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Solenoid spin compensation with bumps

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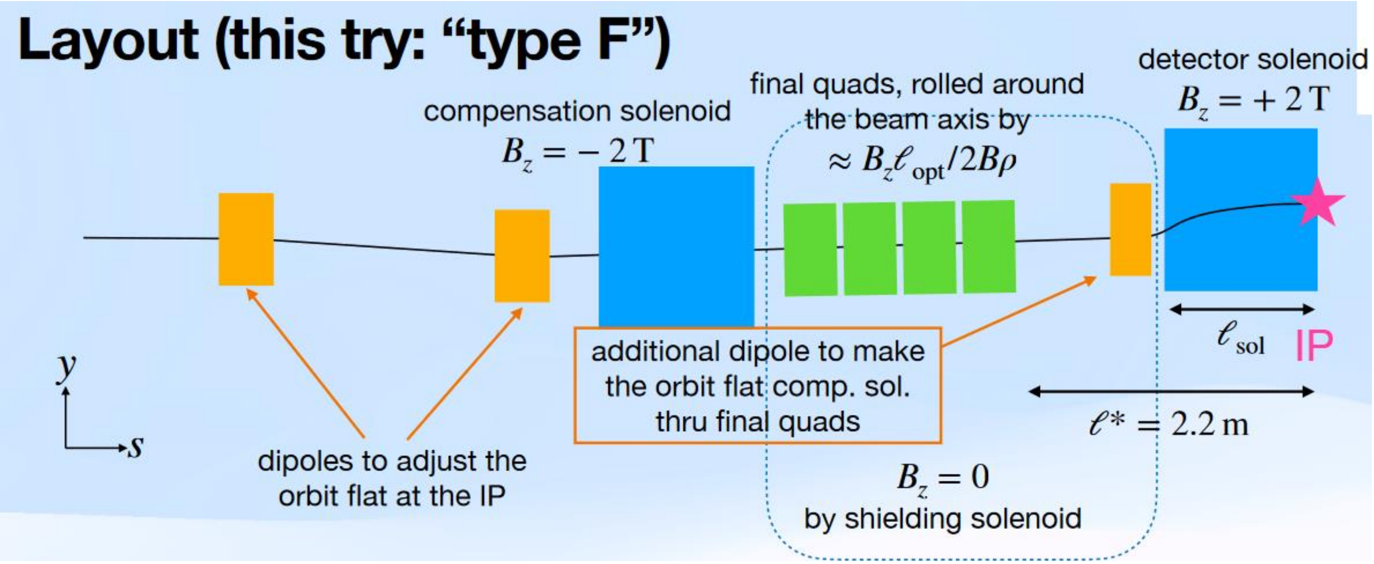
Introduction (1)

- Recently new layouts of the IR with **non-local solenoid compensations** have been discussed at MDI meetings.
- The compensation solenoid is moved out of the inner MDI region to **~±10 m from the** IP. The compensation solenoid field can be lowered (from ~5T to 2T), coupling of solenoid and compensation solenoid are avoided.

K. Oide, https://indico.cern.ch/event/1476514/



- As a side effect, coupling compensation is no longer local and **vertical orbit shifts** appears in the IR.
  - The horizontal crossing angle of the beam through the solenoid generates a vertical orbit deflection that is no longer contained within the MDI region.

Introduction (2)

- The new layout proposal for the IR has an **impact on the n_0 axis** due to **interleaved** spin deflections around the s- and x-axis:
  - **Reduction of the asymptotic polarization to ~1%** based on K. Oide's tracking simulations.
  - Systematic spin tune shifts affecting the energy systematic error – to be evaluated.
- The spin direction could be restored with **vertical orbit bumps** on both sides of every IR.
  - The bumps will have impact on the vertical emittance – to be checked.
- Such a compensation scheme was used successfully at LEP.

- Since Xsuite does not include spin tracking (coming soon?): for this study a simple tracking of the spin was setup (no n_0 axis calculation!), benchmarked on LEP solenoid compensation.
  - First step towards identifying compensation for FCCee.

Part 1: LEP

Solenoids at LEP

- All 4 LEP experiments had solenoids of varying strength (NC and SC).
- LEP had no anti-solenoids, the GLOBAL coupling was corrected using **skew quadrupoles**.
  - There is evidently local coupling between solenoids and skews.

- At **45.5 GeV**, the **spin rotation** around the s-axis due to the **ALEPH solenoid** was **66 mrad**.

$$\int B_{||}\, \mathrm{ds}\ [\mathrm{Tm/rad}] = -\frac{10.479\ \mathrm{Tm}\,/\,(\mathrm{GeV/c})}{\pi(1+a)}\,|\vec{p}|\ .$$

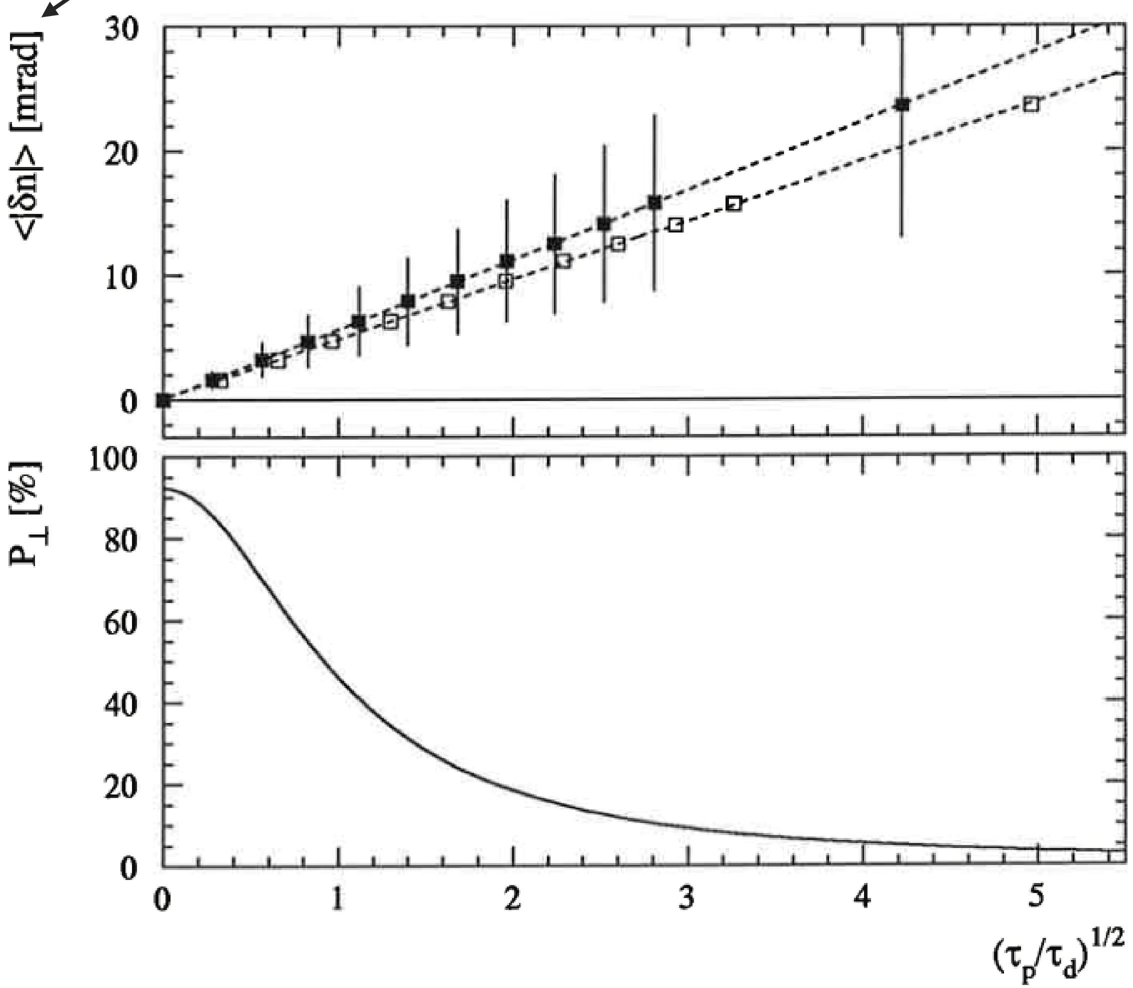
- **Without compensation**, the predicted asymptotic **polarization was in the range 1-5%** - in practice it was generally **~0%**.
  - Without compensation, the energy calibration program at the end of physics fills would have been impossible.

Experiment	BL (Tm)
L3	6.078
ALEPH (SC)	10.082
OPAL	2.613
DELPHI (SC)	9.030

Polarization & n-axis

- Correlation between n-axis deviation from the vertical and expected polarization: for > 20 mrad the expected polarization is lowered to ~few %.
  - Filled squares: linear approx. (SITF)
  - Open squares : non-lin. (SODOM)

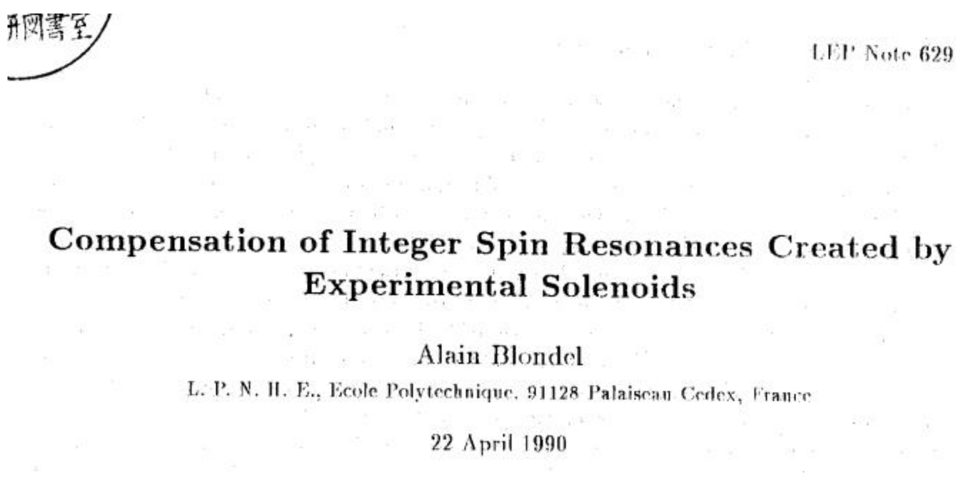
Average deviation of n_0 from vertical direction



Solenoid compensation

Compensation scheme to restore the spin axis using **bumps at the beginning of the arcs** on both side of every IP (nickname: “SolSpin”).

- Took advantage of the **60° vertical betatron arc phase advance** in use around the Z → long bumps, favorable spin phase advance**.**

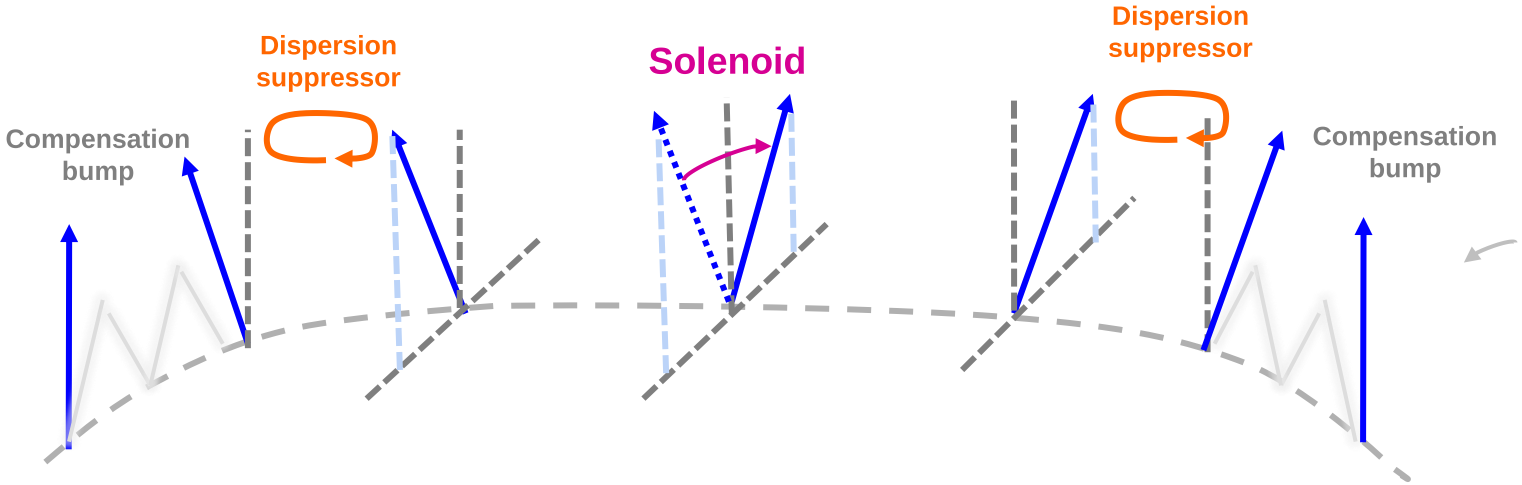

LEP Note 629

Compensation of Integer Spin Resonances Created by Experimental Solenoids

Alain Blondel

L. P. N. H. E., Ecole Polytechnique, 91128 Palaiseau Cedex, France

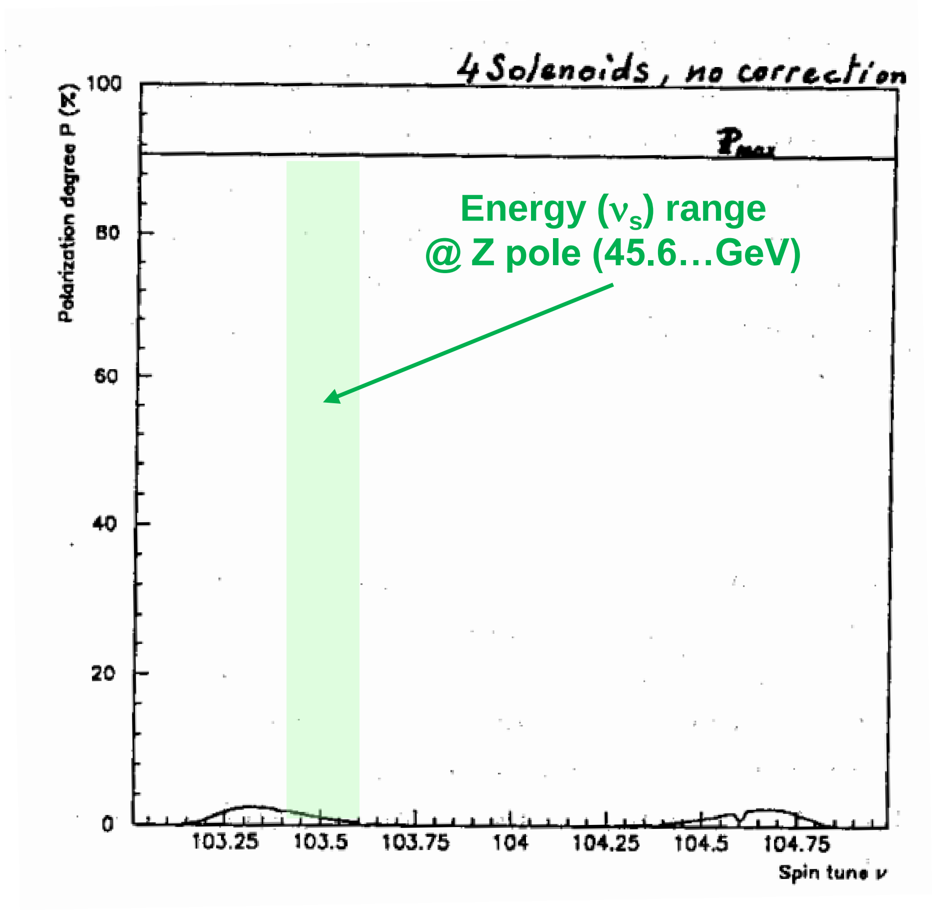
22 April 1990

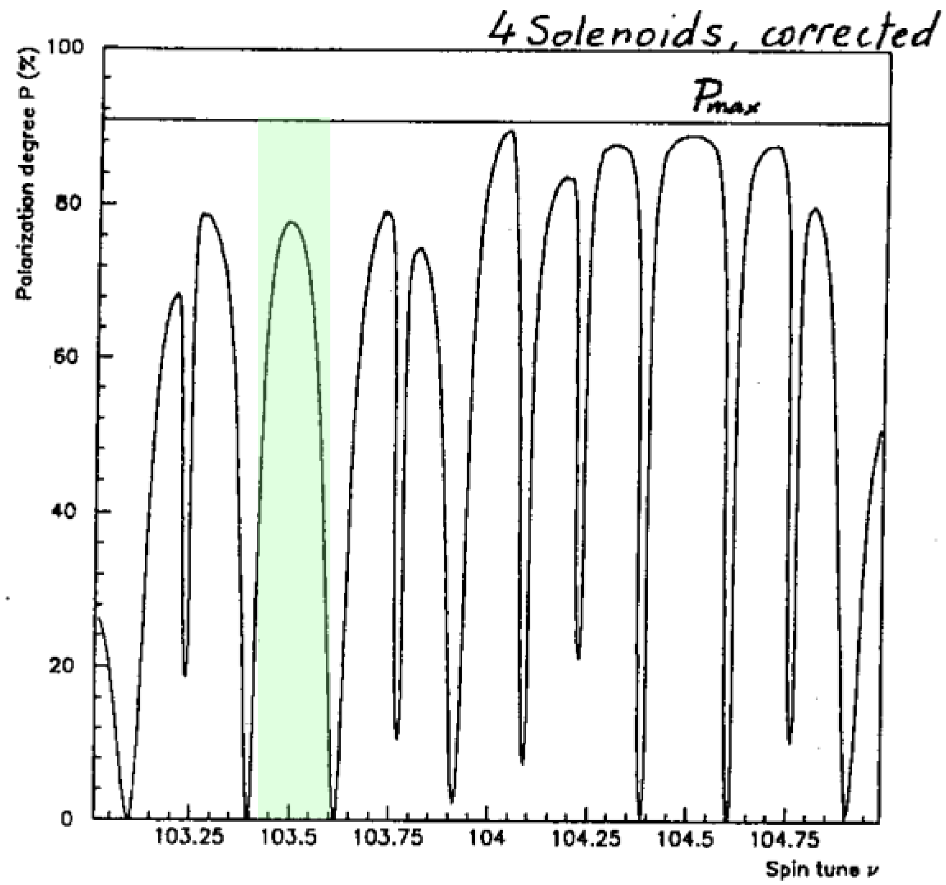


- Double pi-bump to rotate the spin vector out of the vertical.
- Precession in the dispersion suppressor by $\Delta\nu_s$ ~1.1 [2π].
- Rotation by the solenoid.
- Precession in the dispersion suppressor by $\Delta\nu_s$ ~1.1 [2π].
- Double pi-bump to rotate the spin vector back to the vertical orientation.

Solenoid compensation

Predictions (SLIM)





Polarization wo/with SolSpin bumps

Two examples with polarization wo/with compensation bumps.

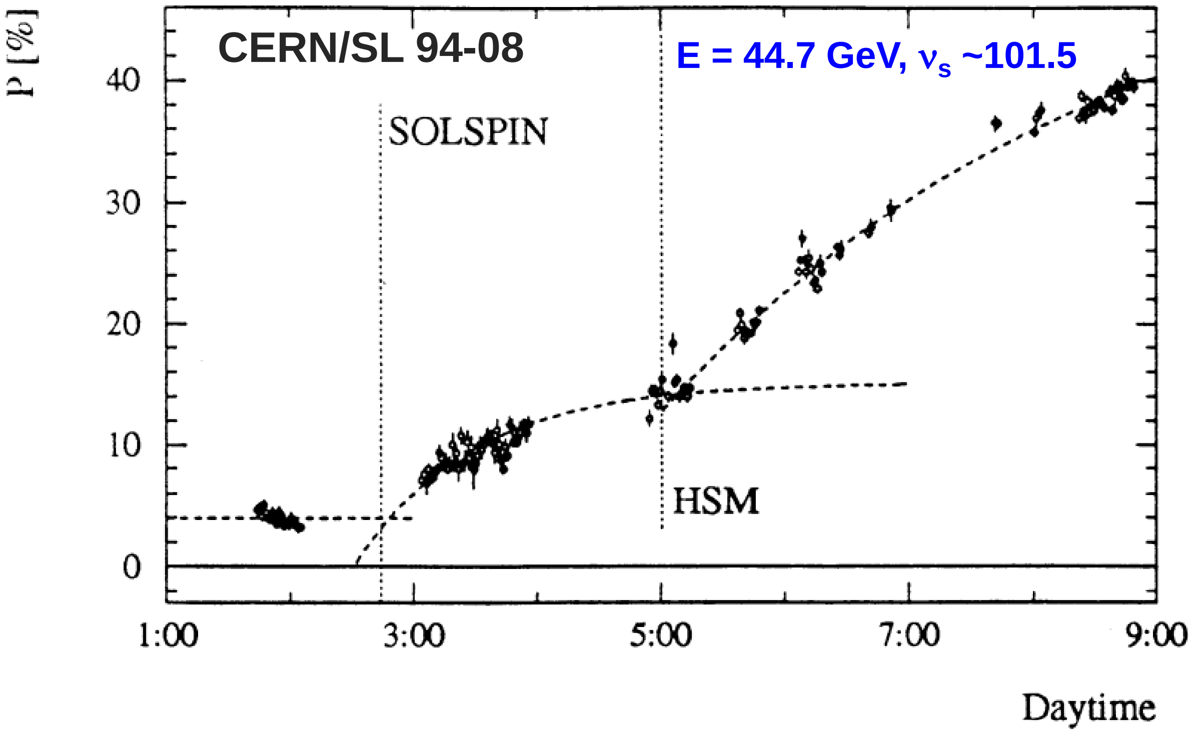
- In the experiment on the left: ~4% polarization without compensation.

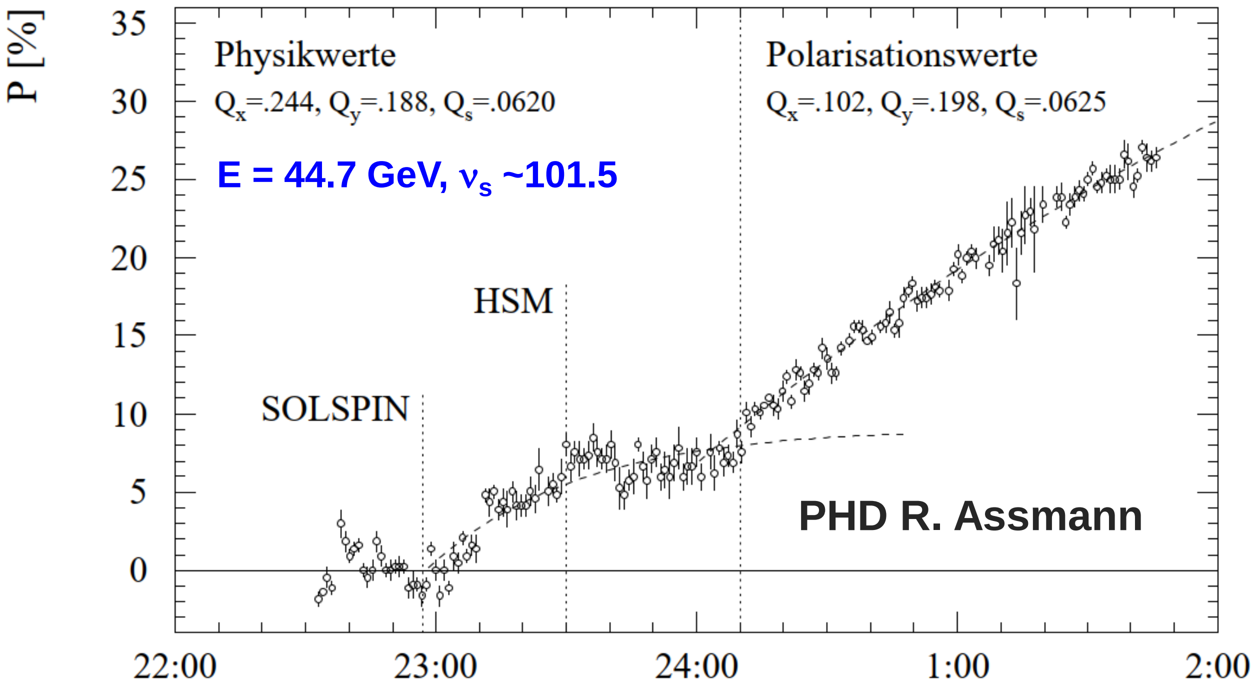
Predicted impact of solenoids (linear):

$\nu = 101.5 \quad (E = 44.7\ \mathrm{GeV}) \quad \rightarrow \quad P_\perp = 6\%$

$\nu = 103.5 \quad (E = 45.6\ \mathrm{GeV}) \quad \rightarrow \quad P_\perp = 1\%$

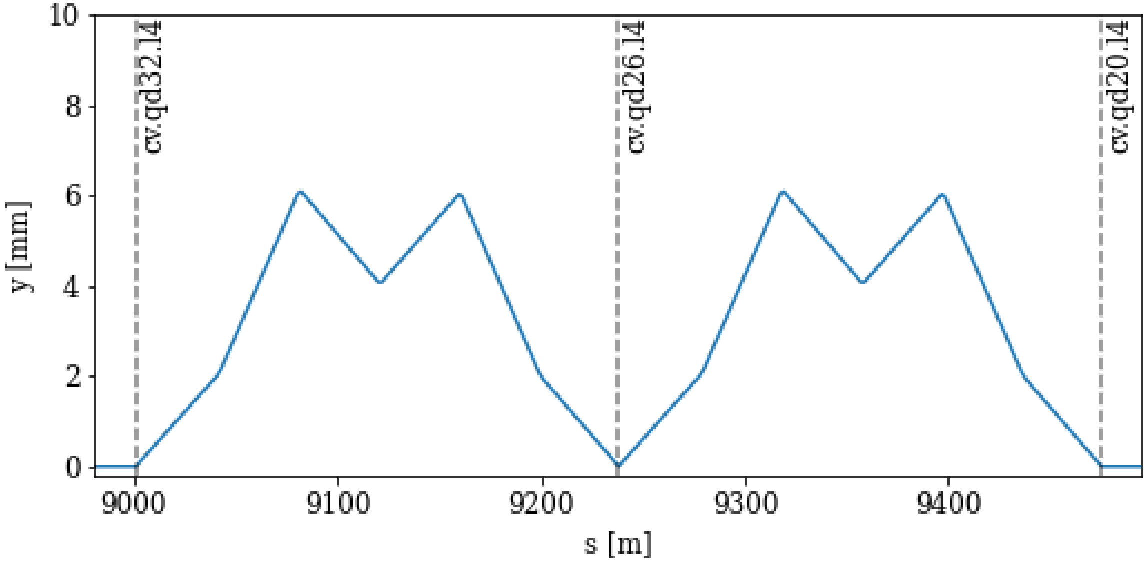
$\nu = 105.5 \quad (E = 46.5\ \mathrm{GeV}) \quad \rightarrow \quad P_\perp = 6\%$





Compensation bumps

Double pi-bump, ALEPH left side

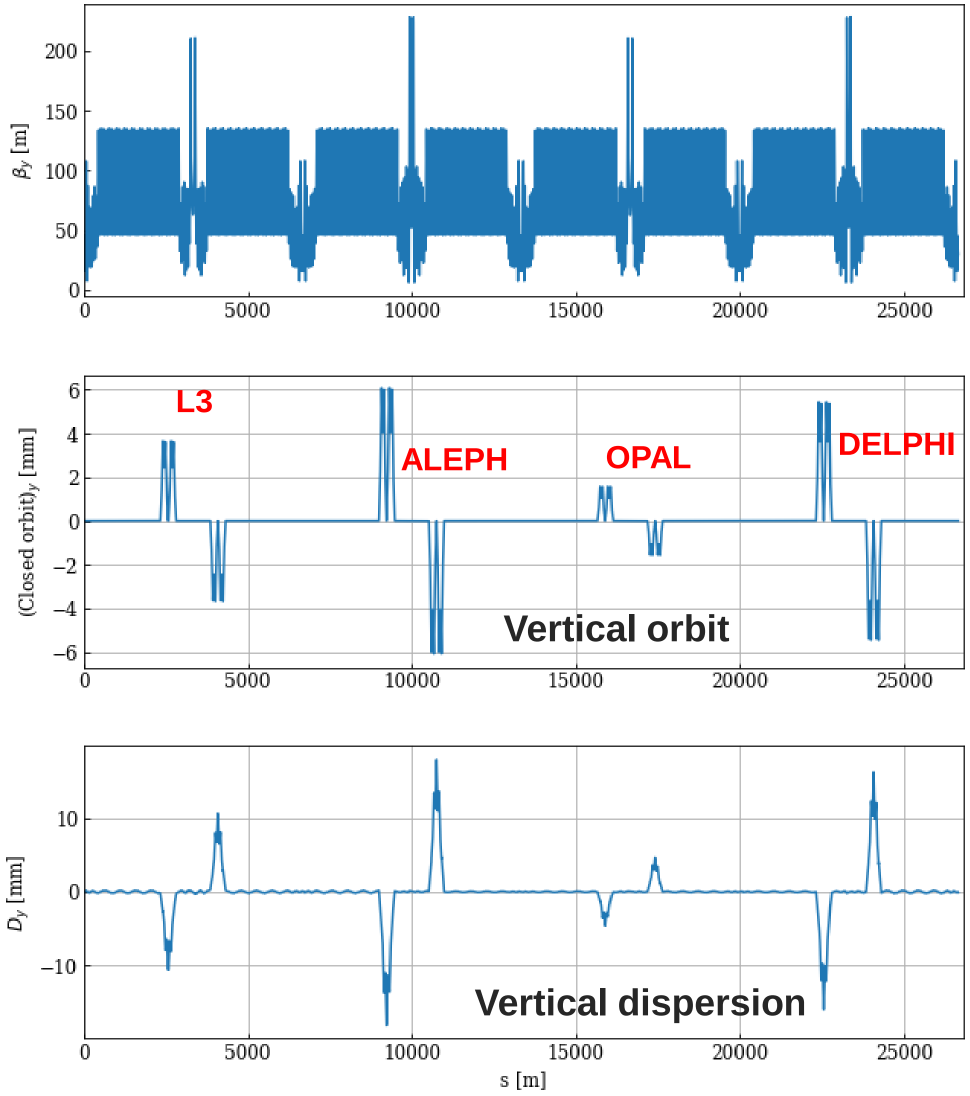


$\Delta\mu_y = 2\pi$

$\Delta\nu_s = 4\pi + \pi/2$

$q_x = 65.33967$ $q_y = 71.09510$
$Q'_x = 0.99$ $Q'_y = 0.98$ $\gamma_{tr} = 50.84$

Complete bump set



Impact on emittance/performance

- The **double pi-bumps at π phase advance** contain well the **vertical dispersion** within the bump region, limiting the vertical emittance growth.
- At the Z, the vertical bumps generate a vertical emittance of $\boldsymbol{\varepsilon_y}$ **~ 150 pm**.
- For a natural horizontal emittance of $\boldsymbol{\varepsilon_x}$ **= 12-30 nm** (wo/with wigglers) for the LEP 90/60 optics (optics with 90° phase advance in H and 60 ° V), this corresponds to $\boldsymbol{\varepsilon_y/\varepsilon_x}$ **~0.5-1.2%.**
  - At 45 GeV LEP operated with $\varepsilon_y/\varepsilon_x$ ~1% in physics production.

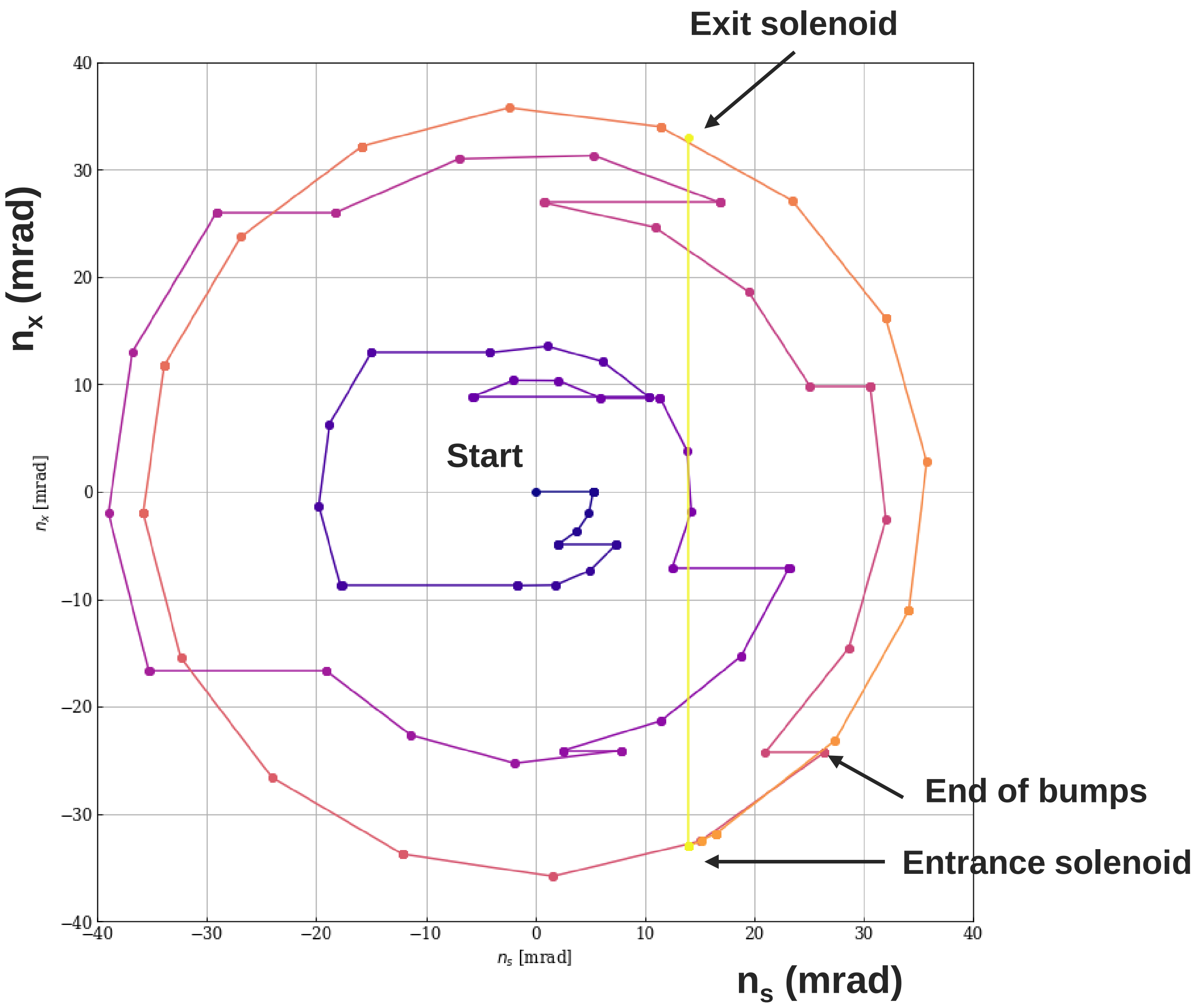
- At LEP no polarization in physics: **polarization studies & energy calibration outside physics data taking → emittance growth not critical.**

Spin path arc to IP

- Spin vector orientation assuming initial vertical direction from **entrance of the left side compensation bump** to the **exit of the solenoid**.

- Color coded from dark blue (start) to yellow (end).
  - Each point: one machine element.

- **Horizontal lines**: spin deflections induced by **vertical orbit correctors** or **offsets in quadrupoles**.
- **Curved sections**: precession in **dipoles**.

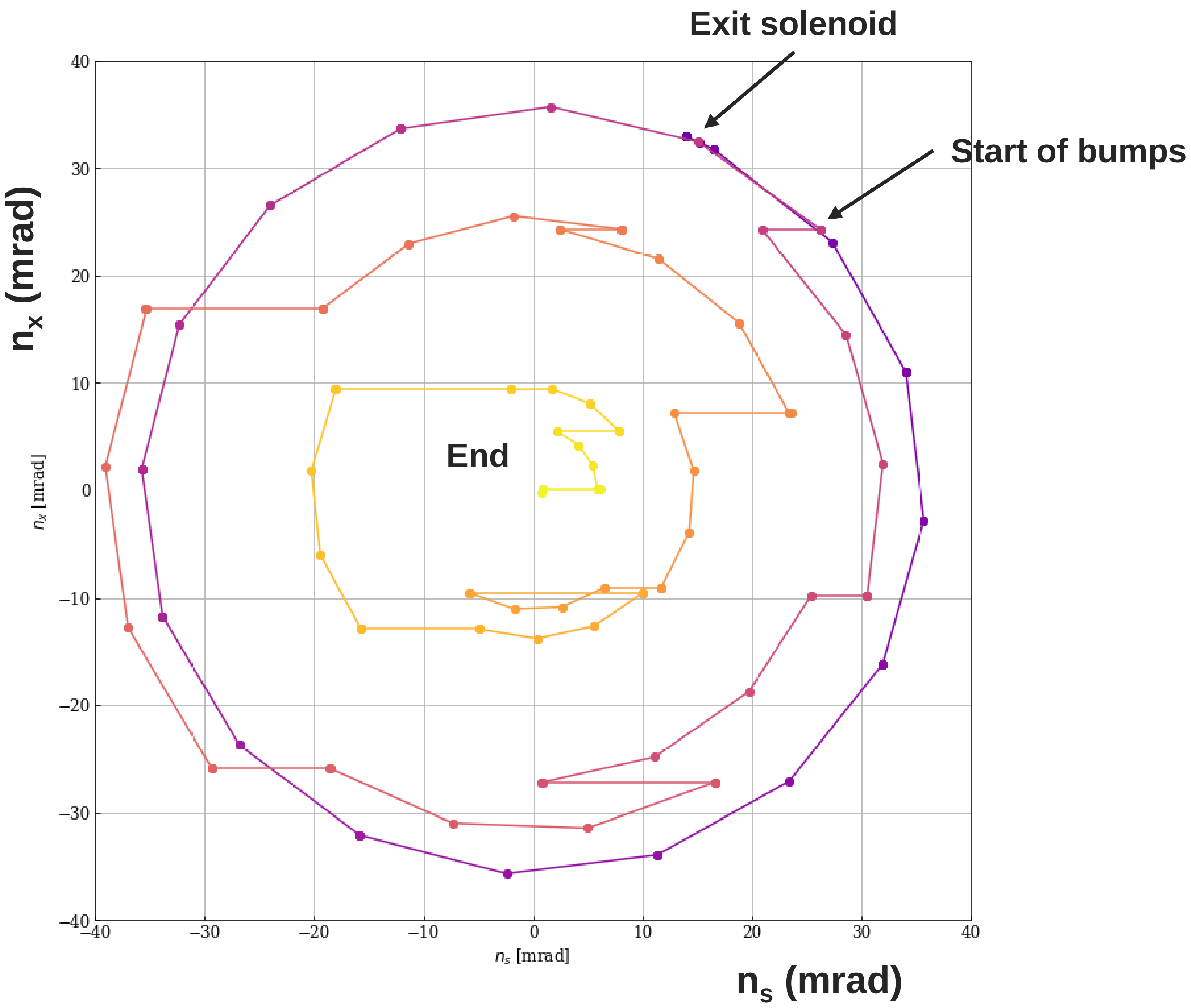


Spin path IP to arc

- Spin vector orientation from **exit of the solenoid** to **the end of the right-side compensation bump**.

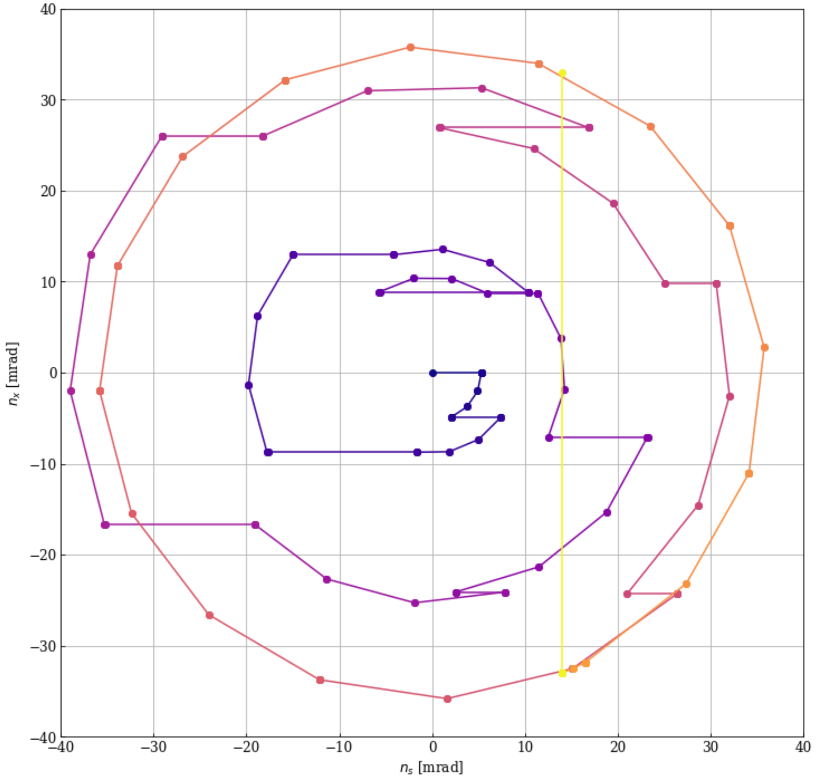
- Color coded from dark blue (start) to yellow (end).

- **Horizontal lines**: spin deflections induced by **vertical orbit correctors** or **offsets in quadrupoles**.
- **Curved sections**: precession in **dipoles**.

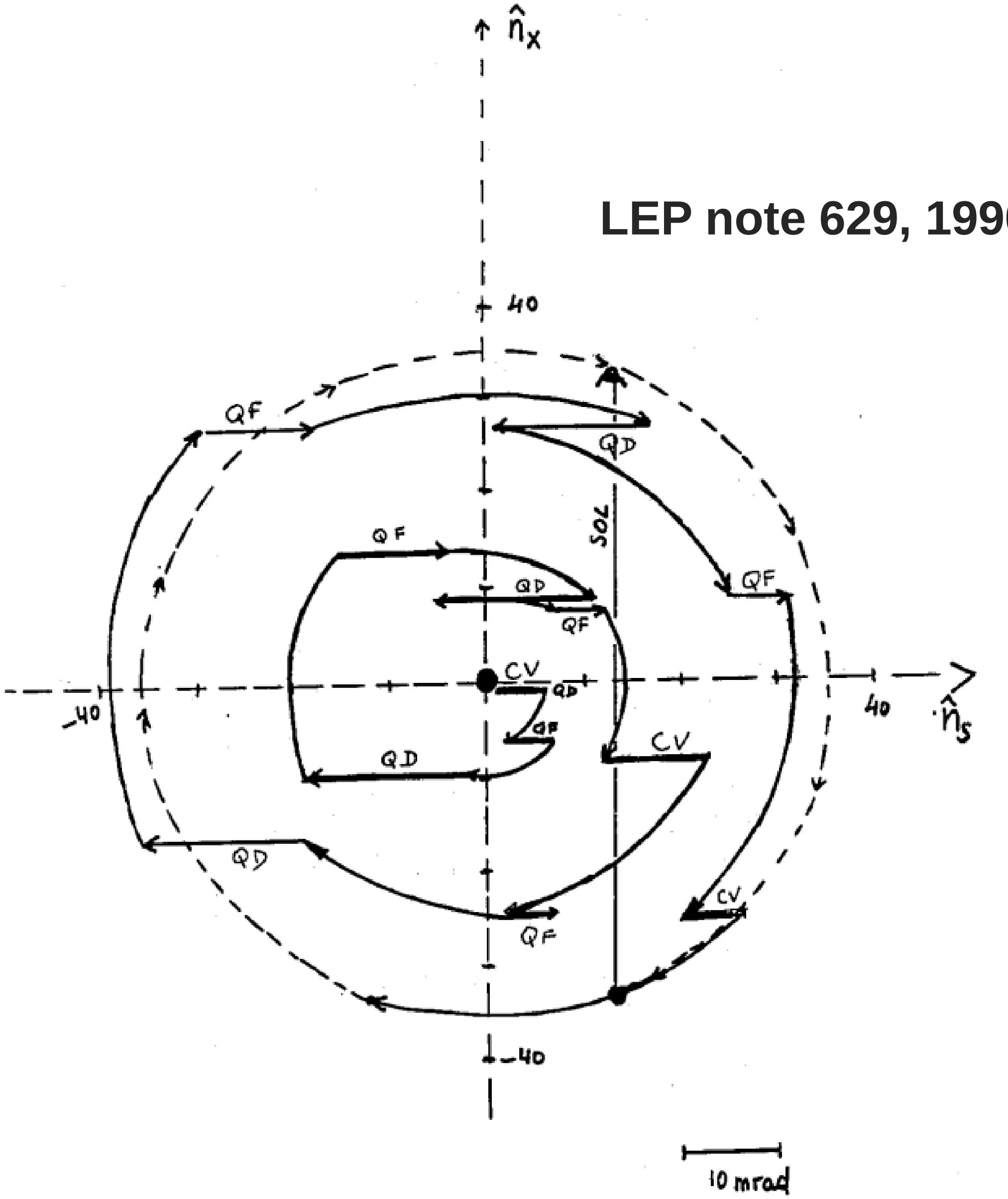


Original versus replay

2024



LEP note 629, 1990



Impact of solenoids on spin tune @ LEP

- The **systematic spin tune shift** due to the solenoids (and compensation bumps) and associated systematic error on the beam (or centre-mass) energy was estimated to be **negligible for LEP**.

- The shift is **difficult to check experimentally** due to the long time required to ramp and compensate the solenoid (→ energy drifts):
  - One single check, no energy change within ±0.44 MeV.

Z. Phys. C 66 (1995) 45

CERN SL/94-71 (BI)

CERN/SL 93-26

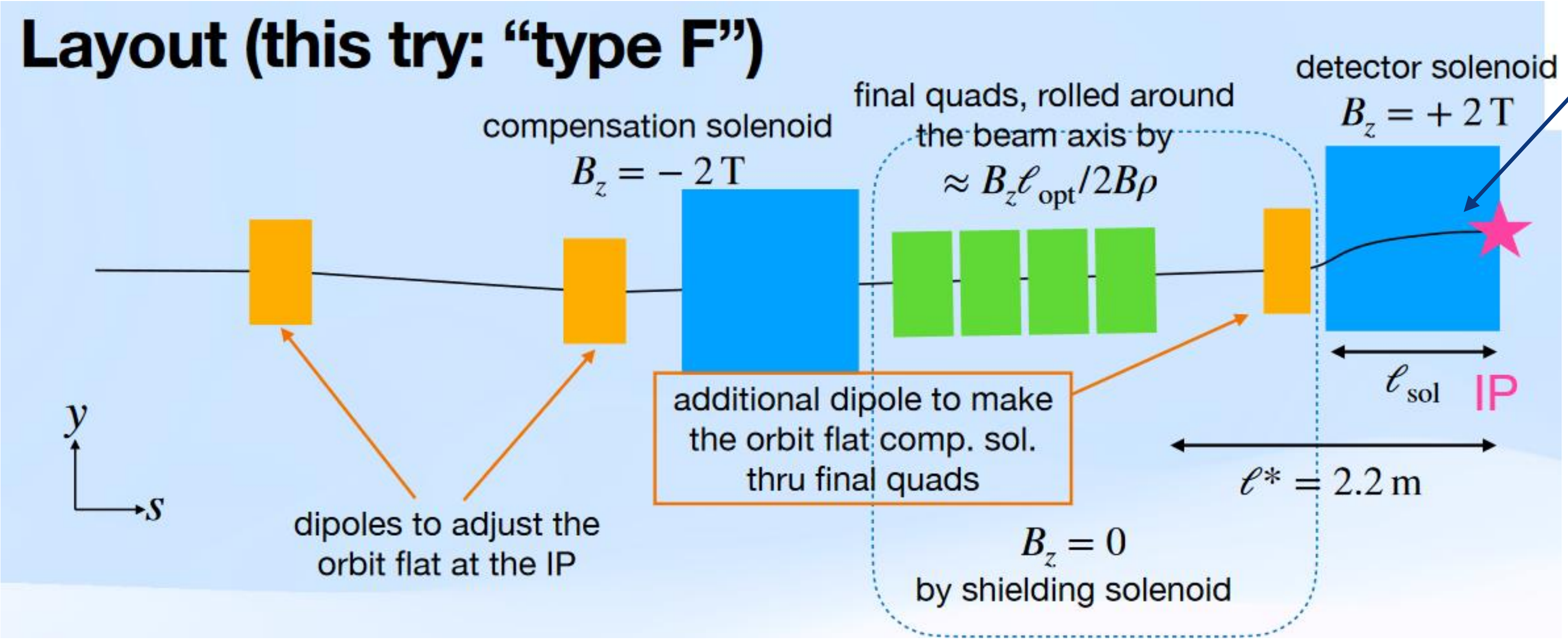
$a\gamma$	δE[KeV, c. of m.]	
	No spin compensation	With spin compensation
105.01	4037	30
.10	473	16
.20	211	12
.30	112	8
.40	50	4
.50	0	0
.60	-48	-6
.70	-114	-10
.80	-211	-14
.90	-475	-18
.99	-3960	-22

! centre-of-mass energy !

Part 2: FCCee

Non-local solenoid compensation concept

- Consider option “F” proposed at the MDI meeting 11.11.2024 (GHC lattice):
  - https://indico.cern.ch/event/1476514/



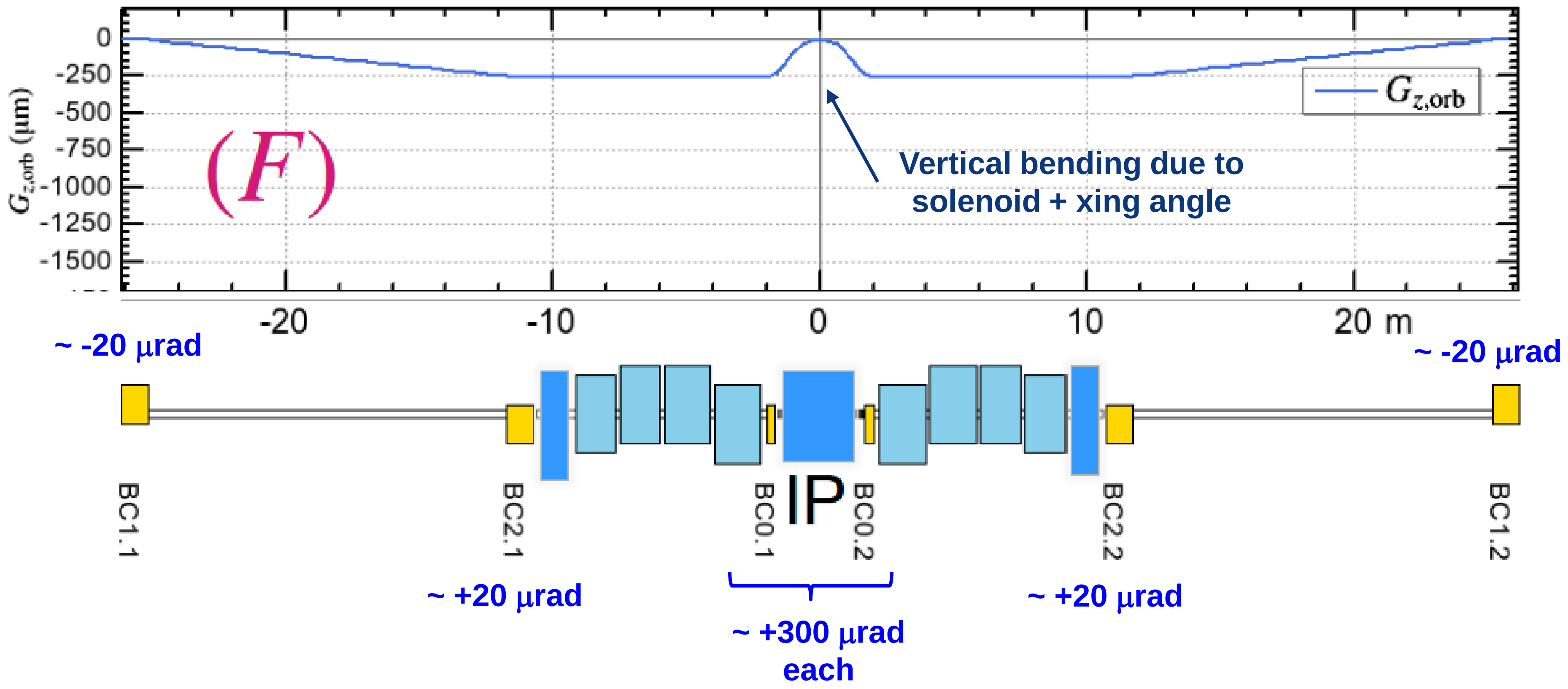
Vertical deflection due to the horizontal crossing angle in the solenoid.

15 mrad (1.2 xing angle) in ~6-7Tm integrated field

Symmetric layout on the right side of the IP

Non-local solenoid compensation geometry

- Orbit around the IP – interleaved horizontal fields + solenoid(s).



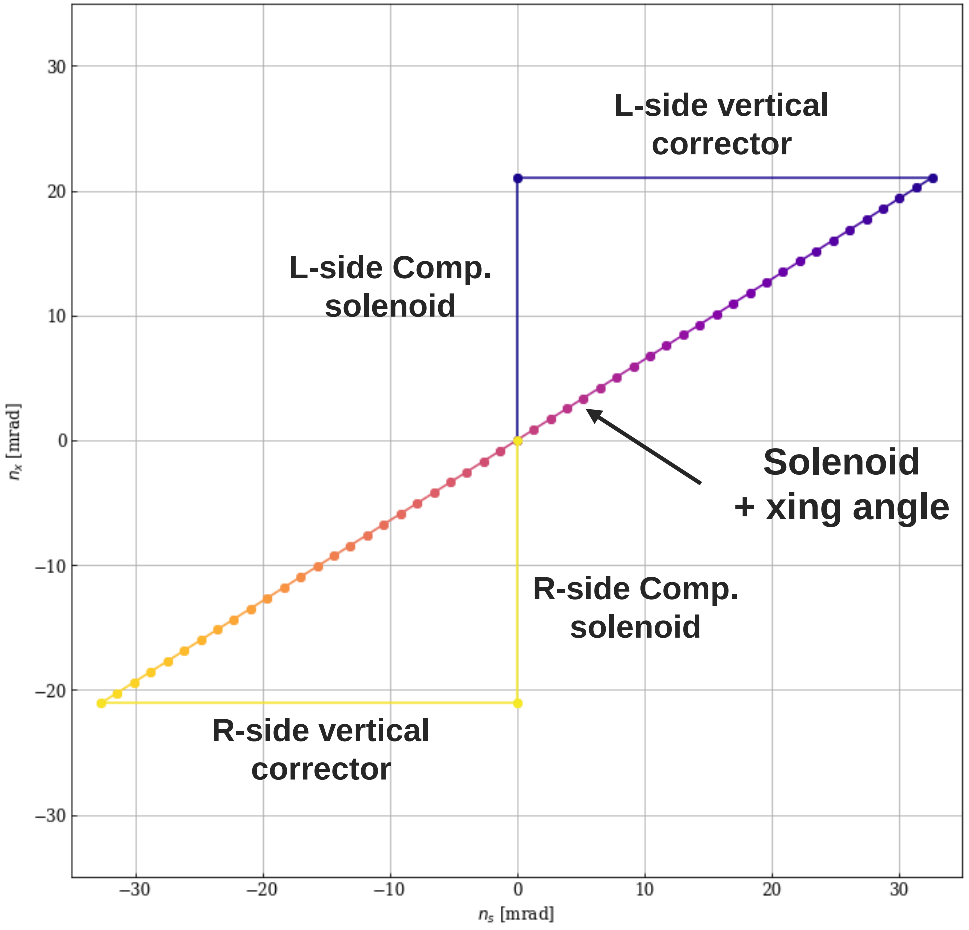
Non-local solenoid compensation

- No MADX version of the geometry is available on Git.
  - In discussion with H. Burkhardt for some ad-hoc madx scripts – but they are for the LCC lattice, not for the GHC.
- The following slides show a first look at the geometry and the possible impact on polarization.

Spin vector tracking

- Tracking the spin vector through left side compensation solenoid, vertical orbit corrector, solenoid (+hor crossing angle), right side vertical orbit corrector, compensation solenoid.
  - Color coded from dark blue (start) to yellow (end).

- Due to the compensation solenoids at ~10m, the vertical orientation is well preserved.

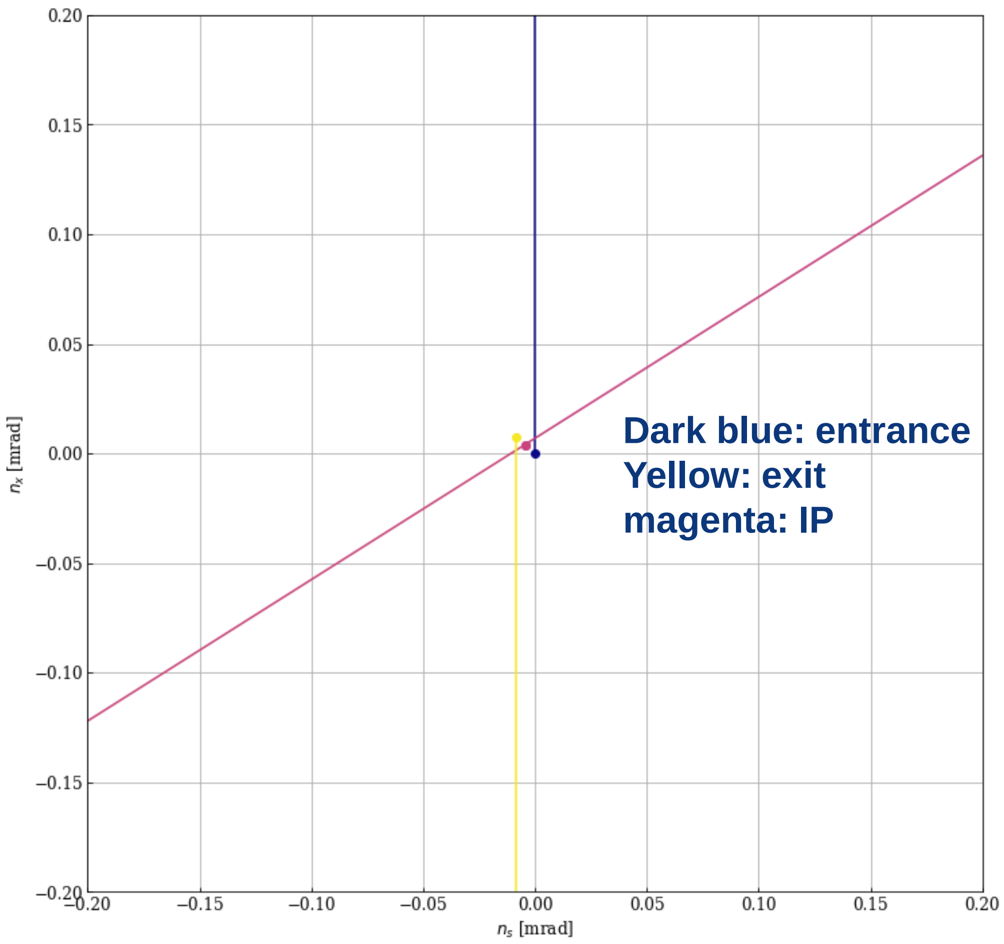


Spin vector tracking - zoomed

- Tracking the spin vector through left side compensation solenoid, vertical orbit corrector, solenoid (+hor crossing angle), right side vertical orbit corrector, compensation solenoid.
  - Color coded from dark blue (start) to yellow (end).

- There is a **small deviation** of the spin from the **vertical** at the exit of the region by **~10 μrad**.
  - Simplified check with discretized spin rotations confirms the deviation magnitude.

- **Due to the small values of the shift, it is very sensitive to details – need to confirm with further studies / geometry checks.**



Discussion

- The LEP solenoid compensation was used as benchmark to check / compensate the impact of the solenoids (+ compensation) for FCCee.

- In the absence of a proper MADX sequence for the local solenoid compensation, a first exploratory investigation was performed.
  - The spin deflections by the (compensation) solenoids are like those at LEP (~6-7 Tm vs 10 Tm).
  - Despite the “not fully” local nature of the compensation, the compensation does also work for the polarization, leaving only a residual deviation of n_0.
  - Compensating bumps can be small !

- SAD tracking by K. Oide yields only ~1% residual polarization (4 IPs !) which looks a bit pessimistic for the small imperfection. Confirmation / cross-check with BMAD needed !