SYNCHRONOUS RF-RECEIVERS FOR BEAM POSITION AND INTENSITY MEASUREMENTS AT THE CERN SPS COLLIDER

R. Bossart, J.P. Papis, V. Rossi

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN), 1211 GENEVE 23 SWITZERLAND

Summary

In view of new modes of operation of the SPS, the old superheterodyne receivers designed for the closed orbit measurements of fixed target beams are being replaced by homodyne 200 MHz receivers with a better time resolution for measuring single bunches. The new receivers have a bandwidth of 4 MHz, a dynamic range of 70dB, and are able to measure the position either of continuous beams with 10^{12} to 5×10^{13} ppp bunched at 200 MHz CW for fixed target physics, or of single bunches shorter than 5ns with 10^9 to 2×10^{11} particles per bunch when the SPS is used as a ppbar collider or as an e^+e^- injector for LEP. The homodyne receiver has been chosen for its simple layout, linearity, excellent noise immunity and high accuracy of the beam centre position. The built-in calibration facility using the intensity signal of the beam allows to calibrate all 240 receivers and acquisition systems of the closed orbit measurement for zero offset errors to less than 5×10^{-3} of the monitor radius and for relative gain errors to less than 4×10^{-2} . The same synchronous receivers, but running at 20 MHz and 50 MHz, are also used for intensity and lifetime measurements of the SPS collider.

Need for new receivers

The three past years of successful collider operation of the SPS have shown that the closed orbit must be corrected not only at injection but mainly in the regions of the low-beta insertions during coasts at 315 GeV/c lasting up to 24 hours. Slow drifts of the closed orbit have appeared during the coast, causing a detuning of the machine. Furthermore when the SPS becomes an e^+e^- injector for LEP, the closed orbit must be corrected for the whole e^+e^- cycles in order to minimise the synchrotron radiation.

The old 216 superheterodyne receivers¹ installed in the accelerator ring together with the electrostatic pick-ups, had been designed for measuring the continuous 200 MHz signals of fixed target beams which fill the ring nearly completely. In collider operation, only a few, but dense single bunches of protons and antiprotons (3×10^{13} ppp) collide from opposite directions in the experimental underground areas. Unfortunately the old receivers had a too low intermediate frequency and did not allow to observe single bunches passing from opposite directions at short intervals. The intermediate frequency of 1.8 ± 0.1 MHz had been chosen to use a cheap transmission cable from the tunnel to the auxiliary buildings where the IF demodulators were housed. The closed orbit of the collider therefore could be measured and corrected only with a special test beam of 20 bunches with a total length of 2 μ s.

Nevertheless, the beam position of single bunches could be measured by 16 directional couplers installed in 1981. Two groups of 4 couplers have been installed in the two low-beta regions of the collider. Both the horizontal and vertical beam position could be measured there by means of a wideband superheterodyne receiver, a fast sample and hold circuit, and a dedicated acquisition system².

In 1982 non-expensive low-loss coaxial cables have been installed between all 216 beam position monitors and the auxiliary buildings, so that all receivers could be removed from the radioactive environment of the tunnel to the auxiliary buildings, where the maintenance and repair are easier.

Among the different alternatives for a new wideband RF-receiver, the homodyne 200 MHz receiver has been adopted because it is the simplest and cheapest solution with the best accuracy of the beam centre position of protons. The homodyne receiver detects directly the amplitude envelope of the RF-signals Σ and Δ . The frequency of measurements has been maintained at 200 MHz, because the position measurement must work also in the future with continuous beams bunched at 200 MHz. Fortunately, the old plug-in units with the matched bandfilters 200 ± 2 MHz could be used again, since its bandwidth allows measurement of two bunches with a minimum time separation of 0.7 μ s.

For the measurement of the intensity of single bunches, a lower frequency must be adopted for the homodyne receivers in order to get a constant sum signal for varying bunch lengths. In order to observe the RF-capture losses at injection and during acceleration, the bunch intensities are now measured by two 20 MHz homodyne receivers which provide a precision of 1% during injection and acceleration. Since 1981 the intensity and lifetime of all individual p and pbar bunches are measured by two 50 MHz receivers, which are insensitive to those fractions of beam spilled out of the master bucket into the two adjacent buckets. The adjacent bunches are rejected by the synchronous detector because of their phase error of 90° at 50 MHz with respect to the master bunch.

For the intensity measurements two directional couplers BPNB (Fig.1) are used. It is a unique feature of the directional coupler to provide separate signals of two beams propagating in opposite directions³. Due to the directivity of 40dB the directional coupler BPNB is an ideal monitor to measure weak antiproton bunches of $0.5\text{--}2 \times 10^9$ pbar in the presence of dense proton bunches of $1\text{--}2 \times 10^{11}$ p, especially when a fraction of protons spill out of the RF-bucket⁴.

Homodyne 200 MHz receiver

The beam position is proportional to the difference Δ of the signals A and B from opposite electrodes of the electrostatic position monitors BPV and BPH. For these linear position monitors, the beam position y is calculated from: $y = a(A-B)/(A+B) = a\Delta/\Sigma$, wherein a is the aperture factor of the monitor. In order to obtain the best possible accuracy of the beam position centre, the vector sum Σ and difference Δ of the monitor signals A and B are formed directly by a hybrid ring installed close to the monitor. The π -hybrid rings provide an excellent isolation $\Delta/\Sigma < 5 \cdot 10^{-3}$ for equal inputs $A=B$ at 200 MHz. The sum and difference signals of the π -hybrids are transmitted by coaxial cables to the auxiliary buildings where the homodyne receivers are housed (Fig.2).

The two RF-signals are passed first through two matched bandpass filters 20012 MHz, which respond to a single bunch signal by a 200 MHz RF-burst 200ns wide ². The RF-bursts are detected by the homodyne receiver in the same way as the 200 MHz CW-signals in fixed target operation. The gains and zero offsets of the sum and difference channel of the receiver can be calibrated by the beam signal directly. In the calibration mode, the coaxial switches disconnect the RF-signal Δ in order to measure the zero offset of the receiver and data acquisition system. Then the RF-signal $\Sigma/2$ is connected also to the difference channel, and the ratio Δ/Σ gives the calibration factor of the relative gains. Due to this calibration facility of the receiver and data acquisition by the beam itself, the position of the beam is measured with an accuracy of 0.5% f.s. $\pm$ 4% rel.. The centre precision of 0.5% full scale is determined by the hybrid rings.

The sum and difference channels of the receiver comprise each a programmable RF-amplifier 0-70 dB (Fig.2). The gain is programmable by computer in steps of 14 dB depending on the beam intensity. The output of the Σ -amplifier (max. level 0 dBm) drives a hard limiter for the synchronous detection of both the Σ and Δ signals. The hard limiter consists of 4 cascaded RF limiter-amplifier integrated circuits, each having 12 dB gain. The phase shift of the limiter output at 200 MHz is very low and amounts to $\pm 2^\circ$ for a dynamic range of 35 dB. Thanks to this excellent and non-expensive hard limiter, the 200 MHz-signals can be demodulated by a homodyne mixer which provides the amplitude envelope of the 200 MHz-signal at the output of the lowpass filter.

The S/N-ratio of the difference channel is improved by the synchronous detection. The immunity of the 200 MHz receivers to external noise caused by power rectifiers allows for a reproducibility of 20 μ m of the beam position measured (table 1).

The synchronous receiver also rejects phase errors φ between the signals of the electrostatic pick ups ¹. For protons and positrons the flight time of beam between the two electrodes has been compensated by different cable lengths between the electrodes and the hybrid ring, but for antiprotons and electrons a phase error $\varphi=38^\circ$ exists between the two signals at the input of the hybrid ring. Since the Δ and Σ cables between the hybrid ring and the receiver have a relative phase difference $\gamma=2...5^\circ$, the centre position of the measurement is shifted by an error ΔX for antiprotons and electrons:

$$\Delta X = 0.5a \sin\varphi \sin\gamma = 1...2\text{mm}.$$

Signal acquisition by gated peak detector, V/F-converter and scaler

In collider mode any single bunch can be selected by a gated peak detector for the closed orbit measurement. A timing gate derived from the revolution frequency of the beam, sets the sample hold module in the tracking mode during 1 μ s. When the bunch signal Σ arrives, an autotrigger working on the peak value of the sum signal Σ sets the S/H into the hold mode. In this way the peak values of Σ and Δ are held for every beam revolution until the next passage of the bunch. The injection trajectory is measured by sampling only the first turn of beam.

For continuous beams for fixed target physics, the autotrigger circuit is disabled, and the beam position can be measured for a sample of beam 200ns long. The sampling gate can be displaced by delaying

the revolution frequency in steps of 100ns for all monitors together along a revolution period of 23 μ s. In order to measure the same sample of beam at all monitors, the sampling signal for each monitor is delayed individually by an adjustable digital delay according to the propagation delay of the beam signals.

The output signals Δ and Σ of the S/H-modules are fed directly to 5 MHz voltage-to-frequency converters, which drive the CAMAC-scalers. The scalers count during 1ms and are read out by a real time computer programme, which calculates the beam position for all 216 beam monitors ³.

Technical specifications of position measurement

receiver frequency : 200 $\pm$ 2 MHz
 programmable gain of receiver : 0.(14).70 dB
 dynamic range of hard limiter : 35 dB
 phase error of hard limiter : $\pm 2^\circ$
 receiver input noise : $N_i=1 \times 10^{-11}$ Watts
 dynamic range of autotrigger : 40 dB
 time delay of autotrigger : $\pm$ 20ns
 linearity of sampled/hold : $\pm$ 1%
 range of beam intensities
 - 200 MHz CW beam : $2 \times 10^{10}...6 \times 10^{13}$ ppp
 - single bunch 5ns long : $3 \times 10^9...9 \times 10^{11}$ ppb
 aperture factors "a" of beam position monitors
 - horizontal el. stat. BPH : a = 82mm
 - vertical el. stat. BPV : a = 46mm
 - directional coupler BPN : a = 23mm
 accuracy of centre position : 0.005 $\cdot$ a max.
 linear error of position measurement :
 0.017 $\cdot$ y rms; 0.04 $\cdot$ y max. (y=beam position)
 position resolution with gate 1ms : $4 \times 10^{-4} \cdot a$
 position resolution with gate 20ms : $2 \times 10^{-5} \cdot a$
 reproducibility with gate 1ms : $4 \times 10^{-4} \cdot a$
 reproducibility with gate 20ms : $10^{-4} \cdot a$

Operational experience

During the SPS shut-down in January 1985, 160 receivers and peak detectors have been installed in four auxiliary buildings. The two remaining sextants of the SPS will be equipped during this summer. The new equipments have proven reliable and accurate during the pulsed collider operation in March 1985. At the very first beam test of the new receivers, the closed orbit has been corrected in four sextants at injection from 8mm peak amplitude vertically to less than 0.5mm for 66 out of 70 monitors without any iteration.

Four new receivers and peak detectors have been used also to measure the amplitude and phase of bunch oscillations of 20...40 μ m amplitude induced by the damper for the tune measurement of the machine in the low-beta insertion regions. With the low-beta insertions off, bunch oscillations of 20 μ m have been measured at two different monitors during 430 beam revolutions by a FFT-spectrum analyser with a relative precision of 5% in amplitude and 3° in phase.

In pulsed collider mode, the same bunches 2px1pbar are accelerated to 450 GeV/c and decelerated to 100 GeV/c for hours. The measurement of the vertical closed orbit at three different energies during 10 cycles in table 1 shows, that the closed orbit changes with energy and that the position measurement for a fixed energy is perfectly reproducible within the resolution of the equipment. The standard deviation of the position measurements is equal or less to 12 μ m for a directional coupler BPN ($\emptyset$ 93mm, a = 23mm).

Table 1 : Vertical beam position of first bunch measured during pulsed collider operation 100-450 GeV/c by directional coupler BPN 22303 at three energies during 10 cycles on 3.4.85.

flat bottom 100 GeV/c		flat top 450 GeV/c		deceleration 350 GeV/c	
$\Sigma 1$	X1(mm)	$\Sigma 2$	X2(mm)	$\Sigma 3$	X3(mm)
1047	3.239	1036	2.091	974	-.145
1047	3.216	1035	2.093	973	-.121
1047	3.239	1035	2.070	972	-.145
1047	3.239	1034	2.118	972	-.121
1046	3.242	1034	2.095	971	-.121
1045	3.245	1032	2.099	971	-.121
1044	3.225	1032	2.099	970	-.121
1044	3.225	1031	2.078	970	-.145
1043	3.229	1031	2.101	969	-.121
1042	3.232	1030	2.103	969	-.121

MEAN POS X1 = 3.233mm STD DEV X1 = .008mm
 MEAN POS X2 = 2.095mm STD DEV X2 = .012mm
 MEAN POS X3 = -.128mm STD DEV X3 = .011mm

The lifetime τ of the first proton bunch measured in table 1 can be calculated from the time decay of the intensity signal Σ after n cycles :

$$\tau = \frac{\Sigma_0}{\Sigma_0 - \Sigma_n} \times nT = \frac{1047}{1047-1042} \times 9 \times 21.6' \approx 11 \text{ hours}$$

The sum signals Σ and beam positions X in table 1 have been measured with a scaler gate opened during lms. A gate width of 20ms provides even better resolutions. The sum signals $\Sigma 1$, $\Sigma 2$ and $\Sigma 3$ are not constant, because the bunch length varies during the cycle.

References

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Fig.1 DIRECTIONAL COUPLER

Fig.2 BLOCK DIAGRAM OF POSITION MEASUREMENT