FCC-ee CM Energy: impact of the RF System

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With input from the BE RF colleagues

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and from T. Tydecks

RF system and energy loss

- From the point of view of energy calibration, the role of the FCC-ee RF system is to compensate the energy loss that is dominated by synchrotron radiation.
  - At the Z, the energy loss per turn U_0 is 35 MeV.
- To first order one can consider that the RF system provides a peak voltage V_{RF} and that the beam sits at a stable phase Φ_s given by:

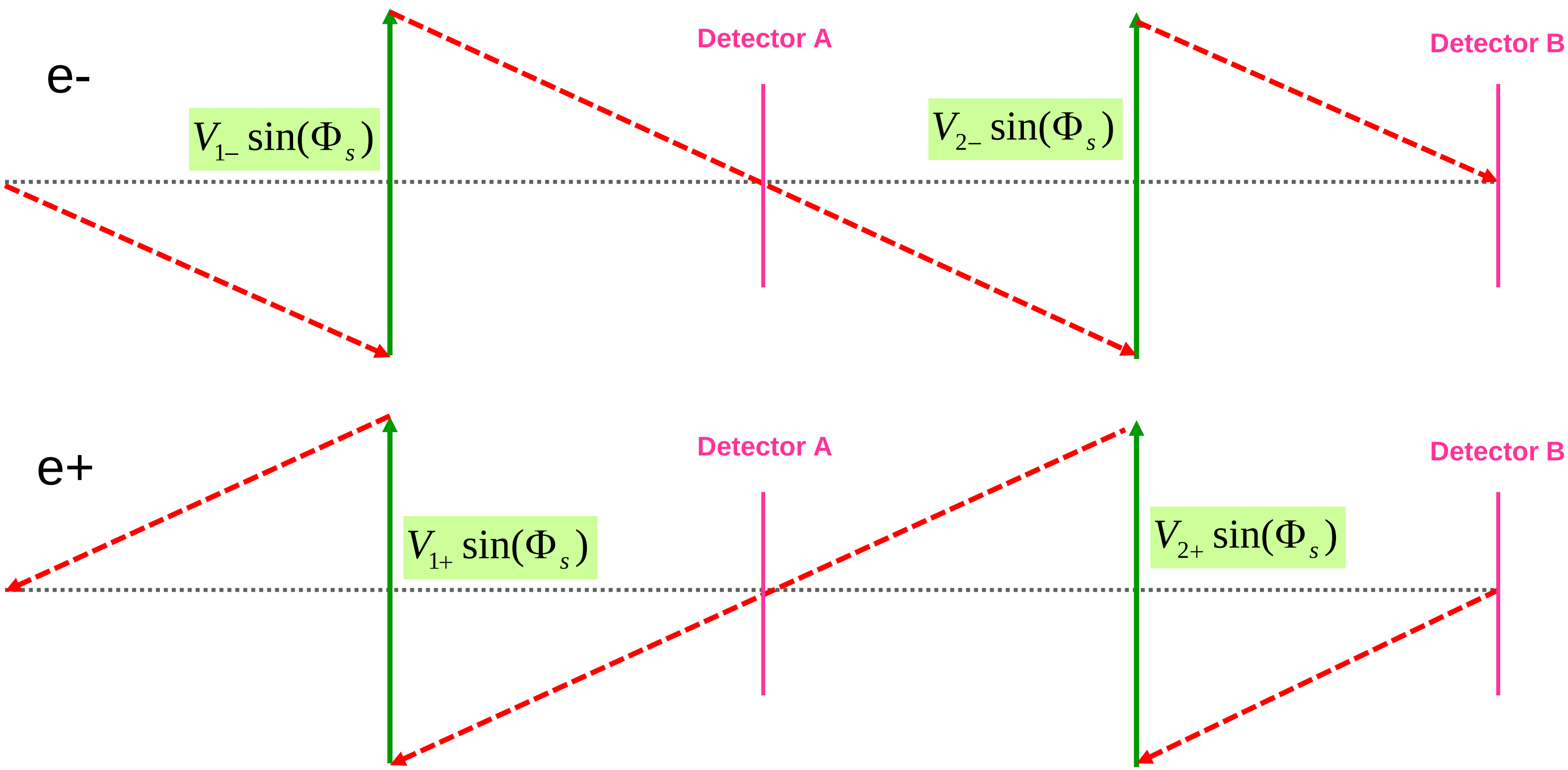
$$\sin(\Phi_s) = \frac{U_0}{V_{RF}}$$

  - At the Z, V_{RF} = 100 MV (for example) → $\Phi_s = \sim 160^o$.
- Between the passage through two successive RF stations, the beam looses energy through radiation in the different magnets.
  - Energy loss due to a element $U_{sr} \propto E^2 B^2$ where B is the magnetic field.
  - Field uncertainties δB lead to loss uncertainties $\delta U_{sr} \propto 2B\delta B$.
- To reconstruct the energy at any place along the circumference we must know where the beam gains and looses energy (and how much).

Z RF system

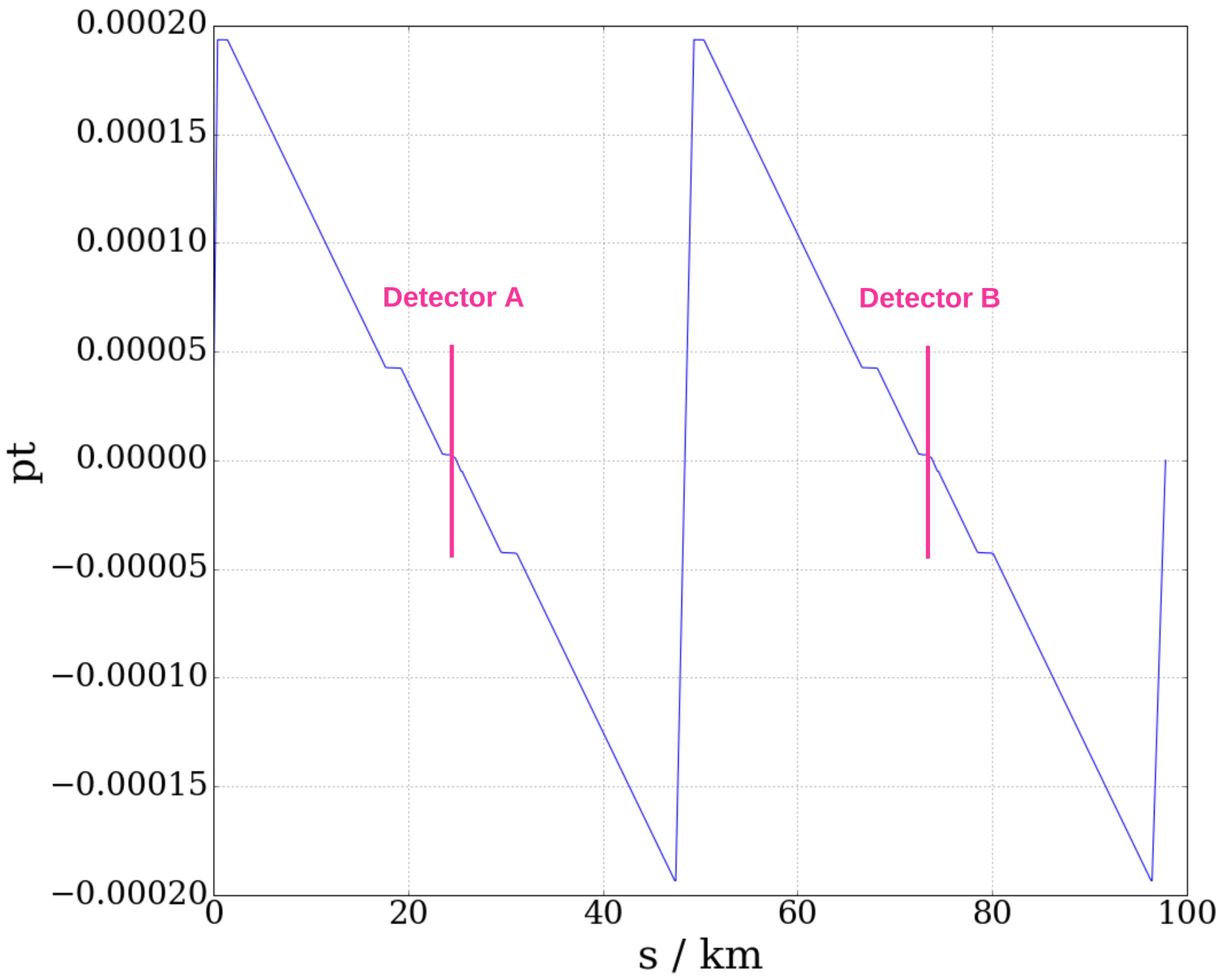
- The Z RF system will consist of 2 RF groups/stations located at opposite sides of the ring.
- Each group consists of 52 cavities with ~ 1 MW power per cavity.
- The cavity peak field is probably 2-3 MV (tbc).
- At the Z **the RF systems of e+ and e- are separated**, errors on phases, alignment and voltages are therefore not directly correlated.
  - Except maybe through calibration techniques (eg RF voltage).
  - **This is completely different from the LEP case where the beams shared the same RF system**. It brings advantages and disadvantages.
  - A longitudinal alignment error can be compensated by a phase shift. Alignment errors are not ‘very’ relevant.
    - Contrary to the LEP case where the alignment errors could not be compensated.
- An important point to note for later: at the Z there is enough RF voltage to operate with a single RF group !

- In the ideal situation each RF group provides the same voltage and the energy along the ring looks as sketched below.
  - Note that due to the asymmetry in the experiments IRs, the experiments do not sit exactly at ‘0’ offset.

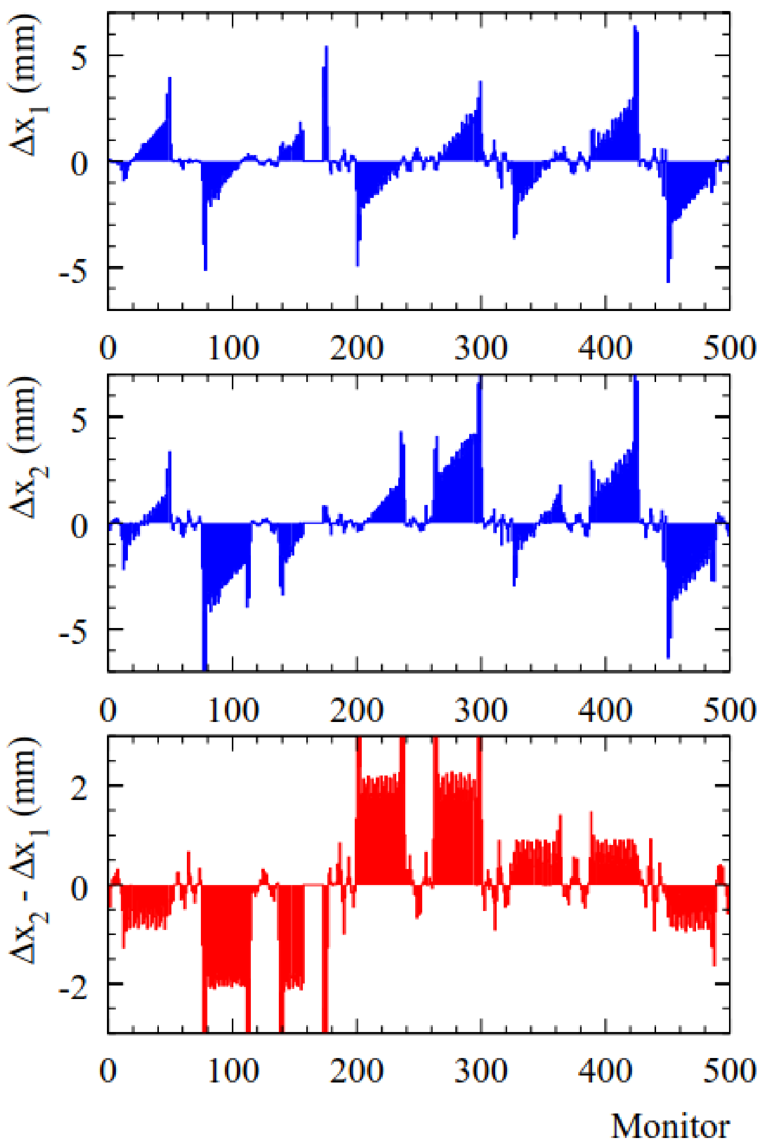


More realistic sawtooth

- Z energy sawtooth simulation of the latest optics (by T. Tydecks).
  - Offset at detector $dE \sim 0.1$ MeV.



- At LEP with both beams in the same vacuum chamber, the energy sawtooth could be measured easily by the BPM system.
  - Closed orbit effects and BPM offsets cancel out to first order when the difference between the beams is considered.
  - This possibility was used for RF system calibration (effective voltage) at LEP2.



Measured RF sawtooth for 2 RF voltage configurations (top, middle) and the resulting difference (bottom)

J. Wenninger, CERN-SL-2002-28 OP

RF System Calibration Using Beam Orbits at LEP

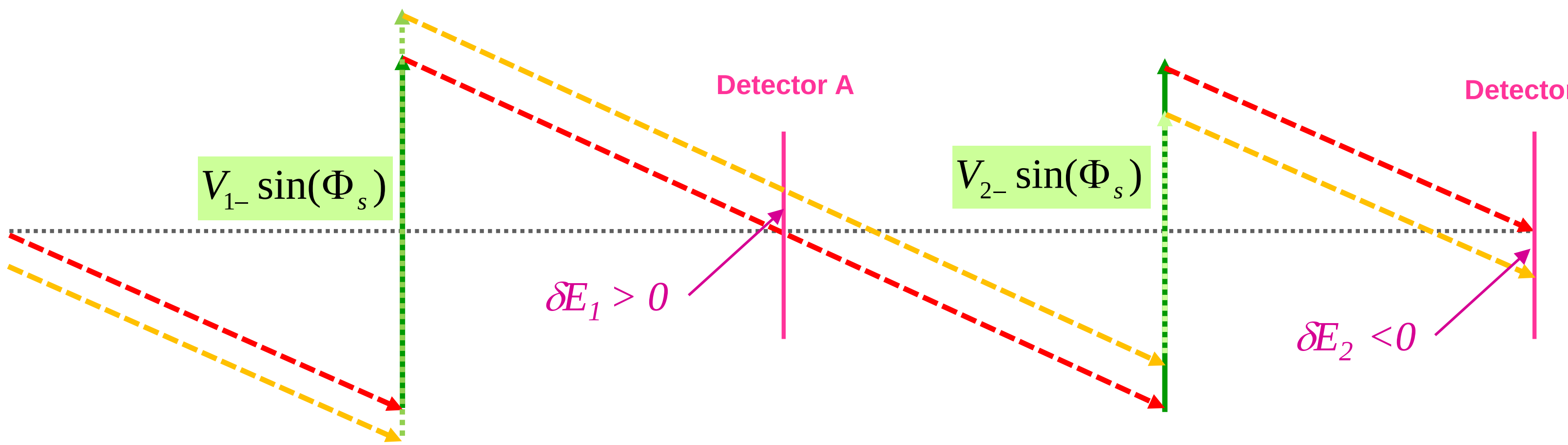
Measuring the sawtooth – FCC-ee

- At FCC-ee, with a tapered machine and e+ and e- in separate vacuum chambers, it is not possible to measure the absolute sawtooth. The LEP tricks do not work, and the closed orbit will strongly perturb measurements.
- It is however possible to work in 'differential' mode and observe:
  - Bunch by bunch differences due to beam loading or parasitic losses,
    - Fill patterns with bunches having different charges.
  - Effects due to changing RF configurations (e.q. changes in voltage, cavity failures etc),
  - Sawtooth changes due to controlled voltage changes to calibrate the RF voltage scale,
  - etc
- Assuming a **BPM accuracy** (short term) of **1 μm** (could do better) and a **peak arc horizontal dispersion** of **30 cm** (60/60 optics), it is possible to **resolve energy changes of 0.15 MeV**.
  - The sub-100 keV scale is within reach !
  - To reach um accuracy & stability requires **very stable temperature control of the tunnel** → heavy effort on that in some light sources.
    - LEP is a disaster area in that respect (poorly designed of ventilation).

RF errors

- If the RF voltage or phase changes in one RF group, the local energy gain will change, the difference must be compensated by the second group → strong correlation of changes / errors between the 2 RF groups.
- To first order the energy change has opposite signs at the 2 experiments !

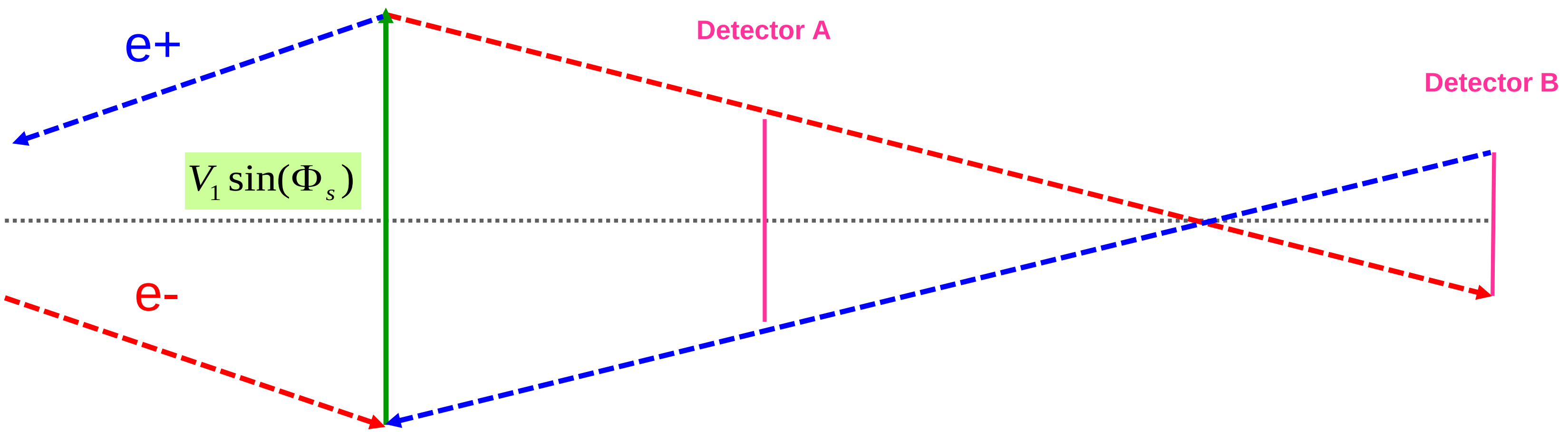
$$\delta E_1 + \delta E_2 \approx 0$$



- By averaging the Z mass of the 2 experiments one can cancel out some of the RF errors (is that 'legal'?).
  - This correlation could also be observed by other means (event asymmetries etc).

Single RF station

- If FCC-ee is operated with a single RF station, this station must by definition provide all the energy. The beam automatically phases in such as to compensate the energy loss.
  - Phase drifts translate into longitudinal position shifts at the IP.
- To first order the cm energy shift is ~ 0 if both beams are powered with a single station at the same point.
  - But the CMs are boosted longitudinally in both experiments.
  - Boost signs and ratios defined by energy loss along the ring → usable to extract some information on energy loss RF-> IP?



Temporary summary

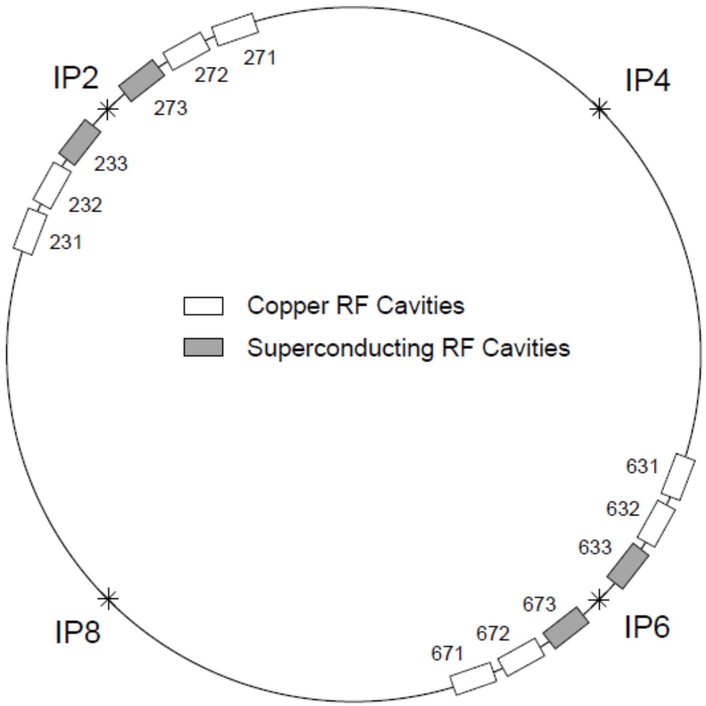
- The impact of RF errors can be minimized by operating with a single RF station !
- For operation with one or two RF stations event properties like energy boost etc are correlated between the two experiments.
  - The correlations can be used to beat down systematic errors.
  - Many systematic errors are strongly correlated, for example between energy points if the energy is scanned, etc. The correlations can help reduced systematic errors, in particular on the Z width.
- Overall the situation seems to be more favourable than for the 8 RF stations (both sides of 4 experiments) including misaligned Cu cavities as we had them at LEP.

Energy loss per turn

- The energy loss along the ring depends evidently on the fields encountered on the path of the beam.
- Since the energy loss due to a element $U_{sr} \propto E^2 B^2$ where B is the magnetic field, field uncertainties δB lead to loss uncertainties $\delta U_{sr}/U_{sr} \propto 2\delta B/B$.
- To determine the energy loss along the ring to **0.1% of U_0 (37 keV) at the Z**, the fields along the beam path must be known with a **relative accuracy of 5×10^{-4}** which is a reasonable target for the integrated magnetic field.
  - The bending field integral is defined by the measured energy which can be used as a constraint.
  - The contribution from the quadrupoles (beam offset due to misalignments) should be estimated from Sandra's closed orbit errors.
- To reconstruct the energy at any place along the circumference we must know where the beam gains and looses energy (and how much).
  - What is happening at the IP with strong beamstrahlung?

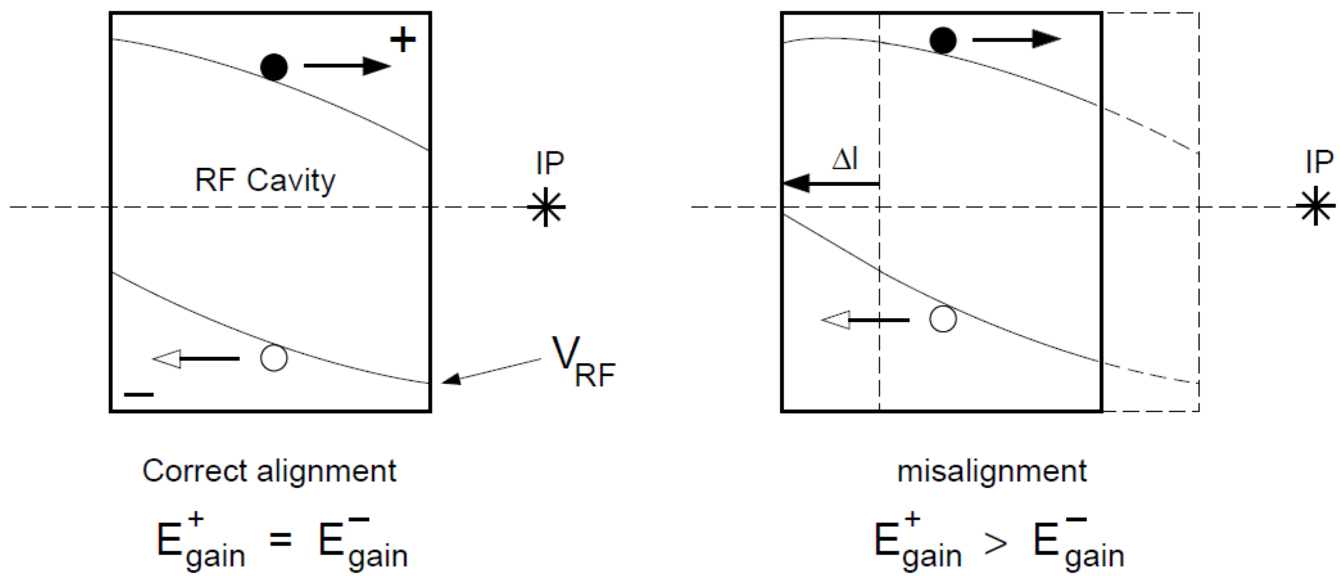
LEP1 RF system

- The LEP1 RF system consisted of a mix of Cu and SC RF.
  - The Cu system was systematically misaligned longitudinally.



LEP1 RF system

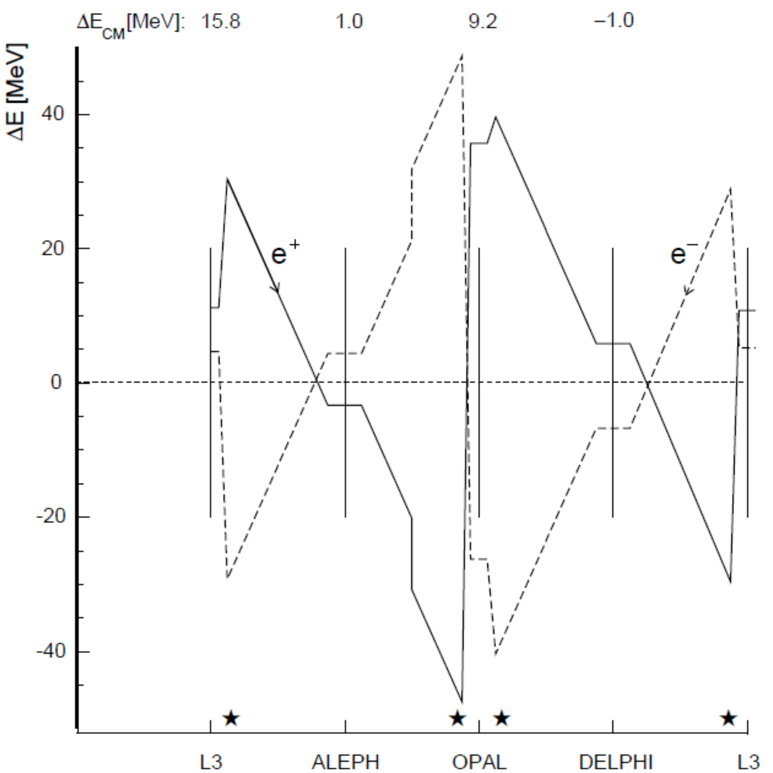
- The LEP RF system was shared by both beams, leading to correlated errors from RF system imperfections, for example alignment errors.
  - Similar to FCC-ee top.



LEP1 RF system

- Due to the asymmetric RF distribution (and errors), the cm shifts were very different in IP2 and IP6 (L3, OPAL) and in IP4 and IP8 (ALEPH and DELPHI).
  - Important energy loss contribution from wigglers.

Example of cm energy corrections at LEP1



LEP1 CM energy error table (from RF)

Error		ΔE_{CM} (MeV)	P ± 2 Corr.	Comments
RF misalignment	IP2	0.6 [0.4]	100%	
	IP6	0.5 [0.4]	100%	uncorrelated
Bunch $\langle z_0 \rangle$ shifts	IP4, 8	0.6	50%	
within a train	IP2	0.8	50%	all IPs correlated
	IP6	0.1	50%	
Voltage scale	IP2	0.4 [0.4]	100%	
	IP6	0.1 [0.4]	100%	IP2 and IP6 corr.
Energy loss	IP2	0.3 [0.6]	100%	
	IP6	0.0 [0.6]	100%	correlated
$\Delta\ell_{26}$	IP4, 8	0.1 [0.1]	100%	IP4 and IP8 anticorr.
Missing data		0.1 [0.2]	50%	all IPs correlated
$Q_s(e^-) - Q_s(e^+)$		0.2	50%	IP4 and IP8 anticorr.
RF misphasing	IP2	0.1 [0.5]	50%	
	IP6	~ 0 [0.5]		IP2 and IP6 anticorr.
$\Delta\alpha = \pm 2 \cdot 10^{-6}$	IP2, 6	0.1 [0.1]	100%	IP2 and IP6 corr.