Update on RF and impedances

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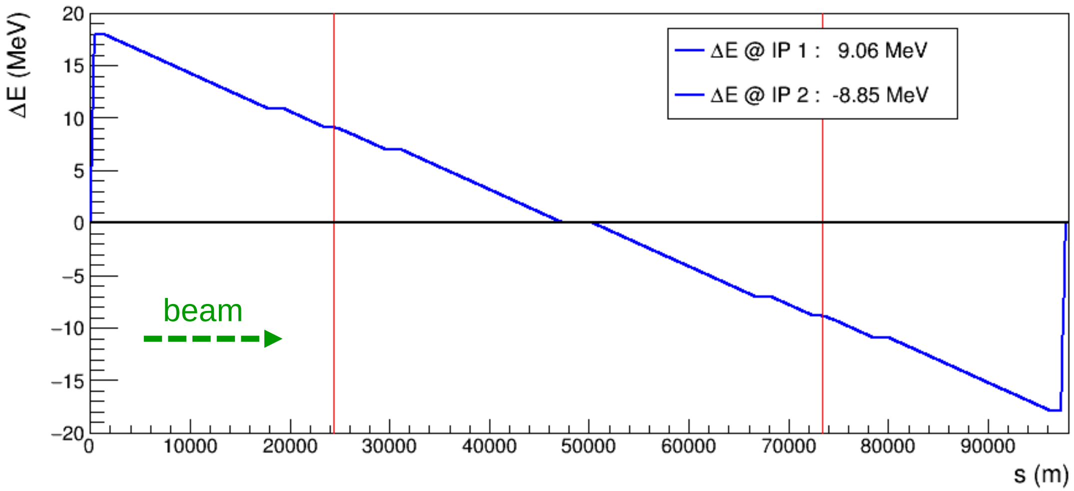
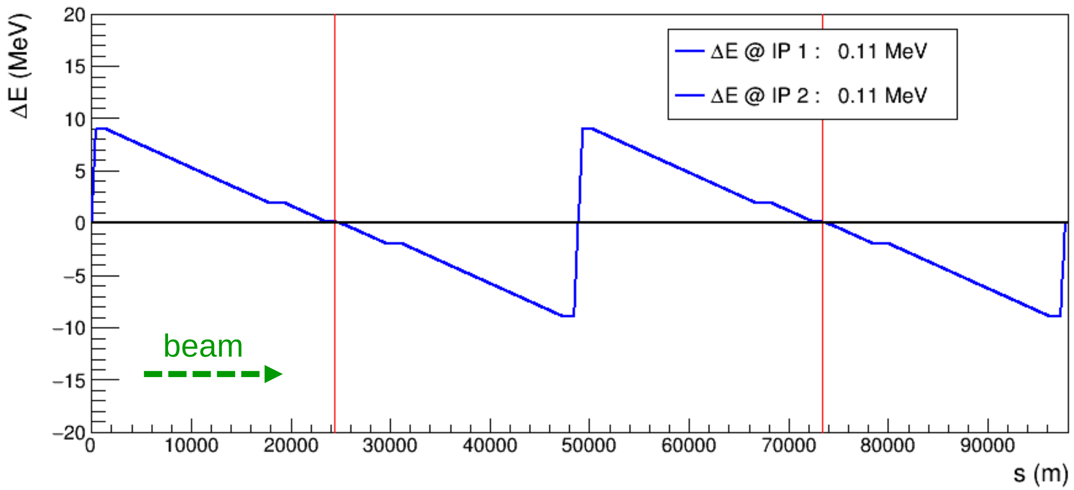
01.02.2018

Sawtooth – 1 vs 2 RF groups

- Energy sawtooth at the Z for 1 and for 2 RF groups per ring.

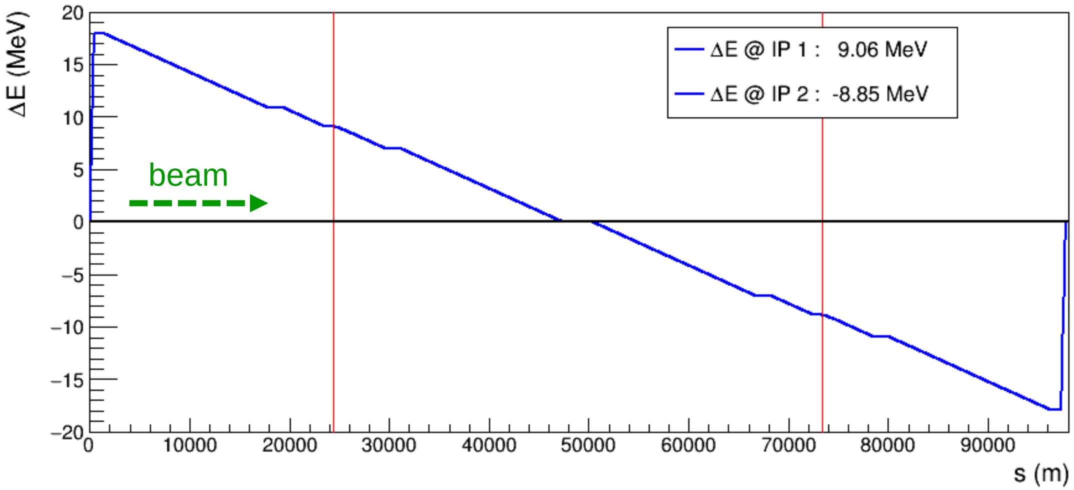


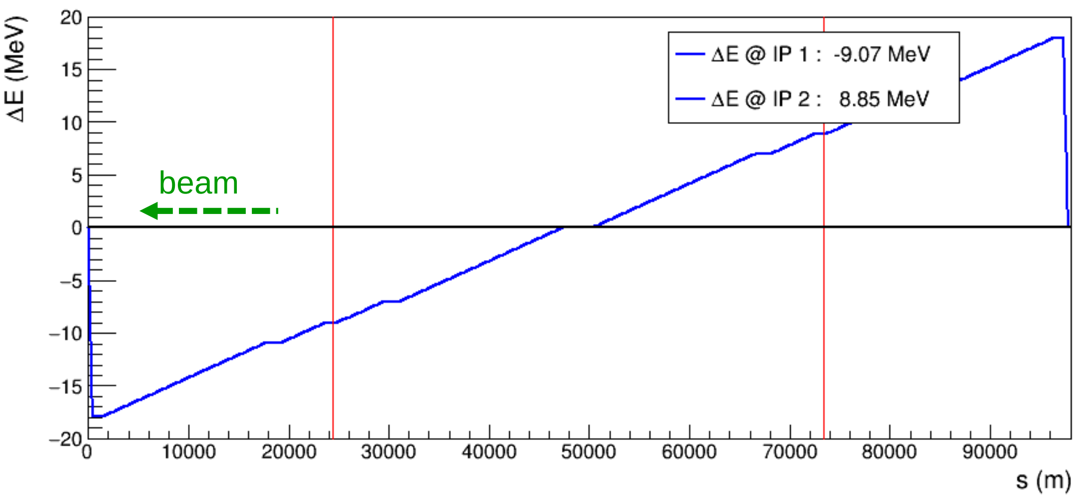


- One RF group:
  - No dependence on RF voltage and phase errors (by definition right) since the energy gain in the RF must always match the energy losses.
  - Larger energy sawtooth.
  - Energy offset at the IP.
- Two RF groups:
  - Local energy depends on voltages and phase errors between the 2 RF stations → adds uncertainty.
  - Smaller sawtooth.
  - ~no energy offsets at the IPs (ideal configuration).
  - RF system errors are anti-correlated between the two exp IPs.

Sawtooth – 1 RF group

- If the RF of BOTH rings is installed at the same point, to first order the energy offsets of the two beams at the exp IPs will be of opposite sign and cancel.
  - $\Delta E_{CM} \sim 0$.



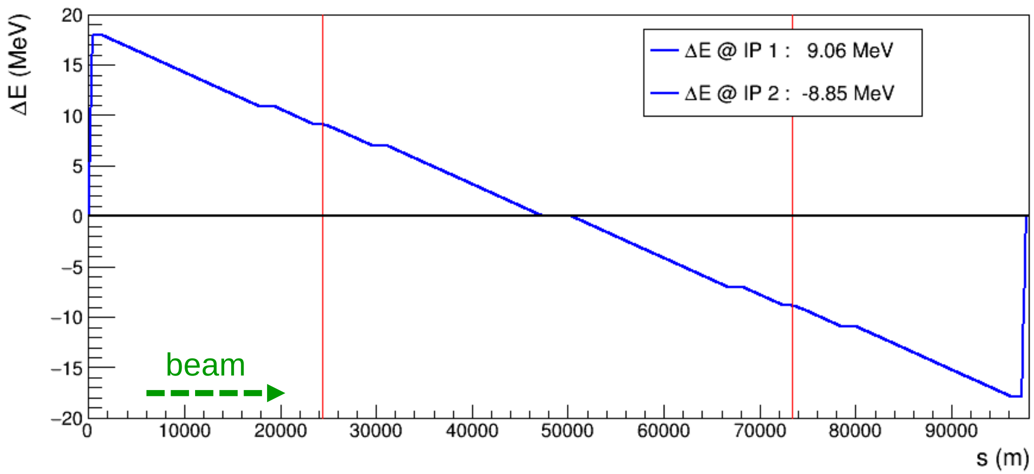


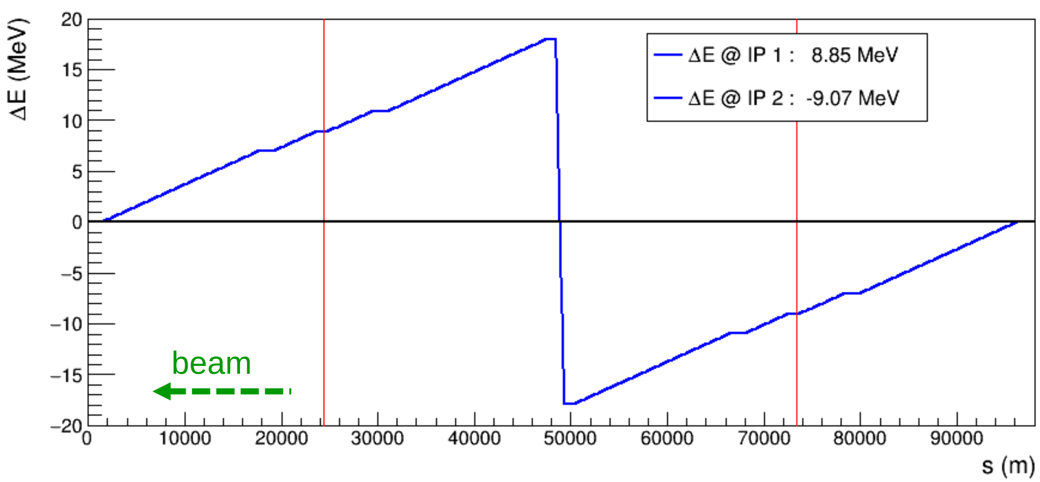
- To first order, as long as the two rings are **completely symmetric**, the CM energy offset at the IPs does not depend a lot on the amplitude of the energy loss along the ring.
- The symmetry will be broken by lattice asymmetries and by impedances.

Note: the correctness of the inverted sequence needs to be checked – numbers may change slightly !

Sawtooth – 1 RF group

- If the RF of the two rings are installed in opposite points, to first order the energy offsets at the exp IPs have the same signs and add up.
  - ΔE_{CM} ~ +18 MeV at one IP, -18 MeV at other OP.





- The CM energy offset at the IPs **depends** on the amplitude and distribution of the energy loss along the ring.
- To first order the average CM energy of the two exp IPs does not depend on the amplitude of the energy loss along the ring.
  - $\Delta E_{CM,1} + \Delta E_{CM,2} \cong 0$.

RF distribution

- To minimize uncertainties related to the RF system, concentrating the RF of one ring in a single point is an advantage.
  - The RF voltage calibration is in principle irrelevant, but should still be used as cross-check (against synchrotron tune etc).
- Further error cancellations occur if the RF systems of both rings are installed in the same point.
  - Not possible due to power distribution (200 MW at one location) and space limitations ?

Sawtooth model

- The energy loss U in a magnet with field B at a beam energy E is given by:

$$U \propto E^2 B^2$$

- The relative energy loss uncertainty is:

$$\frac{\delta U}{U} \propto 2\frac{\delta E}{E} + 2\frac{\delta B}{B}$$

- Assuming that the energy is known to better than 10^{-5}, the uncertainty is dominated by the field uncertainty.
- Consider a ¼ of the ring, U ~ 10 MeV, to achieve **δU = 10 keV**, **δB/B** must be known to **5×10^{-4}** which is not an outrageous requirement for a dipole magnet calibration
  - As long as there is no installation or powering bias, the individual measurement errors should cancel out even more.
  - Impact of orbit offsets in quadrupoles to be checked.

- The longitudinal impedance is dominated by resistive wall, and has non negligible contributions from other distributed systems.
  - Table from CDR, for bunch length of 3.5 mm (M. Migliorati, E. Belli).

Component	Number	$k_l [V/pC]$	$P_l [MW]$
Resistive wall	97.75 km	210	7.95
RF cavities	56	18.46	0.7
RF double tapers	14	6.12	0.23
Collimators	20	38.36	1.45
Beam Position Monitors	4000	31.47	1.19
Bellows	8000	49.01	1.85
Total		**353.4**	**13.4**

$$k_l = 330 [\mathrm{V/pC}]$$

(without RF cavities)

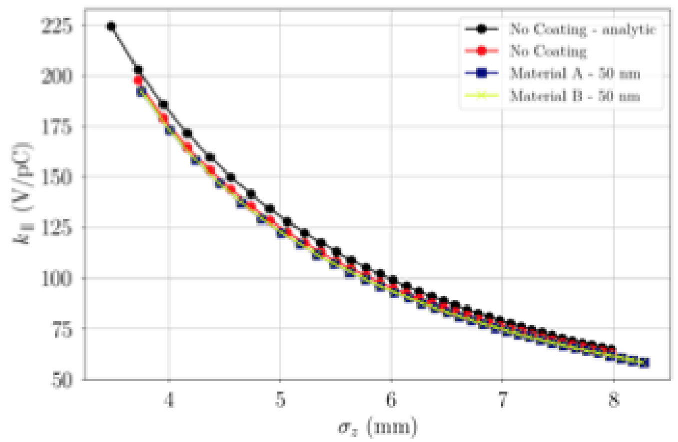
- Consider the distributed impedances (RW, BPMs, bellows), the loss density factor per unit length of machine is

$$\tilde{k}_l = 2.97 [\mathrm{mV/pC\,m}]$$

- This loss factor leads to an energy loss per unit length per particle of 48 eV/m or a loss per turn of 4.8 MeV– more than 10% of the SR losses !

Bunch length scaling

- The loss factors depend on the bunch length, and the scaling depends on the impedance source.
- For RW:



- For bunch lengths of 6-8 mm, one gains a factor > 2, but the energy loss will depend on bunch length evolution and bunch by bunch length differences (bunch position in the train…).
  - Non colliding witness bunches and nominal collision bunches will have different local energies !

Impedance measurements

- The longitudinal impedance losses must be measured in the machine, it is rather improbable that we can predict them well enough.
- At LEP for example the longitudinal loss factor was measured by circulating at the same time a low and a high intensity bunch.
  - The extra energy loss due to impedance of the high intensity bunch can be observed o the orbit in dispersive regions.
  - For FCC-ee the distributed impedance would be visible as a sort of sawtooth when comparing the high and low intensity bunch orbits.

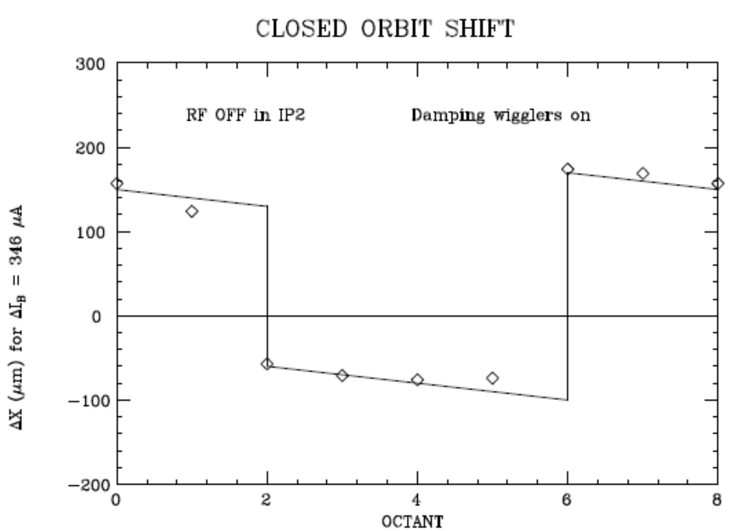


Figure 2. Difference orbits for 2 values of current

LEP example with RF ON is a single point:

Slope due to distributed impedances,

Step due to RF cavity impedance (Copper cav).

Measurements agreed with model to ~ 10%.

D. Brandt et al, *MEASUREMENTS OF IMPEDANCE DISTRIBUTIONS AND INSTABILITY THRESHOLDS IN LEP, EPAC 96.*

Impedance measurements

- A local energy changes at the level of 10 keV due to the impedance at location with H dispersion of 20 cm, leads to a position change of only 40 nm – quite a challenge !
  - It may be possible to determine the overall slope of the energy loss, but not a tiny local step.

- The longitudinal impedance could become an important contribution to the energy uncertainty. To be analysed further.