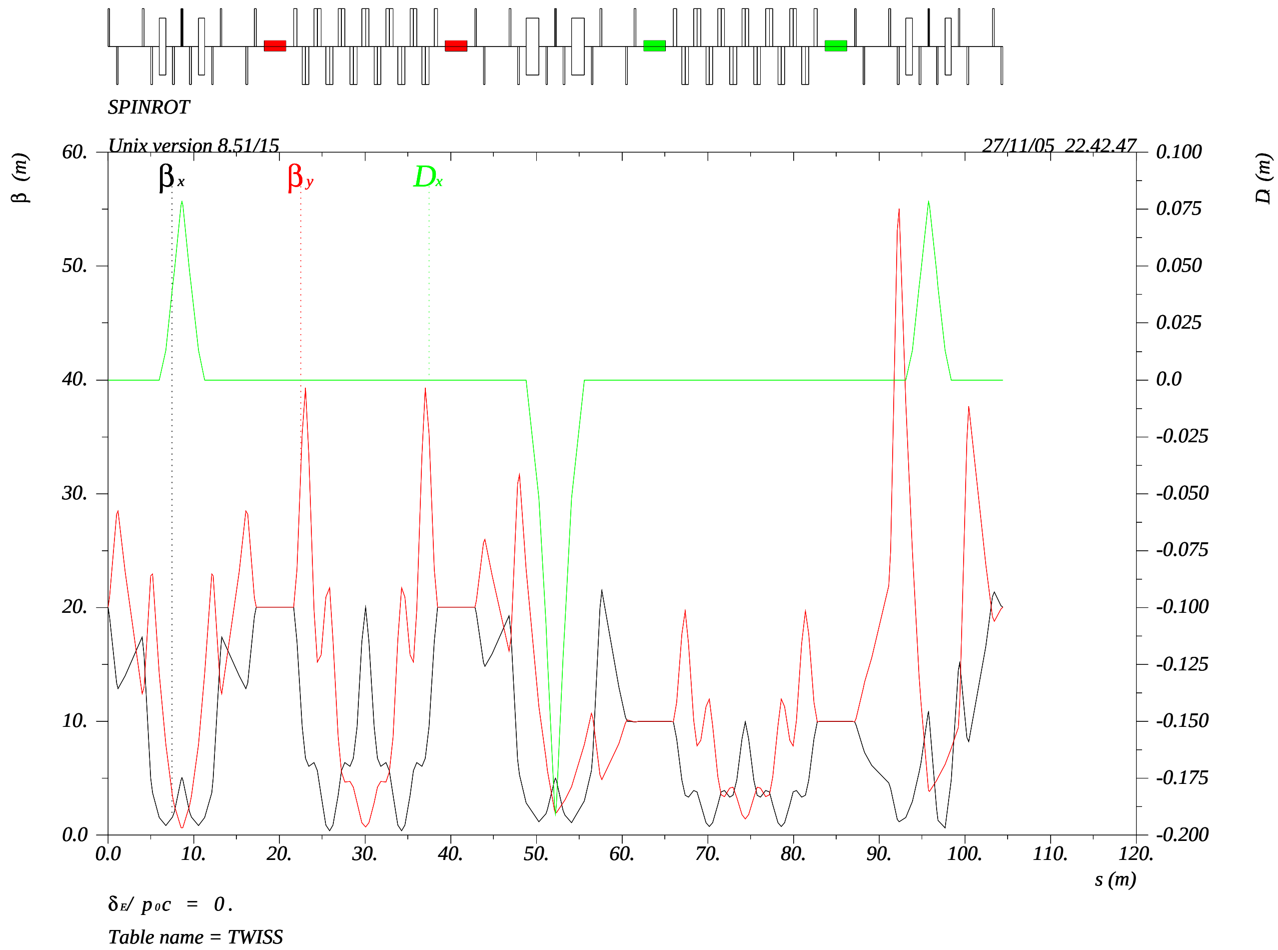
- Dipoles rotate spins: $\theta_s = \gamma \frac{g-2}{2} \theta_b$
- Solenoids rotate spins: (Larmor rotation)
  $\Delta\theta_s = \left[1 + \frac{g-2}{2}\right] \frac{B_s L_s}{B_0 \rho} \approx \frac{B_s L_s}{B_0 \rho} = 2\theta_r$
- Caveat: Solenoids cause cross-plane coupling. The vertical emittance increases
  (≈ 100 times for ILC parameters)
- Solenoid pairs with a corrector (*reflector*), removing cross plane coupling for on-energy particles, are required.
  (+I transformation in x, -I transformation in y)

The spin rotator consists of:

- three bends: net deflection is zero.
  center arc rotates beam by 8°; thus spins by 90°.
- two solenoid pairs, each equipped with a reflector

- For electrons, $\frac{g-2}{2} = 1.16 \times 10^{-3}$, gyromagnetic anomaly a.
- θ_b, bending angle
- θ_r, roll angle of the beam
- $B_0\rho$, beam rigidity
- $B_s L_s$, field integral

Optics layout of the spin rotator



Solenoid settings required

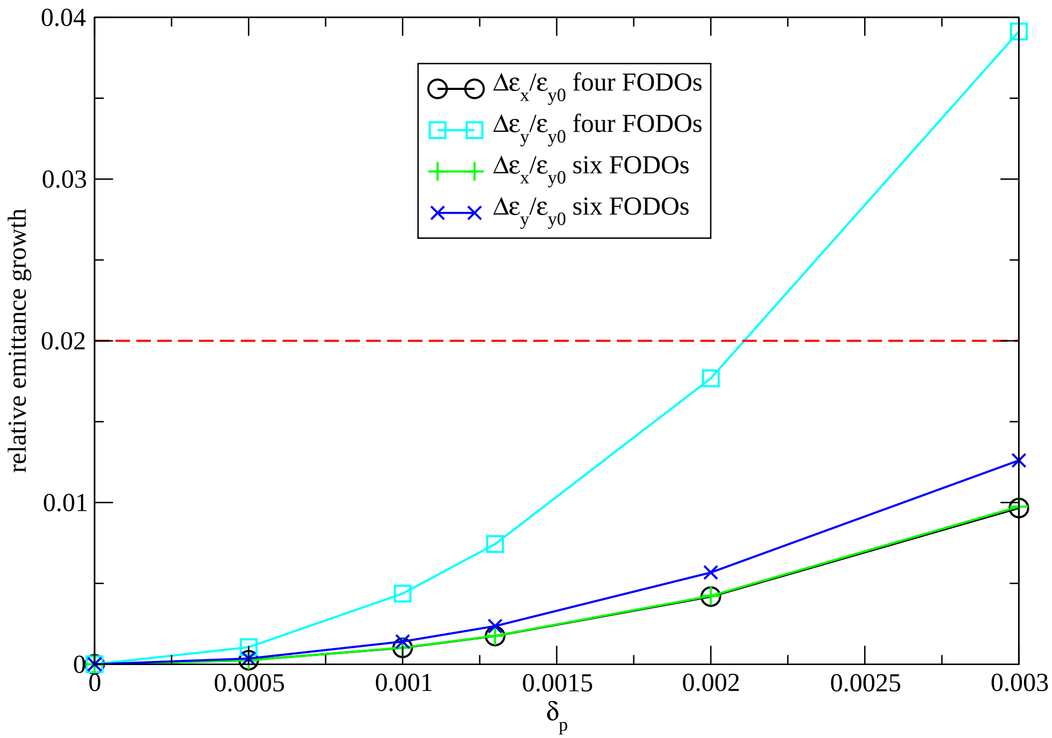
A spin polarized along the vertical direction (originating from the damping ring) has to be converted into one which is longitudinally polarized.

- Net deflection angle is zero.
- Center bend deflects spins by 90°.
  $\theta_s = \frac{\pi}{2} = a\gamma\theta_b \quad \Rightarrow \theta \approx 8^\circ$
  outer bends: $R_y(\pi/4)$, center arc: $R_y(-\pi/2)$
- two solenoid pairs rotate the spins by the total angle ϕ_1 or ϕ_3, respectively $R_z(\phi_1)$, $R_z(\phi_3)$

- a: gyromagnetic anomaly
- Energy is $5\,\mathrm{GeV}$
- $R_y(\phi)$: Rotation around y with angle ϕ
- $R_z(\phi)$: Rotation around z with angle ϕ
- θ_b: bending angle

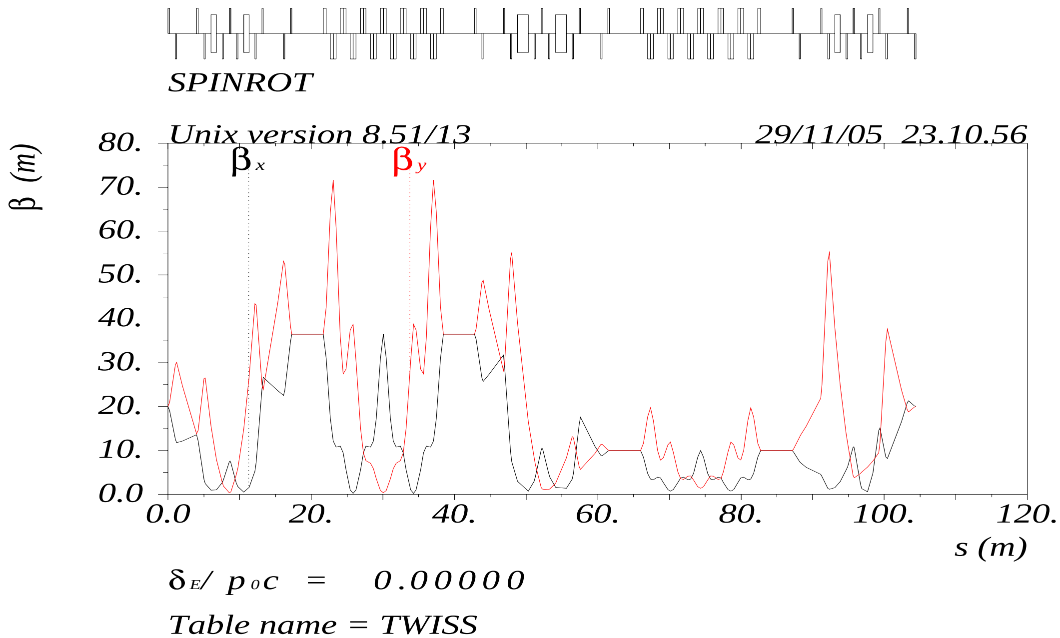
Emittance dilution of the system

- initial system (TESLA): $\frac{\Delta\epsilon_y}{\epsilon_y} = 8.3\%$
- new system utilizing four FODO cells: $\frac{\Delta\epsilon_y}{\epsilon_y} = 7.4‰$
- new system utilizing six FODO cells: $\frac{\Delta\epsilon_y}{\epsilon_y} = 2.4‰$



- nominal $\delta_p = 1.3 \times 10^{-3}$
- initial normalized emittances: $\gamma\epsilon_x = 8 \times 10^{-6}\,\mathrm{m\,rad}$, and $\gamma\epsilon_y = 2 \times 10^{-8}\,\mathrm{m\,rad}$.
- beam energy is $5\,\mathrm{GeV}$

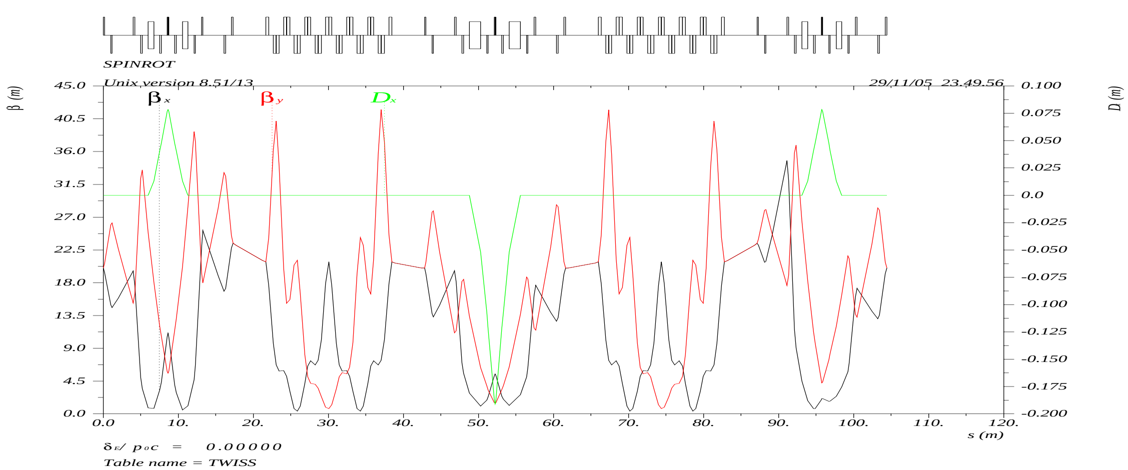
Solution for $2 \times 10\,\mathrm{mrad}$ crossing angle



- nominal $\delta_p = 1.3 \times 10^{-3}$
- initial normalized emittances: $\gamma\epsilon_x = 8 \times 10^{-6}\,\mathrm{m\,rad}$, and $\gamma\epsilon_y = 2 \times 10^{-8}\,\mathrm{m\,rad}$.
- emittance dilution: $\frac{\Delta\epsilon_x}{\epsilon_x} = 9.6‰$ and $\frac{\Delta\epsilon_y}{\epsilon_y} = 6.7‰$ (not optimized)

Solution for a curved linac

- A 20 km linac following the curvature of the earth causes a spin rotation of 109.5° around the x-axis (horizontal). → checked with Merlin
- The excitations for the solenoids and the matching sections are very different than those for a laser straight linac.
- A viable solution is $\phi_1 = 0.24\,\mathrm{rad}$ and $\phi_3 = -0.25\,\mathrm{rad}$, for transforming a spin polarized parallel to the vertical into one which is longitudinal at the IR.

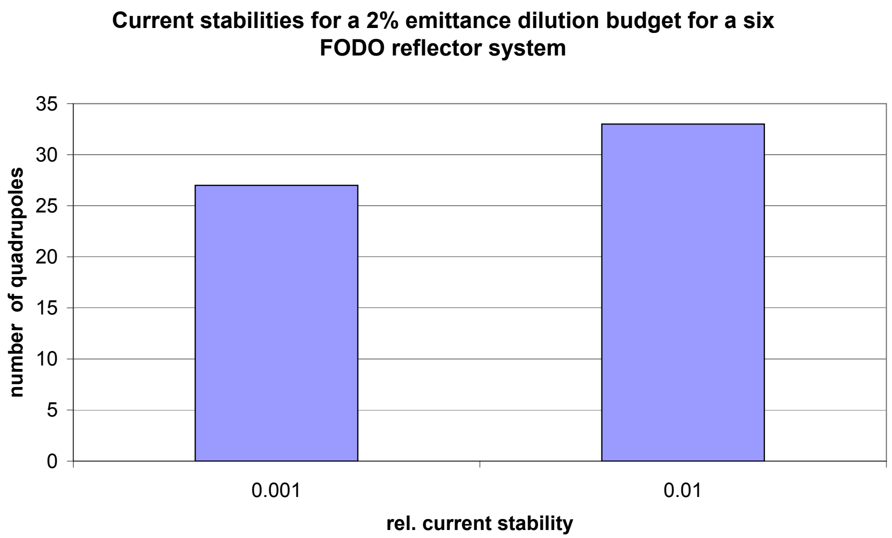


- nominal $\delta_p = 1.3 \times 10^{-3}$
- initial normalized emittances: $\gamma\epsilon_x = 8 \times 10^{-6}\,\mathrm{m\,rad}$, and $\gamma\epsilon_y = 2 \times 10^{-8}\,\mathrm{m\,rad}$.
- emittance dilution: $\frac{\Delta\epsilon_x}{\epsilon_x} = 4.5‰$ and $\frac{\Delta\epsilon_y}{\epsilon_y} = 1.7‰$ (not optimized)

Results of the stability studies I

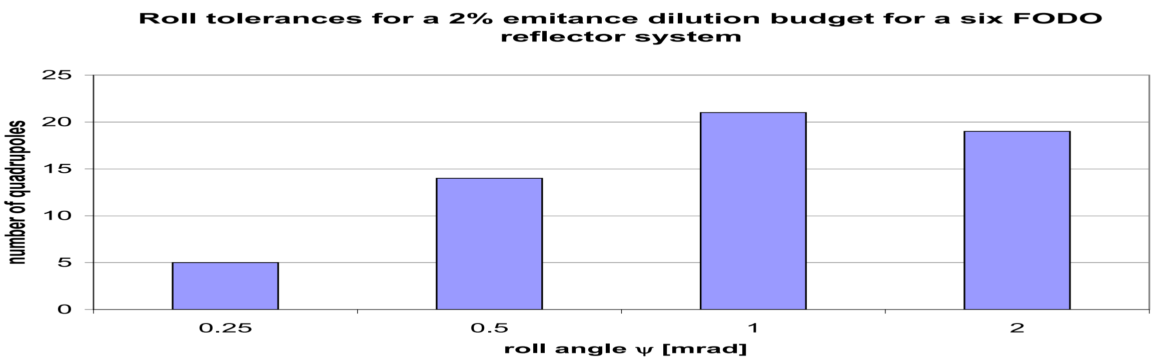
Requirements for power supplies: ($\frac{\Delta\epsilon_y}{\epsilon_y} < 2\%$)

At maximum a relative stability of $1‰$ is required.

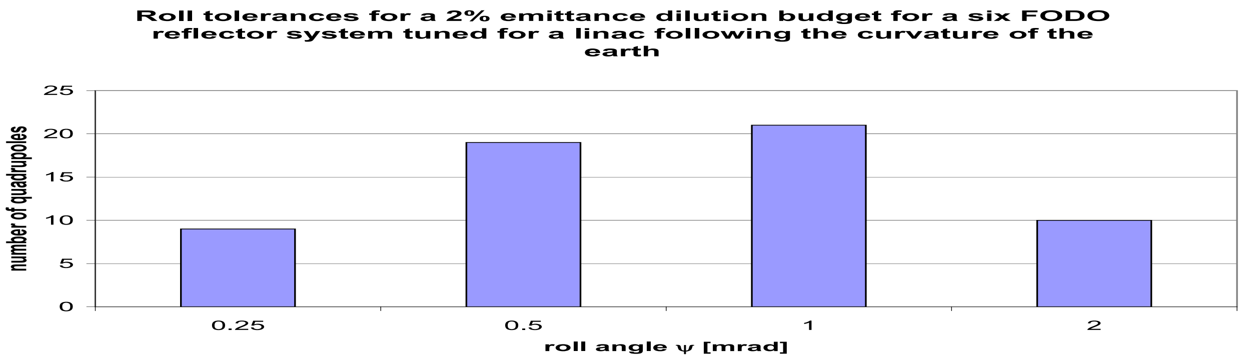


Results of the stability studies II

Roll tolerances for the quadrupoles:



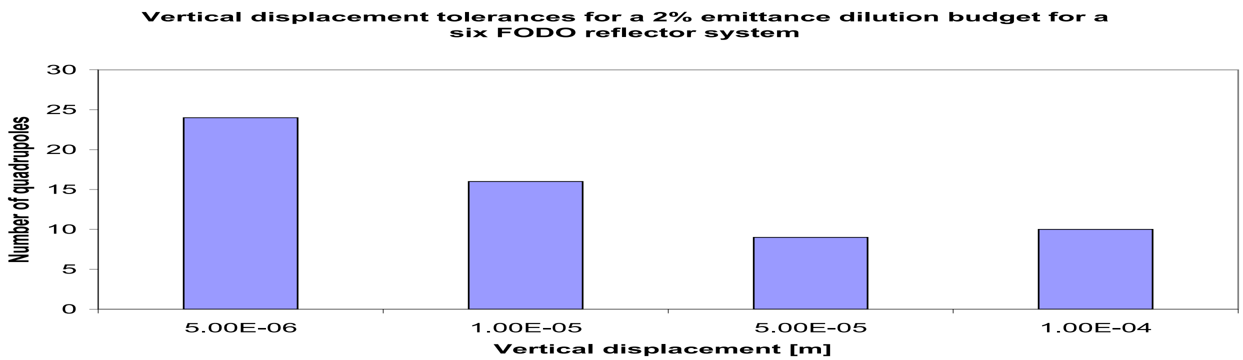
straight



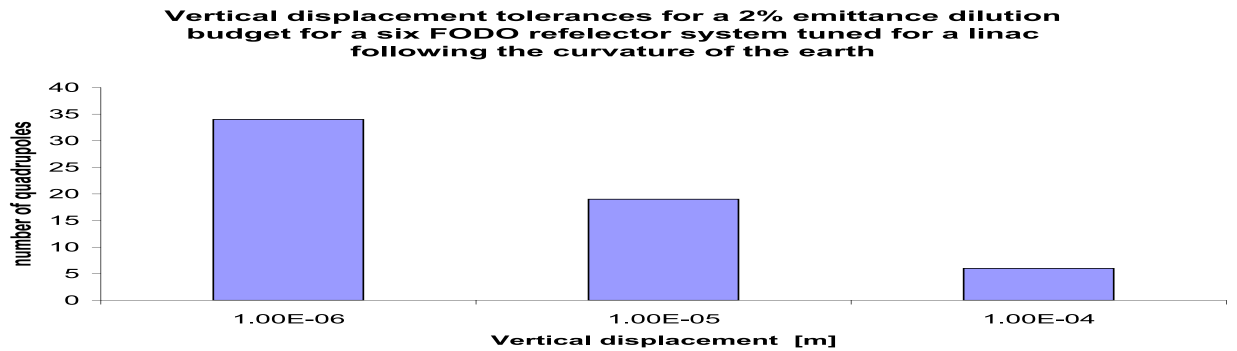
curved

Results of the stability studies III

Vertical misalignment tolerances of the quadrupoles:



straight



curved

Estimation of the longitudinal spin polarization dilution caused by the undulator

- Perturbation theory shows at high energy the longitudinal polarization is altered by
  $\Delta S_z = \sqrt{x_0'^{\,2} + y_0'^{\,2}} \times \frac{W_1}{W_3}$
- x_0' and y_0' are the initial slopes $\approx 10^{-3} \ldots 10^{-4}$ rad.
- W_1 and W_3 are the x and z component of the precession frequency (BMT equation): $\frac{W_1}{W_3} \approx 10^{-3}$

$$\Rightarrow \quad \Delta S_z \approx 10^{-6} \ldots 10^{-7}$$

$\Rightarrow$ Thus, the polarization of the electrons is unaffected by the helical undulator.

Summary

- A spin rotator was developed which meets all the design requirements. Elucidating the final installation tolerances utilizing beam-based alignment techniques is the subject of another investigation.
- The perturbation imposed by the positron source on the electron polarization were calculated and considered negligible.
- Depolarization effects due to misalignment seem to be a non-issue at $5\,\mathrm{GeV}$. Displacing the most sensitive quadrupoles by $10\,\mathrm{mm}$ is required to cause an appreciable effect. The only depolarizing effect originates from parasitic dipole field components caused by misaligned quadrupoles.