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SPS INSTRUMENTATION IN VIEW OF THE LHC

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The next years improvements on existing beam instruments and new installations are foreseen. This presentation will summarize these activities including time scales and expected performance. In detail the following subjects will be covered: Upgrade of the orbit system COPOS, tune measurements, chromaticity measurement system, transverse emittance measurements and a new monitor to measure the matching of the transverse emittance at injection. A specific chapter will treat installations in the SPS aimed at studies for the LHC instrumentation.

Keywords: Instrumentation

1 INTRODUCTION

The specific requirements on instrumentation for the SPS as LHC injector are presently studied by the SLIP (SPS for LHC Injector Project) Working Group and these demands define an upgrade program for the next five years. The full report can be found in Ref. [1]. Apart from these new installations the performance of existing instruments are being reviewed and key instruments like the orbit system COPOS, the tune and chromaticity measurements and emittance measurement devices are being consolidated for the next 20 years of operation of the SPS and also new functionality is added. These consolidation activities are subject of this paper with the aim of general information and in order to stimulate discussions on the proposed modifications.

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2 THE ORBIT SYSTEM COPOS

Figure 1 shows a schematic view of the chain of elements in the orbit measurement system COPOS. In addition to the functionality of each block the year of construction is denoted. Some of the elements are already more than 20 years in operation and as recent investigations have shown are no longer within their original tolerances. Three items have been identified as important items for consolidation and are marked in Figure 1 in order of importance. The following subsections will cover each item separately.

2.1 Acquisition System

The central element in the analog to digital conversion is a voltage to frequency converter. Due to its construction it integrates the analog input over 1 ms which corresponds to 23 machine turns. Hence only first turn trajectories (using gates and hold circuits) or orbit measurements representing a 23 turn average are possible. All applications based on turn to turn measurements like the LEP 1000 turn

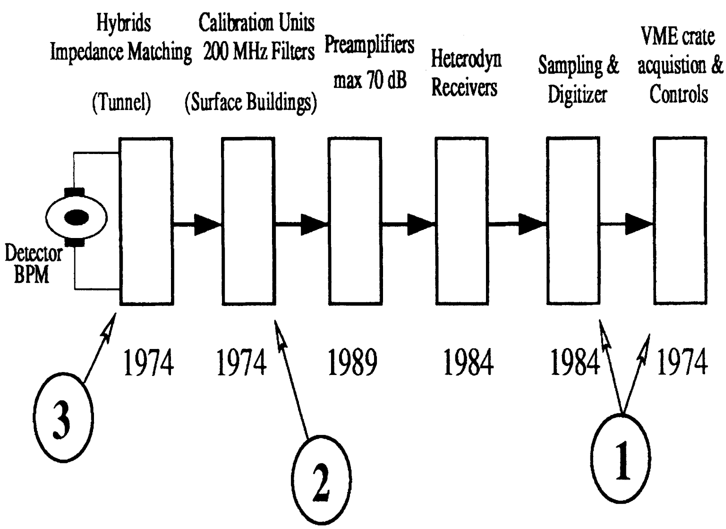

FIGURE 1 Block diagram of the SPS orbit system (COPOS) indicating the dates of the last modification to each of the subsystems.

acquisitions are not possible. This is a severe limitation for machine studies or measurements of the machine lattice functions. For this reason the voltage to frequency converters are replaced by 14-bit ADCs with a conversion time of less than one machine turn. At the same time the size of the memory in the front ends is increased in order to be able to store every turn of every BPM during one elementary cycle. This way the front end system holds all possible data and several users demanding data from different cycle times can be satisfied in parallel. The existing VME front end computers (single CPUs based on a 68000 CPU chip) are replaced by modern double VME Power PC cards.

The time scale for the implementation of the new acquisition system is as follows: At the end of 1997 one new acquisition station will be tested in parallel to an old station. During the 1997/1998 shutdown this old station will be eliminated, such that during the 1998 operation the COPOS system will be a hybrid system of one new station and 5 old stations. During the 1998/1999 shutdown the other 5 stations will be replaced and at the startup 1999 the new acquisition system, from then onwards called MOPOS (Multi-Orbit and POSition), will be available.

2.2 Calibration Unit and 200 MHz Filters

These units are the central elements of the analog preprocessing chain.

The calibration unit is based on reed relais contacts for switching between normal operation and calibration. Due to many unreliable contacts the calibration is not used very often. In the new design these relais will be replaced by semiconductor switches.

The 200 MHz filters have been produced for installation in 1973 and at that time have been trimmed and selected in pairs with 3 permille tolerances on 6 parameters. Recent measurements have revealed that these tolerances are no longer obtained leading to the need for frequent readjustments in the system in order to avoid important measurement errors. All 200 MHz filters will be rebuilt with a technology specifically suited to guarantee long time stability.

The design and the production of 300 calibration and filter units is done in the framework of the CERN–TRIUMF collaboration. The TRIUMF laboratory is charged with producing these units in the following time frame: design and choice of the units by May 1997;

production of prototypes and a first preseries until end 1997; delivery of all units during 1998 and 1999.

2.3 Hybrids and Injection Matching Circuits

These passive elements are located in the tunnel and have suffered from radiation. During the 1997 shutdown many of these units will be examined and after these tests a decision will be taken whether a complete renewal of these units will be needed. Such an exchange could be possible in the 1999/2000 shutdown.

3 TUNE AND CHROMATICITY MEASUREMENTS

3.1 Measurement Hardware

The beams are excited to transverse beam oscillations by using the damping system. In order not to 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 2 showing the layout for the horizontal plane. More details on this system can be found in Ref. [2].

The beam oscillations are measured turn by turn using the BOSC system (Ref. [4]). Figure 3 shows a schematic diagram of the system. The position 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 is stored in a local buffer memory for later treatment. More details on the BOSC acquisition system can be found in Ref. [4].

3.2 Requirements for Leptons

In two consecutive cycles of 400 ms length electrons and positrons are accelerated from 3.5 to 22 GeV/c^2 beam energy and then injected into LEP. In total about 10^{11} particles in 8 bunches are accelerated. A continuous tune measurement throughout the cycle is requested in order to control the betatron tunes and chromaticities for high

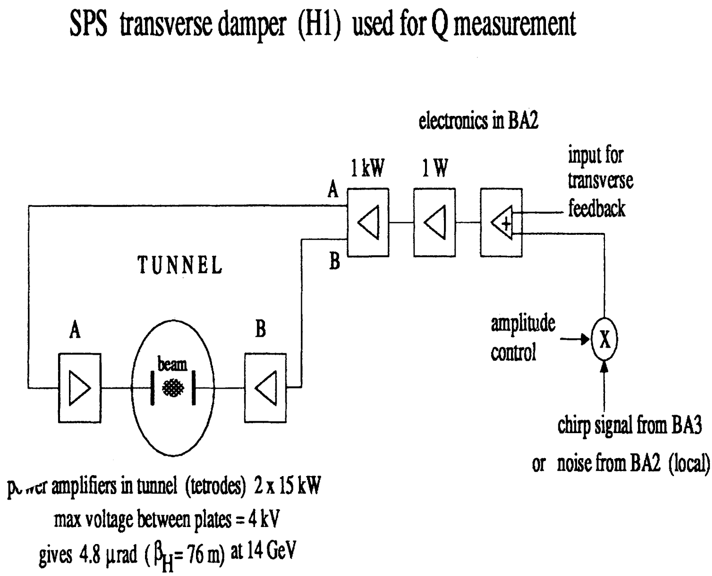

FIGURE 2 Schematic diagram of the horizontal subsystem of the SPS damper as used for tune measurements.

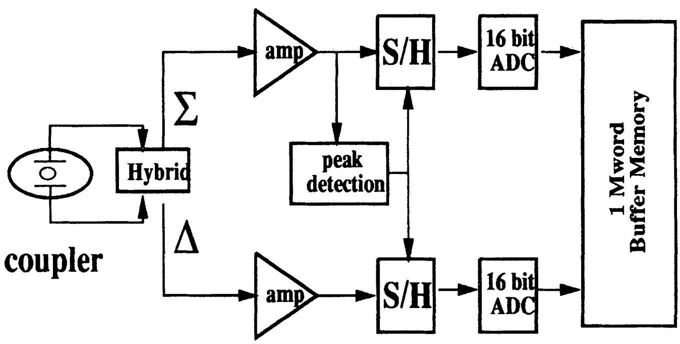

FIGURE 3 Schematic diagram of the front end electronics of the position measurement system (BOSC).

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 ms increment 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 Ref. [3].

3.3 Requirements for Protons

For fixed target experiments more than 4000 proton bunches with a total intensity of $3.5 \cdot 10^{13}$ particles are injected at $14\,\mathrm{GeV}/c^2$ beam energy and then accelerated to $450\,\mathrm{GeV}/c^2$ in a 4.5 s 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 ms 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.

3.4 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 linearly in time within a certain sweep range. This method has been chosen for the proton tune measurements as it gives a good observable signal for low excitation levels. In detail every 30 ms the beam is excited for 20 ms with a sine 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 4 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. The amplitude of the beam oscillation is encoded in different grey scales. One clearly sees that the chirp starts below the beam resonance, crosses it at a certain moment before the chirp stops. After 30 ms 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

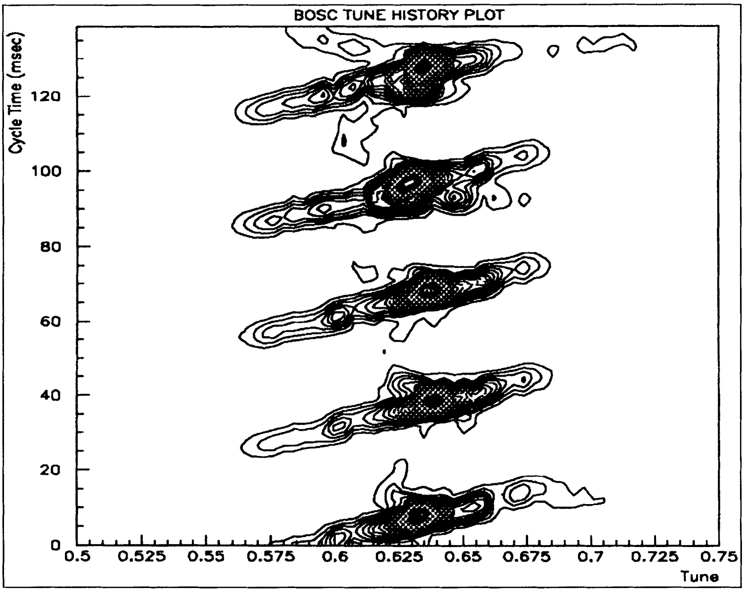

FIGURE 4 The beam response to a chirp excitation. The horizontal scale is tune and the vertical scale is time in the proton cycle.

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 ms corresponds 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 (Ref. [5]).

3.5 Emittance Blowup

The measurements shown in Figure 4 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 to 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 convenient for the following arguments.

In particular, 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:

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

The variables in the above equation are:

- ϵ_0: original emittance $\simeq 20$ mm mrad
- δQ: $\simeq 4 \cdot$ rms tune spread $\simeq 0.012$
- T: SPS revolution period $= 22.3$ μs
- Δt: time interval of beam oscillation $\simeq 2$ ms
- S/N: signal to noise ratio
- x_{noise}: noise figure of detector $\simeq 20$ μm.

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 and the tune spread 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 $\delta Q = 0.012$ has been used for the evaluation of the emittance blowup.

Using Eq. (1) one can compute the resulting emittance blowup through the acceleration cycle. The result is shown in Figure 5 for three different signal to noise ratios. So for example if one had excited the

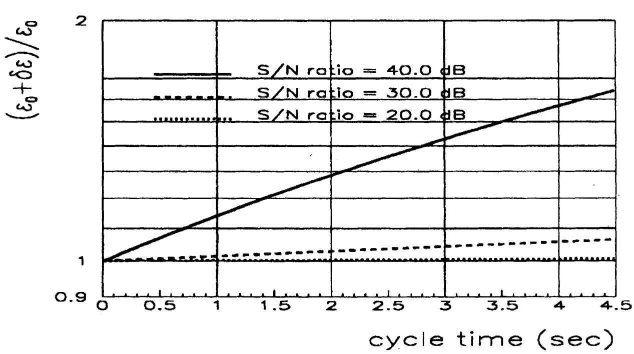

FIGURE 5 Calculated emittance blowup for different signal to noise ratios in the amplitude detector for tune measurements.

beams such that throughout the whole cycle a signal to noise ratio of 40 dB was achieved one would have nearly doubled the original emittance and certainly created beam losses. Usually the excitation function is trimmed such that an average signal to noise ratio of 30 dB is obtained resulting in 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 measurement example above one could have further reduced the blowup by using a smaller excitation early in the cycle, i.e. at low beam energies.

3.6 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 ms 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 measurements:

- A phase locked loop would excite the beams permanently at the resonance. But as a PLL circuit uses the phase information of the beam transfer function the tunes can be measured with much smaller amplitudes (the phase has the maximum slope at the resonance, whereas the amplitude is at its maximum). Very encouraging results with this technique have recently been reported from HERA-p (Ref. [6]).
- 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 ms 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 presently the best method for tune measurements for the proton beams in the SPS. As the machine is very reproducible from one cycle to another chromaticity measurements can be made as difference measurements between tune traces of two cycles with different RF-frequencies, i.e. different beam energies. This tool has been made available for operation in 1996 and results have been reported in Ref. [8].

But during 1997 hardware will be assembled in order to realize a PLL based tune measurement system for the SPS. First results can be expected during 1998.

4 EMITTANCE MEASUREMENTS

Two new developments are briefly mentioned:

- *Thin screen for the observation of the injection matching*: For the purpose of studying the oscillation of beam sizes at injection a thin screen with a turn by turn camera readout has been proposed. As the injection energy is already quite high a screen can be chosen such that the emittance blowup due to multiple scattering is small over the first few hundred turns. All details can be found in Ref. [7].
- *Rest gas Ionization monitor*: A rest gas ionization monitor is successfully used at DESY for continuous monitoring of the beam sizes. A spare device of this type will be installed during the 1996/1997 shutdown into the SPS and should become available for measurements during 1997.

5 SPS FOR LHC DEVELOPMENTS

The LHC machine itself demands new developments for some instruments. It is very convenient to have an operational proton machine in house on which these new instruments can be developed for the LHC. The following items will be implemented in the SPS with the particular interest of studying their performance for the LHC:

- The above emittance measurement devices.
- An online feedback on the betatron tunes and a continuous diagnostic on the chromaticities.
- A stabilization of an orbit segment by local feedbacks. In the SPS this will be used to stabilize the beams at the moment of fast scraping before ejection (see Ref. [1]) and the same technique should be used in the LHC for stabilization of the beams in the cleaning sections.
- In one of the existing transfer lines from the PS to the SPS (TT10) the electronics for the position measurements will be renewed in order to be able to measure bunches independent of their bunching frequency in the PS. A very good candidate for these electronics would be logarithmic amplifiers (such as proposed for the SSC-BPM system), which also will be considered for the LHC orbit system.

6 SUMMARY

A large list of activities has been listed concerning the upgrades and modifications of existing SPS instrumentation. This will be the central activity of the SL beam instrumentation group over the next years before most of the effort will be devoted to the LHC instrumentation.

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