Bunch Intensity Measurement During Injection and Acceleration in the SPS Collider

by

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1) Introduction

During the complicated procedure to transfer antiprotons from the antiproton accumulator into the SPS it is essential to measure the transmission losses.

For the intensity measurement system in the SPS this means the following: the intensity has to be measured in the first turn after injection, by comparing this with the intensity from the CPS one knows the losses in the transfer-channel between the two machines. Particle losses in the SPS occur either directly after injection; at RF-Capture (10 - 20 ms after injection); along the flat bottom (where the machine stays at the injection energy of 26 GeV to inject all bunches) and during the energy ramp from the injection energy to the energy of 315 GeV. On the top energy the focusing of the beams in the interaction region is enhanced, this takes about 2 seconds and can also produce losses.

At injection mainly two mechanisms can cause a loss: either the alignment of the injected beam is bad and losses occur in the first few turns or the bunches are not properly injected into the RF-buckets. This can be detected a few milliseconds later by an electronics with a suitable band pass filter. Therefore the intensity of each individual bunch is measured every turn for 1000 turns after injection. During the ramp and the flat top the losses are detected by measuring each individual bunch at intervals of about 20 ms until the beams are coasting.

The different behavior of the different bunches require individual measurements for all 6 (in the future 12) bunches. Four similar systems were installed: two systems measuring the intensities of the protons and the antiprotons during the first thousand turns and two systems for the intensity measurement until the beams are coasting.

Precise intensity measurements are also needed, together with beam size measurements at the interaction point, to evaluate the luminosity. The beam sizes can be measured either with existing beam profile monitors or (at least in the horizontal plane) by a so-called Van der Meer scan /1/.

In this paper the hardware and the software of the intensity measuring system is described. Then it is demonstrated how the calibration is
done and finally the operational results are presented.

2) The layout of the hardware

Fig. 1 shows the components of the system:

The bunch signal is derived from a directional coupler, which has four orthogonal strips in a cylindrical vacuum chamber /2/. These pick-ups are normally used for position measurements. The directivity is necessary for the measurement of the weak antiproton bunches ($10^8$ particles) in the presence of proton bunches ($10^{11}$ particles). Coaxial relays select one end of the coupler and connect it to the cables which take the signal to the auxiliary building. To obtain a position independent intensity signal, the output of opposing strips is summed in a hybrid, a third hybrid produces the sum of the sums.

The signal produced by the directional coupler is bunch length dependent. This is minimised by the signal processing electronics. The receiver shown in Fig.1 works in the following way. The signal is passed through a narrow band 20 MHz filter. The resulting oscillation is amplified by a programmable amplifier and passed through a second filter /3/. The envelope of the oscillation is then detected by a synchronous demodulator. The pulse height of the output pulse is proportional to the bunch intensity.

This pulse is then sampled by a peak-hold sampler with a 400 ns wide window. The timing window is programmable in 100 ns steps relative to the SPS-revolution trigger signal. This allows the equipment to select the bunch to be measured. The output of the peak/hold unit is converted by a fast successive approximation Analog- Digital- Converter, with 12 bits resolution and 6 microseconds conversion time. This intensity value is stored in a buffer memory which can hold up to 1000 values. The memory allows the equipment to measure the bunch intensity every revolution (23 microsec) for 1000 consecutive turns.

The start of the acquisition of a block of data is triggered by event pulses generated by the SPS-timing system.

Each measurement system is based on a Motorola 6809 microprocessor using a G64-bus /4/. To allow the operator in the main control room to use the equipment, it is interfaced to the SPS-MPX-system. This is an input-output port to a NORD-100 computer of the SPS computer network.

3) The layout of the software

The programs which were developed for the control of the electronics and for the analysis of the data have a threefold purpose: They have to define the hardware status, to read the data and to display the data.

The status of the hardware includes the following parameters:
- the timing-setting of the gates, in which the bunch pulses are expected.

- the gain of the amplifiers which is calculated from the expected intensity

- the acquisition start time of the measurement. For the measurement of the intensity along the first 1000 turns this time has to be some milliseconds before the injection. For the measurement until the beams are coasting this time can be programmed as well as the time interval between acquisitions.

From the SEQUENCER /5/, which is a set of programs which organizes the antiproton transfer, these parameters are automatically set to the necessary values. After the injection the SEQUENCER launches a program to read the data and to display the bunch intensities versus time.

4) The calibration of the system

The pulse height measured with the analog digital converter is proportional to the intensity.

The proportionality factor is determined in the following way:

First the total circulating current is measured with a D.C. beam current transformer (BCT) similar to that developed for the CERN Intersecting Storage Rings /6/. The BCT consists of a toroidal coil around the beam. The beam induces a current in this coil. The BCT is calibrated by injecting a current opposite to the beam current into a one turn calibration winding. When both currents cancel each other the beam current is known to have the same value as the applied current of the current source which is known very accurately. The beam current is then known to an accuracy of about 0.3%.

If only one proton bunch is injected, the total current is concentrated in only this bunch. At the bottom energy protons can nevertheless spill out of the bucket. This reduces the bunch intensity without a change of the total current. On the energy ramp the number of particles in the bunch and the total number of particles is the same, because the protons outside the bucket are lost. When both values are measured at the same time during the energy ramp the calibration factor can be calculated. The accuracy of the calibration of the number of protons in a bunch is about 1%.

There are two mechanisms which can produce low intensity spurious bunches and therefore spoil the calibration. Firstly, it can happen that spurious bunches are injected from the CPS (CERN Proton Synchrotron). This comes from a non perfect operation when the harmonic number is changed from 20 to 6 and not all bunches are suppressed at 3.5 GeV. These bunches are 350 ns apart and can be eliminated by appropriate firing the injection kicked. Secondly, if the injected bunch is too long, its tails will be captured in an adjacent bucket in the CPS. These bunches have to be looked for on dedicated fast oscilloscopes used in the RF-Instrumentation.

After measuring the calibration factor for the protons the calibration for the antiprotons is done in the following way:
Once the equipment is calibrated with protons the equipment is switched over to measure the antiproton intensity. This can simply be done by connecting the cables to the other end of the directional coupler and to change the timing window in the electronics. As the directional coupler is made to very high mechanical precision it can be assumed to have the same sensitivity to antiprotons as to protons. Using the calibration factor already determined for the protons the number of antiprotons is known. This leads to an accuracy in the number of antiprotons of about 2%.

5) Operational results

Fig. 2 shows the result of a good antiproton transmission in the SPS. The transmission efficiency from injection to coast in the SPS in this case is greater than 90%. (The overall transmission from the antiproton accumulator to coasting beams in the SPS was about 80%.) In the case of a bad transmission the displayed intensity data help to identify the reason of the losses. Fig. 3 shows an antiproton injection when the antiprotons were not injected into the right bucket. This kind of loss is typical for a badly synchronized RF between the CPS and the SPS. In the case shown in Fig. 4 a loss during the first seconds occurred. This indicates a too high betatron tune. Because of the large tune spread at low energy some antiprotons are driven on to the forth order resonance and lost.

The measurement is made automatically whenever antiprotons are transferred to the SPS. The data is stored and can be analyzed at any time after the antiproton transfer.

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/4/ G64 is a registered trademark of GESPAC Geneva Switzerland
Fig. 1) Layout of the intensity measurement equipment

The equipment for the injection intensity measurement is called BINJ (Bunch Intensity at Injection).
The equipment for the measurement during the energy ramp and on the flat top is called BICY (Bunch Intensity during the Cycle).
Fig. 2) Injection and cycle intensity of the antiprotons

In this figure a good transmission of the antiprotons is shown. The intensity along the first 1000 turns is displayed for three antiproton bunches in A, B, and C. The losses are negligible. D, E, and F show the intensities from injection until the bunches are coasting. The total losses are smaller than 6%. The three bunches are injected into the CPS with a time difference of 0.4 seconds. The horizontal scale is given in turns for A, B, and C and in milliseconds for D, E, and F. The vertical scale is given in units of $10^6$. 
Fig. 3 | Injection and cycle intensity of the antiprotons

This figure illustrates a bad injection into the RF-bucket. During the first 1000 turns in A, B and C about 10% of the antiprotons are lost. The oscillating signal to be seen can be produced by:

a) Uncaptured particles drift along the machine with respect to the bunch center.

b) Strong changes of the longitudinal shape of the bunch because of the bad injection.

In addition, also along the energy ramp particles are lost. (D, E and F, vertical scale in arbitrary units)
Fig. 4) Injection and cycle intensity of the antiprotons

The injection transmission in this case is reasonable in A, B and C. Antiprotons are lost at injection energy during the first seconds (D, E and F). This indicates a too low betatron tune.