FUTURE
CIRCULAR
COLLIDER

FCC-ee Energy Calibration, Polarization and Monochromatization

D. Barber, M. Benedikt, A. Blondel, A. Bogomyagkov, F. Carlier, E. Gianfelice-Wendt, A. Faus-Golfe, M. Hofer, P. Janot, H. Jiang, J. Keintzel, I. Koop, M. Koratzinos, T. Lefevre, A. Martens, N. Muchnoi, S. Nikitin, I. Nikolaev, K. Oide, T. Persson, T. Pieloni, P. Raimondi, D. Sagan, D. Shatilov, R. Tomàs, J. Wenninger, G. Wilkinson, Y. Wu, and F. Zimmermann

FCC-IS Workshop 2022
WP2: Accelerator
8th December 2022

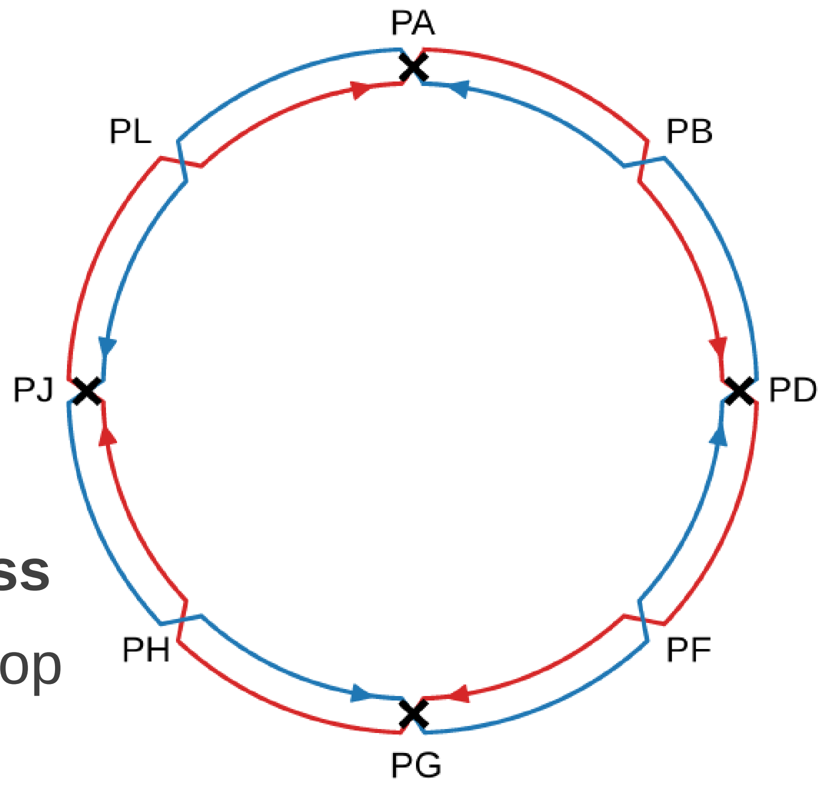
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union’s H2020 Framework Programme under grant agreement no. 951754.

Introduction

Polarization and Centre-of-mass Energy Calibration at FCC-ee, **arXiv:1909.12245**

* with monochromatization

- FCC-ee proposed Higgs and EW-factory
- Up to 4 Interaction Points (IPs): PA, PD, PG, PJ
- Different beam energies: 45.6, 80, 62.5*, 120, 182.5 GeV
- High precision particle physics experiments
  - Statistical precision 4 / 100 keV error on Z- / W-mass from average over 3 / 2 years of physics runs
  - **Goal: systematic precision of 4 / 100 keV on Z- / W-mass**
- Very first specifications and parameters discussed in workshop
- Summarized in document and first conclusions mid by 2023



Energy calibration and polarization working group
indico.cern.ch/category/8678

Workshop September 2022
indico.cern.ch/e/EPOL2022

Future Circular Collider Technical and Financial Feasibility Study
2d FCC Energy Calibration, Polarization and Mono-chromatisation workshop

FCC EPOL WORKSHOP

19-30 September 2022 at CERN

remote participation possible

https://indico.cern.ch/e/EPOL2022

Structure of the EPOL Team

A- Simulations of polarization and spin-tune to beam energy relationship

- -- simulations of spin polarization in realistic machine (also able to calculate emittances, luminosity)
- -- res. depolarization at Z and WW threshold
- -- design and integration of wigglers, RF kickers, in FCC-ee

B. Simulation of the relationship between beam energies and centre-of-mass energy

- -- studies of operation scenarios
- -- control of offsets and vertical dispersion
- -- Impact and control of energy losses: Synchrotron rad., Beamstrahlung, impedance, etc.

C. Polarimeter design and performance

- -- now working to build a global collaboration
- -- Aim to provide integration of polarimeters,
- -- conceptual design and cost estimate of polarimeter for FCC FS

D. Measurements in Particle Physics Experiments

- -- use of dimuons and other processes to determine centre-of-mass energy spread, boost, at and within IP

E. Monochromatization

- -- new ideas for monochromatization in other dimensions than horizontal (x) axis. (time, z)
  - -- what its the limit?

Detailed descriptions from October 2021 recalled, including additions and corrections resulting from work that has already been done

Full lists to be completed by participants during this workshop and aimed to be summarized in one document

Organization

- A dedicated workshop on "FCC-ee energy calibration, polarization and monochromatization (EPOL)" took place from September 19 to 30 2022 at CERN
- **At this occasion there was an EIC-FCC Collaboration Working Meeting on Polarization from September 19 to 23 2022.**

113 registered participants

127 contributions

Organization
A. Blondel
J. Keintzel
FCC secretariat :
D. Goldsworthy
J. Hadre

Program committee
WP1 Eliana Gianfelice, Ivan Koop, Tatiana Pieloni,
WP2 Jacqueline Keintzel, Katsunobu Oide, Jorg Wenninger
WP3 Aurélien Martens, Thibaut Lefèvre, Dave Gaskell
WP4 Patrick Janot, Guy Wilkinson
WP5 Angeles Faus-Golfe, Frank Zimmermann

General :
Alain Blondel, Elke Aschenauer, Tor Raubenheimer,
Vadim Ptitsyn, Todd Satogata, Frank Zimmermann

Indico Event:
https://indico.cern.ch/e/EPOL2022

Synergies with Other Machines

- LEP: polarimeter, operation, depolarization, wigglers
- LHC: operation, orbit measurements,

- **EIC:** polarimeter, spin simulations, depolarization, energy measurements, operations, …
- SuperKEKB: operations, option of polarized beams presently studied
- CEPC
- VEPP-4M: resonant depolarization
- ANKA-KARA: possible experiments

First joint FCC-EIC workshop

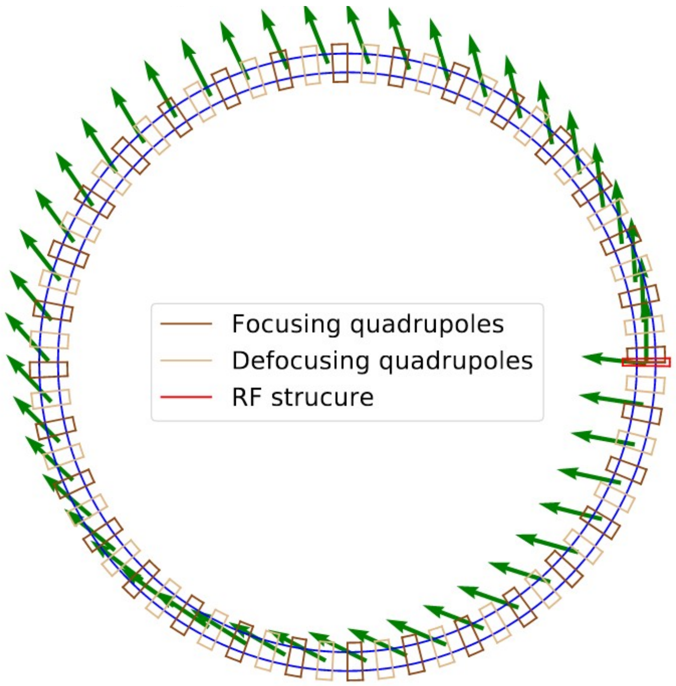
Second joint FCC-EIC workshop on MDI → Talk: M. Boscolo

Third joint FCC-EIC workshop on SRF in spring 2023

A. Bogomyagkov, V. Caudan, E. Gianfelice-Wendt

Beam Energy and Spin Tune

- Beam energy is closely related to the spin tune ν

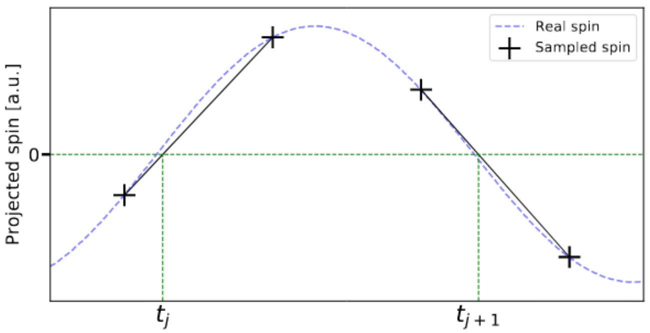


Precession of spin over one revolution in ideal machine with spin tune of about 0.25

Measurement of spin tune will yield the beam energy
→ To be performed for the electron and the positron beam

E … energy
m … mass
c … speed of light
ν … spin tune
a … anomalous magnetic dipole moment

$$E = mc^2\left(\frac{\nu}{a} - 1\right)$$



Spin tune measurement might not be exact beam energy measurement, e.g. **shift due to vertical or longitudinal magnetic fields → to be studied in detail**

Various contributions on the average beam energy estimated

synchrotron oscillations	ΔE/E	$-2\ 10^{-14}$
Energy dependent momentum compaction	ΔE/E	10^{-7}
Solenoid compensation		$2\ 10^{-11}$
Horizontal betatron oscillations	ΔE/E	$2.5\ 10^{-7}$
Horizontal correctors*)	ΔE/E	$2.5\ 10^{-7}$
Vertical betatron oscillations **)	ΔE/E	$2.5\ 10^{-7}$
Uncertainty in chromaticity correction	$O(10^{-6})$ ΔE/E	$5\ 10^{-8}$
invariant mass shift due to beam potential		$4\ 10^{-10}$

F. Carlier, E. Gianfelice-Wendt, T. Pieloni, Y. Wu

Polarization and Spin Tune

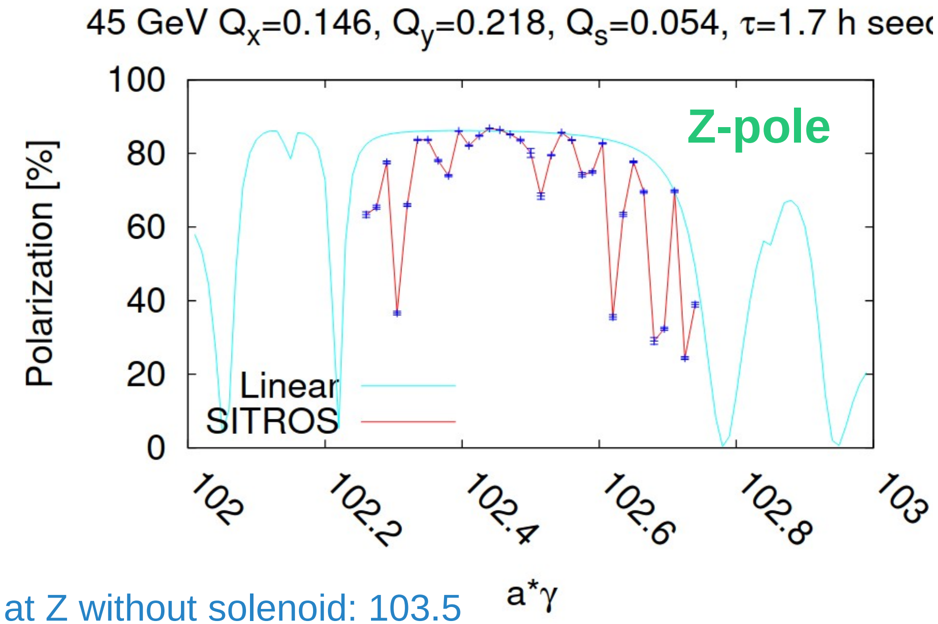
- Lepton beams polarize naturally transversely over time → Sokolov-Ternov-Effect
- Depolarization naturally from synchrotron radiation, resonances, etc.
- Maximum polarization at about 92.4 % in lepton storage rings
- Resonances with transverse and longitudinal axis

Q_x … horizontal tune
Q_y … vertical tune
Q_s … synchrotron tune
m_i, k … integer
a … gyromagnetic moment
γ … relativistic gamma

$$\underbrace{a\gamma}_{\text{Spin tune for ideal machine}} + \underbrace{m_x Q_x + m_y Q_y}_{\text{Transverse planes}} + \underbrace{m_s Q_s}_{\text{Longitudinal plane}} = k$$

Y. Wu: indico.cern.ch/event/1119730/

Strong unexpected resonance found for SITROS simulations



aγ at Z without solenoid: 103.5

E. Gianfelice-Wendt,
indico.cern.ch/event/727555/contributions/3468285, 2019.

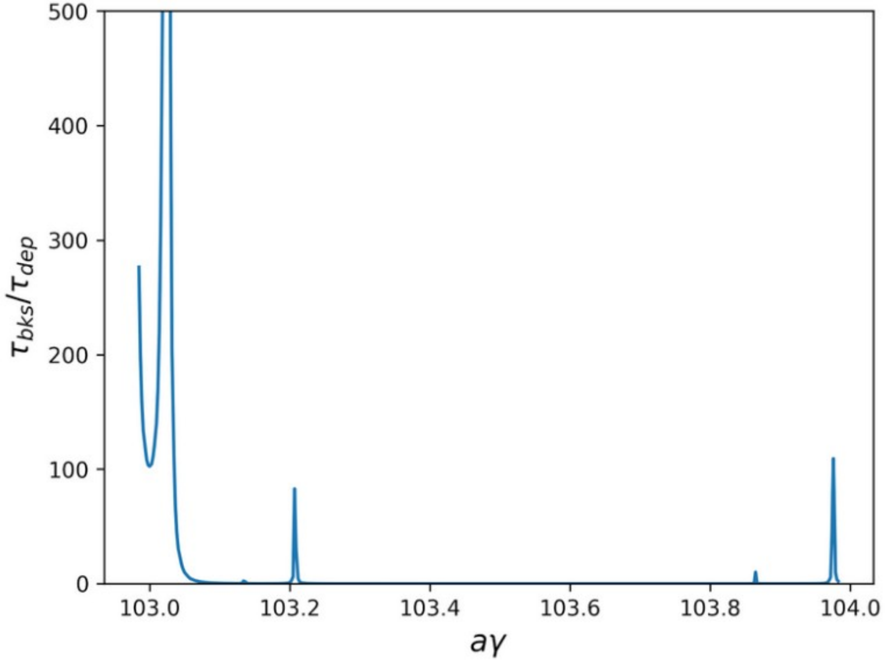
Open question:
Can we inject already polarized electron beams? At which cost?
Do we need special optics and/or tunes?
Do we need harmonic spin matching to increase polarization?

F. Carlier, T. Pieloni, Y. Wu

Error Sensitivity

- Depolarization strength at spin-orbit resonance is sensitive to the orbit
- After closed orbit correction, harmonic spin matching is needed to increase polarization
- Minimum 8 bumps arcs, each with 3 vertical correctors (strength and location under study)

$(\Delta y)_{rms} = 43.7$ µm

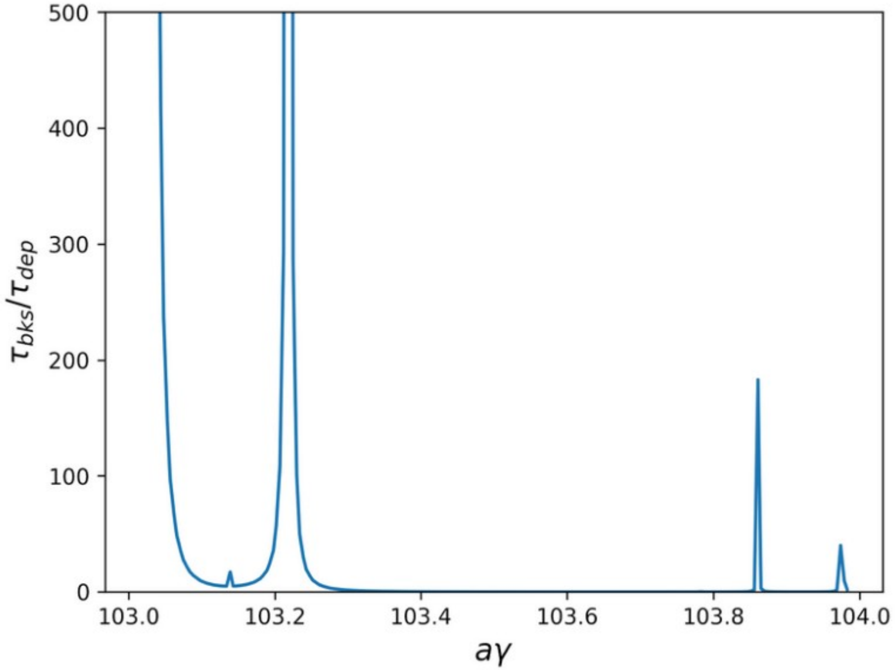


Misalignment errors in Dipoles, quadrupoles Sextupoles to generate effective lattice

$Q_x = .139$ $Q_y = .219$ $Q_s = 0.025$

Small emittances and large Q_s –> Resonances with the longitudinal plane dominating and symmetric ± Q_s

$(\Delta y)_{rms} = 148$ µm

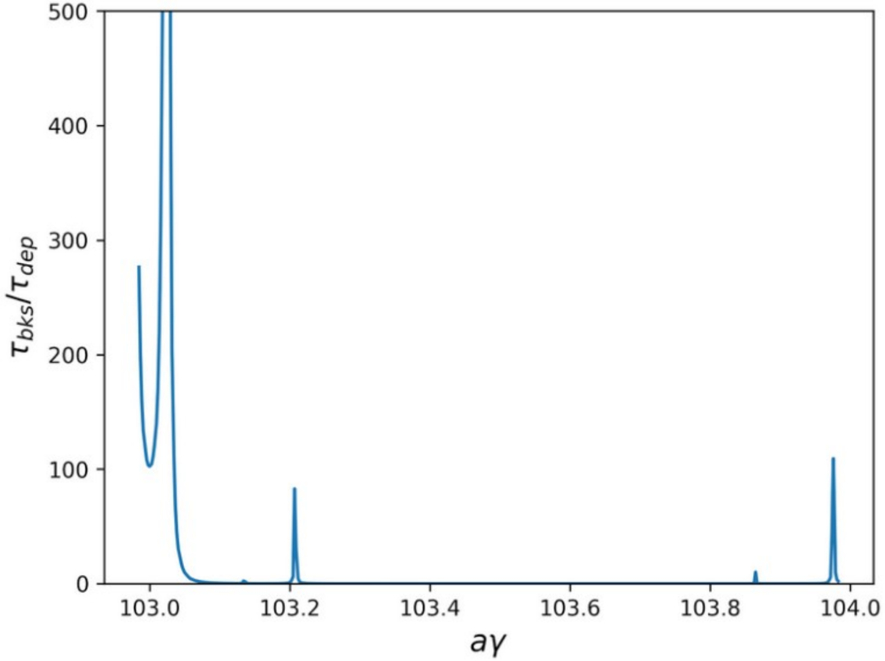


F. Carlier, T. Pieloni, Y. Wu

Error Sensitivity

- Depolarization strength at spin-orbit resonance is sensitive to the orbit
- After closed orbit correction, harmonic spin matching is needed to increase polarization
- Minimum 8 bumps arcs, each with 3 vertical correctors (strength and location under study)

$(\Delta y)_{rms} = 43.7\ \mu m$



Excellent optics tuning, measurement and correction techniques will ensure sufficient polarization

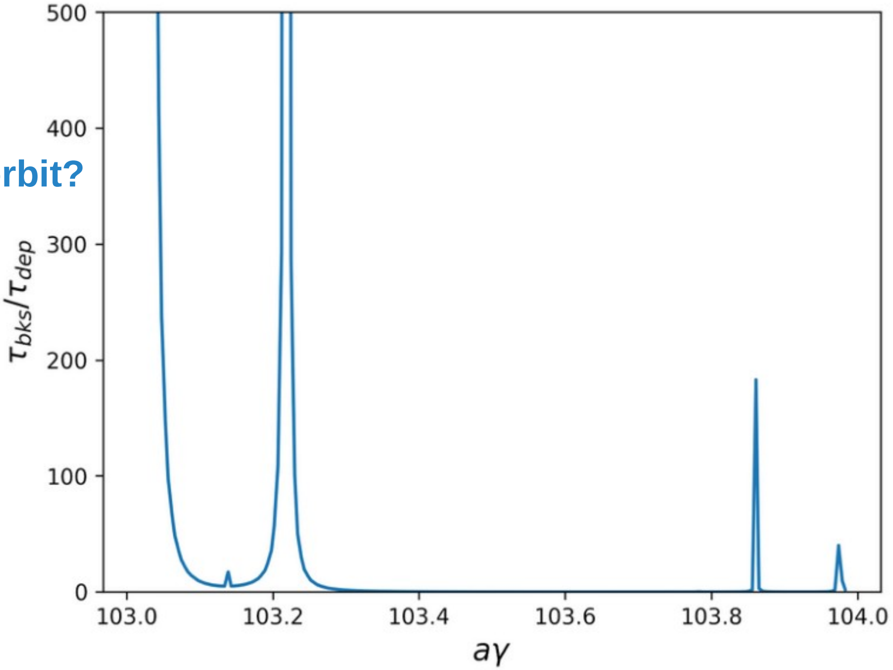
Open question:
How well do we need to correct orbit?

Misalignment errors in
Dipoles, quadrupoles
Sextupoles to generate
effective lattice

$Q_x = .139$ $Q_y = .219$ $Q_s = 0.025$

Small emittances and large Q_s –> Resonances with the longitudinal plane dominating and symmetric ± Q_s

$(\Delta y)_{rms} = 148\ \mu m$



A. Blondel, J. Wenninger

Dispersion and Collision Offsets

- ECM shifts due to opposite sign dispersion → obtained with BPMs around IP

  → Requires about **1 µm precision for BPMs close to IP**

$$\Delta\sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2} \longrightarrow |\Delta\sqrt{s}| = 96\ |u_0|\ [\mathrm{keV/nm}]$$

for $\Delta D^* = 1\ \mu\mathrm{m}$, $\sigma_E/E = 0.13\%$

For **$\Delta D^* = 10\ \mu\mathrm{m}$**, the CM error is **~1 MeV/nm**, i.e., the uncertainty on / average separation must be below **$u_0 < 0.1$ nm to limit the systematic errors < 100 keV.**

  - Even closer to 0.01 nm for σ ~ 20 nm → at the level of a % of the beam size.

- Luminosity or beam-beam (BB) deflection scan to determine collision offsets
- To disentangle dispersion and BB offset at IP → non-colliding high-intensity bunches?

Open question:
Which dispersion can we expect at the IP? → Tuning studies: Talk by R. Tomas
What is the best scheme for non-colliding low-intensity, high-intensity and colliding bunches?
How can we assure that colliding bunches are +/- 5 % of the nominal intensity?

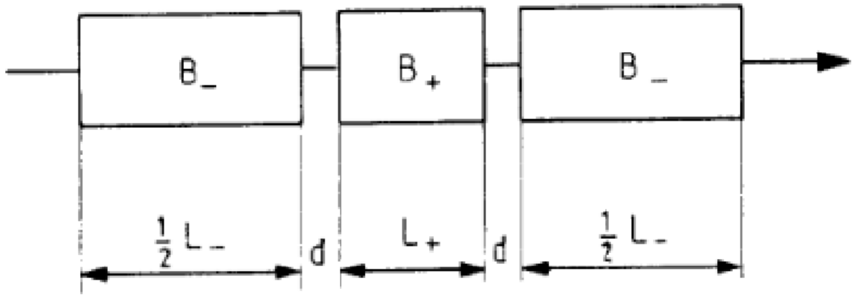
M. Hofer, K. Oide

Wigglers I

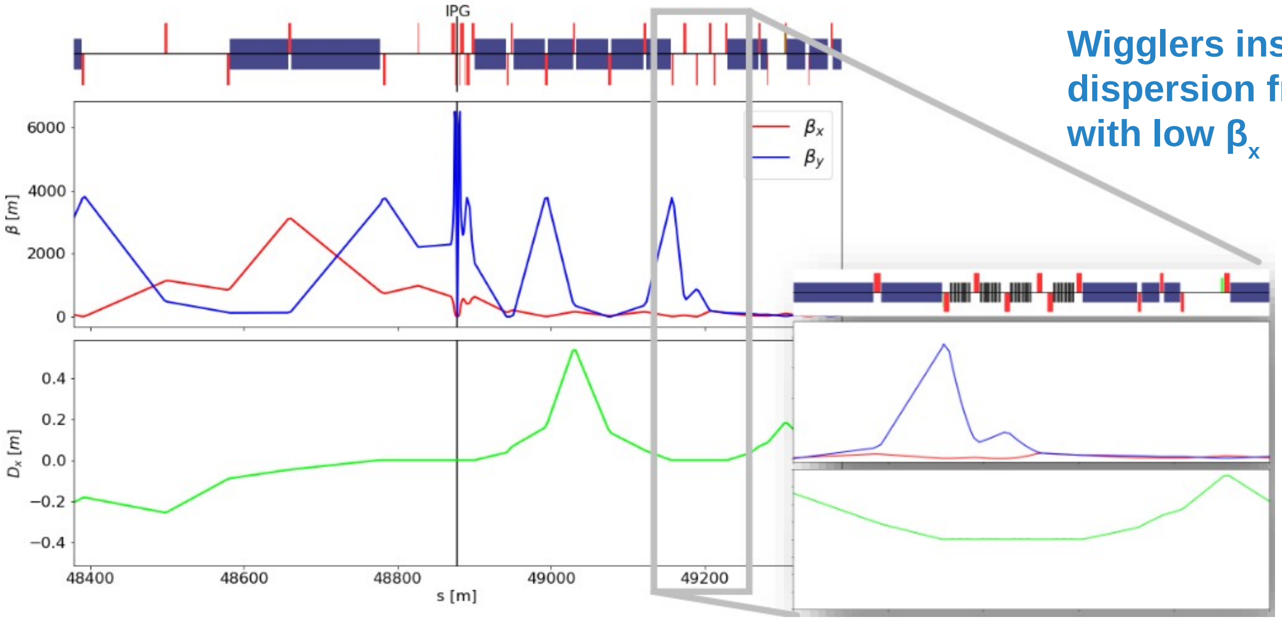
- Very long polarization time in FCC-ee at Z-pole
- Wigglers improve polarization time significantly

$$\left(\frac{\sigma_E}{E}\right)^2 \propto \frac{E^4}{\gamma^3 \tau_p \Delta E_{loss}} \qquad r = \frac{B_+}{B_-} = \frac{L_-}{L_+}$$

Follow 3 three-block design from LEP



Parameter	FCC-ee	LEP
Number of units per beam	24	8
B_+ [T]	0.7	1.0
L_+ [mm]	430	760
r	6	2.5
d [mm]	250	200
Crit. Energy of SR photons [keV]	968	1350



Wigglers installed in dispersion free section with low β_x

For Z-pole:
Polarization time decreases from 248 h to 12 h
Energy spread increases from 17 MeV to 64 MeV

M. Hofer: indico.cern.ch/event/1080577/

M. Hofer, K. Oide, G. Wilkinson

Wigglers II

- Operational scenario:
  - Inject few (~200) low-intensity pilots
  - Use wigglers for ~5-10 % **transverse** polarization
  - Switch wigglers off
  - Inject all high-intensity bunches
  - Use depolarizer
  - Measure spin tune with polarimeter

0 longitudinal polarization required for colliding bunches since it biases physics experiments
→ **Goal: to be controlled to 10^{-5}**

LEP: RDP measurements were performed outside physics collisions; while at FCC-ee, measurements will be performed throughout

- However, dead-time at start of fill at Z energies, as we must wait for polarisation level to accumulated in pilot bunches, when wigglers are in operation

- No physics bunches circulating when wigglers are on (synchrotron radiation)

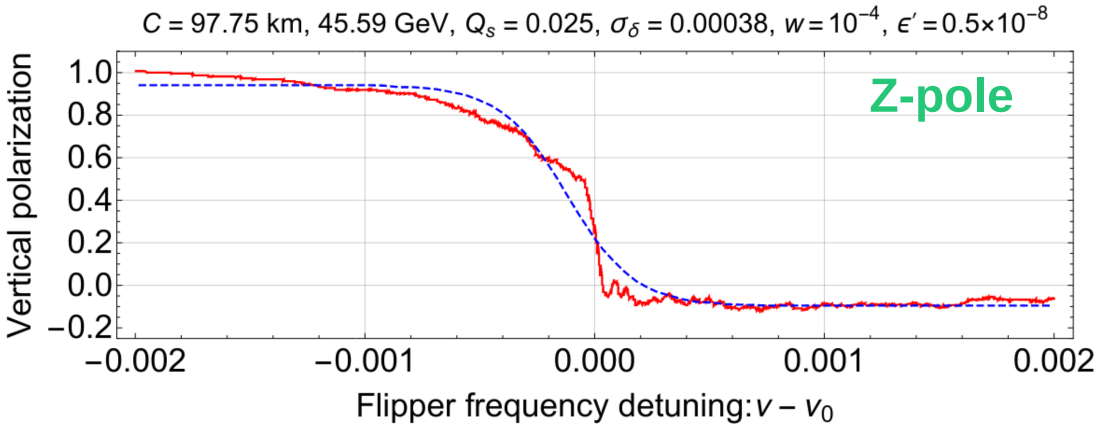
- Estimated time to reach ~10% polarization is ~100 minutes. Significant dead time, the overall impact of which will depend on length of fills.

- **Question: are lower levels of polarisation adequate for RDP when current is higher? If so, maybe possible to reduce time of wiggler operation.**

I. Koop, S. Nikitin, I. Nikolaev

Resonant Depolarization

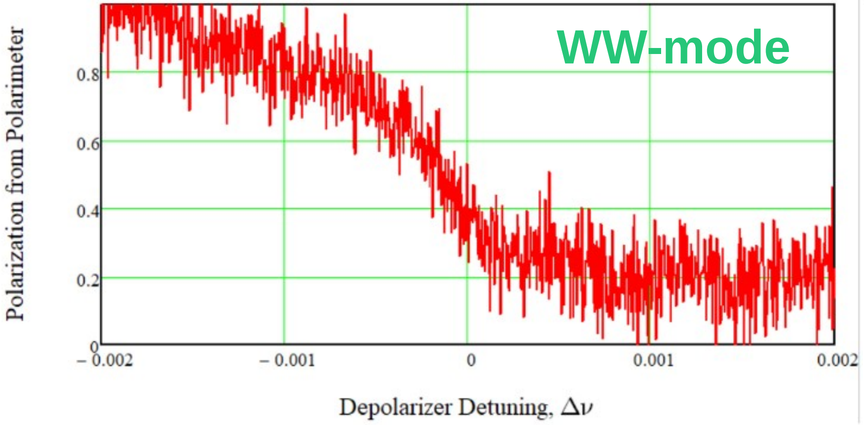
- Continous resonant depolarization (RDP) proceedure foreseen at the Z- and the WW- mode
- Depolarizer sweeps through frequencies ω_d
- Resonant condition $\Omega = n\omega_0 \pm \omega_d$
- Depolarization for dertimination of spin tune



ω_0 … revolution frequency

aγ … ~ spin tune

$$\Omega = \omega_0 \left(1 + a\gamma\right)$$



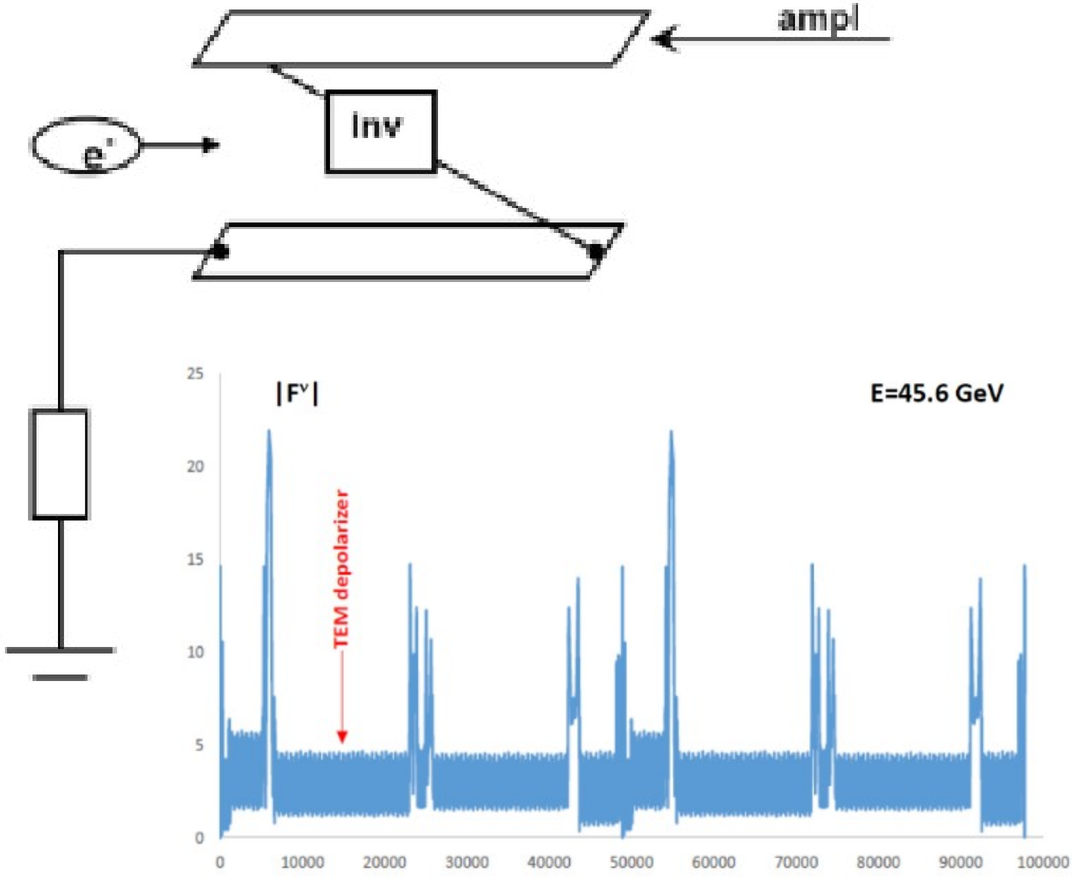
New approach compared to LEP at W-energy

Natural width of spine line due to radiative diffusion much larger than desired level of precision
(Z: 200 keV and W: 1.4 MeV)

Solution: Use of **2 selective kickers simultaneously acting on 2 pilot** bunches and scanning in opposite directions
→ accuracy better than 10 keV

I. Koop, S. Nikitin, I. Nikolaev, J. Wenninger

Depolarizer I



- Implemented as stripline that creates TEM wave propagating towards the beam
- Harmonic amplitude created by depolarizer

$$|w_k| = \frac{\nu B l}{2\pi B\rho}|F^\nu| = |F^\nu|\frac{\nu\phi}{2\pi}$$

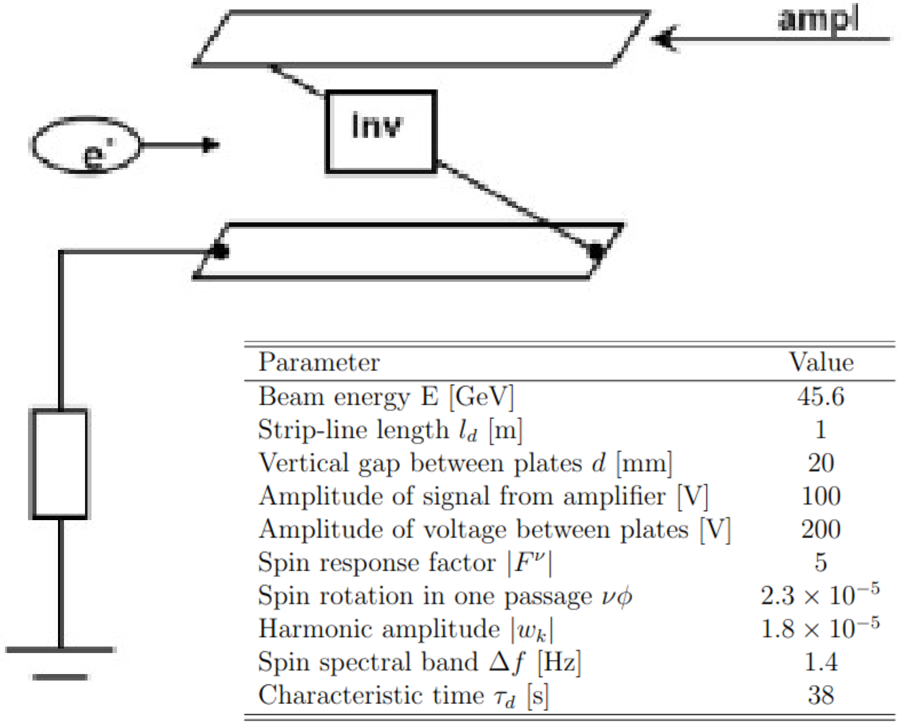
Spin response function

ν … spin tune
B … amplitude of TEM wave
l … strip-line length
νφ … spin rotation angle

- Placed at location with large spin response function, e.g. 5 in the arcs, caveat: accessibility
- Depolarization rate proportional to $|w_k|^2 = \nu^2|F^\nu|^2$

I. Koop, S. Nikitin, I. Nikolaev, J. Wenninger

Depolarizer II



Parameter	Value
Beam energy E [GeV]	45.6
Strip-line length l_d [m]	1
Vertical gap between plates d [mm]	20
Amplitude of signal from amplifier [V]	100
Amplitude of voltage between plates [V]	200
Spin response factor $\|F^\nu\|$	5
Spin rotation in one passage $\nu\phi$	2.3×10^{-5}
Harmonic amplitude $\|w_k\|$	1.8×10^{-5}
Spin spectral band Δf [Hz]	1.4
Characteristic time τ_d [s]	38

LHC transverse feedback system would provide adequate strength and bandwidth even with ¼ of LHC strength

- Implemented as stripline that creates TEM wave propagating towards the beam
- Harmonic amplitude created by depolarizer

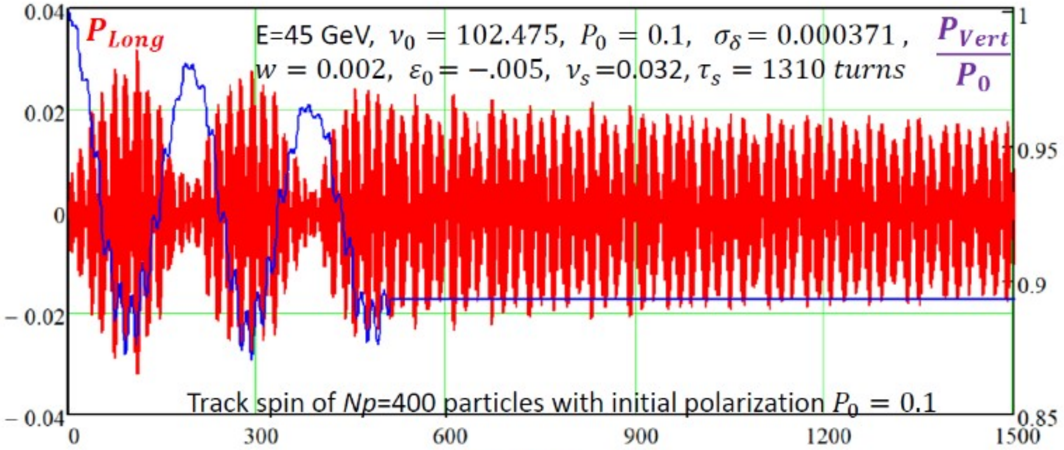
$$|w_k| = \frac{\nu B l}{2\pi B\rho}|F^\nu| = |F^\nu|\frac{\nu\phi}{2\pi} \propto \frac{\nu U l_d |F^\nu|}{E d}$$

- Scan rate 1 keV/s or 0.007 Hz/s
- About 20 mins required for frequency sweep with **w_k ~ 10^{-5}** (rather weak)
- Alternatively with stronger, **w_k ~ 10^{-4}**, leads to adiabatic spin fip and resonance search time < 1 min; requires e.g. 3 times longer plates

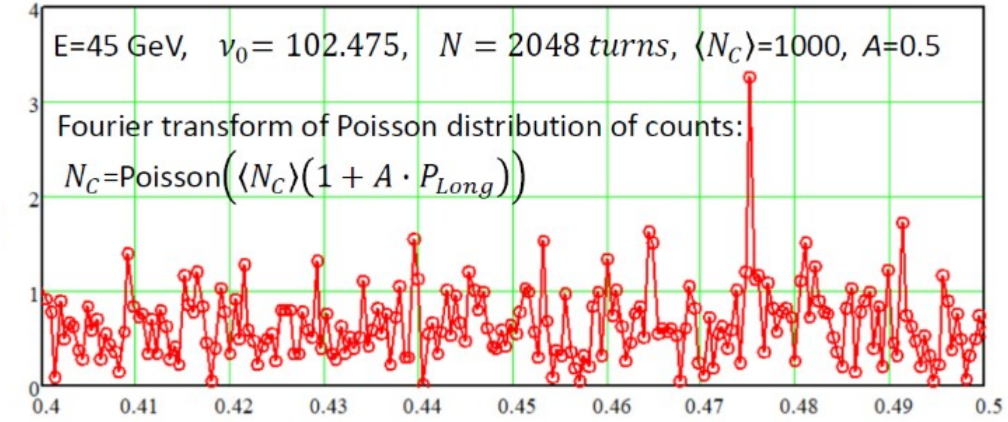
I. Koop, S. Nikitin, I. Nikolaev, G. Wilkinson

Free Spin Precession (FSP) I

- Spin rotation with very strong depolarizer **w_k ~ 10^{-3}**
- Measure oscillation of spin between planes
- Obtain spin tune with Fourier Transformation
- Possibly faster than resonant depolarization



FSP at Z



Open Questions:
Does this require more / less / same level of polarisation as RDP ?

How well must polarisation be measured by polarimeter ?

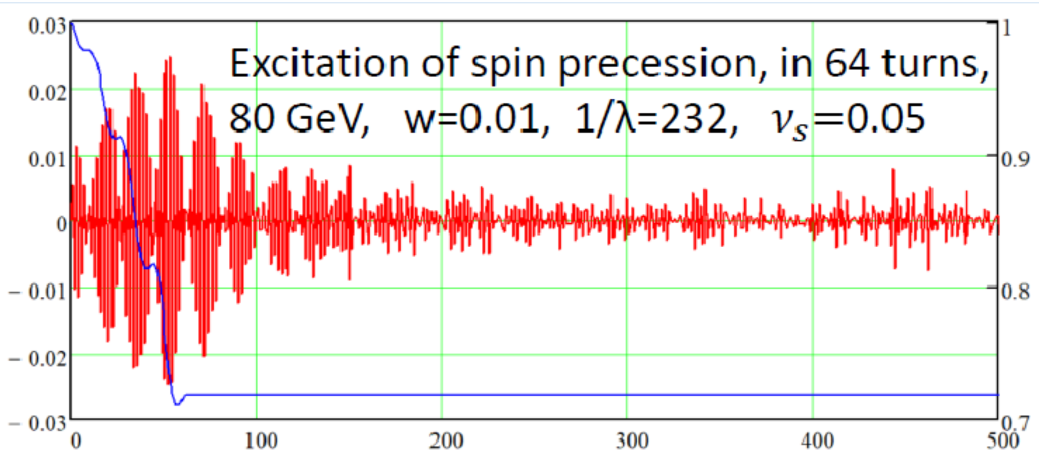
What are the systematics and intrinsic precision ?

How often should measurement be made, e.g. one to accompany every RDP measurement, or less frequently ?

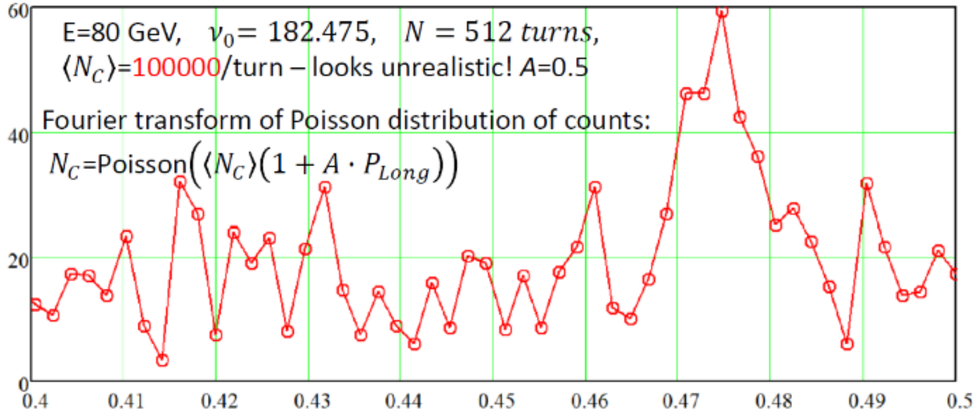
I. Koop, S. Nikitin, I. Nikolaev, G. Wilkinson

Free Spin Precession (FSP) II

- Spin rotation with very strong depolarizer **$w_k \sim 10^{-3}$**
- Measure oscillation of spin between planes
- Obtain spin tune with Fourier Transformation
- Possibly faster than resonant depolarization



FSP at W



Open question:
Is measurement feasible in W+W- regime, and if so what are requirements and what is precision ?

M. Hofer, A. Martens, N. Muchnoi, K. Oide, T. Lefevre, J. Wenninger

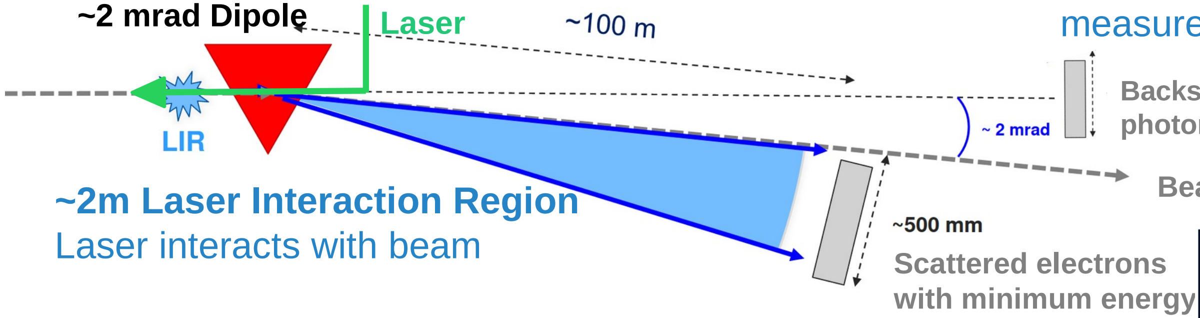
Polarimeter

- For now, most requirements driven by Z-pole requirements and presently studied in detail
- At least one polarimeter per beam required, goal: 1% statistical precision every second
- Used for RDP and FSP for pilot bunches
- Observing longitudinal polarization for colliding ones
- → Integration close to one IP beneficial

Laser requirements: Ytterbium mode-lock laser technology with green light at ~ 515 nm

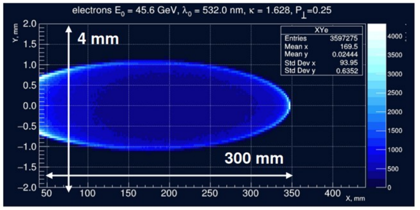
parameter	pilots	colliding bunches
$f_{\text{rep.}}$	3 kHz	30 kHz
U	1 mJ	10x0.5 mJ
σ_t	5 ps	5 ps
$\sigma_{x,y}$ [ps]	300 μm	300 μm
P	3 W	150 W

Allows measurement of three coordinates of beam polarization



~2m Laser Interaction Region
Laser interacts with beam

Scattered electrons to be measured by Si pixel detector



Open question:
How many polarimeters do we need/can we afford?
What is the expected background and radiation at the polarimeter?
Can we test a prototype e.g. at KARA?
→ Beam tests: Talk by B. Härer

M. Hofer and J. Wenninger: indico.cern.ch/event/1108961/
N. Muchnoi: indico.cern.ch/event/1119730/

A. Blondel, T. Persson, D. Shatilov

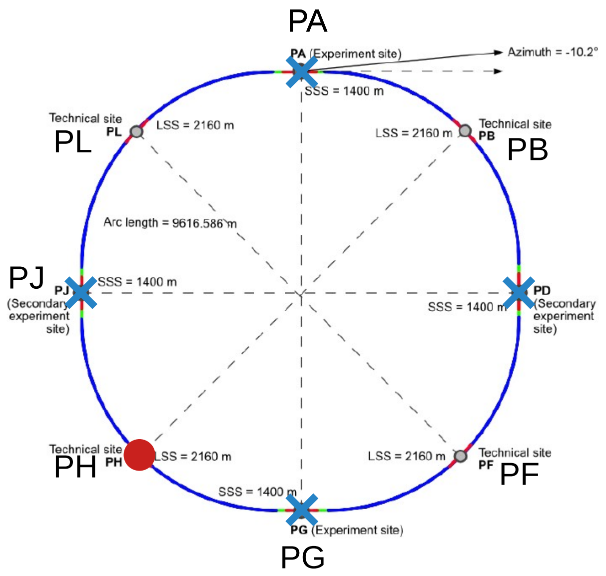
ECM and Boosts for Z-Mode

- **PH: 0.1 GV, 400 MHz** cavity
- $\lesssim$ 0.62 MeV beamstrahlung losses per beam and IP (simulations)
- 40 MeV radiation losses per revolution

One 8 h shift will give 5 keV precision

Sum of losses close to sum of absolute boosts

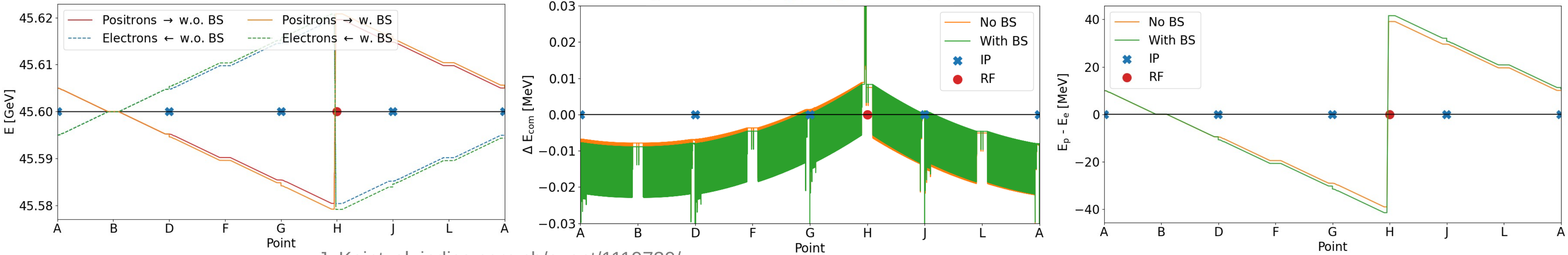
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439



$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos{}^{\alpha}/_{2}$$

Boost: + for e+; - for e-



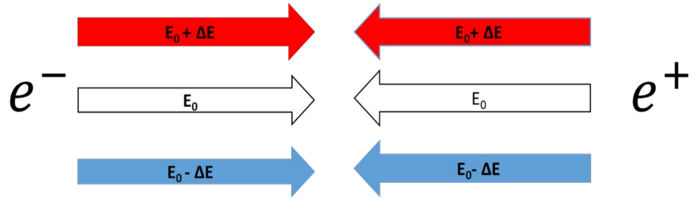
J. Keintzel: indico.cern.ch/event/1119730/

A. Faus-Golfe, H. Jiang, P. Raimondi, F. Zimmermann

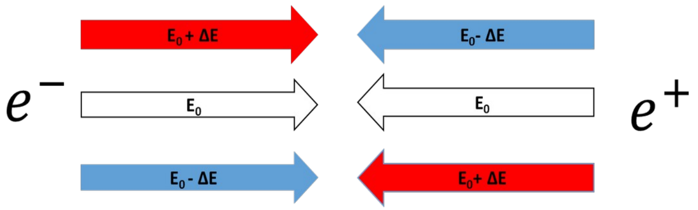
Monochromatization

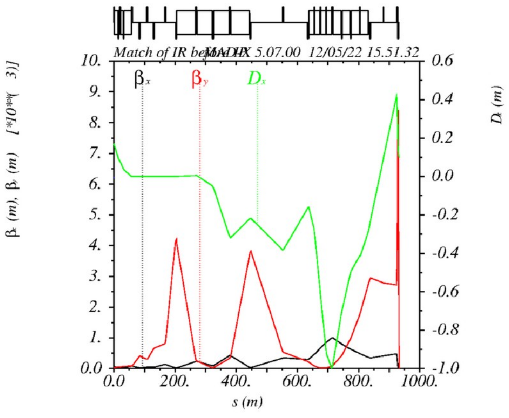
- ECM depends on many factors (collision offsets, dispersion, beamstrahlung, radiation losses, …)
- Monochromatization required to minimize energy spread for certain operation modes

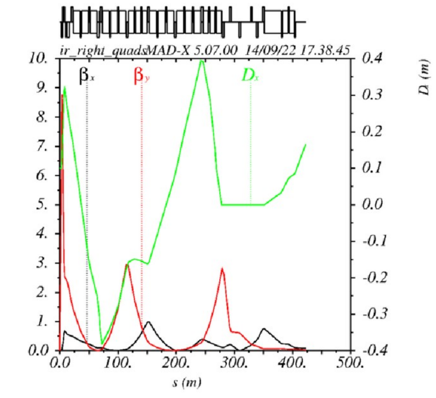
Same sign dispersion at the IP leads to change of ECM



Opposite sign dispersion helps reducing ECM spread
→ **Monochromatization**

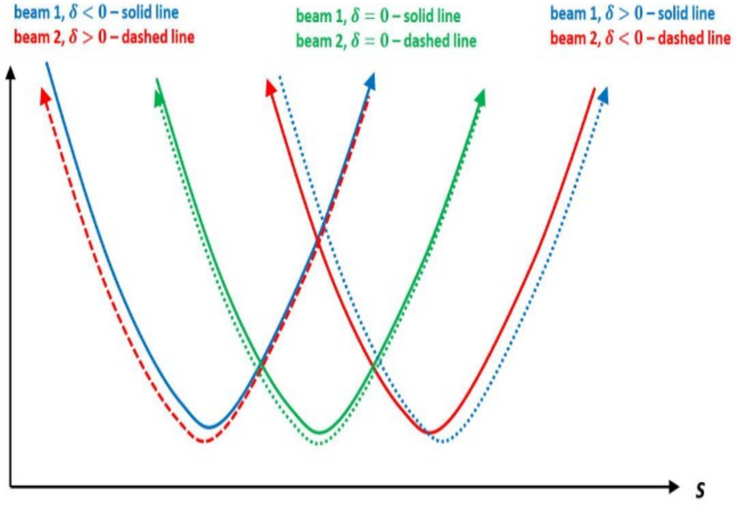






Open question:
Can we have sufficient monochromatization at the Higgs-mode?
What is the impact on luminosity?
Can we test it somewhere, e.g. at DAFNE?
→ Beam tests: Talk: A. Faus-Golfe

Introducing residual non-zero local vertical chromaticity

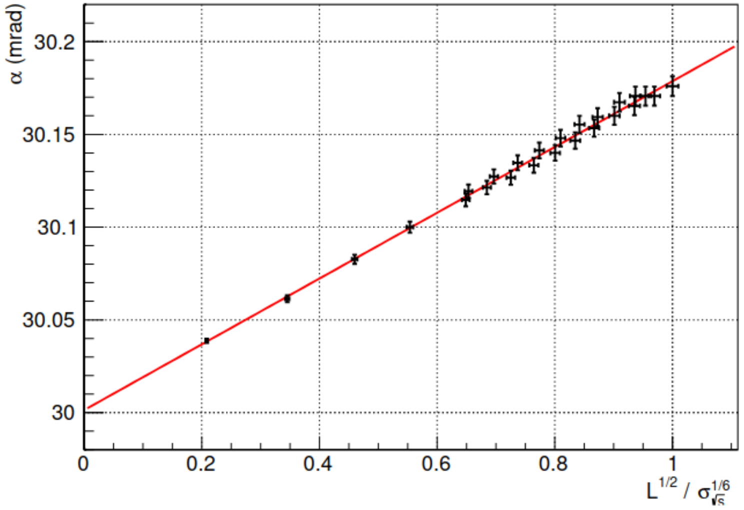


P. Janot, G. Wilkinson

Input From Experiments

- Electron and positron bunches experience mutual electric and magnetic fields
  - → Accelerate (decelerate) bunches before (after) collision and increase crossing angle
- Reliable and frequent logging of all parameters

Change of crossing angle depending on bunch population



Requires stable beams and detector operation from nominal to rather low bunch intensities

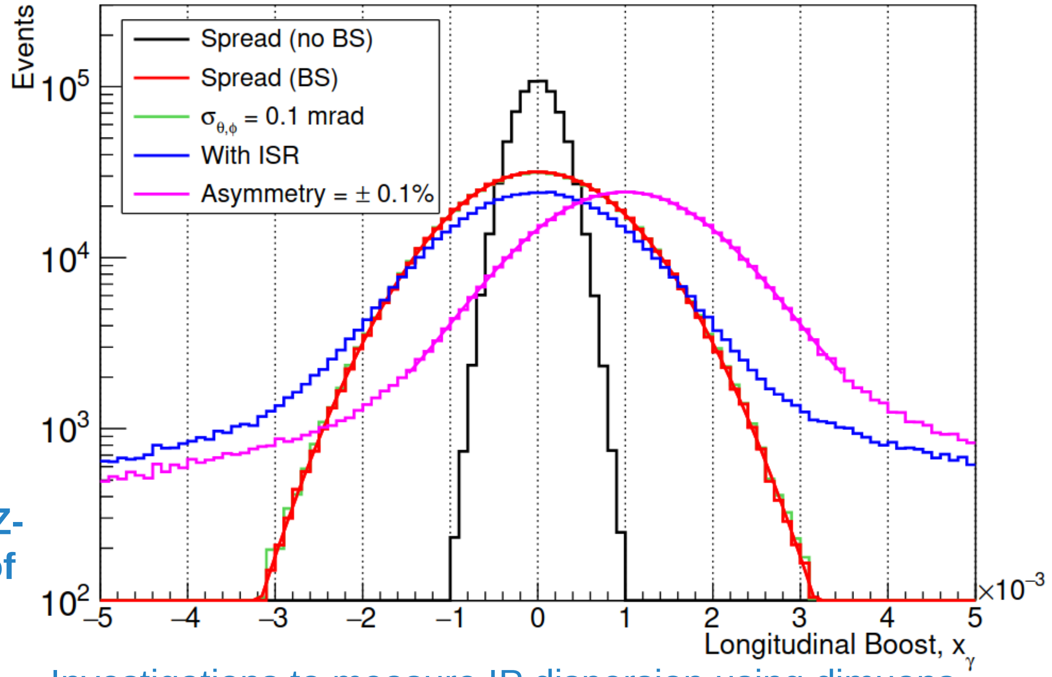
Black: no beamstrahlung
Red: + beamstrahlung
Green: + angular resolution
Blue: + photon emission
Pink: + asymmetry between electron and positron energy

Only asymmetric energies shift the center of the energy spectrum for dimuon events

Measuring 10^6 dimuon events yields precision of 10^{-3}

5 min measurements at FCC Z-mode gives boost precision of 50 keV and one 8 h shift will give 5 keV

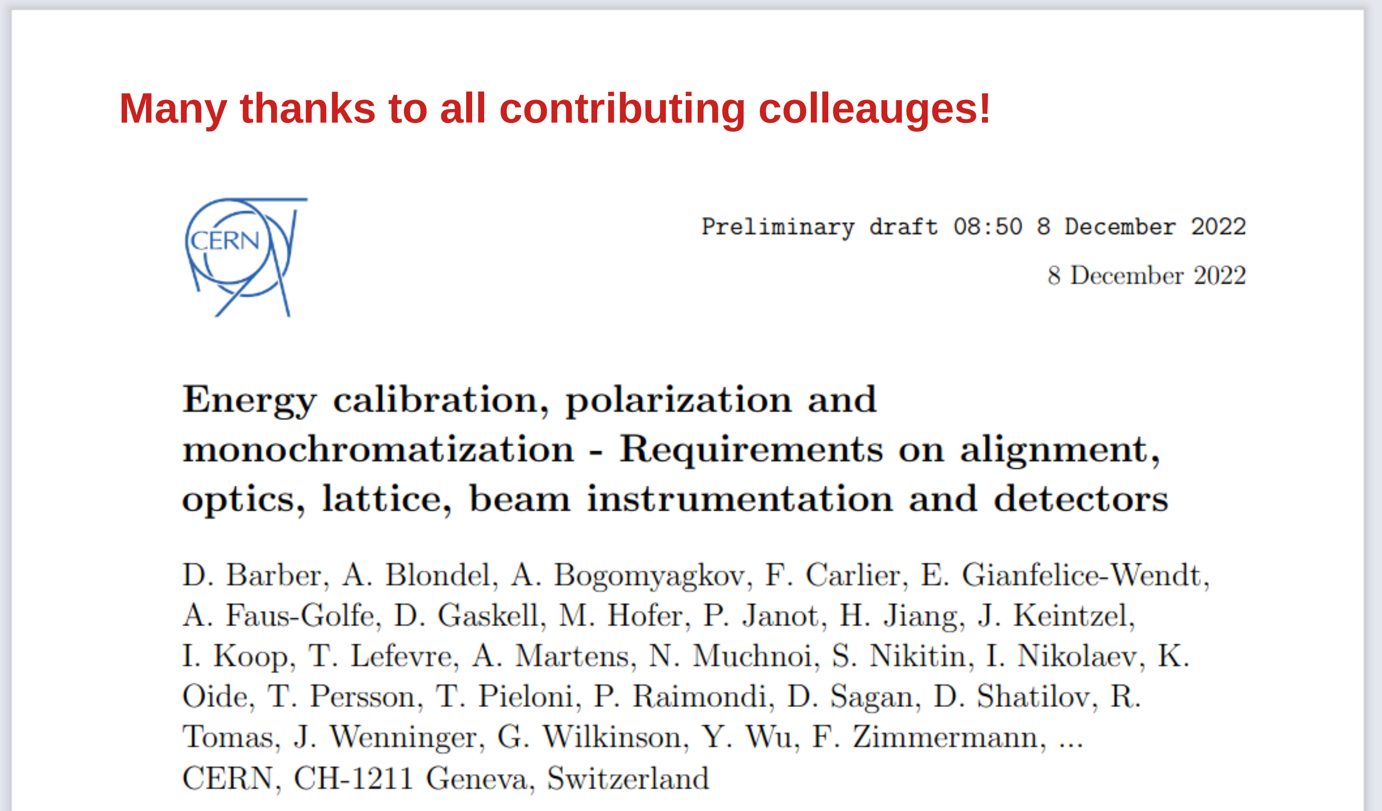
Statistics of 1 million dimuon events at Z-pole
e+e- –> μ+μ- (γ)
(γ)… Initial-State-Photon (ISR)



Investigations to measure IP dispersion using dimuons

Documentation

- Overleaf document presently being prepared and updated
- Milestones: mid-term report by mid 2023 and final version end of 2025



Many thanks to all contributing colleauges!

Preliminary draft 08:50 8 December 2022

8 December 2022

Energy calibration, polarization and monochromatization - Requirements on alignment, optics, lattice, beam instrumentation and detectors

D. Barber, A. Blondel, A. Bogomyagkov, F. Carlier, E. Gianfelice-Wendt,
A. Faus-Golfe, D. Gaskell, M. Hofer, P. Janot, H. Jiang, J. Keintzel,
I. Koop, T. Lefevre, A. Martens, N. Muchnoi, S. Nikitin, I. Nikolaev, K.
Oide, T. Persson, T. Pieloni, P. Raimondi, D. Sagan, D. Shatilov, R.
Tomas, J. Wenninger, G. Wilkinson, Y. Wu, F. Zimmermann, ...
CERN, CH-1211 Geneva, Switzerland

Questions?

FCC-ee energy calibration, polarization and monochromatization

D. Barber, M. Benedikt, A. Blondel, A. Bogomyagkov, F. Carlier, E. Gianfelice-Wendt, A. Faus-Golfe, M. Hofer, P. Janot, H. Jiang, <u>J. Keintzel</u>, I. Koop, M. Koratzinos, T. Lefevre, A. Martens, N. Muchnoi, S. Nikitin, I. Nikolaev, K. Oide, T. Persson, T. Pieloni, P. Raimondi, D. Sagan, D. Shatilov, R. Tomàs, J. Wenninger, G. Wilkinson, Y. Wu, and F. Zimmermann

FCC-IS Workshop 2022

WP2: Accelerator

8th December 2022

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.