IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

THE SPS BEAM INSTRUMENTATION AND CLOSED ORBIT CORRECTION

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Summary

For the running-in and the operation of a large accelerator like the SPS, the beam instrumentation plays a prominent part. Though limiting the beam detectors to where they are strictly necessary, their number is still considerable, leading to a large amount of data to be treated simultaneously. To do this efficiently, hardware and software are equally important and the design of the hardware had to be done jointly with the software. The type of detectors is determined by their function, intensity, position, profile, loss, etc... whereas the type of associated electronics and acquisition systems has to be restricted to a minimum for simplicity, production cost, easy maintenance and fast data treatment. Furthermore the small number of access shafts to the accelerator (6 for 7 km SPS ring circumference) and to the beam transfer lines leads to the transport of tiny signals over long distances (several hundred metres) in a noisy and irradiated environment.

This paper summarizes the performance of the main types of detectors giving some particularities of their hardware and software with some emphasis on the closed orbit measurement and correction system.

Secondary emission monitors for the transfer lines

This type of monitors measures the charges emitted by thin foils or wires as the proton beam passes through. These monitors give a small blow-up to the beam. It is negligible for the transfer lines where the beam passes through only once but it cannot be tolerated for the circulating beam in the ring. Therefore it is largely used in the transfer lines and for the first turn ring experiments. The number of secondary charges is proportional to the number of protons passing through and this ratio (∿5%) is very stable under good vacuum conditions and standard bias voltage. Plain foils intercepting the whole beam are used to measure the beam intensity. Split foils consisting of two half-moons give the beam position. Grids of thin foils with a resolution down to 0.8 mm between two foils, provide beam profiles. Single wires or thin flags moved by stepping motors can scan the beam profile over several cycles; the great resolution of the displacement (0.1 mm) allows a fine analysis of the beam profile.

Each charge collecting element (e.g. each foil of a grid) has its own electronic channel, mainly consisting of an integrator followed by a track and hold device. To avoid possible damage of operational amplifiers by radiation, the charges are carried on twisted pairs from the tunnel to the auxiliary buildings over long distances (several hundred metres). By careful shielding and earthing, charges as low as 20 pico-Coulomb can be detected. The electronics and acquisition system are identical whatever the detector is but the capacitance of the integrator is matched to the range of charges gathered by the detector. A dynamic of 10^3 in the acquisition is available for a given capacitance, e.g. between 10^9 and 10^{12} protons passing through the foil with a capacitance of 1000 pf[1].

Figure 1 shows the horizontal and vertical profiles of the beam measured in the ring during its first revolution at a location where $\varepsilon_H = \varepsilon_V$. With 3 sets of such grids the beam emittance at injection momentum could be calculated and has been found to be $\varepsilon_H \sim \varepsilon_V \approx 1 \times \pi$ mm.mrad at an intensity of 2×10^{12} ppp.

Non-destructive monitors for the circulating beam

Beam intensity is measured by means of beam current transformers. They use the current balancing technique. The proton beam passing through a toroidal core induces a voltage in a 120-turn sense winding. This is amplified and nulled by passing the amplifier output through a 2-turn feedback winding. The feedback signal is taken by differential cable to a precision 100 Ω termination resistor in the auxiliary building. The signal is then processed by Integrate/Hold circuit and Analog to Digital converters. In addition buffer amplifiers provide signals for analog observation. As it is, the system is sensitive enough to measure the beam over one revolution or in the injection line and in the transfer lines for a fast extracted beam. To keep a precision of 0.1 % during the SPS cycle for the main ring transformers, a second harmonic magnetic modulator and detector is included in the amplifiers feedback loop (fig. 2). The performance of the system is as follows:

Dynamic range	100 μA ($\approx 10^{10}$ ppp) → 100 mA ($\approx 10^{13}$ ppp)	
Frequency response	Transfer line	10 Hz → 1 MHz
	Main ring	DC → 1 MHz

Non-destructive beam profiles are taken by using the ionisation beam scanning technique[2]. Three monitors give respectively the vertical profile and the horizontal profiles where the momentum compaction factors are nought and maximum.

The Q-value of the SPS is measured in two parts. The integral part and the half integral part are measured by Fourier analysis of the closed orbit position measurement. The non-integer part is measured by kicking the beam over one revolution and observing the output of a single position pick up station. The signal is processed by a sample and hold followed by an analog to digital converter, triggered at revolution frequency, for 256 revolutions of the machine. Fourier analysis of this data gives the Q-frequency from which the Q-value can be calculated.

Ring beam position detectors[3]

Another important non-destructive system of detector is the ring beam monitor. This system consists of 216 monitors, one horizontal detector, BPH, upstream of each QF, one vertical, BPV, upstream of each QV, where the β function is maximum in each plane respectively. Different types of detectors have been designed for different aperture requirements: the 'electrostatic' type of detectors (103 BPH and 102 BPV) is used in the normal straight sections of the accelerator, whereas another type called 'wall current' detector with an increased aperture (11 BPA) is installed in the enlarged sections for beam injection and extraction.

All beam position detectors work at the accelerator's RF-frequency of 200 MHz, at which the beam delivers a maximum of power output from the detectors. The electrostatic detectors BPH and BPV consist of a pair of symmetric induction electrodes made of stainless steel sheets and mounted on isolating supports inside the vacuum chamber (fig. 3). Since the RF-frequency of the SPS is as high as 200 MHz, the dimensions of the electrodes must be considerably smaller than the RF-wavelength, the limit being at about $\lambda/10 = 150$ mm. For the enlarged straight sections with an aperture of ∅ 269 mm, the wall current detector measures both the horizontal and vertical beam position independent of each other by means of a coaxial cavity in the vacuum chamber[4] (fig. 4). For both detectors the mechanical accuracy of the position measurement is better than 0.5 mm for the beam in the centre, and the linear error is 1% for beam positions inside the half aperture. The sensitivity of the detector signal for a short bunched circulating beam expressed in mA, is 82 μV/mA mm for BPH, 145 μV/mA mm for BPV and 47 μV/mA mm for BPA, according to their internal sizes.

In order to get the best possible accuracy for the beam in the centre position, each pair of detector signals is fed directly into a hybrid ring, which provides the vector sum and difference signals with an accuracy of better than 0.5%, typically 0.3%. The two signals sum Σ and difference Δ are then converted down to an intermediate frequency of 1.8 MHz by a superheterodyne receiver located in a pit under the beam position detector. The superheterodyne receiver has been chosen for its relatively good radiation resistance up to a radiation dose of 10^6 rad, which is crucial for any electronics in the accelerator tunnel[5]. The drifts of the amplification factors and zero offsets of the complete electronic equipment from the beam position detector up to the computer acquisition can be measured and compensated by means of the calibration switch at the input of the receiver. The residual error of the electronic equipment hence is given only by the calibration switch, which has a zero offset of better than 0.1% and a linear error of better than 4%, typically 1.7%.

The local oscillator of the receiver is driven via a frequency multiplier by a synchronisation signal derived from the accelerator's RF-frequency, so that the IF-frequency is kept constant, if the RF-frequency sweeps from 199.5 MHz to 200.4 MHz during acceleration. The IF-signals from the tunnel are demodulated by a synchronous demodulator in the auxiliary building and converted by individual voltage-to-frequency converters 5 MHz for digital acquisition by CAMAC-scalers. This method provides directly the mean position of the beam unaffected from betatron oscillations, if the scaler gate is opened during 1 ms at any time of the acceleration cycle. If the gate is opened during one SPS revolution (23 μs) at injection, the first turn trajectory can be traced with reduced accuracy.

First turn and closed orbit corrections

At low energy the beam position can be corrected by small dipoles:108 in both planes, each correcting dipole being located near the beam position detector. They are DC powered and computer controlled.

The measurement of the first turn trajectory was found to be a powerful tool for a large machine. Associated with the correcting dipole located at about a quarter of betatronic wavelength upstream, the beam can be centred along the machine as in a transfer line.

Automatic closed orbit correction at low energy is currently done on-line using the beam bump method all around the machine. The peak-to-peak amplitudes are reduced horizontally from 35 mm without any correction to 5 mm and vertically from 18 mm to 3 mm. The closed orbit in both planes is acquired within one cycle and the whole set of corrections is applied a few cycles later (figures 5 and 6)

At high energies, the DC powered correcting dipoles are no longer valid to compensate the errors proportional to the field. The closed orbits between 100 GeV and 400 GeV have about the same pattern and peak-to-peak amplitudes showing no evidence of saturation effects. Closed orbit corrections can be done after program analysis by moving a few main quadrupoles. For instance, the vertical peak-to-peak amplitude has been reduced from 20 mm to less than 9 mm by moving 6 quadrupoles a few tenths of a mm.

Software[6]

The SPS control system has a decentralised structure with more than 20 computers interlinked in a star-like configuration. Each computer is in charge of a geographical part of the machine or a specific function. To obtain fast acquisitions and treatments of a large amount of data taken at the same time in different computers, a special software has been developed and incorporated in the general system in order to be 'transparent'. The system consists of three steps:

1. The acquisition by itself which has to be done at the same time for all the data. A pure hardware solution has been chosen for it using either external analog and digital memories, triggered by the general timing system whose events and delays can be set by computers.

2. The transfer of data to the computer, which has to be fast and timed to release the external memories for the next acquisition. It is done globally by using the 'direct memory access' facility initialised by external interrupts and fast real-time programs. Up to 4 acquisitions per cycle are possible.

3. The treatment of data which is selective according to the needs of many application programs and uses special routines giving the maximum flexibility in the use of data transferred at different times. For instance, the difference of two closed orbits in the same cycle can be obtained as well as the beam characteristics of three different extracted beams (slow, fast and fast-slow) in the same extraction channel and within the same cycle.

References

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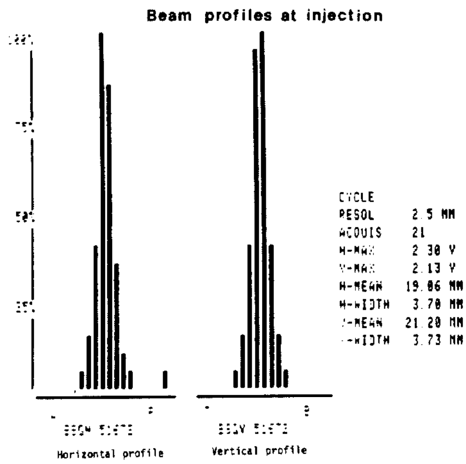

Fig.1. Horizontal and vertical beam profiles at injection

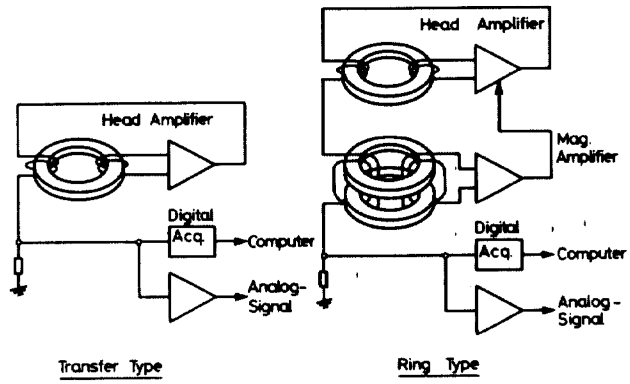

Fig. 2. Beam current transformer

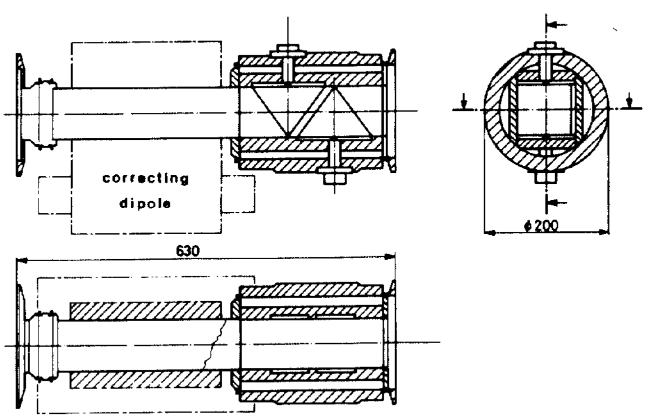

Fig. 3. Vertical beam position detector 'BPV'

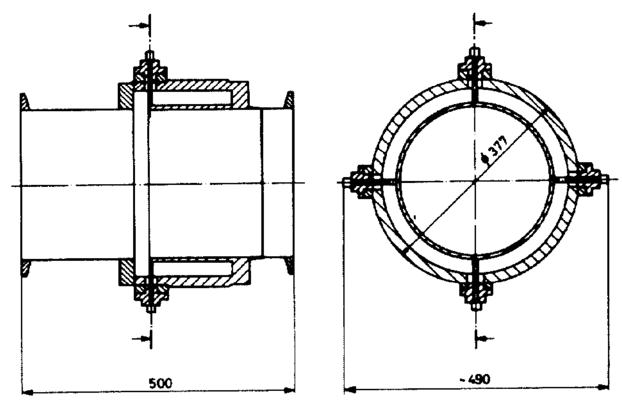

Fig.4. 'Wall current' beam position detector 'BPA'

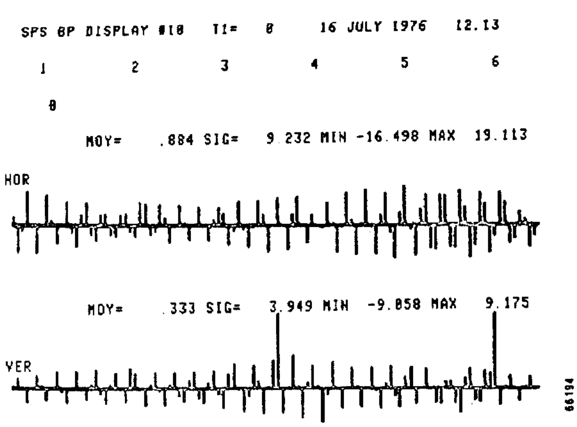

Fig.5. Closed orbit without any correction

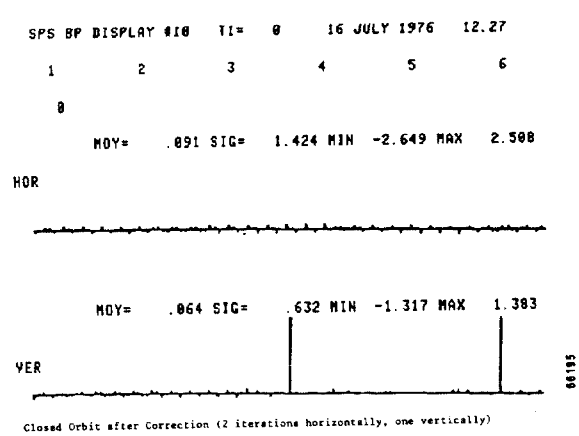

Fig.6. Closed orbit after correction