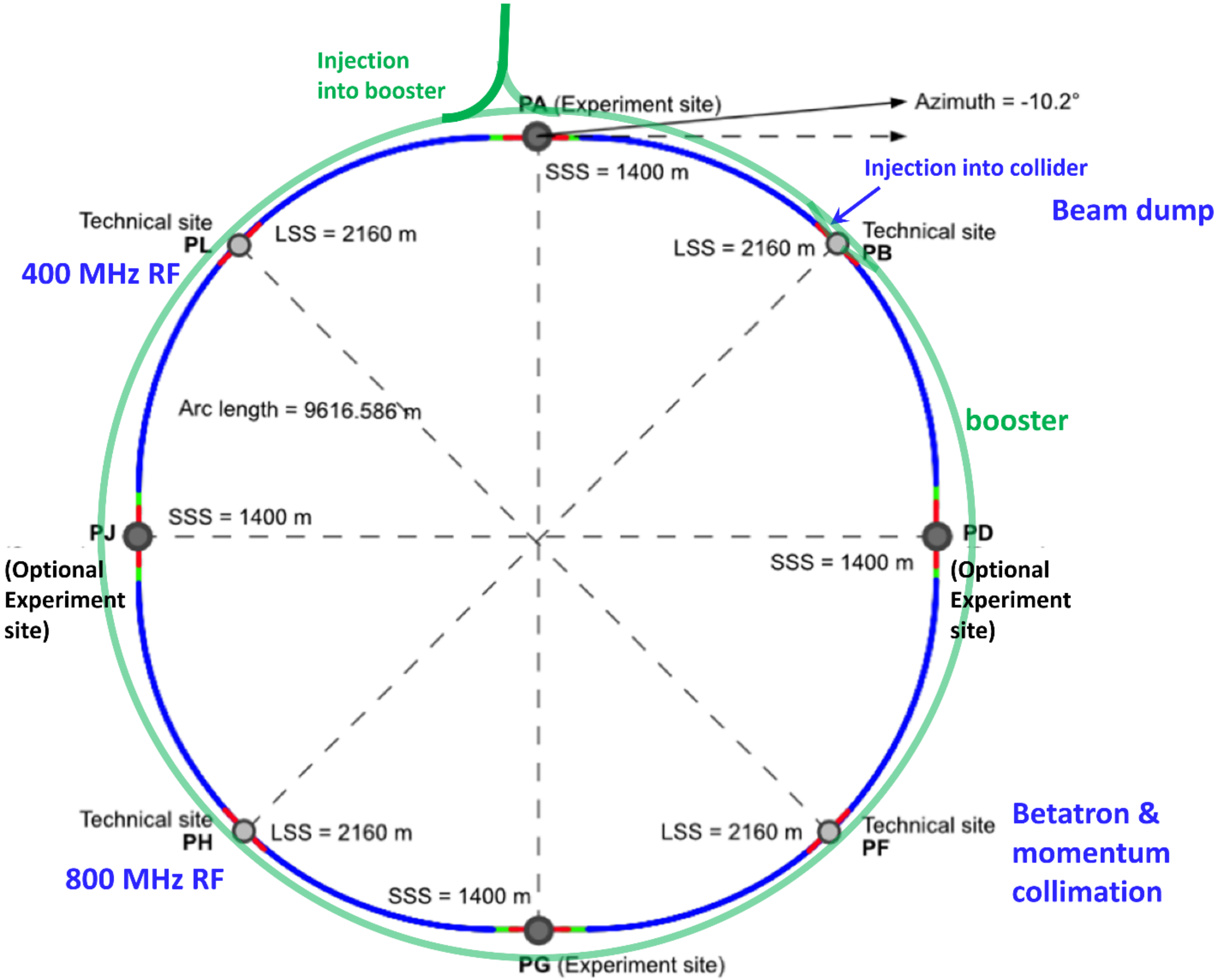
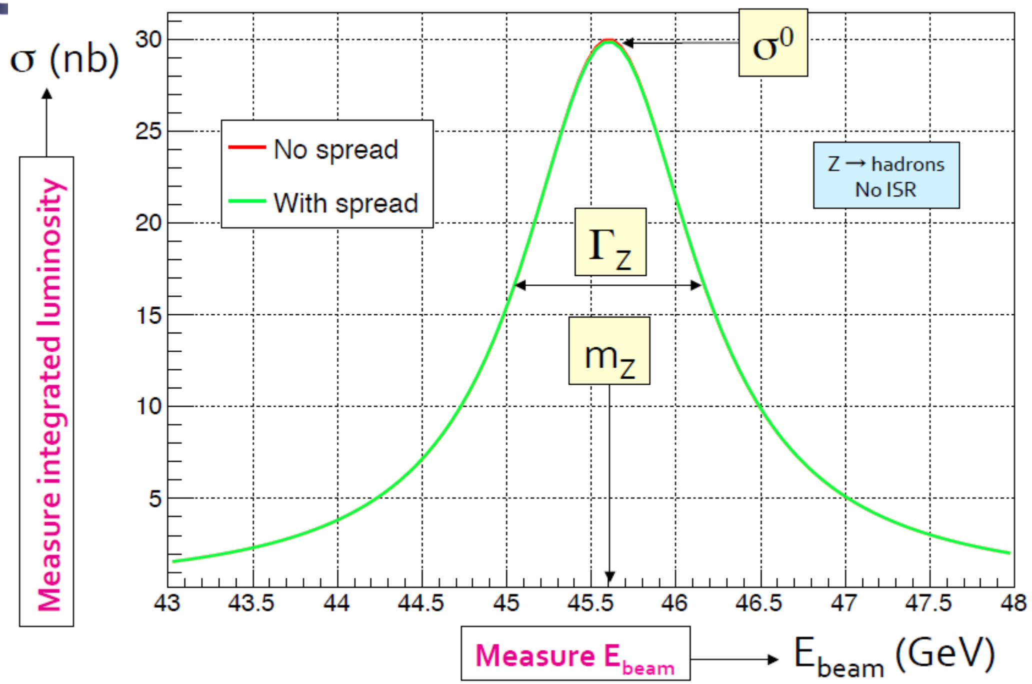
A first go at E_{cm} uncertainties



scan points for m_Z and m_W



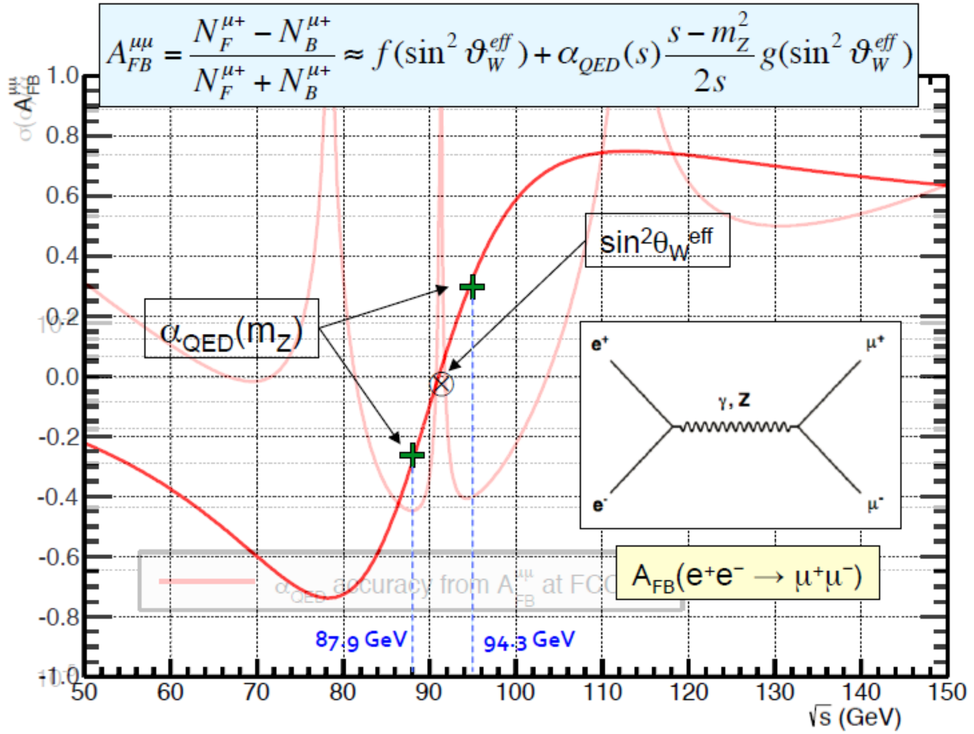
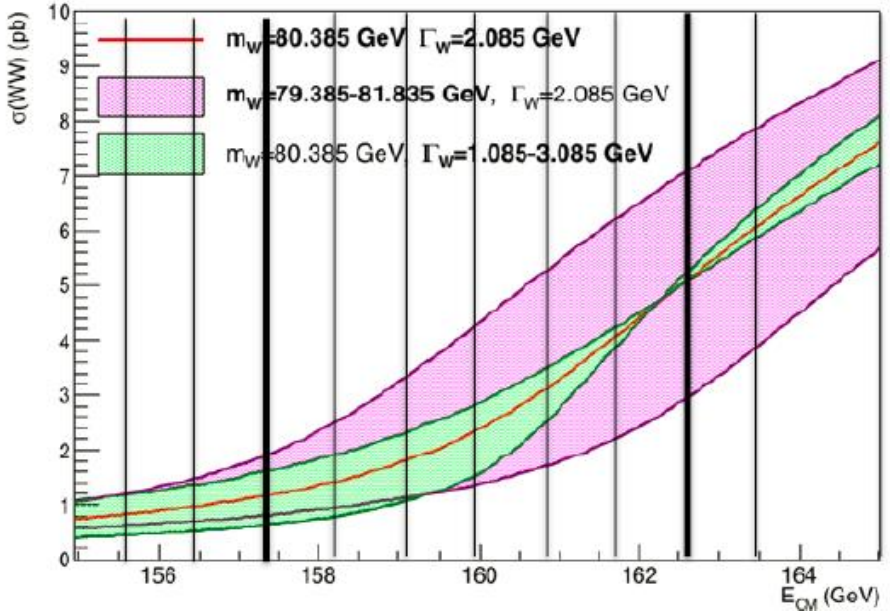


Table 3: Center-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

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^0_{CM}	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



systematic precision at the Z

centre-of-mass energy errors:

$$
\begin{aligned}
\frac{\Delta m_Z}{m_Z} &= \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\text{abs}} \oplus \left\{\frac{\Delta(\sqrt{s_+}+\sqrt{s_-})}{\sqrt{s_+}+\sqrt{s_-}}\right\}_{\text{ptp-syst}} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\text{sampling}}, \\
\frac{\Delta\Gamma_Z}{\Gamma_Z} &= \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\text{abs}} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\text{ptp-syst}} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\text{sampling}}, \\
\Delta A_{\text{FB}}^{\mu\mu}(\text{pole}) &= \frac{\partial A_{\text{FB}}^{\mu\mu}}{\partial\sqrt{s}}\left\{\Delta(\sqrt{s_0}-0.5(\sqrt{s_+}+\sqrt{s_-}))\right\}_{\text{ptp-syst}} \oplus_i \frac{\partial A_{\text{FB}}^{\mu\mu}}{\partial\sqrt{s}}\left\{\frac{\Delta\sqrt{s^i_{0,\pm}}}{\sqrt{N^i_{0,\pm}}}\right\}_{\text{sampling}}, \\
\frac{\Delta\alpha_{\text{QED}}(m_Z^2)}{\alpha_{\text{QED}}(m_Z^2)} &= \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\text{abs}} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\text{ptp-syst}} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\text{sampling}},
\end{aligned}
\tag{3.1}
$$

with $\frac{\partial A_{\text{FB}}^{\mu\mu}}{\partial\sqrt{s}} \simeq 0.09/\text{GeV}$.

Three categories:

- **Abs**olute dominate for Z and W mass
- **ptp** Point-to-point dominate for Γ_Z & $A_{FB}^{\mu\mu}$ (peak and off-peak)
- Due to **sampling** – turns out to be negligible for 1meast /(15 min= 1000s) → 10^4 measts

Table 4. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the initial systematic assumptions.

Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ 100 keV	calib. stats. $200\,\mathrm{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm 0.5\,\mathrm{MeV}$
m_Z (keV)	4	100	70	1	–
Γ_Z (keV)	4	2.5	55	1	100
$\sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	6	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	2.2	–	1

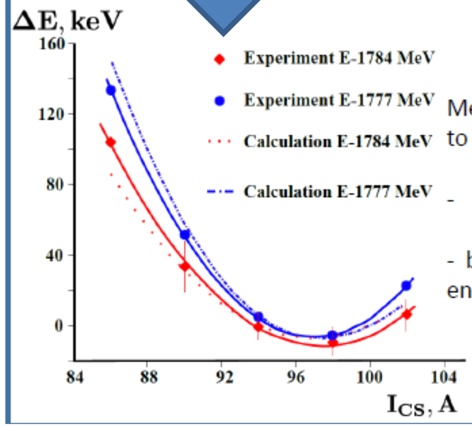
Procedure

1. determination of spin tune and determination of average of beam energies in the arcs
   -- possible controls
   -- possible biases esp. energy dependent biases.

2. from average energy of pilot bunches to centre-of-mass energies
   -- energy losses and beamstrahlung, other losses
   -- collision offsets and opposite sign vertical dispersion

Precision on RDP (Koop, Nikitin)

EXAMPLES OF STUDY OF ACCURACY ISSUES



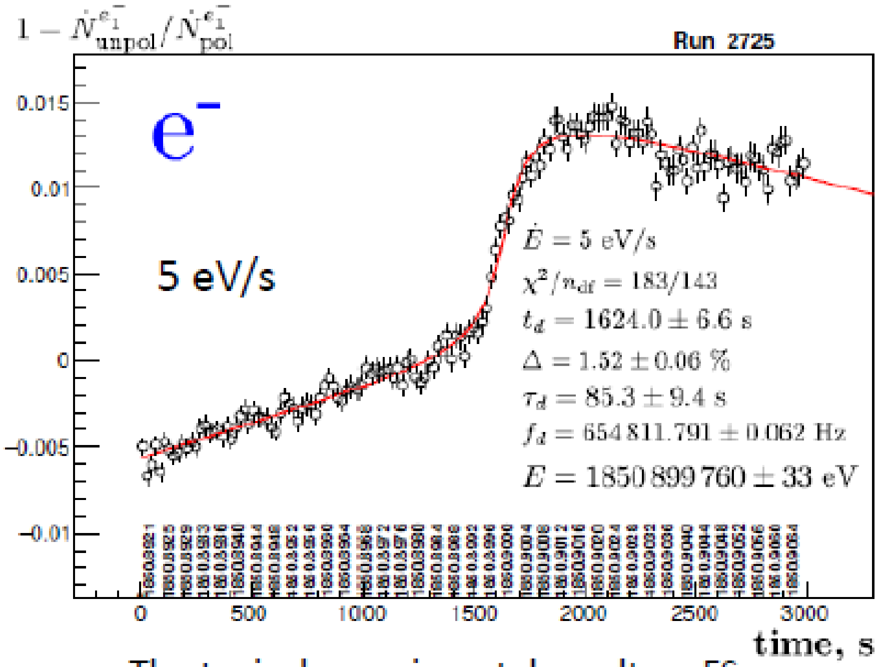
Measurement of spin tune shift related to **decompen**sation of KEDR solenoid:

- optimal anti-solenoid (AS) current found;
- betatron coupling (~1% in AS current) and energy error (down to ~1 keV) minimization

Systematic uncertainties in J/ψ scans (keV):				
Uncertainty source	2002	2005	2008	Common
Energy spread variation	3.0	1.8	1.8	1.8
Energy calibration accuracy	1.6	1.9	1.9	1.6
Energy assignment to DAQ runs	3.7	3.5	3.5	2.5
Beam separation in parasitic I.P.s*	0.9	1.7	1.7	0.9
Beam misalignment in the I.P.	1.8	1.5	1.5	1.5
e^+-, e^--energy difference	1.2	1.3*	1.2	1.2
Symmetric distortion of the energy distribution	1.5	1.3	2.1	1.3
Asymmetric distortion of the energy distribution*	2.1	1.9	1.9	1.9
Beam potential	1.9	1.9	1.9	1.9
Detection efficiency instability	2.3	1.7	1.8	<0.1
Residual machine background	1.0	0.7	0.7	<0.1
Luminosity measurements	2.2	1.7	1.7	1.1
Interference in the hadronic channel	2.7	2.7	2.7	2.7
Sum in quadrature	≈ 7.7	≈ 7.0	≈ 7.2	≈ 5.8

* — correction uncertainty

Andrey Shamov, ϒ(1S)-ϒ(3S). Workshop on e+e- collisions from Phi to Psi, ShangHai, China, August 2022



The typical experimental result on FS.

one time precision: 10-80 eV

we can certainly measure RDP to << 10keV precision (Nikitin PC)

FCC-ee DEPOLARIZER: CONCEPTUAL EXAMPLE (preliminary)

estimate of device parameters for FCC-ee (Nikitin)
if polarimeter can measure depolarization in 10 sec. a precision of 10-7 (4.5 keV) should be achievable.

Not a

Depolarizer linewidth $\delta f_d^* \approx \rho\Delta E \approx 1$ Hz is artificially made using synthesizer ($\Delta E = 100$ keV). Scanning proceeds at average rate $\langle df_d/dt\rangle$, which makes much smaller contribution to line broadening $\sqrt{\langle df_d/dt\rangle} \ll \delta f_d^*$, but nevertheless provides relevant total scanning time in assumed energy interval.For instance, ~ 10 minutes per scan span of 1 MeV or 7 Hz, $\langle df_d/dt\rangle \approx 0.01$ Hz/s. These features are associated with small value of specific scan scale $\rho = 0.007$ Hz/keV at FCC-ee. For comparison, $\rho \approx 2$Hz/keV at VEPP-4M.

FCC-ee TEM depolarizer concept at $E = 45.6$ GeV:

spin harmonic amplitude $|w_k| \propto \frac{\nu UL|F^\nu|}{Ed}$

depolarization time $\tau_d \approx \frac{\delta f_d^*}{4\pi|w_k|^2 f_0{}^2}$

strip-line length $L = 1$ m; gap $d = 20$ mm

amplitude of voltage between plates $U = 100$ V

spin response factor $|F^\nu| = 5$; $|w_k| = 1.8\ 10^{-5}$

$f_0 = 3$ kHz; $\nu = 103.5$; $\delta f_d^* = 1$ Hz

τ_p=256 h; "uncorrelatedness" $\nu^2 \gg \tau_p(\delta f_d^*)^3/f_0{}^2$

and "rapidity" $(\delta f_d^*/f_0)^2 \gg |w_k|^2$ satisfied

bunch depolarized in $\tau_d \approx 28$ second

time for polarization measurement in one point $\tau_m \sim \tau_d$

Parameters are given for scaling and can be changed depending on, for instance, time τ_m required foraccurate measurement of pilot bunch polarization

FCC

Measured and average energy: vertical orbit distortions

Assumptions and definitions

- Spin tune $\nu = \frac{W_{spin}}{\Omega_0} - 1$
- No straight sections: $\Phi(\theta) = \nu\theta$
- Constant vertical beta function: $\beta_y = const = \langle\beta_y\rangle$
- Average over circumference $\langle\rangle$, average over orbits $\bar{\ }$

Results

$$\overline{\Delta\nu} = \frac{\nu^2}{2}\frac{\overline{\langle y^2\rangle}}{Q}\sum_{k=-\infty}^{\infty}\frac{k^4}{(\nu_y^2 - k^2)^2(\nu - k)}$$

$$Q = \frac{\pi}{2\nu_y^3}\cot\pi\nu_y + \frac{\pi^2}{2\nu_y^2}\csc^2\pi\nu_y$$

$$\sigma_{\overline{\Delta\nu}} = \frac{\nu^2\sqrt{3}}{2}\frac{\overline{\langle y^2\rangle}}{Q}\sqrt{2\nu\sum_{k=-\infty}^{\infty}\frac{k^8}{(\nu_y^2 - k^2)^4(\nu - k)^2(\nu + k)}}$$

Measured and average energy: vertical orbit distortions

E, GeV	45.6	78.65	81.3
$\sqrt{\langle y^2 \rangle}$, mm	0.6	0.28	0.27
ν_y	269.22	269.2	269.2
ΔE, keV	-31	-54	-56
$\sigma_{\Delta E}$, keV	46	82	85
$\frac{\Delta E}{E}$	$-7 \cdot 10^{-7}$	$-7 \cdot 10^{-7}$	$-7 \cdot 10^{-7}$
$\frac{\sigma_{\Delta E}}{E}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$

Beam energy shift needs to be added to the actual value of the beam energy, uncertainty is unavoidable and sets the minimum error.

at the Z: 10^{-7} error requires y_{rms} = 0.2mm Tessa indicates more like

Measured and average energy: ring alignment

Beam energy $E = 45.6$ GeV, $\nu = 103.484$, $\Pi = 100$ km

$A_k = 15 \cdot 10^{-3}$ m

k	$\Delta\nu/\nu$	$\lvert\omega_k\rvert$
1	$2 \cdot 10^{-13}$	$5 \cdot 10^{-5}$
2	$4 \cdot 10^{-12}$	$2 \cdot 10^{-4}$
3	$2 \cdot 10^{-11}$	$4 \cdot 10^{-4}$
4	$6 \cdot 10^{-11}$	$8 \cdot 10^{-4}$
10	$2 \cdot 10^{-9}$	$5 \cdot 10^{-3}$
50	$2 \cdot 10^{-6}$	0.12
100	$3.5 \cdot 10^{-4}$	0.5
103	$2.8 \cdot 10^{-3}$	0.5

$A_k = 3 \cdot 10^{-4}$ m

k	$\Delta\nu/\nu$	$\lvert\omega_k\rvert$
1	$1 \cdot 10^{-16}$	$1 \cdot 10^{-6}$
2	$2 \cdot 10^{-15}$	$4 \cdot 10^{-6}$
3	$8 \cdot 10^{-15}$	$9 \cdot 10^{-6}$
4	$2 \cdot 10^{-14}$	$2 \cdot 10^{-5}$
10	$9 \cdot 10^{-13}$	$1 \cdot 10^{-4}$
50	$8 \cdot 10^{-10}$	$2 \cdot 10^{-3}$
100	$1.4 \cdot 10^{-7}$	$1 \cdot 10^{-2}$
103	$1.1 \cdot 10^{-6}$	$1 \cdot 10^{-2}$

seems to require to work on the harmonic compensation for harmonics close to working point.
is that the same as spin matching?

Misalignments and field errors

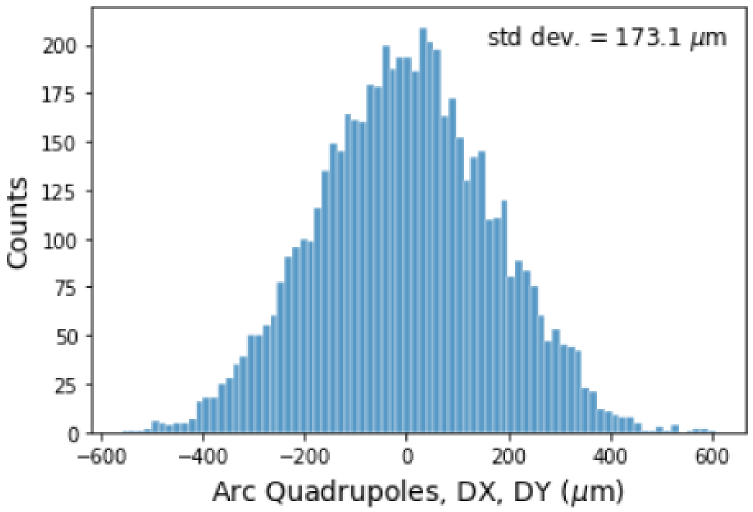
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2\times10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2\times10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 1\times10^{-4}$
Girders	150	150	-	1000	-	-	-
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2\times10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2\times10^{-4}$

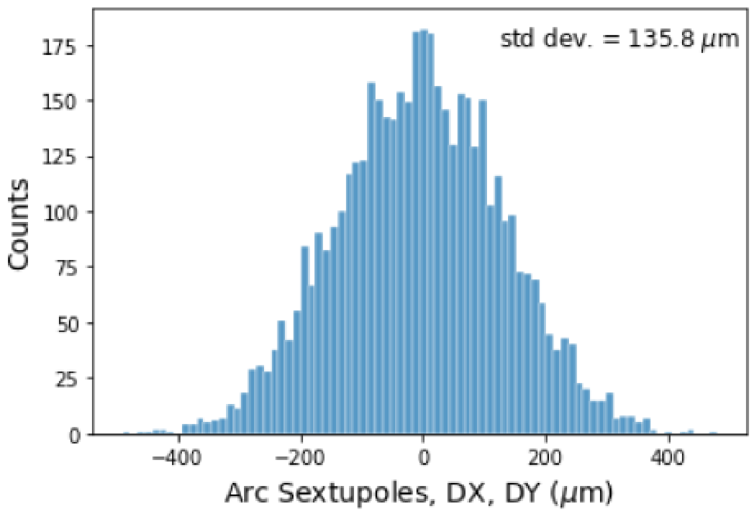
* misalignment relative to girder placement

Misalignments are randomly distributed via a Gaussian distribution, truncated at 2.5 sigma.

This table is not the final set of tolerances.

Distributions of arc quadrupoles and sextupoles, total DX and DX misalignments:

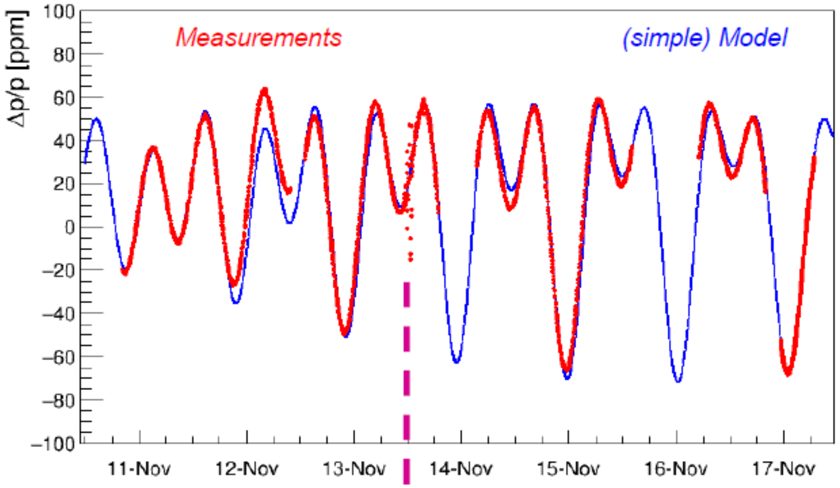




Beam energy will be corrected continuously for e.g. tides, by moving RF frequency. Orbit will be accordingly modified and continuously sampled. This is not necessarily a bad thing as it should provide i. some verification of the constance of RDP upon orbit changes. BPM quality will be at O(microns) level

Tides – not just @ LEP

LHC feels the tides like LEP. A long stable period with long fill thanks to low luminosity provided one of the nicest and cleanest tide measurements @ LEP/LHC (measured with BPMs).

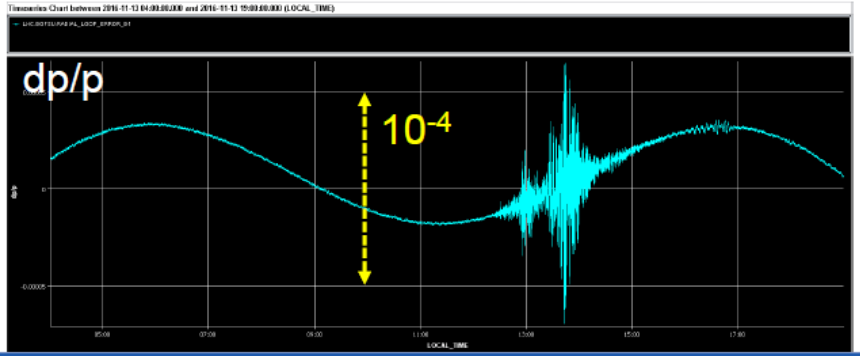


Tide observations (from orbit changes) over one week at 4 TeV in 2016

(expressed in energy change Δp/p)

Earthquake in New Zealand

The pressure waves induce a modulation of the circumference similar to tides



From beam energy to E_{CM} for 2 IP

$$\sqrt{s} = 2\sqrt{E_b^+ E_b^-}\cos\alpha/2, \quad \approx E^+_b + E^-_b$$

Energy gain (RF) = losses in the storage ring
Synchrotron radiation (SR)
beamstrahlung (BS)

$\Delta_{RF} = 2\Delta_{SRi} + 2\Delta_{SRe} + 2\Delta_{BS}$

at the Z (O of mag.):

$\Delta_{SR} = 2\Delta_{SRi} + 2\Delta_{SRe}$ =40 MeV

$\Delta_{SRe} - \Delta_{SRi} \approx \alpha/2\pi\ \Delta_{SR}$ = 0.19 MeV

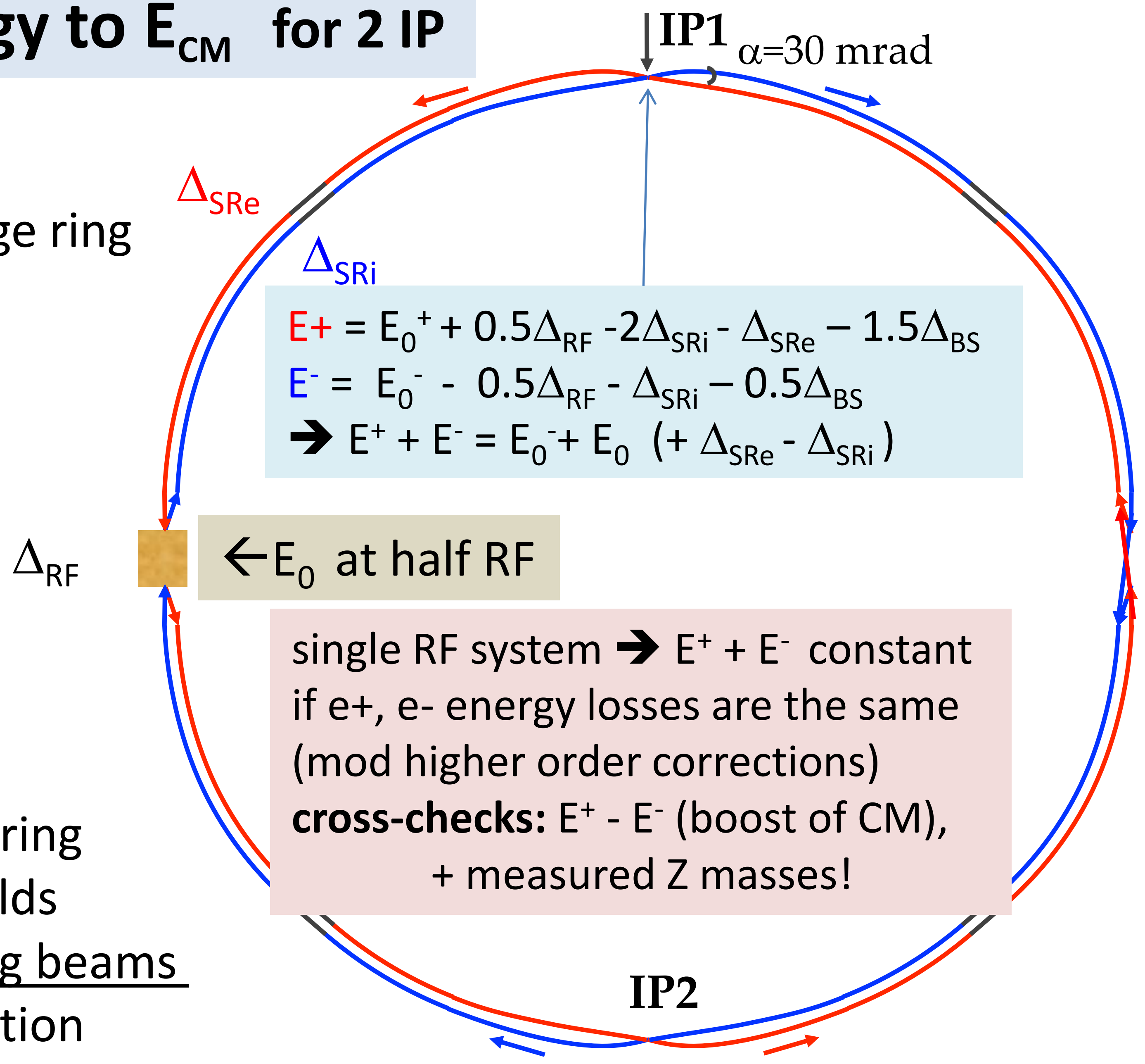
Δ_{BS} = 0 up to 0.62 MeV

the average energies E_0 around the ring are determined by the magnetic fields

➔ <u>same for colliding or non-colliding beams</u>

-- measured by resonant depolarization

<u>-- can be different for e^+ and e^-</u>



$E+ = E_0^+ + 0.5\Delta_{RF} - 2\Delta_{SRi} - \Delta_{SRe} - 1.5\Delta_{BS}$

$E^- = E_0^- - 0.5\Delta_{RF} - \Delta_{SRi} - 0.5\Delta_{BS}$

➔ $E^+ + E^- = E_0^- + E_0 \ (+\Delta_{SRe} - \Delta_{SRi})$

← E_0 at half RF

single RF system ➔ $E^+ + E^-$ constant
if e+, e- energy losses are the same
(mod higher order corrections)
cross-checks: $E^+ - E^-$ (boost of CM),
+ measured Z masses!

From beam energy to E_{CM} for 4 IP

$\sqrt{s} = 2\sqrt{E_b^+ E_b^-}\cos\alpha/2, \quad \approx E^+_b + E^-_b$

Energy gain (RF) = losses in the storage ring=
Synchrotron radiation (SR)+ beamstrahlung (BS)

$\Delta_{RF} = 4\Delta_{SRi} + 4\Delta_{SRe} + 4\Delta_{BS}$

Δ_{SRi} energy loss on octant
where beam is in **internal ring**
< Δ_{SRe} energy loss on octant
where beam is in **external ring**

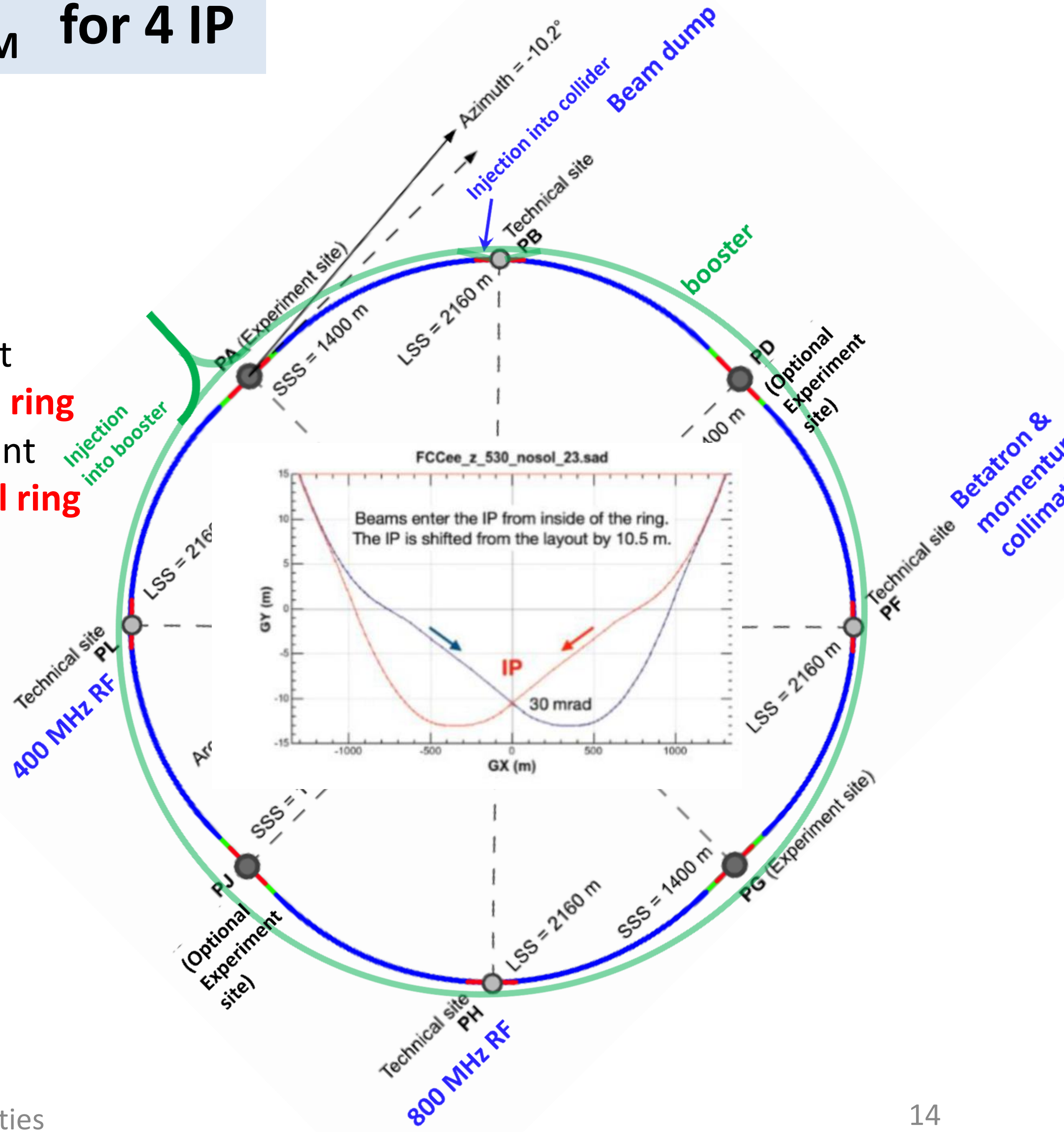
at the Z:

$\Delta_{SR} = 4\Delta_{SRi} + 4\Delta_{SRe}$ =40 MeV

$\Delta_{SRe} - \Delta_{SRi} \approx \alpha/2\pi\ \Delta_{SR}$ = 0.19 MeV

Δ_{BS} = 0 up to 0.62 MeV

beam always comes to IR from the inside ring



the average energies E_0 around the ring
are determined by the magnetic fields
➔ <u>same for colliding or non-colliding beams</u>
-- measured by resonant depolarization
-- can be different for e^+ and e^- -- RF gains are not the same

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

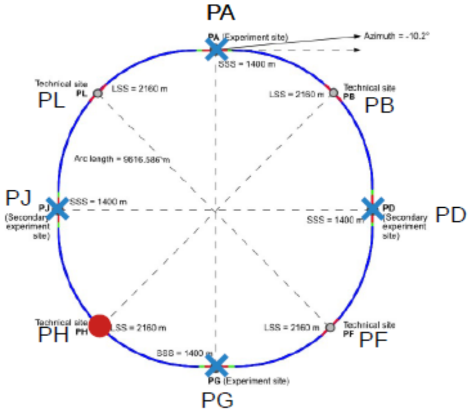
One 8 h shift will give 5 keV precision

Sum of losses close to sum of absolute boosts

Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

1 RF → almost constant ECM

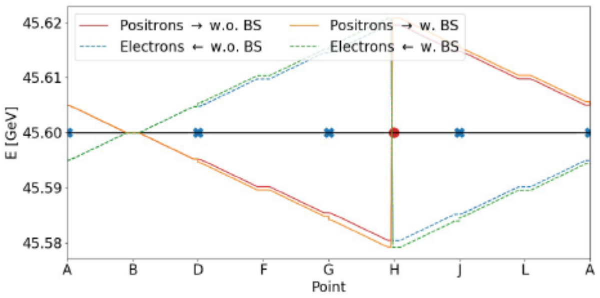
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

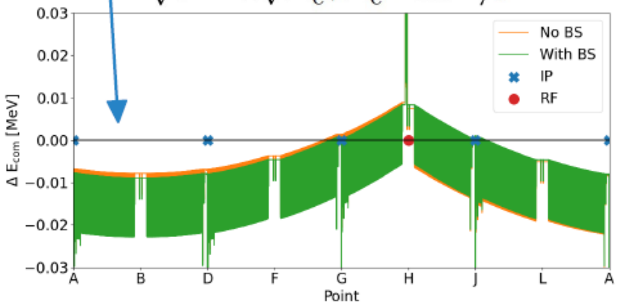


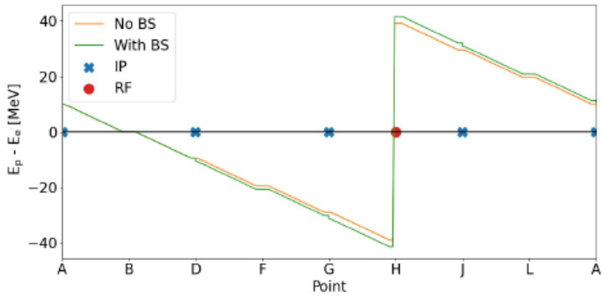
Boost: + for e+; - for e-

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

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







many simplifying assumptions
-- ΔBS same for all IP
-- energy losses same for all arcs
-- γ^4 effect ignored

$$\Delta_{RF} = 4\Delta_{SRi} + 4\Delta_{SRe} + 4\Delta_{BS}$$

E-J = E0- + ΔRF/2 - ΔSRi - ΔBS/2
E+J = E0+ + ΔRF/2 -4 ΔSRi - 3 ΔSRe -7 ΔBS/2

EcmJ = E-J + E+J = E0+ +E0- + ΔRF -5 ΔSRi - 3 ΔSRe -4 ΔBS = **E0+ +E0- - (ΔSRi - ΔSRe)**
BoostJ = E-J - E+J = **E0- - E0+ + 3 ΔSRi + 3 ΔSRe + 3 ΔBS**
BoostA= E0- - E0+ + ΔSRi + ΔSRe + ΔBS
(other two ibid with reverse sign)

-- ECM shift due to # in SR in vs ext
-- all Ecm are the same
-- boosts measure the energy losses
-- differences between the rings will show up.

FCC

Dmitri Shatilov

so far we have 6 measurements.

E0 is measured from RDP
(or/and) from precession frequency for e+ and e-
What do we gain with having both?
Analysis of systematics

Boosts are measured at all IPs

Additional measurements
1- beamstrahlung dump/monitor might be able to measure total BS energy or at least inform about variations
2- beam energies are measured in polarimeters and can provide test of linearity over short range of energy.
3. possibly an undulator?
4. beam

	Z	ttbar
IPs	4	4
β_x^*/β_y^* [mm]	150 / 0.8	1000 / 1.6
N_p [10^{11}]	2.53	2.64
σ_z (bs) [mm]	15.3	2.95
<X'> [μrad]	70	13
$\sigma_{X'}$ [μrad]	73	56
$\sigma_{Y'}$ [μrad]	54	55
$\langle N_{photons} \rangle$/turn	0.127	0.202
dE/turn [MeV]	0.261	16.34
$\langle E_\gamma \rangle$ [MeV]	2	81
BS power/IP [kW]	334	82

Opposite sign vertical dispersion and collision offsets

see slides by Jorg on 20 September and AB FCC week in Paris slides in spares..

Clearly concluded from this workshop
Luminosity scans required to calibrate the center of bunch position with a luminosity scan
Further studies require the ability to deconvolute the dispersion at IP from dispersion at BPM. Clearly of interest to use the pilot bunches as reference, since they are sensitive to dispersion in BPMs but not at IP.

Generally considered that the precision of dispersion times resolution on the collision offset should give an uncertainty the order of 20keV on the enegy offsets due to this source. There remains significant work to do

IP dispersion measurements @ FCC-ee

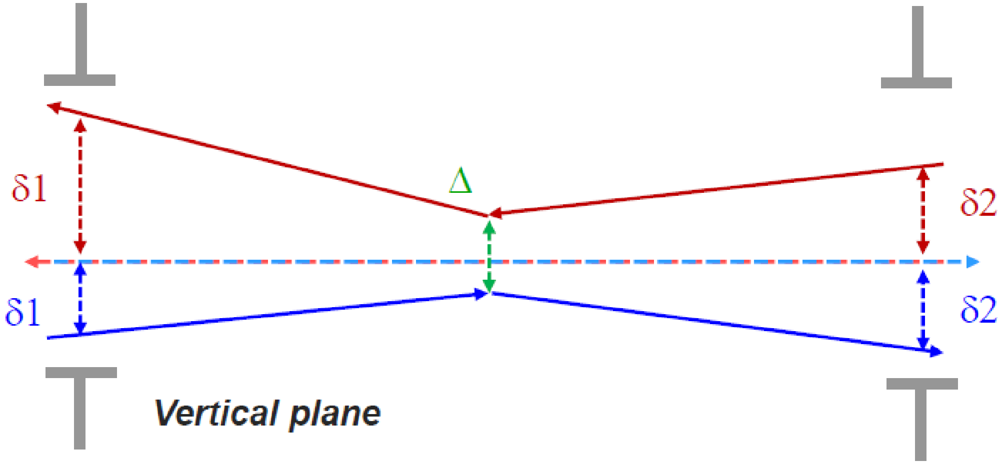
For an energy change of **dp/p = ±0.1%** and **ΔD* = 10 μm**

→ The separation change at the IP is **Δy = 10 nm – without BB !** – **measurable with a separation scan** since we must be able to control the separation << 1 nm.

The BB kick due to such a change is $y' = \frac{-4\pi\xi}{\beta^*}\Delta y$

→ y_s' = -6 μrad for ξ = 0.1, β* = 1 mm (self-consistent).

At the first **BPMs** (~2 m), the **displacement due to the BB kick is ~12 μm** to which one must add the shift due to the **local dispersion at the BPM** → no direct extraction of the dispersion from the BPM readings.



δ2, δ1, δ2, δ1, Δ receive contributions from the local dispersion and from the BB kick @ IP.

conclusions

1. there seems to be no problem reaching excellent precision on RDP (10 keV per meaasurement)

2. The FCC-ee goal of 10^{-7} precision defines tolerances and constraints that look challenging.
Particularly the requirement of a ring vertical alignment of 2.10^{-4} over 1 Km (200 microns)
How does this compare with Tessa's alignment exercise?
Verification with simulation tools is fundamental to validate and understand these systematics
→ per machine seed measure the energy, the rms orbit deviation and the derivative
to characterize the dependency of the CME and spin tune
tools need to be developed both for simulations of RDP and spin precession

3. Energy losses Seem to be well constrained by the boost measurements. Possibility to monitor Beamstrahlung with the beam dump instrumentation should be investigated.

4. We have three tools to investigate the beam collision biases
   -- luminosity scans as absolute reference (every hour?)
   -- constant monitoring with beam beam deflection monitoring
   -- can we use the pilot bunches as reference both for alignment and dispersion?

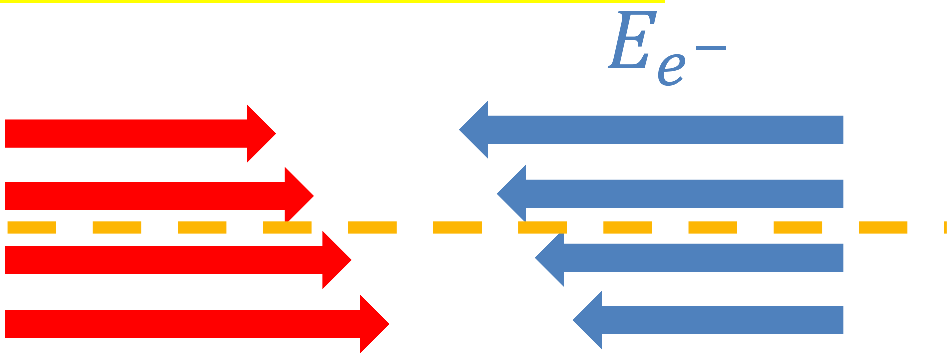
5. On the whole there are many questions requiring answers but the precision level of O(10 keV) seems like a good target at the Z.

6. some insight about the WW but need to be further extended

7. much documentation is needed.

From beam energy to E_{CM}

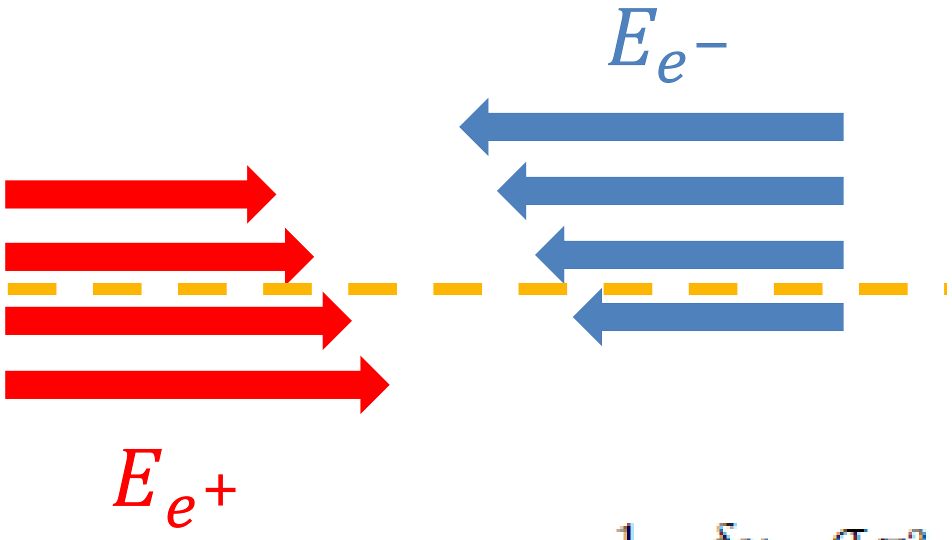
opposite sign dispersion



E_{e^+}

No effect on ECM

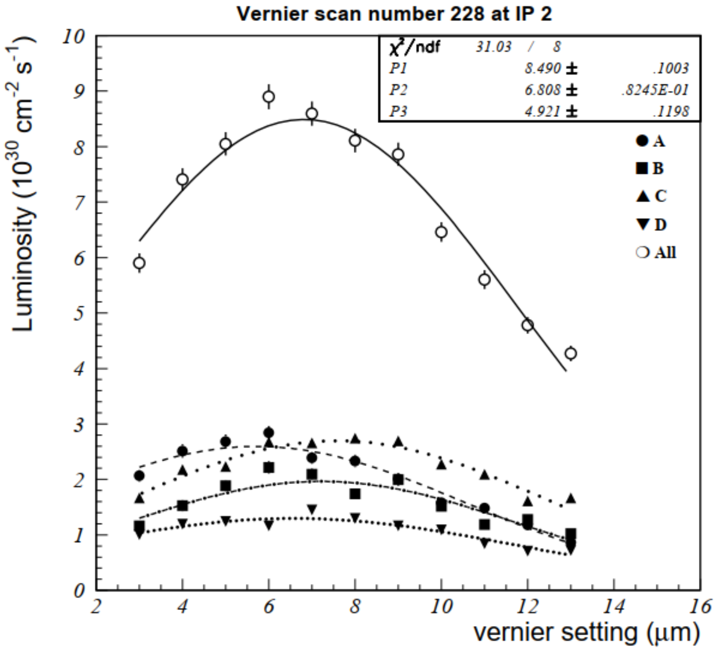
NB energy spread is reduced.

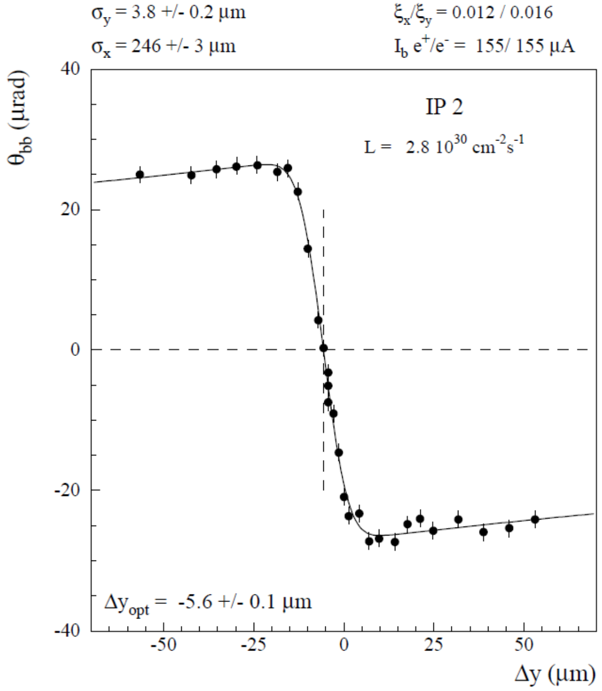


ECM lowered: $\Delta E_{\rm CM} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_b}^2}{E_b} \cdot \Delta D_y^*$

Experience from LEP: Vernier scans

Relative position of beams measured to +- 80 nanometers from one scan





precision requires going far from maximum
➔ loose beam?

Try beam-beam deflection?

FCC vernier scans

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 is accurate to 1% sigma_y, we get a precision of 400 keV.
  the process should be simulated

- we need 100 beams scans to get an E_{CM} accuracy of 40keV – suggestion: vernier scan every hour or more.
- It is likely that Vernier 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. ***(provided no systematic effects show up)***

- **The dispersion must be measured as well; this can be done by using the vernier scans with offset RF frequency**

- this would lead to lots of Vernier scans!

critical effect is in the vertical plane, but horizontal plane should be investigated as well

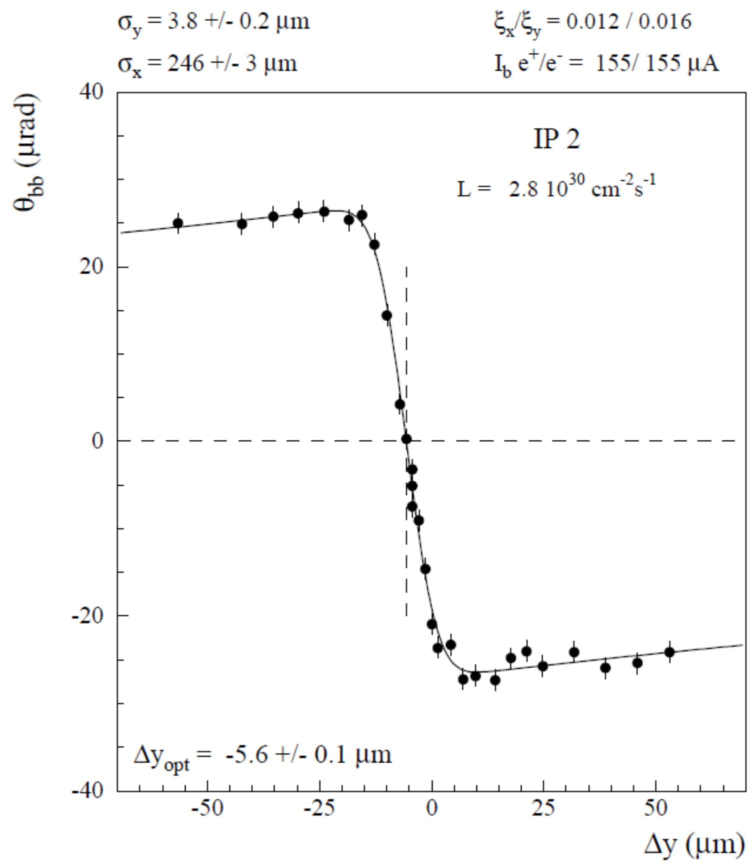
beam-beam deflection scans were already used at SLC, KEK and LEP

Luminosity Optimisation Using Beam-beam Deflections at LEP

C. Bovet, M.D. Hildreth, M. Lamont, H. Schmickler, J. Wenninger,
CERN, Geneva, Switzerland

CERN-SL-96-025
https://inspirehep.net/literature/420668

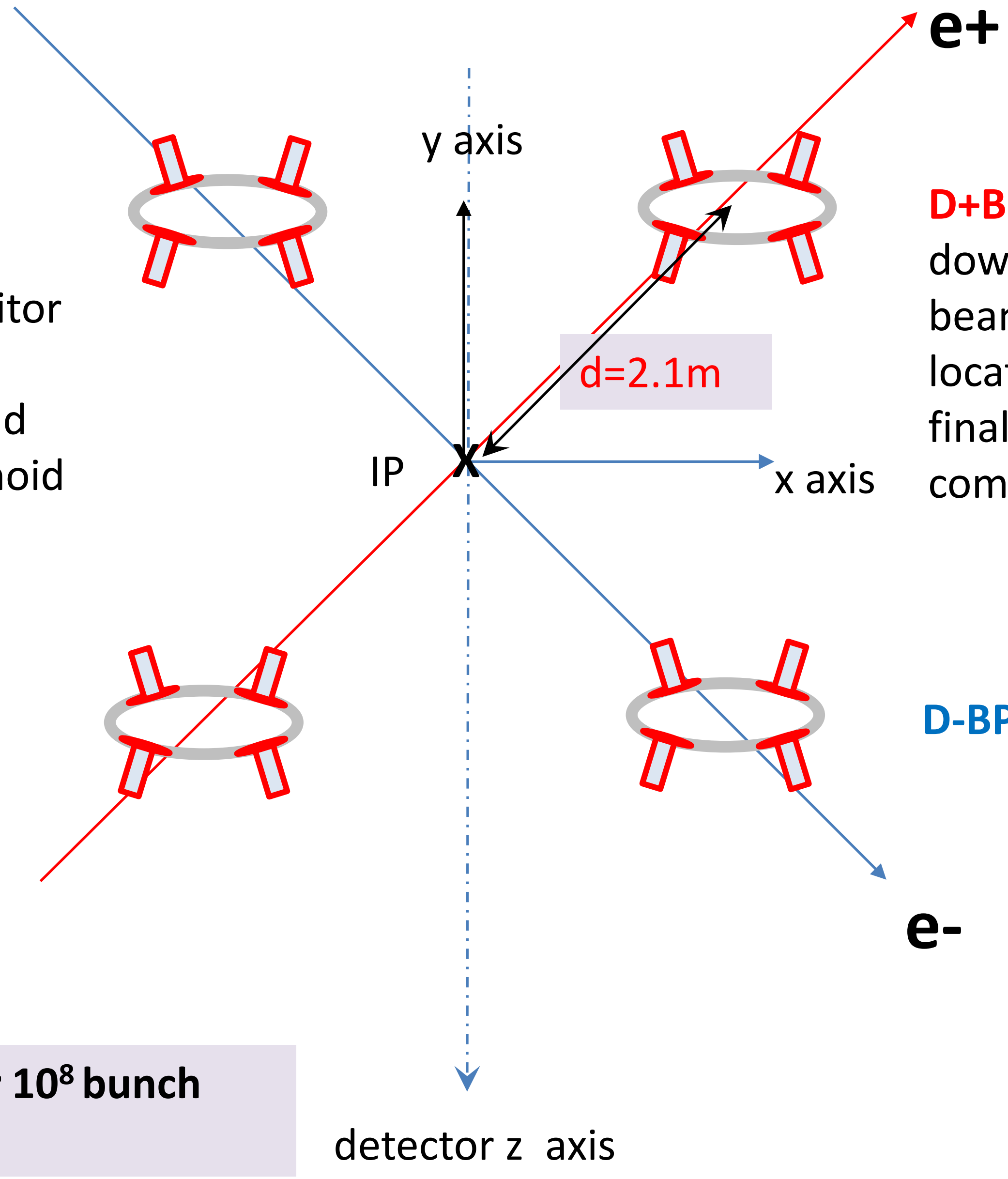
Uncertainty on Δy_{opt} = -5.6±0.1 μm
is 1/40 of the vertical beam size 3.8±0.2 μm
which was itself measured in the process



beam-beam deflection measurement at FCC-ee as if in « squished perspective » looking from behind detectors endcaps

U-BPM

upstream electron
beam position monitor
located between
final focus quads and
compensating solenoid



D+BPM

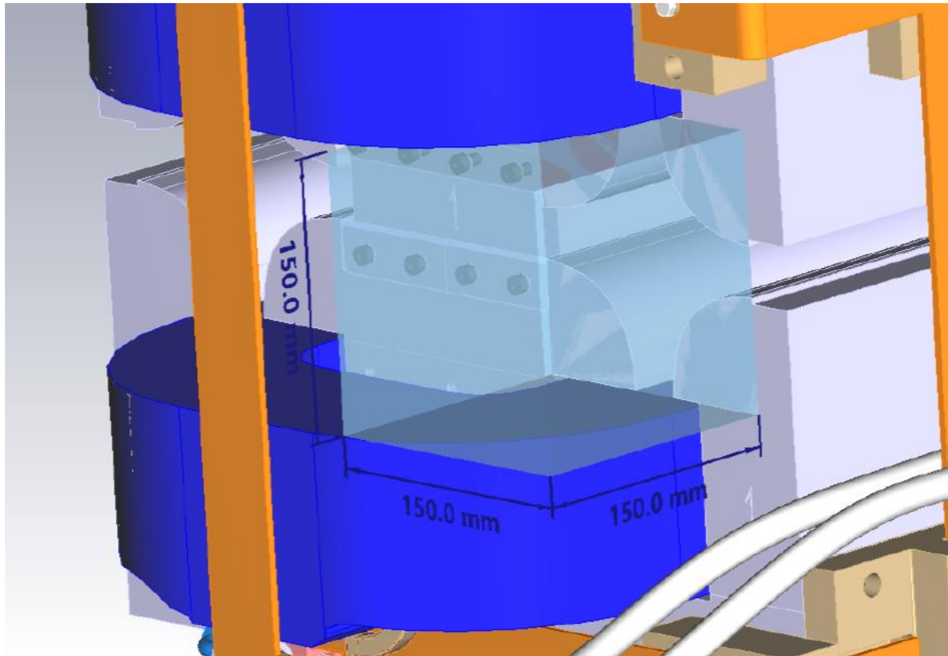
downstream positron
beam position monitor
located between
final focus quads and
compensating solenoid

U+BPM

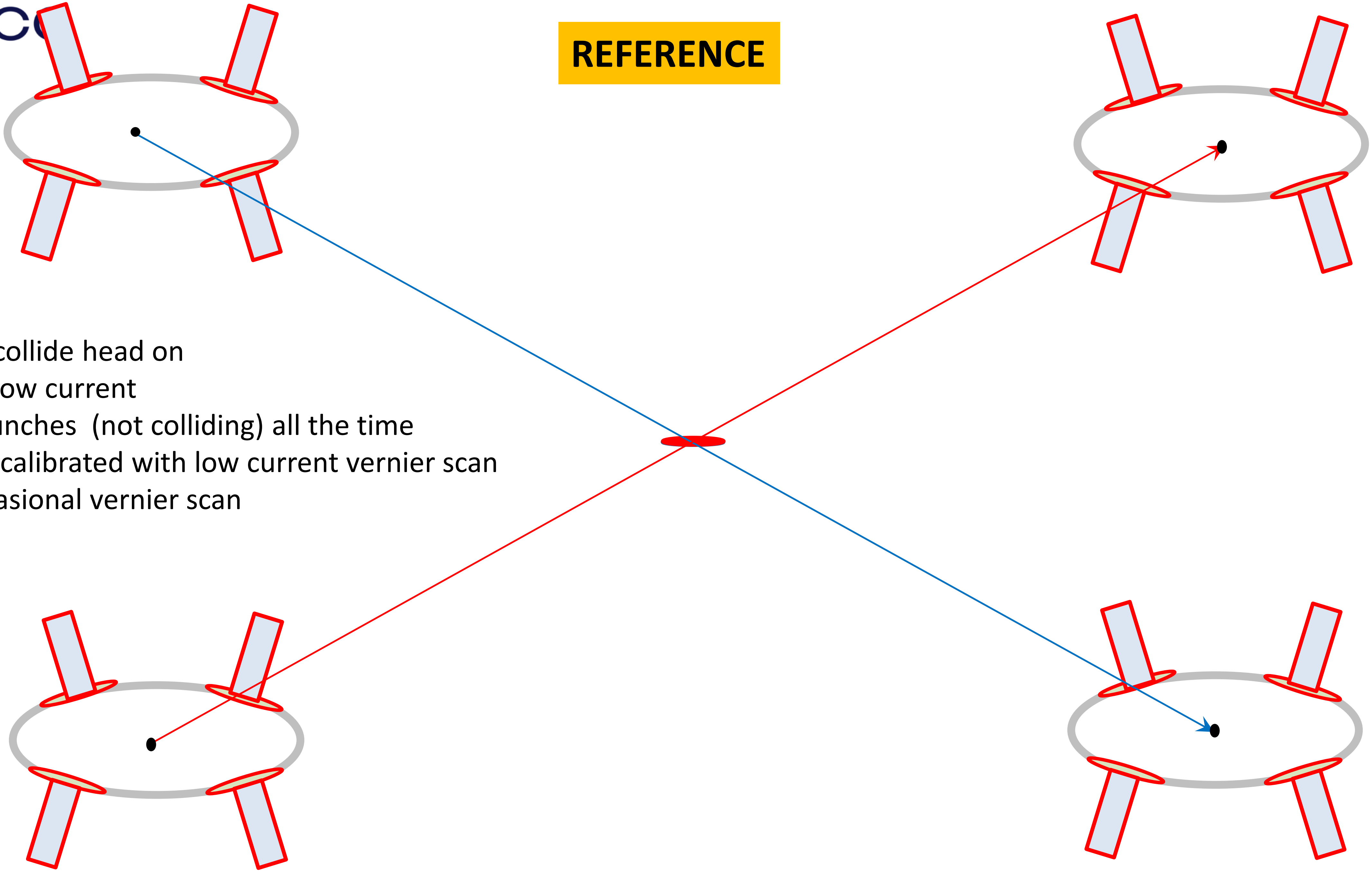
D-BPM

BPM precision over 10^8 bunch passages is ~1µm

BPM in arc magnets



REFERENCE



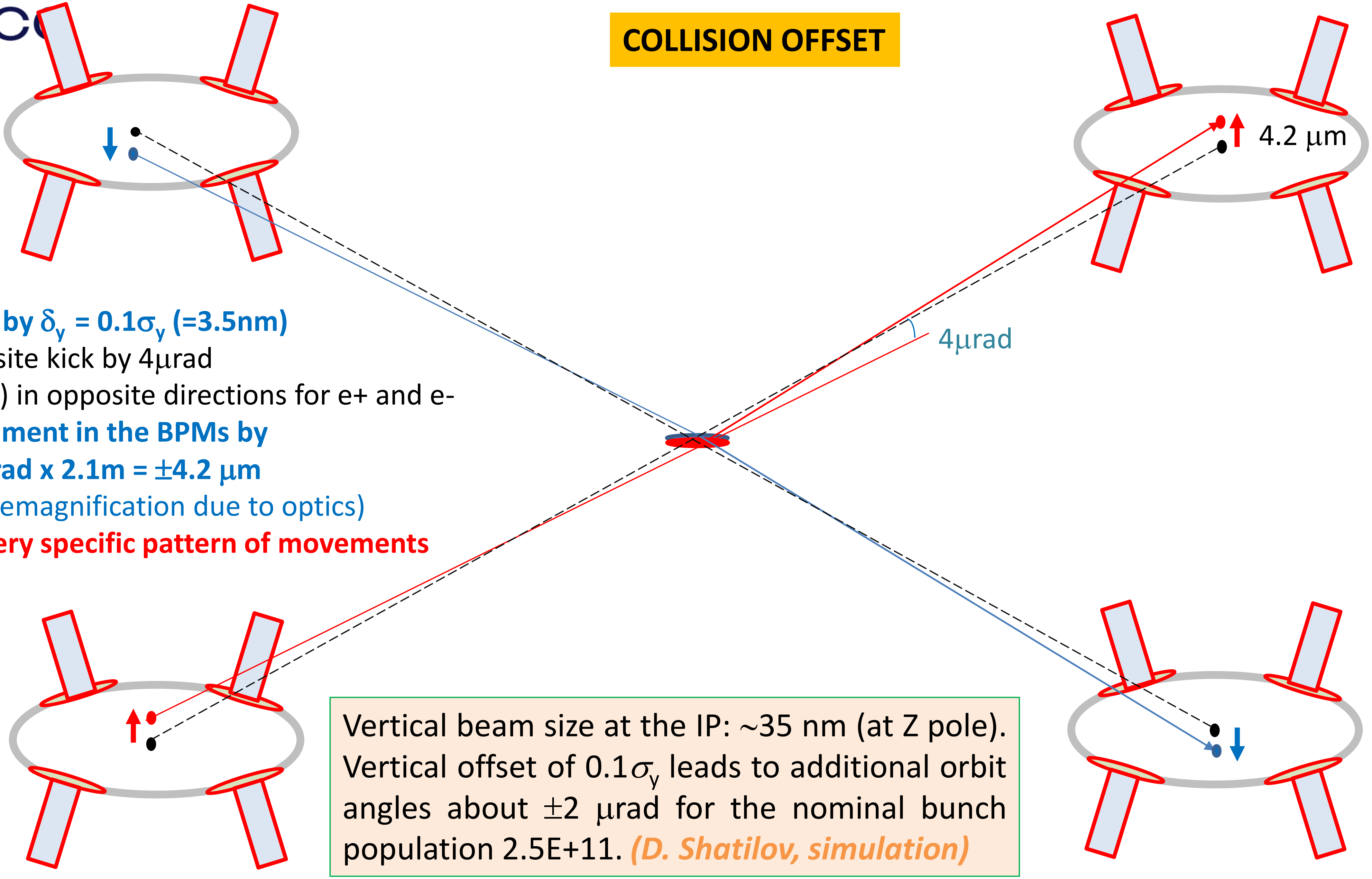
1. beams collide head on
   -- or at low current

1’. pilot bunches (not colliding) all the time

1’’ can be calibrated with low current vernier scan

1’’’ or occasional vernier scan

COLLISION OFFSET



2. **offset by $\delta_y = 0.1\sigma_y$ (=3.5nm)**

➔ opposite kick by 4μrad

(Shatilov) in opposite directions for e+ and e-

➔ **movement in the BPMs by**

± 2 μrad x 2.1m = ±4.2 μm

(x1000 demagnification due to optics)

with a very specific pattern of movements

Vertical beam size at the IP: ~35 nm (at Z pole). Vertical offset of $0.1\sigma_y$ leads to additional orbit angles about ±2 μrad for the nominal bunch population 2.5E+11. ***(D. Shatilov, simulation)***

Measurements of offsets and Opposite Sign Vertical Dispersion (OSVD)

Purely statistical and preliminary arguments:

OFFSETS:

Four measurements of 4.2 micron displacement with 1 micron precision can be made with 10^8 bunch passages (assume 10000 bunches in each beam)

→ **every 3 seconds**

→ **measurement of beam beam offset with precision of 0.1 * 35nm / 4.2 / √4 = 1/80 of beam size or ~0.4nm**

A normalization of the measurements needs to be performed using a luminosity scan every so often (hour?)

Nbit would be nice to have a reference continuously **CAN WE USE THE PILOT BUNCHES?**

LEP did not have pilot bunches, but maybe we can use them? (there is a debate on this)

Pilot bunches would provide 10^8 bunch measurements in 2 minutes (only 250 bunches of each beam)

OSVD

we cannot really measure the dispersion at IP directly,

but the beams will move in opposite directions upon a change of RF frequency

→ we measure the opposite sign vertical dispersion (OSVD) this way!

Assuming that a relative momentum change of 10-3 is feasible, this measurement corresponds to a measurement of opposite sign vertical dispersion D*y(e+)-D*y(e-) with a precision of 0.4 micrometer.

Plugging this into the equations of the earlier page this leads to a measurement of the possible shift in energy with a precision **of ± 20 keV each time the dispersion measurement is done. THIS IS VERY PROMISING because in particular it requires very little scanning across the beam.**