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EPOL:
The roadmap to the final report

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On behalf of the
FCC-ee EPOL working group

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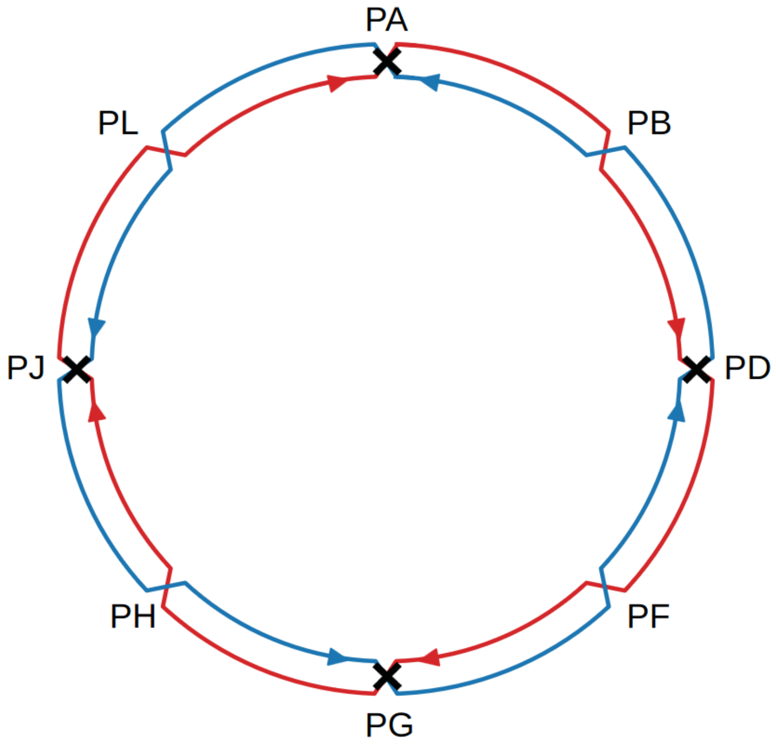
FCC Week 2023
London, United Kingdom
June 08, 2023

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.

FCC-ee Overview

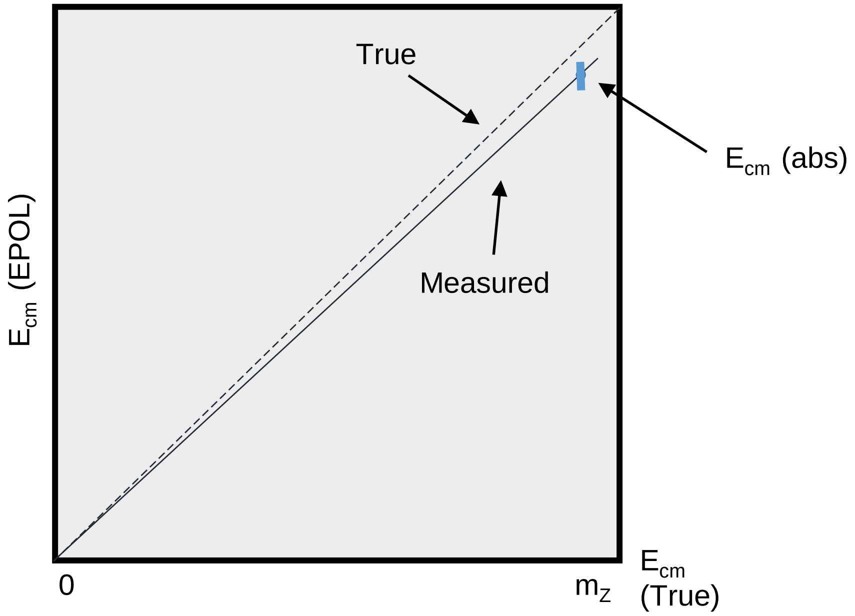
- **Particle Physics:**
- Higgs and electro-weak factory
- 4 baseline beam energies and diverse particle physics program
  - 45.6 GeV: Z-pole
  - 80 GeV: W-pair-threshold
  - 120 GeV: ZH-production
  - 182.5 GeV: top-pair-threshold
- High number of statistics

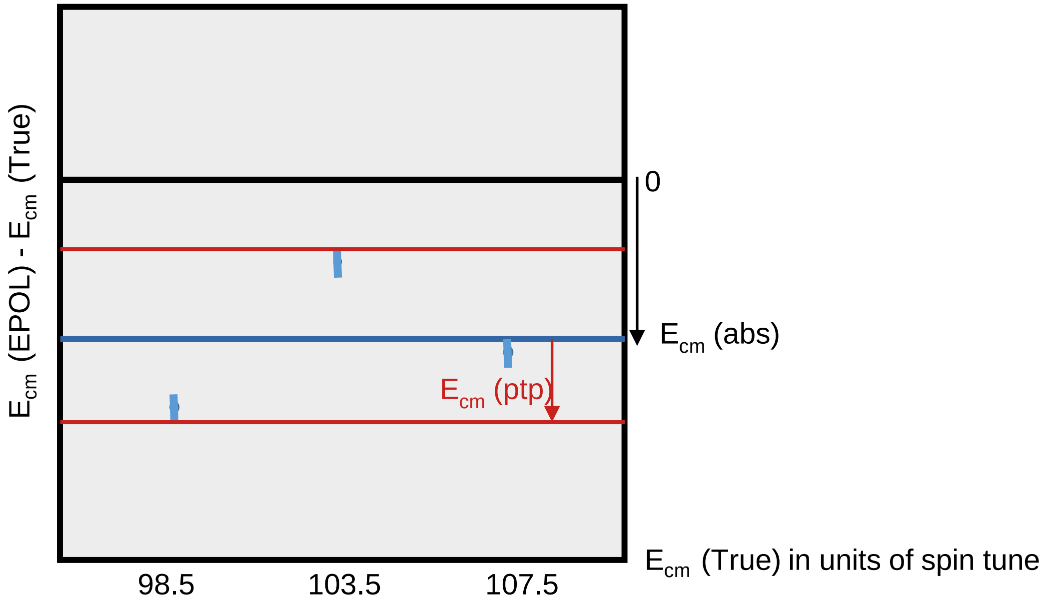


- **Accelerator Physics:**
- 4-fold super-symmetric layout
  - Up to 4 Interaction Points (IPs)
  - 1 RF-section per beam
  - 1 collimation section
  - 1 section for injection and dump
- Nanometer beam size at IPs
- Strong synchrotron radiation

Precision particle physics experiments ⟺ Center-of-mass energy determination

Center-of-mass Energy Uncertainty





- Error between measured and true E_{cm}
- Large effect on mass measurement
- Stems from systematic errors

- Fluctuation between measurements
- Large effect on resonance width measurements
- Stems from variability of measurement conditions

Courtesy: A. Blondel

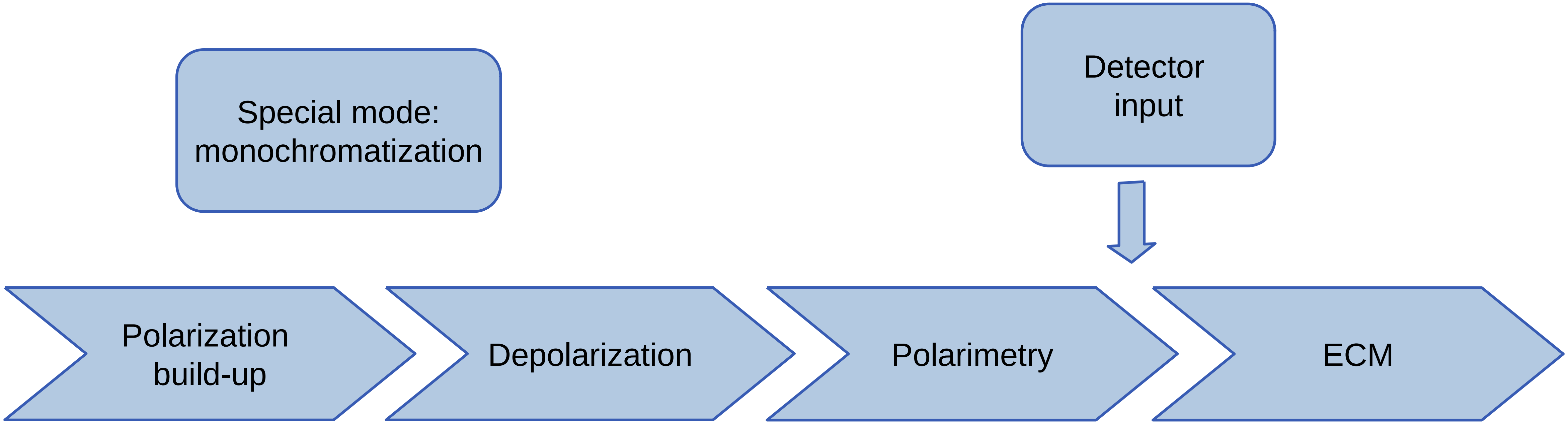
Expected Precision

	Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) $\pm$ **0.05** MeV
Z	m_Z (keV)	**4**	100	**28**	1	–
	Γ_Z (keV)	**4**	2.5	**22**	1	**10**
	$sin^2\theta_W^{\text{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	**2**	–	**2.4**	0.1	–
	$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	**3**	0.1	**0.9**	–	**0.05**
WW	Further clarification ongoing			300 keV	150 keV	
	m_W(MeV)	**0.200**	**(?)**	75 keV?		
	Γ_W (MeV)			(75?)	small	OK

- Large expected luminosity → huge statistics → small statistical error: **4 / 100 keV per Z / W - boson**
- Aim to achieve same order of magnitude for systematic errors → Scope of the **EPOL working group**
- EPOL: Energy calibration, polarization and monochromatization

arXiv:1909.12245

How to?



- Resonances
- Wigglers
- Beam tests

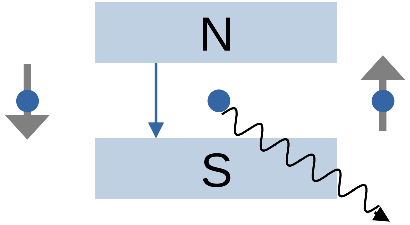
- Resonant depolarization
- Free spin precession

- Polarimeter incl.
- laser, Si-detectors
- e.g. EIC experience

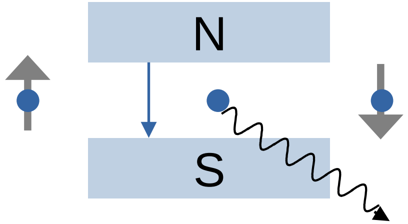
- Systematic errrors
- Statistical errors
- Accurate models

Polarization Build-Up

More likely
(by factor ~25)



Less likely



- Statistically every 10^{10} emitted synchrotron photon flips the spin
- Probability depends on the initial spin orientation

- Leads to a natural **polarization build-up** over time
- Orientation is **anti-parallel** to the guiding magnetic field

- Maximum theoretical polarization of **92.4 %**
- Spin precesses through the lattice → Spin tune

$$\nu = a * \gamma_{Rel}$$

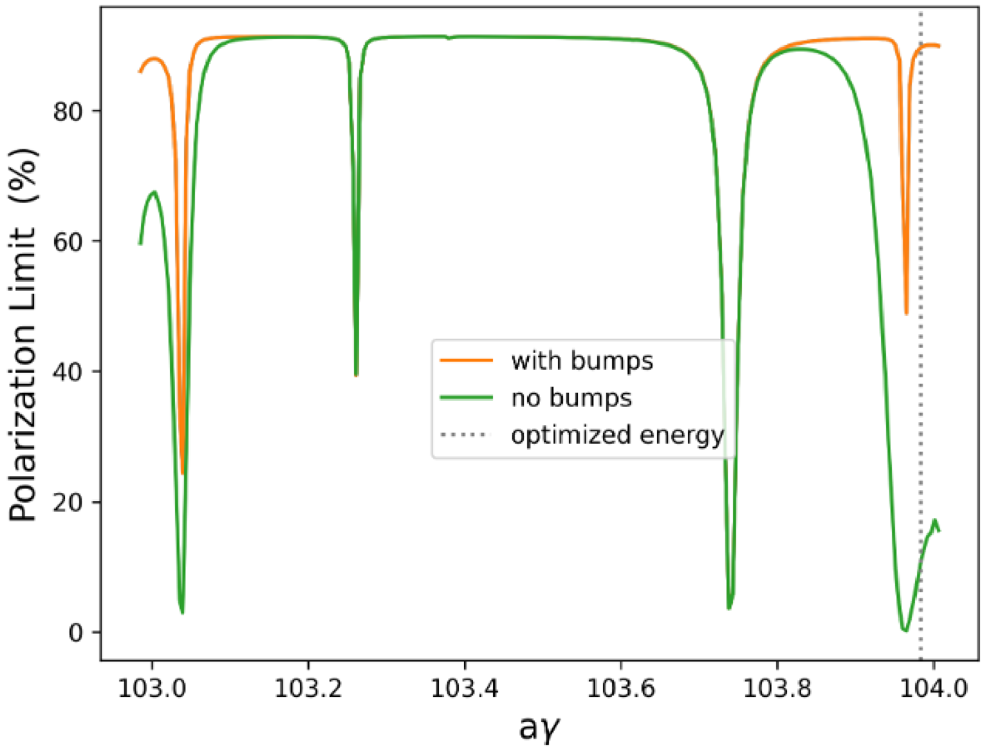
a … gyro-magnetic anomaly
γ_{Rel} … Lorentz-factor

Resonances and Orbit Bumps

- Polarization decreases with resonances, orbits, machine errors etc.
- Improved with special closed-orbit bumps

- Example: at 45.394 GeV → ν = 103.016
- Maximum polarization improved from 60 to 87 %
- Requires orbit and angle measurement between dipoles

- *What is the max. allowed closed orbit for polarization?*
- *How many BPMs are needed where, with which precision?*
- *Can this scheme be tested somewhere?*

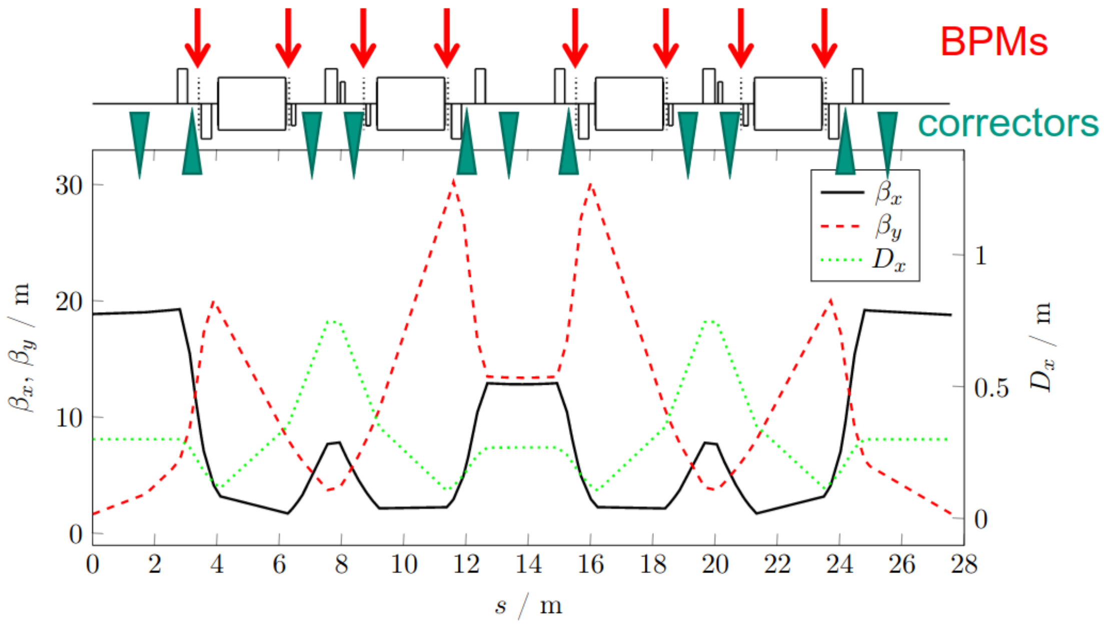


Courtesy: Y. Wu

Beam Test Polarization and Bumps

- KARA at KIT, polarization time ~ 10 min
- Polarization measurements via Touschek lifetime change

- Possible beam test:
- Generate strong depolarizing source
- Find orbit bumps to increase max. polarization

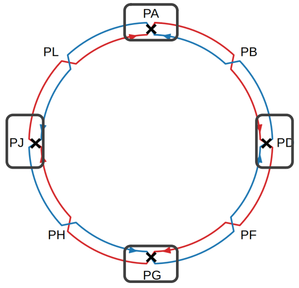


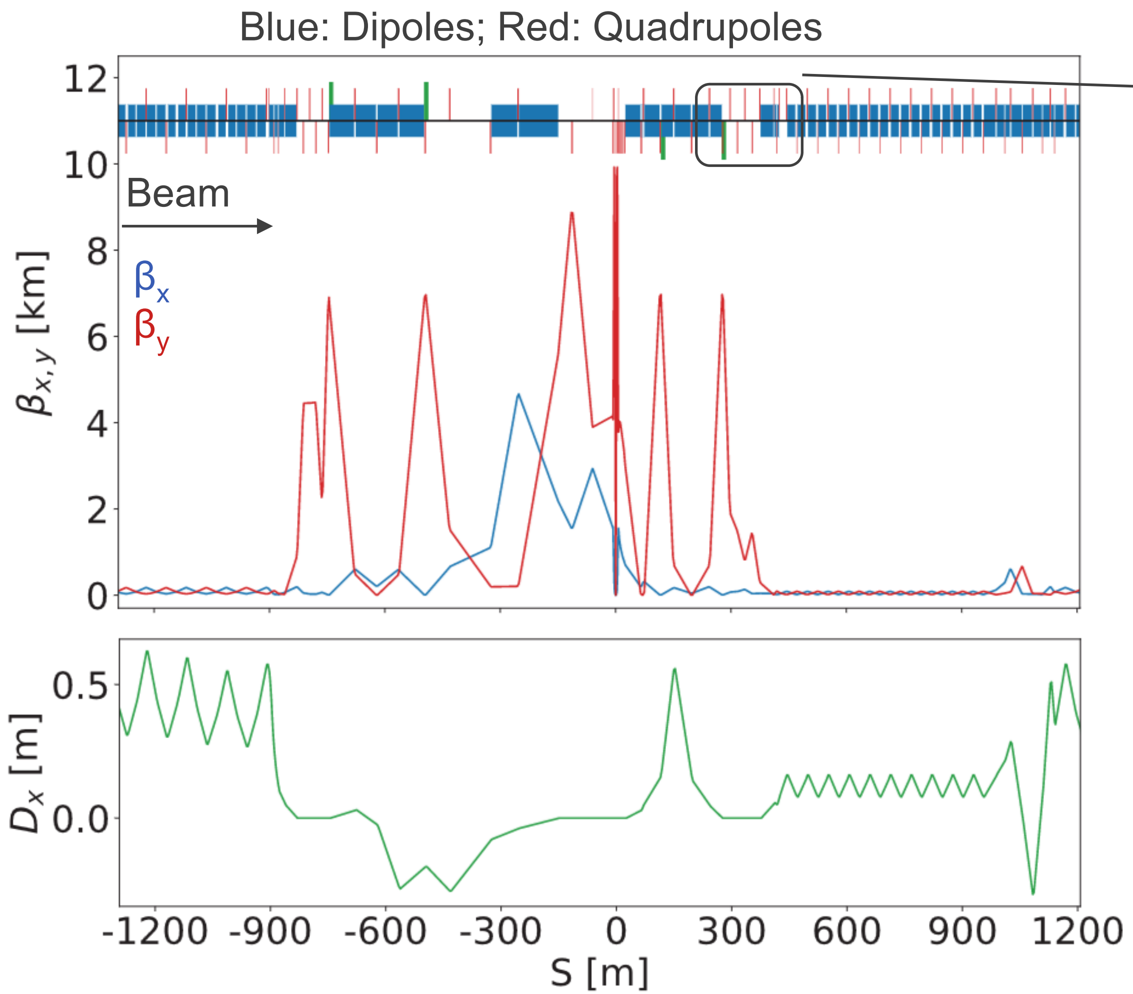
sector 1 (one quarter)

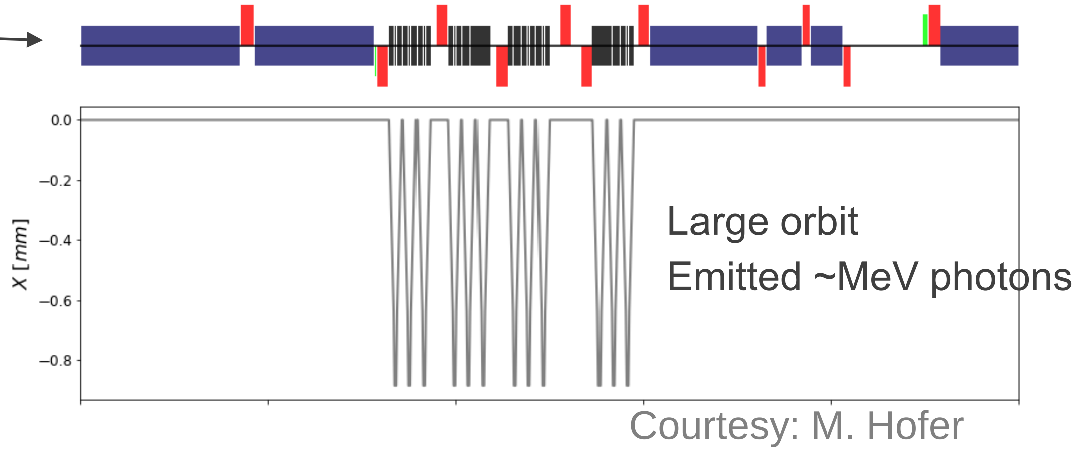
- *Can FCC-ee orbit bumps be tested at KARA?*
- *Possible long term idea: Is it possible to install and test an FCC-like polarimeter?*

Courtesy: B. Härer, E. Blomley

Wigglers



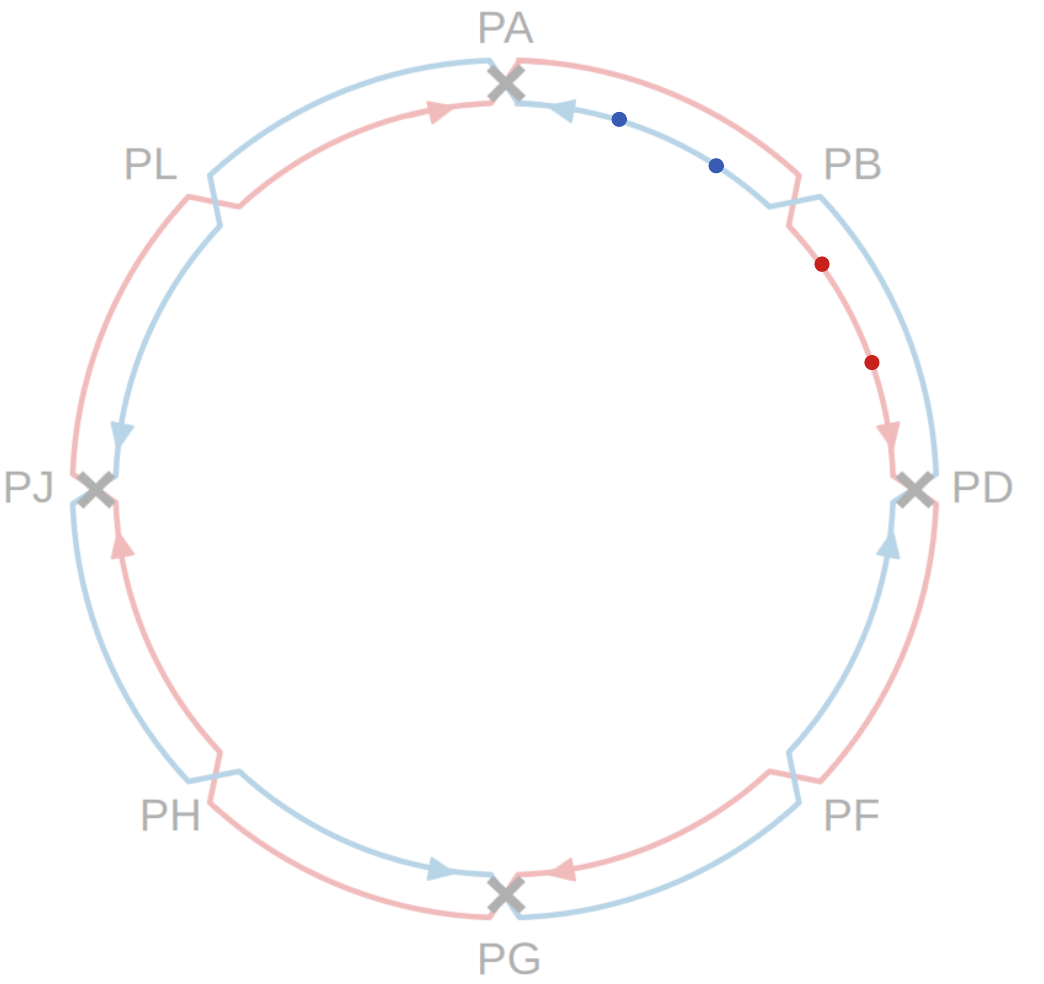




- At 45.6 GeV energy: Polarization time of 248 h
- Solution: wiggler magnets
  - Reduce polarization time to 12 h
  - Increase energy spread by factor ~ 3.5
- *Aim to have a realistic design of wiggler magnet.*

Operational Scenario

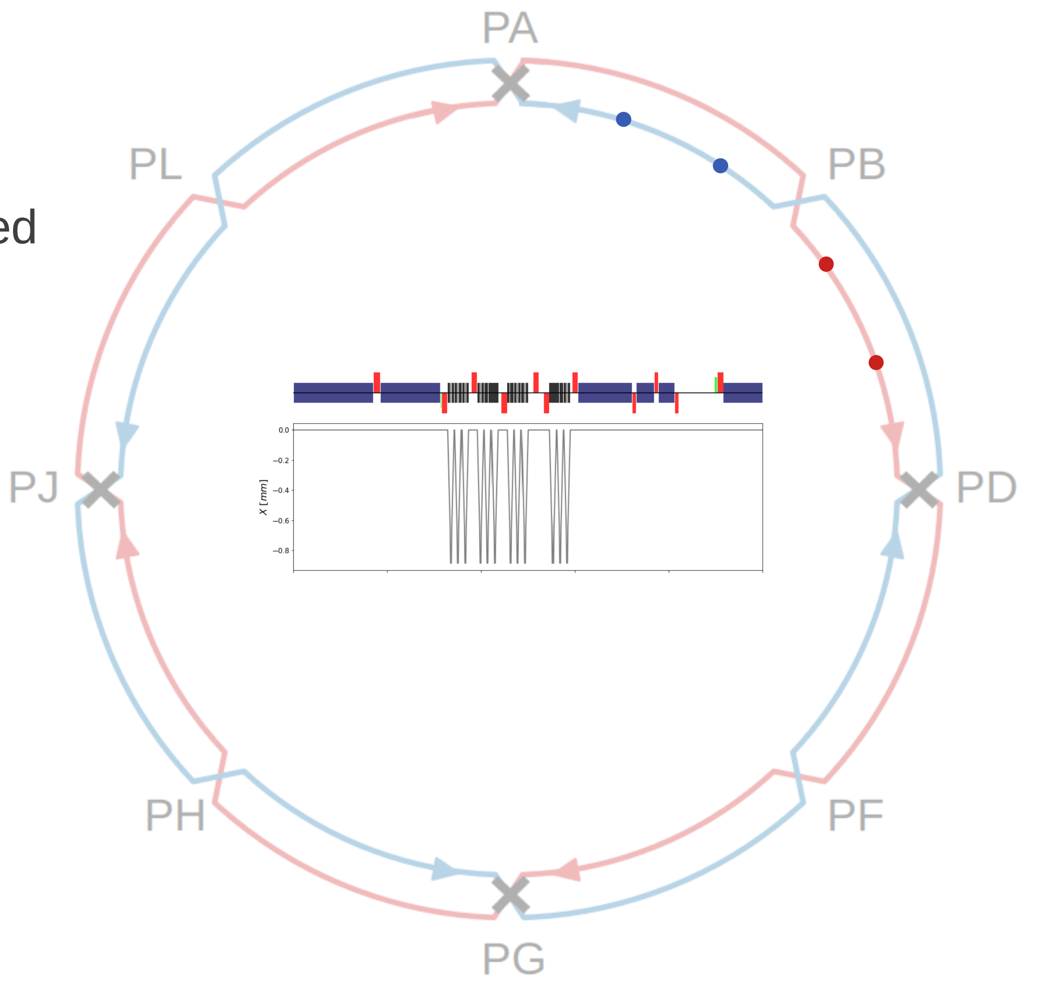
- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)



Operational Scenario

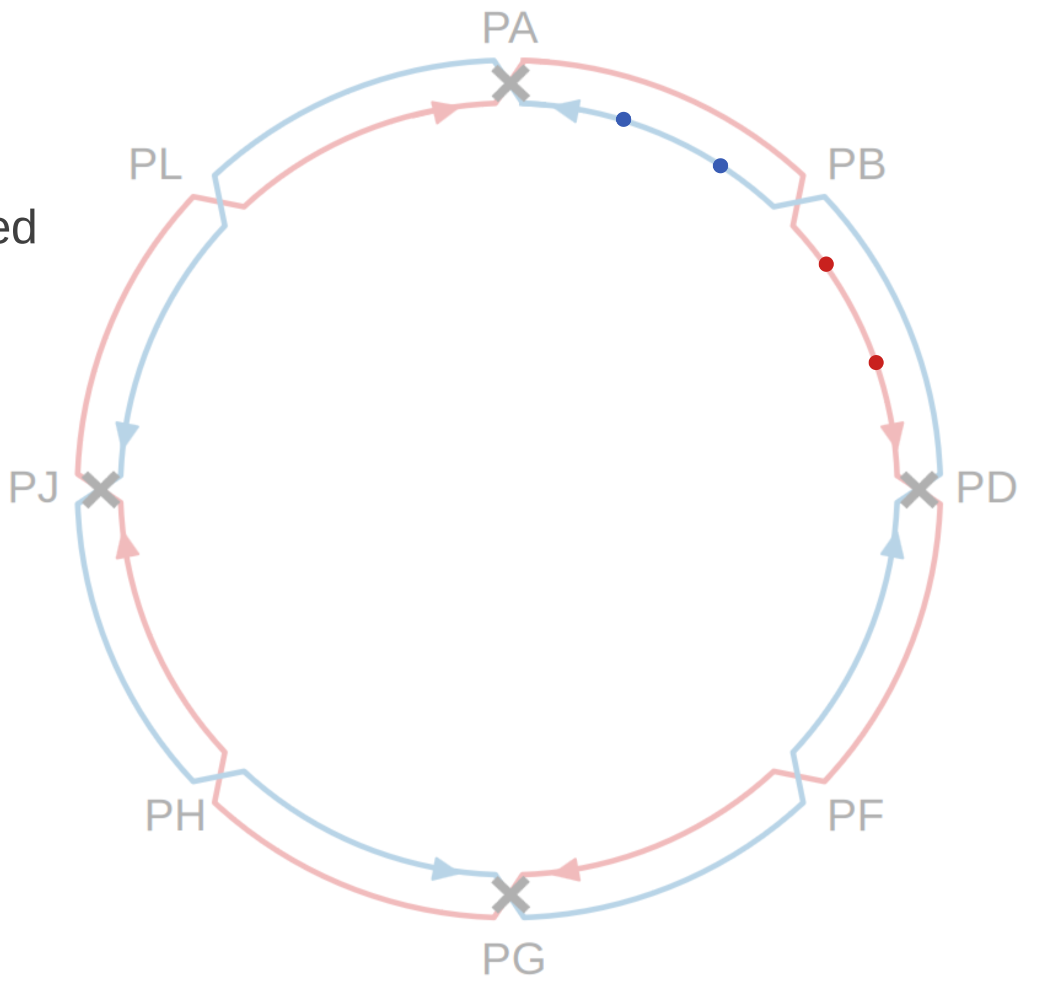
- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)

- Switch on wigglers until ~5-10 % **vertical polarization** reached



Operational Scenario

- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)
- Switch on wigglers until ~5-10 % **vertical polarization** reached
- Switch wigglers off



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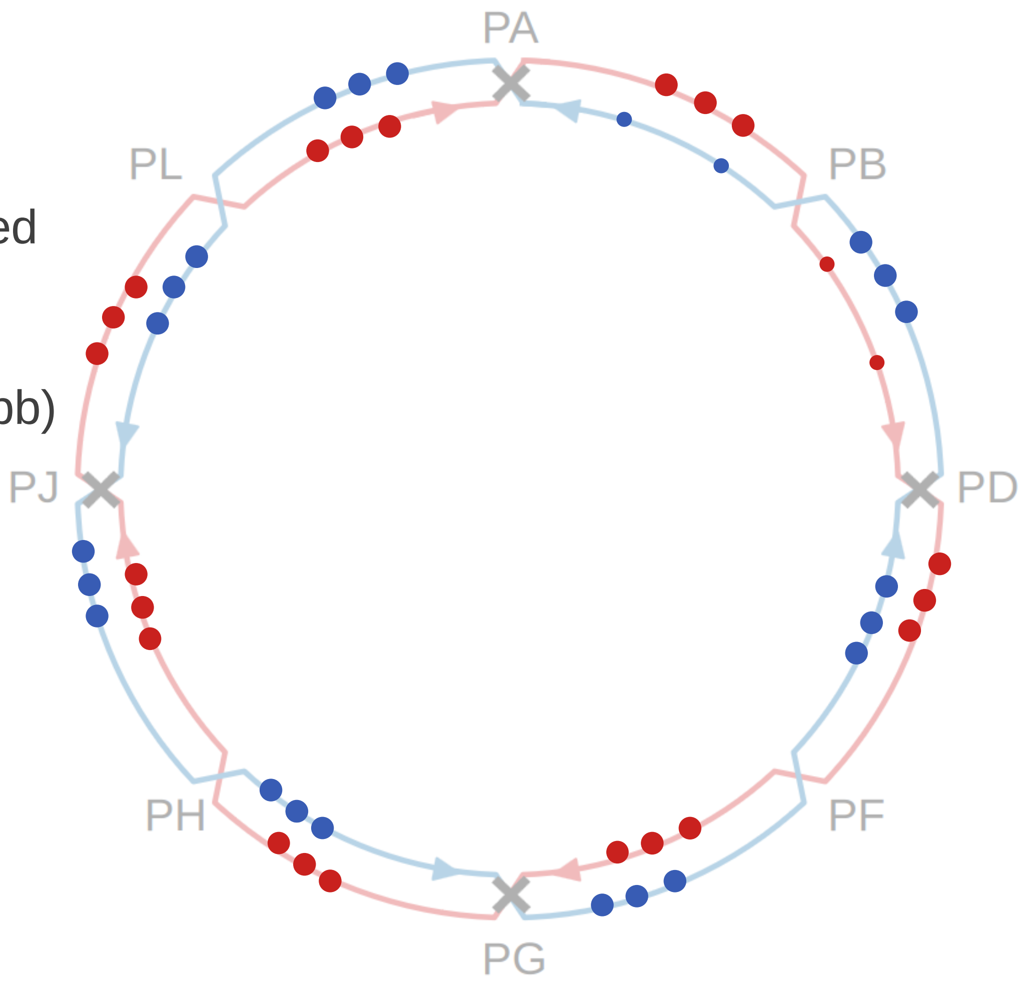
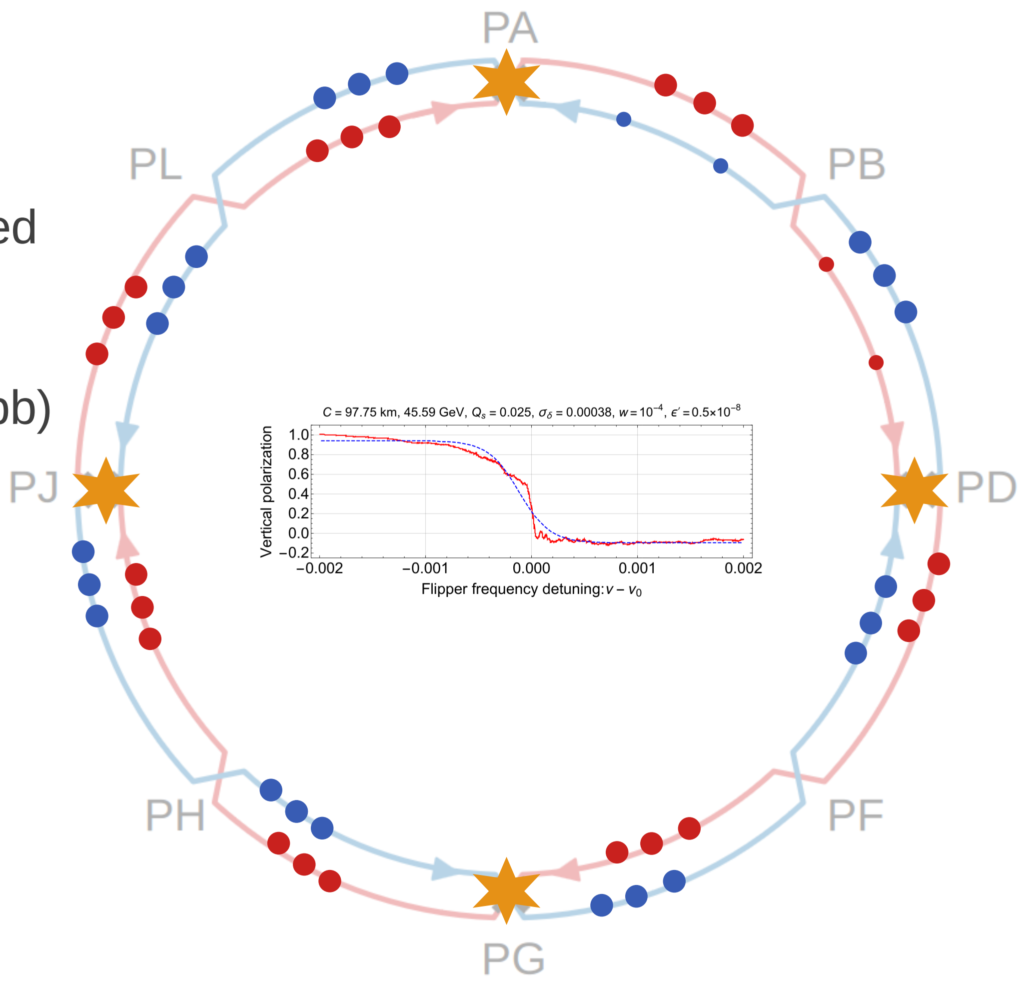
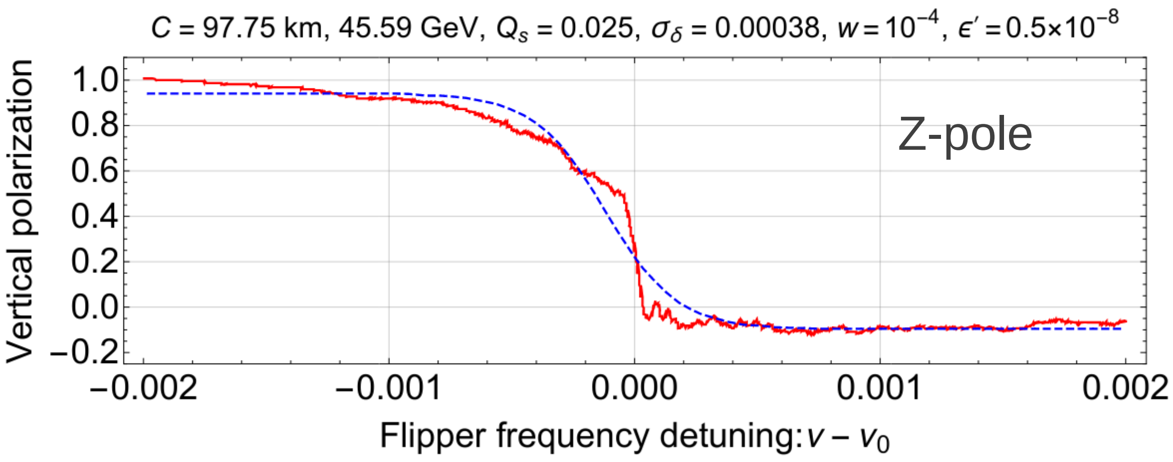


Operational Scenario

- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)
- Switch on wigglers until ~5-10 % **vertical polarization** reached
- Switch wigglers off and inject ~10^5 colliding bunches (~10^{11} ppb)
- Measure beam energy with pilots while collisions take place
- *What is the minimum required polarization level?*
- *Which pilot bunch intensities are required?*
- *What is their lifetime and do they need to be topped-up?*

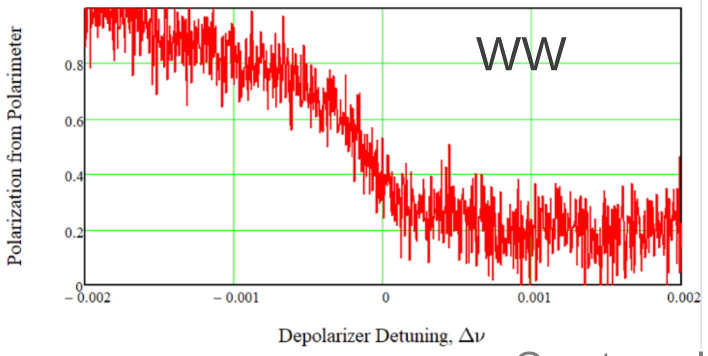


Resonant Depolarization



Natural width ~ 200 keV at Z

And 1.4 MeV at W



Courtesy: I. Koop

- Independent depolarizers per beam
- Easily accessible for maintainance
- TEM wave propagating towards a pilot bunch
- Varying exciting frequency

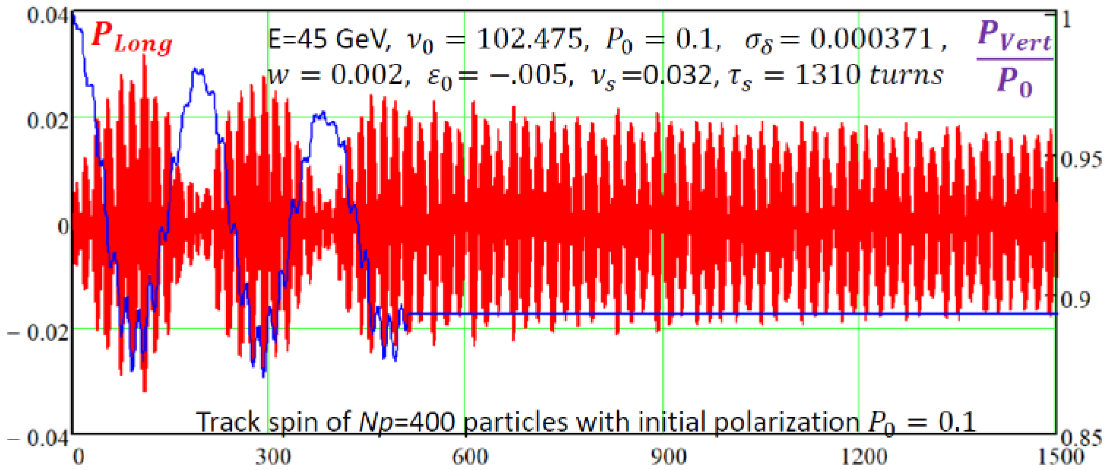
- Exciting frequency = spin tune = depolarization

- *Where is the best location for depolarizers?*
- *Do we need to scan in opposite directions simultanesouly? (2 depolarizers per beam?)*

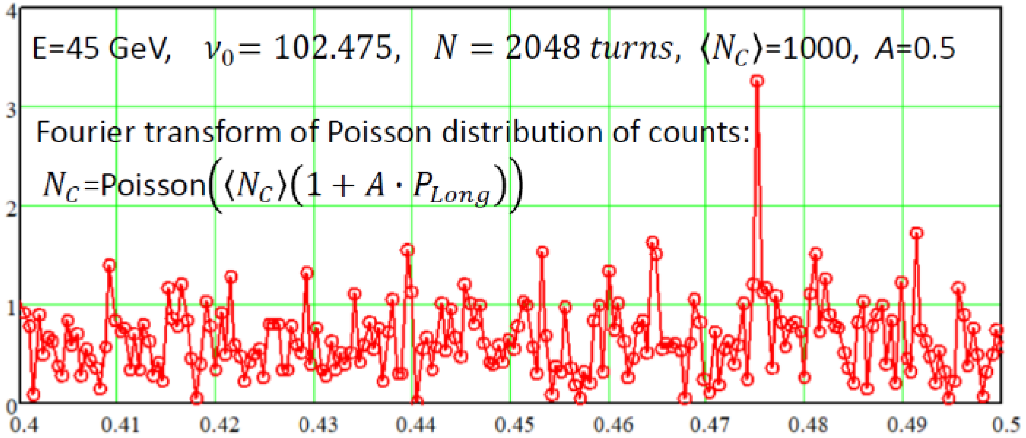
Free Spin Precession

- Stronger depolarizer kicks the vertical spin into other plane
- Observation of oscillation between these planes
- Spin tune obtained via Fourier Transform
- Yields the full spin spectrum

- *Is this technique feasible in a realistic machine?*
- *How often should this be performed?*
- *Can we flip the spin and re-use the same bunches?*



FSP at Z

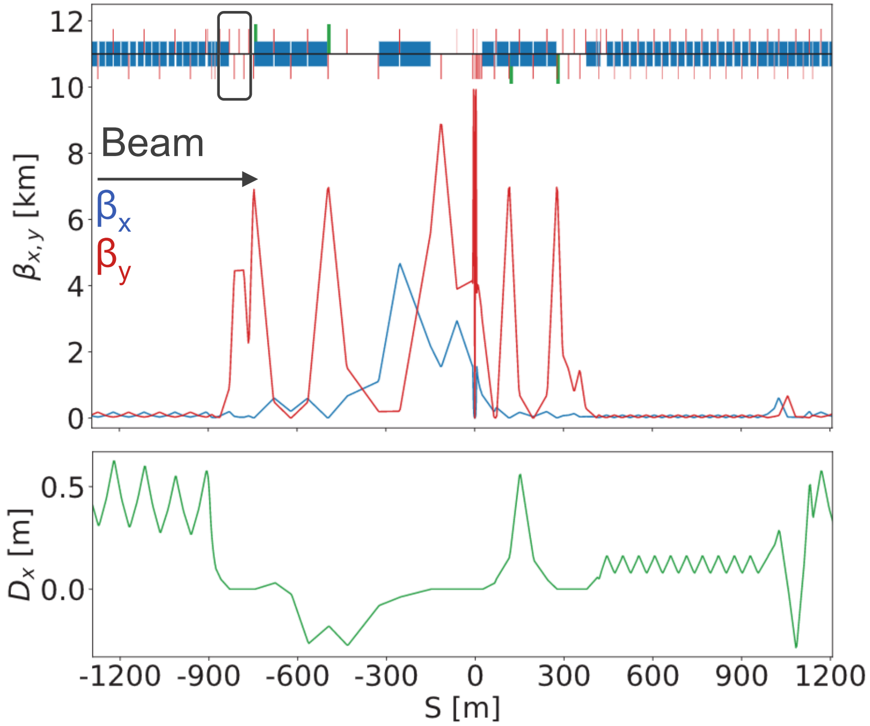


Courtesy: I. Koop

Polarimeter

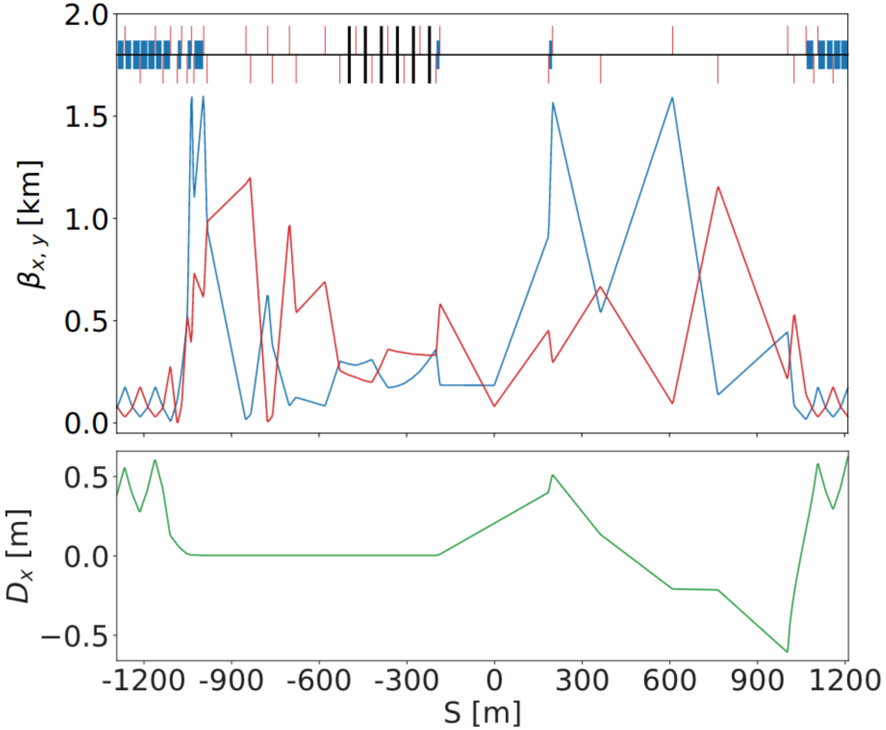
- In present experimental interaction region design space foreseen, but possibly more space in RF-section
- *Where is the best integration point for the polarimeters?*

Blue: Dipoles; Red: Quadrupoles



EIR

Blue: Dipoles; Red: Quadrupoles

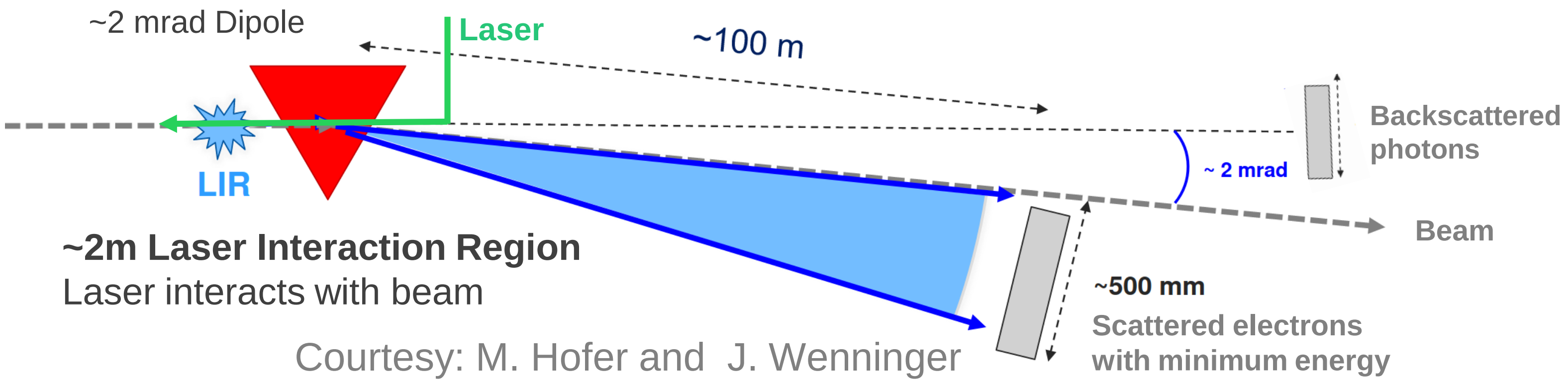


RF-Section

Polarimeter

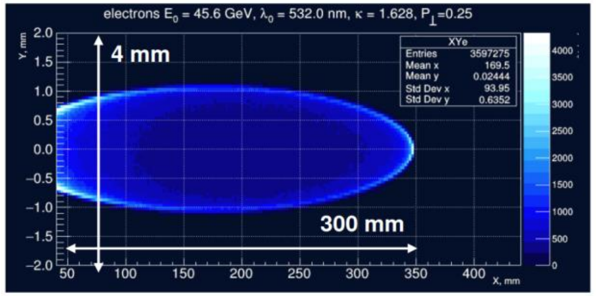
- ~ 520 nm circular polarized laser interacts with beam
- Back-scattered photons sufficient for resonance measurement
- Additional measurement of scattered electrons for 3D spin vector
- At least 1 polarimeter per beam

- *What can be gained more polarimeters?*
- *Can we learn from other projects, such as from EIC-experts?*



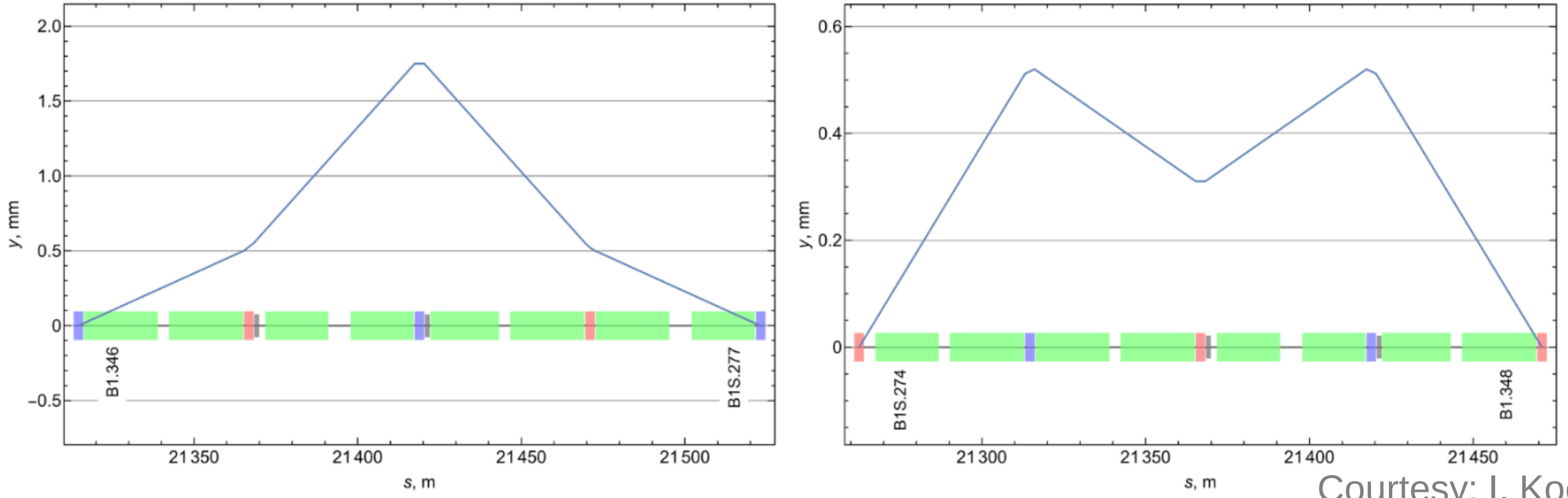
Courtesy: M. Hofer and J. Wenninger

Scattered electrons to be measured by Si pixel detector



Courtesy: N. Muchnoi

Colliding Bunches Polarization

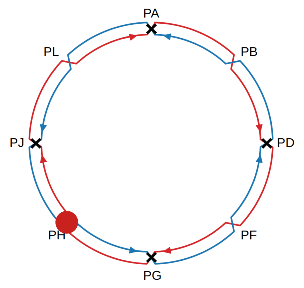


Courtesy: I. Koop

- **Take away message:**
- **Longitudinal** polarization could spoil measurements and must be **< 10-5**
- Depolarizers must also act on colliding bunches → Consider closed-orbit bumps to avoid impact at IP
- To be measured also with polarimeters

- *What could be the impact of RF-kickers acting on colliding bunches?*
- *Which RF-kicker and polarimeter design is the most suitable for pilot and colliding bunches?*

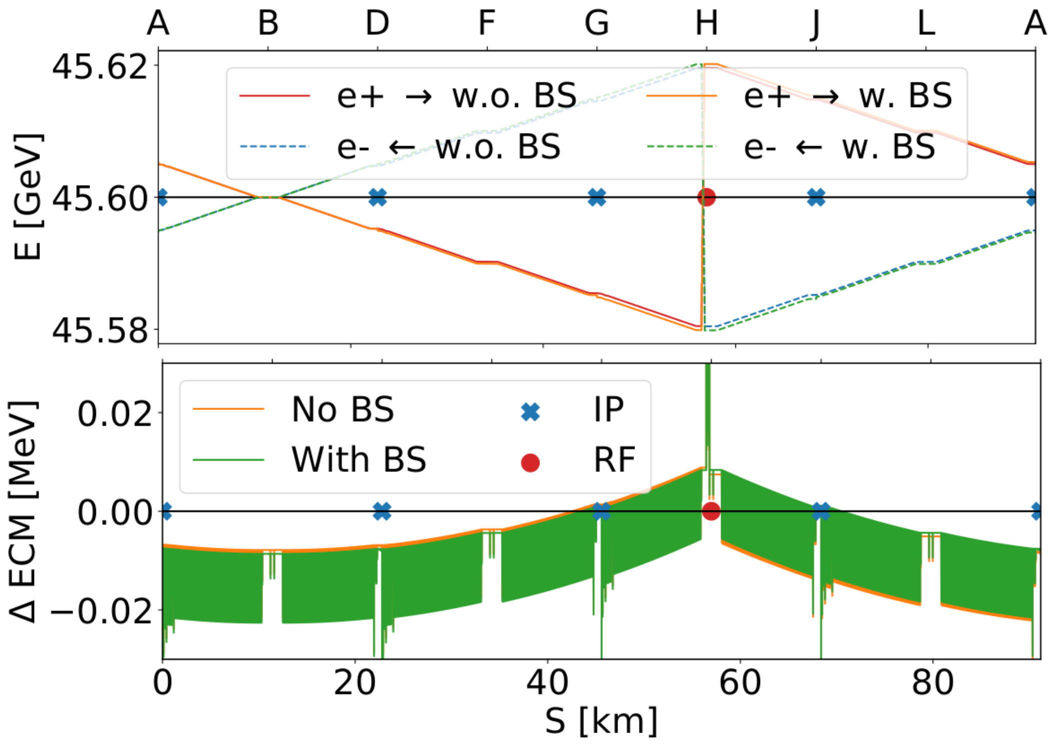
From Beam Energy to E_{CM}



- 40 MeV synchrotron radiation losses per turn
- Additional beamstrahlung (BS) (synchrotron radiation due to
- field of colliding bunch) ≲ 0.62 MeV/beam/IP

- **Same RF-section for both beams** to compensate losses
- ΔE_{cm} ~ -8 keV (PA, PD) and ~0.7 keV (PG, PJ)
- Boosts ~ +/- 10 MeV (PA, PD) and ~ +/- 30 MeV (PG, PJ)

- Pilot and colliding bunches have different local energy
- Accurate models essential
- *What are the systematics between pilot bunches and colliding ones?*



Dispersion and Collision Offset

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

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

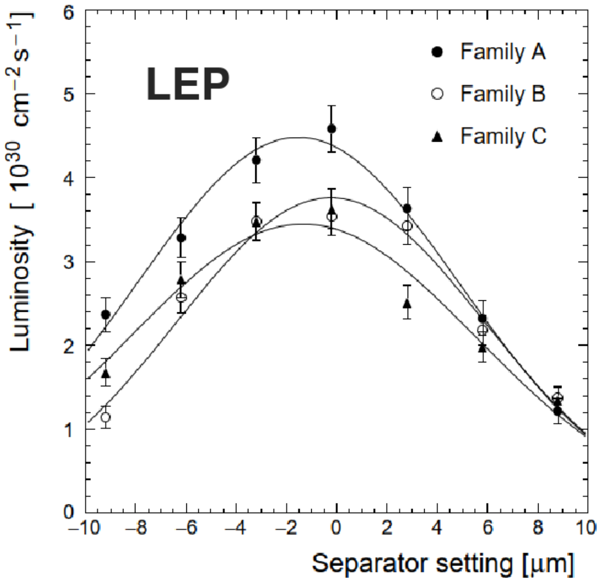
for $\Delta D^* = 1\ \mu m$, $\sigma_E/E = 0.13\%$

D… Dispersion
σ_u … transverse beam size
u_0 … collision offset

For **ΔD* = 10 μm**, 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.**

- Measurement and control of dispersion and collision offsets at IP essential
  - **ΔD < 1 μm** relaxes requirements on collision offsets

- *Can it be demonstrated that collision offsets can be controlled to ~0.1σ_y?*
- *How can we best measure dispersion at the IP? (RF-shift, orbit bump)*



[J. Wenninger: Beam-beam and OSVD]

Experiments

- G. Wilkinson: *Di-muon events - “The gift that keeps on giving”*
- Reliable and frequent logging of parameters essential
- Possibility to measure Z-bosons from higher E_{cm} events

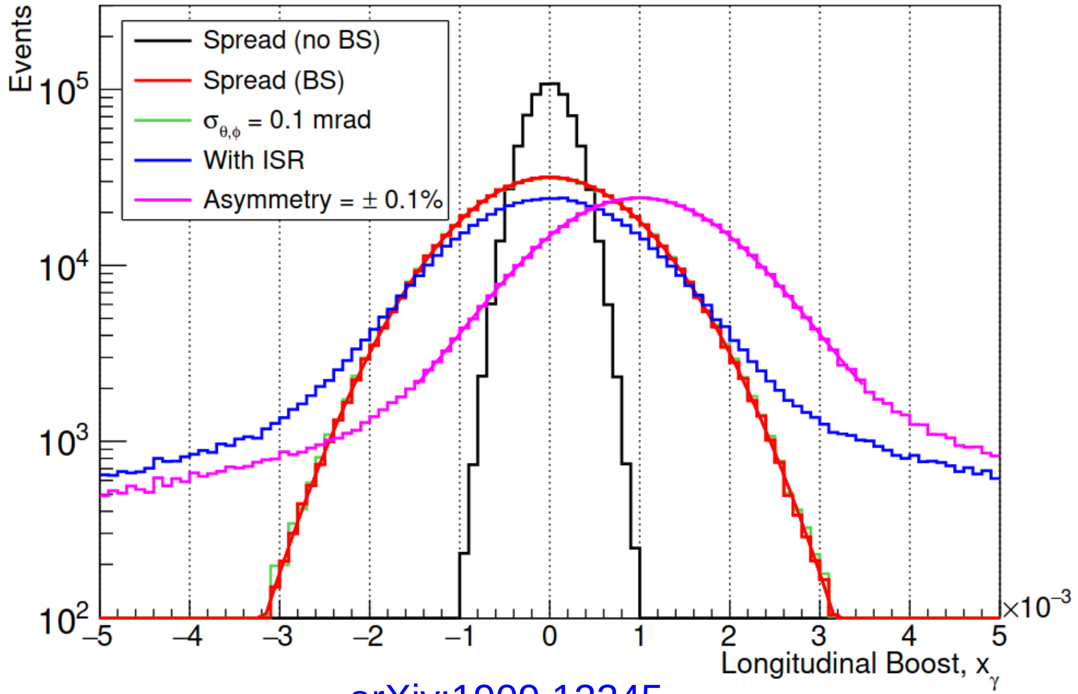
One million di-muon events per 8h shift
~ 5 keV statistical precession achievable

10^6 dimuon events at Z-pole: e+e- –> μ+μ- (γ)
(γ)… Initial-State-Photon (ISR)

Important message

All these results come from ‘proof-of-principle’ studies. They need to be repeated and consolidated with state-of-the-art ISR generators, proper simulation, realistic treatment of detector resolutions *etc.*, and extended to other fermion types and (in top regime) WW events. Many important & interesting studies to be performed !

Boost reconstruction from di-muon events

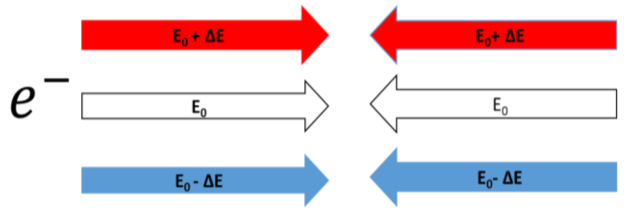


arXiv:1909.12245

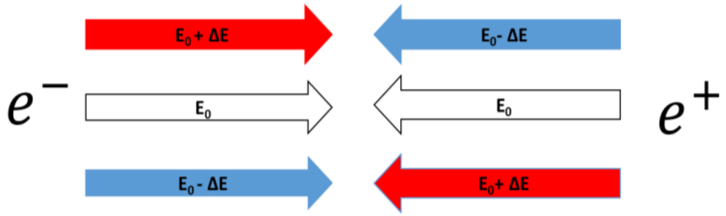
Monochromatization

- 62.5 GeV beam energy corresponds to the peak of Higgs-production with narrow width of 4.2 MeV
- For minimization of collision energy spread –> monochromatization techniques required
- *What is the most suitable monochromatization technique and how can it be implemented?*

Introducing dispersion



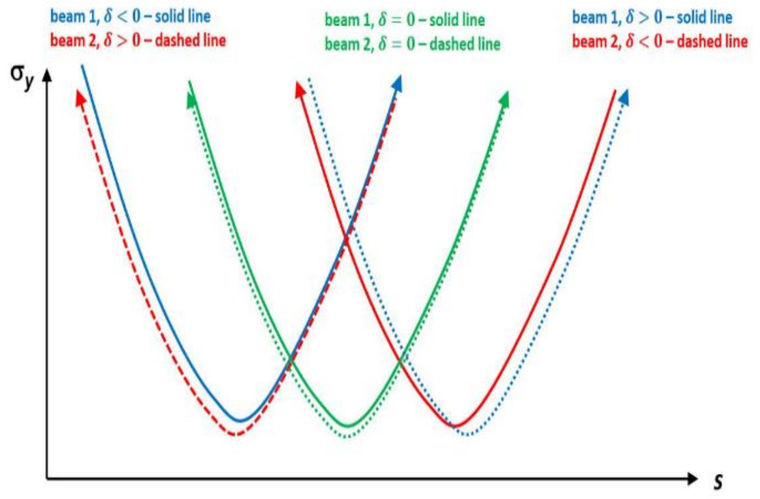
Same sign dispersion at the interaction point leads to change of E_{CM}



Opposite sign dispersion helps reducing E_{CM} spread

Courtesy: A. Faus-Golfe, H. Jiang and P. Raimondi

Introducing chromaticity



Non-zero local vertical chromaticity to reduce collision energy spread presently explored

Summary

- High precision particle physics experiments require excellent determination of E_{cm} and collision boosts

- Presently aimed to achieve *4 / 100 keV* systematic uncertainty for the *Z- / W- mass –> EPOL*

- A lot of great results produced so far and summarized in the mid-term report and FCC-note

- Many questions aimed to be answered until the end of the feasibility study, including beam tests

Regular EPOL meetings:
indico.cern.ch/category/8678/
Typically every second Thursday 16:30-18:30

Any help is welcome!

Mailing list:
fcc-ee-PolarizationAndEnergyCalibration@cern.ch

Self-subscription from:
https://e-groups.cern.ch/e-groups/EgroupsSearch.do

Thank you!

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On behalf of the FCC-ee EPOL working group

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Algorithm for disentangling of SR and coherent losses

Two beam Energies in a detector $\boldsymbol{E_e}$, $\boldsymbol{E_p}$ depend on beam currents ***I1, I2*** (coherent losses) and on SR losses. These dependences can be parametrized via simple power law:

$$E_e = E1 + a1 \cdot (I1)^{\alpha} + b1 \cdot (E1)^{\beta}$$
$$E_p = E2 + a2 \cdot (I2)^{\alpha} + b2 \cdot (E2)^{\beta}$$

- where ***E1, E2*** - RD-energies; ***I1, I2*** – beam currents;
α, β – the coherent and the SR power law degrees
$\boldsymbol{a1}$, $\boldsymbol{a2}$, $\boldsymbol{b1}$, $\boldsymbol{b2}$ – unknown fit coefficients.

In our MC simulation we chose α=1, β=4. Power law index α can be measured/fitted by interpolation of the closed orbit shift dependence on the current in high dispersion places near RF straight section (Jorg's remark at august 2022 EPOL meeting).

Energy boost: $E_e - E_p = E1 - E2 + a1(I1)^{\alpha} - a2(I2)^{\alpha} + b1(E1)^{\beta} - b2(E2)^{\beta}$

N equations: *n*=1, 2, …, *N* with known *E*1, *E*2; *I*1, *I*2; α, β; and with unknown linear fit coefficients $a1$, $a2$, $b1$, $b2$. The reconstructed c.m. energy is a sum of beams energy:

$$E_{cm} = E_e + E_p = E1 + E2 + a1(I1)^{\alpha} + a2(I2)^{\alpha} + b1(E1)^{\beta} + b2(E2)^{\beta}$$