Spin Rotator for Linear Colliders

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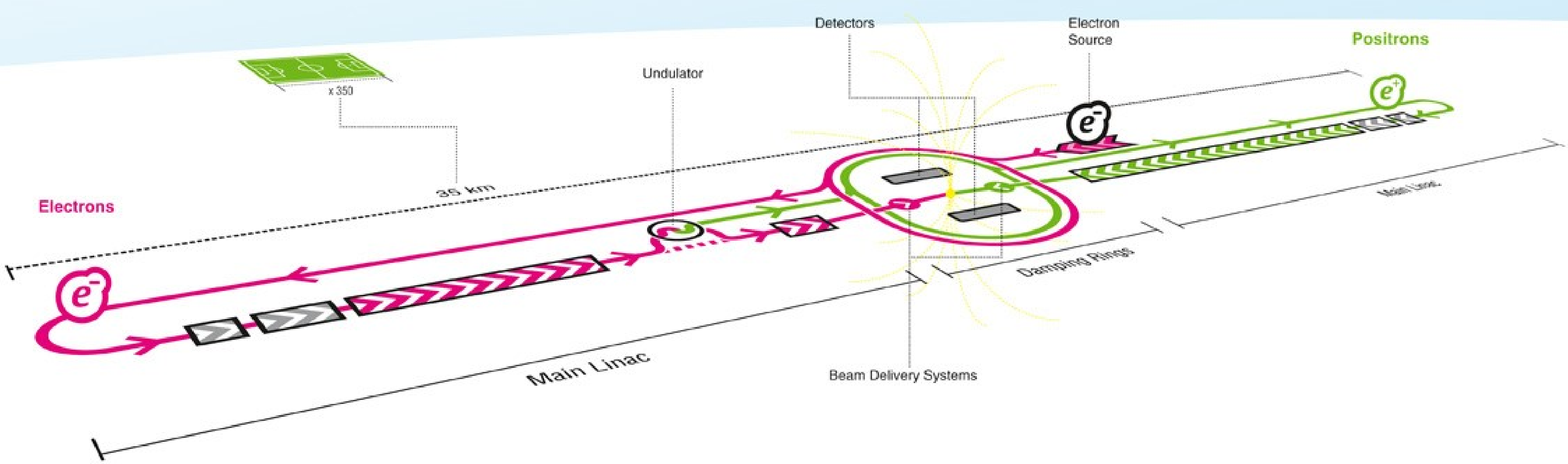


Outline

- Introduction.
- Fundamentals of Spin dynamics.
- ILC Spin Rotator.
- Summary.

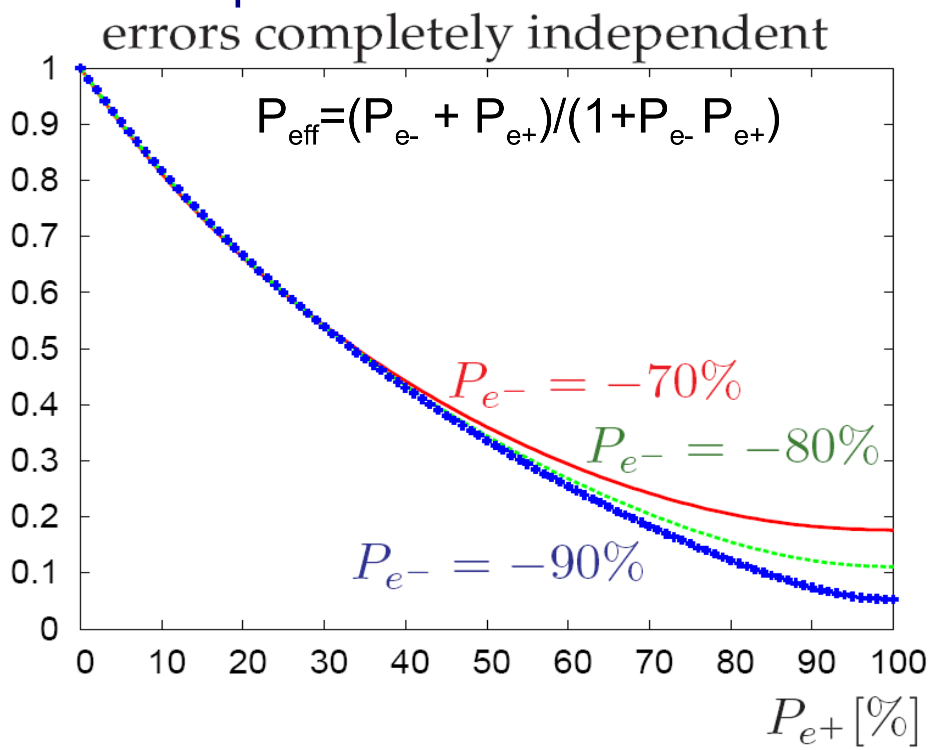
Introduction (1)

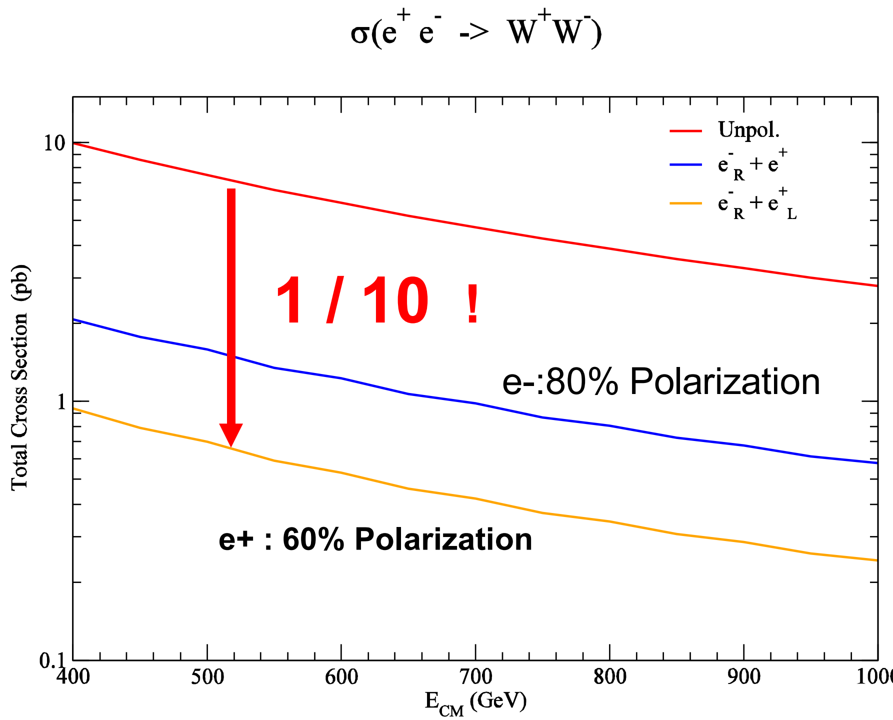
- Introduction
- Fundamen-tals
- ILC Spin Rotator
- Summary

- Spin Control : Spin is one of the most important parameter in LC.
  - Determine the initial states precisely -> high accuracy.
  - Compensate the background processes through helicity selection -> high S/N ratio.
  - Then, Spin direction of electrons (optionally positrons) at IP should be controlled as desired.
- Polarization Preserve :
  - Any depolarization processes, which destroy beam polarization, should be avoided during acceleration, transport, storage, etc.

Introduction (2)

Relative error on effective polarization





with GRACE System Developed by Computational Physics Group in KEK

New Physics Search

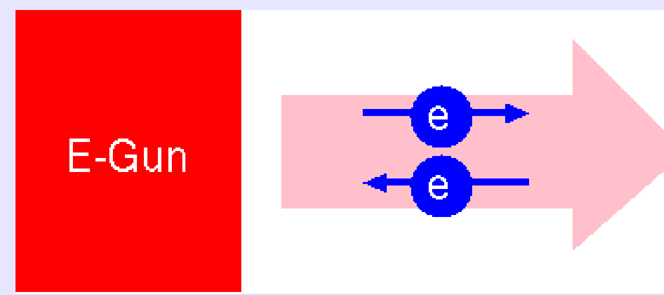
Background Suppression

H. Shimizu/
S. Riemann

Polarization

- Polarization is defined as
  - N_p: number of electrons, which have parallel spin to the polarization vector.
  - N_n: number of electrons, which have anti-parallel spin to the polarization vector.

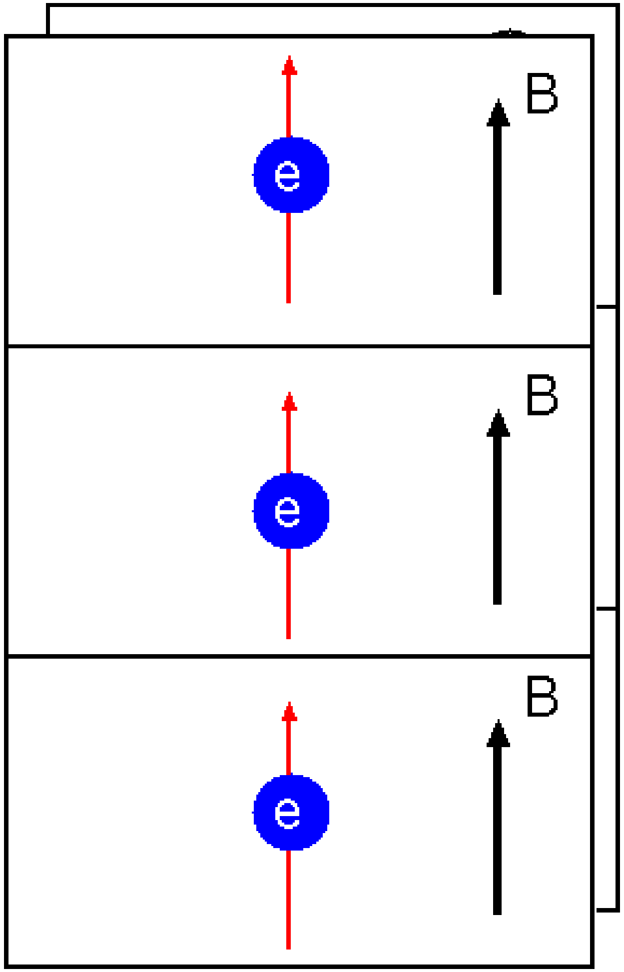
$$P = \frac{N_p - N_n}{N_p + N_n}$$



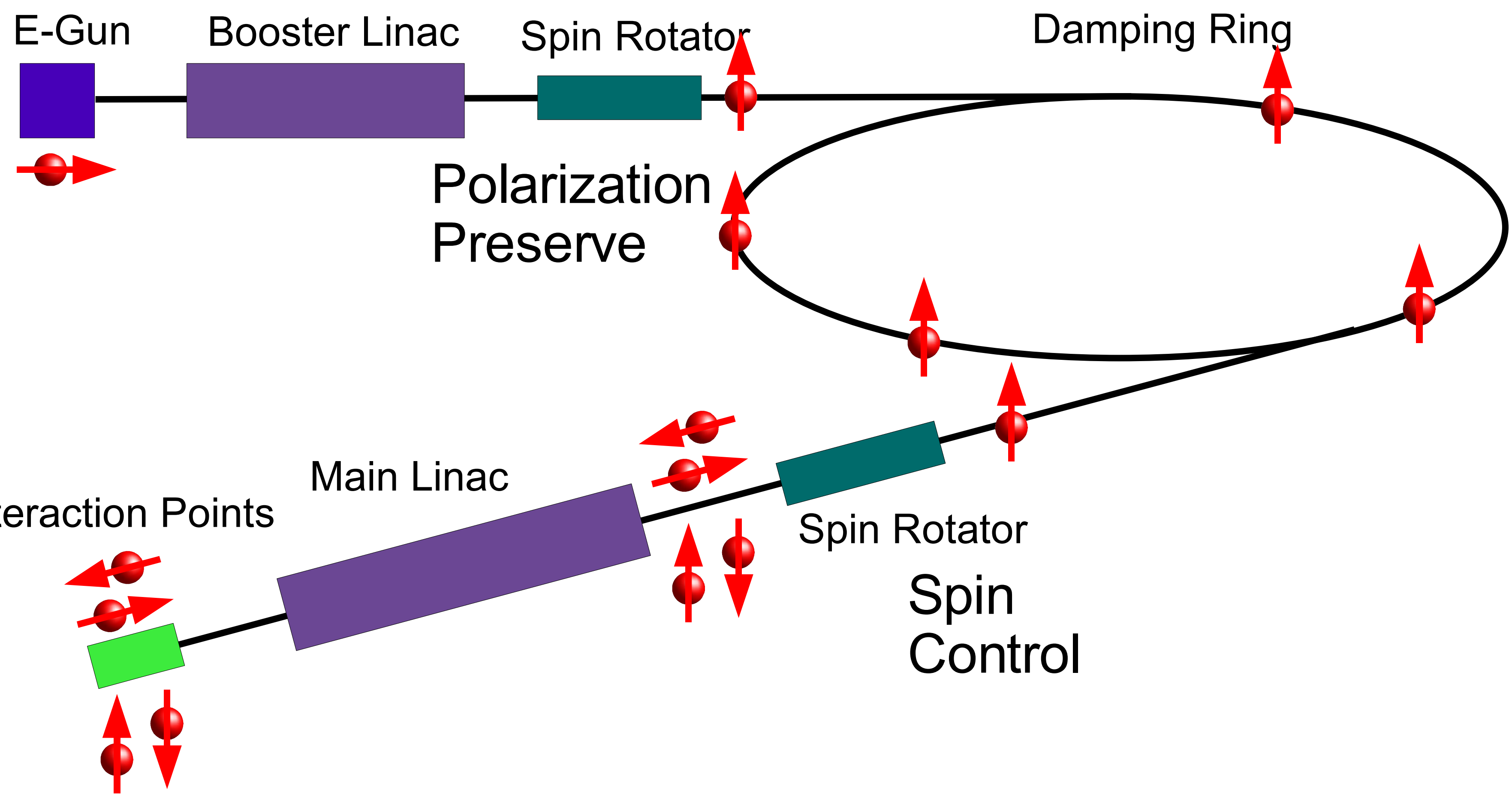
- Polarization is >80% (90% parallel, 10% anti-parallel) at the gun exit. The polarization vector is longitudinal direction.

Polarization Preserve

- If polarization vector is in horizontal plane in DR, spin precesses during the storage.
- Because the precession frequency depends on the beam energy, the precession phase is randomized by energy spread.
- This randomization causes a significant depolarization. The spin direction has to be perpendicular to the horizontal plane.



Spin Rotators in LC



Thomas-BMT Equation

$$\frac{d\vec{P}}{dt} = \vec{\Omega}_0 \times \vec{P}$$

$$\vec{\Omega}_0 = \frac{-e}{m\gamma}\left[(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\parallel + \left(G\gamma + \frac{\gamma}{1+\gamma}\right)\frac{\vec{E}\times\vec{v}}{c^2}\right]$$

- $\vec{P}$: polarization vector.
- $G = \frac{g-2}{2}$ is anomalous magnetic moment, g is gyro-magnetic ratio ; G~0.00115965 for electrons.
- $\vec{E}, \vec{B}$: Electro and magnetic field.

Solenoid Magnet

- In solenoid field (only longitudinal B field):

$$\frac{d\vec{P}}{dt}=\frac{-e}{m\gamma}(1+G)\vec{B}_0\times\vec{P}$$

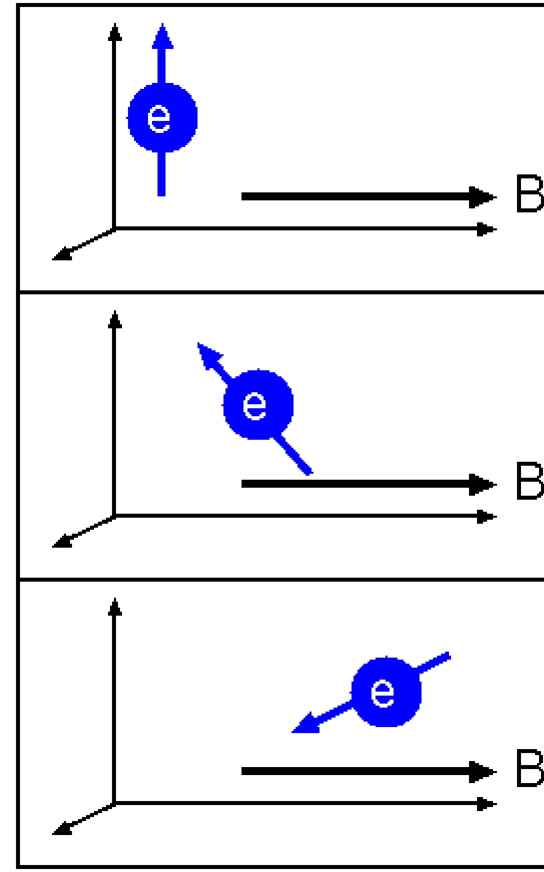
- Integrating this equation,

$$\vec{P}(t)-\vec{P}(0)=\frac{e}{m\gamma}(1+G)\int B_0\times\vec{P}\,dt$$

$$\phi(t)=\frac{\vec{P}(t)-\vec{P}(0)}{|\vec{P}|}=\frac{e}{m\gamma}(1+G)\sin\theta\int B_0\,dt$$

- If the initial polarization is purely transverse to B_0,

$$\phi(t)=\frac{e}{m\gamma\beta c}(1+G)\int B_0\,ds$$



Bending Magnet

- In dipole magnet (only vertical B field):

$$\frac{d\vec{P}}{dt}=\frac{-e}{m\gamma}(1+G\gamma)\vec{B}_0\times\vec{P}$$

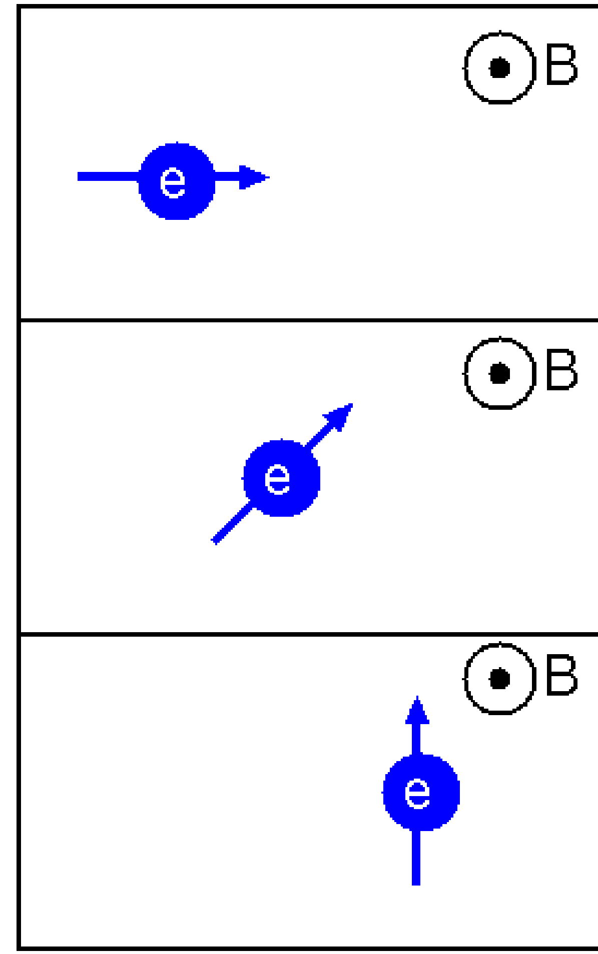
- Bending angle of the particle trajectory by the dipole field is

$$\frac{d\vec{v}}{dt}=\frac{-e}{m\gamma}\vec{B}_0\times\vec{v}$$

- Then, if we see the polarization vector in the co-moving frame with the particle velocity,

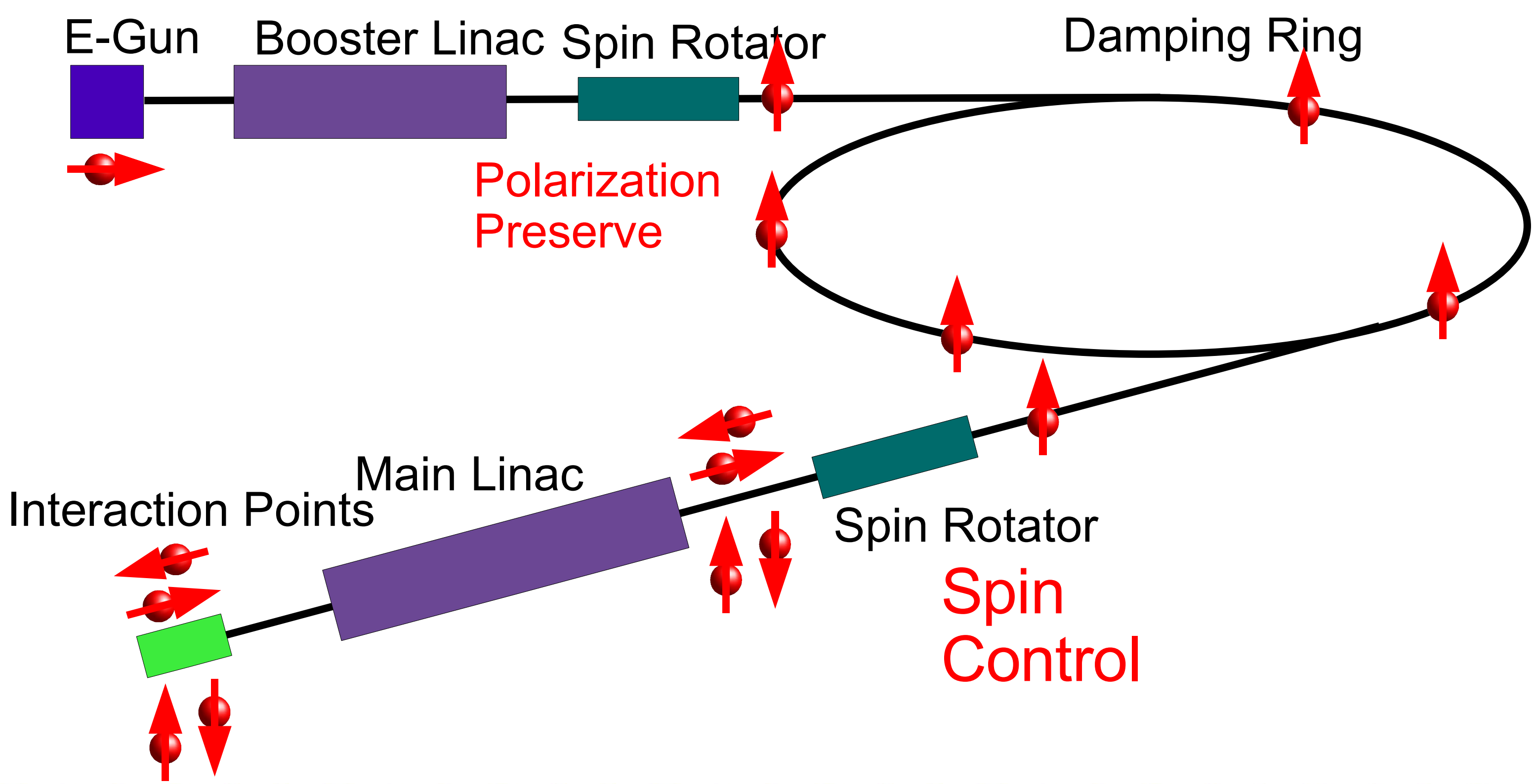
$$\frac{d\vec{P}'}{dt}=\frac{eG}{m}\vec{B}_0\times\vec{P}$$

$$\phi'(t)=\frac{\vec{P}'(t)-\vec{P}'(0)}{|\vec{P}'|}=\frac{eG}{m\beta c}\int B_0\,ds$$



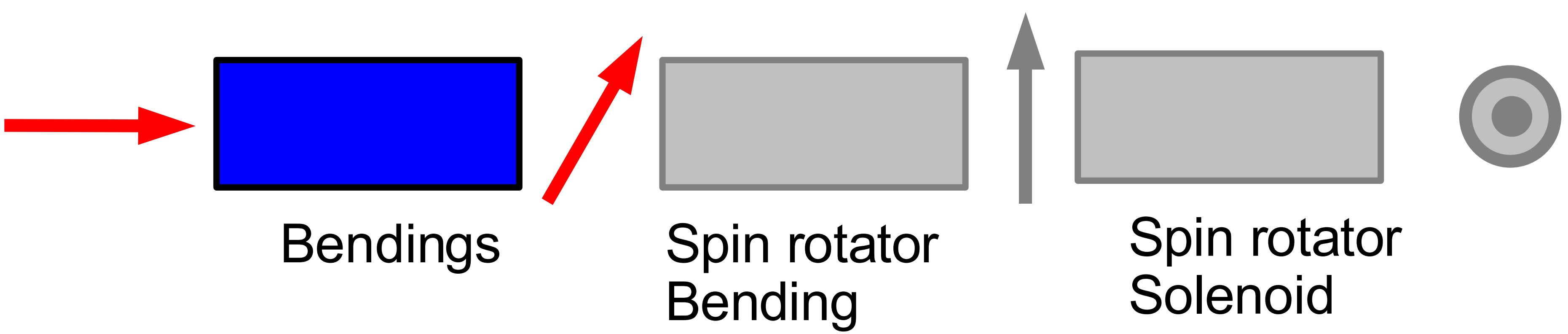
Spin Rotator in LC

- Longitudinal Polarization should be perpendicular before DR injection.
- Polarization control after DR.



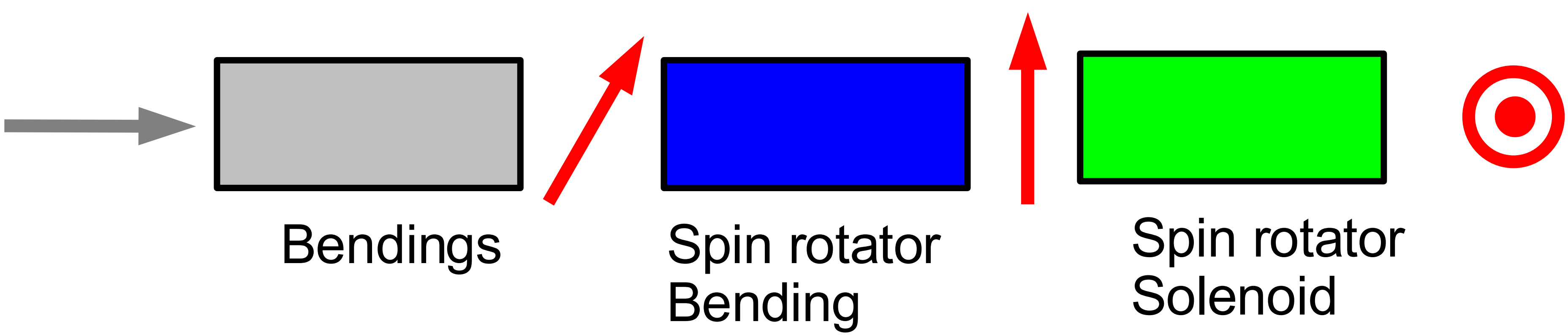
Before DR (1)

- Spin direction of generated beam from the polarized electron source is longitudinal.
- By passing many bendings, Spin precession in the horizontal plane is occurred.



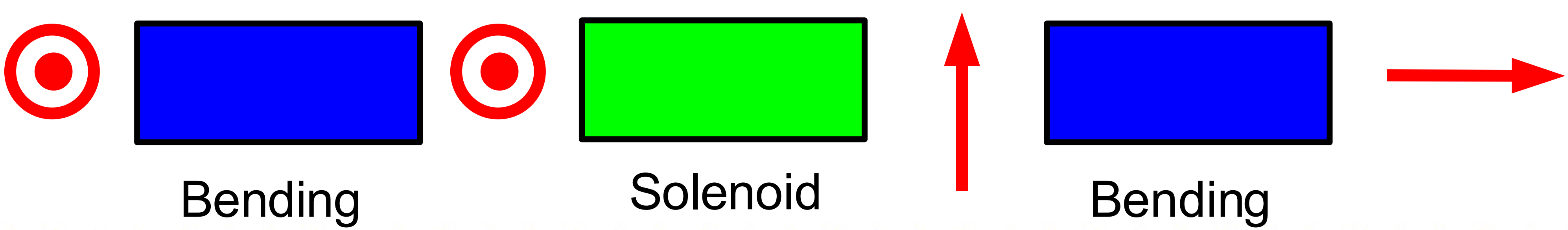
Before DR (2)

- Polarization vector should be adjusted to right perpendicular to beam direction by bending.
- Solenoid magnet rotate the polarization vector along beam axis by 90 deg.
- The polarization vector becomes right perpendicular to horizontal plane; It is ready for DR injection.



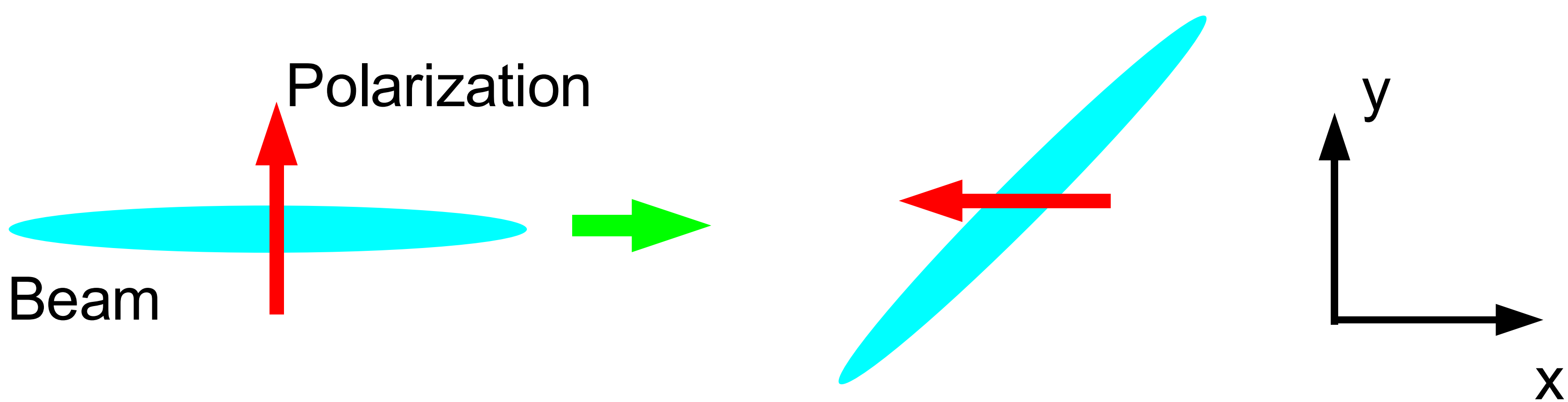
After DR

- Spin in DR is aligned to perpendicular to the horizontal plane.
- In RTML (Ring To Main Linac), this perpendicular polarization is preserved.
- This perpendicular polarization should be operated as desired:
  - Forward and backward longitudinal polarization.
  - Any transverse directions.



Emma Rotator (1)

- The transverse beam emittance has a large aspect ratio : 8μm in horizontal and 20 nm in vertical.
- Solenoid field rotates not only the spin, but also transverse phase spaces.
  - **Solenoid increases the vertical emittance via the coupling between the horizontal and vertical motion.**



Emma Rotator (2)

- Roll by a solenoid magnet (φ_b) is one half of the spin rotation angle(φ_s)

$$\phi_s = 2\phi_b$$

- Spin rotation simultaneously rotate the beam orbit and makes the x-y coupling and emittance growth.

- Vertical emittance after this rotation is

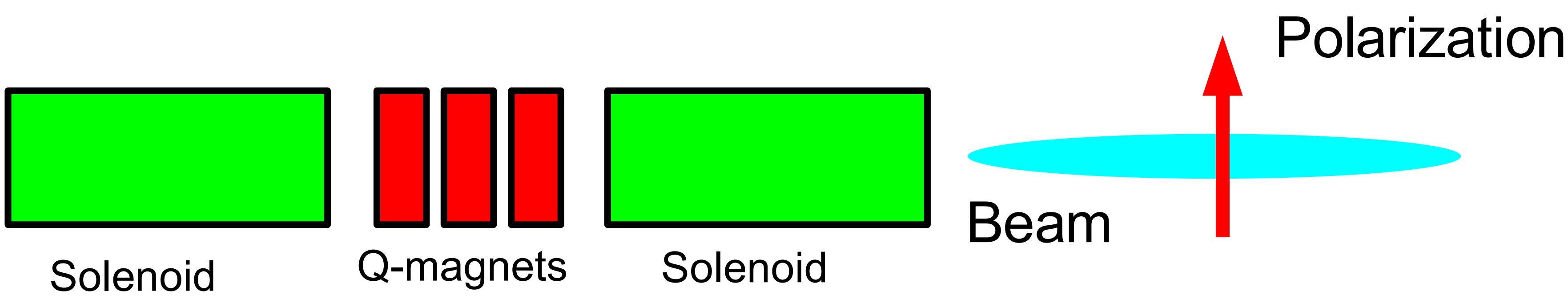
$$\epsilon_y^2 = \epsilon_{x0}^2 S^4 + \epsilon_{y0}^2 C^4 + \epsilon_{x0}\epsilon_{y0} C^2 S^2 (\beta_x \gamma_y - 2\alpha_x \alpha_y + \beta_y \gamma_x)$$

$$C \equiv \cos(\phi_s/2) \quad S \equiv \sin(\phi_s/2)$$

$$\alpha_{x,y}, \beta_{x,y}, \gamma_{x,y} : \textit{Twiss parameters}$$

Emma Rotator (3)

- Is it possible to rotate only the spin and not the particle phase space? -> Yes, that is Emma rotator = Solenoid + Q magnets + Solenoid.
- Each solenoid rotates spin and phase space with exactly same amount.
- Q magnets change the betatron phase with 360 deg in x and 180 deg in y. Rotation by the two solenoids are canceled out (no emittance growth).
- The total rotation angle of Emma spin rotator is 2φ, where φ is rotation angle by a single solenoid.



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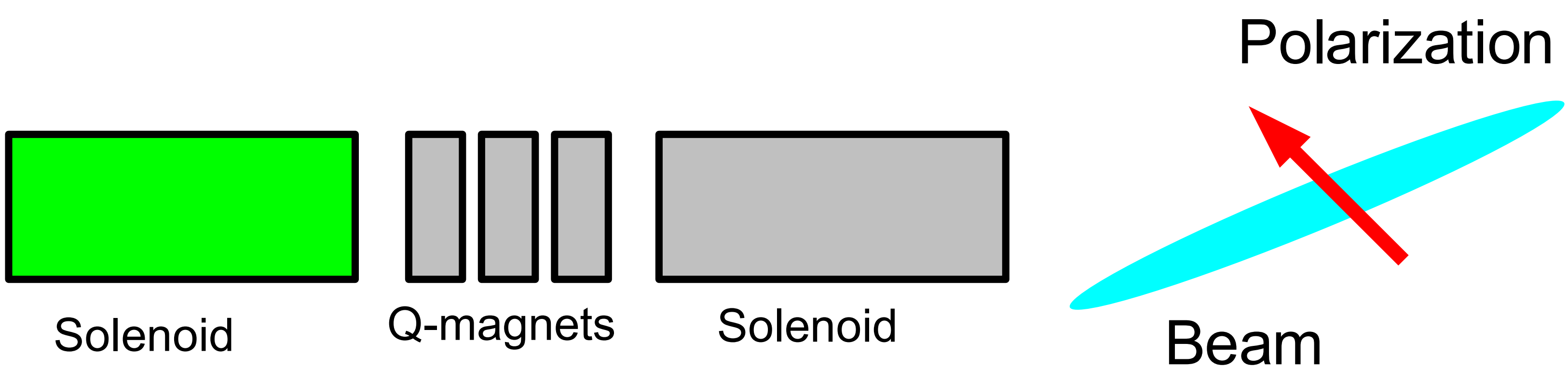

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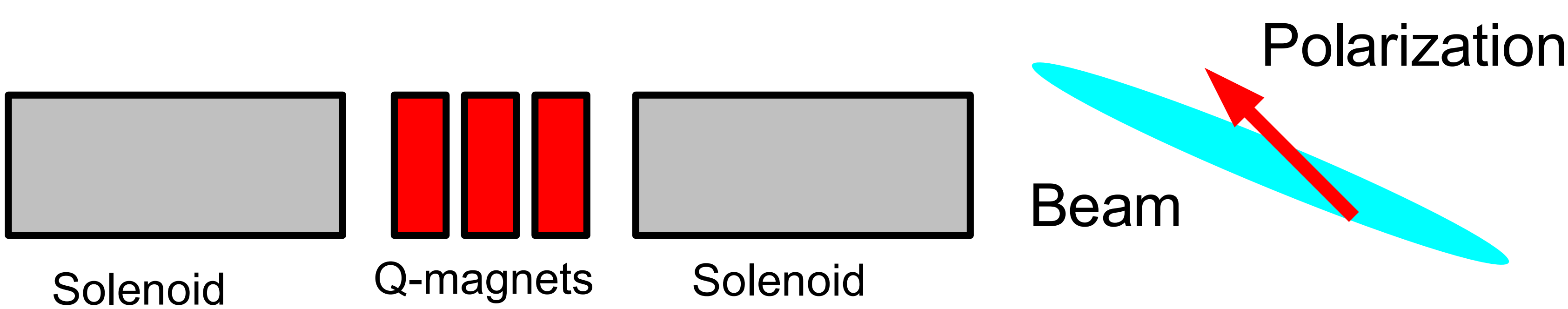

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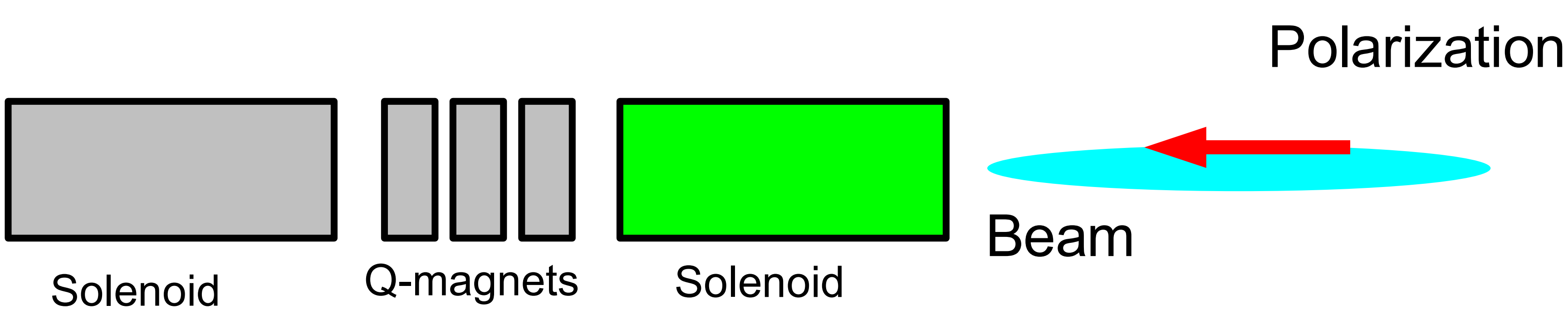

Transfer Matrix

- Transfer matrix of a solenoid

$$R_S = \begin{bmatrix} C^2 & SC/k & SC & S^2/k \\ -kSC & C^2 & -kS^2 & SC \\ -SC & -S^2/k & C^2 & SC/k \\ kS^2 & -SC & -kSC & C^2 \end{bmatrix}$$

- Inserting a reflector beam line between two solenoids, the matrix is

$$R_S \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} R_S = \begin{bmatrix} C & S/k & 0 & 0 \\ -kS & C & 0 & 0 \\ 0 & 0 & -C & S/k \\ 0 & 0 & kS & -C \end{bmatrix}$$

- X-Y coupling terms are vanished by this insertion. Emittance growth by the coupling is cured.

ILC Spin rotator

- ILC Spin rotator = Solenoid Rotator + Dipole Rotator + Solenoid Rotator.
  - Solenoid rotator consists of two solenoid magnets and one reflector between them.
- Changing the angle of the solenoid rotators, spin direction can be controlled as desired.

Initial	Solenoid 1	Dipole	Solenoid 2	Final
↑	90	90	90	→
↑	0	90	0	↑
↑	0	90	90	◎
↑	180	90	0	↓
↑	180	90	90	×
↑	-90	90	0	←

Summary

- Spin rotators in LC has two rolls.
  - Polarization preservation (spin rotation before DR).
  - Spin control (spin rotation after DR).
- Spin rotation without any xy coupling (vertical emittance growth), is implemented by Emma rotator.
- With these Spin rotators, the longitudinally polarized beam generated at E-Gun (positron source) is transported without any significant depolarization and collisions with any combination of spin directions at interaction point are implemented.

References

- P. Emma, "A Spin Rotator System for the NLC", NLC note 7 (December 1994)
- P. Schmid and N. Walker, "A Spin Rotator for the ILC", EUROTeV-Report-2006-68 (June 2006)
- P. Schmid "A Spin Rotator for the ILC", EUROTeV-Report-2005-24 (Feb 2006)