Swiss Accelerator
Research and
Technology

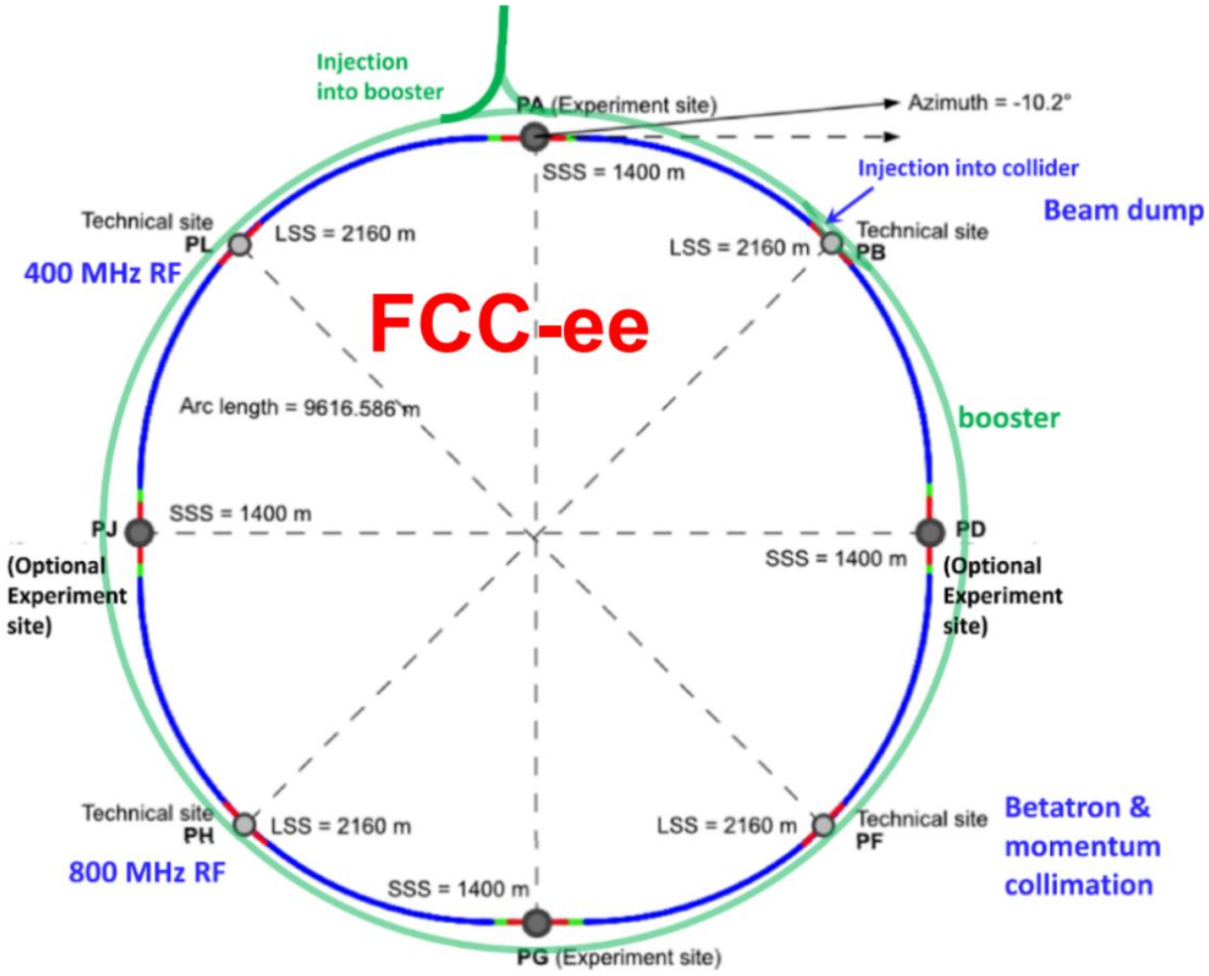
Polarization Studies

Y. Wu, J. Keintzel, T. Pieloni, F. Carlier, M. Seidel, A. Blondel, D. Barber, E. Gianfelice, D. Sagan, R. Tomas, F. Zimmermann and the EPOL WG

CHART Meeting 11th October 2023, PSI

FCC-ee

- first stage of the FCC
- an electron-positron collider
- around 100 km circumference
- 4 Interaction Points (IPs)
- 4 operation center-of-mass energies:
  Z^0 bosons (91 GeV), WW pairs (160 GeV), Higgs bosons (240 GeV) and top quark pairs (350-365 GeV)
- a Higgs and electroweak factory



Why we need high-precision centre-of-mass energy calibration?

- the basis for precise measurements of the standard model particle properties
- make it possible for the new rare process detection
- opportunities to observe possible violations of established symmetries
- precise measurements in FCC-ee will contribute to the measurements in the following hadron collider FCC-hh

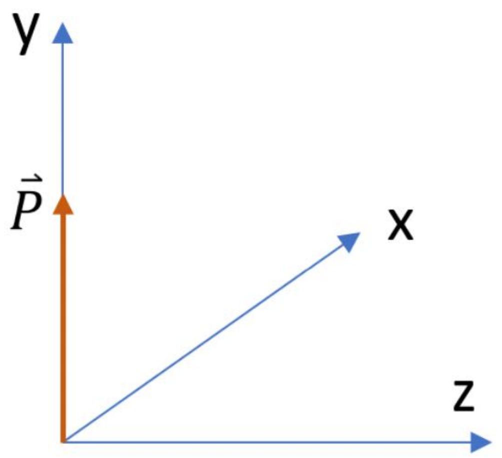
The current precision targets for the energy calibration:
4 keV at Z mass (10^{-8}) and 100 keV at W mass (10^{-6})

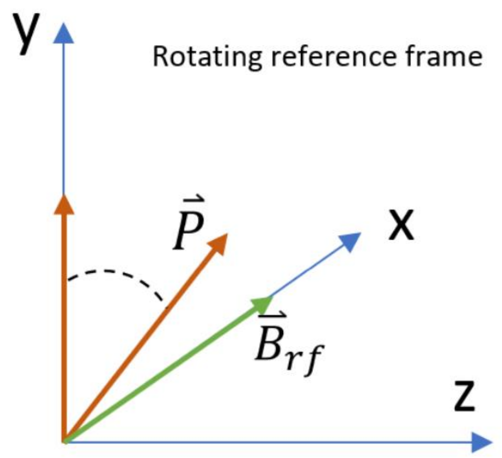
($>$ 500 and 300 times more precise than in Large Electron-Positron Collider (LEP))

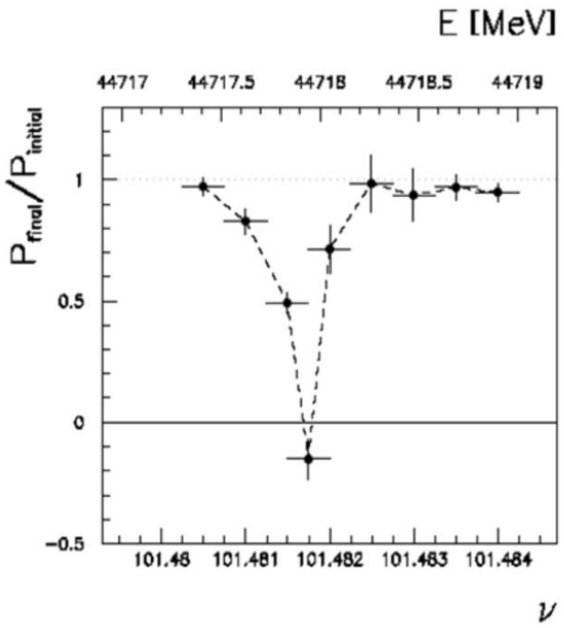
Resonant depolarisation is the only way to achieve this target!

Ensure a sufficient spin polarization level (at least $5-10\%$)

Resonant Depolarization







Operation scheme:

- Use wigglers to enhance radiation at the beginning of fills to shorten polarization build-up time
- Use non-colliding bunches for energy calibration

1. Build-up experties in polarization
2. Define models and tools
3. Study the FCC-ee case and input to the CDR++

Contents

- Introduction

- Equilibrium polarization in realistic machine
  - Simplified error scheme for collider
  - Realistic errors and orbit correction scheme

- Harmonic Spin Matching techniques: 3 methods compared

- Conclusions

Contents

- Introduction
- Equilibrium polarization in realistic machine
  - Simplified error scheme for collider
  - Realistic errors and orbit correction scheme
- Harmonic Spin Matching techniques: 3 methods compared
- Conclusions

Polarization Beams basics

- Sokolov-Ternov (ST) effect
  - spin-flip during synchrotron radiation emission
  - e-/e+ beams are gradually polarized in the rings
  - $P_{ST} \approx 92.4\%$ in a uniform field, less than P_{ST} in non-uniform fields
- Radiative depolarization
  - spin diffusion: a large number of stochastic photon emissions result in a random walk of $|\hat{S} \cdot \hat{n}|$.
  - total polarization level of a beam is decreased

ST effect + radiative depolarization ⇒ equilibrium polarization

	τ_{ST}	τ_{BKS}	τ_{dep}	
FCC-ee $(\Delta y)_{\rm rms} = 72\,\mu{\rm m}$	11 779 min	11 773 min	4.26×10^6 min	90 min for 10% with wigglers (CDR)
HERA (26.7 GeV)	~ 43 min	~ 40 min	~ 10 min	$\tau_{dk} \sim 8$ min
LEP	~ 310 min 46 GeV	—	~ 24 min 46.5 GeV	30 min for 10% no wigglers

Numerical Tools: BMAD

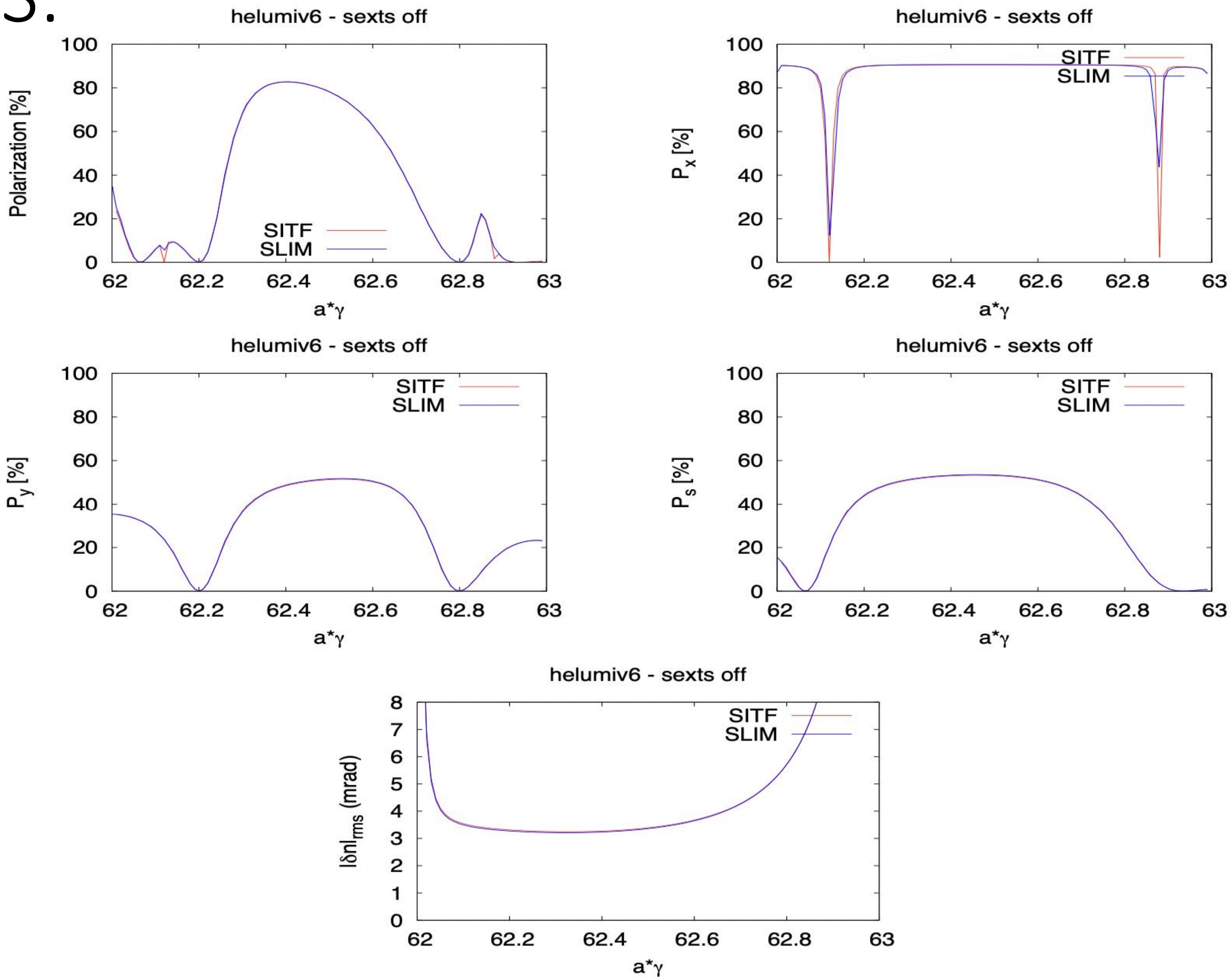
- An open-source subroutine library for charged-particle simulations in accelerators
- Has been developed at Cornell University and has been in use since the mid 1990s
- What Bmad can do?
  - model processes like radiation excitation, radiation damping, Touschek scattering, etc.
  - **first order spin-orbit simulations and nonlinear spin tracking simulations**
  - **various tracking algorithms**
  - **maximized flexibility**
  - **an active group of users and developers**
  - ......

Benchmark to SITROS:

Extensive tests were performed on FCC-ee simplified lattice between:

- **SITROS (E. Gianfelice**) model developed and benchmarked to HERA collider. Reference from CDR.
- **BMAD** by D. Sagan Cornell University **(Y. Wu**)

Initial results were very different but after breaking down the effects both models show an excellent agreement



Contents

- Introduction

- Equilibrium polarization in realistic machine
  - Simplified error scheme for collider
  - Realistic errors and orbit correction scheme

- Harmonic Spin Matching techniques: 3 methods compared

- Conclusions

First simplified machine orbit errors model

- Use an effective model to simulate **residual orbits after lattice correction**
- Random small errors generated from truncated Gaussian distributions (truncated at 2.5 σ)

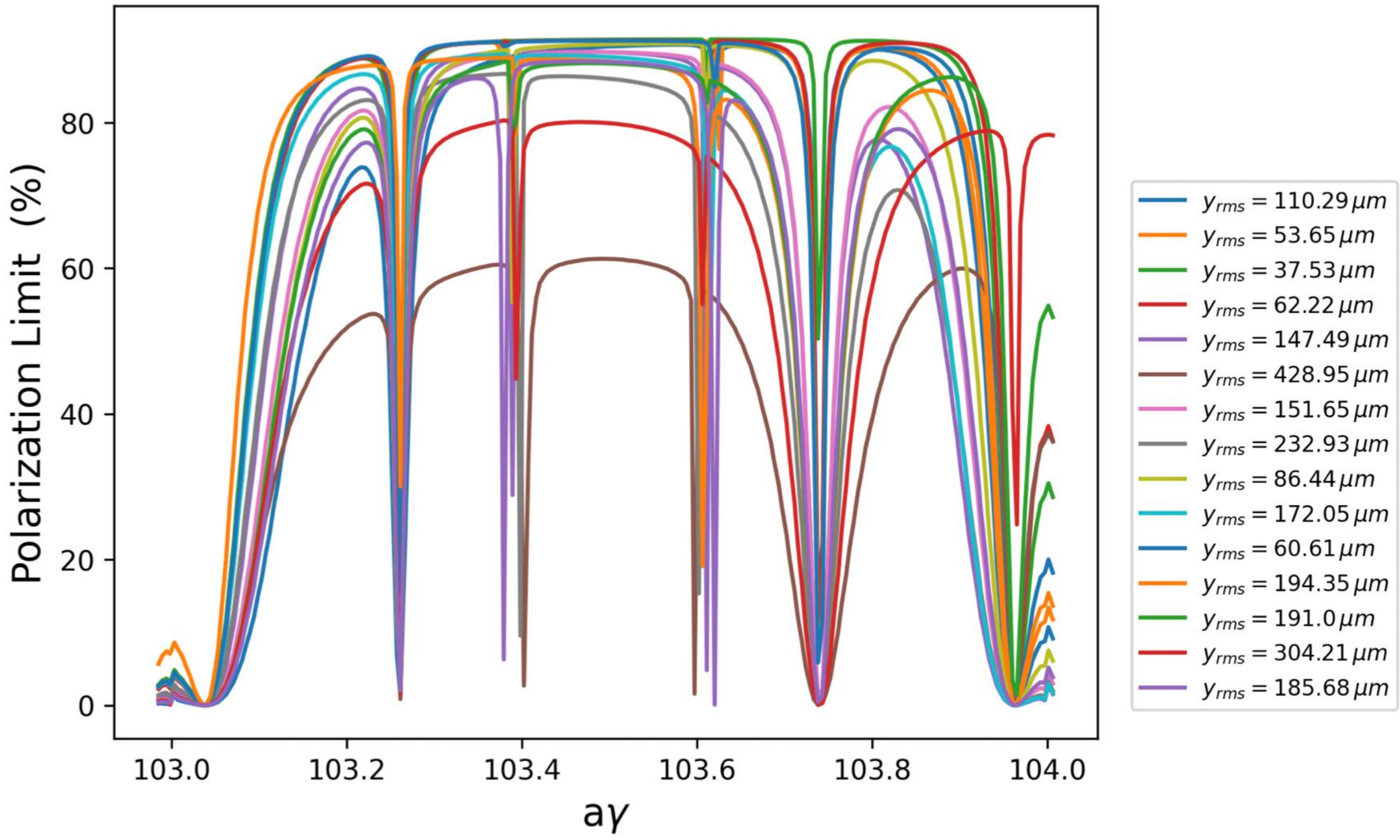
Type	$\sigma_{\Delta X}$ (nm)	$\sigma_{\Delta Y}$ (nm)	$\sigma_{\Delta Z}$ (nm)	$\sigma_{\Delta PSI}$ (μrad)	$\sigma_{\Delta THETA}$ (μrad)	$\sigma_{\Delta PHI}$ (μrad)
Arc quadrupole	120	120	120	2	2	2
Arc sextupole	120	120	120	2	2	2
Dipoles	120	120	120	2	0	0
IR quadrupole	120	120	120	2	2	2
IR sextupole	120	120	120	2	2	2

Polarization is deprecated in the presence of errors.

Setting 2

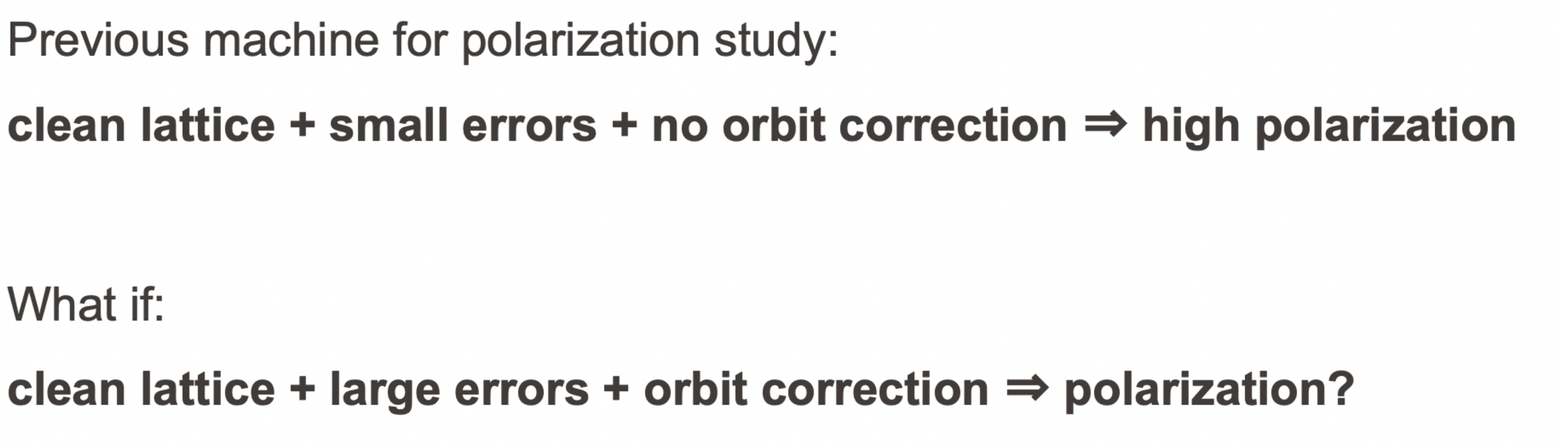
$\sigma = 200\,\mathrm{nm}$ for x,y,z misalignments

$\sigma = 2\,\mu\mathrm{rad}$ for angular deviations



Worse Orbit excursions give larger effects → orbit correction is the key

Two ways to test polarizations:



Previous machine for polarization study:

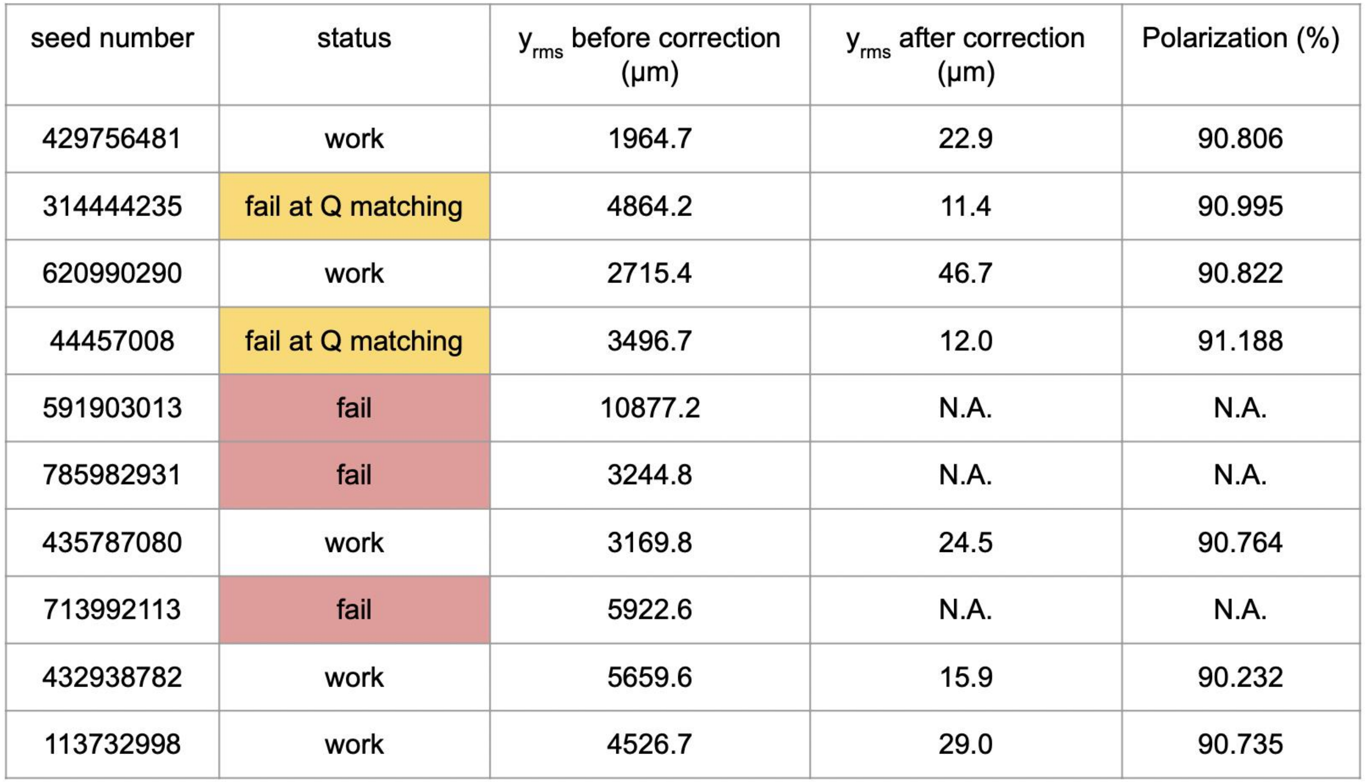
clean lattice + small errors + no orbit correction ⇒ high polarization

What if:

clean lattice + large errors + orbit correction ⇒ polarization?

Realistic Machine

$\sigma_{dx/dy/ds}$=50um for all non IR elements



seed number	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%)
429756481	work	1964.7	22.9	90.806
314444235	fail at Q matching	4864.2	11.4	90.995
620990290	work	2715.4	46.7	90.822
44457008	fail at Q matching	3496.7	12.0	91.188
591903013	fail	10877.2	N.A.	N.A.
785982931	fail	3244.8	N.A.	N.A.
435787080	work	3169.8	24.5	90.764
713992113	fail	5922.6	N.A.	N.A.
432938782	work	5659.6	15.9	90.232
113732998	work	4526.7	29.0	90.735

Which alignment tolerances can we accept from polarization point of view?

What counts is the closed orbit, if it exist and can be corrected → polarization is large

For polarization studies:

Methods 1: large $\sigma_{dx/dy/ds}$ + orbit correction

Methods 2: small $\sigma_{dx/dy/ds}$ + no orbit correction

same final y_{rms}

P=?

P=?

seed number	final y_{rms} (μm)	$\sigma_{dx/dy/ds}$ of M.1 (μm)	Polarization of M.1 (%)	$\sigma_{dx/dy/ds}$ of M.2 (μm)	Polarization of M.2 (%)
892727030	30.1	30	91.288	0.375	91.477
690427689	7.4	30	91.251	0.131	91.541
688758431	7.7	30	91.438	0.078	91.539

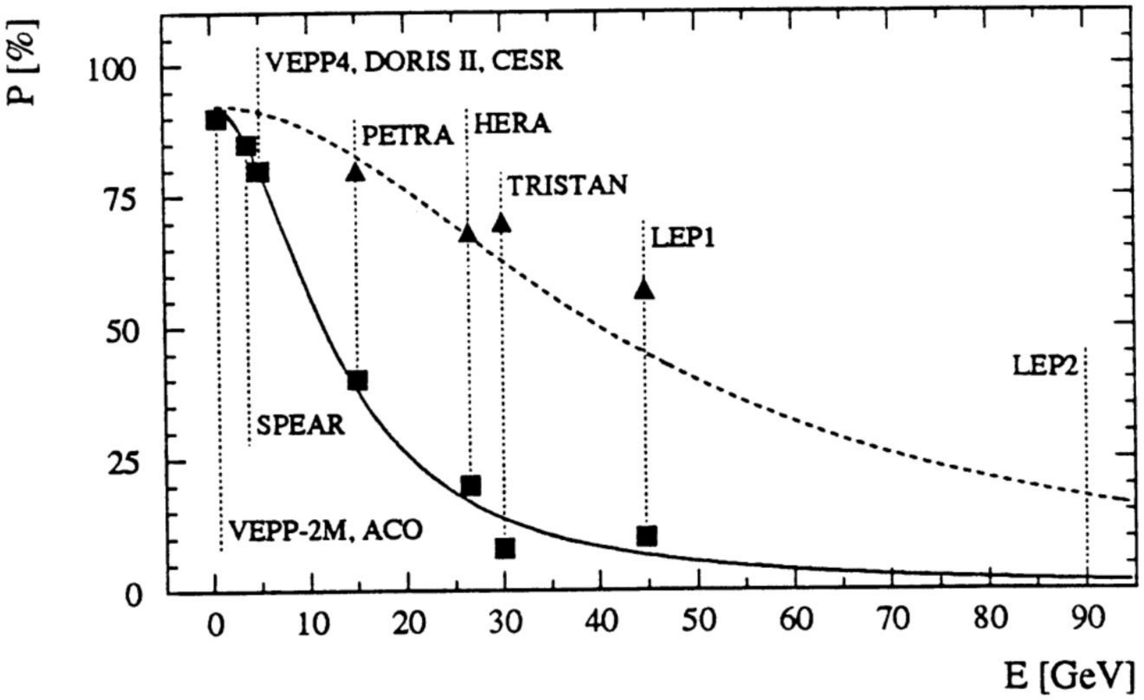
1. Polarization remains high once the closed orbit is found and properly corrected
2. So far, using small $\sigma_{dx/dy/ds}$ + no orbit correction for convenience in polarization studies, to some extent, remains reasonable

Both approaches lead to similar results: 50 μm give high polarization
Now exploring larger misalignment tolerances ensuring 90% of seed

Contents

- Introduction
- Equilibrium polarization in realistic machine
  - Simplified error scheme for collider
  - Realistic errors and orbit correction scheme
- Harmonic Spin Matching techniques: 3 methods compared
- Conclusions

Harmonic Spin Matching to increase polarization levels



Maximum measured polarization in different storage rings with HSM (triangles) and without HSM (squares)

R. W. Assmann, et al. Polarization Studies at LEP in 1993. No. CERN-ALEPH-PUB-94-135. CM-P00061204, 1994.

HSM methods:

1. HERA formalism (used in HERA)

   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. Rossmanith-Schmidt scheme (used in PETRA)

   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.

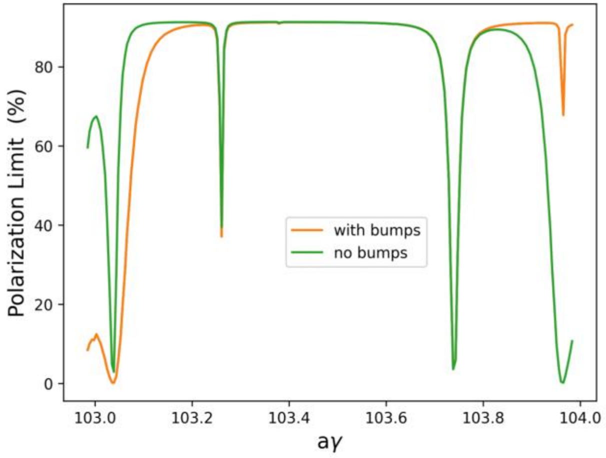
3. LEP method (Deterministic) (used in LEP)

   R. W. Assmann, Optimierung der transversalen Spin-Polarisation im LEP-Speicherring und Anwendung für Präzisionsmessungen am Z-Boson. Diss. Munich U., 1994.

HSM methods:

- Methods have been studied
- Tools in Place to simulate
- Preliminary results

Using 4 bumps which are optimized at 45.82 GeV ($a\gamma = 103.983$)



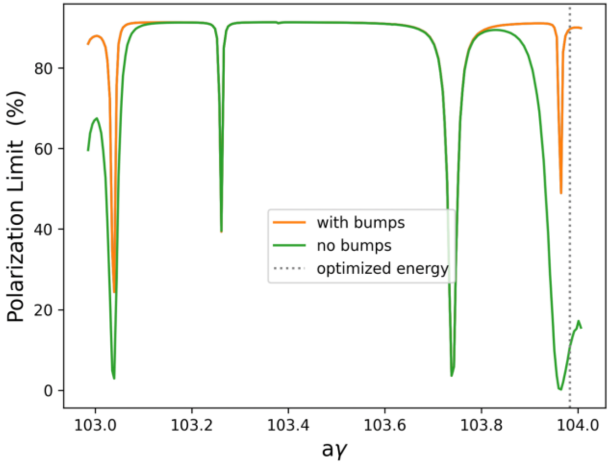
At 45.82 GeV ($a\gamma = 103.983$)

Method	$(\delta n_0)_{rms}$ (mrad)	Polarization (%)
no correction	2.28	10.68
HERA formalism	0.90	90.96
Rossmanith-Schmidt scheme	0.90	89.65
Modified R-S scheme	1.01	84.71
LEP method	2.03	13.72

Many questions remained regarding all three schemes

45.82 GeV ($a\gamma = 103.983$)

δn_0 : 2.28 mrad $\Rightarrow$ 0.90 mrad , P_{DK} : 10.68% $\Rightarrow$ 89.65%



Conclusions

- Numerical tools have been benchmarked and are in used for FCC-ee polarization studies (BMAD good support from D. Sagan from Cornell University Code owner)
- Benchmark with SITROS took sometime but is now in very good agreement (good collaboration with E. Gianfelice FNAL)
- Studies of misalignment errors on polarization level on-going for realistic FCC-ee lattice and orbit correction schemes
  - Polarization mainly depends on closed orbit level
  - Polarization level is sufficient for energy calibration (5-10%) when closed orbit exist
  - @ higher energies feasibility has to be still proved
- Harmonic Spin Matching methods investigated and showed great improvement in polarization (HERA, R-S), LEP method to be understood
- Resonance depolarization not yet simulated and studied
- Possible tests of models on operational machine (KARA @ KIT) under consideration

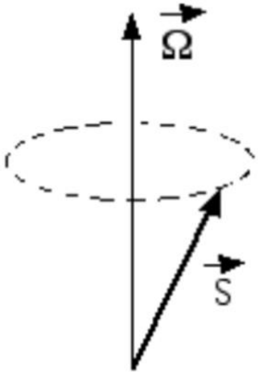
Publications and Presentations:

- Y. Wu, “Spin Polarization Simulations for the Future Circular Collider e+e- using BMAD” 2nd FCC Energy Calibration, Polarization and Mono-chromatisation (EPOL) workshop, CERN, 22 Sep 2022.
- Y. Wu, “First trials of harmonic spin matching in the FCC-ee” FCC-FS EPOL group and FCCIS WP2.5 meeting 16, CERN, 15 Dec 2022.
- J. Keintzel et al., “FCC-ee energy calibration and polarization”, in PoS, Vol. 414, ICHEP2022, p. 0048.
- J. Keintzel et al., “Centre-of-mass energy in FCC-ee”, in Proc. IPAC’22, Bangkok, Thailand, June 2022.
- Y. Wu, “Spin Polarization Simulations for the Future Circular Collider e+e- using BMAD” Workshop on Beam Polarization, Hiroshima University, 9 Feb 2023,
- Y. Wu, “Updates on the Exploration of Harmonic Spin Matching in the FCC-ee” FCC-FS EPOL group and FCCIS WP2.5 meeting 18 - Joint with FCC-ee tuning meeting, CERN, 16 Feb 2023.
- Y. Wu, “Updates on the Exploration of the Possible Spin Matching Methods used in the FCC-ee” FCC-FS EPOL group and FCCIS WP2.5 meeting 21, CERN, 13 Apr 2023,
- Y. Wu, “Comparison of Harmonic Spin Matching Schemes using Orbit Bumps in the FCC-ee” FCC Week 2023, London, 5–9 Jun 2023.
- Y. Wu, “Comparison of Harmonic Spin Matching Schemes using Orbit Bumps in the FCC-ee” Optics Tuning and Corrections for Future colliders workshop, CERN, 26–28 Jun 2023.
- Y. Wu et al., “Spin polarization simulations for the Future Circular Collider e+e- using Bmad”, in Proc. eeFACT'22, Frascati, Italy, September 2022, TUZAS0104, pp. 103-107, 2023.
- Y. Wu et al., “Spin-polarization simulations for the Future Circular Collider e+e- using Bmad”, in Proc. IPAC'23, Venice, Italy, May 2023, SUPM010, MOPL055, 2023
- J. Keintzel et al., “The status of the energy calibration, polarization and monochromatization of the FCC-ee”, in Proc. IPAC’23, Venice, Italy, May 2023.

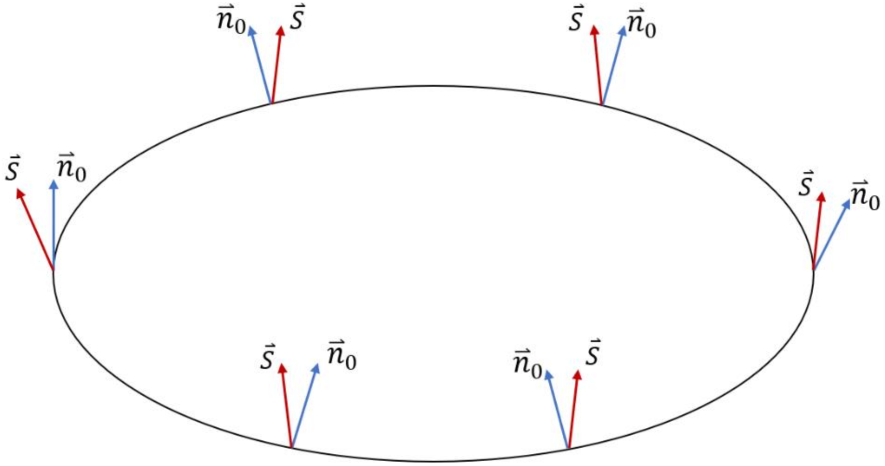
Polarization Beams basics

Thomas-BMT equation

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega}_{\mathrm{BMT}} \times \vec{S}$$



$\hat{n}_0(s)$: one-turn periodic solution of the T-BMT equation on the closed orbit
the precession axis for arbitrary spins on the closed orbit



- Spins on the closed orbit precess around $\hat{n}_0$ for ν_0 turns in every revolution
- ν_0: closed orbit spin tune
- $\nu_0 = a\gamma$ in the perfectly aligned flat ring without solenoids
- $\nu_0 \neq a\gamma$ in general