Energy calibration at LHC

J. Wenninger

Motivation

- In general there is not much interest for accurate knowledge of the momentum in hadron machines.
  - In fact the largest interest is in understanding the machine magnetic model – from the machine side.
- At the LHC TOTEM requested a momentum determination with an accuracy of 0.05% at 7 TeV/c to minimize the contribution of the beam momentum uncertainty to the error on the total cross section measurement.
  - First study on the possibility to reach such targets in LHC Project Note 334.

Beam momentum measurements

- The momentum is defined by the integrated magnetic field on the closed orbit.

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

- Contributions to the integral (typical values):
  - Dipoles ≥ 99.9%
  - Quadrupoles ≤ 0.1%
  - Dipole correctors some 0.01%
  - Higher multipoles ~0.01% level

Magnet measurements

- The LHC magnet group has build up a sophisticated magnet model WISE/FIDEL to predict the magnetic field (errors) in view of operation.
  - Mixture of modeling and actual magnet measurements.
- The expected accuracy on the momentum (purely dipole part) is:
  - Absolute field ~ 0.1%
  - Relative field ~ 0.01% - tbc
- Those values are close to the requirements – but cross-checks with direct beam measurements are recommended.

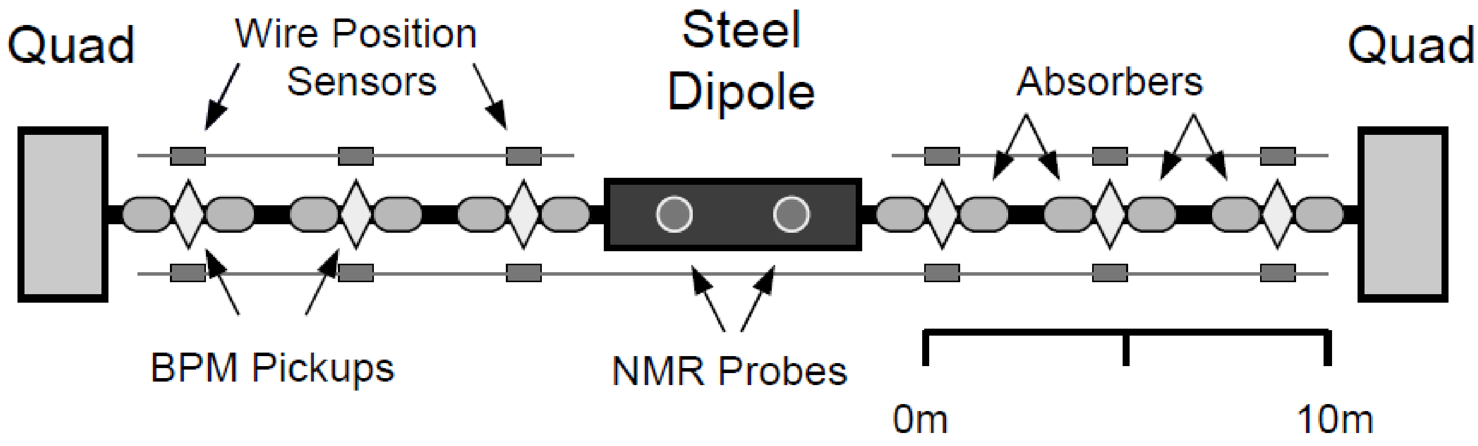
Momentum measurement techniques (1)

- For electron machines resonant depolarization provides a high precision measurement, but this technique does not work for proton beams.
  - e+/e- beams polarize spontaneously (synch. radiation), and the spin precession frequency is proportional to the energy.
  - See LEP…
- For '*not too relativistic*' beams, RF / revolution frequency measurements of 2 different ion species under **EXACTLY** the **same field conditions** provide a means of accurate momentum measurements for hadrons.
  - The only option we have with the **present** LHC.

Momentum measurement techniques (2)

- Momentum measurements using a spectrometer system.
  - Requires a well calibrated and monitored dipole.
  - Some open drift space on either sides to determine the angles with beam position monitors.
  - Spectrometer should be (re-)calibrated at some energies, and used for extrapolation.
  - Not easy to find a location in the LHC…

LEP spectrometer



Proton-ion calibration principle (1)

- The speed β (and momentum *P*), RF frequency f_{RF} and circumference *C* are related to each other:

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

*1 equation, 2 unknowns (**C** & **β/P**)*

  - The speed β_p of the proton beam is related to *P*:

$$\beta_p^2 = \frac{P^2}{P^2 + (m_p c)^2}$$

  - For an ion of charge Z, the momentum is *ZP* and the speed of the ion β_i is given by:

$$\beta_i^2 = \frac{P^2}{P^2 + (m_i c / Z)^2}$$

our 2nd equation:

- *2 unknowns (**C** & **β/P**),*
- *2 measurements (f_{RF}).*

Proton-ion calibration principle (2)

- The 2 equations for β_p and β_i can be solved for the proton momentum P:

$$P = m_p c \sqrt{\frac{\kappa^2 \mu^2 - 1}{1 - \kappa^2}}$$

$$\kappa = \beta_i / \beta_p = \boxed{f^i_{RF} / f^p_{RF}}$$

Depends on the RF frequency ratio that can be measured 'accurately'.

$$\mu = \frac{m_i}{Z m_p} \, .$$

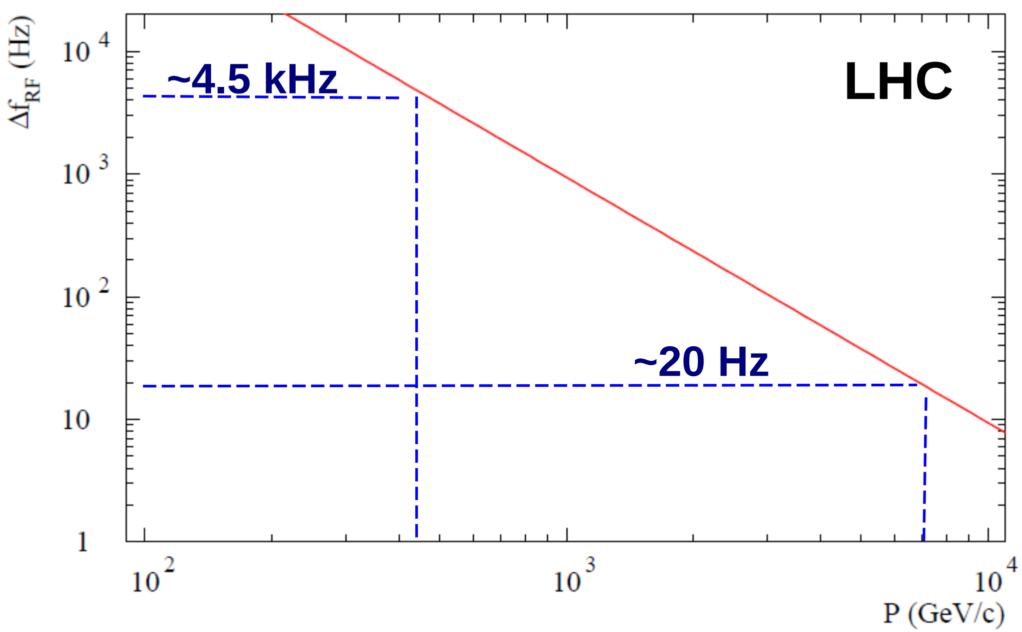
$$P \cong m_p c \sqrt{\frac{f^p_{RF}}{2\Delta f}(\mu^2 - 1)}$$

$$\Delta f = f^p_{RF} - f^i_{RF}$$

Proton-ion calibration scaling

- As the ions become more relativistic, the difference with proton decreases, vanishing when $\beta = 1$.
- The frequency difference scales with $1/P^2$:

$$\Delta f = \frac{hc}{C}(\beta_p - \beta_i) \simeq \frac{h m_p^2 c^3}{2CP^2}(\mu^2 - 1)$$



Measurement accuracy: ~1 Hz

(LEP experience)

Good for injection

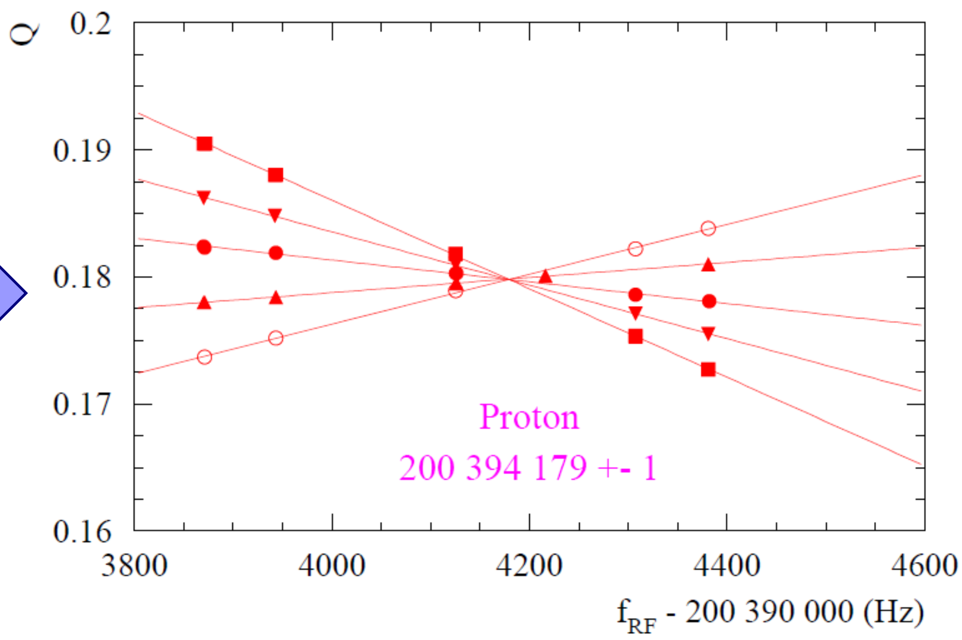
Tough (hopeless?) at 7 TeV

Measurement of the circumference

- The circumference of the ring *C* is defined by the center of the quadrupole magnets: the corresponding RF frequency is the 'central RF frequency'.
- To determine the RF frequency at which the beam is centered in the quadrupoles (on average) one can use:
  - Beam position monitors – require the mean radial error to vanish.
    - subject to significant systematic errors.
  - Use a technique to center the beam in the sextupoles:
    - Similar radial center,
    - Fixed radial offset,

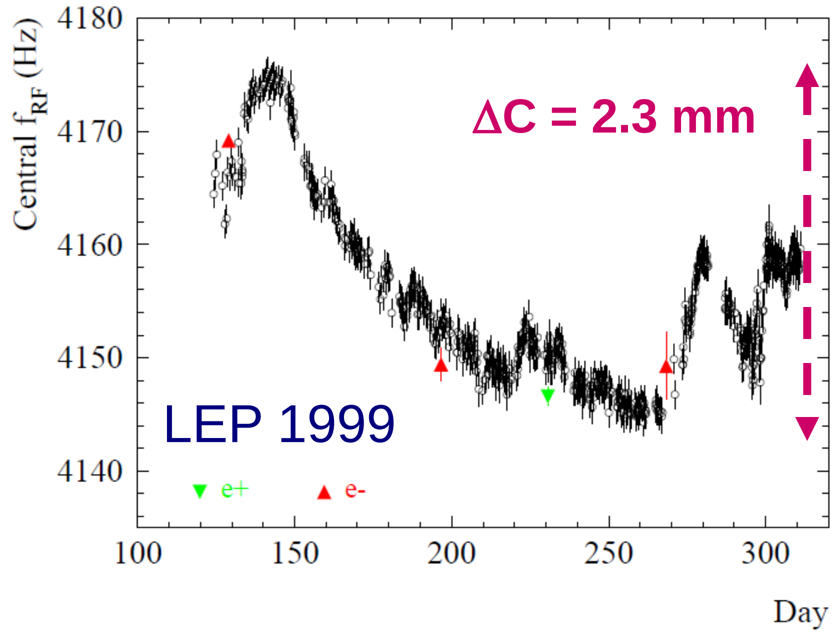
  with respect to the quadrupoles.

Central RF frequency of protons in the SPS



Measurement of the circumference

- The LHC ring is permanently deforming due to geological forces.
  - Earth tides, water table height…
- Knowledge of the deformations limit the precision when p and Pb measurements are performed on consecutive machine cycles.
  - LEP : ~1 Hz ⇒ 70 μm on *C*.



- The mixed p-Pb opens up the possibility to measure simultaneously both species (and invert the rings).
  - Could significantly improve systematic errors.

Proton – Pb^{82+} calibration at injection

- From the 2010/11 runs, one can extract 'parasitic' information on the momentum from p and Pb.
  - Accuracy of the frequencies estimated to ~ ±5 Hz (as no careful dedicated measurement) → uncertainty on Δf ~ ±10 Hz.
  - Rough correction of tides included.

Run	Δf (Hz)	E (GeV)
2010	4652	449.90 ± 0.35
2011	4638	450.58 ± 0.35

Magnetic model:

450.00 ± 0.45 GeV

- Transporting a p-ion calibration of the SPS (450 GeV) to the LHC one obtains a consistent value:

$$P_{inj-SPS} = 450.35 \pm 0.25 \ (\text{GeV/c})$$

Proton – Pb^{82+} calibration at 3.5 TeV

- The p-Pb ramp performed in October 2011 can be used for a rough estimate of the proton momentum at 3.5 TeV.

$$P_{3.5TeV} = 3.47 \pm 0.10 \text{ (TeV/c)}$$

- Due to the absence of careful calibration of the BPMs / circumference, the error is rather large. But an error in the per mill range could be achievable at 3.5/4 TeV in 2012.
  - Take advantage of the p-Pb run.

Mixed p-Pb operation

- In mixed operation of p and Pb, the systematic errors could be reduced significantly through simultaneous measurements of both p and Pb, and by flipping p-Pb in the 2 rings.
  - MD request submitted for 2012 to check such a method at 450 GeV, and to evaluate the systematic errors.
  - The mixed mode could be used to reduce the errors significantly at 7 TeV – depending on the MD outcome.

Summary

- Energy calibration at the LHC can be done to some extend by comparing ion and proton frequencies.
  - Good prospects at low energy, very challenging at 7 TeV.
- The momentum measurement at injection is consistent with the value of 450 GeV within better than 0.1%.
  - Magnetic model accuracy confirmed at injection.
- The mixed operation of p and Pb opens the possibility to reduce the errors as compared to initial expectations.
  - If some MD time is allocated in 2012, the systematic errors could be evaluated more accurately.