Continuous Tune Measurement up the SSC Ramp

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Introduction

The ramping time to raise the energy of the SSC from 1 TeV at injection to 20 TeV at storage is about 1000 seconds. This is an order of magnitude larger than the Tevatron cycle time (120 seconds), and two orders larger than the typical SPS cycle time of 21.6 seconds. It will be very desirable, if not absolutely essential, to be able to automatically measure the closed orbits, tunes, chromaticities and the linear coupling continuously during the ramp. After measuring these quantities as functions of time, and after sufficient computation, the optics may then be corrected for the next ramp.

It is relatively easy to make many successive beam position measurements, so long as the associated electronics have enough memory, as demonstrated by every day experience in the Tevatron. Continuous tune measurement is a less conventional procedure in proton accelerators, first demonstrated (to my knowledge) in the SPS, during the commissioning of pulsing-coasting operation[1]. Automatic chromaticity and linear coupling measurements are possible if automatic tune measurement is possible, since both are based on a few, or several, tune measurements. For example, the minimal chromaticity measurement consists of three tune measurements, with the RF frequency first set nominally, and then offset slightly positive and negative.

This note shows that the techniques described in reference [1] (reprinted here as an appendix) can be adapted to measure the tunes thousands of times during the ramp of a badly tuned SSC, without unacceptable beam loss and without severe hardware requirements. It also appears to be possible to perform continuous tune measurement during luminosity production ramps, in a well tuned SSC, without a significant loss of luminosity.

Tune Measurement and Beam Growth

The tunes are readily measured by kicking the beam, and collecting turn-by-turn data at a beam position monitor (BPM) for Fourier analysis. This is destructive for proton beams, in the sense that the emittance of the beam is irreversibly increased. Fourier analysis of the natural Schottky noise spectrum is promising because it is non-destructive, but appears to take at least several seconds per measurement, too slow to be of practical use during the ramp.

Assume that the minimum kick necessary for tune measurement makes the center of charge oscillate with a peak displacement of δ at a focussing quadrupole. (All sizes and displacements in the SSC refer to a point with $\beta = 350$ metres.) In the absence of noise it is ideally sufficient that δ be only one bit of resolution in the beam position monitors, although in practice it is probably advantageous for the beam kick to be, say, twice this size. Noise is unimportant in Tevatron orbit measurements, where the BPM signal is digitised with a least count size of 0.16 millimetres. In the SPS, with $\beta \approx 100$ metres, the minimum kick required for detection by standard BPMs was 1 microradian, corresponding to $\delta = 0.1$ millimetres. Both of these numbers are somewhat arbitrary, and do not represent a fundamental limit – routine BPM resolutions of less than 10 microns are not unthinkable. Specialised postion detectors can have much greater accuracy. For example, the Schottky noise pickups in the SPS have a sensitivity of about 1 micron, sufficient to detect 10 nanoradian ($\delta = 1$ micron) kicks.

If the beam is excited by n kicks of amplitude δ at a constant energy, its final mean square size is given by

$$\sigma^2_{final} = \sigma^2_{initial} + n\,\delta^2 \qquad 1$$

This result is independent of the shape of the beam distribution, but assumes that the kicks are independent of one another - there is enough time between kicks for all phase information to be lost. It typically takes much more than 100 turns for the beams to decohere completely.

Decoherence

The two most important sources of decoherence are tune variation with betatron amplitude, and tune variation with energy (chromaticity).

Tune variation with amplitude is strongest in the SSC in the collision lattice, when a particle with concurrent 1.0 centimetre oscillations in both planes suffers tune shifts of −0.0037 and −0.0034 horizontally and vertically[2]. This means that the signal from a beam with $\sigma = 1.0$ centimetre in the collision lattice will decohere in $n_d \approx 250$ turns, which is nonetheless adequate for tune measurement with 0.001 resolution (see reference 1). However, if the beam size at storage has its nominal value,

$$\sigma_0 = (\varepsilon_N \beta / \gamma)^{1/2} = 0.13 \quad \text{millimetres} \qquad 2$$

using a normalised emittance of $\varepsilon_N = 10^{-6}$ metres, then the tune spread across the beam is negligible ($< 10^{-6}$), since it is quadratic in amplitude.

At top energy the relative momentum spread in the beam is expected to be about 10^{-4}, so that a net chromaticity of 40 will produce a tune shift of 0.004, and a decoherence time of 250 turns. Such values of chromaticity (and worse) will probably be commonplace during coarse tuning of the SSC. However, the final chromaticities in a well tuned SSC will probably be limited by the accuracy of the tune measurements themselves, and it is reasonable to hope for maximum tune spreads significantly less than 0.002, the synchrotron frequency at storage. When this happens the signal only partially decoheres, to recohere 'completely' after each synchrotron period. Such ringing is commonly observed in the Tevatron.

Results

The beam must not aquire a final size σ_{final} comparable to the beam pipe radius, otherwise most of the beam will be lost. Some beam loss may be possible without quenching the magnets, if low intensity beams are used for diagnostic purposes. Roughly speaking then (in the spirit of this note) σ_{final} may not exceed 10.0 millimetres, or

$$n^{1/2}\,\delta \quad < \quad 10.0 \qquad \text{millimetres} \qquad\qquad 3$$

This shows that about 10^4 tune measurements are possible with $\delta = 0.1$ millimetre kicks. Even this is a conservative estimate, since it is assumed that all kicks occur at storage energy, while really the kicks at lower energies should be derated by a factor of E_{kick}/E_{store}. If one such tune measurement is made every 300 turns, and the circulation frequency of the SSC is $f_{rev} = 3$ kiloHertz, the tunes may be measured continuously for 1000 seconds, the time scale of the ramp.

The SPS was coarsely tuned for pulsing-coasting operation using just such a repetitive sequence of discrete 'Multi-Q' tune measurements. This was followed by fine tuning using a phase locked loop system of 'Continuous-Q' tune measurements, in which the beam was continuously driven, allowing tune measurements to be made every 6 milliseconds. In this case equation 1 may be modified to give

$$\sigma^2_{final} \;=\; \sigma^2_0 \;+\; (n\,/\,n_d)\,\delta^2 \qquad\qquad 4$$

where it is assumed that there is one independent kick of amplitude δ per decoherence time. Taking the

SPS value of $\delta = 1$ micron, conservatively estimating the decoherence time to be $n_d = 600$ turns, and using $n = 3\ 10^6$ turns for the ramping time, the final beam size is estimated to be

$$\sigma^2_{final} = (0.13)^2 + (0.07)^2 = (0.15)^2 \quad \text{millimetres}^2 \qquad 5$$

This shows that it is possible to continuously measure the tunes during each and every ramp of the SSC, even during luminosity production ramps.

Acknowledgements

I wish to thank Chris Saltmarsh and Rudiger Schmidt for the many useful comments and suggestions they have made to me, on this and related topics.

References

1. See the appendix, which reprints R. Bossart et al, Tune Measurement and Control at the CERN-SPS, Vancouver PAC, 1985. IEEE NS-32 p. 1902.
2. Table 4.2-2 of the Conceptual Design Report, page 121.

APPENDIX

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TUNE MEASUREMENT AND CONTROL AT THE CERN-SPS

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SUMMARY

Two complementary techniques have been developed which allow the betatron tunes to be controlled during energy ramping of the SPS to a precision of better than ±0.002. By the use of these techniques the setting-up of the SPS as a collider and a fixed target machine is substantially simplified and better physics understanding has been gained. The first technique uses an *electrostatic beam deflection every 60 ms.* A Fast-Fourier Transformation of the beam response in a dedicated computer yields the betatron tunes with a precision better than 0.01. In the second technique the beam is continuously excited. The frequency of the excitation is measured and fed back to the beam by a Phase-Locked-Loop. This measurement is accurate to better than 0.001 but requires a reasonably well tuned machine. Tune deviations are automatically compensated by acting on the main quadrupoles through a software loop.

The pulsed proton-antiproton collider

Operating as a p-pbar collider the SPS normally works at a constant energy of 315 GeV. As a fixed target machine the energy is ramped from 14 GeV up to 450 GeV. *To achieve the maximum energy of 450 GeV in collider* mode in order to produce p-pbar interactions with 900 GeV in the center of mass, the SPS runs with cyclic energy variations from 100 GeV to 450 GeV (fig.1 and /1/).

To obtain an acceptable lifetime for the particles (bigger than 1-2 hours) the betatron tunes of the protons have to be kept away from resonances up to the fourth order. The antiprotons suffer from higher order resonances up to at least the tenth order because of the beam-beam effect. The tunes have to be carefully chosen to avoid crossing these resonances /2/. Fig.2 shows the tune diagram at 100 GeV. Two proton bunches each with a bunch intensity of $6*10^{10}$ particles and one antiproton bunch with $6*10^{9}$ particles, typical for this operation, are assumed. The single particle tune is the tune of a particle which is not influenced by the electromagnetic fields of the other particles. This tune is chosen to be 26.678 (QV) and 26.688 (QH). The space charge forces in the dense proton bunch change the tune of the individual particles and produces the large betatron frequency spread at 100 GeV shown in fig.2. Inversely proportional to the square of the energy the spread becomes negligible at the highest energy. The tune spread of the antiprotons comes from the beam beam effect and is consequently energy independent. To avoid crossing third and tenth order resonances the tunes have to be kept constant during the cycle to an accuracy better than 0.005.

Tune measurement of a proton beam

Tune measurements in the SPS are done in different ways according to the different modes of operation. If the tunes are constant, i.e. in the operation at a fixed energy the tune is measured by observing the natural Schottky noise of the bunches without kicking the beam. If this extremely weak signal is averaged over a long enough time this non-destructive measurement yields the tune.

When the machine conditions are changing, e.g. changing the energy, the tunes also may change. The maximum rate at which corrections can be applied is once every 30 milliseconds, because the SPS magnet currents are *changed in a smooth way corresponding to reference data* every 30 milliseconds. The measurement of the tune has to be done in this time. This is achieved by exciting the beam via a kicker and measuring the beam response.

One problem arises from the chosen working point with horizontal and vertical tunes very close to each other, i.e. QH-QV<0.01. Random skew quadrupole components and non-zero vertical orbit positions in the chromaticity correcting sextupoles produce a coupling of the horizontal and vertical betatron oscillations. In this case the beams oscillate in one plane with two frequencies. The coupling can cause :

- a change of the betatron frequencies of the order of the coupling term (<0.01).

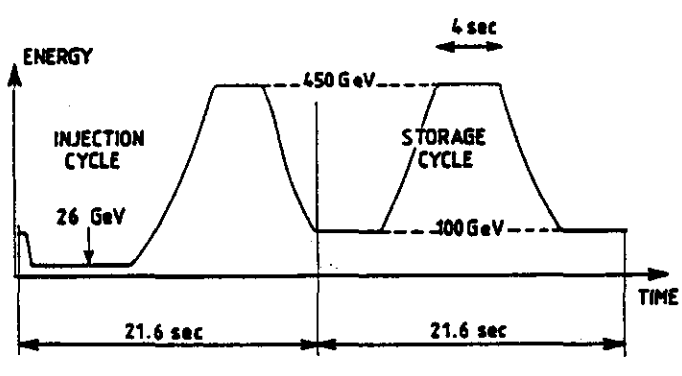

Fig.1 Energy versus time in the pulsed collider

The injection cycle 1 and the storage cycle 2 are shown. In coast only cycle 2 is used.

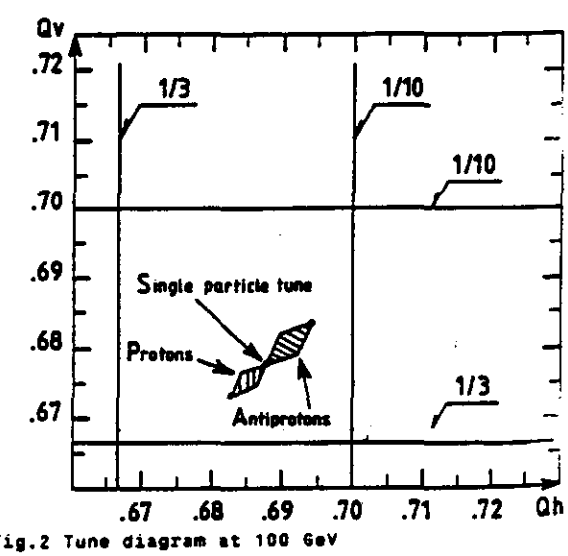

Fig.2 Tune diagram at 100 GeV

The diagram shows the single particle tune as well as the area which is occupied by the tunes of the protons and antiprotons.

- a measurement of the wrong frequency, because a monitor observing the beam oscillations in one plane measures both the horizontal and vertical frequency.

The coupling can be compensated with the help of skew-quadrupoles. For a clean measurement with the desired working point the coupling has to be reduced to less than 0.005.

To allow tune measurements under all circumstances two complementary techniques have been developed. The first technique (MULTI-Q) gives a measurement of the tunes with an accuracy of about 0.01. As described below this technique is relatively insensitive to a small residual coupling. The second technique (CONTINUOUS-Q) requires a reasonably well tuned machine. Here the tunes are measured with an accuracy better than 0.001.

In both methods the beam is kicked. Unwanted effects of these kicks are emittance growth, particle losses and an increase of the background in the experiments. Thus tune measurements may only be done during the setting-up periods of the machine.

The more sensitive the pick-up, the less kick strength is required. Pick-ups with a high sensitivity were already available, those used for Schottky signal observations /3/. These pick-ups, 2 pairs of 3 metre long plates, one for the horizontal and the other for the vertical plane are used for both methods.

To correct the tune the following method is applied. During the setting-up the tune is measured all along the cycle. The required change of the main quadrupole currents needed for the correction of the tunes at 30 millisecond intervals is calculated and stored in digital form. The correction data are then transferred to the computer which drives the power supplies.

The MULTIQ System

The MULTIQ system measures the tune in one cycle by kicking the beam every 60 msec. The beam response is measured and subsequently the data are Fourier Analysed to find the tune value.

The layout of the system is shown in fig.3. The acquisition of the data is controlled by a micro processor which performs the following sequence of actions :

1) A signal is sent to an electrostatic deflector to kick the beam in one turn in each plane with a deflection of about 0.001 mrad at 315 GeV /4/. The resulting beam response is measured by the horizontal and the vertical Schottky plates for 256 turns and digitised on each turn.

2) After this time has elapsed, the beam position signals recorded in the digitisers are read out and stored in the memory of the microprocessor.

3) The microprocessor then waits until it is time to start the aquisition of the next data point, and repeats this sequence.

A mini computer reads out the horizontal and vertical beam position for each data point, altogether about some 200 kBytes. Then the following analysis is performed :

1) A Fast Fourier Transform to produce a frequency power spectrum.

2) The spectrum is searched for main and subsidiary peaks, and the tune values corresponding to these peaks are calculated. The coupling between the horizontal and vertical planes can often produce extra peaks in the power spectrum.

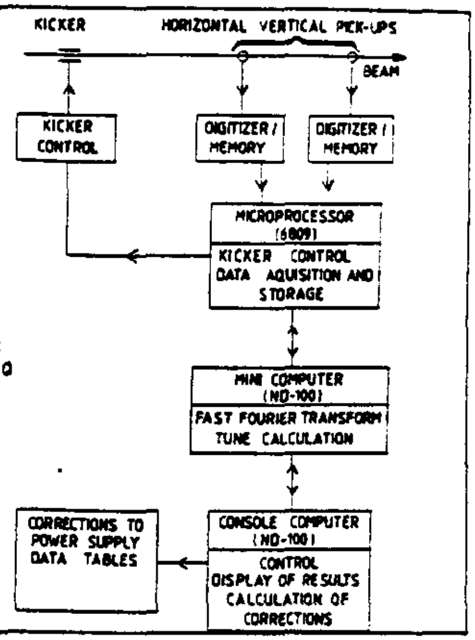

Fig.3 Layout of MULTIQ

3) If two peaks occur in the spectrum, an attempt is made to decide which one corresponds to the true tune in the measured plane. This is done by comparing the peaks in each plane and looking for coincidence of tune values. Ambiguities are resolved by the use of an assumption such as QH>QV.

4) The ratio of the power in the peaks found in each plane is used to find an indication of the strength of the coupling.

After the analysis of all the points is finished the results are displayed as plots of tune versus time in the cycle. The MULTIQ system is considered to be very much an operational system, and the analysis has been structured in such a way as to give maximum help to the operator through the use of sophisticated diagnostics and control.

The system works well in the different operational modes of the machine like the p-pbar collider and the fixed target machine. It is insensitive against the betatron frequency spread (i.e. due to the space-charge forces). The system has also been found to be extendable so that automatic chromaticity measurements could be made on the machine all through the cycle. This is done by making tune measurements on 2 cycles with two different energies achieved by changing the frequency of the RF. From the tunes measured for two different energies the chromaticity is calculated /5/.

The CONTINUOUS-Q system

The hardware for the continuous tune measurement shown in fig.4 has been described in detail in /6/. In this system betatron oscillations are continuously excited by kicking the bunches every revolution with a kicker in one plane. The response of the beam to the kick is measured by the Schottky pick-up previously described and the excitation signal is phase-locked onto the received signal. In this way the excitation frequency tracks the betatron frequency. To get a measure of the tune this frequency is converted to a voltage. This latter voltage is digitized every 6 milliseconds and the data are stored in a computer memory.

With the sensitive Schottky pick-ups used kicks smaller than 10^{-8} rad are sufficient for the measurement. With this small amplitude of kick the intensity loss during one cycle of 21.6 sec is less than 0.5 % and the

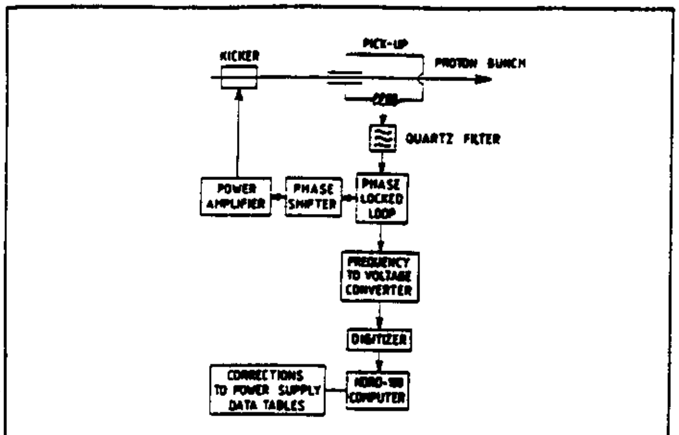

Fig.4 Layout of CONTINUOUS-Q

emittance growth less than 2.5 %. After calibration done with a frequency generator to simulate the beam signal the measurement precision is better than 43 Hz, i.e. 0.001.

If the betatron oscillations are coupled the phase locked loop can lock on either the horizontal or the vertical betatron frequency especially if the tunes are crossing. To allow a clean measurement the coupling has to be reduced to less than 0.005. Before the optimization of the tunes with this method the tunes are normally corrected with MULTIQ to an accuracy such that they are not crossing.

RESULTS

The setting up of the machine for the pulsed collider is done with protons only. The machine is set to follow the supercycle of fig.1, an injection cycle followed by a storage cycle. Without any correction the tune in the storage cycle shows large variations (fig.5). A significant part of the protons are lost because of crossing resonances. The first optimization is done with MULTI-Q. After two or three correction iterations the tune variation is reduced by a factor of ~10 (fig.6). The tunes are no longer crossing resonances and the particle losses are small.

Further optimization of the tunes is done with CONTINUOUS-Q in storage (storage cycle only). After two steps the tune variation is reduced a further factor ~3. The maximal excursions are about ± 0.002.

The correction of the tunes must be done with a low intensity bunch otherwise the measured tune is shifted by the coherent tune shift caused by the interaction of the beam with its surroundings. This shift is approximately inversely proportional to the energy and can change the measured tune by about 0.004 and therefore spoil the correction.

The optimization procedure described takes about two to three hours. The tunes change during storage by less than 0.002 caused by magnet-heating.

After correcting the tunes to the values of 26.678/26.688 the lifetime of the bunches is no longer limited by the small residual tune changes. At the start of a storage period the lifetime is about 2-3 hours for both protons and antiprotons, climbing up to about 7-8 hours during the first two hours of storage.

The importance of keeping the tunes at the nominal working point was demonstrated by the following observation: The tunes were increased by 0.01 placing the antiprotons on tenth order resonances. This strongly reduced their lifetime to about 20 minutes.

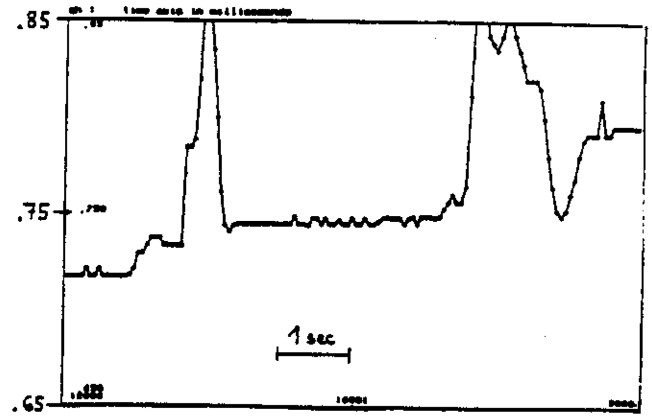

Fig.5 Tune during a part of the cycle before any corrections were applied

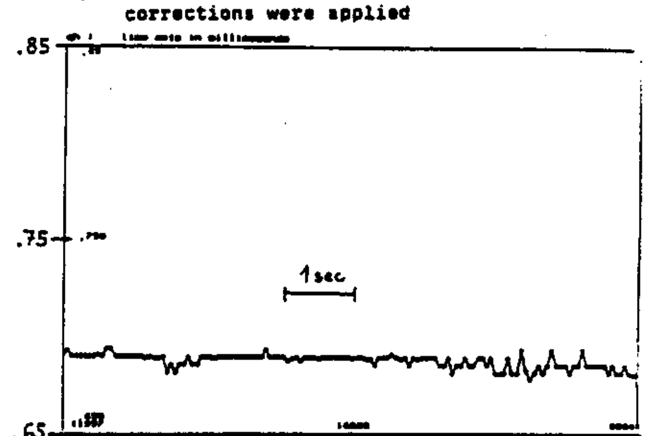

Fig.6 Tune after the correction with MULTIQ

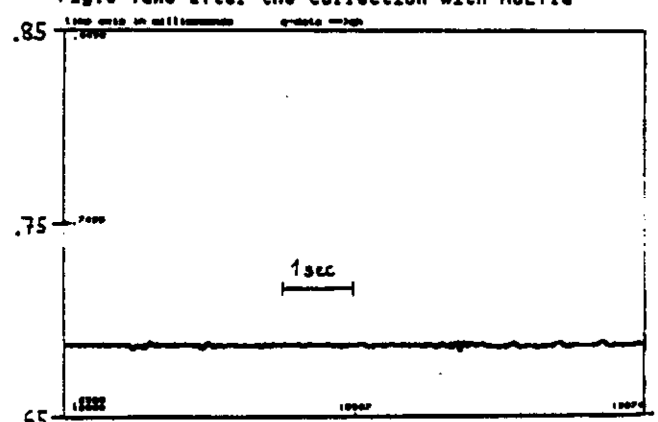

Fig.7 Tune after two additional correction iterations with CONTINUOUS-Q

ACKNOWLEDGEMENT

We would like to thank J.Gareyte and R.Lauckner for many helpful discussions.

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