The LEP RF Model

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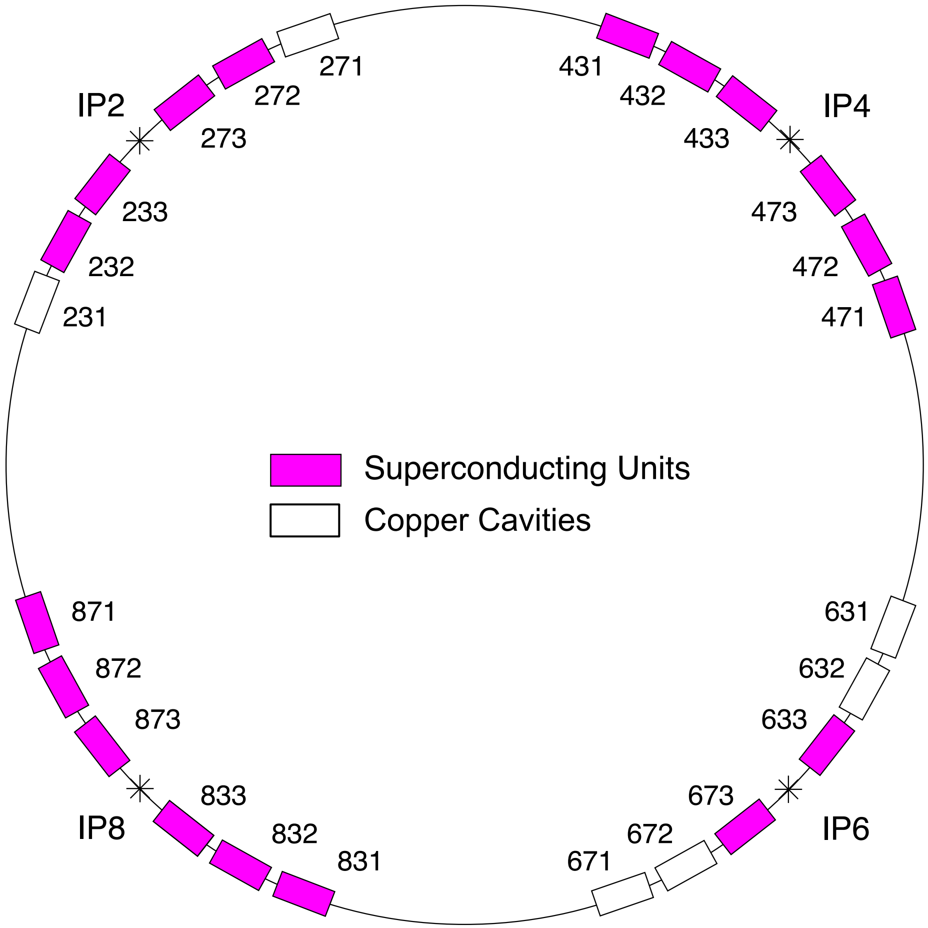
(Original developer: Günter Quast & others)

Synchrotron Energy Loss … sucks

- …sucks energy out of the beam
  - Reminder:
    - $E_{loss} \propto E^4/r^2$
- have to replenish with RF cavities or some other source of RF acceleration
- leads to very local jumps in beam energy around a storage ring
- Energy variation around the ring must be included to calculate the local beam energy at a given point

Example from LEP2 Running

- LEP2 RF in 1997:

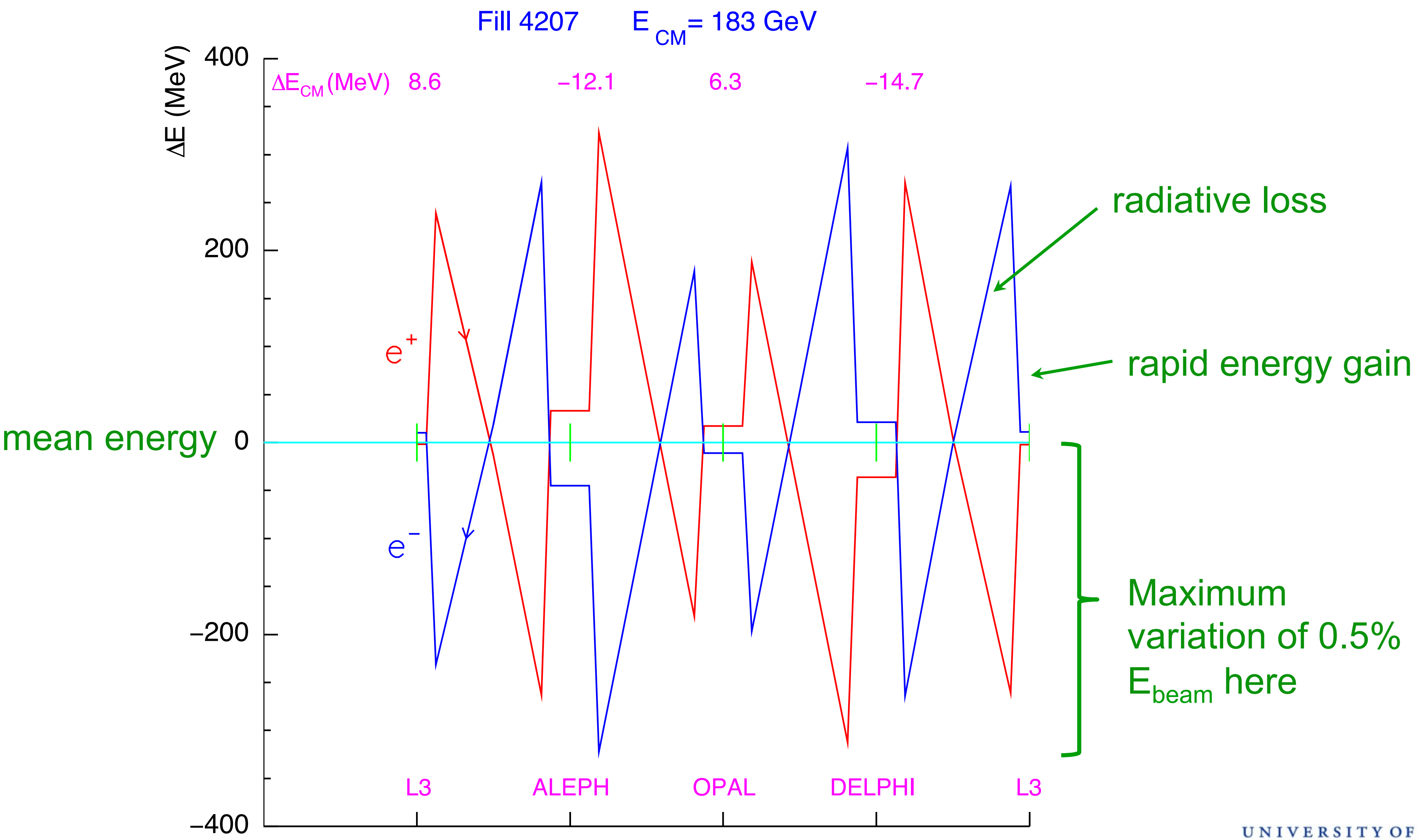


RF Parameters:
- gradient: ~6 MV/m
- ~ 100 MeV of gain per cavity

At maximum Energy, energy loss per turn was about 4% of E_{beam}

Local Gain/Loss leads to "Sawtooth"

- At 91.5 GeV/beam:



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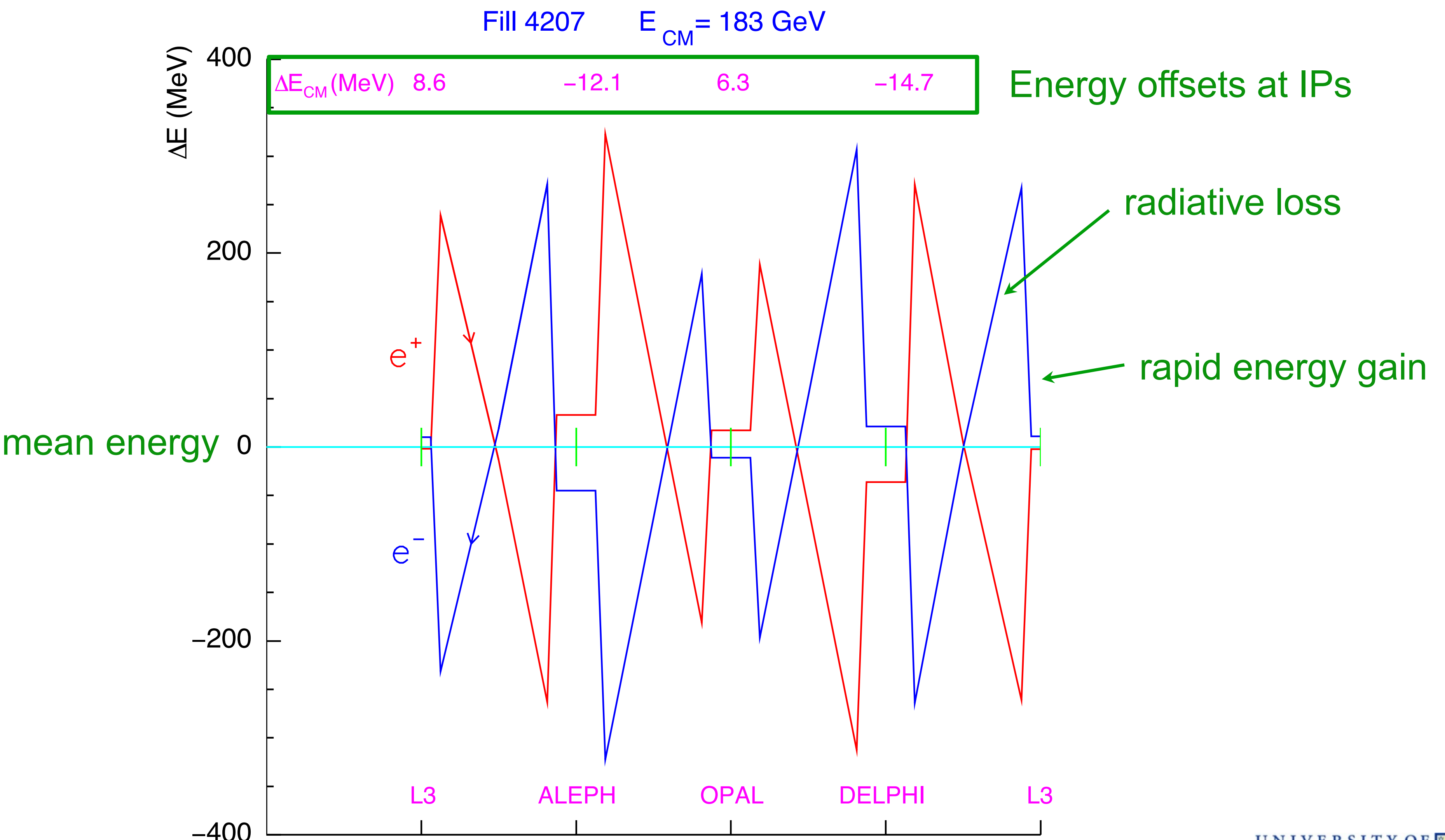
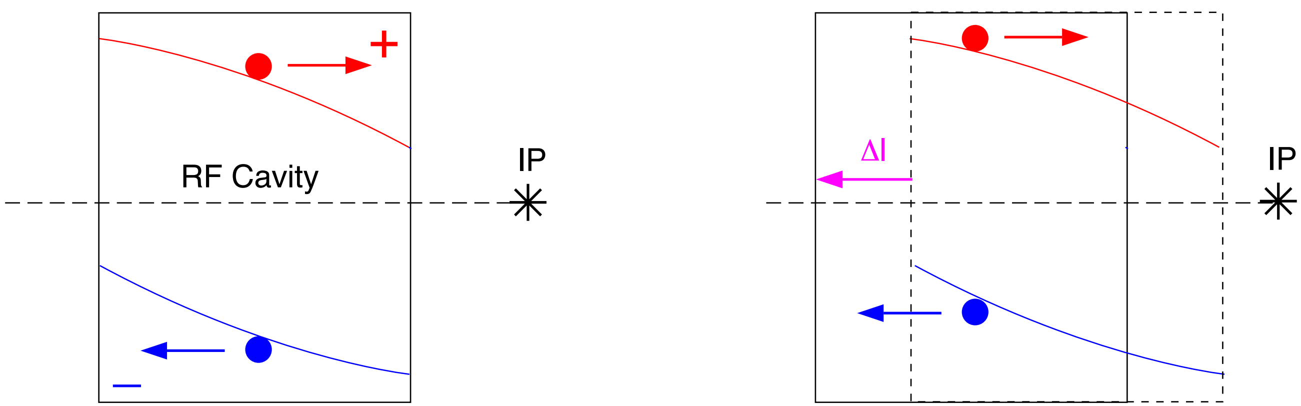


Why are there energy offsets?

- Unequal power distribution in cavities
  - cavities trip off, etc.
- RF phase errors
- Cavity Misalignment:

anything that gives counter-rotating beams different energy gains



Correct alignment

$E^{+}_{gain} = E^{-}_{gain}$

misalignment

$E^{+}_{gain} > E^{-}_{gain}$

- Classic problem at LEP: copper cavities were 1 inch too far from the IPs, leading to local ΔE of 20 MeV

RF Model Ingredients

- Fixed parameters:
  - RF frequency
  - Distance from RF cavity to IP
  - Phase (quasi-fixed)
  - Arc length differences around ring (if non-zero)
  - Bunch spacing (if trains), “nominal” on-phase bunch
- Time-varying parameters: (Must be monitored/stored)
  - Nominal beam energy
  - Cavity voltages
  - Beam currents
    - worried about cavity loading, induced field effects, HOM, etc.
  - longitudinal feedback voltages (if any)
  - [Q_s measurements]
  - [BPM differences in arcs (measure of sawtooth)]

Calculation of RF Corrections

Relatively Simple procedure:

- Given the total energy loss and prospective energy gains, compute the stable RF phase angle for the aggregate RF voltage.
  - includes all known effects that modulate energy gain at each cavity
  - This effectively gives the energy gain for each beam in each cavity, allowing the computation of the sawtooth and the energy at each IP, for each beam.

Outputs and Cross-checks

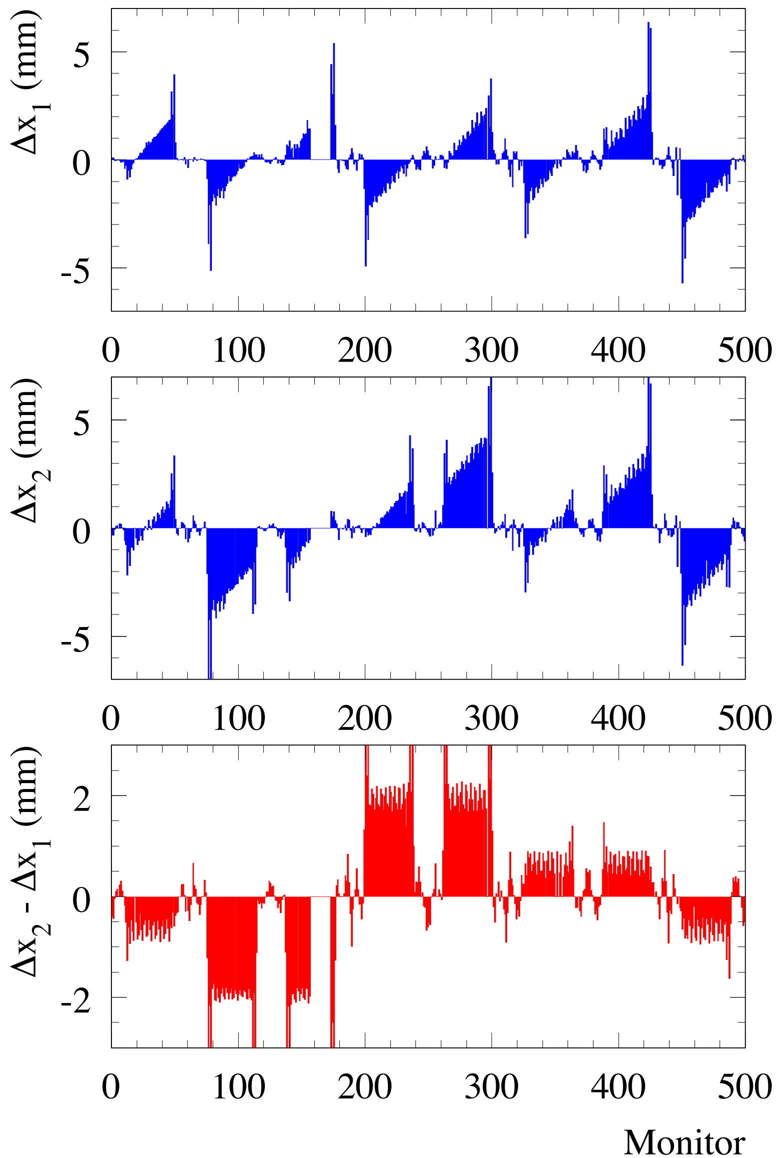
In addition to the energy corrections, one can also find:

- Stable RF phase and overall voltage are easily related to Q_s, which can be calculated and compared with measured values
  - Can also use measured Q_s to determine/cross-check voltage scale calibration
- Calculated energy difference in arcs can be related to difference in BPM measurements for the two beams given the dispersion
  - cross check with orbit data
- Changes in the stable RF phase can move the collision point longitudinally by ~mm.
  - Can cross check this with data from the experiments

These three constraints/cross-checks are fairly robust for testing the internal consistency of the model

Example: BPM Sawtooth

- Orbit differences can be a powerful constraint on the RF model
- can also be used to measure/cross-check assumptions on RF system input parameters
  - e.g. phases



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Overall Precision of RF Model

- At LEP2, IP corrections were substantial

Year	'96		'97	'98	'99				'00	
E_{CM}^{nom} [GeV]	161	172	183	189	192	196	200	202	205	207
IP 2 (L3)	19.8	19.4	8.2	6.0	8.8	8.2	8.0	8.0	3.4	3.0
IP 4 (ALEPH)	-5.6	-5.8	-10.8	-9.2	-12.6	-14.0	-13.8	-13.0	-11.0	-9.8
IP 6 (OPAL)	20.3	19.8	5.6	-2.6	-5.8	-5.2	-5.4	-4.4	-0.6	0.0
IP 8 (DELPHI)	-9.4	-8.4	-13.2	-10.4	-17.2	-16.0	-15.0	-14.0	-11.4	-9.8

- we estimated a systematic error of 8-10 MeV per correction
  - was treated as fully correlated between IPs in order to compute overall error on the beam energy