

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

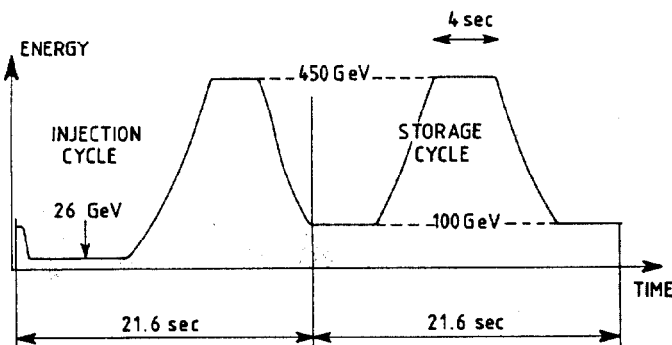


Fig.1 Energy versus time in the pulsed collider

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

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).

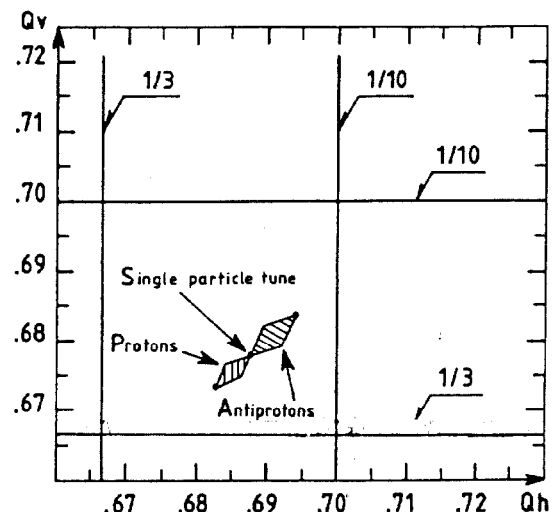


Fig.2 Tune diagram at 100 GeV

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 MULTI-Q System

The MULTI-Q 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 acquisition 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

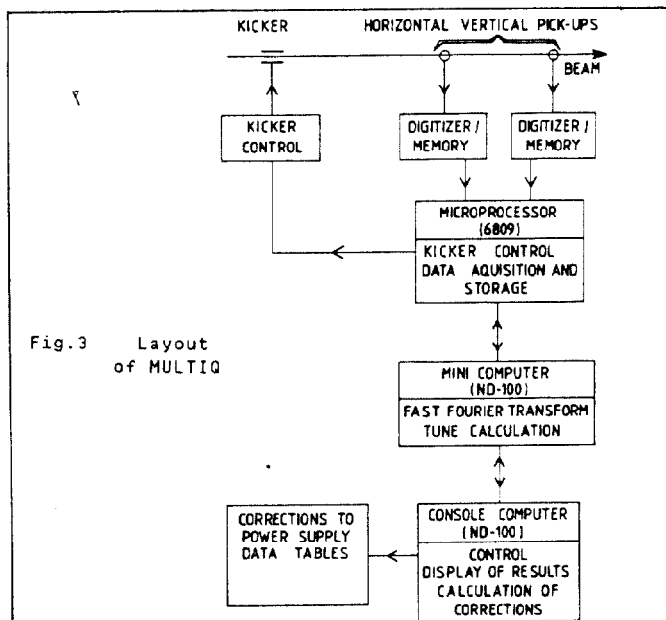


Fig. 3 Layout of MULTI-Q

extra peaks in the power spectrum.

- 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 $Q_H > Q_V$.
- 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.

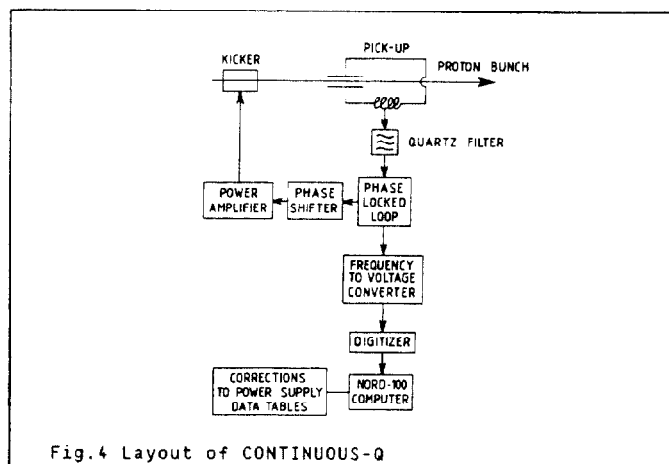
After the analysis of all the points is finished the results are displayed as plots of tune versus time in the cycle. The MULTI-Q system is considered to be very much an operational system, and the analysis has been structured in such a way as to give maximum help to the operator through the use of sophisticated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

The system works well in the different operational modes of the machine like the p-bar 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



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 MULTI-Q 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.

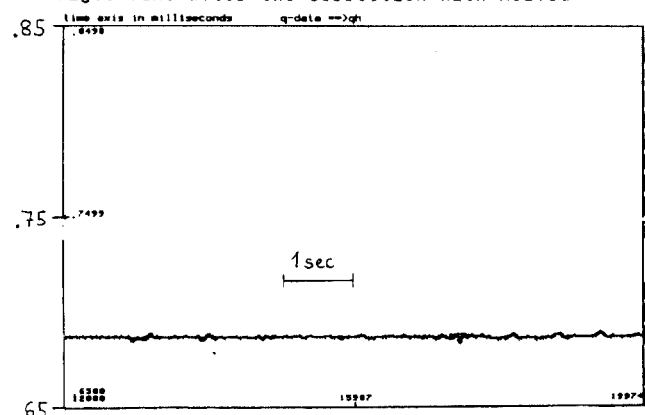
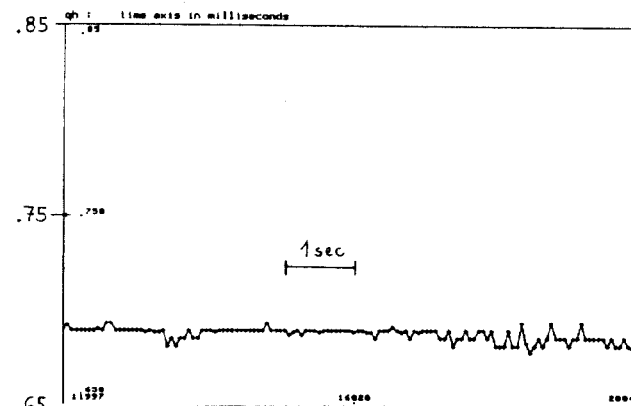
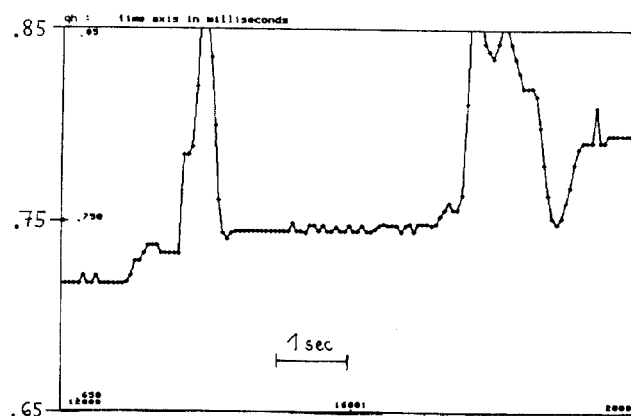
Further optimization of the tunes is done with CONTINUOUS-Q in storage (storage cycle only). After two steps the tune variation is reduced a further factor ~ 3 . The maximal excursions are about ± 0.002 .

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.



ACKNOWLEDGEMENT

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