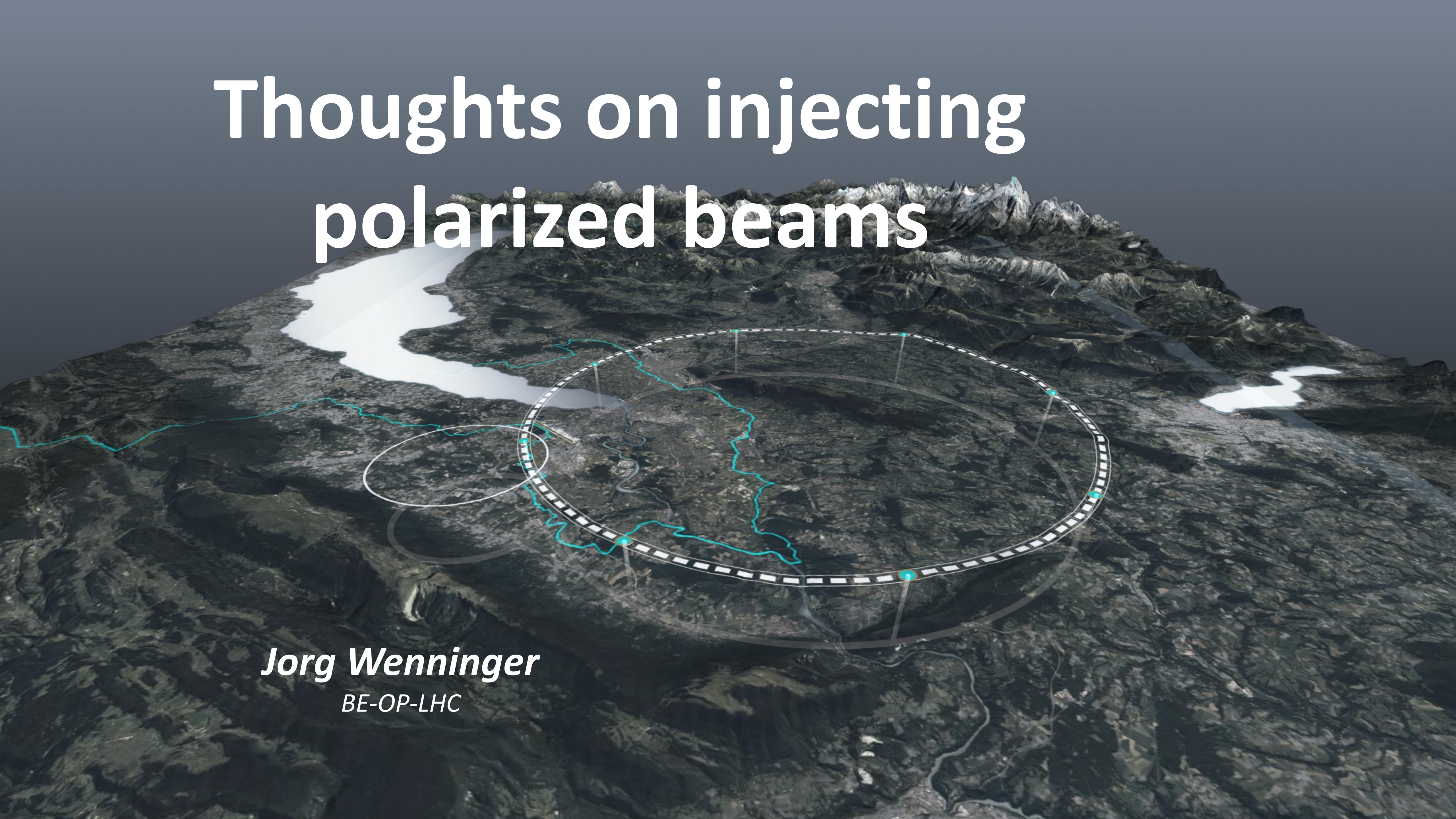
Thoughts on injecting polarized beams

Jorg Wenninger
BE-OP-LHC



Motivation for injection of polarized beams

Very accurate **beam energy calibration** is driving the interest in **transverse *P*** at FCCee.

- A polarization of ~10% should be sufficient but should be confirmed by a full depolarization process simulation including measurement errors of the polarimeter.

The very long polarization build-up time can only be overcome in the collider itself with **strong asymmetric wigglers** and an **operation model** that requires a ~**2h period to polarize low intensity bunches** (synch. radiation power !) before injecting the main beam (wigglers off).

- Frequent beam aborts can render this process quite inefficient.

Consider injection of **e+/e- polarized 'close to the source'** and transported through linac, transfer lines and transfer channels as well as through the booster.

- Challenge lies in **preserving the polarization** through the chain.

Spontaneous polarization in e+/e- rings

Spontaneous build-up of transverse polarization in planar e+/e- rings (**Sokolov-Ternov**) due to emission of synchrotron radiation.

- **Small asymmetry** in the cross for synch radiation emission for ending up **with magnetic moment // or anti-//** to the guiding dipole field.
- Asymptotic polarization level: $P_{ST} = 92.4\%$
- The polarization is aligned in the **vertical** direction (along **bending field**).
- Build-up time τ_{ST}: $\tau_{ST}[s] \simeq \frac{99}{2\pi} \frac{C[m]\rho^2[m]}{E^5[GeV]}$ or $\tau_{ST}[s] \simeq 3654 \frac{(R/\rho)}{B^3[T]E^2[GeV]}$
- At 45.6 GeV : LEP $\tau_{ST} \approx 5.5h$, FCCee $\tau_{ST} \approx 220h$

C = circumference
R = radius
ρ = bending radius
B = bending field

Spin precession

Spin/polarization vector **precession** in EM fields is described by the **Thomas-BMT equation**:

$$\frac{d\boldsymbol{P}}{dt} = \boldsymbol{\Omega} \times \boldsymbol{P} \qquad \boldsymbol{\Omega} = -\frac{e}{mc}\left[\left(a + \frac{1}{\gamma}\right)\boldsymbol{B}_\perp + \frac{1+a}{\gamma}\boldsymbol{B}_\parallel - \left(a + \frac{1}{\gamma+1}\right)\boldsymbol{\beta} \times \boldsymbol{E}\right]$$

E represents the electric field

For **γ >> 1**:

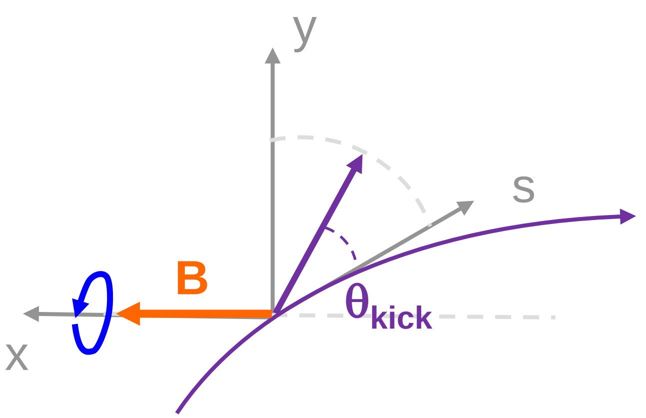
$$\boldsymbol{\Omega} = -\frac{e}{mc}\left[\left(a + \cancel{\frac{1}{\gamma}}\right)\boldsymbol{B}_\perp + \frac{1+a}{\gamma}\boldsymbol{B}_\parallel - \left(a + \cancel{\frac{1}{\gamma+1}}\right)\boldsymbol{\beta} \times \boldsymbol{E}\right]$$

~ independent of γ for transverse B-fields !

~ 1/γ for longitudinal B-fields (solenoids)

$B_\perp$ / $B_{||}$ correspond the field components <u>orthogonal</u> / <u>parallel</u> to the <u>particle velocity</u>.
a is the anomalous magnetic moment, a ~ 10^{-3} for e.

Spin tune



If the beam trajectory is **perturbed by a kick** θ_{kick} due to a **transverse magnetic field**, the associated **spin precession angle** θ_{spin} around the axis of the perturbing B-field is:

$$\theta_{spin} = (a\gamma + 1)\theta_{kick}$$

In a perfectly planar ring, the number of **spin precessions per turn** around the **vertical bending field** is proportional to the integrated magnetic field which defines the **beam energy**:

$$\nu_s = a\gamma = \frac{E}{0.440648\ [GeV]}$$

ν_s = no of precessions / turn = θ_{spin}(1-turn)/2π = **spin tune**

ν_s = 103.5 @ Z pole, ν_s = 45.4 at 20 GeV

Machine imperfections and resonance - depolarization

In the presence of **machine imperfections** (misalignments, field errors..) build-up of polarization can be perturbed. The impact can be characterized by a **depolarization time τ_D**.

The **asymptotic P and the build-up time are reduced**.

$$P_\infty = \frac{P_{ST}}{1+X}\left(1 - e^{-t(1+X)/\tau_{ST}}\right) \qquad \tau_{pol} = \frac{\tau_{ST}}{1+X} \qquad \text{with} \qquad X = \tau_{ST}/\tau_D$$

If a **polarized beam** is **injected with polarization P_{inj}**, the polarization will **evolve towards P_∞** with **time constant τ_{pol}**.

Observation: even for injection of polarized beams, P_∞ / τ_{pol} **should be sufficiently “large”** for a depolarization measurement to take place under good conditions.

General comment for rings

The **stable P direction** is always the **vertical direction** (the direction of the bending field).

- The P component in the x-s plane will decohere due to energy spread (→ spin tune spread) and synchrotron radiation.

Polarized beams should (must) be **injected with a vertical polarization**.

If the injected P level does not match the equilibrium polarization P_∞ , it will **evolve towards P_∞ with time-constant τ_{pol}**.

- τ_{pol} should be **significantly larger** than the time span that the beam will spend in the ring.
- Example: 20 polarized bunches are injected for energy calibration, to be performed every 5 mins. The bunches will last 100 mins before fresh bunches are needed. τ_{pol} should be significantly longer than 2 hours.

Periodic injection of a few polarized bunches that spend only a "short" time in the ring relaxes constraints on P_∞ and τ_{pol} .

- The depolarized bunches must be '**eliminated**' from the ring before replacing them by fresh polarized bunches.

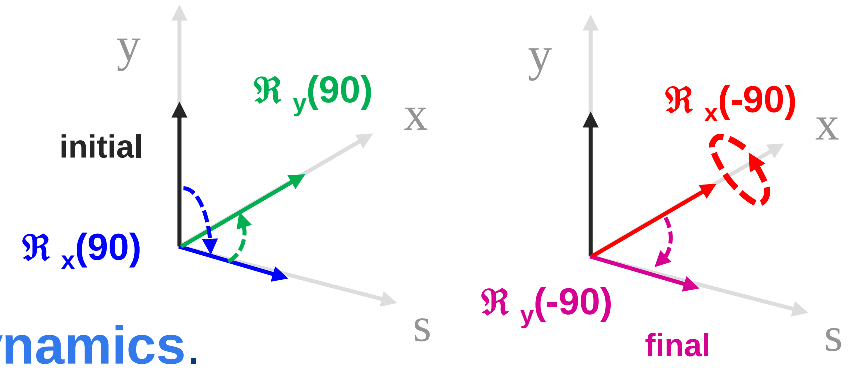
Spins and rotation matrices

The spin (polarization) vector evolution is described by **rotation matrices $\mathfrak{R}_u(\theta)$** around axis u (=x,y,s) of the B-field.

The fact that **rotations do not commute** has important consequences.

$\mathfrak{R}_x(-90)\,\mathfrak{R}_x(90) = \mathbf{I}$ and $\mathfrak{R}_y(-90)\,\mathfrak{R}_y(90) = \mathbf{I}$

But: $\mathfrak{R}_y(-90)\,\mathfrak{R}_x(-90)\,\mathfrak{R}_y(90)\,\mathfrak{R}_x(90) \neq \mathbf{I}$



Non-commutation of rotations has **a deep impact on spin dynamics**.

The spin orientation can be **manipulated locally without affecting the beam trajectory** outside a defined region: **spin rotators**, (Siberian) **snakes** – see later.

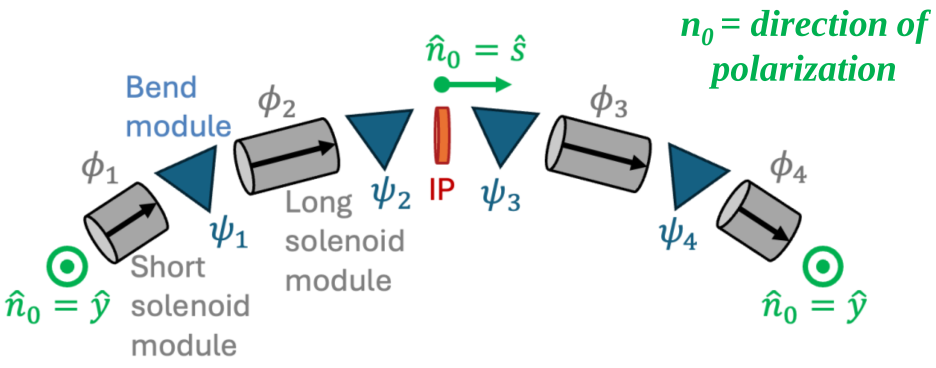
- This effect can also break the relation between spin tune and energy !

Spin rotators - example

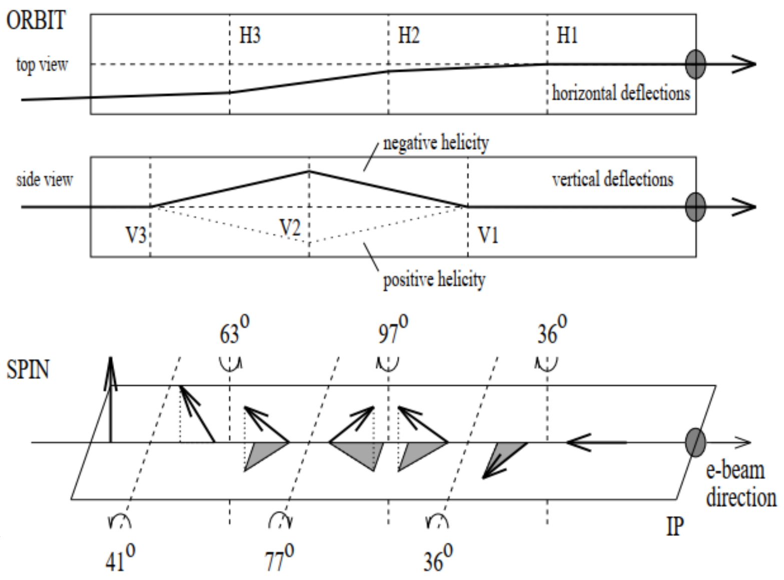
Solenoids: **alone or in combination with dipole fields** can be used to rotate the spin vectors.

- Very large (many Tm) solenoids are required at high(er) energy.
- Betatron coupling must be corrected by skew quads.

HERA-e spin rotator: from **vertical** polarization in the arc to **longitudinal** polarization at the collision point with **interleaved horizontal and vertical dipoles**, on both sides of the IPs.



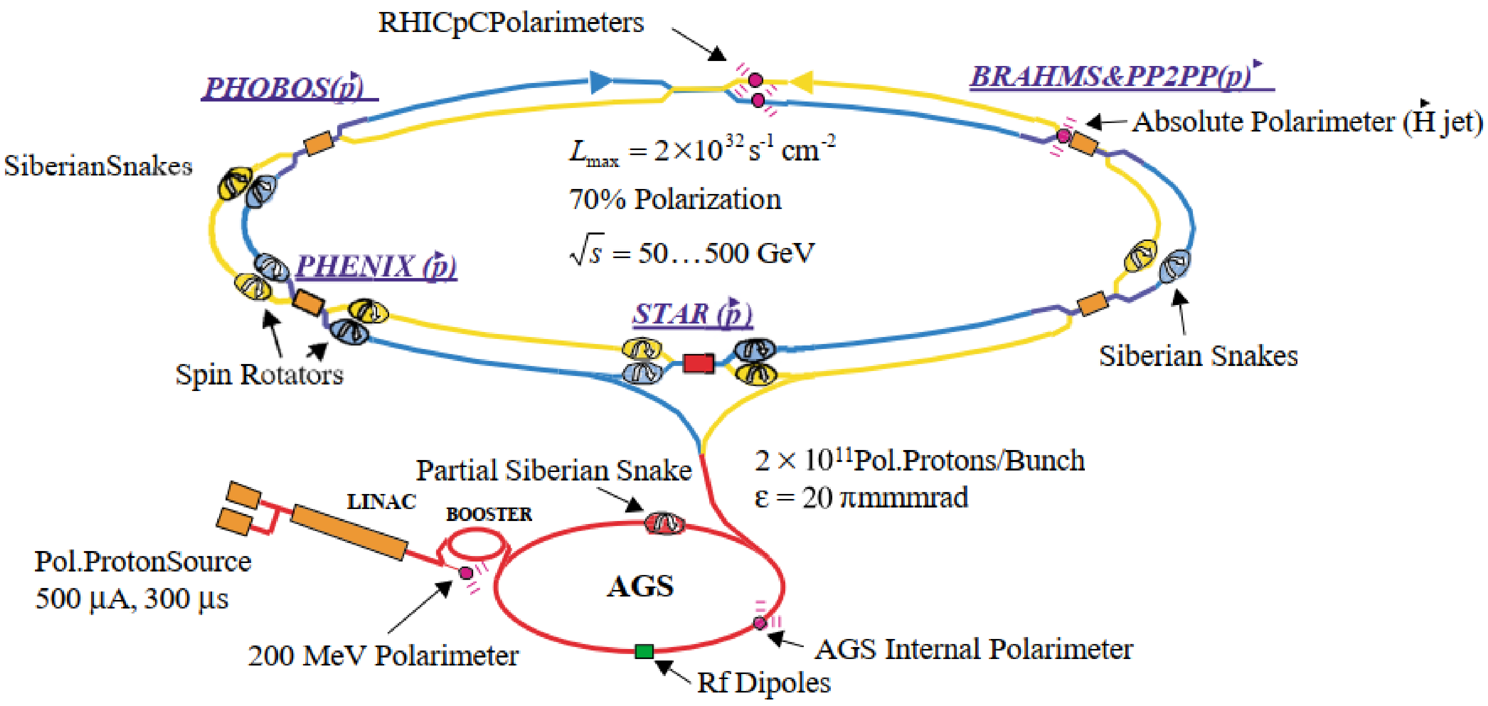
EIC spin rotator design: 2 solenoids + 2 dipole strings on both sides of the interaction point



D. Barber, EPAC 96

RHIC

- RHIC operated periodically with **polarized proton beams**.
- The polarized protons were **transported and accelerated** through a linac, booster and the AGS to RHIC where the final acceleration took place.
  - ~90% source polarization → ~70% polarization in RHIC



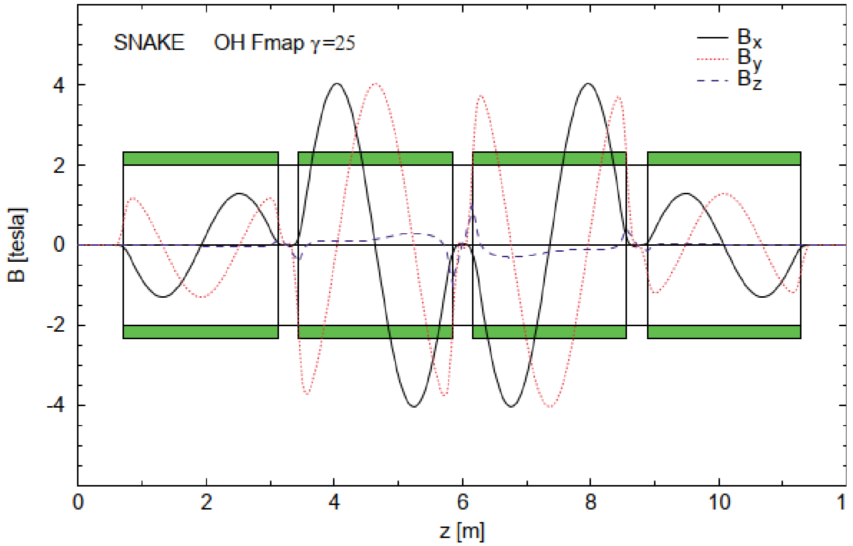
RHIC spin rotators and snakes

Polarized beam operation relied on **spin rotators** and **snakes** (full polarization flip) composed of superconducting **helical dipoles**.

- **Transverse B_x and B_y fields of helical shape**, with N periods (N = 1 for RHIC).

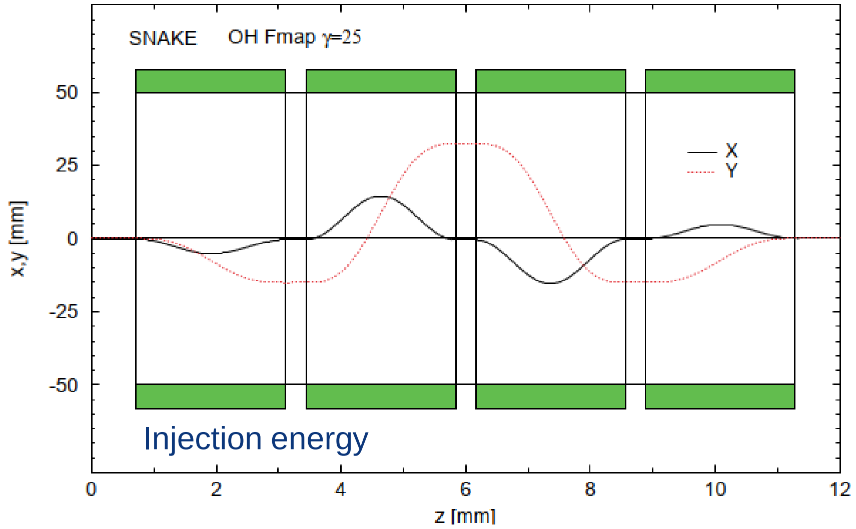
A combination of 4 helical dipoles provides full control of the spin orientation.

B fields

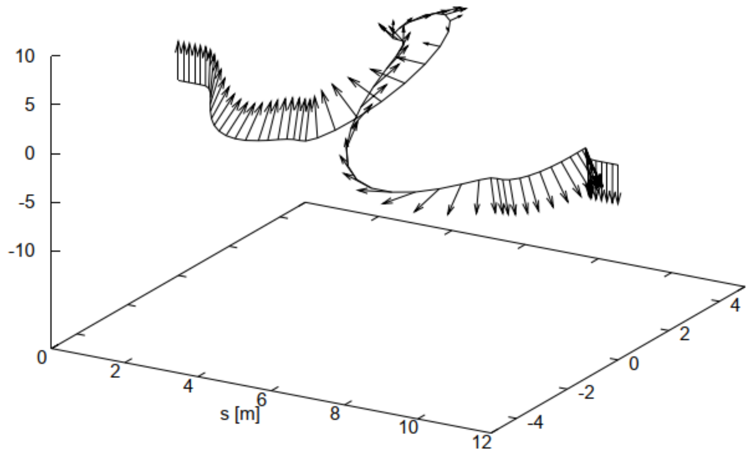


10 m

Beam orbits



Spin flip in a snake



I. Alekseev et al, NIMA 499 (2003) p 392

Production of polarized beams for FCCee

For e- beams, there are two options:

- Production of **polarized e- at the source** (SLC, EIC).
- Building up transverse polarization in a **damping ring by the Sokolov-Ternov effect**.

For e+ beams, only the second option applies.

Polarized beams in a damping ring

Energy scaling of τ_{pol} requires a **large B field** (small bending radius ρ) to achieve a sufficiently short τ_{pol} **~few mins**:

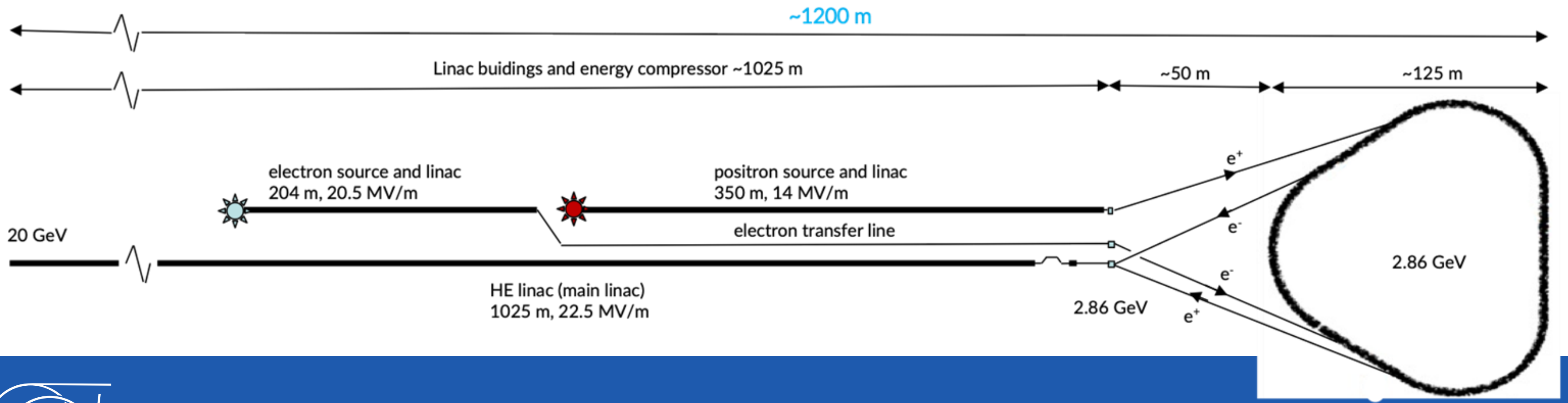
- At **E = 2.86 GeV**, B = 1.5 T (ρ = 6.4 m), C = 80 m → τ_{pol} **~4 mins**
- And/or **strong asymmetric wigglers**.

$$\tau_{ST}[s] \simeq 3654 \frac{(R/\rho)}{B^3[T]E^2[GeV]}$$

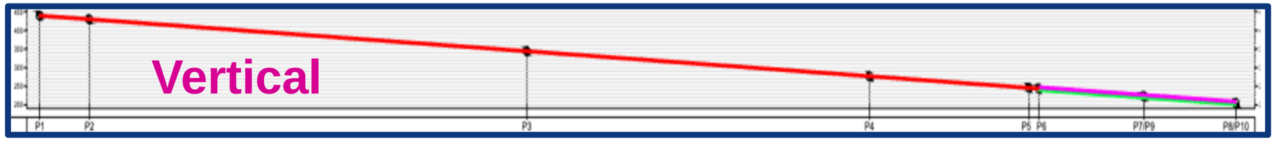
The current FCCee damping ring design would require strong **asymmetric wigglers** to reduce τ_{pol} to reasonable values (**TBC**).

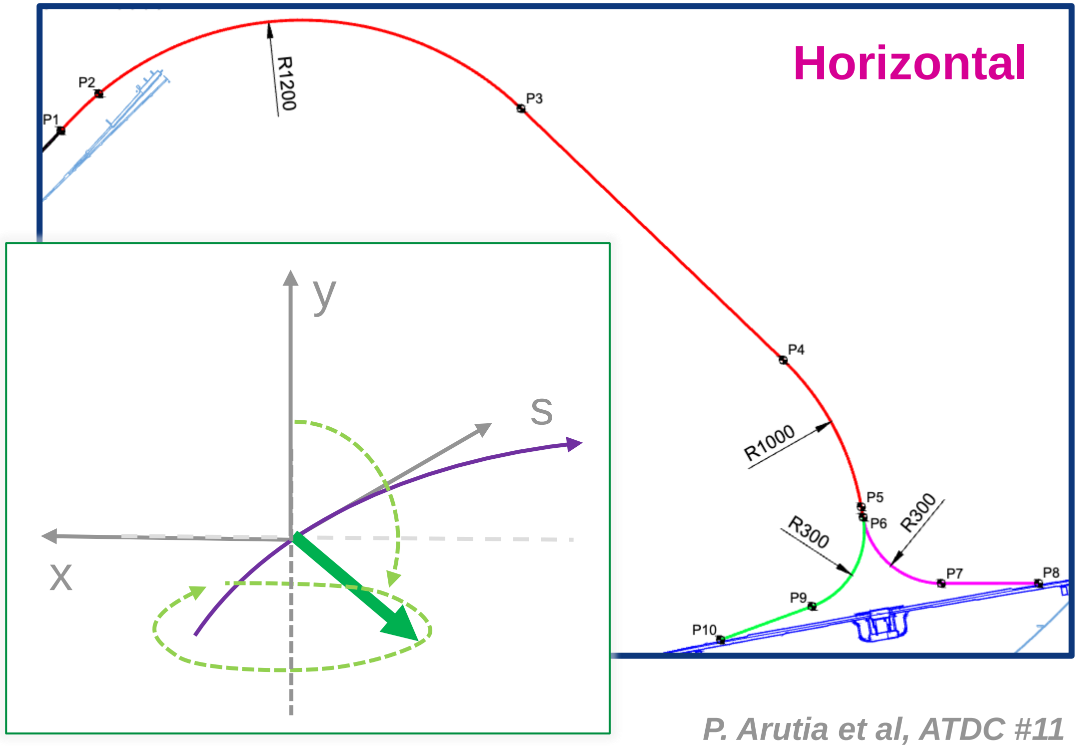
- It may not be compatible with regular top-up for collisions.

Consider a dedicated DR for polarized beam production !



Linac to booster





Vertical P of DR to be kept vertical in LINAC.

The transfer from LINAC to booster involves **vertical and horizontal bending**: a **spin rotator**.

- E = 20 GeV, aγ = ~ 45.4
- The initial downward bend of ~3° **rotates the P vector by ~140°** → **precession** of H component in the TL by **~25.5 / 5.3 turns** for e-/e+.
- Vertical bending at end of line unlikely to restore vertical P.

P. Arutia et al, ATDC #11

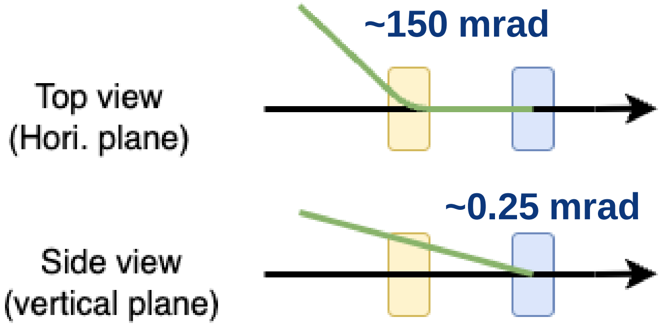
Adapt TL design and/or install **spin rotators before booster injection** to restore vertical P.

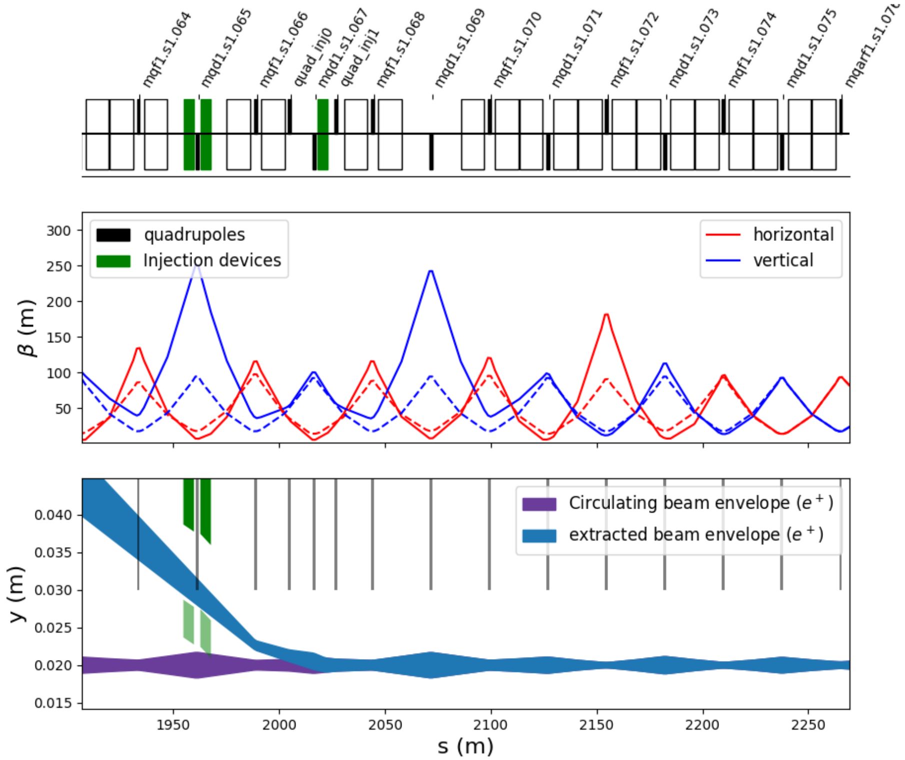
Booster injection

The **horizontal injection dipoles + septum** add a little over one complete turn: **rotation of ~1.07 [2π].**

The **vertical deflections** (quad + kicker) contribute very little, **rotation ~0.002 [2π].**

Little concern if ***P* is vertical** when the beams enter this region.





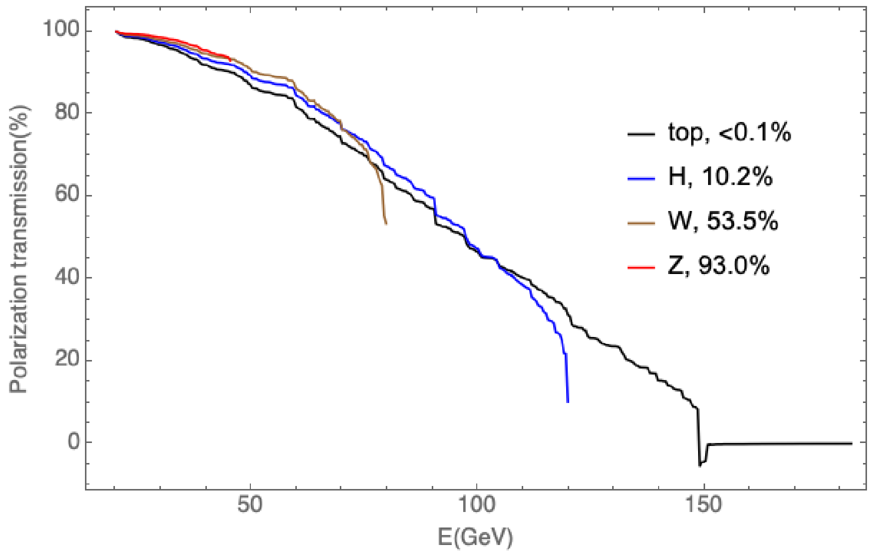
Z. Duan, 182nd FCC-ee Optics Design Meeting

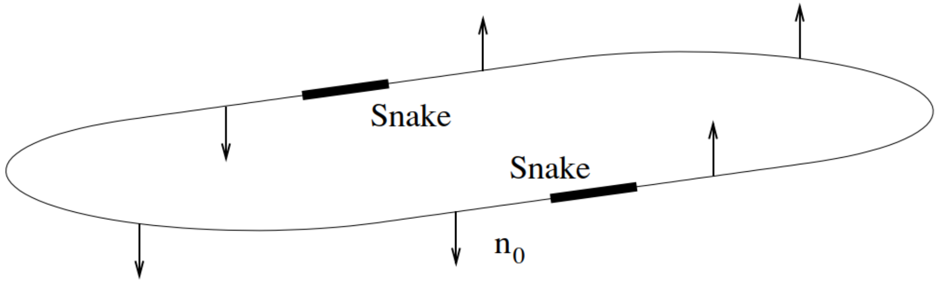
Booster ramp

Injection into the booster of bunch with vertical polarization.

The polarization must be maintained throughout the ramp. A study by Z Duan seemed to indicate **good preservation for the booster** – to be confirmed.

The **installation of 2 snakes** (180° polarization flip, RHIC, $\nu_s = 1/2$!) or of a **partial snake** (AGS) could boost preservation of polarization by making it less sensitive to resonances.





Ring with 2 snakes: polarization is up in one half and down in the other half of the ring.

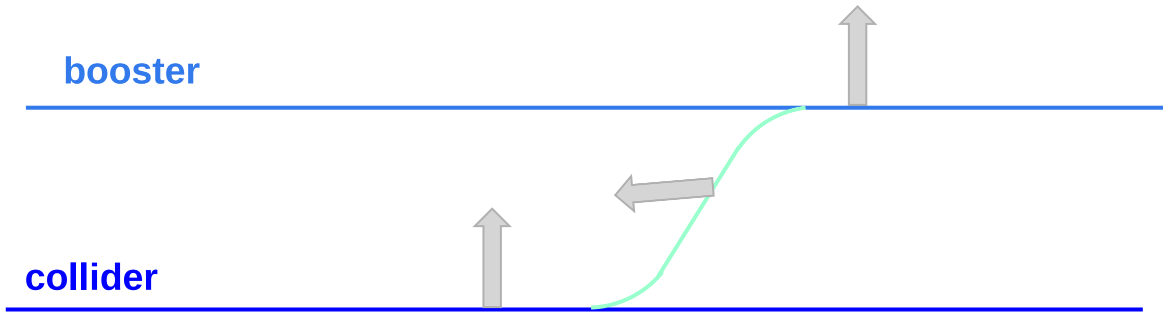
Booster to collider transfer

No detailed design available for this presentation.

It is planned to:

- Deflect the beam out of the booster horizontally.
- Use vertical bends to bring the beam into the plane of the collider.
- Inject horizontally into the collider.

This order (no **interleaved** of H/V bending) will **preserve** the **vertical** $\boldsymbol{P}$ from booster → collider.



Polarimetry, depolarization

Injection of polarized bunches requires **polarimeters** along the chain **from source to collider** for tuning and diagnostics.

Rough inventory:

- 2 polarimeters in the collider (e+ and e-).
- 2 polarimeters in the booster, able to measure from injection to flat top.
  - But not necessarily continuously along the ramp?
- 1 polarimeter at the end of the LINAC.
- 1 polarimeter per damping ring. Rely on Touchek lifetime?

Needs to be backed by a design study.

Depolarizers will also be required in **all rings** – DR, booster, collider – to determine the spin tune and calibrate the polarimeters.

Summary

Based on experience at SLC and RHIC for example, **production and injection of polarized e+e- seems feasible**.

Production and injection of polarized beams must be **integrated into the design from the beginning** since it may require:

- Dedicated sources of polarized e+/e-,
- Optics and transfer design that integrate polarization aspects,
- Devices to control and preserve the polarization (rotators, snakes),
- Dedicated diagnostics.

There is however a need for a significant **design effort** which requires expertise and simulation tools on polarization.

SLC

- The SLC at Stanford operated with **longitudinally polarized e- beams**.
- The e- source produced **~80% longitudinally polarized e-** that were accelerated to ~1.2 GeV, injected for 8 ms into a damping ring, then transported to the IP.
  - The P was rotated into the vertical plane before entering the RD with bends and solenoids. ST P build up was negligible.
  - The P was vertical at the exit of the DR.
- **Vertical trajectory bumps** were used to rotate the spin orientation in the SLC arcs **from vertical to longitudinal** (see LEP solenoid compensation).
  - Solenoids were abandoned when SLC switched to flat beams (quality would have been compromised).