

Beam Polarization Studies — Status and Challenges

Yi Wu, Léon Van Riesen-Haupt,
Tatiana Pieloni, Mike Seidel

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Energy calibration in the FCC-ee

- **Four operation center-of-mass energies**

Z bosons (91 GeV) to top quark pairs (350-365 GeV)

- **High precision COM energy calibration**

- **The current precision targets**

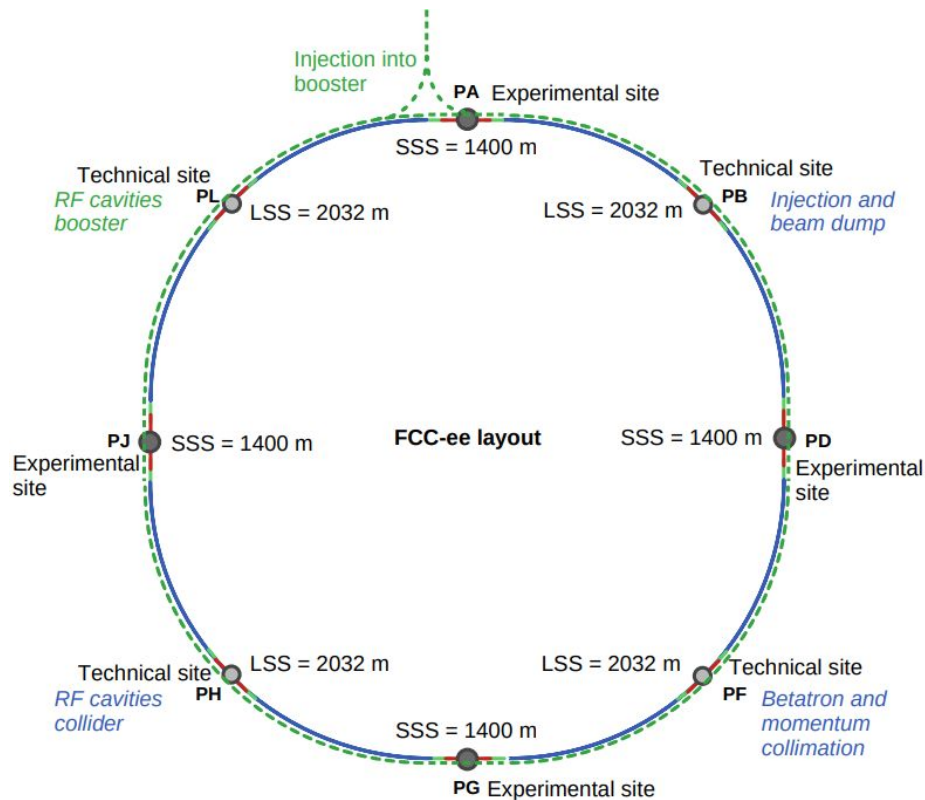
statistical: 4 keV at Z mass

systematic: 100 keV at Z mass

- **Resonant depolarization is the way to achieve this target**



requires a sufficient transverse spin polarization level



Spin polarization

Thomas-BMT equation

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

instantaneous spin precession frequency

$$\Omega = \Omega_0(1 + a\gamma) \quad \Omega_0 = eB_{\perp}/\gamma mc$$

closed orbit spin tune

$$\nu_0 = \frac{\langle \Omega \rangle}{\Omega_0} - 1 = a\langle \gamma \rangle$$

$$\vec{P} = \frac{\sum_{i=1}^N \langle \vec{S}_i \rangle}{|\langle \vec{S}_i \rangle| N}$$

perfect flat ring

$$P \approx 92.4\%$$

real machine

$$P < 92.4\%$$

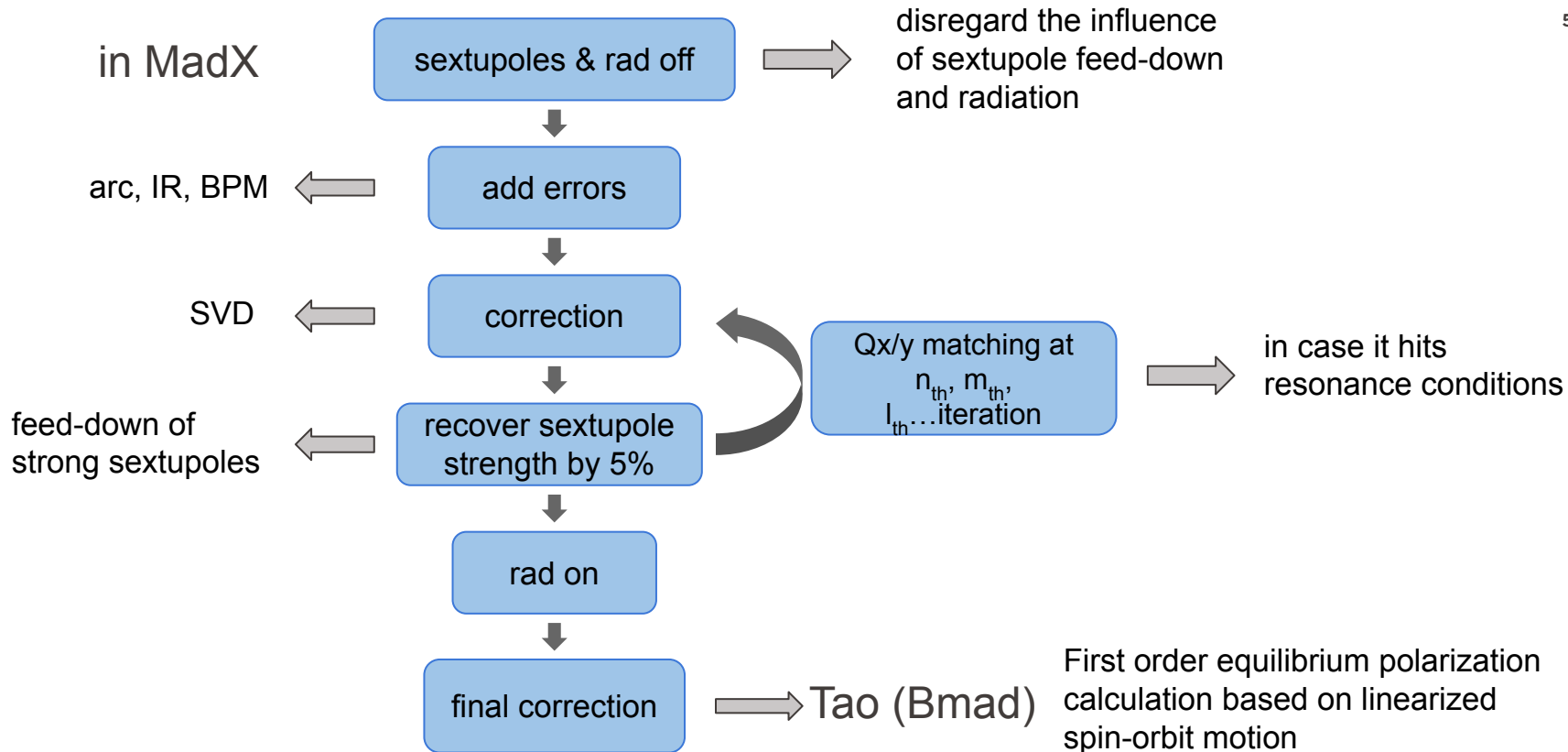
$$\nu' = a\langle \gamma \rangle + \Delta\nu$$

How much?

[*] Magnet figures from Maxwell's equations for magnets, A. Wolski, <https://cds.cern.ch/record/1333874/files/1103.0713.pdf>

[*] Spin polarization theory reference: D. P. Barber, G. Ripken, Sections 2.6.6-2.6.8, Handbook of Accelerator Physics and Engineering, 3rd Edn., World Scientific, Singapore, 2023.

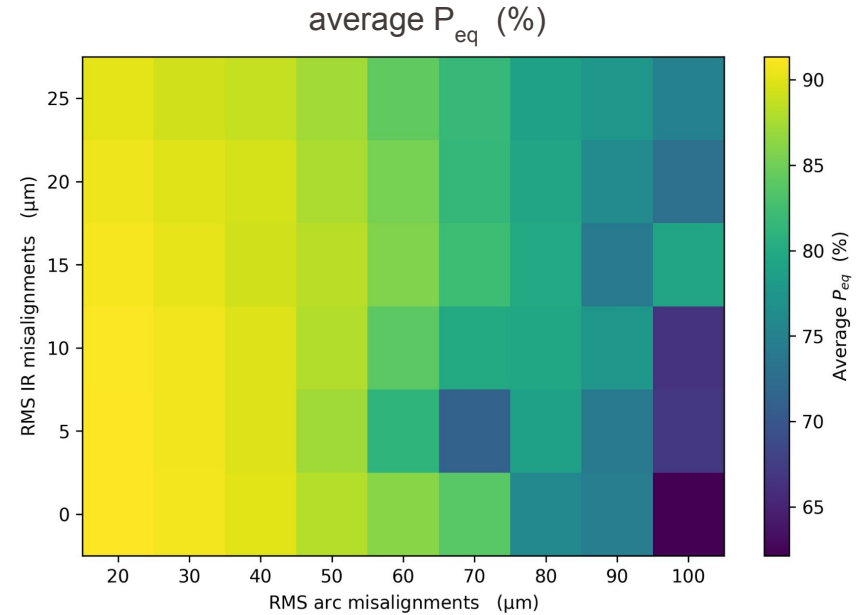
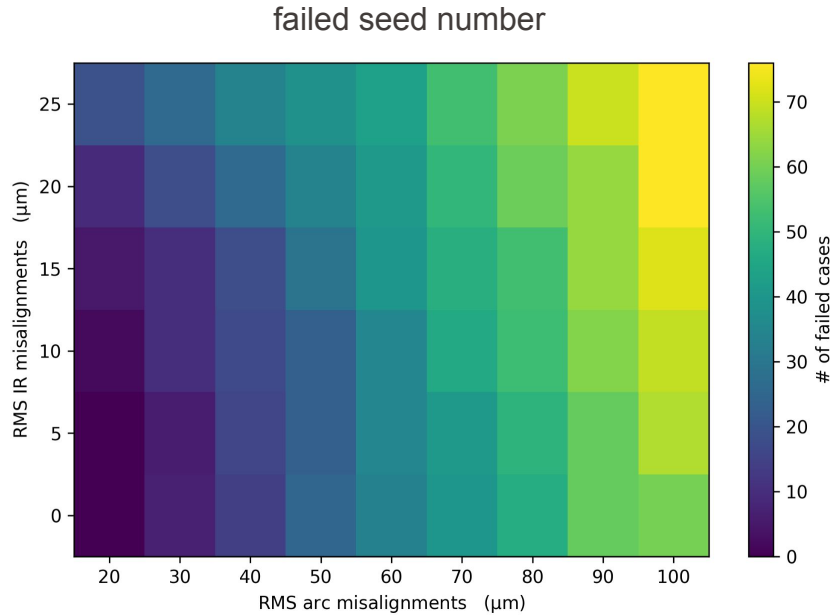
Polarization with imperfections and corrections



This procedure has demonstrated robust performance across the majority of error seeds

Misalignments in arc & IR

same 100 initial seeds for each square on the colormap



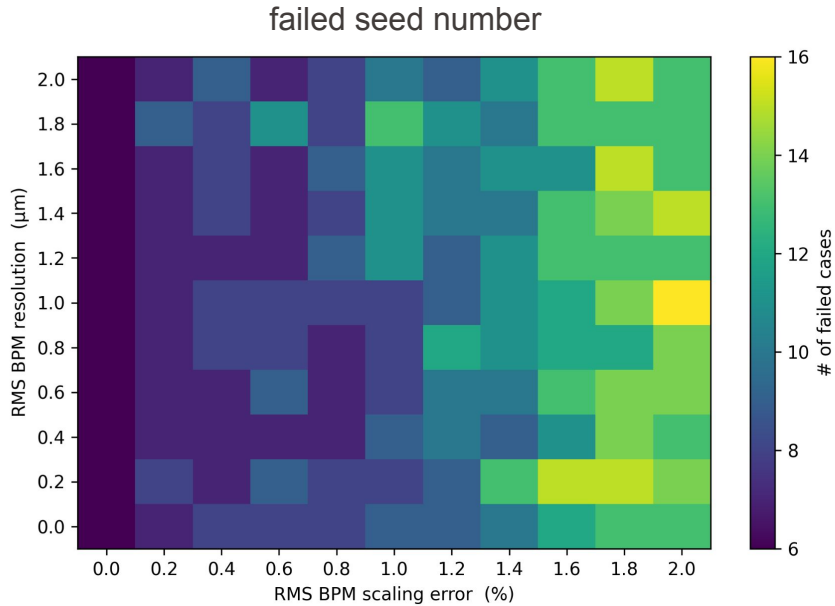
IR misalign. have a bigger impact on closed orbit search

arc misalign. dominates the influence to P_{eq}

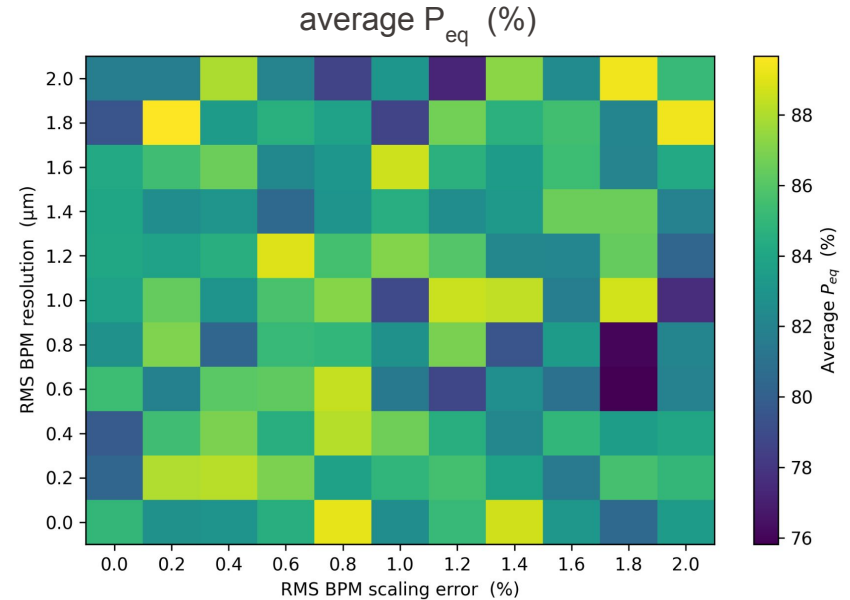
BPM scaling error and resolution

same 50 initial seeds for each square on the colormap

+ 30 μm misalign. in arc
+ 10 μm misalign. in IR

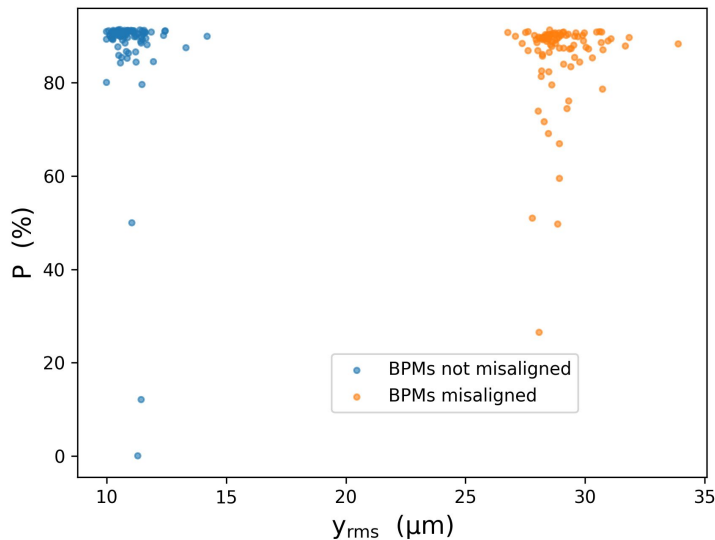


scaling error dominates the impact for closed orbit search

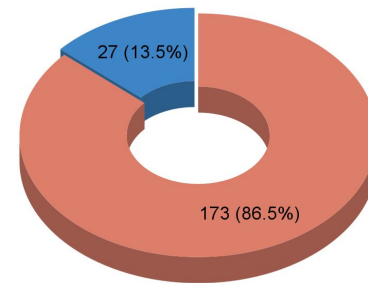


random impact on P_{eq}

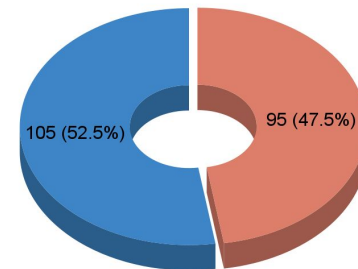
- + 40 μm arc misalignment
- + 10 μm IR misalignment
- + 100 μrad non IR dipole roll (DPSI)
- + BPM 5% random missing+1% random scaling errors+1 μm random resolution



BPM not misaligned



● Succeed ● Fail

BPM misaligned **together with quads**

● Succeed ● Fail

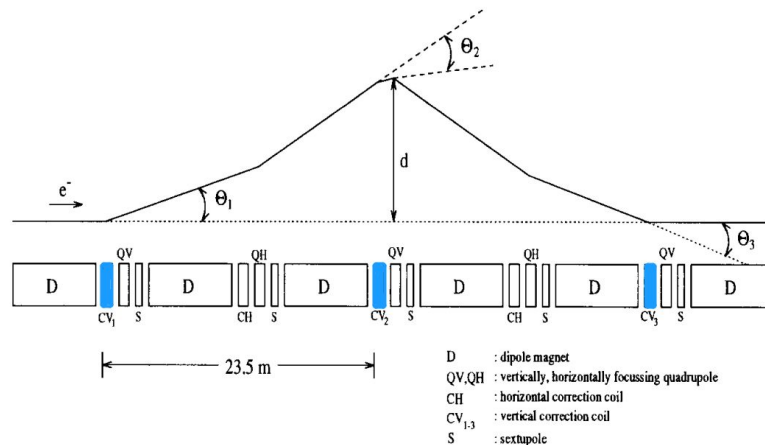
■ larger residual orbits, and greater variance in polarization

Harmonic Spin Matching Schemes

Harmonic spin matching

Conventional lattice correction + harmonic spin matching

- Misaligned ring $\rightarrow n_0(s)$ not vertical \rightarrow stronger spin diffusion
- HSM uses multiple vertical orbit correctors to create an additional controllable n_0 tilt and reduce $(\delta n_0)_{\text{rms}} \rightarrow$ elevate polarization
- Use closed vertical bumps to keep orbit perturbation localized



a schematic of a bump in HERA*

■ [*] D. P. Barber, et al. "High spin polarization at the HERA electron storage ring." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 338:2-3 (1994): 166-184.

Harmonic spin matching

Each closed bump can be represented using a single variable, and each bump has an independent and linear contribution to the Fourier coefficients of δn_0

$$\mathbf{MK} = \mathbf{C}$$

K: amplitudes (the first kick value) of the bumps

C: real and imaginary parts of the required harmonics coefficients

M: response matrix

If the harmonics 0 and 1 of a misaligned lattice is **A**, the bumps should generate **-A**, and bump amplitudes can be estimated via inverting the response matrix

$$\mathbf{K} = \mathbf{M}^{-1}(-\mathbf{A})$$

Three correction schemes that could potentially be used in the FCC-ee have been tested

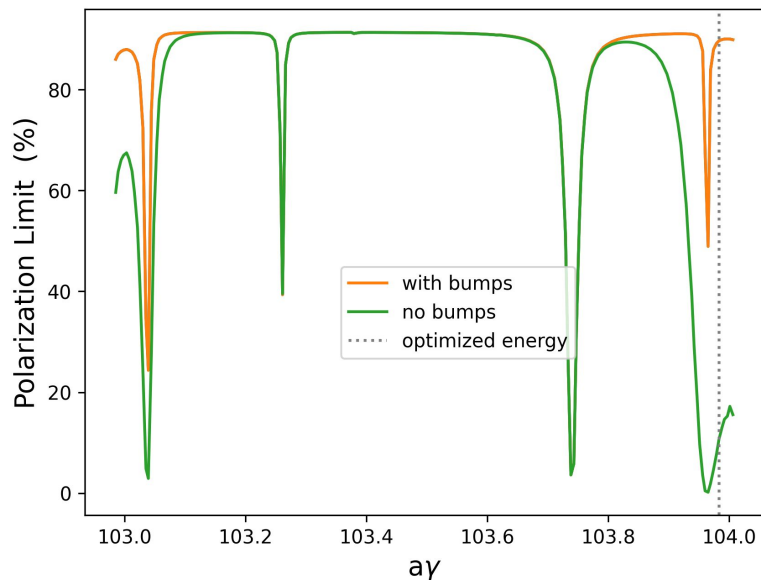
1. HERA formalism¹
2. Rossmannith-Schmidt scheme²
3. LEP method³

[1] D. P. Barber, et al. A general harmonic spin matching formalism for the suppression of depolarisation caused by closed orbit distortion in electron storage rings. No. DESY--85-044. DESY, 1985. [2] R. Rossmannith and R. Schmidt, Compensation of depolarizing effects in electron-positron storage rings. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 236.2 (1985): 231-248. [3] R. W. Assmann, Optimierung der transversalen Spin-Polarisation im LEP-Speicherring und Anwendung für Präzisionsmessungen am Z-Boson. Diss. Munich U., 1994.

Rossmanith-Schmidt scheme*

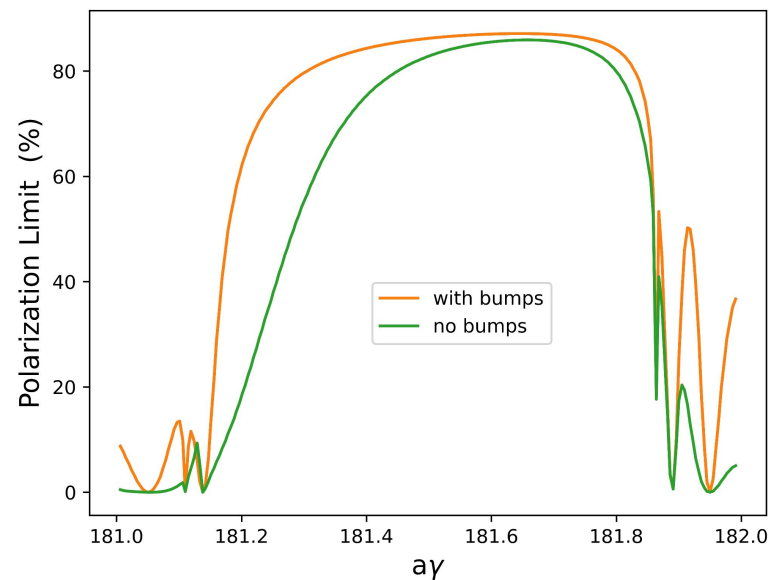
45.82 GeV ($a\gamma=103.983$)

$(\delta n_0)_{\text{rms}}$: 2.28 mrad \Rightarrow 0.90 mrad P: 10.68% \Rightarrow 89.65%



80.192 GeV ($a\gamma=181.986$)

$(\delta n_0)_{\text{rms}}$: 5.87 mrad \Rightarrow 2.88 mrad P: 4.69% \Rightarrow 34.65%



Further refinement is needed to adapt this method to realistic machine conditions

■ [*] R. Rossmanith and R. Schmidt, "Compensation of depolarizing effects in electron-positron storage rings". Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 236.2 (1985): 231-248.

Spin Tune Shift under Imperfections

Average energy estimation

In real machine measurement

spin tune ν' measured by RDP = amplitude dependent spin tune (ADST) + δ_1

$$\begin{aligned}
 &= \text{closed orbit spin tune } \nu_0 + \delta_2 \\
 &= a\langle\gamma\rangle + \delta_3
 \end{aligned}$$

$$\nu' = a\langle\gamma\rangle + \Delta\nu$$

incorporates the contribution from systematic error

Average energy estimation

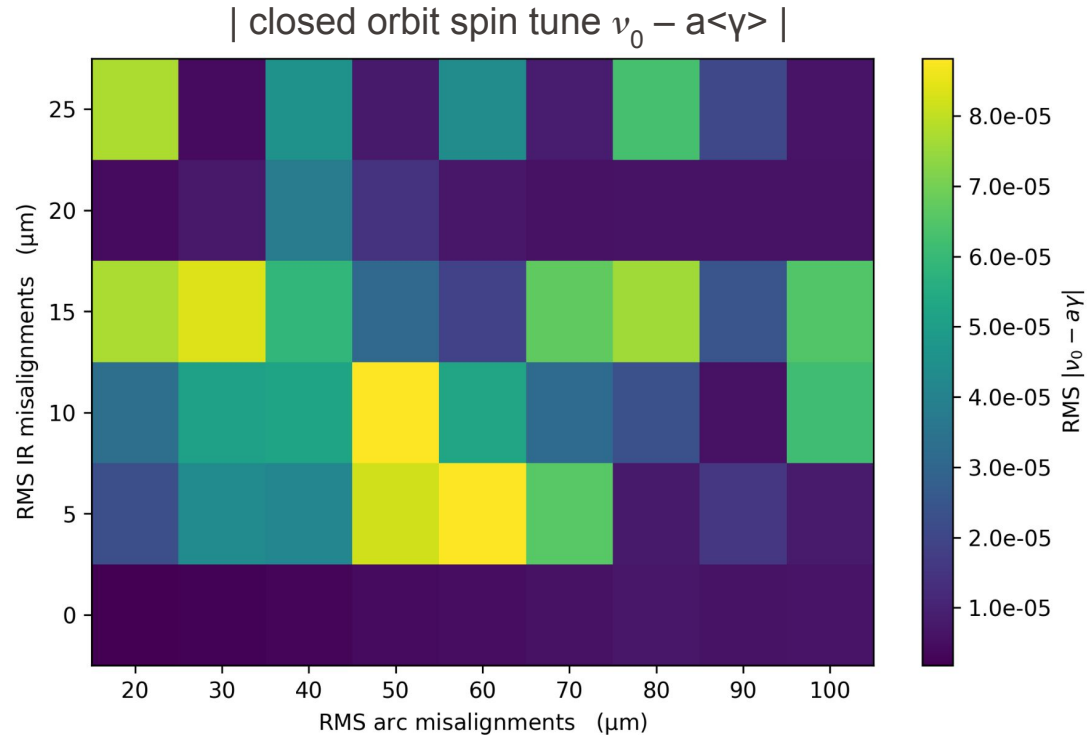
Only in perfectly aligned flat lattice

$$\nu_0 = a \langle \gamma \rangle = \frac{a}{m} E_{\text{ave}} \approx \frac{a}{m} \frac{\int E(\theta) d\theta}{2\pi}$$

assume that $d\theta$ only happens in bending dipoles

tests in clean lattice at different reference energies
 \Rightarrow less than 0.3 keV difference

Spin tune shift colormap



$\nu = aE/m \Rightarrow 2.27e-4$ tune shift gives 100keV error

adding additional complex factors could easily push it beyond the precision target

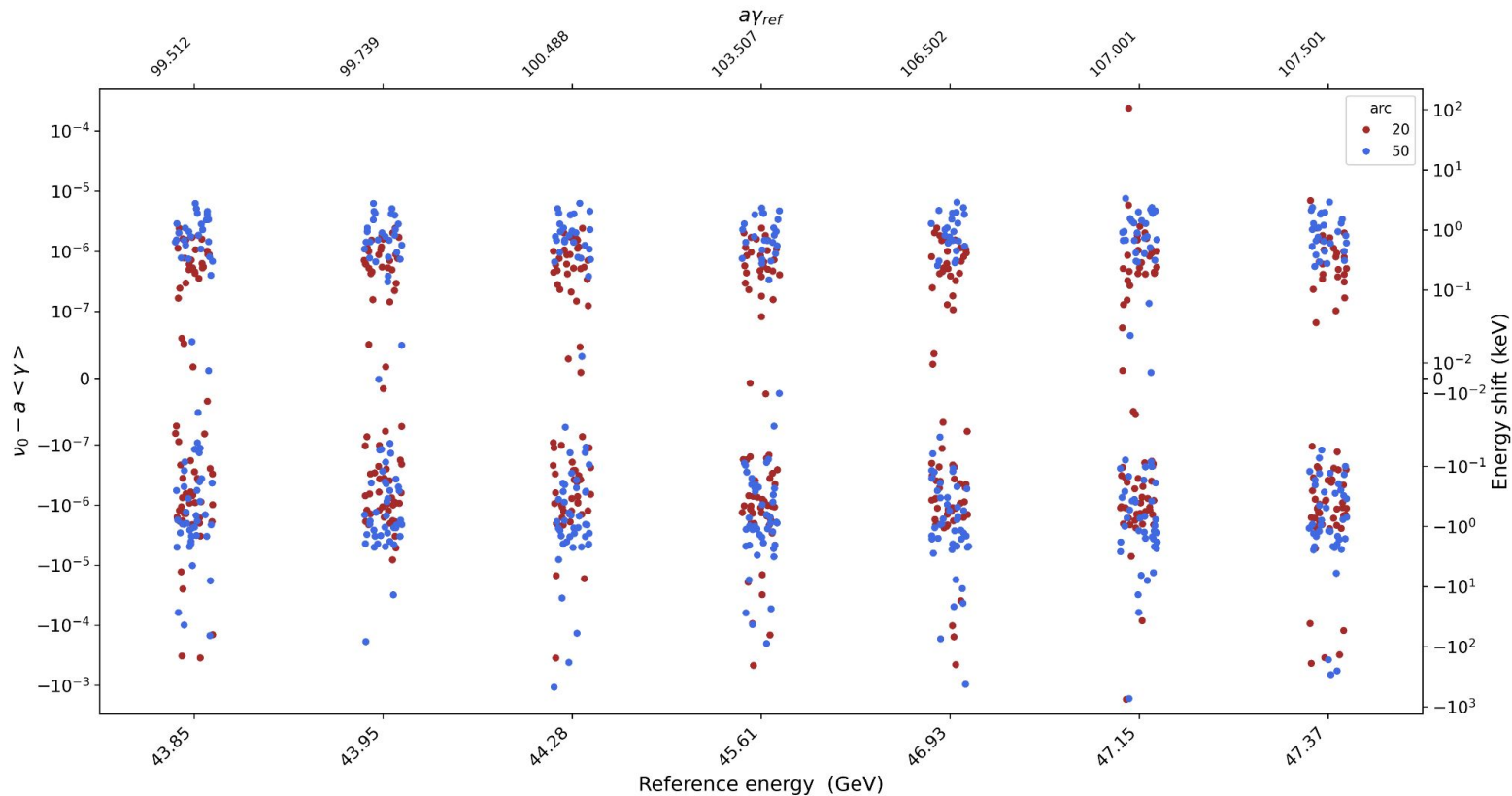
Off Z pole

Scan point	\sqrt{s} (GeV)	E_b (GeV)	Spin tune
$\sqrt{s_-}$ A	87.69	43.85	99.5
$\sqrt{s_-}$ Request	87.9	43.95	99.7
$\sqrt{s_-}$ B	88.57	44.28	100.5
$\sqrt{s_0}$	91.21	45.61	103.5
$\sqrt{s_+}$ A	93.86	46.93	106.5
$\sqrt{s_+}$ Request	94.3	47.15	107.0
$\sqrt{s_+}$ B	94.74	47.37	107.5

Centre-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

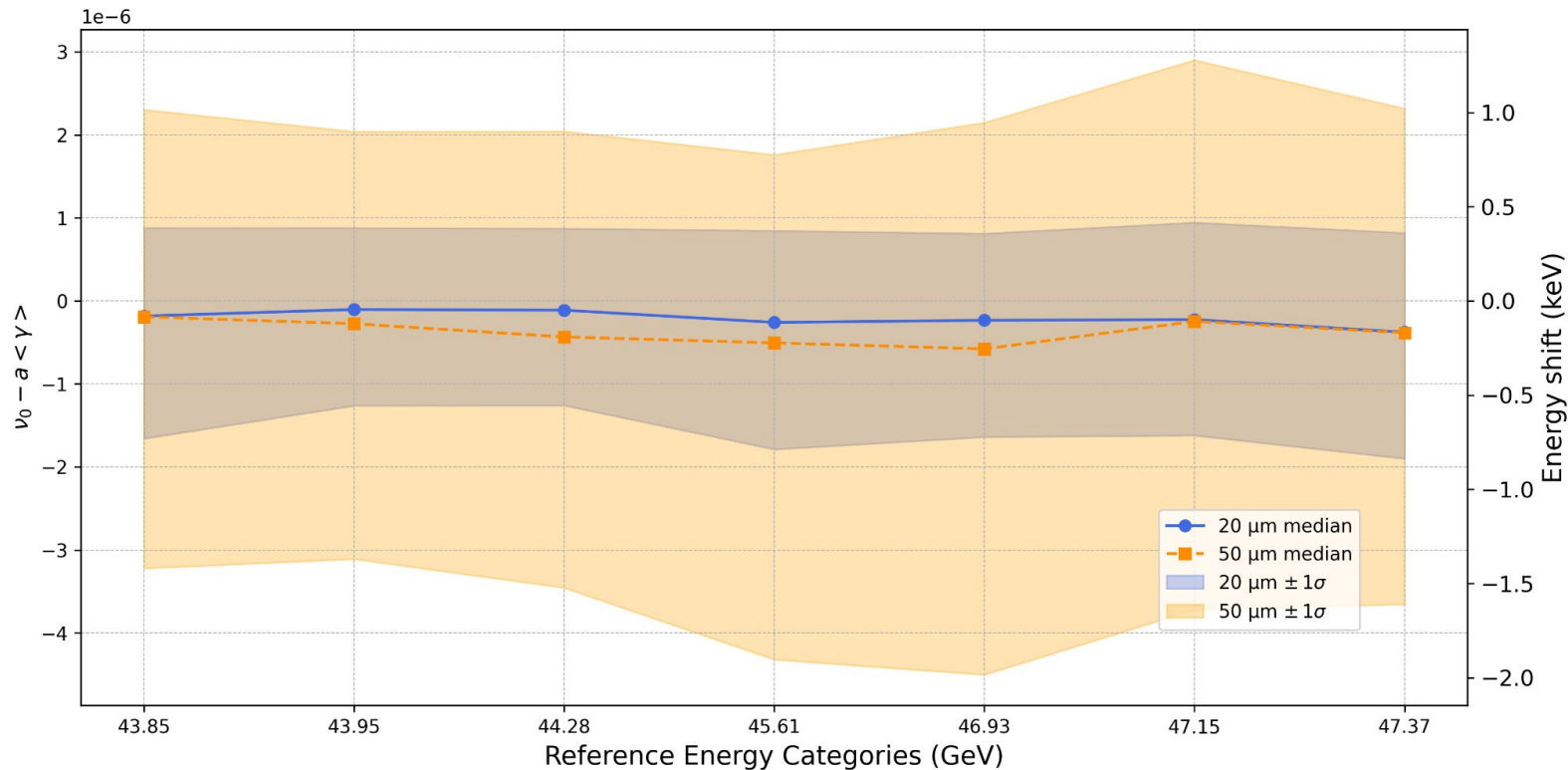
Off Z pole spin tune shift

20/50 μm in arc, 10 μm in IR, the same 100 initial seeds



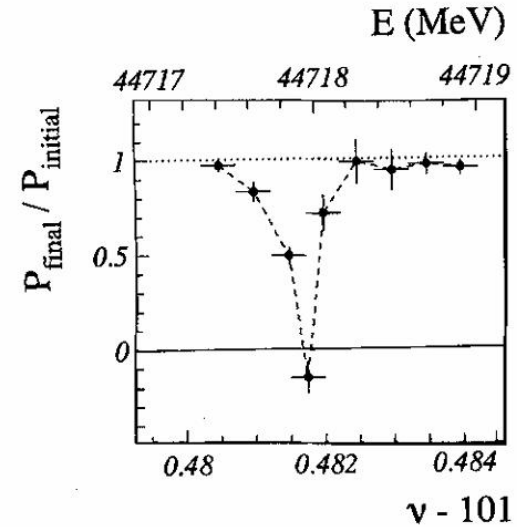
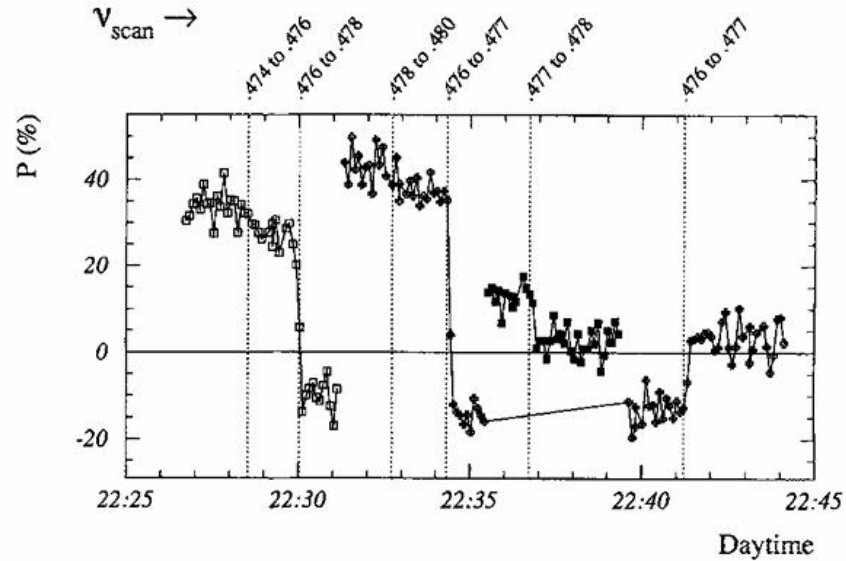
Off Z pole spin tune shift

20/50 μm in arc, 10 μm in IR, the same 100 initial seeds

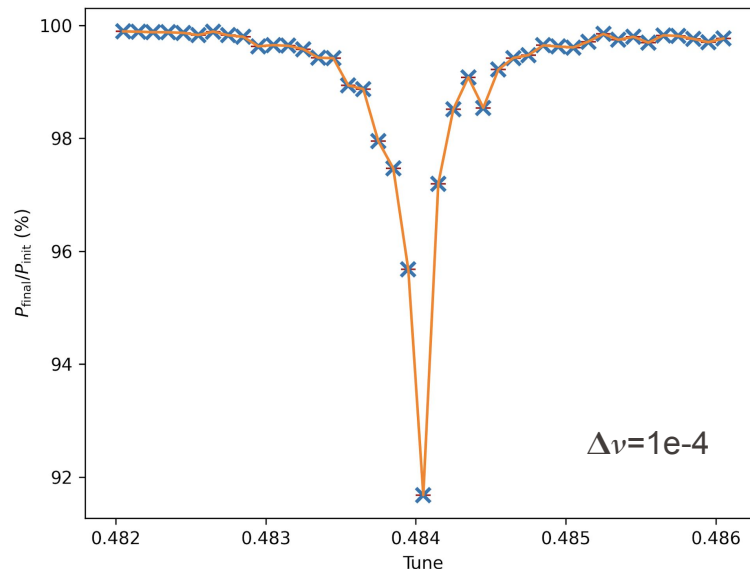
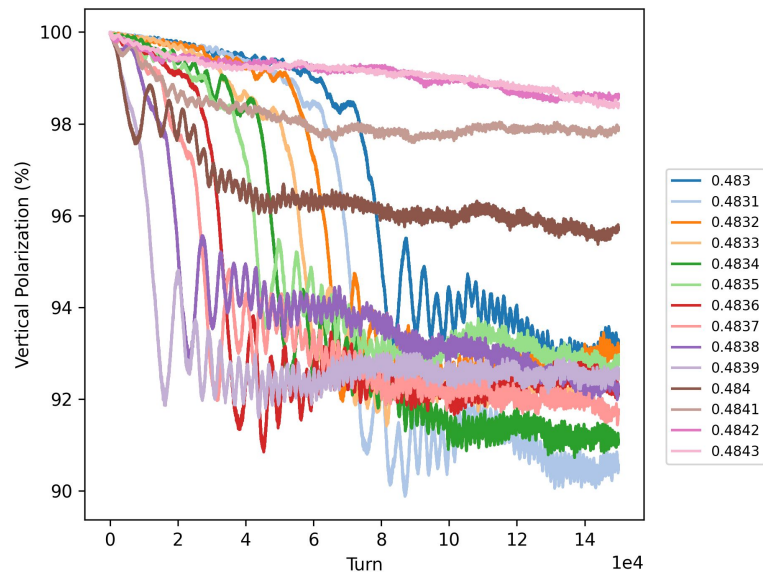


Resonant Depolarization Study

Resonant depolarization in LEP



Resonant depolarization in FCC-ee

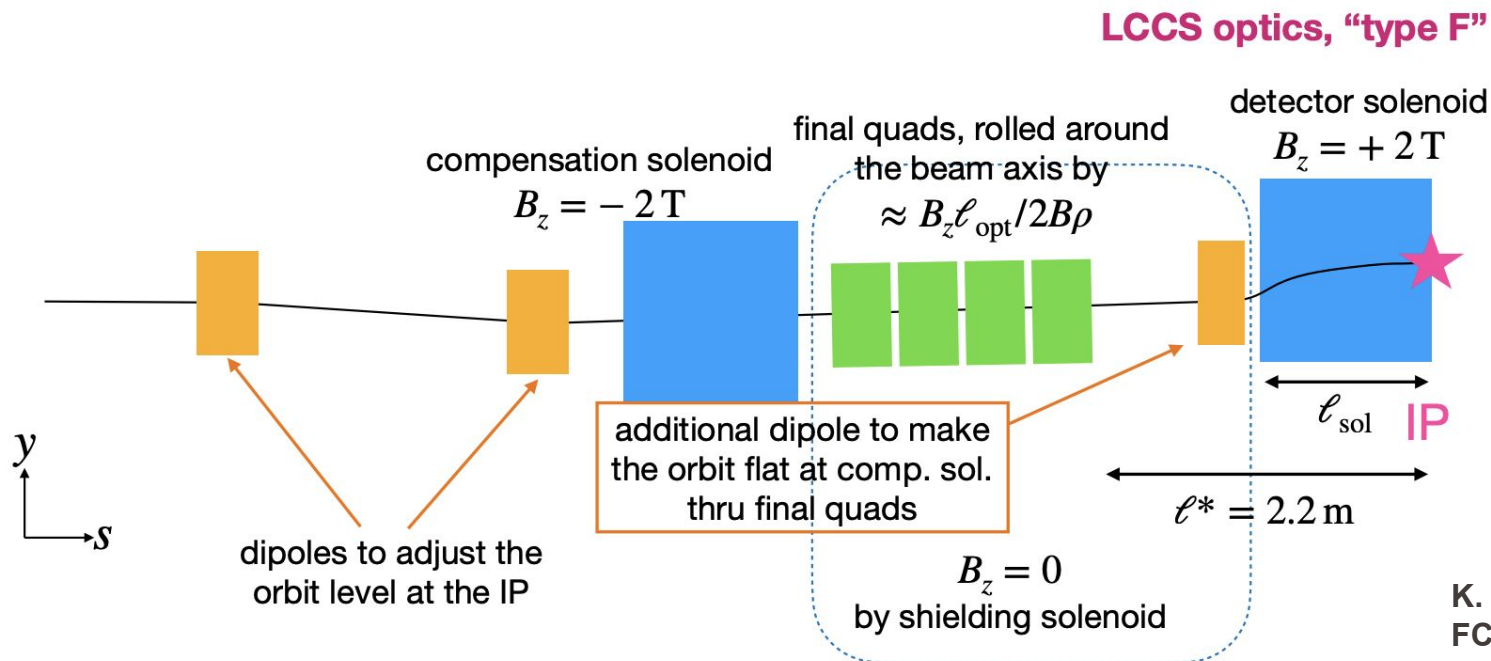


- Preliminary simulations of RDP using Bmad
 - determine key experimental details (ac kicker strength, ramp-up rate, imperfections etc)
 - estimate the precision of energy measurement
- Reproduce the LEP RDP through simulation
- Benchmark Bmad and Xsuite* in RDP simulation

■ [*] G. Iadarola, "Spin and polarization in Xsuite", https://indico.cern.ch/event/1546092/contributions/6508546/attachments/3069530/5430065/003_xsuite_spin.pdf

Non-local Solenoid Compensation Scheme

Non-local Solenoid Compensation Scheme



K. Oide
FCC Week 2025
20 May 2025

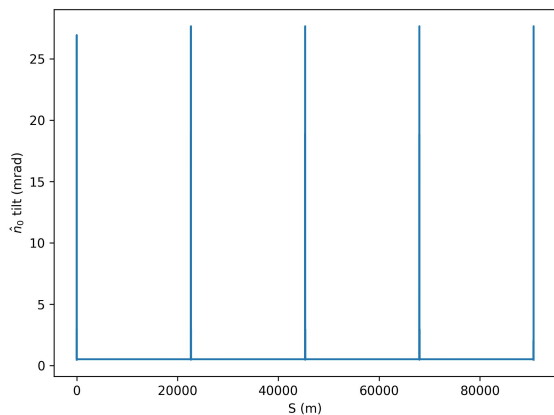
SAD to Bmad translation

- SAD-like solenoid not trivially available in MAD-X
 - alternative “fieldmap” approach provided by Helmut Burkhardt
 - translation to Bmad complicated and no longitudinal field
- Parallel approach of direct SAD to Bmad translation
 - resolved technical challenges in SAD to Bmad solenoid translation
 - the updated code will be reported to the Bmad team and included in upcoming releases
 - achieved consistent orbit and optics outputs from both codes
$$(\Delta x)_{\text{rms}} = 5.9\text{e-}8\text{m} \quad (\Delta y)_{\text{rms}} = 4.6\text{e-}8\text{m} \quad (\Delta z)_{\text{rms}} = 3.6\text{e-}8\text{m} \quad (\Delta\beta_x/\beta_{x0})_{\text{rms}} = 0.188\% \quad (\Delta\beta_y/\beta_{y0})_{\text{rms}} = 0.130\%$$
- Completed linear and nonlinear spin simulations with the translated lattice

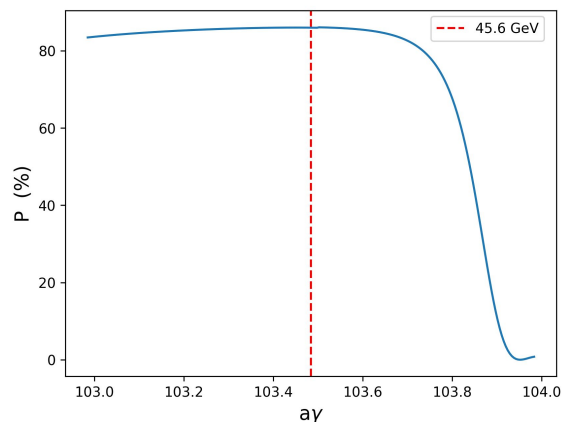
Non-local Solenoid Compensation Scheme

- Maximum n_0 tilt by solenoid is 27.67 mrad, effectively reduced to 0.5 mrad by anti-solenoid
- First-order polarization remains high near the nominal energy
- Nonlinear spin tracking (1k particles, 50k turns) indicates an equilibrium polarization of 86%

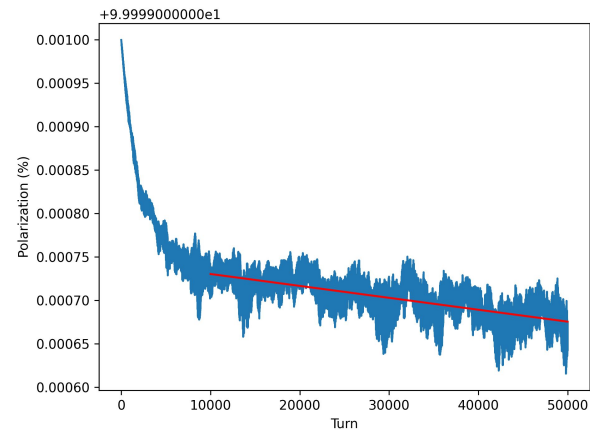
No significant signs of reduced polarization in this scheme from Bmad
Investigate the reasons for the different polarization predictions from the two codes



n_0 tilt from vertical



first order P near nominal energy



non linear spin tracking at 45.6 GeV

Conclusion

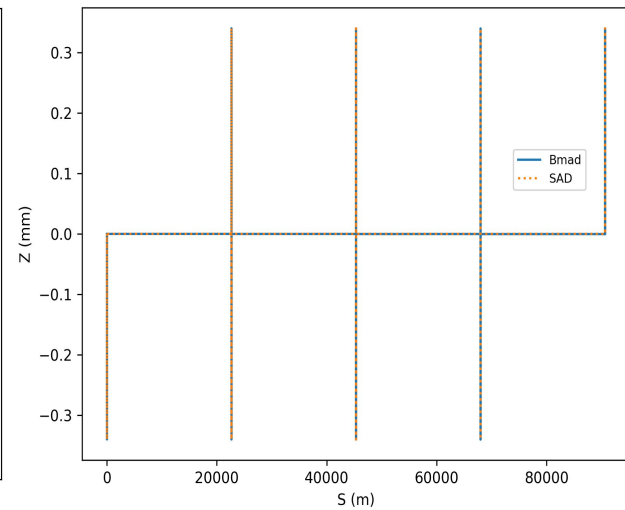
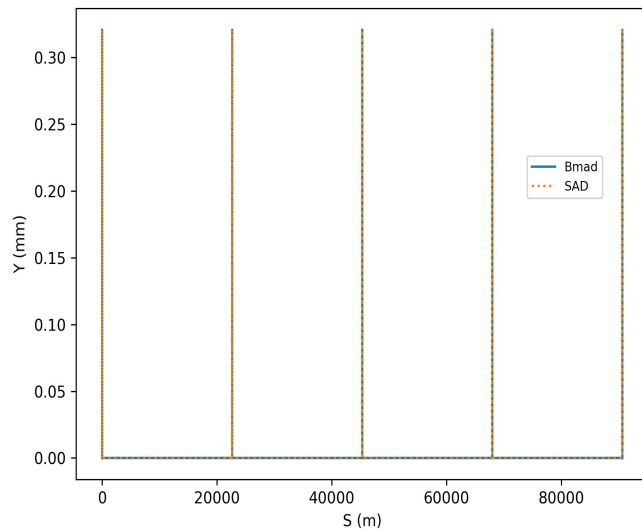
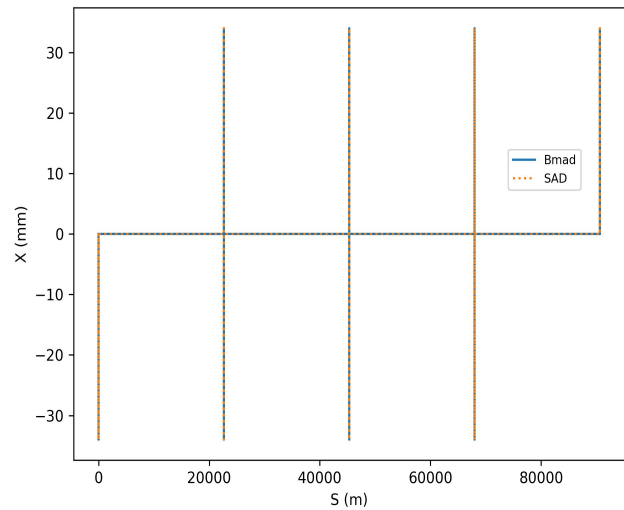
- A polarization above 20% is consistently achieved under all conditions tested, including arc misalignments up to 100 μm and IR misalignments up to 25 μm
- Majority of closed orbit spin tune shifts caused by imperfections remain within the systematic error limit
- Harmonic spin matching improves polarization level in the presence of big n_0 tilt
- Preliminary studies of resonant depolarization in FCC-ee are currently underway
- Preliminary polarization studies of the non-local solenoid compensation scheme indicate high polarization levels near the nominal energy

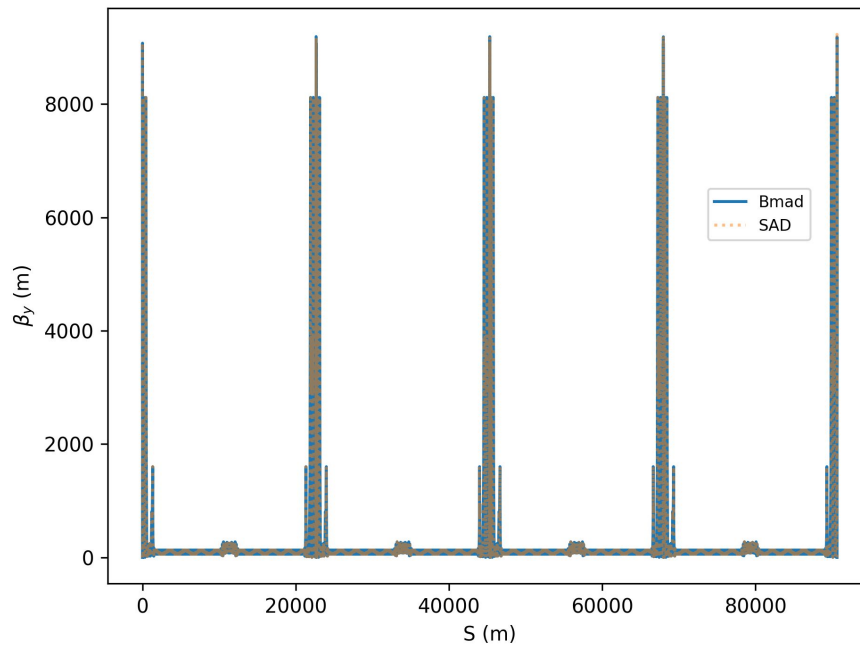
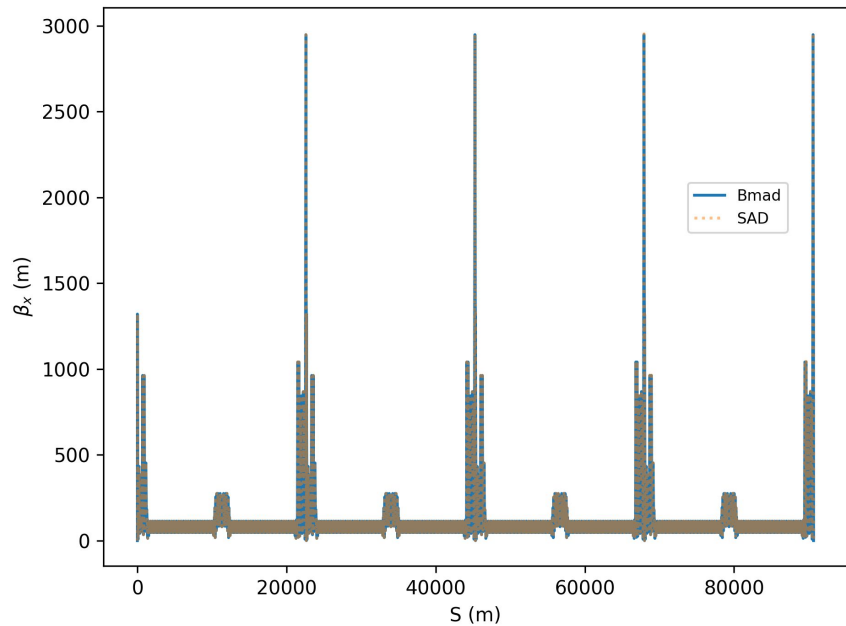
Outlook

- Include more error types in lattice correction procedure, along with optics matching, dispersion correction, chromaticity correction etc.
- Further refine the application of HSM scheme in realistic machine settings
- Improve the spin tune shift estimation
- Key experimental parameters in RDP will be determined through simulation studies
- Benchmarking studies between Bmad and Xsuite in spin tracking will be shortly be conducted
- Investigate the reasons for the different polarization predictions from the SAD and Bmad

▪

Thank you!





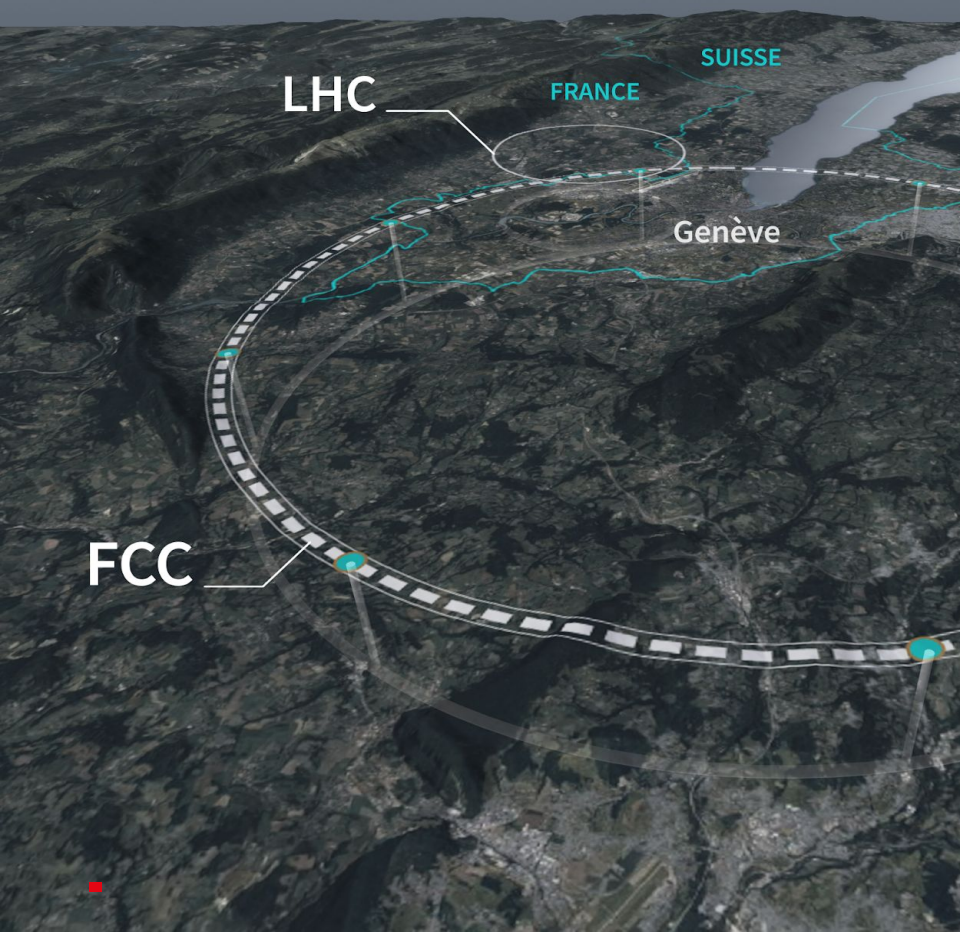


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