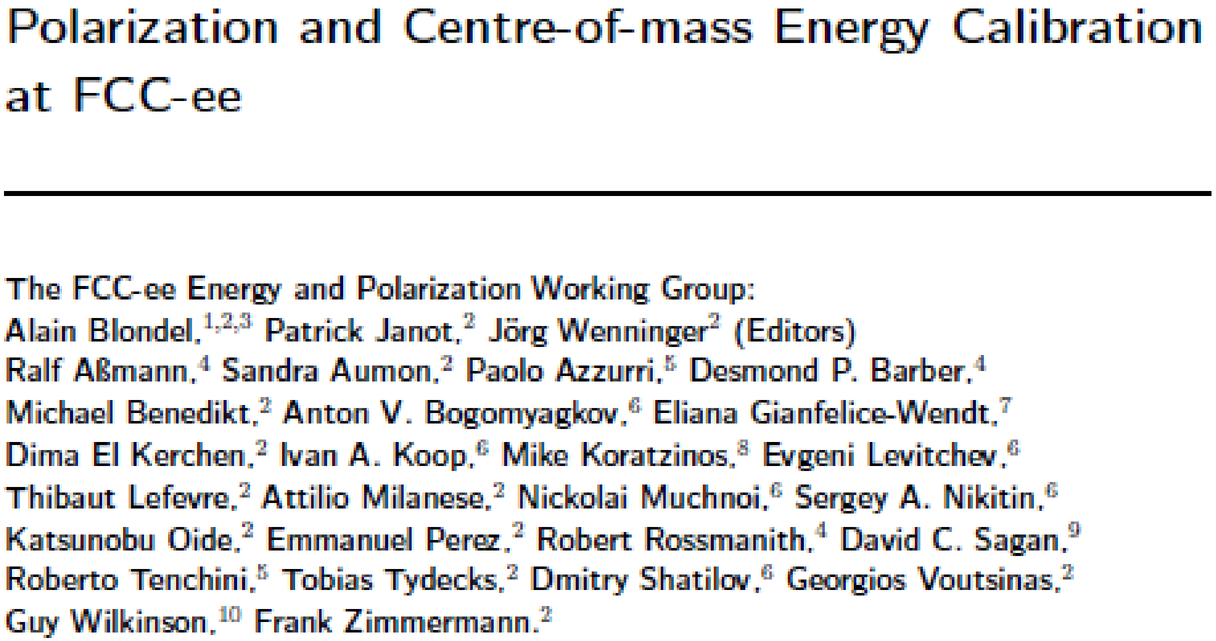
FCC-ee beam polarization and Energy Calibration
(starting a list of) MDI requests



Polarization and Centre-of-mass Energy Calibration at FCC-ee

The FCC-ee Energy and Polarization Working Group:
Alain Blondel,[1,2,3] Patrick Janot,[2] Jörg Wenninger[2] (Editors)
Ralf Aßmann,[4] Sandra Aumon,[2] Paolo Azzurri,[5] Desmond P. Barber,[4]
Michael Benedikt,[2] Anton V. Bogomyagkov,[6] Eliana Gianfelice-Wendt,[7]
Dima El Kerchen,[2] Ivan A. Koop,[6] Mike Koratzinos,[8] Evgeni Levitchev,[6]
Thibaut Lefevre,[2] Attilio Milanese,[2] Nickolai Muchnoi,[6] Sergey A. Nikitin,[6]
Katsunobu Oide,[2] Emmanuel Perez,[2] Robert Rossmanith,[4] David C. Sagan,[9]
Roberto Tenchini,[5] Tobias Tydecks,[2] Dmitry Shatilov,[6] Georgios Voutsinas,[2]
Guy Wilkinson,[10] Frank Zimmermann.[2]

Some references (not a complete set!):

B. Montague, Phys.Rept. 113 (1984) 1-96;

Polarization at LEP, CERN Yellow Report *88-02;*

Beam Polarization in e+e- , AB, CERN-PPE-93-125 Adv.Ser.Direct.High Energy Phys. 14 (1995) 277-324;

L. Arnaudon et al., Accurate Determination of the LEP Beam Energy by resonant depolarization, Z. Phys. C 66, 45-62 (1995).

Spin Dynamics in LEP http://dx.doi.org/10.1063/1.1384062

Precision EW Measts on the Z Phys.Rept.427:257-454,2006 arXiv:0509008v3

D.P. Barber and G. Ripken ``Handbook of Accelerator Physics and Engineering" World Scientific (2006), (2013)

D.P. Barber and G. Ripken, Radiative Polarization, Computer Algorithms and Spin Matching in Electron Storage Rings arXiv:physics/9907034

for FCC-ee:

First look at the physics case of TLEP arXiv:1308.6176, **JHEP 1401 (2014) 164**

DOI: 10.1007/JHEP01(2014)164

M. Koratzinos FCC-ee: Energy calibration IPAC'15 arXiv:1506.00933

E. Gianfelice-Wendt: Investigation of beam self-polarization in the FCC-ee arXiv:1705.03003

October EPOL workshop: https://indico.cern.ch/event/669194/

Requirements from physics

1. Center-of-mass energy determination with precision of ± 100 keV around the Z peak
2. Center-of-mass energy determination with precision of ± 300 keV at W pair threshold
3. For the Z peak-cross-section and width, require energy spread uncertainty $\Delta\sigma_E/\sigma_E = 0.2\%$

NB: at 2.3 10^{36}/cm^2/s/IP : **full LEP statistics** 10^6 μμ 2.10^7 qq in **6 minutes** in each expt

-- use resonant depolarization as main measuring method

-- use pilot bunches to calibrate during physics data taking: 100 calibrations per day each 10^{-6} rel

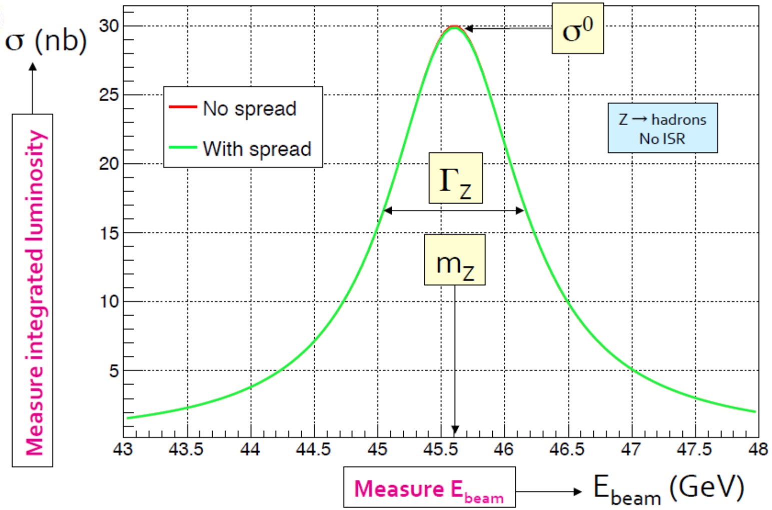
-- long lifetime at Z requires the use of wigglers at beginning of fills

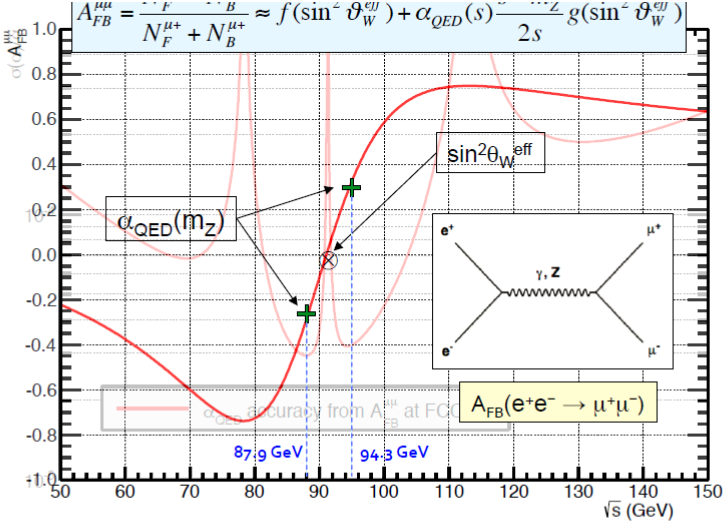
➔ take data at points where self polarization is expected

$$\boxed{\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}} \approx N + (0.5\pm0.1) \qquad \mathbf{E_{CM}} = \left(N + (0.5\pm0.1)\right) \text{ x } 0.8812972 \text{ GeV}$$

Given the Z and W widths of 2 GeV, this is easy to accommodate with little loss of statistics.

It might be more difficult for the Higgs: √s= 125.09+-0.2 corresponds to ν_s *= 141.94+-022*





scan proposed for FCC-ee

Scan point	Centre-of-mass Energy	Beam Energy	Spin tune
E_{CM}^{-} A	87.69	43.85	99.5
E_{CM}^{-} Request	87.9	43.95	99.7
E_{CM}^{-} B	88.57	44.28	100.5
E_{CM}^{0}	91.21	45.61	103.5
E_{CM}^{+} A	93.86	46.93	106.5
E_{CM}^{+} Request	94.3	47.15	107.0
E_{CM}^{+} B	94.74	47.37	107.5

probably a 5 point scan allowing measurement with different

Hardware requirements: wigglers

Given the long polarization time at Z, wigglers will be necessary.
An agreement was reached on a set of **8 wiggler units per beam**

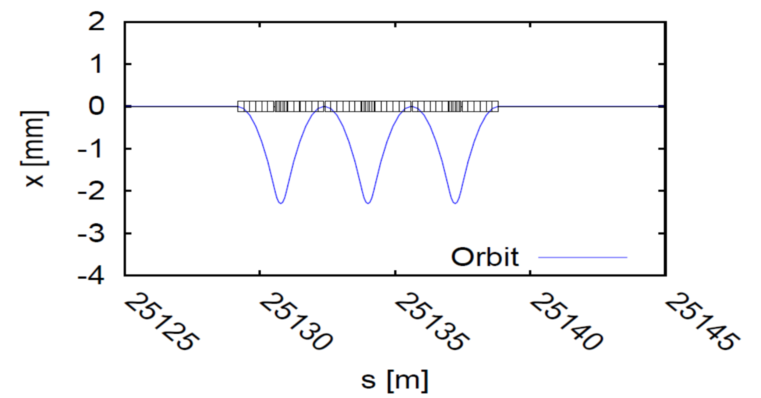
Polarization wigglers

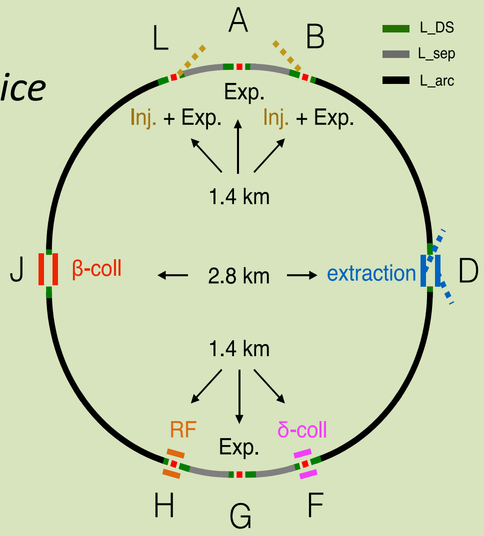
8 units per beam, as specified by *Eliana Gianfelice*

$B+=0.7$ T $L+ = 43$cm $L-/L+ = B+/B- = 6$

at $E_b = 45.6$ GeV and $B+= 0.67$ T

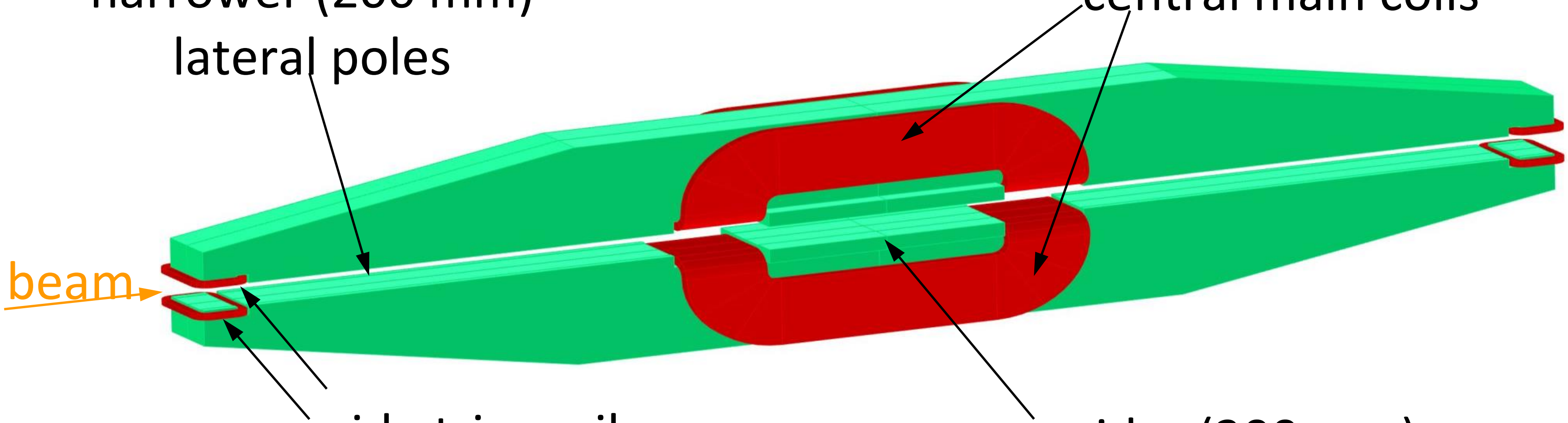
=> $P=10\%$ in 1.8H $\sigma_{Eb} = 60$ MeV $E_{crit}=902$ keV





placed e.g. in dispersion-free straight section H and/or F

First single pole magnetic concept, keeps some of the ideas of the LEP design, in particular the “floating” poles



narrower (200 mm) lateral poles

central main coils

side trim coils

wider (300 mm) central pole

mass ≈ 4 tons

A. Milanese

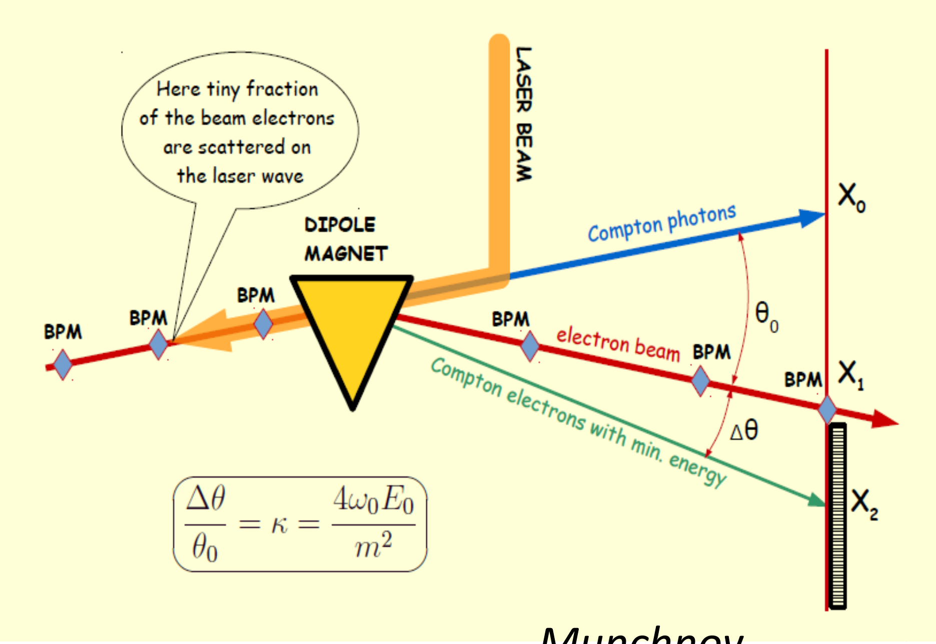
Hardware requirements: polarimeters

2 Polarimeters, one for each beam

Backscattered Compton $\gamma + e \rightarrow \gamma + e$ **532 nm (2.33 eV) laser; detection of photon and electron.**

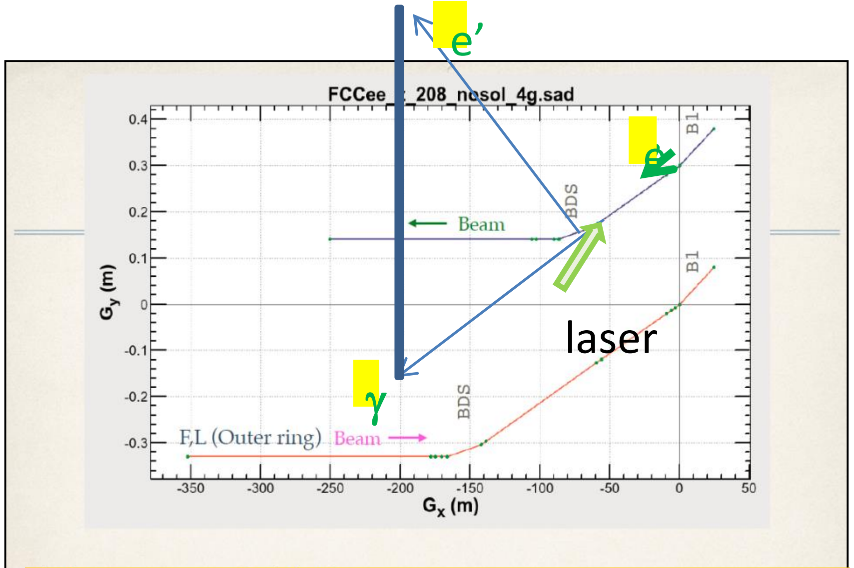
Change upon flip of laser circular polarization → beam Polarization ±0.01 per second

End point of recoil electron → beam energy monitoring ± 4 MeV per second



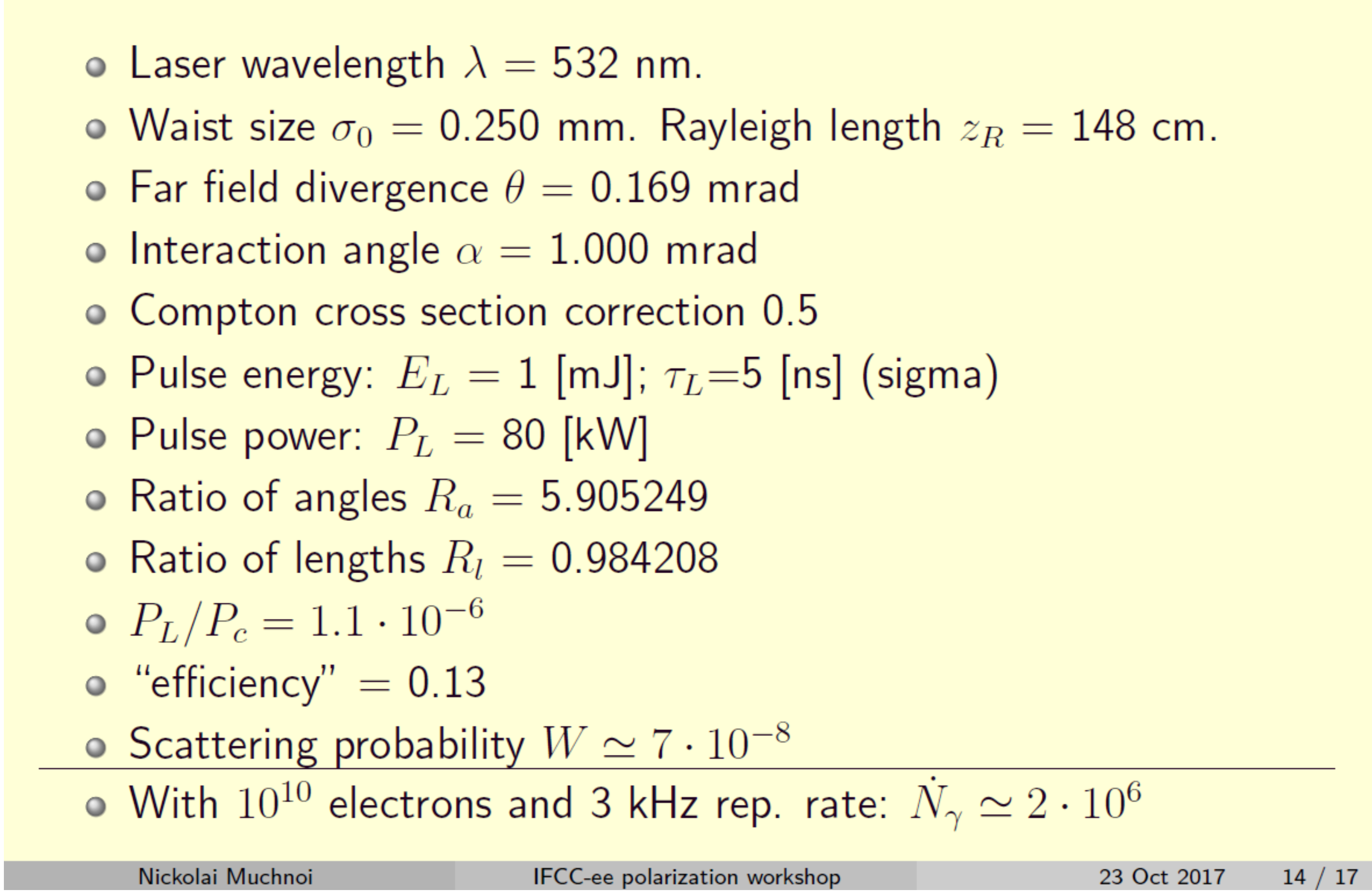
$$\frac{\Delta\theta}{\theta_0} = \kappa = \frac{4\omega_0 E_0}{m^2}$$

Munchnoy



install photon-electron IP on inner ring in points H and F *(Oide)*

Compton Polarimeter: Rates



- Laser wavelength $\lambda = 532$ nm.
- Waist size $\sigma_0 = 0.250$ mm. Rayleigh length $z_R = 148$ cm.
- Far field divergence $\theta = 0.169$ mrad
- Interaction angle $\alpha = 1.000$ mrad
- Compton cross section correction 0.5
- Pulse energy: $E_L = 1$ [mJ]; τ_L=5 [ns] (sigma)
- Pulse power: $P_L = 80$ [kW]
- Ratio of angles $R_a = 5.905249$
- Ratio of lengths $R_l = 0.984208$
- $P_L / P_c = 1.1 \cdot 10^{-6}$
- "efficiency" $= 0.13$
- Scattering probability $W \simeq 7 \cdot 10^{-8}$

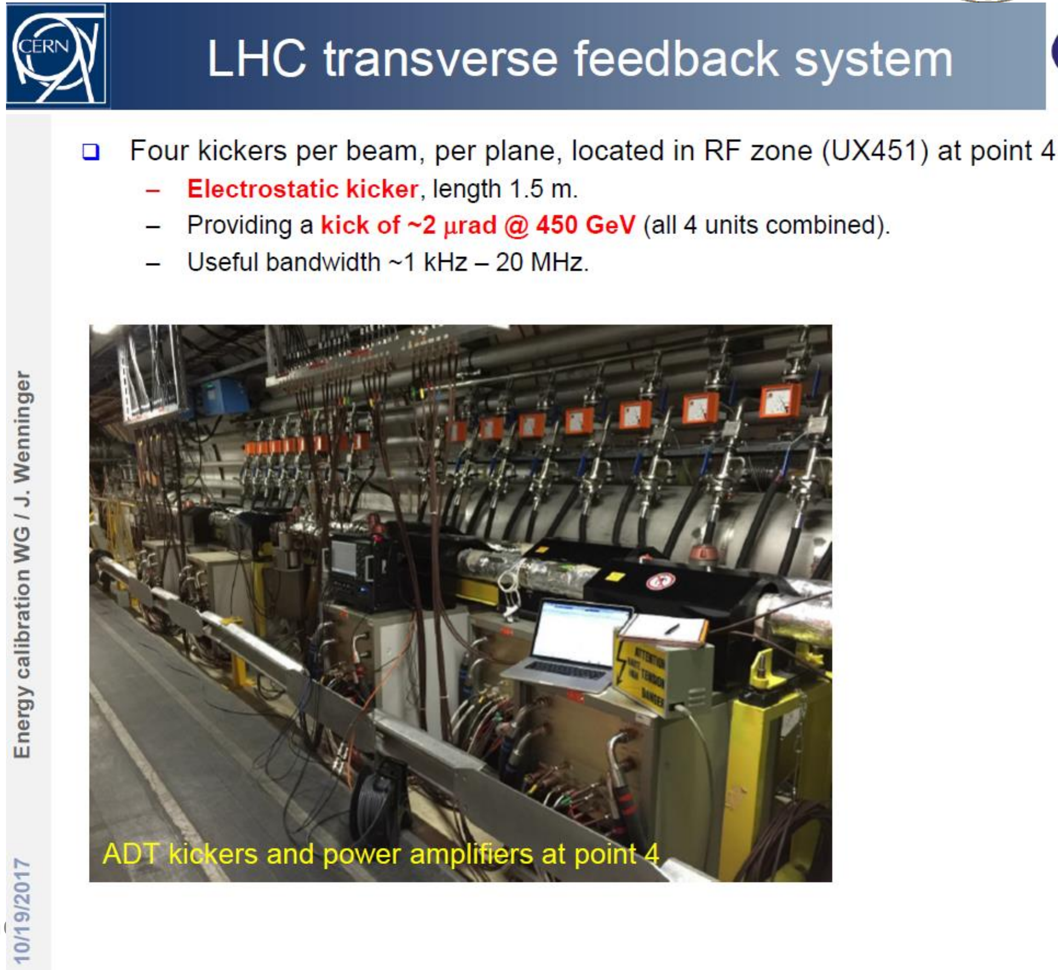
- With 10^{10} electrons and 3 kHz rep. rate: $\dot{N}_\gamma \simeq 2 \cdot 10^6$

Nickolai Muchnoi IFCC-ee polarization workshop 23 Oct 2017 14 / 17

Depolarization

This is not-so trivial in FCC-ee!
16700 bunches circulate
time-between-bunches = 19ns,
depolarize one-and-only-one
of them.
Kicker must have fast (<9ns) rise.

The LHC TF system works essentially on a bunch by bunch basis for 25ns.
They would provide a transverse kick of up to ~20 mrad at the Z peak with ~10 MHz bandwidth. This is 10x more than what we may need-
➔ **a priori OK !**



LHC transverse feedback system

- Four kickers per beam, per plane, located in RF zone (UX451) at point 4
  - **Electrostatic kicker**, length 1.5 m.
  - Providing a **kick of ~2 μrad @ 450 GeV** (all 4 units combined).
  - Useful bandwidth ~1 kHz – 20 MHz.

ADT kickers and power amplifiers at point 4

Energy calibration WG / J. Wenninger

10/19/2017

What else do we need?

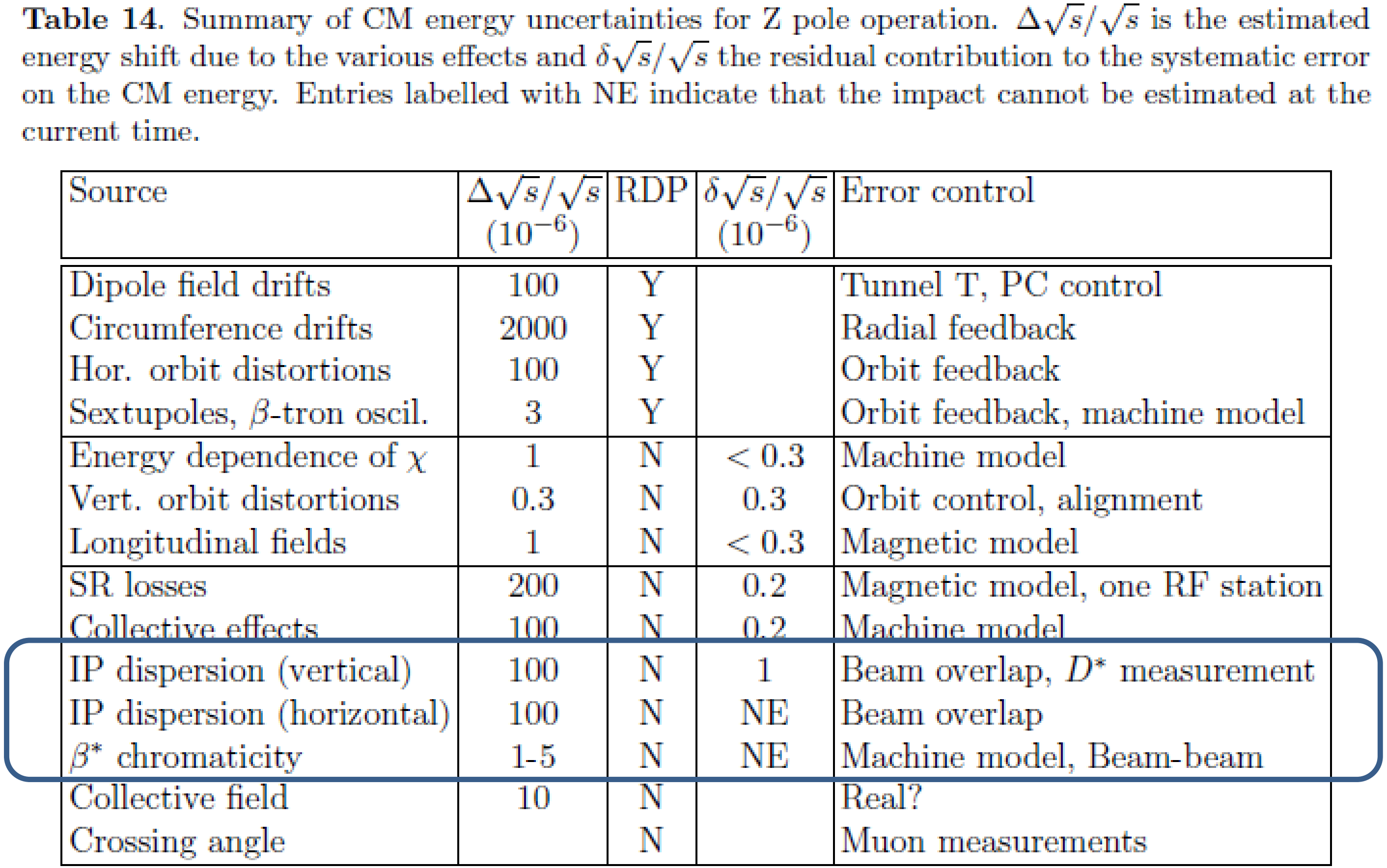


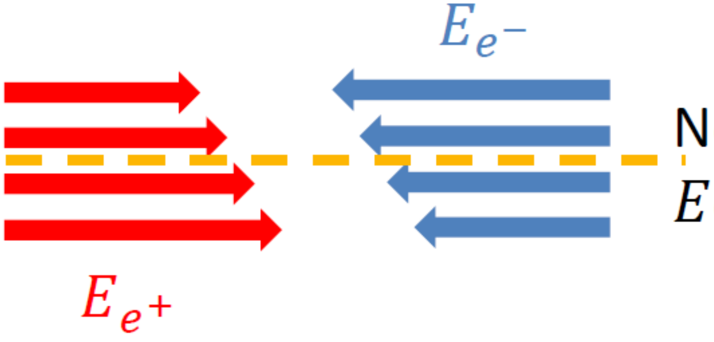
Table 14. Summary of CM energy uncertainties for Z pole operation. $\Delta\sqrt{s}/\sqrt{s}$ is the estimated energy shift due to the various effects and $\delta\sqrt{s}/\sqrt{s}$ the residual contribution to the systematic error on the CM energy. Entries labelled with NE indicate that the impact cannot be estimated at the current time.

Source	$\Delta\sqrt{s}/\sqrt{s}$ (10^{-6})	RDP	$\delta\sqrt{s}/\sqrt{s}$ (10^{-6})	Error control
Dipole field drifts	100	Y		Tunnel T, PC control
Circumference drifts	2000	Y		Radial feedback
Hor. orbit distortions	100	Y		Orbit feedback
Sextupoles, β-tron oscil.	3	Y		Orbit feedback, machine model
Energy dependence of χ	1	N	< 0.3	Machine model
Vert. orbit distortions	0.3	N	0.3	Orbit control, alignment
Longitudinal fields	1	N	< 0.3	Magnetic model
SR losses	200	N	0.2	Magnetic model, one RF station
Collective effects	100	N	0.2	Machine model
IP dispersion (vertical)	100	N	1	Beam overlap, D^* measurement
IP dispersion (horizontal)	100	N	NE	Beam overlap
β^* chromaticity	1-5	N	NE	Machine model, Beam-beam
Collective field	10	N		Real?
Crossing angle		N		Muon measurements

the largest
(or uncalculated)
errors are related to
collision effects

From beams to centre-of-mass: Dispersion (opposite sign) at the IP

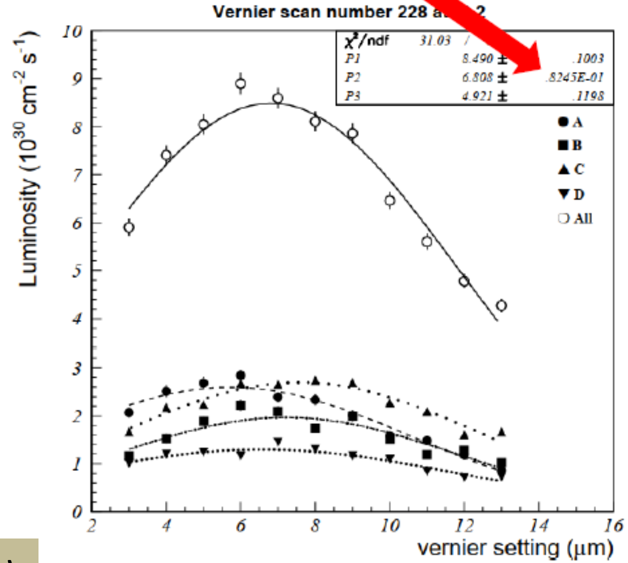
Experience from LEP – Vernier scans

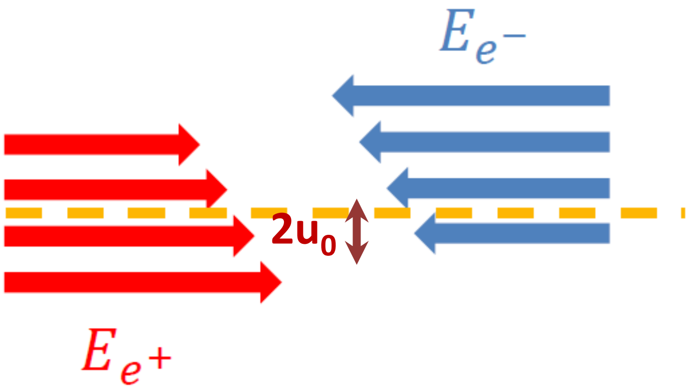


No effect.

$$ECM = (E_{e^+} + E_{e^-})$$

Relative position of beams measured to 80 nanometers from one scan





ECM lower than $(E_{e^+} + E_{e^-})$

This is proportional to the product of the dispersion times the collision offset $2u_0$

(u is x or y)

beam size at IP
sigma_x= 6.4 μm
sigma_y= 28nm

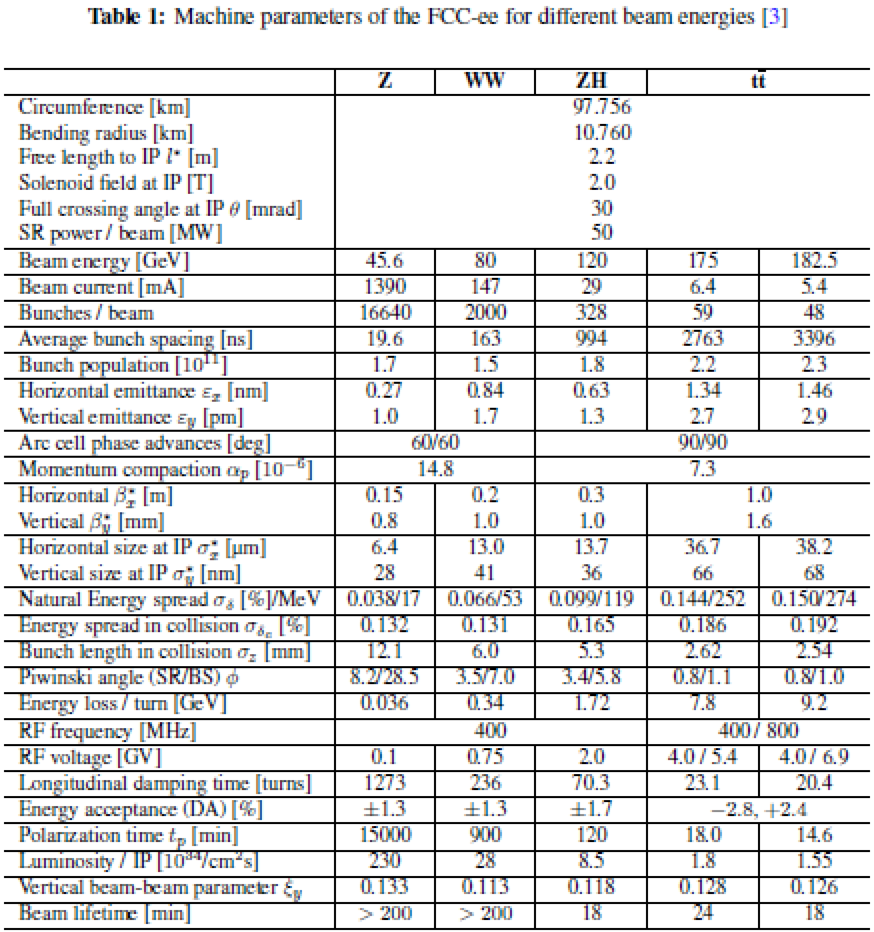
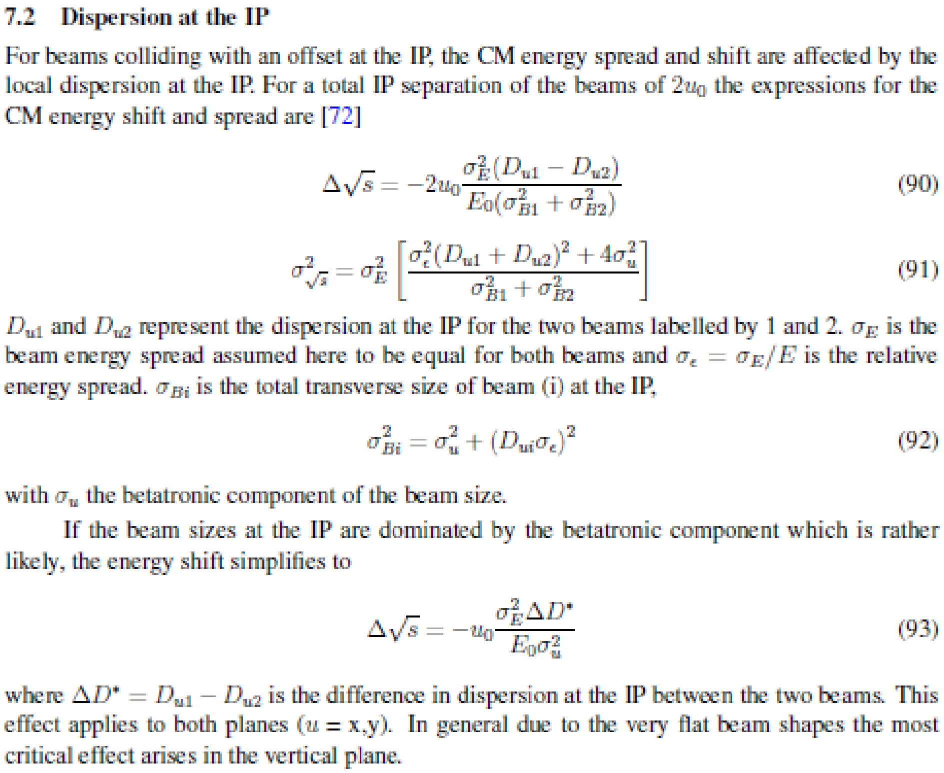


Table 1: Machine parameters of the FCC-ee for different beam energies [3]

	Z	WW	ZH	$t\bar{t}$	
Circumference [km]	97.756				
Bending radius [km]	10.760				
Free length to IP l^* [m]	2.2				
Solenoid field at IP [T]	2.0				
Full crossing angle at IP θ [mrad]	30				
SR power / beam [MW]	50				
Beam energy [GeV]	45.6	80	120	175	182.5
Beam current [mA]	1390	147	29	6.4	5.4
Bunches / beam	16640	2000	328	59	48
Average bunch spacing [ns]	19.6	163	994	2763	3396
Bunch population [10^{11}]	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x [nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y [pm]	1.0	1.7	1.3	2.7	2.9
Arc cell phase advances [deg]	60/60		90/90		
Momentum compaction α_p [10^{-6}]	14.8		7.3		
Horizontal β_x^* [m]	0.15	0.2	0.3	1.0	
Vertical β_y^* [mm]	0.8	1.0	1.0	1.6	
Horizontal size at IP σ_x^* [μm]	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ_y^* [nm]	28	41	36	66	68
Natural Energy spread σ_δ [%]/MeV	0.038/17	0.066/53	0.099/119	0.144/252	0.150/274
Energy spread in collision σ_{δ_c} [%]	0.132	0.131	0.165	0.186	0.192
Bunch length in collision σ_z [mm]	12.1	6.0	5.3	2.62	2.54
Piwinski angle (SR/BS) ϕ	8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.1	0.8/1.0
Energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.2
RF frequency [MHz]	400			400 / 800	
RF voltage [GV]	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Longitudinal damping time [turns]	1273	236	70.3	23.1	20.4
Energy acceptance (DA) [%]	±1.3	±1.3	±1.7	−2.8, +2.4	
Polarization time t_p [min]	15000	900	120	18.0	14.6
Luminosity / IP [10^{34}/cm^{2}s]	230	28	8.5	1.8	1.55
Vertical beam-beam parameter ξ_y	0.133	0.113	0.118	0.128	0.126
Beam lifetime [min]	> 200	> 200	18	24	18



7.2 Dispersion at the IP

For beams colliding with an offset at the IP, the CM energy spread and shift are affected by the local dispersion at the IP. For a total IP separation of the beams of $2u_0$ the expressions for the CM energy shift and spread are [72]

$$\Delta\sqrt{s} = -2u_0 \frac{\sigma_E^2(D_{u1}-D_{u2})}{E_0(\sigma_{B1}^2+\sigma_{B2}^2)} \tag{90}$$

$$\sigma_{\sqrt{s}}^2 = \sigma_E^2 \left[\frac{\sigma_\epsilon^2(D_{u1}+D_{u2})^2+4\sigma_u^2}{\sigma_{B1}^2+\sigma_{B2}^2}\right] \tag{91}$$

D_{u1} and D_{u2} represent the dispersion at the IP for the two beams labelled by 1 and 2. σ_E is the beam energy spread assumed here to be equal for both beams and $\sigma_\epsilon = \sigma_E/E$ is the relative energy spread. σ_{Bi} is the total transverse size of beam (i) at the IP,

$$\sigma_{Bi}^2 = \sigma_u^2 + (D_{ui}\sigma_\epsilon)^2 \tag{92}$$

with σ_u the betatronic component of the beam size.

If the beam sizes at the IP are dominated by the betatronic component which is rather likely, the energy shift simplifies to

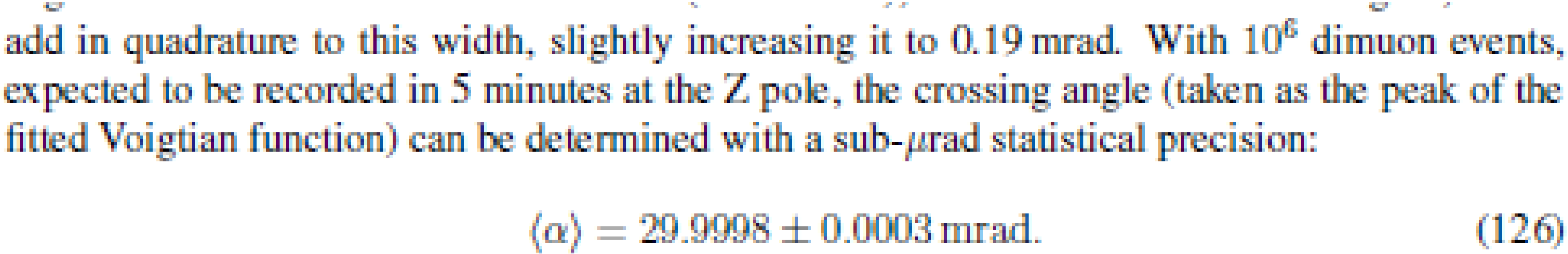
$$\Delta\sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0\sigma_u^2} \tag{93}$$

where $\Delta D^* = D_{u1} - D_{u2}$ is the difference in dispersion at the IP between the two beams. This effect applies to both planes (u = x,y). In general due to the very flat beam shapes the most critical effect arises in the vertical plane.

For FCC-ee at the Z we have in vertical direction:

- Parasitic dispersion of e+ and e- beams at IP 10um
  the difference is $\Delta D_y^* = 14\mu m$.
- Sigma_y is 28nm
- Sigma_E is 0.132%*45000MeV=60MeV
- **Delta_ECM is therefore 1.4MeV for a 1nm offset**
- Note that we cannot perform Vernier scans like at LEP, we can only displace the two beams by ~10%sigma_y
- Assume each Vernier scan accurate to 1% sigma_y, we get a precision of 400 keV.
  the process should be simulated
- we need 100 vernier scans to get an E_{CM} accuracy of 40keV – suggestion: vernier scan every hour or more.
- It is likely that Van der Meer scans will be performed regularly at least once per hour or more. (→100 per week) we end up with an uncertainty of ~10keV
  over the whole running period.
- **The dispersion must be measured as well; this can be done by using the vernier scans with off set RF frequency**

critical effect is in the vertical plane, but horizontal plane should be investigated as well note that **if there is a transverse momentum in the collision** this can be measured from the muon pairs



add in quadrature to this width, slightly increasing it to 0.19 mrad. With 10^6 dimuon events, expected to be recorded in 5 minutes at the Z pole, the crossing angle (taken as the peak of the fitted Voigtian function) can be determined with a sub-μrad statistical precision:

$$\langle\alpha\rangle = 29.9998 \pm 0.0003\,\text{mrad}. \tag{126}$$

Janot et al.

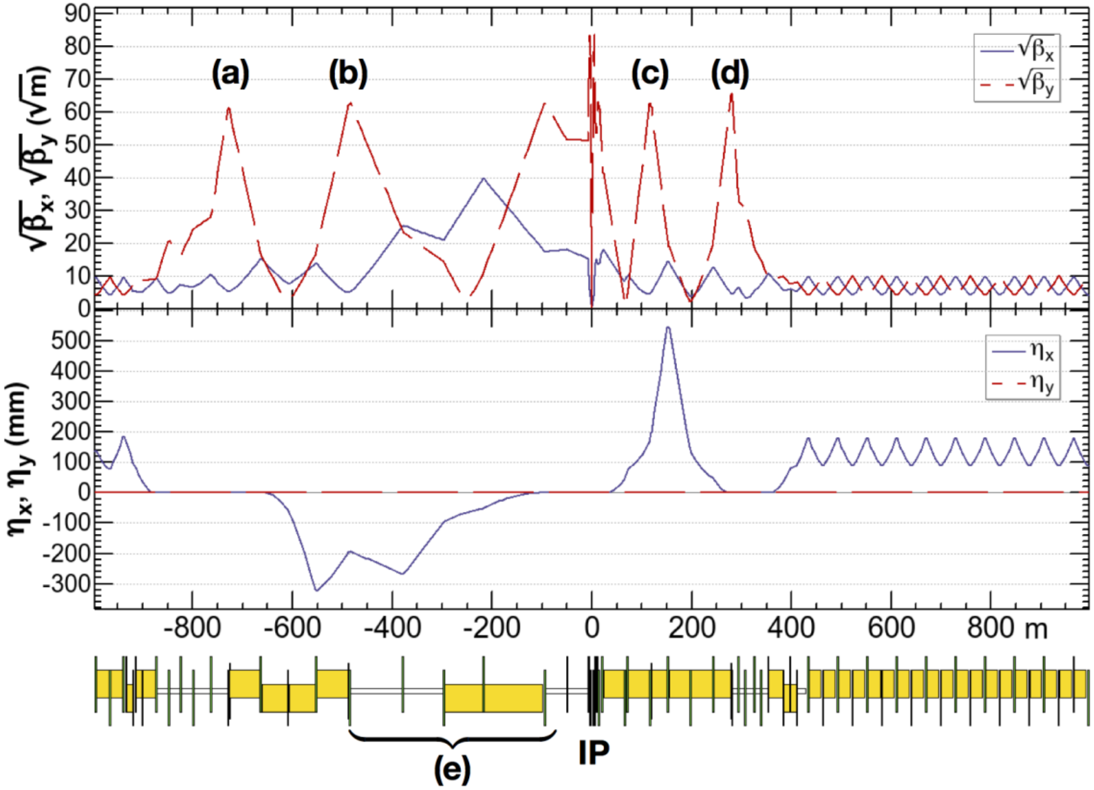
i.e. 0.3 microradians every ~5 (~30) minutes on (off) the Z pole. This assumes that the current can be raised in the machine without changes in parameters.

However this is not a measure of the beam offset,
so that an independent measurement is essential.

At full luminosity, a vernier scan is a tricky operation and beam beam blow up effects might affect the result

Therefore a beamstrahlung or radiative bhabha monitor seeems highly worthwhile as it gives information on the direction of the interacting particles.
it detects
the hard photons emmitted in either e+e- → e+e- γ
or
the hard beamstrahlung photons
emitted along the beam direction at interaction point.
Photons are not affected by the IR magnetic fields.
The beam-beam offset leads to a shift in the beamstrahlung photon beam which is **proportional** to the offset (and to the charge of the opposite beam) for small offsets.
the measurement is passive
the zero position can be operationally established by colliding beams at lower intensity where large vernier scan amplitude is possible.

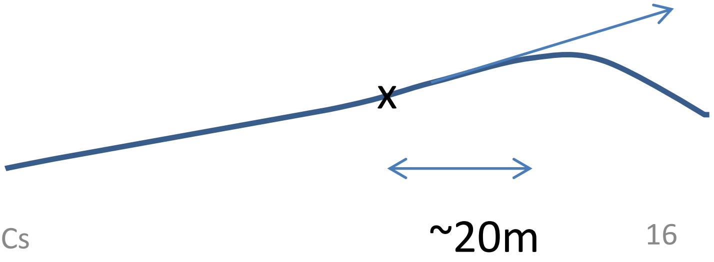
An angular kick of up to 0.18 mrad is expected in the horizontal plane due to EM attraction.



the first dipole is about 20m away from the IP
 0.1mrad is 2mm

detector size of a few cm is certainly sufficient.

Will the Synchrotron Radiation hit at the same place? or completely obscure the detector?

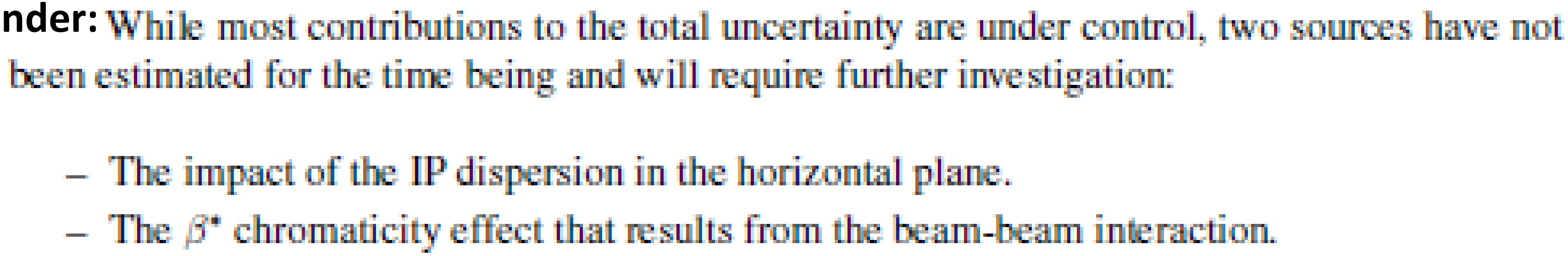


Conclusion

The largest systematic uncertainty in the energy calibration that we have identified so far is the interplay between beam offsets and opposite sign ertical dispersion
The largest effect is proesumably in the vertical plane but the horizontal one should be eventually investigated.

The proposed solution is to perform ernier scans regularly. This may be tricky and not devoid of sources of uncertainty. This strongly suggest to evaluate the possibility of an
on-axis monitor for photons from beamstrahlung and radiative bhabha to be located in the outgoing arm of the detector.

reminder:



While most contributions to the total uncertainty are under control, two sources have not been estimated for the time being and will require further investigation:

- The impact of the IP dispersion in the horizontal plane.
- The β^* chromaticity effect that results from the beam-beam interaction.