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Beam Momentum Calibration at the LHC

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Summary

The TOTEM experiment at the LHC has 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. In this note three possible calibrations methods are discussed and their expected accuracies are estimated. These methods are the evaluation of the momentum from the magnetic calibration tables and the central frequency, the comparison of revolution frequencies of lead ion and proton beams and finally the option of a dedicated magnetic spectrometer.

1 Introduction

One of the aims of the TOTEM experiment [1] is the precise measurement of the total p-p cross-section that can later be used for luminosity measurements. The measurement principle relies on the optical theorem that relates the total cross-section to the imaginary part of the forward scattering amplitude. The total cross-section measurement of TOTEM depends quadratically on the beam momentum

$$\sigma_{tot} \propto \frac{1}{P^2} \tag{1}$$

through the measurement of the angular dependence of the electric scattering rates at small angles. The momentum error contributes to the final error on the cross-section measurement as $\frac{\Delta\sigma_{tot}}{\sigma_{tot}} = 2\frac{\Delta P}{P}$. To minimize the contribution of the momentum uncertainty on the cross-section measurement, TOTEM requires an uncertainty $\frac{\Delta P}{P} < 5 \cdot 10^{-4}$.

The 12 year beam energy calibration programme of LEP was extremely successful in providing accurate beam energies between 40 and 100 GeV/c. Although resonant depolarization, the workhorse of LEP energy calibration, is not available at the LHC, the experience gained on LEP is also relevant for LHC energy calibration. In particular the studies on the ring circumference variations are important in the context of the LHC.

[1]This is an internal CERN publication and does not necessarily reflect the views of the LHC project management.

This note first describes briefly the main ingredients to the machine energy. The measurement of the central frequency is presented in some details, and the calibration method based on the comparison of proton and ion beams is discussed, including experiences with such measurements at the SPS. Finally the requirements on a dedicated magnetic spectrometer are evaluated.

2 Beam Momentum and Fields

In a storage ring like the LHC, the average beam momentum P of each ring is defined by the integral of the bending field B on the closed orbit

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

where Ze is the total particle charge, with $Z = 1$ for protons and $Z = 82$ for Pb^{82+} Lead ions. s is the longitudinal position along the beam orbit. The contributions to the beam momentum can be decomposed into

$$P = P_d + P_q + P_\epsilon \tag{3}$$

where P_d and P_q are respectively the contributions of the dipoles and the quadrupoles to the field integral. Other elements (for example horizontal correctors) can give additional small contributions P_ϵ to the momentum. P_d depends on the integrated dipole field $(BL)_d$ and accounts usually for almost 100% of the beam energy since the dipoles define the nominal momentum,

$$P_d = \frac{e}{2\pi}(BL)_d \ . \tag{4}$$

P_q depends on the orbit length C through

$$P_q = -\frac{1}{\alpha}\frac{C - C_c}{C} \ . \tag{5}$$

It is a function of the momentum compaction factor α, $\alpha \simeq 3.3 \cdot 10^{-4}$ for the LHC, of the actual orbit length (circumference) C and of the length of the central orbit C_c (the machine circumference). In general P_q does not account for more than few permill of the bending field integral. On the central orbit the beam is by definition centered on average in the quadrupoles and P_q vanishes.

The speed βc of a beam particle is related to the revolution frequency f_{rev} and to the RF frequency f_{RF},

$$\beta c = C f_{rev} = \frac{C f_{RF}}{h} \tag{6}$$

where h is the harmonic number of the RF system. c is the speed of light. For the LHC the nominal RF frequency is 400.87 MHz and $h = 35640$. The central RF frequency f^c_{RF} is defined with Equation 6,

$$f^c_{RF} = \frac{h\beta c}{C_c} \ . \tag{7}$$

For a perfectly aligned machine the definition of the central frequency f_{RF}^c (and of the central orbit length) is unambiguous. It corresponds to the RF frequency (or orbit length) for which the beam is centered in *all* quadrupoles. In a real machine with misaligned magnets the beam is travelling on a closed orbit that is not centered in each quadrupole. In such a case the central frequency corresponds to the RF frequency for which the beam is centered *on average* in the quadrupoles. Since the central frequency must be measured and is only meaningful with the beam, the actual value may have a small dependence on the beam steering through the quadrupoles.

3 Central Frequency Measurements

Since the central frequency plays a very important role for energy calibration, we give here some details on the measurement techniques. The experience and experimental data collected at LEP are very useful to understand the problems that will have to be faced at the LHC.

3.1 Average Radial Beam Position

The simplest technique to determine f_{RF}^c consists in varying the RF frequency until the beam is on average centered radially in the beam position monitors (BPMs). The accuracy of this method is limited by offsets between the electric center of the monitors and the adjacent quadrupoles. For the LHC the expected alignment errors are in the range of 300-500 μm for each of the 500 monitors, thus limiting the statistical accuracy on the radial positioning to $\sim$ 20 μm. The error may be reduced below 50 μm at a later stage if the BPM offsets are determined by K-modulation as it was done for LEP. The LEP experience showed also that this method of measuring f_{RF}^c is easily dominated by systematic errors and long term stability of the BPMs.

The determination of the radial position by BPM measurements is however very powerful to interpolate in time between central frequency measurements performed with more accurate but also more time (and beam) consuming methods. Such an interpolation was used very successfully at LEP. Some results will be discussed below.

3.2 Sextupole Magnetic Center

A second f_{RF}^c measurement method takes advantage of the lattice sextupoles that are generally installed next to the arc quadrupoles. Their magnetic center is aligned within tolerances of some hundreds of microns on the magnetic axis of the quadrupoles. Consequently it is equivalent to center the beams in the sextupoles or the quadrupoles, the only limitations being due the the relative alignment tolerances and to the limited number (and therefore sampling) of elements.

The determination of the sextupole magnetic center is based on the fact that the betatron tune is independent of the sextupole setting when the beam is on the magnetic axis of the sextupole. To determine this axis, the tune is measured as a function of the radial position for a number of different chromaticity settings (positive and negative). As long as the RF frequency changes are performed within a short range around the central frequency, the

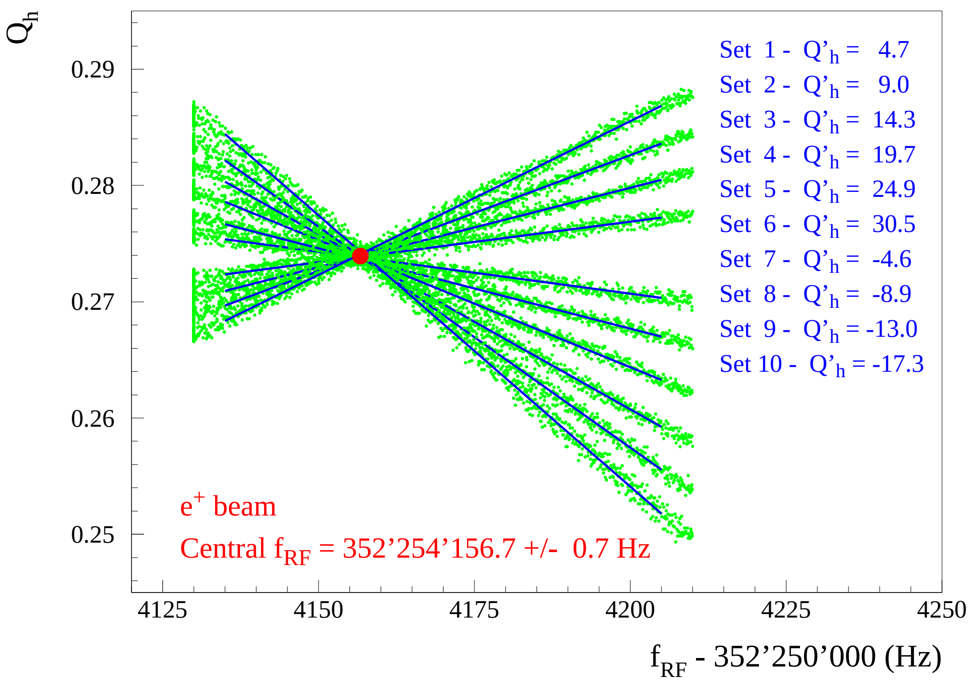


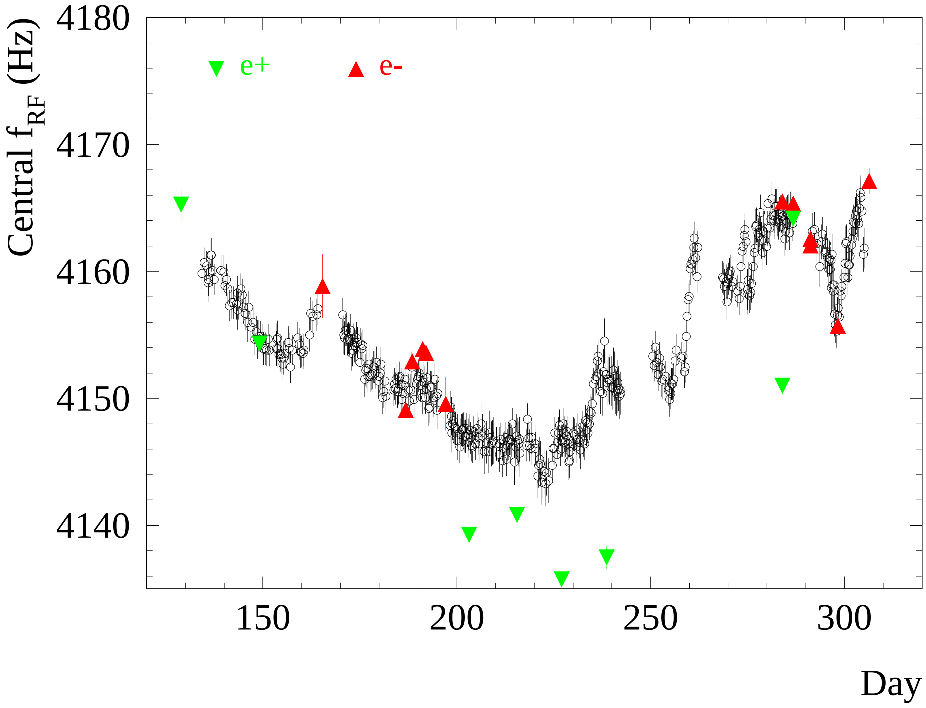
Figure 1: Example of a central frequency measurement at LEP. The tune dependence on RF frequency is measured for a number of chromaticity settings Q'_h. At the crossing point of the measurements the beam is centered in the sextupoles since the tune is independent of Q'_h : this frequency setting corresponds to the central frequency. This measurement was based based on a PLL (Phase Locked Loop) tune measurement providing data at a few Hz.

tune dependence on RF frequency is linear for a given chromaticity setting. The central frequency is obtained from the crossing point of lines for different chromaticity, as can be seen in Figure 1. The measurement can be performed by varying either the horizontal or the vertical chromaticity, in which case the beams are mainly sensitive to the horizontal and vertical sextupole families. This provides a means to check systematic alignment effects between sextupoles and quadrupoles.

The relative alignment between sextupoles and quadrupoles sets an intrinsic limit to the *absolute* accuracy of the central frequency determined by this method. The error on the central frequency σ_f is related to the alignment RMS σ_{SQ} between sextupoles and quadrupoles by

$$\sigma_f \simeq f_{RF} \frac{\sigma_{SQ}}{\bar{\rho}\sqrt{N_S}} \simeq 7 \text{ [Hz/mm] } \sigma_{SQ} \tag{8}$$

where $\bar{\rho}$ is the average bending radius, f_{RF} is the RF frequency and $N_S \sim 380$ is the number of sextupoles. The alignment accuracy of $\sigma_{SQ} \simeq 0.2$ mm leads to an uncertainty on the absolute central frequency of approximatively $\pm$ 1.5 Hz.



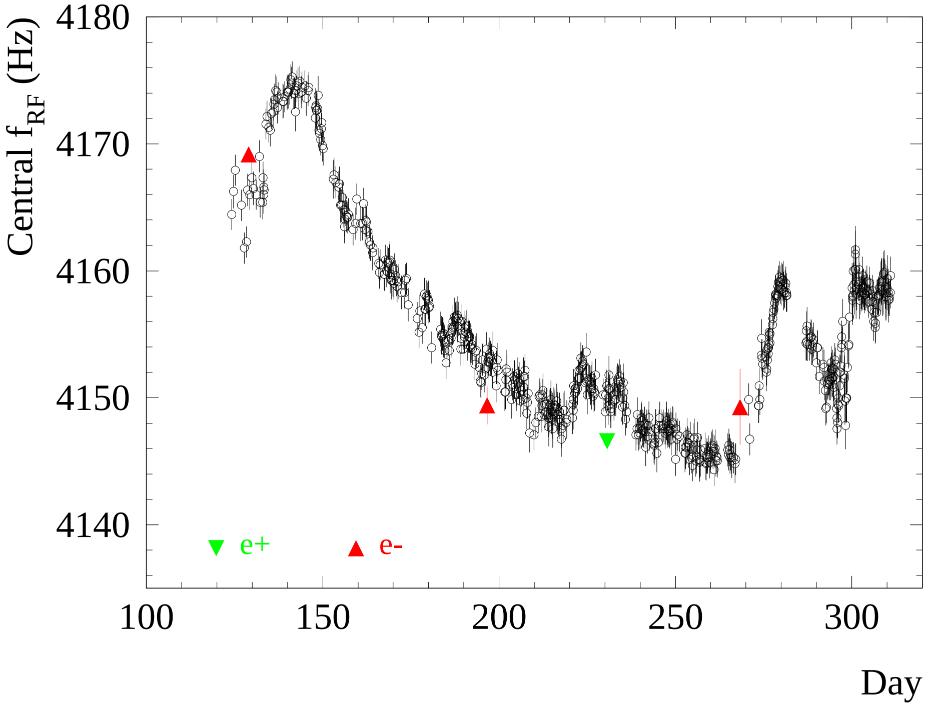


Figure 2: Evolution of the LEP central RF frequency during the 1998 (top) and 1999 (bottom) LEP runs [4]. The open points are obtained from BPM measurements and are normalized to the actual central frequency measurements (filled triangles). Only the last four digits of the central frequency are given, $f_{RF}^c = 352'25.'...$ Hz. $\Delta f = +1$ Hz corresponds to $\Delta C = -100\ \mu$m.

3.2.1 LEP Circumference Measurements

The experience gained on the stability of the LEP machine and tunnel applies directly to the LHC. The LEP circumference was submitted to permanent changes due to periodic and aperiodic strains. The most commonly known periodic effect is the influence of Earth Tides that changes the circumference at high tides by 1 mm over 12 hours [2, 3, 4]. The tidal effects are modelled and experimentally verified to an accuracy of $\sim 5\%$ from the LEP data. Besides the tides, the LEP circumference was subject to constant circumference variations related apparently to the underground water conditions (water table height under the Jura). The correlations and predictions of such influences can at best be qualitative. Figure 2 shows the long term evolution of the LEP central frequency for the 1998 and 1999 runs. The circumference is measured in every fill using the radial position obtained from 240 arc BPMs that is cross-calibrated against direct central frequency measurements. The evolution of f^c_{RF} is similar for every year. First the central frequency decreases (and the circumference increases) between spring and summer and increases again in the autumn. The "spikes" where the frequency increases rather sharply before it relaxes again follow periods of heavy rainfall.

The f^c_{RF} error for a given fill was typically around $\pm$ 2 Hz, which corresponds to an uncertainty on the circumference of $\pm$ 200 μm for the LEP RF frequency of 352.254 MHz. On short time scales of a few hours the accuracy was improved to $\pm$ 50 μm or better, at least within the same fill and at constant energy. Such small errors were difficult to estimate precisely in the absence of a sufficiently accurate and independent measurements. Comparisons with the variation of the LEP beam energy determined by resonant depolarization were limited by the overall accuracy of the LEP energy model. Uncertainties were due to the beam position monitor system (sampling of the orbit and systematic errors) and to subtle systematic effects related to ground motion and orbit corrector settings [4].

4 Magnetic Calibrations

The simplest way to estimate the beam momentum is to derive it from the magnetic calibration curves of the dipoles (also referred to as excitation curves). For dipoles magnets that are measured in cold (super-conducting) conditions in SM18, the contributions to the error are given by the cold measurement accuracy of 3×10^{-4}, the longer term reproducibility 10^{-4} and the setting of the current 10^{-4}, yielding a conservative estimate of 5×10^{-4} [5]. For magnets that are not measured in cold conditions, there is an additional error of 5×10^{-4} from the correlation between cold and warm measurements [5]. Since it is not clear presently how many magnets will be measured on the test benches in SM18, a safe error estimate for the dipole field error at 7 TeV/c is $\sim 7 \times 10^{-4}$.

For a complete momentum determination, the contribution of the quadrupoles due to a difference between actual and central orbit length must also be added. The additional error from this term is 2×10^{-4} for a f^c_{RF} accuracy of $\pm$2 Hz, i.e. similar to LEP.

In summary it appears that with the magnet measurement program in SM18, the momentum should be known to better than 0.1% at 7 TeV/c. A more precise estimate can be made in 2006/2007 when the measurement program of the machine dipoles will be completed.

5 Energy Calibration with Ion Beams

This precise absolute momentum calibration method takes advantage of the fact that the revolution frequency (and therefore f^c_{RF}) is different for ions and protons due to the different ratio of charge over rest mass. Using this technique, a precise energy calibration was performed at LEP with protons and positrons at 20 GeV/c [6]. Two such calibrations were performed at the SPS, one in 1991 using proton and Oxygen ions at 270 GeV/c [7] and another in 2002 using proton and Pb^{53+} beams at 450 GeV/c [8].

The speed βc of a particle is related to the revolution frequency f_{rev} and the RF frequency f_{RF} by Equation 6. To determine β and therefore the particle momentum, both the machine circumference and the revolution frequency must be known at the same time. If the nominal machine momentum and the circumference are stable (within a certain tolerance) over a sufficiently long time interval, it is possible to determine those parameters by measuring the revolution frequency for two particles with different charge over mass ratio that are successively injected into the same magnetic machine and on the same orbits.

The speed $\beta_p c$ of the proton beam is related to its momentum P and its rest mass m_p by the well known relation

$$\beta_p^2 = \frac{P^2}{P^2 + (m_p c)^2} \ . \tag{9}$$

An ion with charge Ze, injected into the same magnetic machine and on the same orbit than the proton beam has a momentum $P_i = ZP$. The speed $\beta_i c$ of the ions is

$$\beta_i^2 = \frac{P^2}{P^2 + (m_i c/Z)^2} \tag{10}$$

with m_i the ion rest mass. These two equations can be solved for the proton beam momentum P, yielding

$$P = m_p c \sqrt{\frac{\kappa^2 \mu^2 - 1}{1 - \kappa^2}} \tag{11}$$

with

$$\kappa = \beta_i / \beta_p = f^i_{RF} / f^p_{RF} \tag{12}$$

and

$$\mu = \frac{m_i}{Z m_p} \ . \tag{13}$$

μ is the number of nucleons per charge of the ion : $\mu \simeq 2.5$ for fully stripped Pb^{82+} lead ions. Equation 11 can be approximated by

$$P \cong m_p c \sqrt{\frac{f^p_{RF}}{2\Delta f}(\mu^2 - 1)} \tag{14}$$

where $\Delta f = f^p_{RF} - f^i_{RF}$ is the RF frequency difference between the proton and ion beams.

The measurement error on P is dominated by the accuracy of the RF frequency determination since all other parameters entering Equations 11 and 14 are known with high accuracy. The measurement error σ_P on P is dominated by the term

$$\frac{\sigma_P}{P} \simeq \frac{\sqrt{\sigma^2_{f^p_{RF}} + \sigma^2_{f^i_{RF}}}}{2\,\Delta f} \tag{15}$$

with $\sigma_{f^p_{RF}}$ and $\sigma_{f^i_{RF}}$ the measurement errors on the central RF frequencies of the proton and ion beams. For highly relativistic beams, the difference between β_p and β_i decreases rapidly. The frequency difference Δf between the beams follows from Equation 14,

$$\Delta f \cong \left(\frac{m_p c}{P}\right)^2 \frac{f^p_{RF}}{2}(\mu^2 - 1) \tag{16}$$

and scales quadratically with μ. The dependence on $1/P^2$ makes the measurement very difficult at the highest energies. As the speeds of both beams approach c the differences tend to vanish.

5.1 Experience at the SPS

In 1991 a momentum calibration was performed at the SPS for the UA4 experiment. The central RF frequency of proton and Oxygen ions was measured at the collider momentum of 270 GeV/c [7]. The central frequency was determined by centering the beams in the beam position monitors. The quoted uncertainty on the central frequency was ~ 1 Hz. The error on the beam momentum 0.1 GeV/c.

The same calibration technique was used again at 450 GeV/c in 2002 to determine precisely the momentum of the LHC beams at extraction from the SPS [8]. It relied on beams of protons and Pb^{53+}, the later being used instead of standard Pb^{82+} for its larger value of μ and therefore larger Δf (Equation 16). At 450 GeV/c the frequency difference Δf was close to 6.2 kHz for a proton RF frequency of 200.394 MHz, see Figure 3. This time the measurement was performed by centering the beam in the sextupoles using tune measurements. The accuracy of a single central frequency measurement was around 1 Hz. The final momentum accuracy of the calibration was 0.14 GeV/c at 450 GeV/c. Attempts to perform a precise calibration using the beam position monitors in a similar way as for the 1991 calibration failed due to large and uncontrolled systematic errors. When the 2002 calibration is scaled to the magnetic settings of the 1991 calibration using the reference magnet Nuclear Magnetic Resonance probes, the resulting momentum differs by more than 1 GeV/c from the 1991 result. One conclusion of the 2002 calibration is that the error of the 1991 calibration may have been under-estimated by up to one order of magnitude, underlining the sensitivity of such BPM measurements to systematic effects.

5.2 Calibration at the LHC

The frequency difference between protons and Pb^{82+} lead ions that will be available in the first years of LHC is given by Equation 16. Due to the strong dependence on P, the frequency difference shrinks by more than 2 orders of magnitude between 450 GeV/c at the SPS extraction / LHC injection and 7 TeV/c at the LHC. The resulting values of Δf become extremely small as can be seen in Figure 4. For a momentum determination at 7 TeV/c with a relative accuracy of 10^{-3}, the central frequency difference must be determined to 20 mHz, which corresponds to a relative accuracy on the circumference of 4×10^{-11} or to an absolute accuracy of 1 μm on the LHC circumference. Such values seem at present far beyond the experimental possibilities, in particular when the LEP experience and the complex 2 ring geometry of the LHC are taken into account.

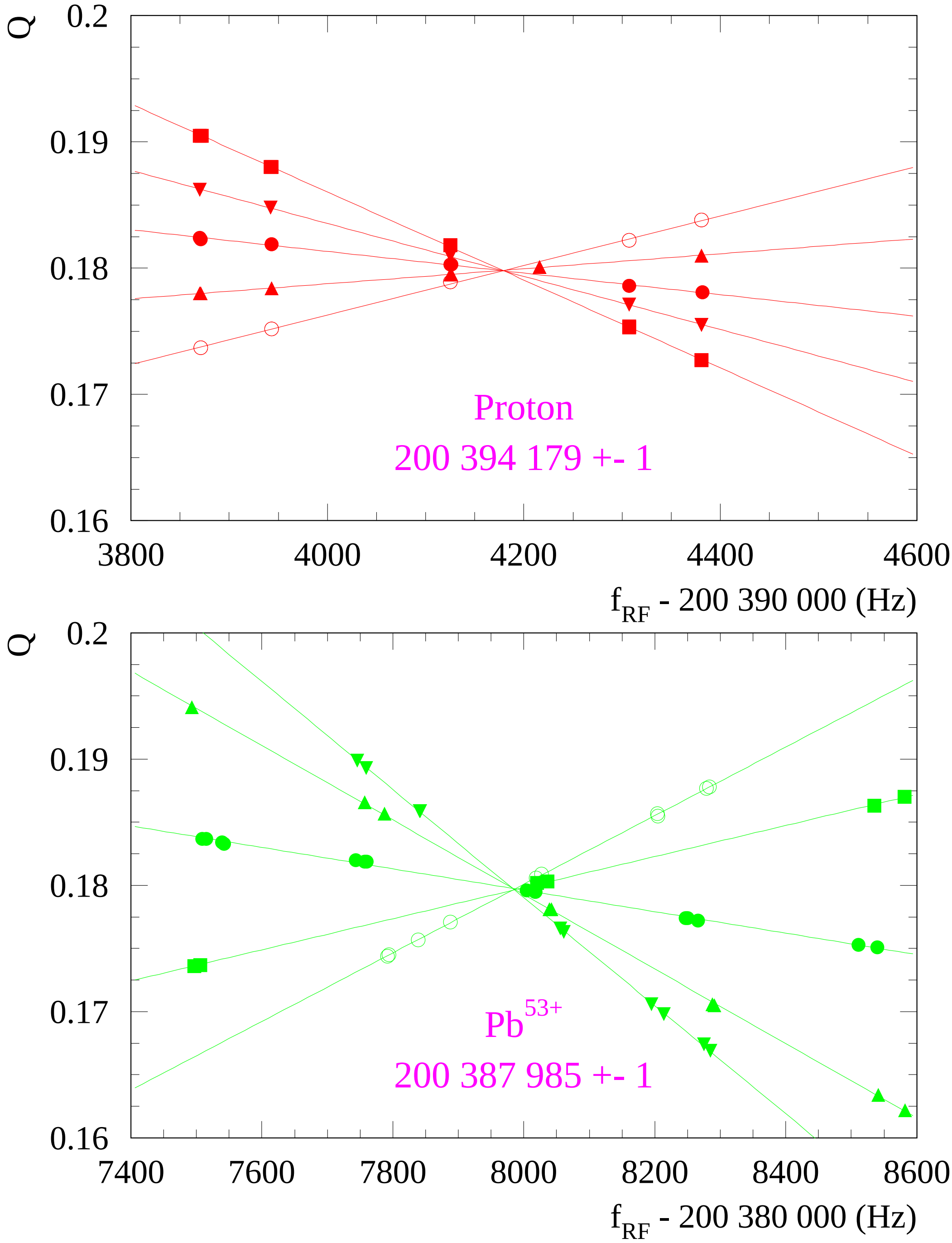


Figure 3: Horizontal tune dependence on RF frequency for different settings of the machine chromaticity for proton (top) and Pb^{53+} beams (bottom) at a proton equivalent momentum of 450 GeV/c in the SPS (from Reference [8]). The central RF frequency (and its error) that corresponds to the crossing point is indicated for each beam.

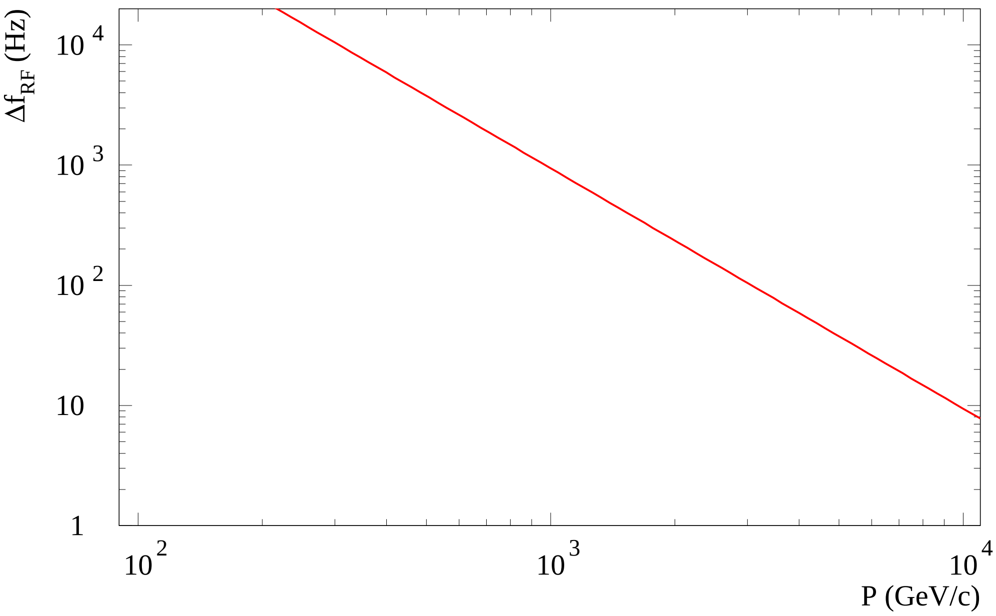


Figure 4: Expected central RF frequency difference between proton and Pb^{82+} beams as a function of the beam momentum at the LHC. At 7 TeV/c the frequency difference is only $\sim$ 20 Hz.

Due to the slow LHC machine cycle a measurement will cover a time span of at least 3 hours and include at least 2 distinct ramps from 450 GeV/c to 7 TeV/c. The consequences on the stability of the machine are very stringent. There are at least 2 distinct limitations to such a momentum calibration.

The first issue is related to the assumption that the ring circumference does not change between the central frequency measurement of the proton and ion beam. From the LEP data and experience, it seems very difficult to reduce the 50 μm uncertainty of the LEP circumference measurements by almost two orders of magnitude, even over short time scales. The main difficulty arises from the fact that two separate machine cycle must be used, one for protons and another one for ions. The LEP experience has shown that it is very delicate to interpolate between two runs.

The second problem is the limited accuracy of the tune measurement and the required machine stability during each of the measurements. Both at the SPS and at LEP, an individual central frequency measurement was limited to $\pm$ 1 Hz (or 100 μm on the circumference) due to tune measurement errors and stability.

From the past experience an estimate for the accuracy of the central frequency measurements at the LHC is in the range of $\pm$ 0.1-2 Hz. This does not provide the required measurement accuracy on the frequency difference Δf as long as it is limited to 20 Hz.

On the other hand a good measurement may be performed at injection and up to about 1 TeV/c or higher, where it may be used to verify the validity of the dipole calibration data.

5.3 Special Lead Ion Beams

For the 2002 energy calibration in the SPS, a special Pb^{53+} beam was injected into the SPS without stripping in the TT2-TT10 transfer line and accelerated to 450 GeV/c. Under normal operating conditions the stripper foil removes the remaining electrons such that a fully stripped Pb^{82+} beam is injected in the SPS. Since the average charge per nucleon is significantly lower, the Pb^{53+} beam has a smaller speed and Δf increases.

From Equations 13 and 16, it is clear that the strong momentum dependence could be compensated by increasing μ proportionally to P. To increase Δf to 1 kHz at 7 TeV/c, μ must be increased by a factor 7, which requires a beam of Pb^{10+} in the LHC. Such a beam must be transmitted by the entire injector chain and accelerated in the LHC, which poses important challenges on RF and vacuum systems due to the low(er) lifetime of Pb^{10+}.

The ECR ion source foreseen for LHC lead ions produces a beam of Pb^{27+} [9], although ions of lower charge state are also extracted. The Pb^{27+} beam is stripped to Pb^{54+} at the end of Linac 3, before being injected into the LEIR ring [10]. If a Pb^{27+} beam could be accelerated by the LHC injector chain and the LHC itself, the increase in Δf would correspond almost exactly to a factor 10. Such a beam may provide relative measurement accuracies of 0.1% up to momenta of 3 TeV/c. The lifetime of Pb^{27+} in LEIR is however critical due to recombination losses with electrons from the electron cooler and charge exchange with the residual gas in the vacuum chamber, but it may be acceptable [11]. The main (or at least first) important problem in the injector chain are field limitations of some dipoles in the transfer line from Linac 3 that prevent the transport of Pb^{27+} to LEIR [11].

Even if a Pb^{27+} beam is transmitted through the entire injector chain, a serious measurement problem arises in the LHC from the low charge state of such an ion beam : since the charge is reduced by a factor 3 or more compared to the normal Pb^{82+} beam, the LHC beam position monitors will have difficulties to detect this beam unless their electronics is upgraded to a higher sensitivity. A very good transmission efficiency will be required from the entire injector chain, despite the lower beam lifetimes.

In summary a special Pb^{27+} beam for the LHC does not seem feasible with the presently foreseen hardware in parts of the injector chain and in the LHC. It might however be envisaged at a later stage, provided a more in depth analysis of all the issues and the experience with Pb^{82+} in the LHC proves that such a scheme is feasible and worth additional effort.

6 Magnetic Spectrometer

One of the three energy calibration techniques used at LEP for high beam energies consisted of a magnetic spectrometer. The core of the spectrometer was a dedicated, individually powered dipole magnet with a very accurate calibration. This dipole was surrounded on either side by 3 dedicated BPMs installed in a 20 meter long field-free region. The BPM triplets provided a precise relative beam angle measurement on both sides of the magnet. The BPMs were linked and surveyed by a wire positioning system. The BPM and alignment system resolutions were in the range of 1 μm. The magnet was equipped with in situ Nuclear Magnetic Resonance probes to survey the field. All elements were connected to dedicated cooling systems to ensure a stable and reproducible operating temperature. The aim of the spectrometer device was to extrapolate a precise energy calibration in the range of 40 to

60 GeV to the LEP200 operating energy range of 90 to 100 GeV/c. It is important to note that no absolute calibration was required from the spectrometer.

A similar spectrometer device may be envisaged for an accurate calibration of the LHC beam energy, based on a precise absolute calibration with lead ions beams in the range 450 to 1000 GeV/c. The interpolation range covers a factor 7 to 15 in momentum, compared to a factor 2 for LEP.

The principle of the spectrometer calibrations can be briefly summarized as follows. BL defines the known field integral of the spectrometer dipole, and θ is the deflection angle provided by the dipole. For a perfect cross-calibration of the spectrometer dipole and the other main machine dipoles, θ remains at a fixed value independently of the beam momentum since the dipole is part of the accelerator lattice. The entire spectrometer device is cross-calibrated at a given reference point r where the beam momentum P_r is well known from another measurement technique. The relation between θ, BL and P_r is

$$\theta_r = e\frac{(BL)_r}{P_r} \tag{17}$$

At the momentum of interest labelled by the index c, the same relation holds

$$\theta_c = e\frac{(BL)_c}{P_c} \ . \tag{18}$$

Since θ_c must be equal to θ_r with high precision, the previous relation can be re-expressed as

$$P_c = e\frac{(BL)_c}{\theta_r + \Delta\theta} \tag{19}$$

where $\Delta\theta = \theta_c - \theta_r \ll \theta_r$ is the difference in angle between the reference point and the point to be calibrated. The momentum P_c is therefore given by

$$P_c = \frac{(BL)_c}{(BL)_r} P_r \left(1 - \frac{\Delta\theta}{\theta_r}\right) \ . \tag{20}$$

An accurate measurement of the momentum requires :

- A precise knowledge of the integrated field of the spectrometer dipole BL throughout the entire operating range.
- An accurate absolute calibration of the momentum at the reference point. This calibration point should be as close as possible to the momentum setting to be calibrated to minimize the lever arm of the interpolation.
- Very precise beam position measurements to minimize the uncertainty on $\Delta\theta$.

The accuracy on $\Delta\theta$ is given by the measurement accuracy and the stability of the spectrometer BPMs. For set of 3 equidistant BPMs, spaced by a distance L, the resolution on the angle measurement σ_θ on either side is

$$\sigma_\theta = \frac{\sigma_{BPM}}{\sqrt{2}\,2L} \tag{21}$$

where σ_{BPM} is the measurement accuracy of the BPMs. For a lever arm L of 5 m between BPMs corresponding to a total spectrometer extend of more than 10 m on either side of the spectrometer dipole, and an angle θ of 1 mrad, a measurement of the deflection angle with a relative accuracy of 10^{-4} requires a BPM accuracy of 1 μm. This is a very challenging number, since the LEP experience has shown that it is very difficult to control the systematic errors to that level while the beam conditions vary significantly over the energy range that must be covered [12].

Due to the constraints on field monitoring, both inside the spectrometer magnet and in the nominally field free region around it, a normal conducting dipole must probably be used as spectrometer. This leaves the 'dogleg' dipoles in IR3 and IR7 as best locations for a spectrometer, although the high(er) levels of radiation expected in those areas generate additional complications. With the new optics and layout in IR7, there may be sufficient space (> 10 m) for a spectrometer around the inner dogleg dipole. This option may therefore be considered as an upgrade of the machine.

7 Conclusion and Discussion

A momentum calibration entirely based on the knowledge of the LHC dipole field is likely to provide a momentum uncertainty of 0.1% or better at 7 TeV/c. Such a method relies however on the long term stability of the magnetic field in the dipoles, and an independent and direct momentum measurement of the beam may be desired as a cross-check.

A calibration based on proton and fully stripped lead ion beams is very difficult at the LHC due to the very high momentum. The difference of central RF frequency between protons and ions is too small at 7 TeV/c. The experimental techniques used so far do not provide a sufficient accuracy. This method may however provide accurate ($< 0.1\%$) calibrations in the momentum range of 0.45 to 1 TeV/c to verify the validity of the magnetic measurements. With sufficient experience it may be possible to extend the calibration range to higher beam momenta without degrading the accuracy. A very good understanding of the LHC BPM system will be mandatory, including differences between lead ions and protons.

Special lead ion beams with a lower charge state, for example Pb^{27+}, could extend the range of accurate calibration based on the comparison of proton and ion beams. For the time being however this option is not feasible unless a number of hardware modifications are performed in the LEIR transfer lines and on the LHC BPM electronics. A more detailed investigation is required to validate such a method.

Finally a spectrometer system similar to what was used for energy calibration at LEP200 is a possible, but also very challenging future option.

8 Acknowledgements

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