MULTITURN MEASUREMENTS AT THE CERN SPS

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Abstract

The CERN SPS multiturn facility, based on the new beam orbit measurement system MOPOS, enables the User to acquire the position of the beam at each beam position monitor (BPM) over a number of consecutive turns. When the multiturn acquisition is synchronised with a perturbation imposed on the beam (for instance a fast kick), useful information about the optics of the SPS and the dynamic behaviour of the beam can be extracted from the data. A measurement of the amplitude and phase of the betatron oscillation at each BPM can be used to compare the theoretical optics functions with the real ones, and possibly to detect localised errors. Differences between two such measurements can be used to study the dependence on a variable parameter (e.g. beam intensity, beam energy, etc.) and therefore indirectly measure quantities, like the impedance, distributed along the ring. Finally, due to the 90 degrees phase advance lattice, plotting the positions measured at two consecutive BPMs against each other gives information about the behaviour of the beam in the transverse phase space. Results of measurements performed at the CERN SPS are presented.

1 MULTITURN MEASUREMENT FACILITY AT THE SPS

New software has been developed to acquire beam position data from all the SPS BPMs for many consecutive turns. The software consists of two parts: multiturn acquisition and multiturn analysis. The multiturn acquisition program allows to retrieve multiturn data using the MOPOS system [1] and to save the data for later analysis. The multiturn analysis program provides the User an easy way to display and analyse the data.

2 HARMONIC ANALYSIS OF BEAM OSCILLATIONS

Harmonic analysis can be used to measure the amplitude and phase of coherent transverse oscillation at BPM locations [2, 3]. The oscillations can be due to a kick imposed on the beam, or they can be e.g. injection oscillations.

The beam positions at fixed location s during consecutive turns can be written as $u_{\rm i} = A\cos(2\pi qi + \phi)$, where i is the turn index, q is the fractional part of the tune, $A = \sqrt{a\beta(s)}$ is the amplitude and ϕ is the phase of the oscillation.

During measurements, the beam is usually given a transverse kick, after which it starts performing coherent oscillations. The beam positions are recorded with the multiturn system, and the amplitudes A and the phases ϕ are measured using harmonic analysis.

Harmonic analysis also provides a way to measure the tune. The oscillation amplitude from harmonic analysis is plotted for a range of tune values in Fig. 1. The position of the peak indicates the tune with high precision. The tunes measured this way using 113 SPS BPMs are combined in a histogram in Fig. 2. The width of this tune distribution is only 5×10^{-6}, which shows that the effect of the errors on BPM position reading is negligible.

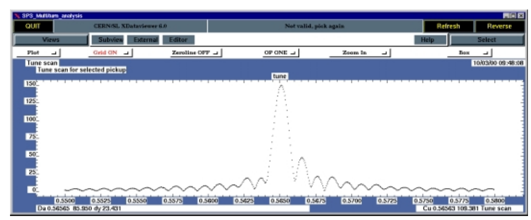

Figure 1: Tune scan.

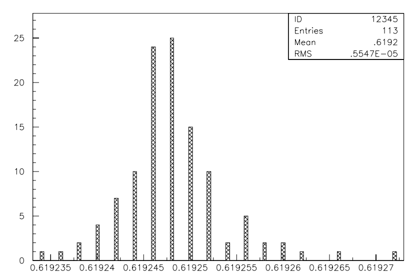

Figure 2: Tune distribution.

3 BETA BEATING MEASUREMENT

One application of multiturn measurements and harmonic analysis is finding out errors in the betatron function. Beta beating can be caused by a gradient error at s_0 where beta function is β_0 and phase function is μ_0:

$$\frac{\Delta\beta}{\beta}(s) = \frac{\Delta k\, L\beta_0 \cos(2\pi Q - 2|\mu(s) - \mu_0|)}{2\sin(2\pi Q)},$$

where Δk is the gradient error, L is magnet length, $\mu(s)$ is phase function and Q is the tune. The modulation of the beta function propagates around the ring with twice the betatron frequency.

In the experiment, the beam oscillation amplitudes and phases were measured at all SPS BPMs in two conditions: once with usual optics and once with an extra quadrupole turned on. In this way, the beta and phase beating caused by this extra quadrupole could be measured. The results are shown in Fig. 3 together with the predictions calculated with the MAD program. The quadrupole that causes the beating (located at 5885 meters in the SPS ring) is indicated by a black disc in the figures. A very good agreement is found between the measured beating and the predictions calculated with MAD program.

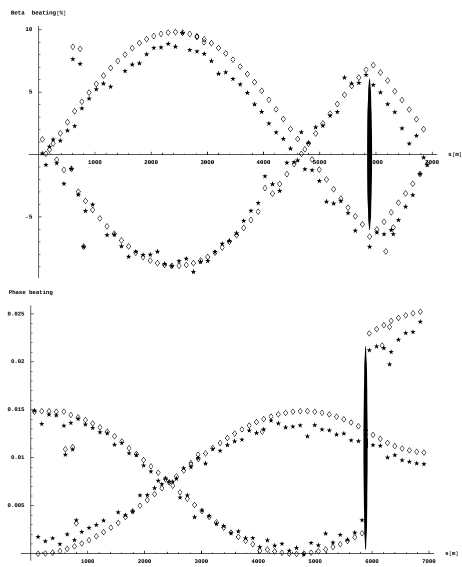

Figure 3: Beta beating (upper part) and phase beating (lower part) at vertical BPMs. The measured points are shown with stars, and theoretical predictions with open diamonds.

4 IMPEDANCE MEASUREMENTS

Another application of the multiturn system is the measurement of SPS impedance. The betatron tune and betatron phase advance depend on the transverse impedance. Measuring the tune dependence on bunch current using one BPM gives the impedance of the whole accelerator. In addition to this, it is possible to measure the betatron phase advance at each individual BPM and get information about how the impedance is distributed around the accelerator.

Both tune shift and impedance distribution measurements were performed using single bunches with intensities ranging from 10^{10} to 10^{11} protons at 26 GeV beam energy.

4.1 Tune shifts

The variation of vertical tune as a function of bunch population is shown in Fig. 4. The measured tune shift ($\Delta Q_{\rm x,y}/\Delta N_{\rm protons}[10^{10}]$) is -0.003. More details about SPS tune shift measurements can be found in [4].

4.2 Impedance distribution

The distribution of impedance around SPS can be estimated by measuring the dependence of betatron phase advance

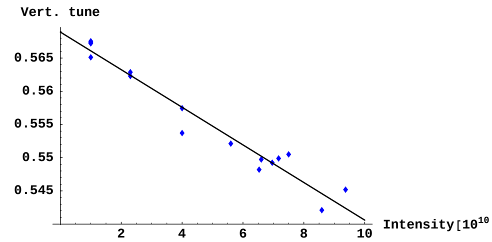

Figure 4: Vertical tune as a function of SPS beam intensity.

on bunch population. Similar measurement has been performed at LEP [5]. Figure 5 shows the vertical phase advance

$$\frac{d\mu_y}{2\pi\, dN_{\rm protons}[10^{10}]}$$

around the SPS circumference. The results, based on a small number of data sets, show some scatter from BPM to BPM. However, a step can be seen at about $s = 600$ meters, which could indicate that a significant fraction of SPS impedance is located at the injection region. The result in Fig. 5 integrated around the whole SPS ring matches well with the measured vertical tune of $\Delta Q_{\rm y}/\Delta N_{\rm protons}[10^{10}] = -0.003$.

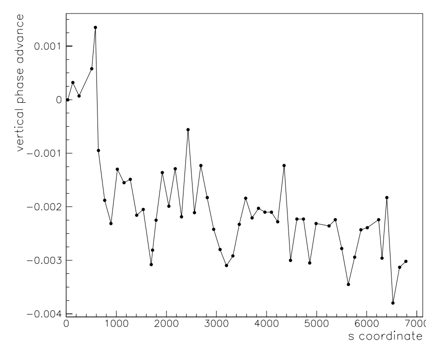

Figure 5: The effect of transverse impedance on the vertical betatron phase.

5 BEAM LOSS MEASUREMENTS

The BPM sum signal is proportional to beam intensity, which makes it possible to measure beam losses during multiturn measurements. When the beam is given a large kick, part of the beam hits an aperture limitation and the resulting loss in beam intensity can be displayed by plotting the sum signal from one BPM during 1000 turns (see Fig. 6). In this case a large fraction of the beam is lost during one turn in the accelerator.

Since sum signals are measured with many BPMs around the accelerator, it is also possible to measure the locations of the beam losses. The sum signals from all the SPS BPMs during one turn after a vertical kick are shown in lower part of Fig. 6. The locations where beam intensity decreases can be identified with aperture limitations. The locations of beam losses measured this way have been compared with the results from the SPS beam loss measurement system, and a good agreement is found. The BPMs can be used to measure aperture limitations only when a large fraction of the beam intensity is lost, i.e. they are not very precise in measuring small losses. On the other hand, the measurement using BPM sum signals does not depend on the exact location of the losses. For example, if particles are lost inside a bending magnet, the losses may not be visible using other beam loss monitors but the losses can still be measured using BPM sum signals.

Figure 6: BPM sum signal (proportional to beam intensity) during 1000 turns measured with one BPM (upper figure) and BPM sum signal from every SPS BPM during one turn (lower figure).

6 BEAM PHASE SPACE

Phase space diagrams allow to get more understanding about the beam behaviour when e.g. the beam is close to a resonance. [6]. In a phase space diagram, the beam is represented by a point $(x, x^{'})$ during each passage through a BPM, where x is the position and $x^{'}$ is the angle of the beam. The beam position can be directly measured with one BPM, and the beam angle can be found out by measuring the position at another BPM separated by 90 degrees betatron phase advance. In this case, the position at the second BPM represents derivative of the position (i.e. angle) at the first BPM.

In the SPS, the phase advance between consecutive BPMs is in most cases close to 90 degrees. An example of a phase space measurement using two consecutive BPMs is shown in Fig. 8. The horizontal beam position during the phase space measurement is shown in Fig. 7. The beam is given a large horizontal kick after about 40 turns, after which it starts performing coherent betatron oscillations. The three lines in the beam position plot indicate that the beam is close to third integer resonance. In fact, an exact tune measurement using a tune scan indicates that the horizontal tune is slightly above 2/3. The phase space plot also shows the fact that the beam is close to third integer resonance. The first 40 turns before the kick are shown in the middle of the phase space plot, and after the kick there are three separate arms in the phase space.

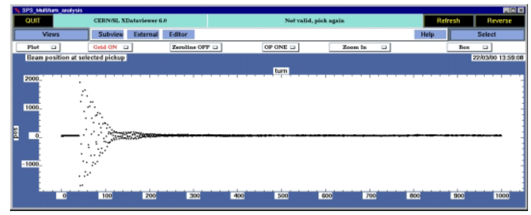

Figure 7: Beam position during phase space measurement.

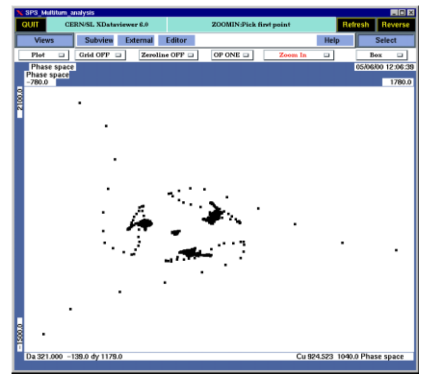

Figure 8: Beam phase space.

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