FUTURE
CIRCULAR
COLLIDER

EPOL Status and First Technical Specifications

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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**

1st FCC Beam Instrumentation Workshop
21st November 2022

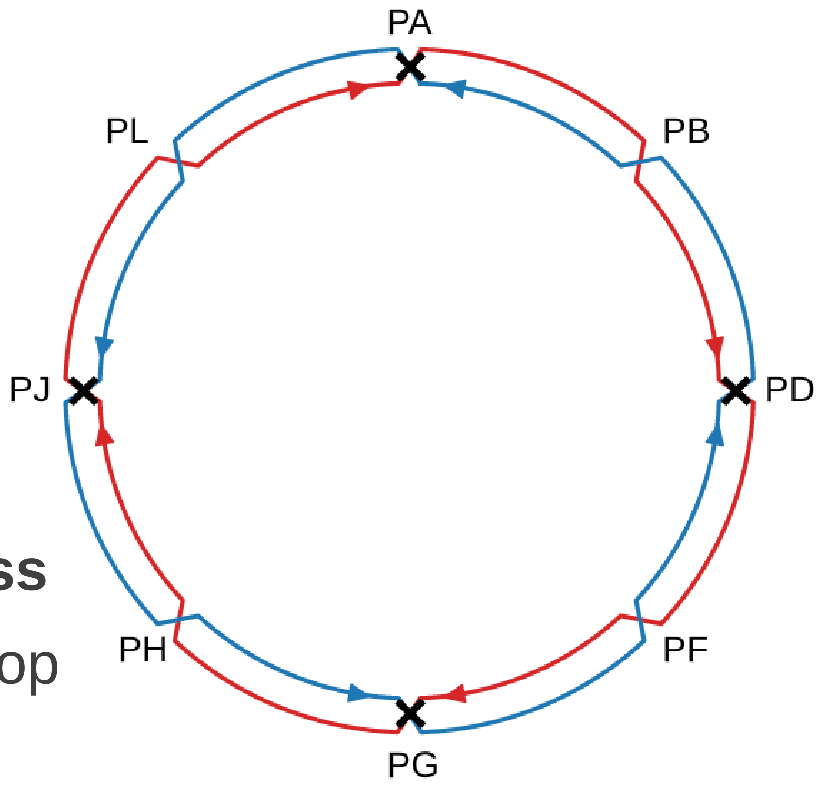
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

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

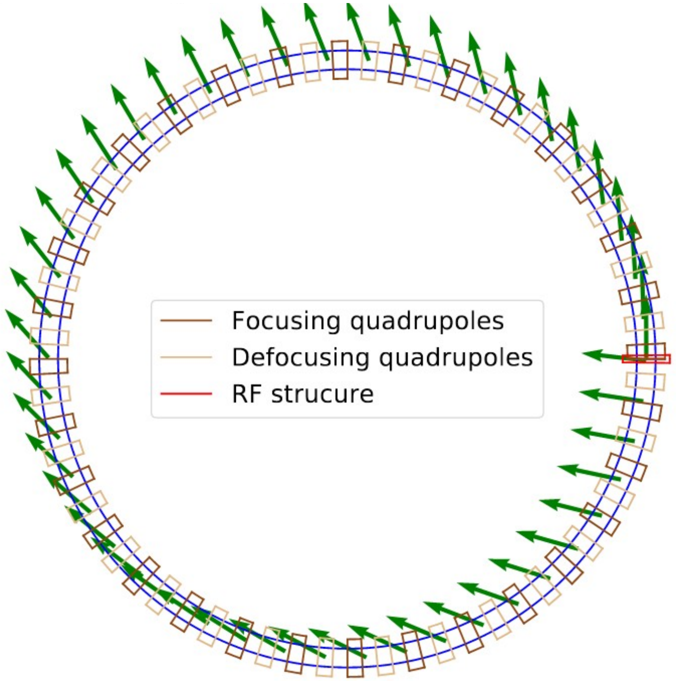
Workshop September 2022
indico.cern.ch/e/EPOL2022

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

Beam Energy and Spin Tune

- Beam energy is closely related to the spin tune ν

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



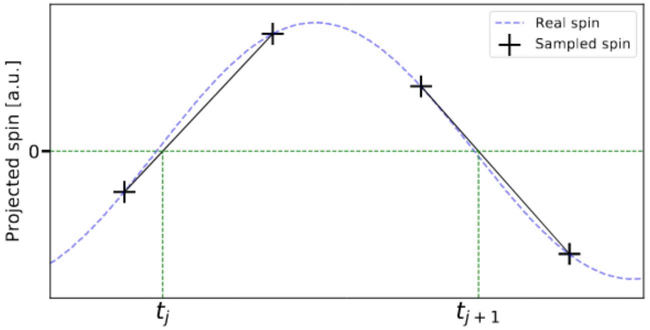
Precession of spin over one revolution in ideal machine with spin tune of about 0.25

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

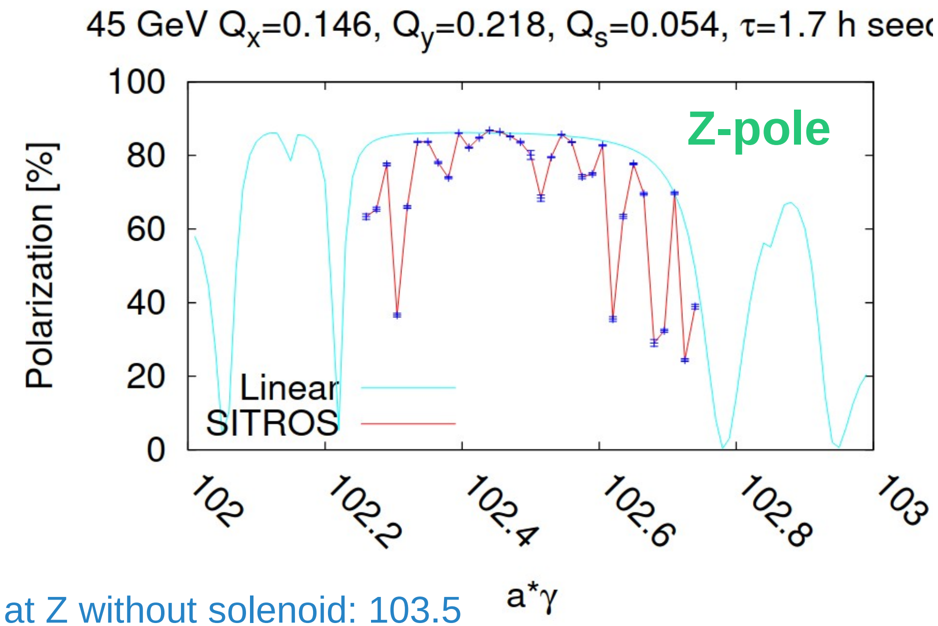
Strong unexpected resonance found for SITROS simulations

$$\underbrace{\tau^{-1}}_{\text{Effective polarization rate}} = \tau_{bks}^{-1} + \underbrace{\tau_{dep}^{-1}}_{\text{Depolarization rate}}$$

Baier-Katkov-Strakhovenko polarization rate

$$\tau_{bks}^{-1} = \frac{5\sqrt{3}}{8}\frac{\hbar r_e \gamma^5}{m_e C} \oint ds \frac{1 - \frac{2}{9}(\hat{n}_0(s)\cdot\hat{s})^2}{|\rho(s)|^3}$$

Polarization direction in ŷ for planar ring



aγ at Z without solenoid: 103.5

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

- 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

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

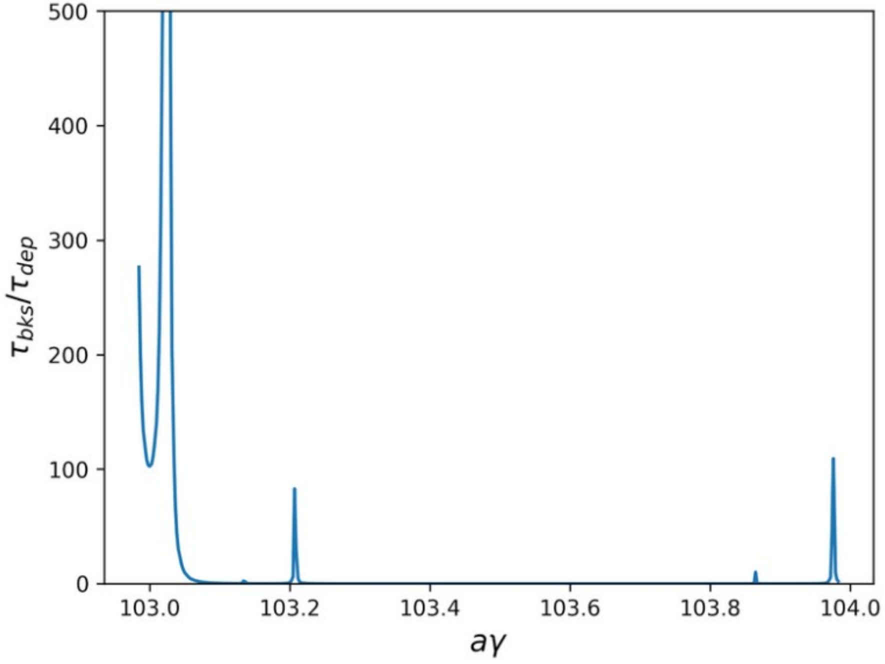
Y. Wu: indico.cern.ch/event/1119730/

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)

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

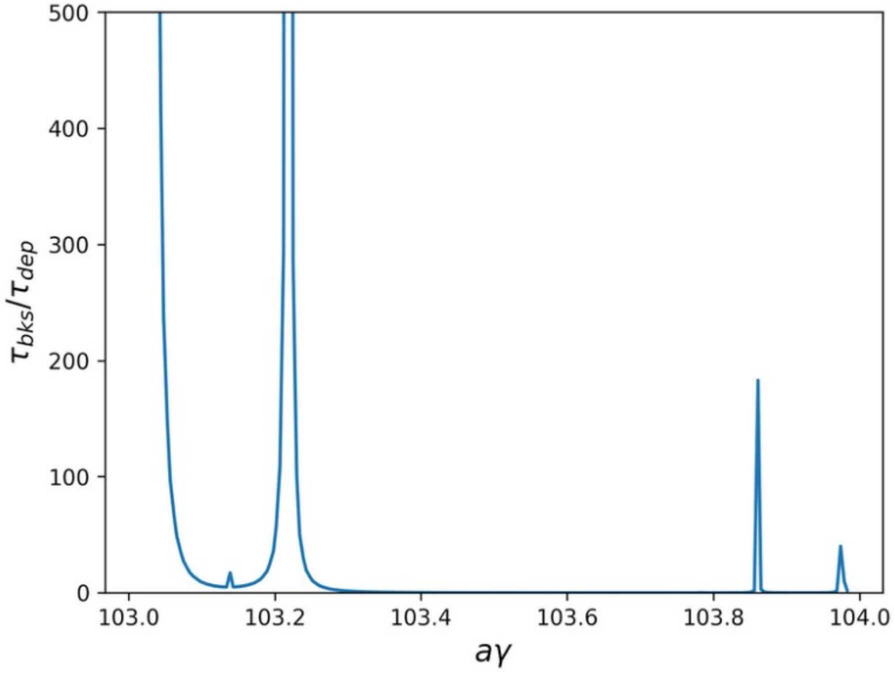


Misalignment errors in Dipoles, quadrupoles Sextupoles to generate effective lattice

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

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

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



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Error Sensitivity

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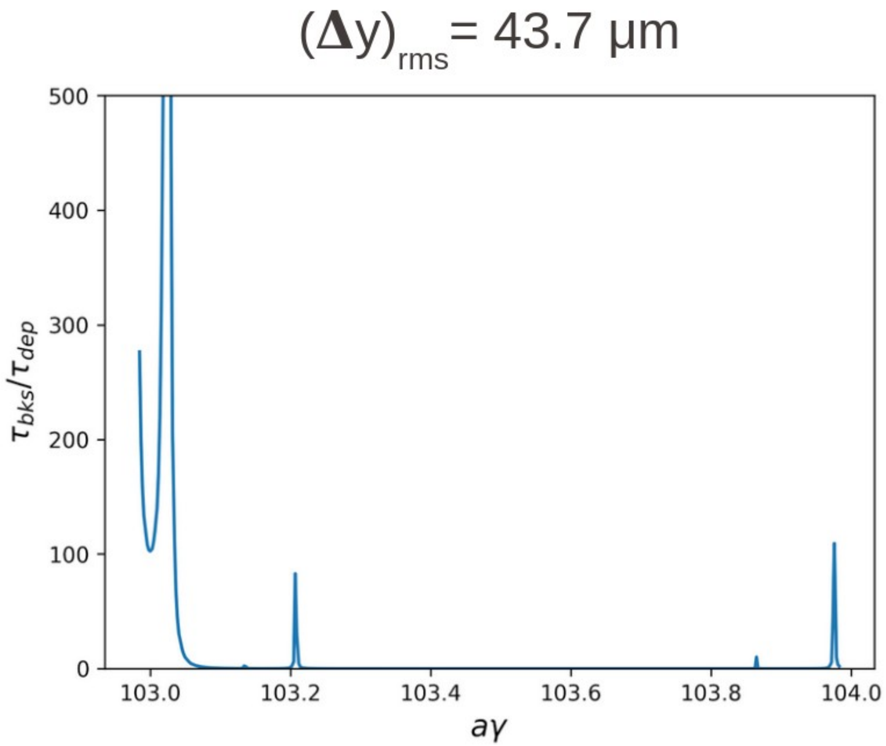

Excellent optics tuning, measurement and correction techniques will ensure sufficient polarization

Misalignment errors in Dipoles, quadrupoles Sextupoles to generate effective lattice

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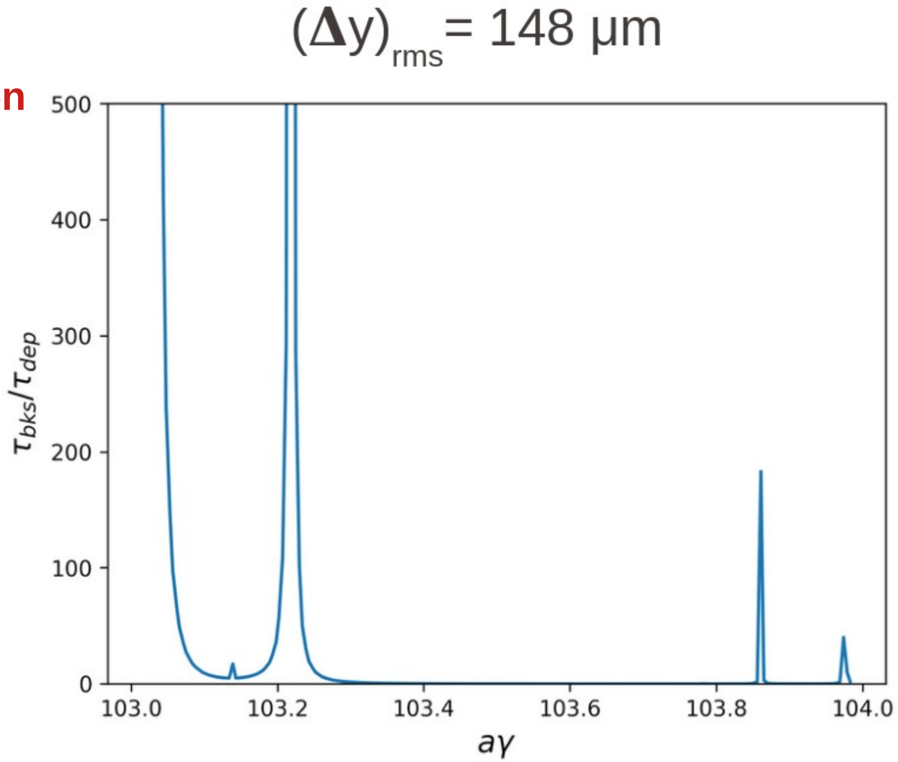
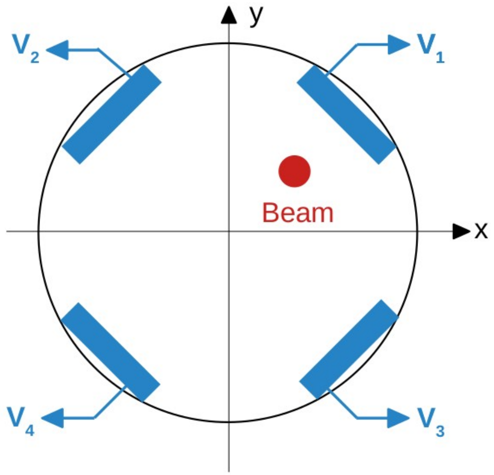


Optics Measurements

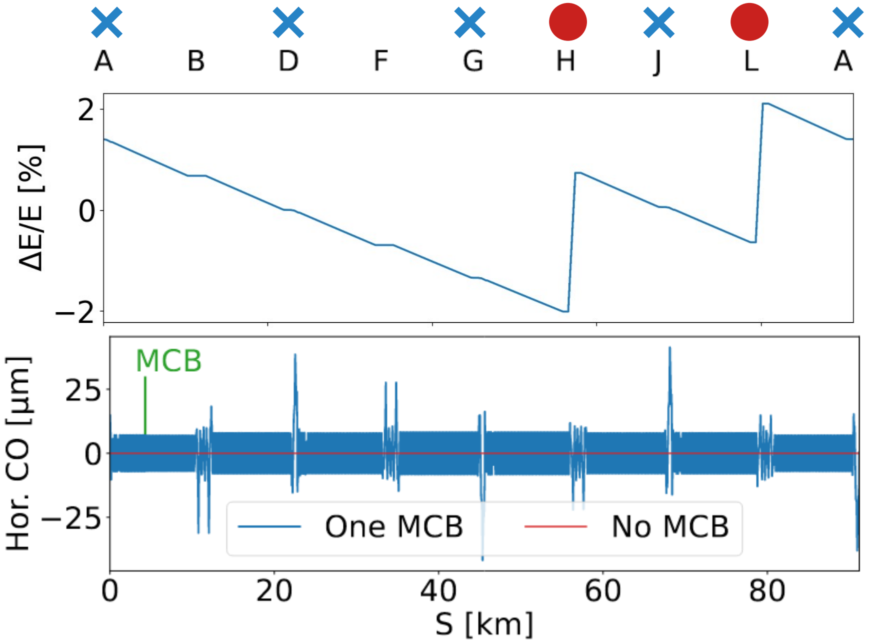
- Beam Position Monitors (BPMs) essential
- 2 techniques



BPMs either next to
- every quadrupole
- every sextupole
- interleaved quadrupole-sextupole element
- …

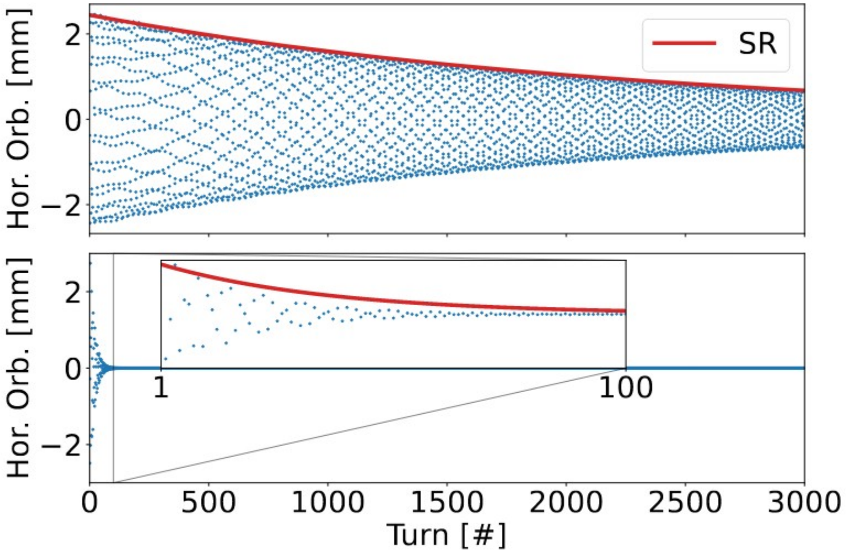
Tuning studies will help deciding

Orbit response matrix
At beam energy 182.5 GeV and radiation losses/turn about 10 GeV → Large energy variation of about ± 2 %, tapering applied
Effect of SR losses on ORM to be explored



Turn-by-Turn Measurements
Procedure: Beam excitation → harmonics analysis (Fourier Transform) → optics analysis

Z-mode: 2300 damping time is slow enough to use single kicks for TbT measurements
ttbar mode: 40 turns damping time and thus single kicks too fast for TbT measurements (use e.g. AC-dipole as in LHC, or transverse feedback with amplification as in SKEKB)



BPM Requirements

- Beam Position Monitors (BPMs) essential
- 2 techniques

Orbit response matrix
Average over several turns

Turn-by-Turn Measurements
Turn-by-turn measurements
Bunch-by-bunch measurements
Goal phase error below 1x10^{-3}

FCC-Z mode, no arc sextupoles, no radiation, 100 seeds, 1000 turns

Goal of relative phase advance error with respect to ideal model achievable with

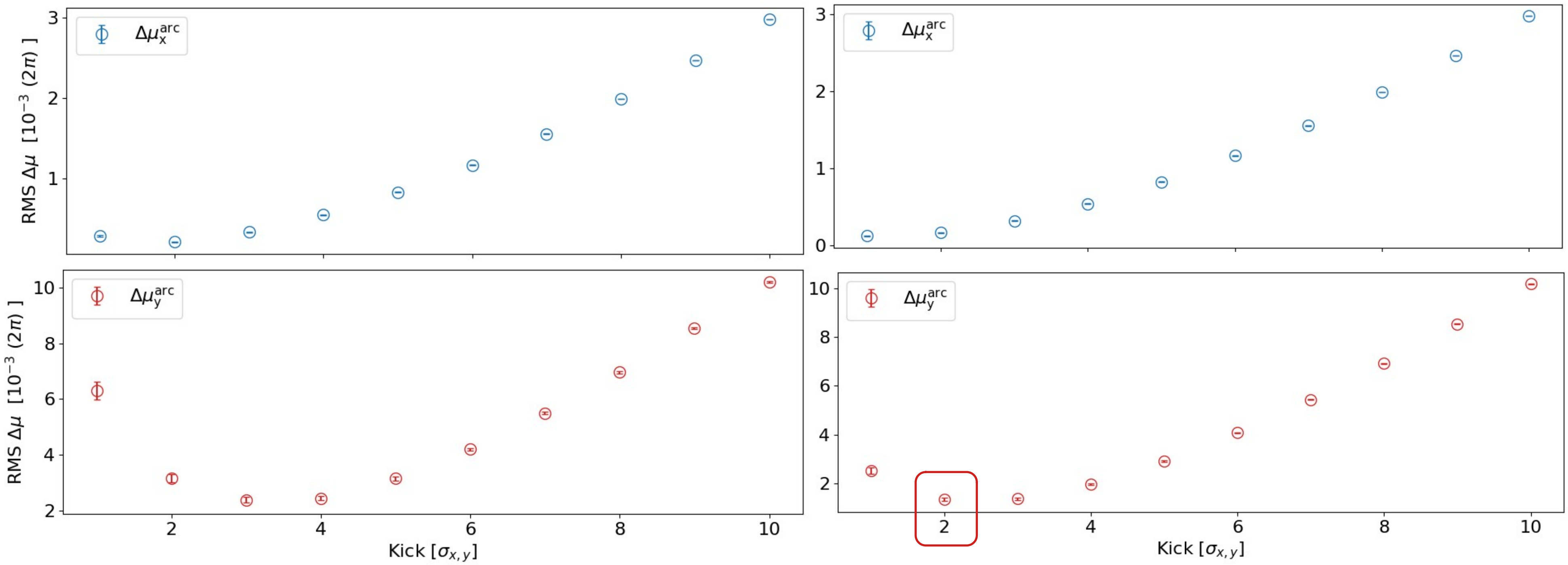
Horizontal 5 µm BPM resolution

Vertical ~2 µm BPM resolution

Using more turns can reduce phase advance error further

5 µm BPM resolution

2 µm BPM resolution



R. Tomas, G. Wilkinson

BPM Requirements

- Beam Position Monitors (BPMs) essential
- 2 techniques

Orbit response matrix
Average over several turns

Turn-by-Turn Measurements
Turn-by-turn measurements
Bunch-by-bunch measurements
Goal phase error below 1x10^{-3}

Parameter		**FCC-Z**	**FCC-ttbar**
Bunch intensity [10^{11}]	Low-intensity pilot High-intensity non-colliding High-intensity colliding	~0.1 2.43 2.43	~0.1 2.37 2.37
Bunch length [cm]	Low-intensity pilot High-intensity non-colliding High-intensity colliding	< 0.38 0.38 1.32	< 1.57 1.57 2.21
Number of bunches [-]	Low-intensity pilot High-intensity non-colliding High-intensity colliding	~200 A few 16640	- - 48

Stored at the same time

EPOL: ~5 energy calibrations with 2 pilots/h x 24h storage = ~200 low intensity pilot bunches = ~ 20 x 10^{11} stored particles

Optics measurements and corretions: Could correspond to measurements with e.g. ~ 20 bunches each with 10^{11}

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**

$$\Delta\sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2}$$

⇨

$$|\Delta\sqrt{s}| = 96\ |u_0|\ [\mathrm{keV/nm}]$$

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?

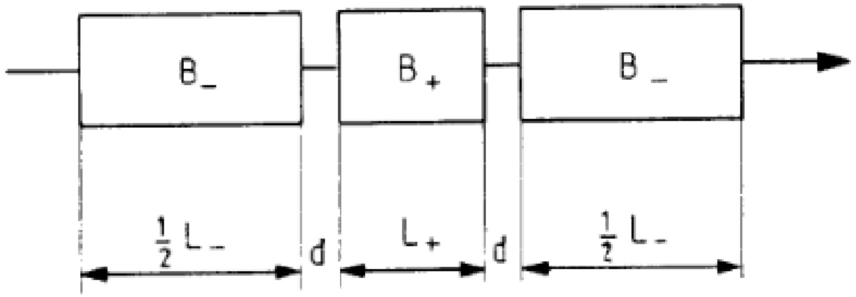
M. Hofer, K. Oide

Wigglers I

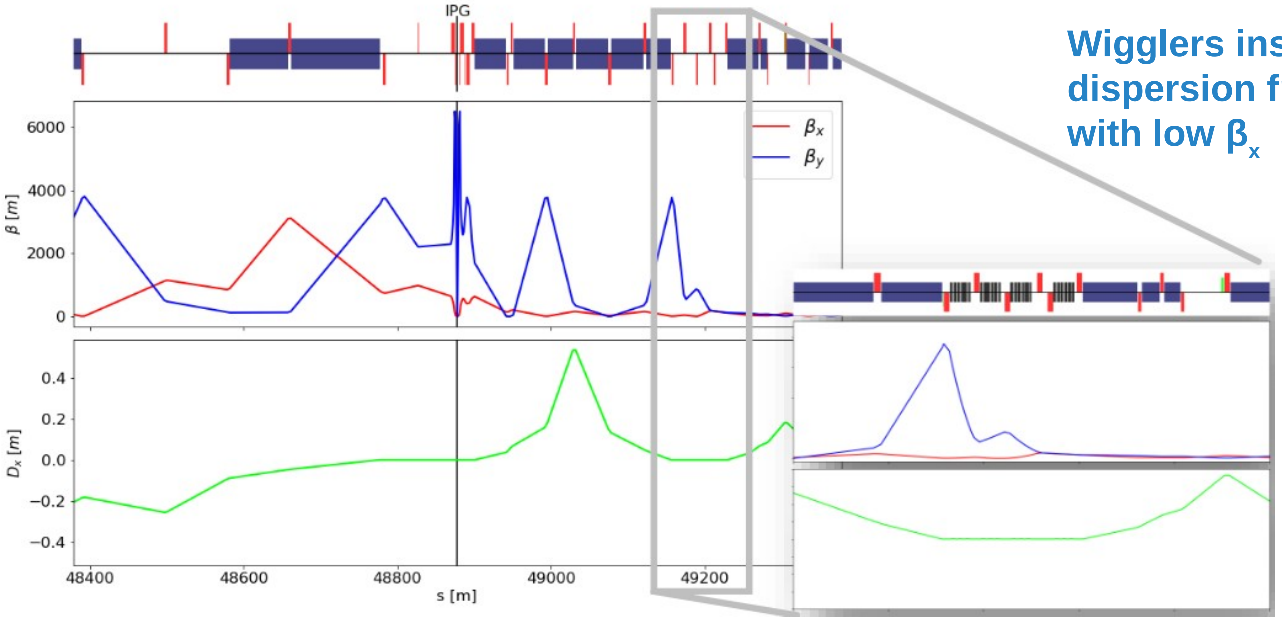
- Very long polarization time in FCC-ee at Z-pole
- Wigglers improve polarization time significantly

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

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.

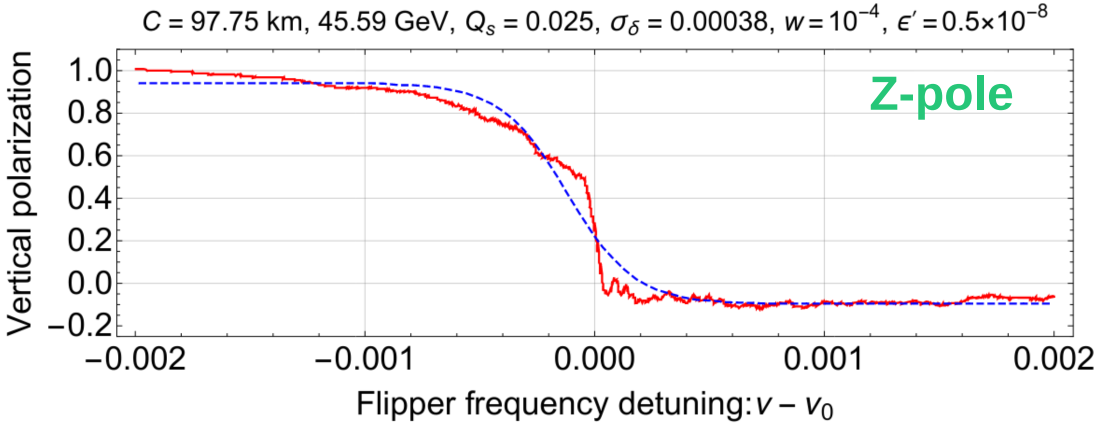
I. Koop, S. Nikitin, I. Nikolaev

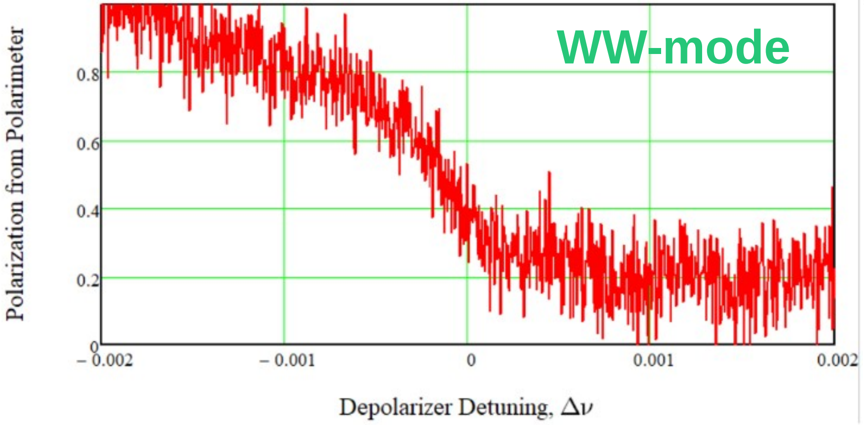
Resonant Depolarization

- 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

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





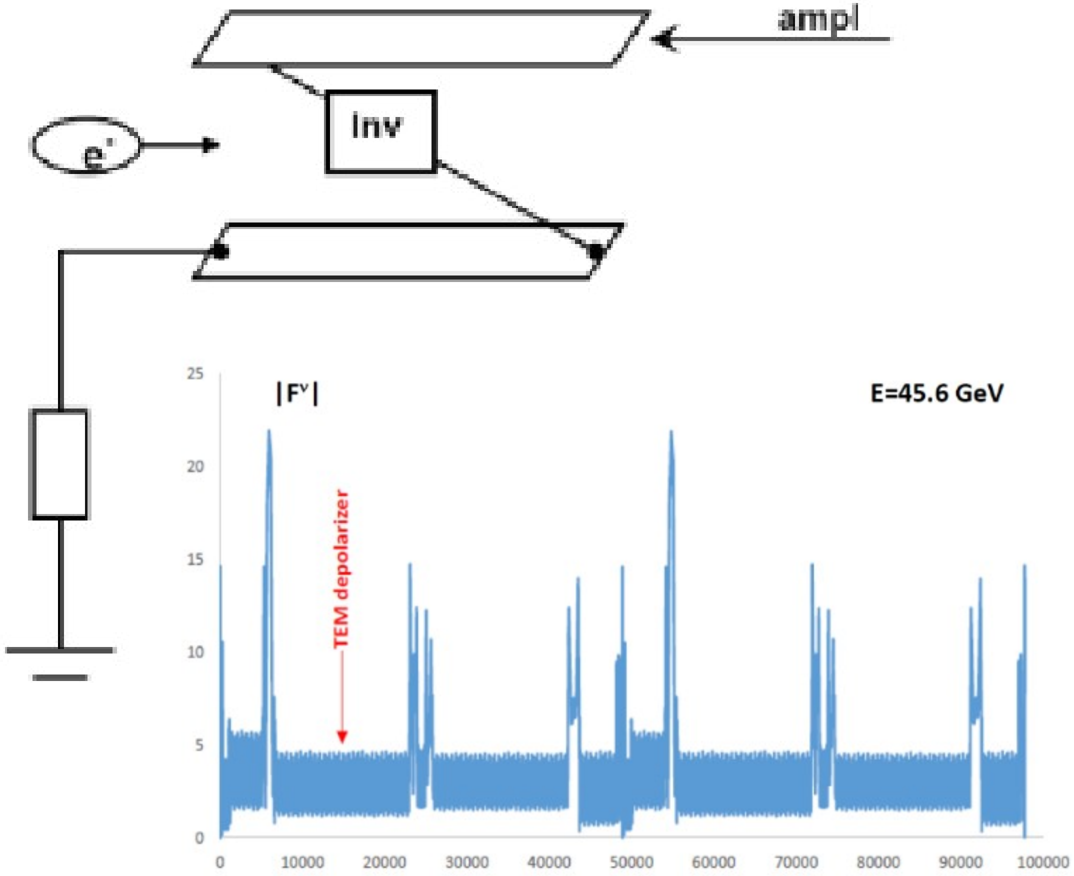
New approach compared to LEP at W-energy

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

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

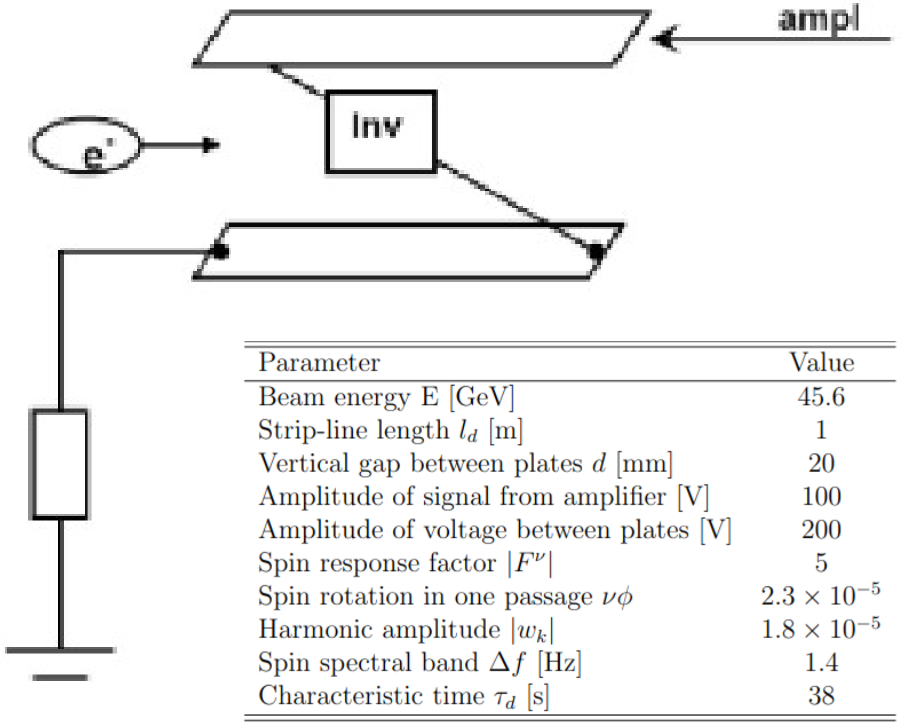
Spin response function

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

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

- 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

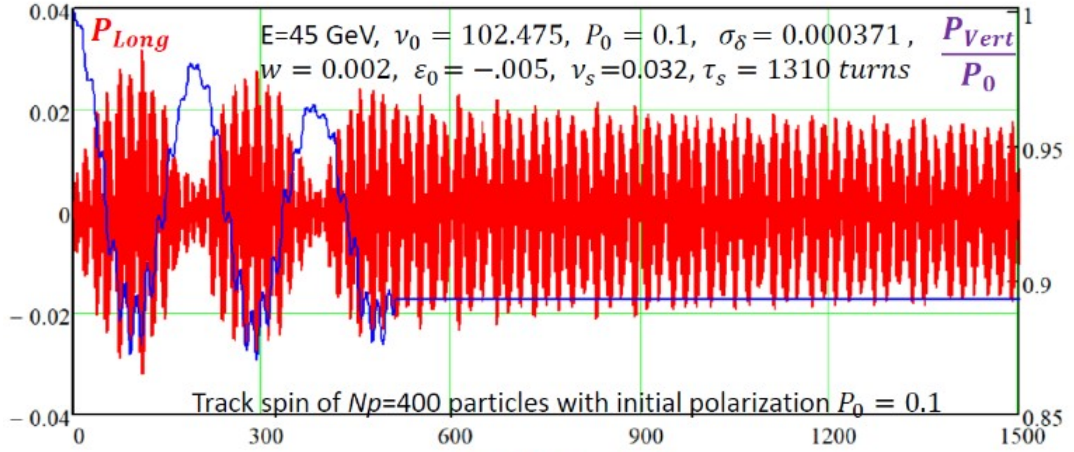
- Spin rotation with very strong depolarizer $\mathbf{w_k \sim 10^{-3}}$
- Measure oscillation of spin between planes
- Obtain spin tune with Fourier Transformation
- Possibly faster than resonant depolarization

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

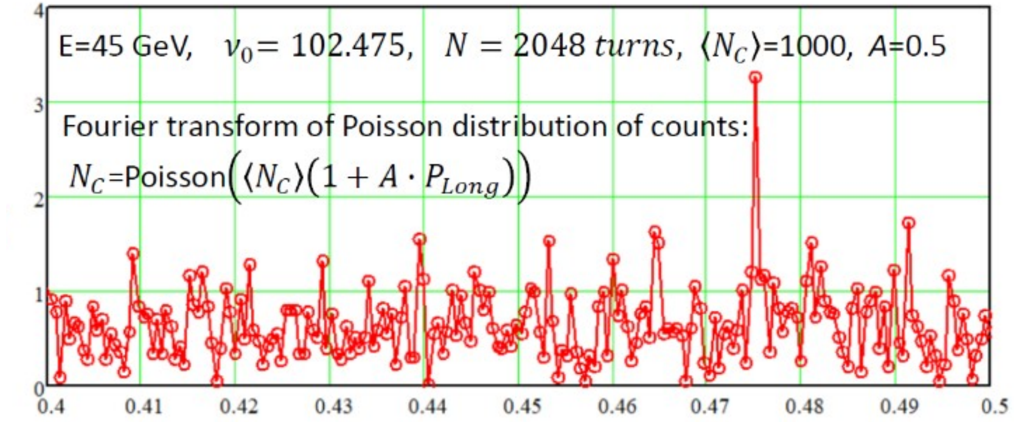
How well must polarisation be measured by polarimeter ?

What are the systematics and intrinsic precision ?

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



FSP at Z



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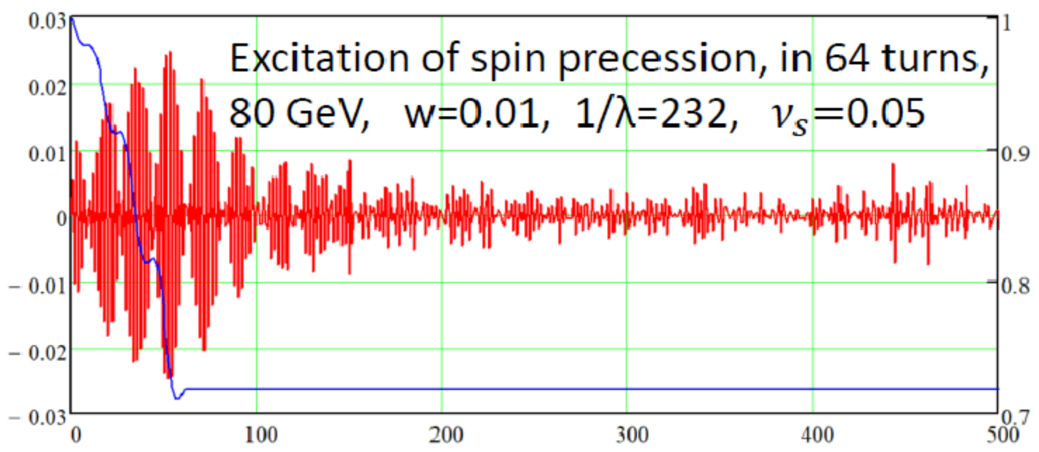
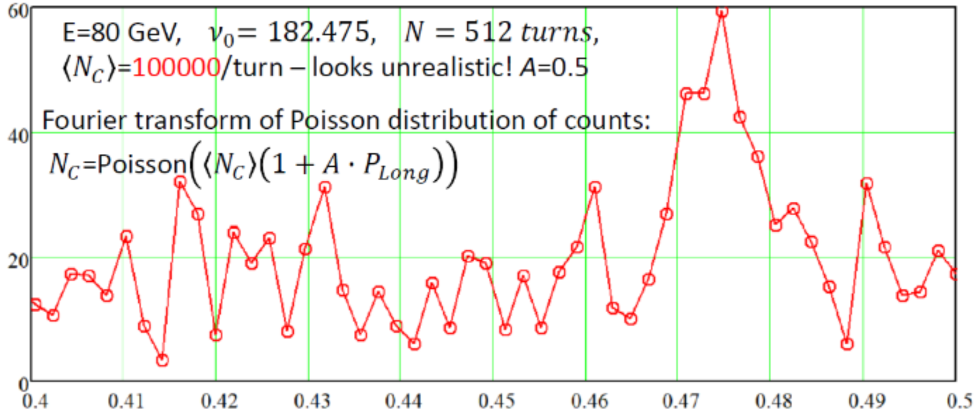
Free Spin Precession (FSP) II

- 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

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



FSP at W



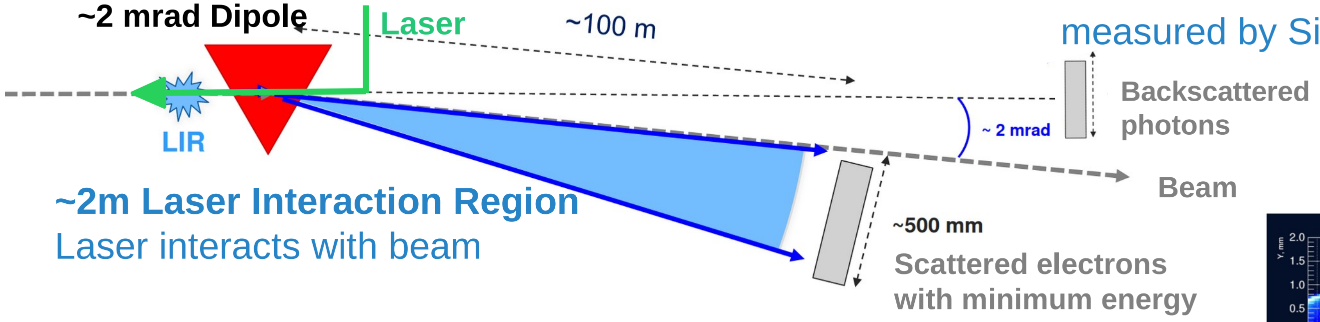
M. Hofer, A. Martens, N. Muchnoi, K. Oide, T. Lefevre, J. Wenninger

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

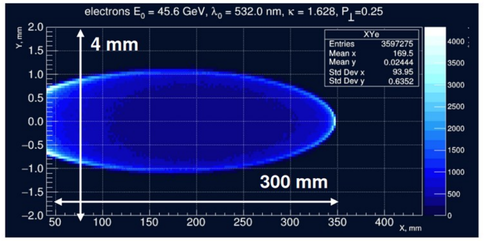
parameter	pilots	colliding bunches
$f_{\mathrm{rep.}}$	3 kHz	30 kHz
U	1 mJ	10x0.5 mJ
σ_t	5 ps	5 ps
$\sigma_{x,y}$ [ps]	300 μm	300 μm
P	3 W	150 W

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



Laser requirements
Ytterbium mode-lock laser technology frequency doubled to provide green light at about 515 nm

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

A. Blondel, T. Persson, D. Shatilov

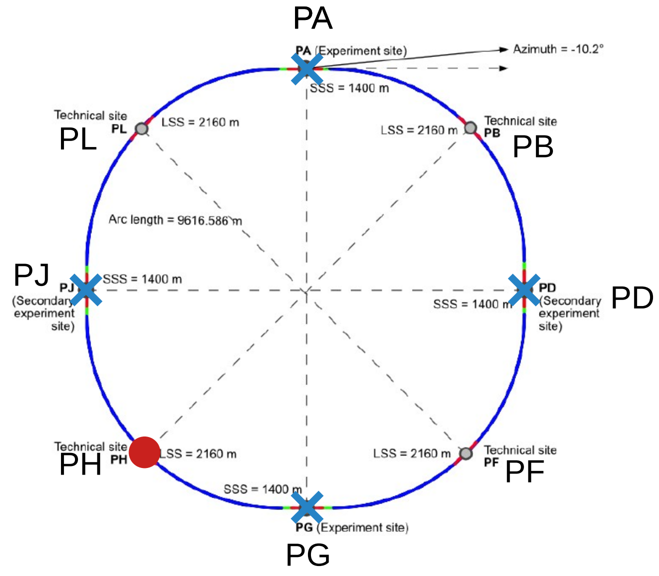
ECM and Boosts for Z-Mode

- **PH: 0.1 GV, 400 MHz** cavity
- ≨ 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

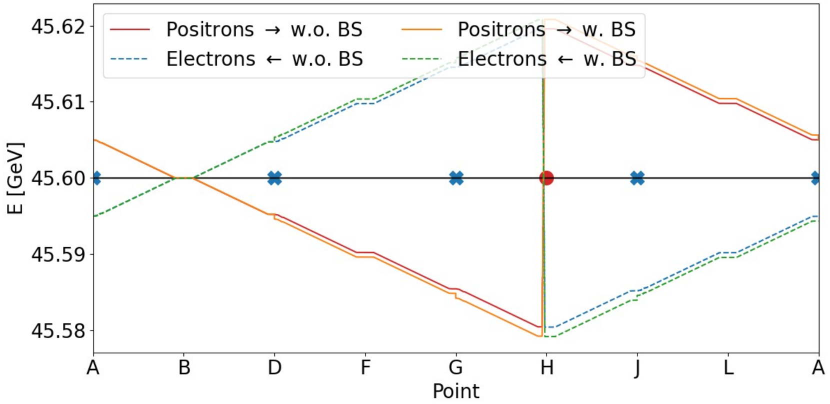
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

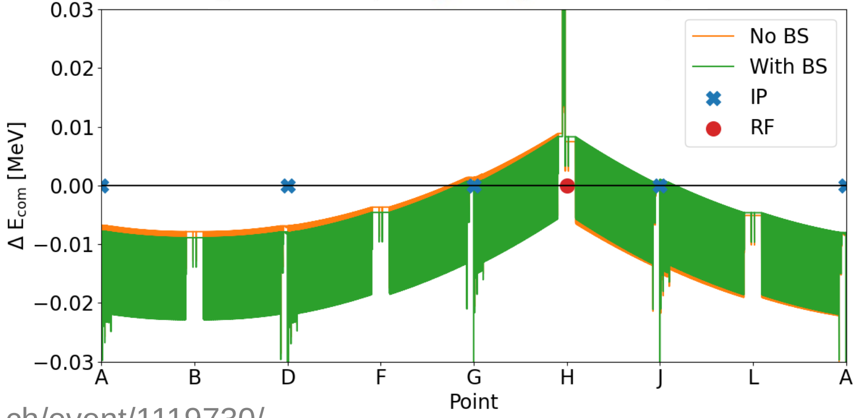


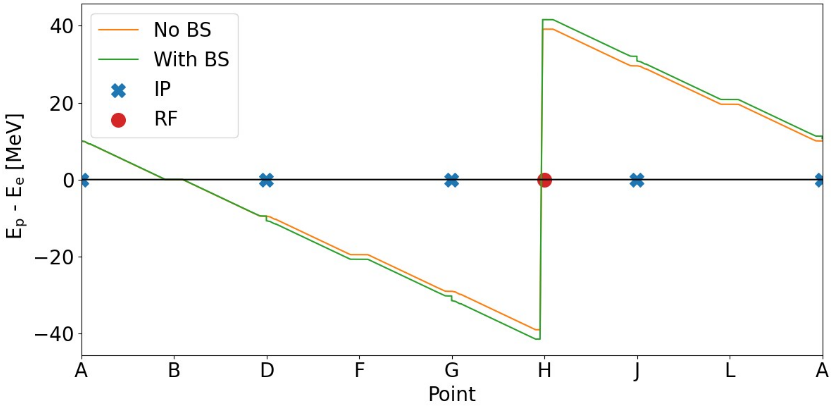
$$\Delta E \propto \gamma_{\text{rel}}^4$$

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

Boost: + for e+; - for e-







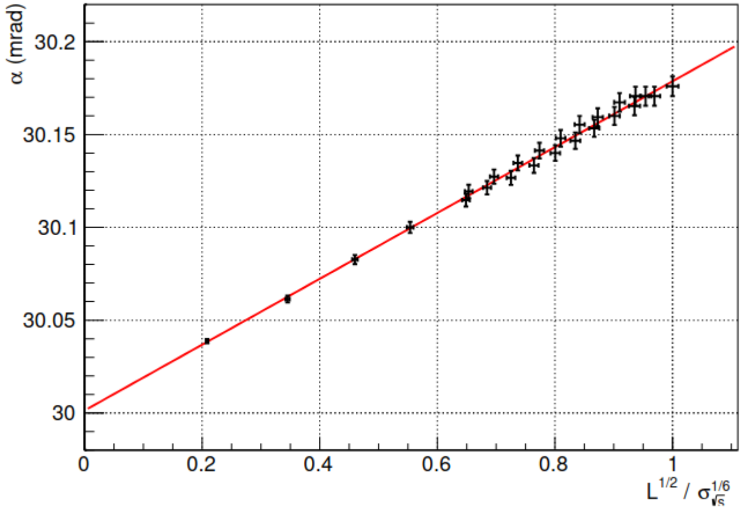
J. Keintzel: indico.cern.ch/event/1119730/

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

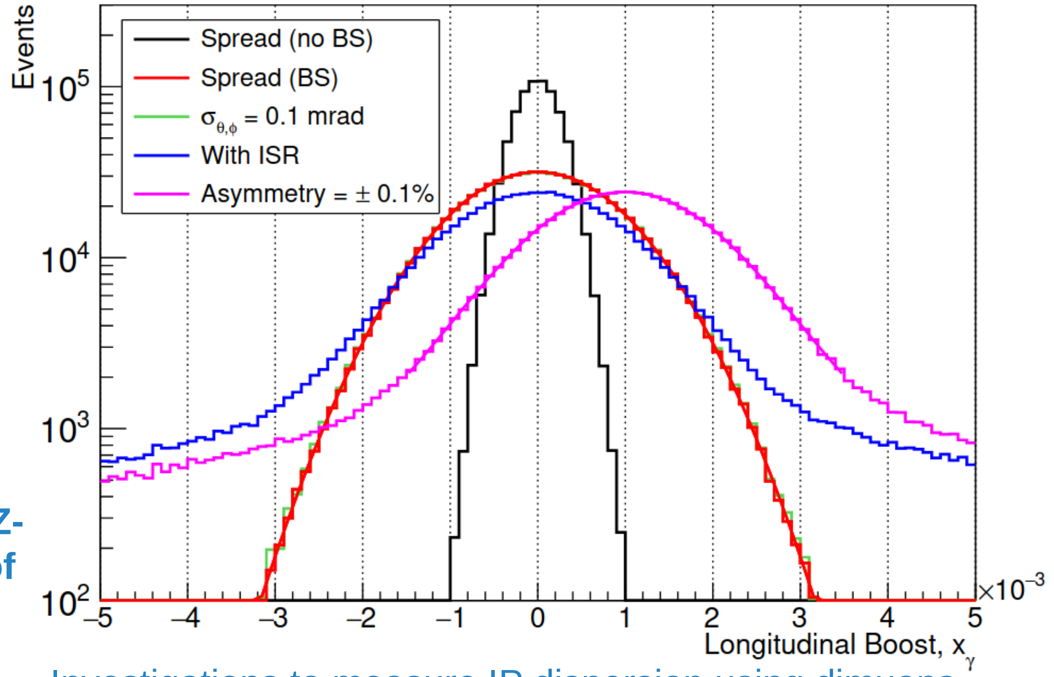


Requires stable beams and detector operation from nominal to rather low bunch intensities

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

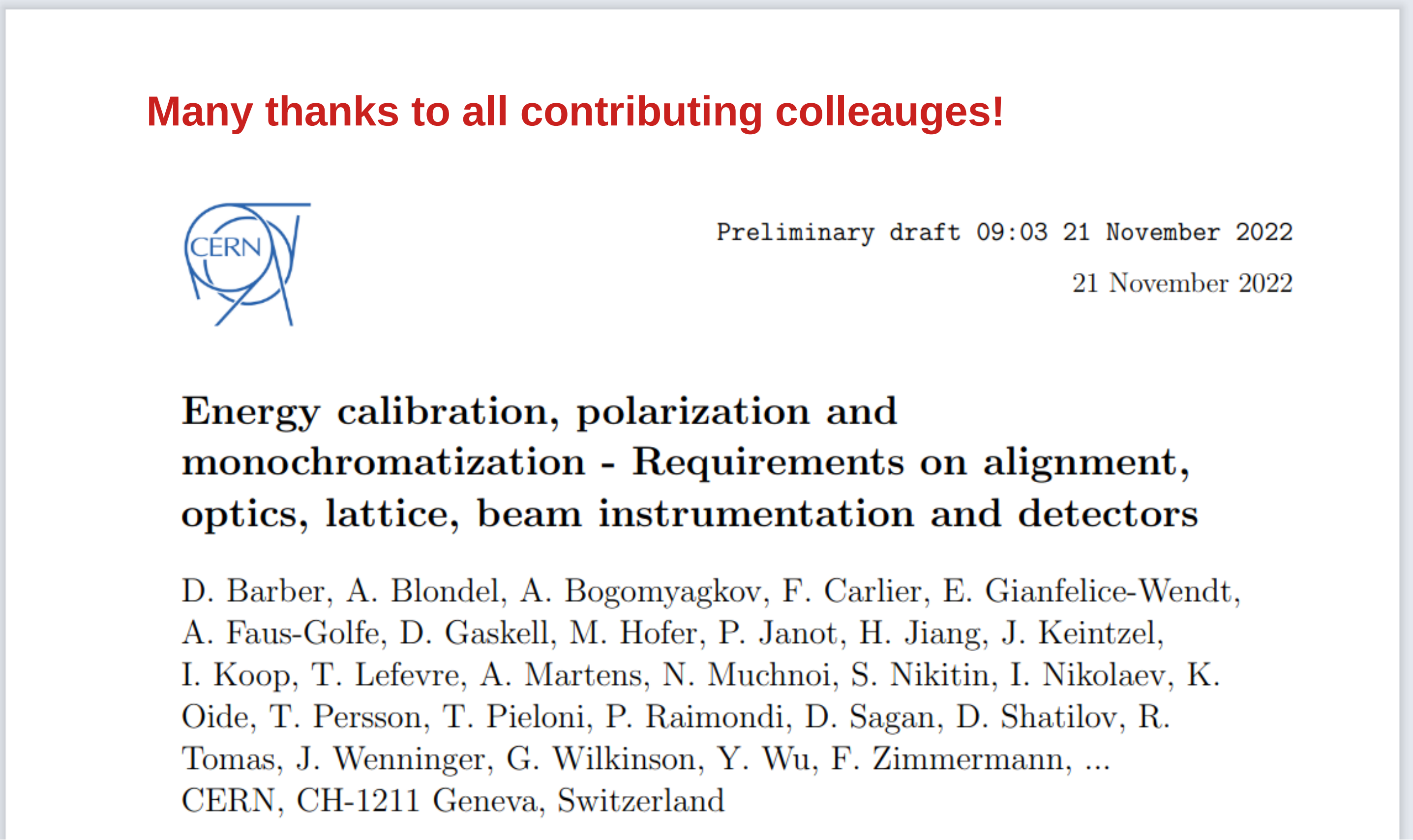
Statistics of 1 million dimuon events at Z-pole
e+e- –> μ+μ- (γ)
(γ)… Initial-State-Photon (ISR)



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 09:03 21 November 2022`

21 November 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

FUTURE
CIRCULAR
COLLIDER

CERN

Questions?

EPOL Status and First Technical Specifications

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

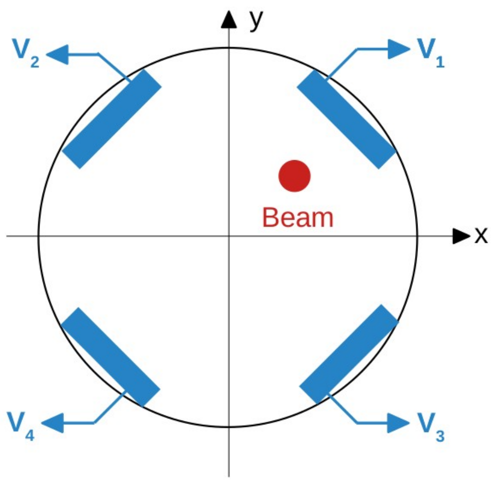
1st FCC Beam Instrumentation Workshop
21st November 2022

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.

BPM Requirements

- Beam Position Monitors (BPMs) essential
- 2 techniques

Schematic possible button BPM for FCC-ee



Buttons typically rotated by 45° due to strong synchrotron radiation

Orbit response matrix

Average over several turns

Turn-by-Turn Measurements

Turn-by-turn measurements
Bunch-by-bunch measurements
Goal phase error below 1x10^{-3}

FCC-Z mode at 45.6 GeV single particle tracking