Tune Measurements in the SPS as Multicycling Machine

C. Boccard, W. Höfle, H. Jakob, L. Jensen, R. Louwerse, L. Vos, H. Schmickler
CERN, Geneva, Switzerland

Abstract

Throughout the operation cycle of the SPS different particles are accelerated: high intensity protons, leptons and heavy ions. For each particle type a measurement of the betatron tunes along the acceleration cycle is required. The paper describes the different excitation and data analysis methods used in order to minimize beam blowup during the measurements (protons) or in order to optimize the time resolution (leptons). Measurement examples are given.

1 MEASUREMENT HARDWARE

The beams are excited to transverse beam oscillations by using the damping system. In order not disturb the proper functioning of the system against transverse instabilities the analog excitation signals are added to the driving stage of the power amplifier. The gain and other parameters of the damper are not changed. The situation is illustrated in figure 1 showing the layout for the horizontal plane. More details on this system can be found in [1].

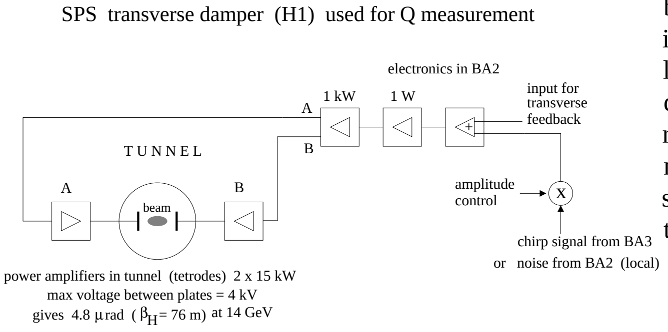

Figure 1: Schematic diagram of the horizontal subsystem of the SPS damper as used for tune measurements.

The beam oscillations are measured turn by turn using the BOSC system [3]. Figure 2 shows a schematic diagram of the system. The postion information from a directional coupler is split into a sum signal (Σ) and a difference signal(Δ). The sum signal is used in a peak detection circuit to produce the gates for samplers of the sum and difference signals. After analog to digital conversion the data are stored in a local buffer memory for later treatment. More details on the BOSC aquisition system can be found in [3].

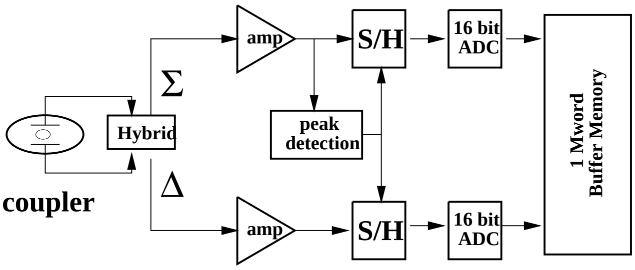

Figure 2: Schematic diagram of the front end electronics of the position measurement system (BOSC).

2 REQUIREMENTS FOR LEPTONS

In two consecutive cycles of 400 msec length electrons and positrons are accelerated from 3.5 GeV/c^2 to 22 GeV/c^2 beam energy and then injected into LEP. In total about 10^{11} particles in 8 bunches are accelerated. A continous tune measurement throughout the cycle is requested in order to control the betatron tunes and chromaticties for high acceleration efficiency. For leptons the emittance blowup is a less important issue. Therefore the beams are excited with random kicks (white noise) and the tune information is obtained by measuring the beam motion turn by turn and by a sliding FFT and automatic peak finding. In practice a 1024 turn long data window is used as input for the FFT and then this data window is advanced in steps of 43 turns (43 turns correspond to a 1 msec increments in time). Chromaticities are measured on consecutive cycles as difference of tune measurements for different Rf-frequencies. More details on lepton measurements have already been published in [2].

3 REQUIREMENTS FOR PROTONS

For fixed traget experiments more than 4000 proton bunches with a total intensity of $3.5 \cdot 10^{13}$ particles are injected at 14 GeV/c^2 beam energy and then accelerated to 450 GeV/c^2 in a 4.5 second long cycle. At these high intensities any beam blowup caused by permanent beam excitations for tune measurements has to be minimized in order to avoid beam losses. A tune measurement throughout the cycle with a time resolution of one measurement every 30 msec is desired resulting in 150 measurements per acceleration cycle.

The following chapter will give details on the measurement procedure followed by a chapter evaluating the resulting emittance blowup.

4 CHIRP MEASUREMENTS

In case of a ”Chirp” excitation the beams are excited with a sine wave and the frequency of the sine wave is increased linearily in time within a certain sweep range. This method has been choosen for the proton tune measurements as it gives a good observable signal for low exciation levels. In detail every 30 msec the beam is excited for 20 msec with a sin wave ranging in frequency from tunes of 0.55 to 0.7. Listening to such frequency modulated sine waves on a loudspeaker gives the impression of a singing bird. For this reason the excitation is called ”chirp” in the literature.

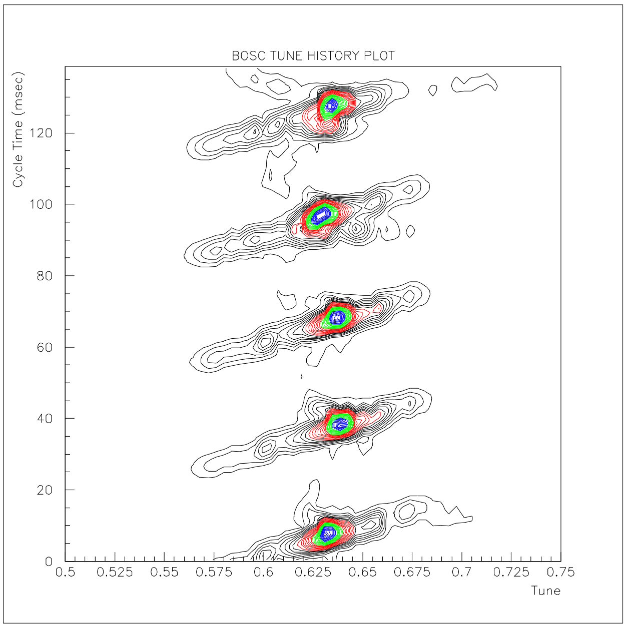

Figure 3: 3-dimensional representation of the beam response to a chirp excitation.

Figure 3 nicely illustrates the resulting beam oscillation during a chirp excitation. The horizontal scale is tune and the vertical scale is time in the proton cycle. In color code (visible in this document as grey scales) the amplitude of the beam oscillation is encoded. One nicely sees that the chirp starts below the beam resonance, crosses it at a certain moment before the chirp stops. After 30 msec the measurement starts again. Following the amplitude maxima by eye already gives the development of the machine tune as a function of time. In practice the tunes are obtained with an automatic peak finder in the following way: A datawindow corresponding to 1024 machine turns is centered around the measured beam oscillation during a complete chirp excitation (20 msec correspond to 860 machine turns). In the amplitude spectrum the tune is defined via the maximum oscillation amplitude. Further tune resolution is obtained by interpolating between bins at the maximum [4]. The resulting curve for the whole acceleration cycle is shown in figure 4.

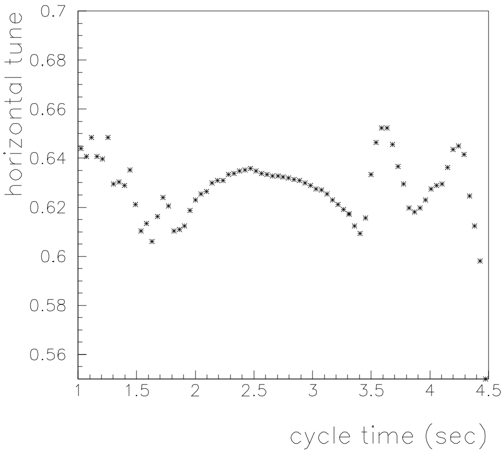

Figure 4: Measured horizontal tune as a function of cycle time.

5 EMITTANCE BLOWUP

The measurements shown in figure 3 have been obtained with a total intensity of $6 \cdot 10^{12}$ protons, hence with about a fifth of the nominal intensity for fixed target operation. It is now of extreme importance to evaluate the resulting emittance blowup in order top demonstrate that the chirp measurement procedure can safely be used at nominal intensity.

The emittance blowup created by a transverse beam oscillation can be written in a form which is convienent for the following arguments. Especially the rms beam amplitude is written as a product of the noise figure of the oscillation detector and the signal to noise ratio of the measurement. The equation reads:

$$\frac{\delta\epsilon}{\epsilon_0} = \frac{(S/N \cdot x_{\rm noise})^2}{\beta} \cdot \delta Q \cdot \frac{\Delta \mathrm{t}}{T} \cdot \frac{1}{\epsilon_0} \tag{1}$$

The variables in the above equation are:

- ϵ_0: original emittance $\simeq$ $20 \mu rad$
- δQ : $\simeq$ 4$\cdot$ rms tune spread $\simeq$ 0.012
- T: SPS revolution period = 22.3 μ sec
- $\Delta \mathrm{t}$: time interval of beam oscillation $\simeq$ 2msec
- S/N: signal to noise ratio (see figure 5)
- $x_{\rm noise}$: noise figure of detector $\simeq$ 20μm

The two unknown variables S/N and ΔQ in the above equation have been obtained from the measurements. The amplitude above noise can directly be measured from the spectra (figure 5) and the tunespread δQ is taken as 4 times the rms width of the measured tune peak. As the measured tune spread varies very little throughout the cycle a constant value of δQ = 0.012 has been used for the evaluation of the emittance blowup.

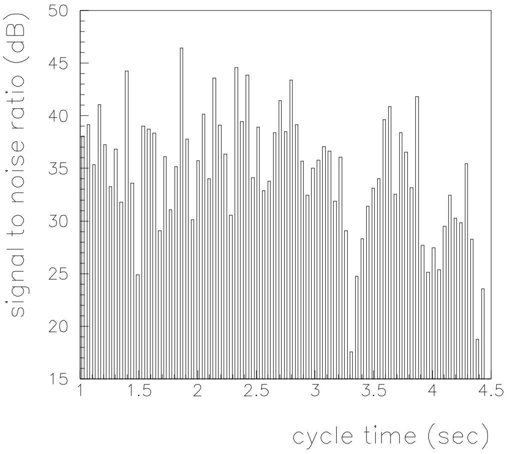

Figure 5: Measured signal to noise ratio as a function of cycle time.

Using equation 1 one can compute the resulting emittance blowup through the acceleration cycle. The result is shown in figure 6 for three differnt signal to noise ratios. So for example if one had excited the beams such that throughout the whole cycle one had had a signal to noise ratio of 40 dB one would have nearly doubled the original emittance and certainly have created beam losses. But looking at figure 5 one can see that the measurements yielded an average signal to noise ratio of 30 dB resulting in turn to a blowup of less than 10%. In general one can say that a quite reliable tune measurement can already be achieved with 20 dB signal to noise ratio. So for the above measurement example one could have further reduced the blowup by using a smaller excitation early in the cycle, i. e. at low beam energies. This indeed is possible as the excitation level is controlled by a function generator which is synchronized to the acceleration cycle.

6 DISCUSSION

The above analysis has shown that with a chirp excitation and a control of the excitation amplitude a reliable tune measurement throughout the proton acceleration cycle can be provided. With an ordinary but well tuned directional coupler and a 16-bit digitization system a noise figure of 20 μm is achieved. With a signal to noise ratio of 30 db throughout the cycle one would have to accept an emittance blowup of about 10% for having 150 tune measurements at 30 msec intervals. The blowup could only be reduced by working with lower excitation levels and eventually improving the noise figure of the oscillation detector.

The choice of chirp excitation has to be compared to other possible measuremnts:

- A phase locked loop would excite the beams permanentely at the resonance and hence result in much larger blowups, although for a PLL a smaller signal to noise ratio than 30 dB is needed to keep the lock on the resonance.

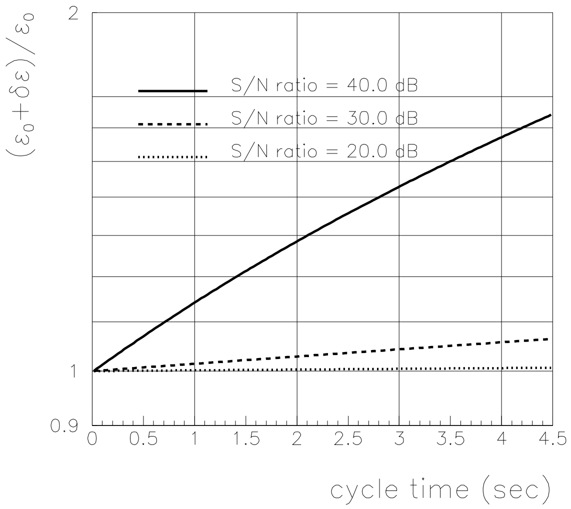

Figure 6: calculated emittance blowup for different signal to noise ratios in the amplitude detector for tune measurements.

- Excitation of the beams with bursts of white noise and a similar data treatment as in the case of chirp excitation. In that case one would in fact obtain similar results as with chirp excitation. In particular if one limited the burst time to 2 msec which corresponds roughly to the time the chirp needs to pass through the resonance the emittance blowup would be the same. The important difference is that for a white noise excitation a much larger excitation strength is needed, as much of the excitation energy is not used to excite the resonance. In case of the SPS this would certainly be a limiting factor for high beam energies due to limitation in the maximum kick strength of the damper system.

Considering the above arguments the chirp excitation is the best method for tune measurements for the proton beams in the SPS.

7 REFERENCES

[1] **The new damper of the transverse instabilities of the SPS at high intensities.**, R. Bossart et al., SPS/ABM/RB/81-1

[2] **SPS Tune Measurements**, H. Jakob et al.,
Proceedings of the 2nd European Workshop on Beam Diagnostics (DIPACII) in Travemünde, DESY Report M-95-07

[3] **The BOSC Project**, A. Burns et al.
CERN Divisional Note, SL 90-68 (AP)

[4] **Study of the Accuracy and Computation Time Requirements of FFT based Tune Measurements in LEP**,
H. Schmickler, LEP/BI/Note 87-10