Flat top energy stability at the LHC

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SPS Operation

- Beam energy : basic dependencies.
- Stability : expectations from magnets & experience from LEP & SPS.
- Absolute energy calibration.

More details and references to LEP work can be found in LHC Project note 334.

Fundamentals I

- For a particle of charge Z in a planar ring, the momentum p is proportional to the magnetic field integral $\int B(s)ds$ (⊥ to the machine plane) on the beam orbit :

$$p = \frac{Ze}{2\pi} \oint B(s)ds = Z \times 47.7[\mathrm{MeV/c/Tm}] \times \oint B(s)ds$$

- After all, accelerators are spectrometers with a limited (~ permill) momentum acceptance !

- To understand how the beam energy varies, we must know how the fields sampled by the beam depend on time, on the machine state and on external conditions.

Fundamentals II

The length of the beam orbit L is defined by the RF frequency f_{RF} because the RF frequency is an integer multiple h (harmonic number) of the revolution frequency f_{rev}:

$$f_{RF} = h f_{rev} = \frac{h\beta c}{L}$$

βc is the speed if the particles. At the LHC, f_{RF} = 400.87 MHz, h = 35640.

The beam momentum, RF frequency, orbit length, machine circumference and magnetic field integral are correlated.

Magnetic fields

The contributions to the field integral (and therefore to the momentum) can be roughly split into three components :

$$p = p_d + p_Q + p_\varepsilon$$

with contributions :

		Typical contribution
• p_d	from dipole magnets	$\geq$ 99.8%
• p_Q	from quadrupole magnets	$\leq$ 1-2 permill
• p_ε	from higher order fields, orbit correctors…	~ 10^{-4} or less

Dipoles Dominate

- By 'construction' the main dipoles define the energy → largest contribution to p.

- The absolute field is expected to be known to ~ 0.1% from the SM18 magnet measurements. For comparison :
  - LEP ~ 0.1%
  - SPS ~ 0.2%

- The reproducibility of the dipoles is expected to be better than 10^{-4} . For comparison :
  - LEP $\leq 10^{-4}$ (despite abnormal temperature sensitivity and vagabond DC currents from trains)
  - SPS $\leq 4 \times 10^{-5}$ (knowledge limited by accuracy of instruments)

- Note that a good field reproducibility is only achieved with a correct and reproducible magnet cycling (between fills).

Quadrupoles matter !

- Quadrupoles are interleaved with the dipole to focus the beam. Their *B(s)* field is proportional to the distance to the magnet axis.

- Ideally the beam is centered on the axis of every quadrupole → no net field ! In a real machine it can only be centered on average.

- The contribution of the quadrupoles depends on *L* (⇔ defines how far away the beam is on average from the quad. axis) and on a property of the optics, the momentum compaction factor α :

$$\frac{dP_Q}{P} = -\frac{1}{\alpha}\frac{L-L_c}{L_c} \cong -3030\,\frac{L-L_c}{L_c}$$

L = actual orbit length
L_c = central orbit length ⇔ beam centered on average in the quadrupoles - defines the machine circumference !

Large enhancement !!!

Example :

$$\frac{dP_Q}{P} = 10^{-4} \Rightarrow \frac{L-L_c}{L_c} \cong 3\cdot 10^{-8} \Rightarrow L-L_c = 0.9\,\mathrm{mm}$$

RF frequency again…

- Remember that L is defined by the RF frequency and ideally $\boldsymbol{L = L_c}$. A change of RF frequency (at fixed dipole field !) leads to a change of energy via the fields of the quadrupoles.

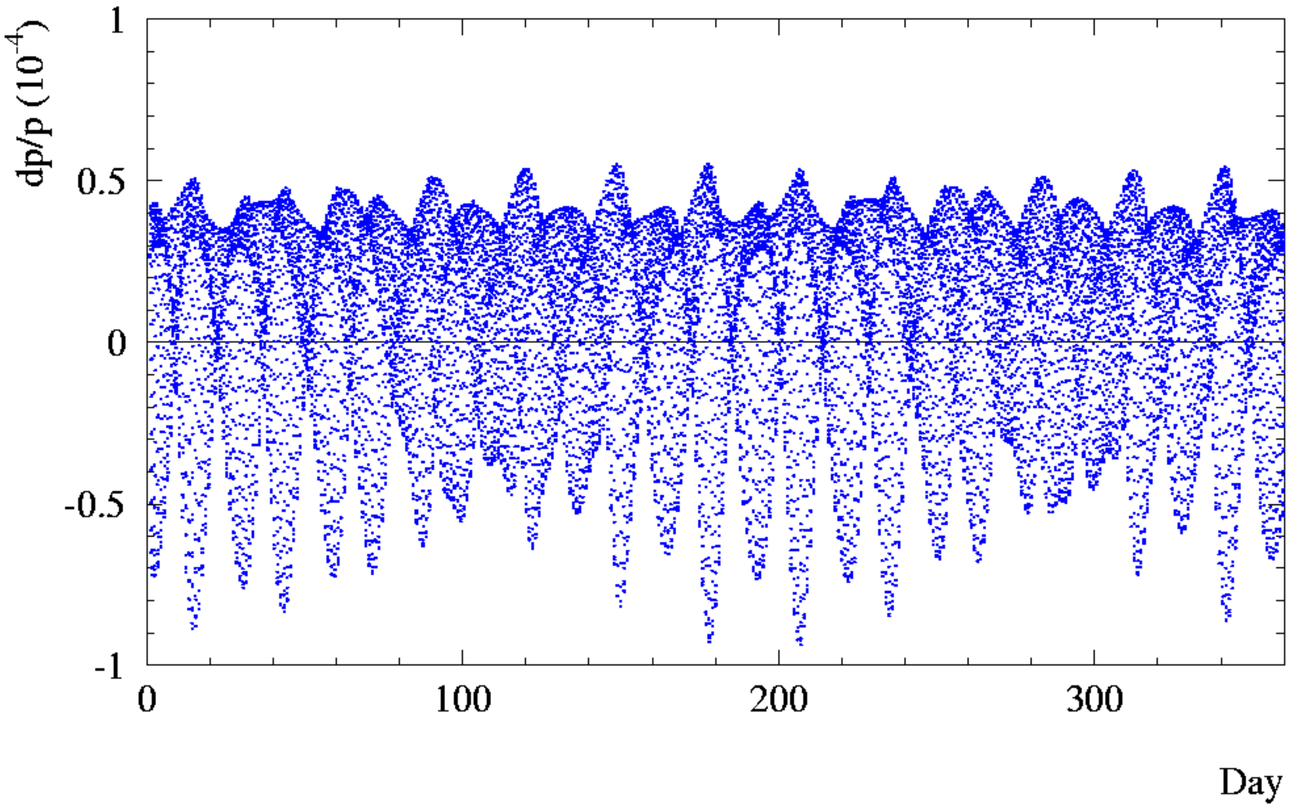
- The RF frequency corresponding to L_c is called the central RF frequency. The measurement of L_c is not very difficult … but beware of systematic errors ! Relative measurements can be very accurate !

- By symmetry the energy changes also when the circumference changes !!

Earth tides in 2007-2008…

Earth tides provoque elastic deformations of the crust that change the machine circumference and therefore L_c. They affected the LEP beam energy, and the LHC will feel them too !

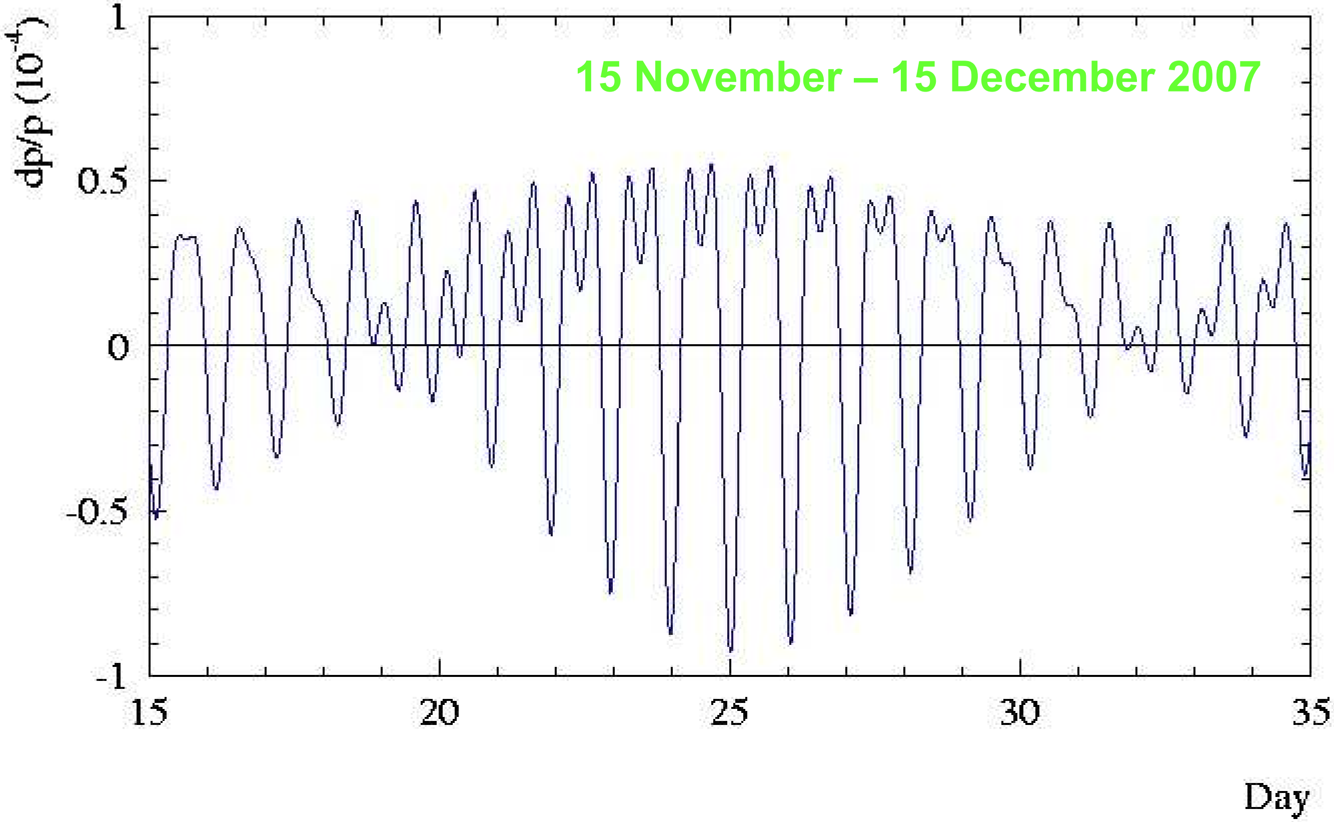
Below is the predicted energy shift due to tides from 01 June 2007 – 31 May 2008



The accuracy of the prediction is at the level of a few % (from LEP data).

Tides in more details

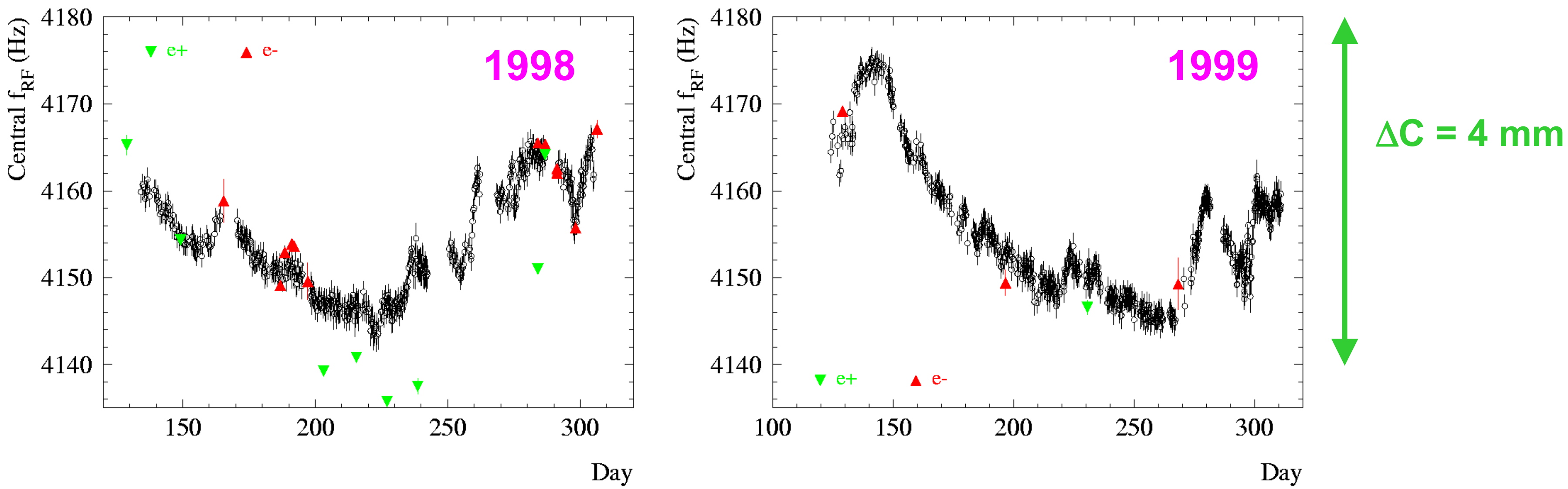
Tide details for November-December 2007



LEP (LHC) circumference

- The LEP ring was also subject to large (but slow) L_c changes over a run. Beam position monitors and dedicated central RF frequency measurements (for absolute calibration) were used to track changes.
- A similar excercice will have to (and can be) made at the LHC !

Example of the long term evolution of the LEP circumference (here the last 4 digits of the central frequency of 352 MHz) – corrected for tidal effects :



Other contributions…

- Higher order fields (mainly sextupole) can also contribute to the energy when the beam orbit is not well corrected. For the LHC I expect this effect to be negligible ($\approx 10^{-5}$), as it was for LEP, because the orbit must be extremely well controlled (feedback).

- Orbit correctors (small dipole used to correct the beam orbit – mainly to counteract the quadrupole misalignement) can affect the momentum when they are powered systematically with the same sign.
  - A carefull orbit correction can prevent / limit energy changes from this source to $\leq 10^{-4}$. It is also possible to correct for it – as was done for LEP energy calibration.
  - Note that sometimes orbit correctors are used on purpose to change p :
    - Orbit correctors were used at LEP to boost the energy.
    - Orbit correctors will be used during LHC injection to stabilize the LHC momentum wrt the SPS.

Summary on stability and accuracy

Contribution	Absolute calibration : rel. accuracy (10^{-4})	Stability (10^{-4})
Dipoles	≈ 7	< 1
Quadrupoles	≈ 2	4-5
Others	< 1	< 1

- The momentum is expected to vary by :
  - $4\text{-}5 \times 10^{-4}$ over a year
  - $1\text{-}2 \times 10^{-4}$ over 24 hours
- The variations are driven mostly by circumference changes that can be measured / predicted to $< 5 \times 10^{-5}$ (or better). We can build on the LEP experience !

Absolute energy calibration

At LEP energy calibration was based 2 important ingredients :

- The beams could polarize spontaneously in favourable conditions (a consequence of synchrotron radiation).
- The spin precession frequency is is proportional to $\int B(s)ds$ and therefore to p.

→ resonant depolarization to determine the energy from the spin precession frequency.

To use a similar method at the LHC would require polarized protons – not really in the baseline !

We must turn to other methods…

Ions …

- It is possible to determine the machine circumference L_c and absolute proton momentum p at the same time from a measurement of the difference in revolution frequency of a proton and 'ion' beam (i.e. the difference of speed !) :

$$P \cong m^p c \sqrt{\frac{f^p_{RFc}}{2(f^p_{RFc} - f^i_{RFc})}(\mu^2 - 1)}$$

$$\mu = \frac{m^i}{Z m^p}$$

$$f_{RFc} = \text{central RF freq.}$$

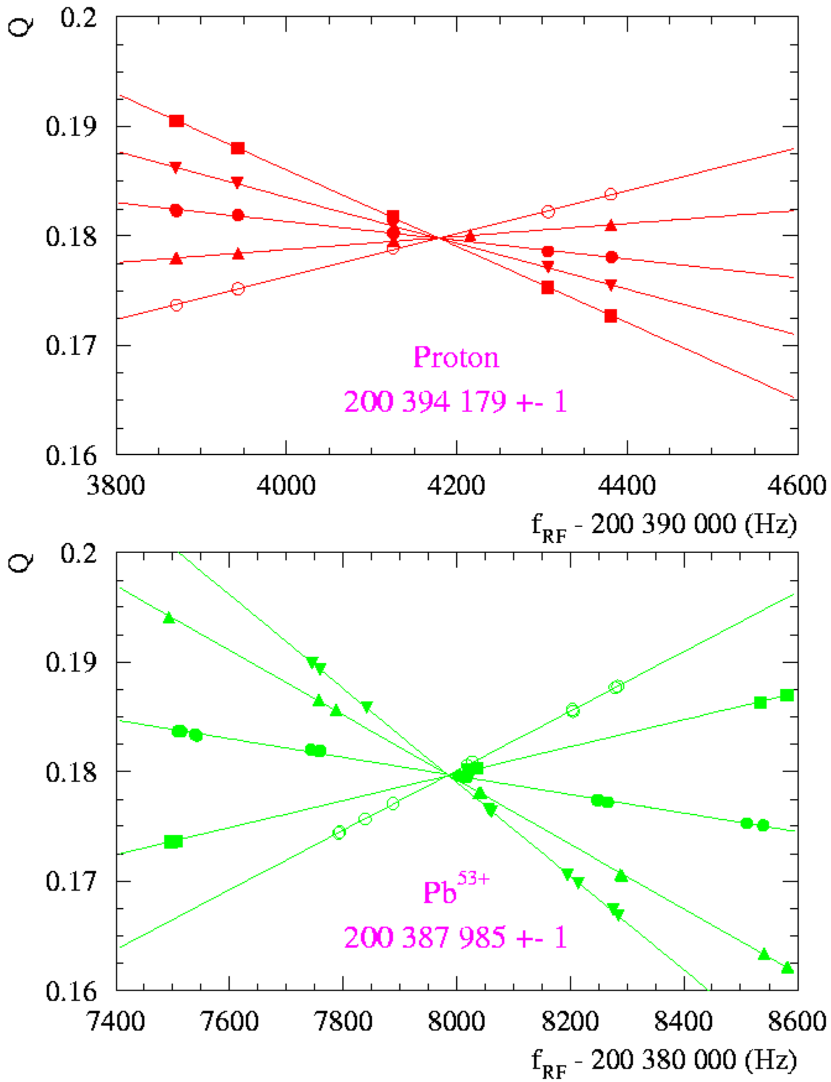
(p = proton, i = ion)

- This technique was already used at LEP (e^+/ p) and SPS (p / Pb).

- **The tricky bit :** the machine state must be identical (fields, orbit length…) for the two beams or the differences must be known precisely !

SPS Example : p / Pb

At the end of 2002, the last SPS Pb beams before the LHC area where used to perform a calibration of the SPS at 450 GeV/c. To enhance the accuracy, Pb^{53+} was used instead of fully stripped Pb^{82+}.



<u>Frequency difference Pb^{53+}-p :</u>

Δf = 6.2 kHz (with an error of ~ 2 Hz)

SPS proton momentum at 450 GeV/c :

p = 449.18 ± 0.14 GeV/c

i.e. an accuracy of 3×10^{-4}.

Ions at the LHC

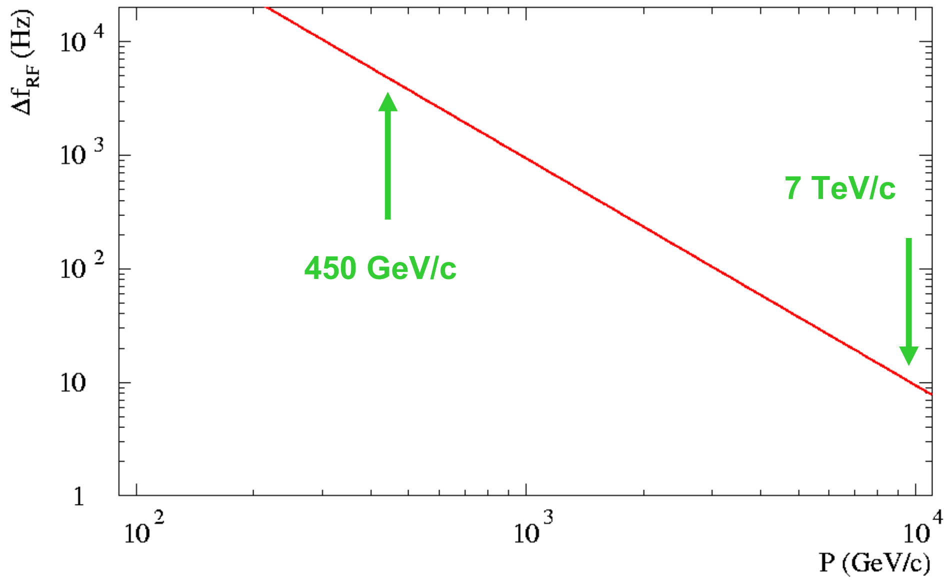
- The 'problem' with ions at the LHC is the small difference they exhibit as compared to protons. RF frequency differences scale with $1/p^2$ (so does the difference in speed !!).

- At 7 TeV/c requirements on measurement accuracy and machine stability (fields & *L*) seem beyond any hope !

- A reasonable calibration may be obtained up to ~ 1 TeV/c.

RF frequency difference between protons and Pb ions versus momentum :

- Δf ~ 20 Hz at 7 TeV/c
- Accuracy ~ 0.5-1 Hz (LEP best !)



A spectrometer

- One (of three) energy calibration methods for LEP200 where resonant depolarization did not work (no polarization …) was based on a **spectrometer magnet** :
  - A special dipole magnet calibrated to an accuracy of ~ few 10^{-5} and heavily instrumented with temperature and field probes.
  - The dipole was surrounded by ~ 15 m long field and magnet free region equiped with high precision beam position monitors (O(µm)) to measure the beam angle through the spectrometer dipole.
  - With this device the calibrations performed at 45 GeV using resonant depolarization were extrapolated to 100 GeV with an accuracy of ~10^{-4}.
- A priori such concept could work at the LHC. Some issues :
  - Longer lever arm for extrapolation (0.45-1 TeV/c → 7 TeV/c).
  - Space !!!!!!!!

Summary

- At the LHC the momentum at flat top is expected to vary by :
  - $4\text{-}5 \times 10^{-4}$ over a year
  - $1\text{-}2 \times 10^{-4}$ over 24 hours
  - The variations are driven mostly by circumference changes.
- The absolute p is expected to be known to slightly better than 0.1%.
- The dominant error on the absolute momentum is coming from the knowledge of the dipoles.
- Absolute calibrations using Pb ions can give accuracies of ~ few $\times 10^{-4}$ up to ~ 1 TeV/c : provides a cross-check of the dipoles at low(er) field…
- Absolute p calibrations at 7 TeV/c to ~ 10^{-4} require new (and delicate) spectrometers, polarized protons (?), other ideas….