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ORBIT AND TRAJECTORY MEASUREMENT WITH LOW INTENSITY LEAD ION BEAMS IN THE SPS

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Abstract

The orbit measurement system of the CERN SPS was designed to measure the position of dense proton beams with an intensity of up to 0.28 A. The lower design limit for the lead ion beam intensity has been fixed at 35 μA. This requires a substantial extension of the dynamic range. We describe the properties of the system and its modifications together with the results obtained for sulphur ion beams in the past and lead ions more recently.

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I. INTRODUCTION

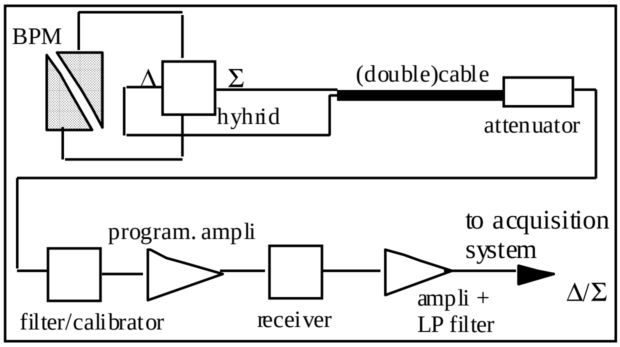
The SPS has accelerated and extracted light ions, deuterons, oxygen and sulphur, since 1985 [1]. The operation of the machine could be ensured satisfactorily with the existing closed orbit measurement system and this for two reasons. The deuteron beam intensity was not much less than standard proton intensities. For the other more scarce light ion beams, the magnetic machine was set-up with a pilot beam having the same rigidity as the ions but with more intensity to allow measurements. In the latter case the magnetic states of the PS injector and of the SPS were perfectly matched. This convenient procedure was no longer valid for the operation with the heavy Pb-ions. Indeed, PS is handling only partially stripped ions (Pb^{+53}) and the conversion to Pb^{+82} is done in the transfer line between the two machines. Therefore it became a fundamental requirement that the SPS magnetic set-up for orbit (and tune) should be done with the heavy ion beam without the safety net of a more intense pilot beam. In the following we will quantify the boundary conditions, the limitations of the existing system, the implemented modifications and the results obtained so far.

II. TOTAL CHARGE OF LEAD ION BEAMS

Several different design figures for total charge have been quoted during the years preceding the actual operation for physics with lead ions in 1994. Very early in the project [2] 4.1 10^9 *c* was mentioned. Note that '*c*' stands for *electronic charge*. In the more recent design report [3] this quantity had gone up to 32 $10^9 c$. At the time when the upgrade of the orbit measuring system was designed it was still the lower intensity that was *en vogue*. Moreover, oxygen and sulphur ion intensities ranged from 0.3 to 3 $10^9 c$. For these reasons a lower design limit of 5 $10^9 c$ was adopted. It should be noted that the SPS handles typically 30000 10^9 *c* in the form of protons, i.e. a factor of 8000 (78 dB) in dynamic range. The comparison is valid since in both cases the beam is spread out along the machine circumference and is not concentrated in a few bunches as in the Sp$\bar{p}$S or LEP.

III. PROPERTIES OF NORMAL ORBIT MEASURING SYSTEM

The vast majority of the monitors in the SPS are of the electrostatic type. The position properties of the electromagnetic ones are not very different from the vertical standard position monitors while the properties of the large aperture magnetic ones come close to the horizontal monitors. Therefore, and to simplify the argumentation, only standard vertical and horizontal monitors (BPM) will be considered. The transverse impedance is $Z_\perp = 152\,\Omega/\mathrm{m}$ vertically and $86\,\Omega/\mathrm{m}$ horizontally. The schematic layout of the system is shown in Figure 1.



Layout of SPS orbit measuring system
FIGURE 1

The electrode signals generated by the BPM are combined (3dB signal gain) in a hybrid circuit in a sum(Σ) and a difference(Δ). Both are sent over a long cable to the auxiliary building where the processing electronics is located. The length of the cables depends on the position of the monitor in the machine and varies from about 300m to 700m. In order to achieve the same electronic aperture for all, attenuators are added to the shorter cables. The average attenuation is around 26dB.

The next element is a 200MHz bandpass filter combined in a calibrator unit. The signal bandwidth of the filter is 4.9MHz. The Σ signal is attenuated by 6dB (splitter for calibration). The filter attenuation is 4.5dB. The homodyne receiver is preceded by a set of programmable amplifiers. The amplification step is

10dB and the switching is done with PIN diodes. The receiver selects one 200MHz sideband of the signal and shifts it to DC. The other sideband now at 400MHz is removed by a lowpass filter (3 MHz) incorporated in the output operational amplifier.

The resolution properties of the measuring chain are determined by the signal power in the Δ channel that is confronted with noise. The normal operation of the system is such that the noise generated at the input of the programmable amplifiers is dominant. It may be useful to point out that the performance is dictated by the Δ channel and not by the Σ channel. This can be understood as follows. Call the error, which is generated by the noise, e_Σ and e_Δ for the Σ and Δ channels respectively. The unperturbed position is computed from :

$$x = \frac{\Delta}{\Sigma}, \tag{1}$$

while the perturbed position is given by:

$$\sqrt{x^2 + e_x^2} = \sqrt{\frac{\Delta^2 + e_\Delta^2}{\Sigma^2 + e_\Sigma^2}} = \frac{\Delta}{\Sigma}\sqrt{\frac{1+\left(e_\Delta/\Delta\right)^2}{1+\left(e_\Sigma/\Sigma\right)^2}}. \tag{2}$$

The errors e_Σ and e_Δ are of comparable magnitude. The Δ signal is in most practical cases only a small fraction (r.m.s. less than 10%) of Σ. Hence it can be concluded that the numerator of (2) dominates the result. The calculation continues as follows. The noise power is :

$$P_N = 4kT\Delta f, \tag{3}$$

where k is Boltzmann's constant, T the absolute temperature and Δf the noise bandwidth. The action of the receiver is such that the bandfilter noise bandwidth δf is reduced by a factor two: $\Delta f = \delta f / 2$. The noise figure of the amplifier doubles the noise power. Finally the noise voltage is :

$$V_N = \sqrt{2 P_N R} = 2\mu V. \tag{4}$$

It should be noted that the load resistance $R = 50\Omega$ and that the filter bandwidth $\delta f = 4.4\,MHz$. The signal produced by the monitor is attenuated gradually up to the input of the amplifier. The total attenuation for the Δ signal is 27.5 dB. This reduces the transverse impedance from 86(152) to 3.6(6.4) Ω/m in the horizontal (vertical) plane. The noise voltage then leads to a noise dipole moment in h (v) of:

$$(Ix)_N = 0.56\,(0.32)\mu Am. \tag{5}$$

The current associated with the lower limit of the number of particles (5 10^9) is 35μA. From (5) follows a resolution of **16 mm(9mm)** for single turn acquisition or measurement of trajectory. The orbit averaging occurs over 43 turns yielding a resolution for orbit measurement of **2.5mm(1.4mm)**. It may be worth mentioning that resolution and r.m.s. error are synonymous. Clearly, the expected performance of the normal beam trajectory and orbit measuring system was and is inadequate to handle operationally the very low intensity heavy ion beams.

IV. HIGH RESOLUTION ORBIT SYSTEM.

Any modification must be such that the operating of both the high intensity multi bunch proton beams and the very dense quasi single bunch lepton beams is not hindered. The radioactive ambience associated with the proton beams excluded from the very start the installation of electronics in the tunnel close to the position monitors. Also the multicycling(*) between the different modes of operation had to be preserved and extended.

The main task was to find ways to increase the signal to noise ratio sufficiently. The first element of the adopted strategy was to fetch the signal with a good quality amplifier as close as possible to the monitor. Hence it was decided to install low noise 30dB preamplifiers before the filters (4.5 dB gain) and before the equalising attenuators of the short cables. The value of the equalising attenuators for one third of the monitors(equipped with short cables) is 12dB, for one other third(medium length cables) between 6 and 9dB and the remaining monitors (long cables) have no attenuators at all. The noise factor of the new preamplifiers is 2.5dB, i.e. 1 dB gain compared with the normal situation. Summing it all up we can expect a gain of 17.5 dB (linear factor 7.5) for the short cables, 13dB (linear factor 4.5) for the medium length cables and 5.5dB (linear factor 1.9) for the long cables. The *trajectory* resolution for a 35μA beam improves from 16mm (9mm) to **2.1mm (1.2mm)**, **3.6mm (2mm)** and **8.4mm (4.8mm)** respectively. The expected performance for the long cable case cannot yet be considered to be satisfactory.

Moreover, a particular problem arose during previous light ion runs. An important intensity modulation was observed along the machine

(*) One 14.4 s cycle of the SPS consists of one 9.6 s 450(400) GeV/c cycle for protons or ions and four 1.2 s 3.5-20GeV/c cycles for leptons(electrons and positrons). Multicycling is the term used to describe the mode changes for many equipment between the various elementary cycles.

circumference. This in itself is not detrimental to the performance but unfortunately, the modulation was not stable from injection to injection. Therefore, even after careful set-up, data sampling occurred randomly in dense and less dense beam portions. To avoid these accidents we decided to incorporate after the homodyne receiver a low pass filter. This serves two purposes :

- smooth out the effect of intensity modulation along the circumference.
- reduce the noise bandwidth, hence increase the resolution also for the long cables.

The choice of the filter bandwidth was governed by injection considerations. Indeed it seemed interesting to preserve a maximum resolution for the injected beam so that a trajectory measurement is possible. The beam from the injector, the CERN PS, is delivered in four injection cycles. The duration of one injected beam (batch) is 2μs, the revolution period of the injector. The low pass filter should safeguard a maximum amount of information concerning this batch. It is easy to convince oneself that the low pass filter characteristic that matches best the $\sin(x)/x$ spectrum of the batch, has a break point frequency of:

$$f_{lp} = \frac{1}{\pi\tau} = 0.16\,\text{MHz} \quad . \qquad (6)$$

This yields an extra linear resolution factor of ~3.5. The set of *trajectory* resolution figures for short, medium and long cables become finally: **0.6mm(0.35mm)**, **1mm(0.6mm)** and **2.4mm(1.4mm)**. The *orbit* resolution figures are **0.1mm(0.05mm), 0.17mm(0.1mm)** and **0.4mm(0.2mm)**. It should be noted that the noise filter has to be operated in multicycling mode so that the operation with the dense lepton bunches is not impaired.

V.RESULTS OBTAINED AND CONCLUSION

In December 1994 the SPS has injected and accelerated lead ions. The intensities gradually increased during the operation period. This allowed a check of the orbit measurement system under different conditions.

In a stable (from an intensity point of view) operation period, a number of monitors were logged for typically a few 100 cycles. The resolution of the system was defined as the r.m.s. spread in the measured positions. The variations in the horizontal plane were not taken into account since they were caused by real position changes between cycles (rf causes small changes in beam radial position from cycle to cycle). A few typical data sets are shown in Table 1, the summary of all data sets is shown in Table 2.

TABLE 1: Example of data set for long, medium and short cable.

BPM	N	Intensity	r_m	r_e	r_m/r_e
		10^9	μm	μm	
2.01	560	43	90	78	1.15
2.09	560	43	40	33	1.2
5.19	210	32	150	200	0.75

BPM : name of monitor
N: number of orbit acquisitions
$r_{m,e}$: resolution (**m**easured, **e**xpected)

TABLE 2: Summary of resolution measurements

Mode	number of sets	average r_m/r_e	spread in r_m/r_e
NR	25	0.92	0.43
HR	3	0.95	0.4
HR + F	7	1.56	0.47

NR: normal without low noise preamplifiers
HR: high resolution with preamplifiers
HR+F: high resolution with preamplifiers and filter

The intensity in the Table 1 assumes that the intensity all around the machine is equal to the intensity of the small beam portion (200ns) that is sampled. The real charge in the machine is less than that since the real charge distribution is not uniform.

As can be seen from the Table 2 there is quite a good agreement between the measurements and the expected resolution for the normal case and the high resolution case without noise reduction filter. The performance of the noise reduction filter is low by a factor **1.6**. This in fact confirmed laboratory measurements made shortly before the ion physics run. Indeed, we had noticed that the filter branch of the digitising unit has an unusual high noise level. For total preamplifier gains larger than 70 dB this phenomenon caused no problem since the amplified noise is larger. However, in practice the ion intensities were higher than expected and a gain setting of 70 dB was used where the theoretical performance could not be achieved. Of course, this situation is not satisfactory. This technical problem will be corrected.

A second problem has been known for some time. Auxiliary building 3 houses the 200 MHz acceleration system. The rf power is generated in the building (where also the orbit processing electronics is located) and is sent down to the travelling wave cavities in high power coaxial lines. Both the rf system (a few **MW**) and the orbit system (several **pW**) operate at 200MHz.

For quite a few monitor stations signal pick up occurred in the (small signal) Δ channel at a level that made a proper measurement impossible. We were not able to establish clearly at what point the pollution occurred since *good* and *bad* monitors are randomly distributed with respect to their physical position in the tunnel but also with respect to the fact whether they are equipped or not with normally shielded cables or very well shielded cables.

The implemented modifications were worth the effort, notwithstanding the two problems that were met. The full resolution (full performance with filter and pre amplifiers) possibilities were successfully exploited in the kicked tune measurement up to the highest beam momenta.

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