

# Injecting polarized beams

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# Motivation for injection of polarized beams

High accuracy **beam energy calibration by resonant depolarization** is driving the interest in **transverse  $P$**  at FCCee.

In the current baseline, the long natural polarization build-up time @ Z is “overcome” with **strong asymmetric wigglers** and an **operation model** requiring **~2h to polarize low intensity bunches** (synch. radiation power !) before injecting the main beam (wigglers off).

- ▶ Frequent beam aborts can have a **strong impact on machine availability**.

In this presentation we consider the injection of **polarized e+/e-** that are transported through linac, transfer lines and transfer channels as well as through the booster.


- ▶ Challenge lies in **preserving the polarization** through the chain – **work started**.

# Spontaneous polarization in e+/e- rings

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

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

- ▶ For FCC ee @ 45.6 GeV:  $\tau_{ST} \approx 220h$   Can be lowered with **asymmetric wigglers** of sufficiently large B field.  
→ **Not compatible with nominal beam**

# Machine imperfections and resonances - 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  $\tau_D$** .

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

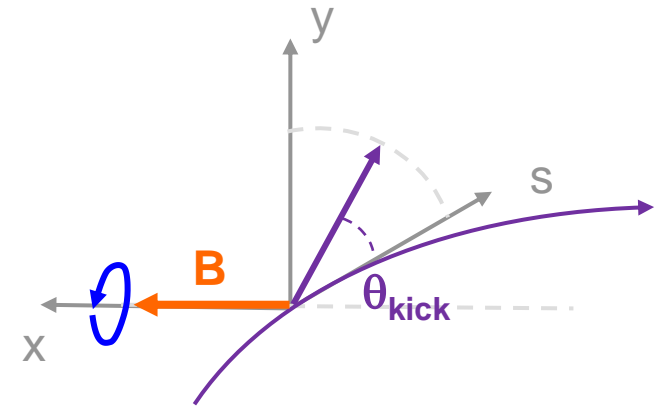
$$P_\infty = \frac{P_{ST}}{1+X} (1 - e^{-t(1+X)/\tau_{ST}}) \quad \tau_{pol} = \frac{\tau_{ST}}{1+X} \quad \text{with } X = \tau_{ST}/\tau_D$$

If a beam is **injected with initial polarization  $P_{inj}$** , its polarization will **evolve towards  $P_\infty$**  with **time constant  $\tau_{pol}$**  which must be sufficiently long to 'complete your business'.

# Spin deflection and tune

If the beam trajectory is **perturbed by a kick**  $\theta_{kick}$  from a **transverse magnetic field**, the associated **spin precession angle**  $\theta_{spin}$  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 **beam energy**:

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

$\nu_s$  = no of precessions / turn =  $\theta_{spin}(1\text{-turn})/2\pi$  = **spin tune**

$\nu_s = 103.5$  @ Z pole,  $\nu_s = 45.4$  @ 20 GeV

Due to the **non-commutation of rotations**, interleaved horizontal, vertical and longitudinal magnetic fields may lead to a **non-preservation of the spin direction**.

- ▶ A closed vertical bump in an arc section can become a spin rotator !

# Production of polarized beams for FCCee

- ▶ Production of **polarized e-/+** at the source (SLC, EIC, JLAB...).
  - ▶ Very efficient for e-,  $P \sim 80\%$  achievable.
  - ▶ e+ production from polarized e-,  $P \sim 4-5\%$  estimated.
  - ▶ Polarization is longitudinal, must be rotated into the vertical plane before entering the DR.
- ▶ Building up transverse polarization in a **damping ring by the Sokolov-Ternov effect.**

*P. Craievich, FCC week 2025*

*E. Granador, FCC week 2025*

*K. Aulenbacher, FCC week 2025*

# Polarized beams in a damping ring

**Large B fields** (small bending radius  $\rho$ ) are required to achieve a sufficiently short  $\tau_{ST}$  **~few mins**:

- ▶ At  $E = 2.86 \text{ GeV}$ ,  $B = 1.5 \text{ T}$  ( $\rho = 6.4 \text{ m}$ ),  $C \approx 80 \text{ m} \rightarrow \tau_{ST} \sim 4 \text{ mins}$
- ▶ Can be booster with **strong asymmetric wigglers**.

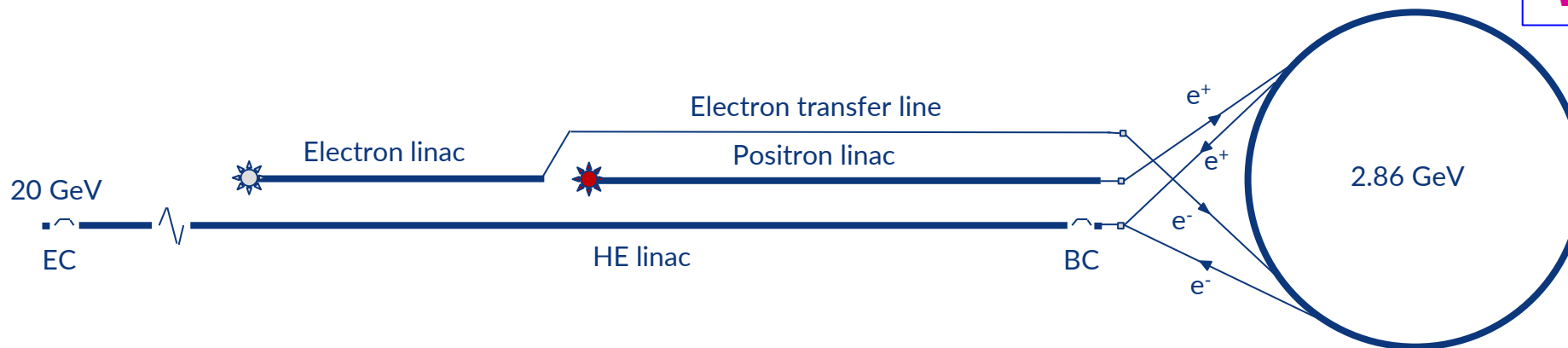
$$\tau_{ST}[s] \simeq 3654 \frac{(R/\rho)}{B^3[T]E^2[GeV]}$$

The FCCee damping ring design would require strong **asymmetric wigglers** to reduce  $\tau_{ST}$  to acceptable levels.

- ▶ Disruptive for regular top-up operation.

**Consider a dedicated DR for polarized beam production**

**Work initiated – C. Carli et al**



*P. Craievich, FCC week 2025*

*A. De Santis, FCC week 2025*

# Linac to booster

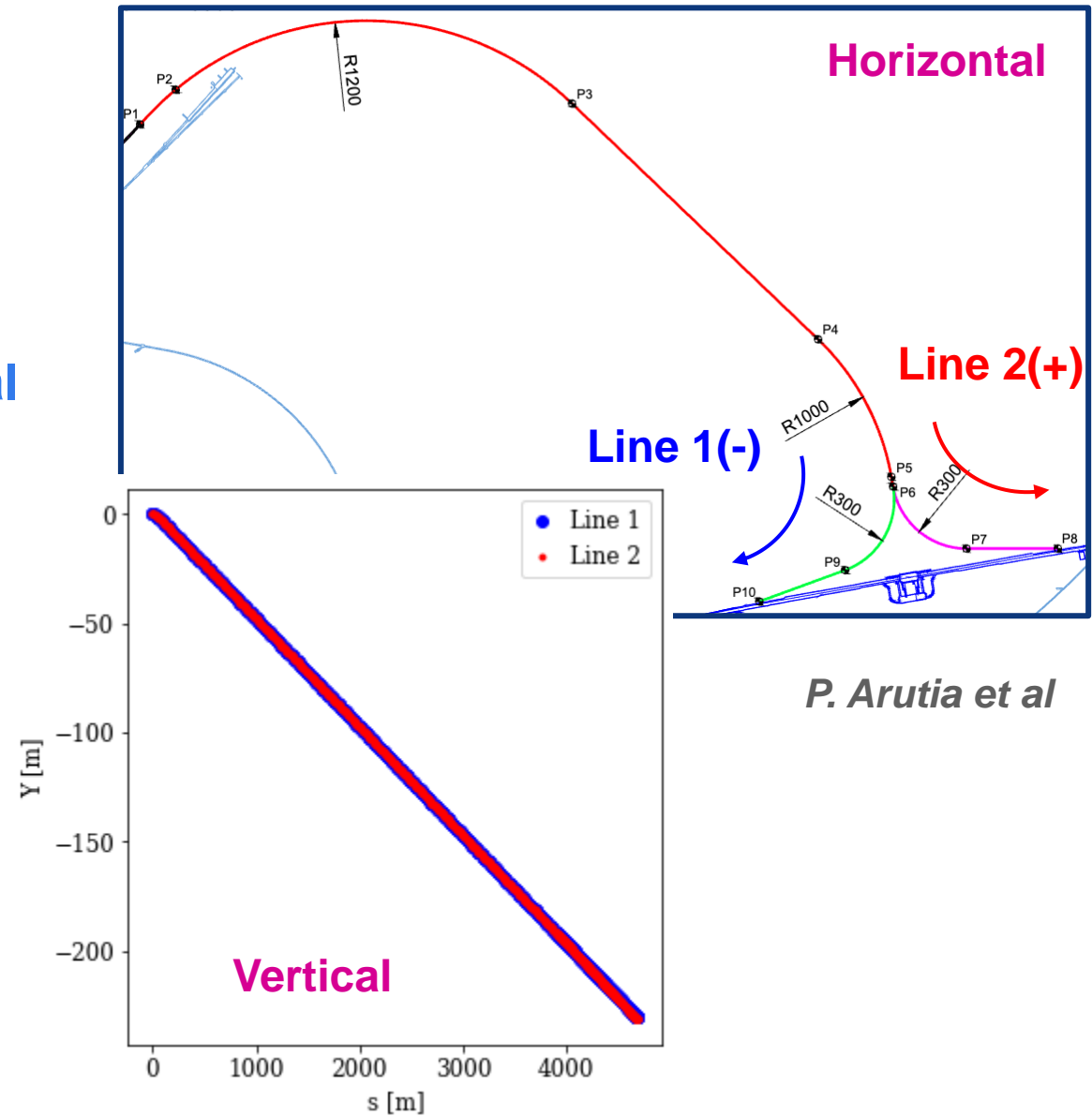
The vertical  $P$  in the DR should be maintained vertical in the LINAC.

The transfer from LINAC to booster involves **vertical and horizontal bending** → the vertical spin orientation may not be preserved !

- ▶ Downward bend/slope of 3%.
- ▶ Vertical bends are at the extremities of the TL, makes life “easier”.

*S. Yue, FCC week 2025*

Since **no start-to-end optics is available**, a simplified spin tracking relying only on the geometry (dipoles) was used to estimate the transmission.



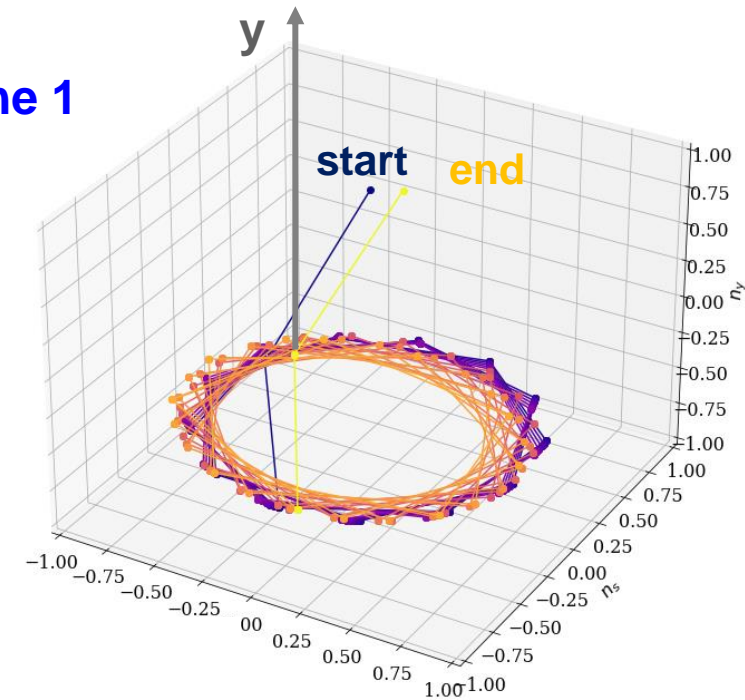
# Transport in the TL

The initial downward bend of  $\sim 3^\circ$  **rotates the  $P$  vector by  $\sim 140^\circ$ : precession of the horizontal component.**

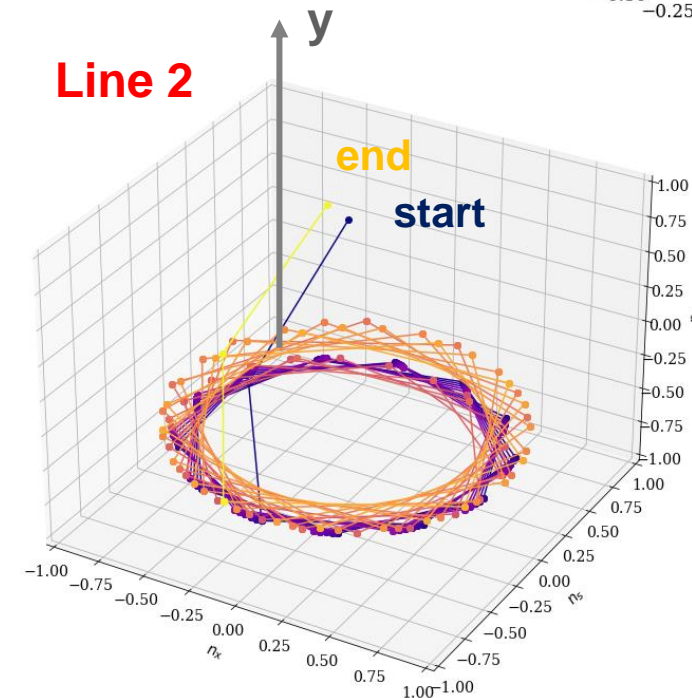
By lowering the linac energy to **19.873 GeV** ( $a_\gamma = 45.0994$ ), the number of precessions can be adjusted to **25.04 / 4.97 turns** and it is possible to **preserve  $>90\%$  of the initial polarization** in both lines.

With the current layout, there may not be a need for special spin rotating devices !

Line 1



Line 2



Color-coded from **dark blue** (start of line) to **yellow** (end of line).  
Initial polarization vertical.

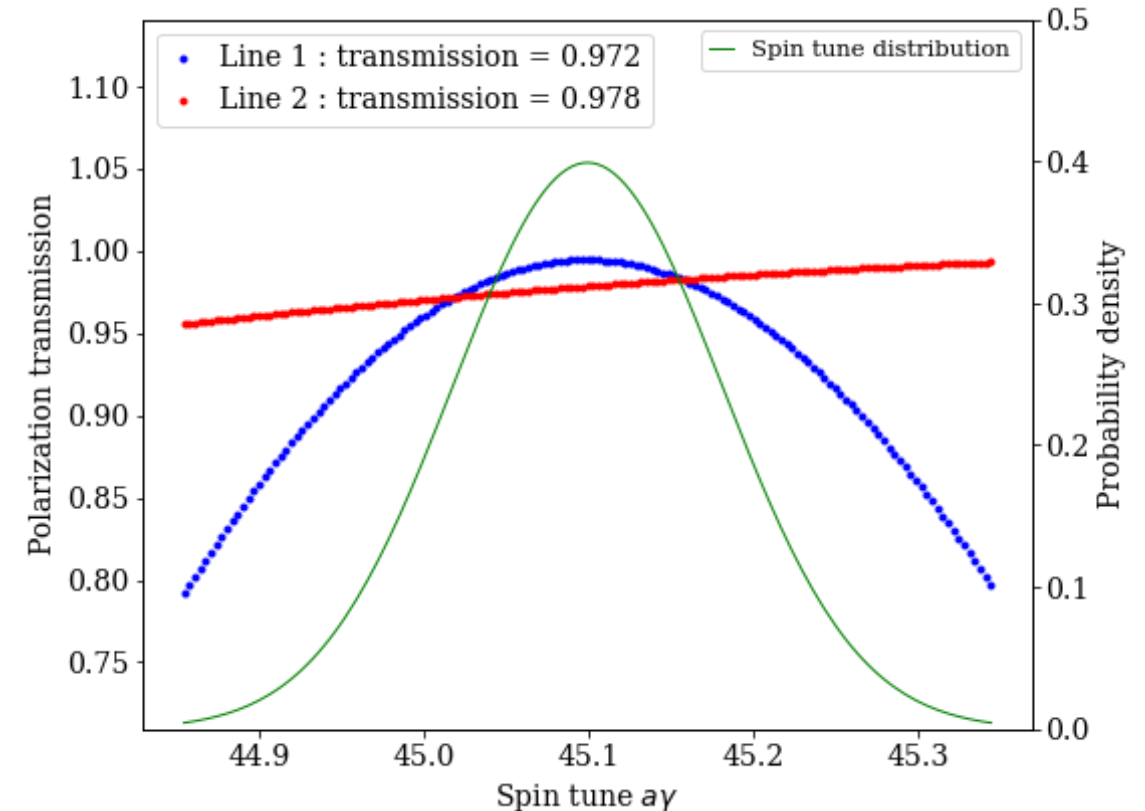
# Transport in the TL (2)

Current assumptions for energy spread and jitter at the end of the linac:

- ▶ **RMS energy spread  $\sigma_s = 0.1\%$ .**
- ▶ **Energy jitter  $\delta_s = 0.3\%$   $\rightarrow$  assumed 2 x rms.**

With those assumptions, the transmission of the **vertical polarization component is ~97%** for both lines.

**Simulations will be refined with Xsuite when an end-to-end model of the TL will be available.**



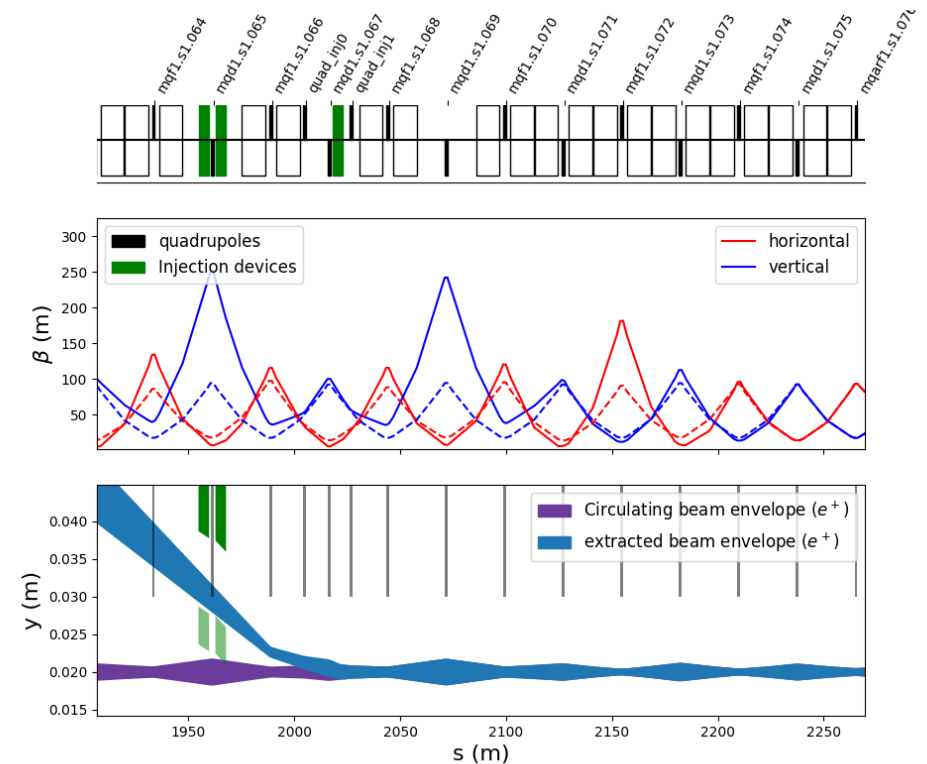
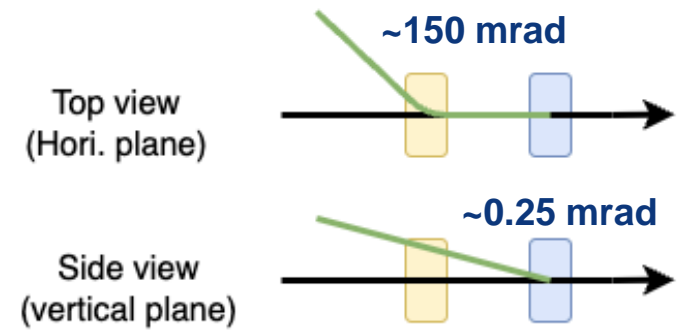
Vertical component of the polarization at the end of **Line 1** and **Line 2** (transmission) as a function of  $a\gamma$  and  **$a\gamma$  distribution** (E spread + jitter).

# Booster injection

The **horizontal injection dipoles + septum** add  $\sim$  one complete turn of spin precession: **rotation  $\sim 1.07$  turns.**

The **vertical deflections** (quadrupole + kicker) contribute very little, **rotation  $\sim 0.002$  turns.**

At this stage, **little concern for  $P$  transmission** provided  $P$  is **vertical** when the beams enter this region.



*S. Yue, FCC week 2025*

# Booster ramp

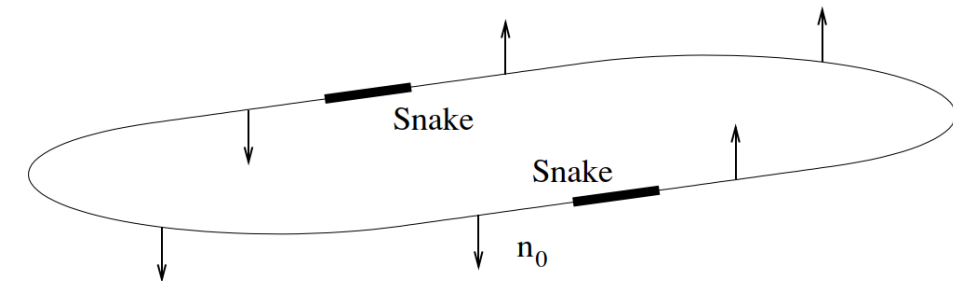
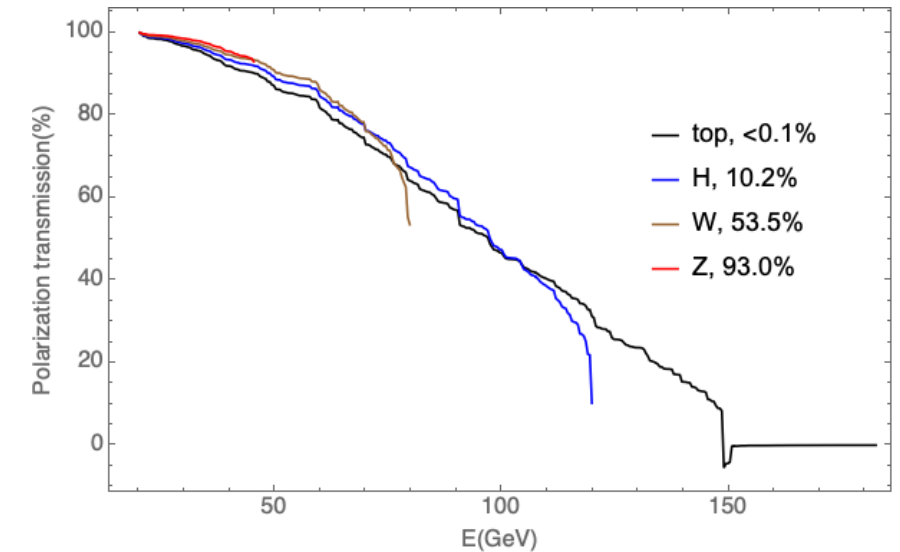
Injection into the booster of bunches with vertical  $P$ .

The polarization must be maintained throughout the ramp, **crossing many resonances**. A study by Z. Duan indicated **good preservation for the booster**.

► > 90% transmission @ Z.

The **installation of 2 snakes** ( $180^\circ$  polarization flip,  $\nu_s = 1/2$  !) could boost preservation of polarization by making it less sensitive to resonances – **to be studied**.

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



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

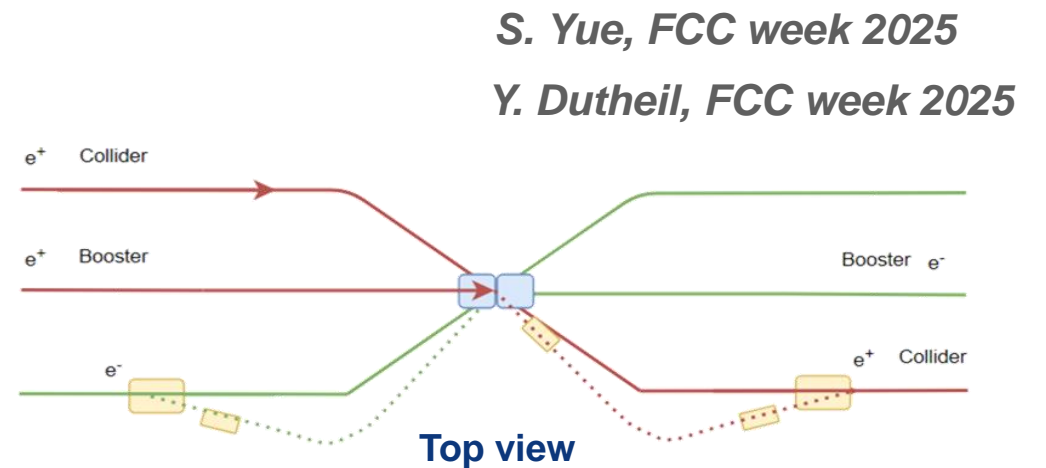
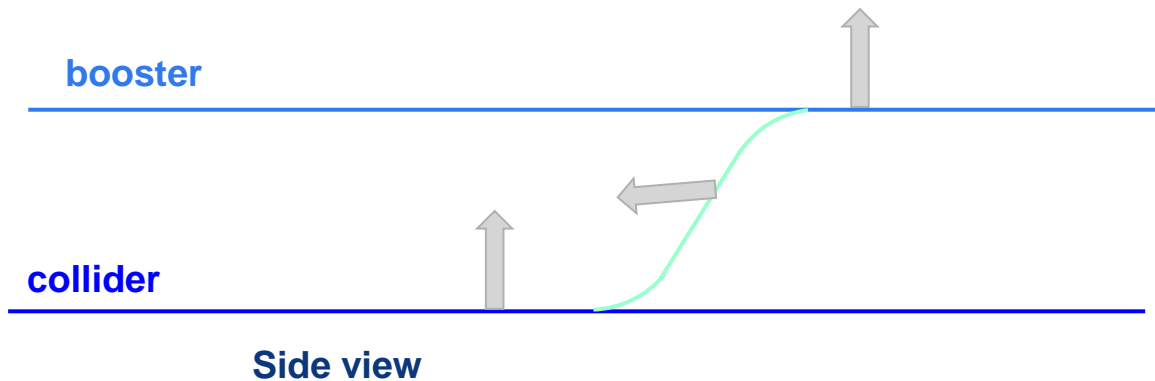
# Booster to collider transfer

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** H/V bending) will **preserve** the **vertical  $P$**  from booster  $\rightarrow$  collider.



# Polarimetry, depolarization

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

Possible inventory:

- ▶ 2 polarimeters in the collider (e+ and e-) – no energy calibration without them !
- ▶ 2 polarimeters in the booster, able to measure from injection to flat top
- ▶ 1 polarimeter at the end of the LINAC or end of the TL?
- ▶ 1 polarimeter per damping ring (alternatively rely on Touschek lifetime)

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

# Summary

Based on the current knowledge and design, **injection of polarized e+e- seems feasible with transmission of > 80% from end of Linac to collider @ Z.**

The results must be **consolidated with more detailed simulations** and with checks of all machine interfaces (injection/extraction).

- ▶ Details of Linac to booster line optics and of injection/extractions regions required – summer 2025.
- ▶ Study need for devices to manipulate the polarization (rotators, snakes).

Production scheme for polarized beams must be established.

Polarization measurement and depolarizer requirements must be defined for the entire chain.



# Spin precession

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

$$\frac{d\mathbf{P}}{dt} = \boldsymbol{\Omega} \times \mathbf{P} \quad \boldsymbol{\Omega} = -\frac{e}{mc} \left[ \left( a + \frac{1}{\gamma} \right) \mathbf{B}_{\perp} + \frac{1+a}{\gamma} \mathbf{B}_{\parallel} - \left( a + \frac{1}{\gamma+1} \right) \boldsymbol{\beta} \times \mathbf{E} \right] \quad \mathbf{E} \text{ represents the electric field}$$

For  $\gamma \gg 1$ :

$$\boldsymbol{\Omega} = -\frac{e}{mc} \left[ \underbrace{\left( a + \cancel{\frac{1}{\gamma}} \right) \mathbf{B}_{\perp}}_{\text{~ independent of } \gamma \text{ for transverse B-fields !}} + \underbrace{\frac{1+a}{\gamma} \mathbf{B}_{\parallel}}_{\text{~ } 1/\gamma \text{ for longitudinal B-fields (solenoids)}} - \left( a + \cancel{\frac{1}{\gamma+1}} \right) \boldsymbol{\beta} \times \mathbf{E} \right]$$

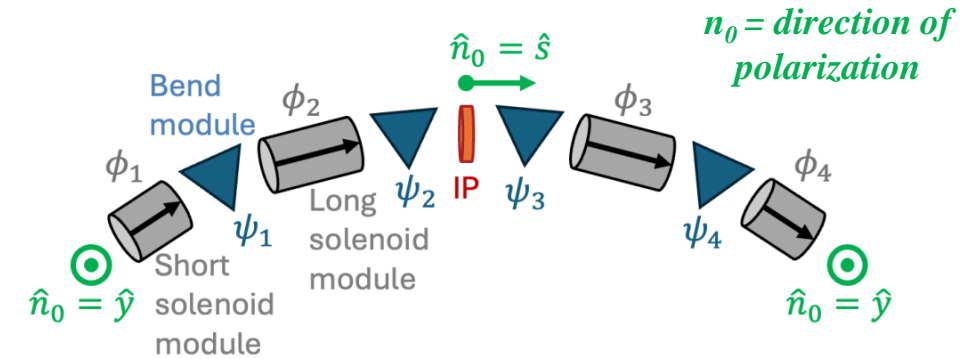
$\mathbf{B}_{\perp} / \mathbf{B}_{\parallel}$  correspond the field components orthogonal / parallel to the particle velocity.  
 $a$  is the anomalous magnetic moment,  $a \sim 10^{-3}$  for e.

# Spin rotators - example

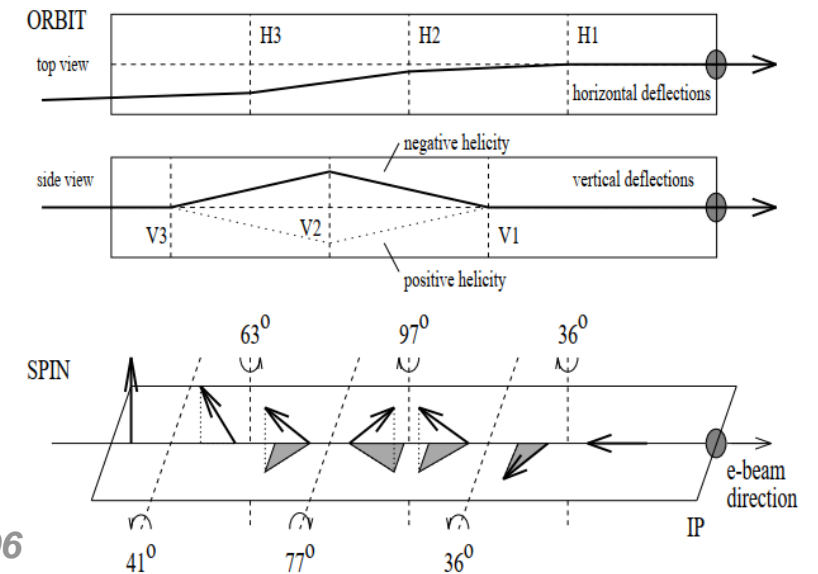
**Solenoids: alone or in combination with dipole fields** can be used to rotate the spin vectors.

- ▶ 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*

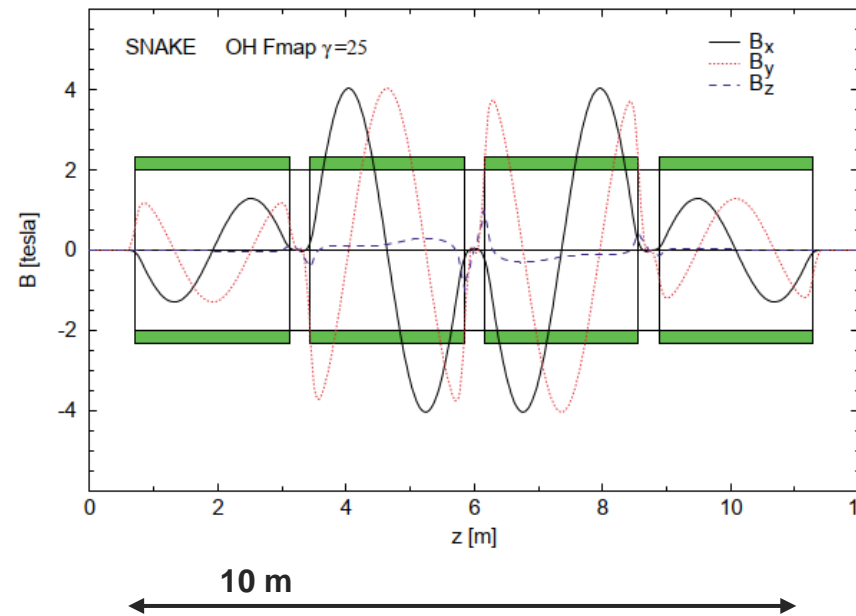
# RHIC spin rotators and snakes

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

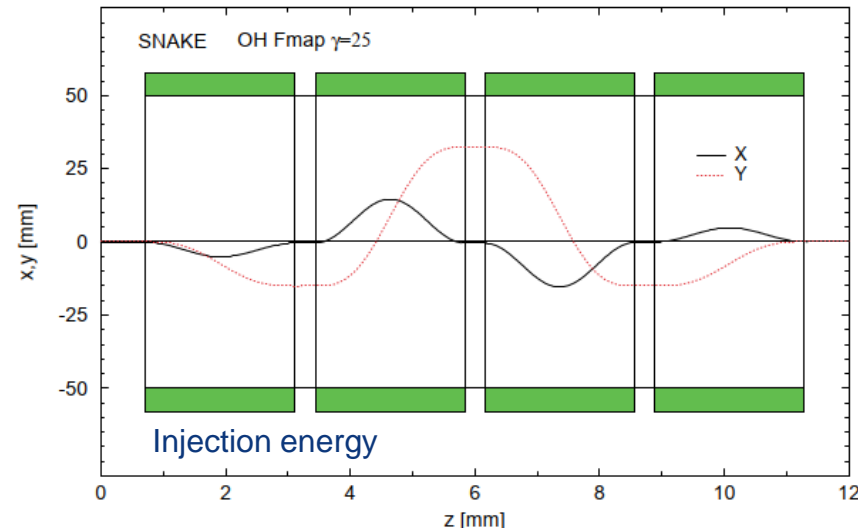
- ▶ **Transverse  $B_x$  and  $B_y$  fields of helical shape**, with  $N$  periods ( $N = 1$  for RHIC).

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

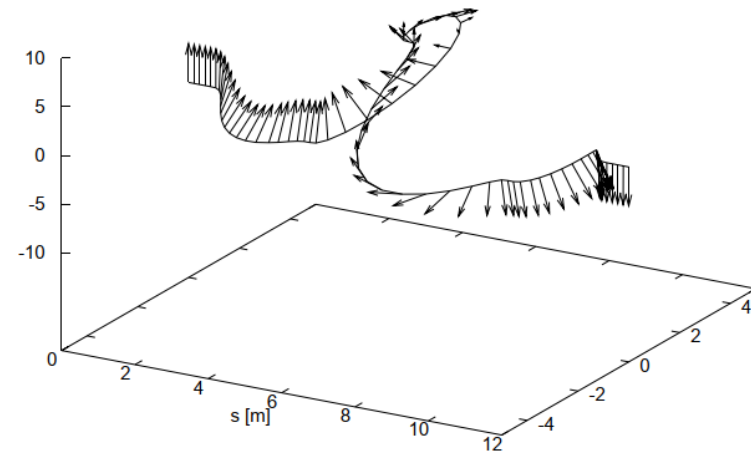
### B fields



### Beam orbits



### Spin flip in a snake



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

# An example - RHIC

RHIC operated periodically with **polarized proton beams**. At FCC-ee the radiative polarization build-up time is so long that the difference to protons at RHIC is not very large.

The polarized protons were **transported and accelerated** through a linac, booster and the AGS to RHIC where the final acceleration took place.

- ▶ ~90% source P → ~70% P in RHIC
- ▶ Relied on special devices for transverse polarization preservation: “Siberian snakes”

