Synchronous receiver for closed orbit measurement

of single bunches

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

1. Introduction

A synchronous receiver 200 MHz was developed in 1973 and was tested at Daresbury DNPL. The synchronous receiver was not retained for the closed orbit measurement of the SPS at that time for two reasons: the output amplifiers (IC op amps) were not radiation resistant in the electronic pits of the tunnel, and the zero crossing detector (GPO 400) had not enough dynamic range and phase stability.

In the meantime, cheap low loss coaxial cables CK-50 have been installed in the tunnel, so that the electronic equipments could be removed from the tunnel to the auxiliary buildings. Recently hard limiters (Plessey SL 532 C) with excellent phase tracking have become available as zero crossing detectors at 200 MHz. Due to the cheap hard limiters, the homodyne receiver 200 MHz has become an interesting alternative again for closed orbit measurement.

Like the superheterodyne receiver, the homodyne receiver is working with the existing 180° hybrid rings providing an excellent accuracy of < 0.5" for the centre of the closed orbit. The homodyne receiver is much less sensitive than a phase detector to phase or amplitude errors between the pick-up electrodes and the detector. There is no need for a calibrator or other electronics in the tunnel in the case of the homodyne receiver.

2. Signal power of electrostatic pick-ups

The output voltage \( U \) of the electrostatic pick-ups for a well centered beam is proportional to the beam current \( I \) and to the transfer impedance \( Z_t \), which is given by the geometry of the electrodes

\[
U = Z_t \cdot I
\]

\( Z_t = 6.6 \ \Omega \) for BPH, beam position horizontal

\( Z_t = 6.3 \ \Omega \) for BPV, beam position vertical

1) R. Bossart and H. Rossi, Test of beam position monitors at DNPL, LAB II-CO/RB/73-48

2) S. Battisti, R. Bossart, H. Schünbacher. H. van de Voorde, Radiation damage to electronic components, CERN 75-18

3) R. Bossart, Influence des erreurs de phase sur l'orbite fermée mesurée avec un récepteur synchrone, SPS/ABM/83-06V0700G.
The beam current $I$ is proportional to the number of particles $N$ and to the Fourier component $b$ of the beam intensity at 200 MHz:

$$ I = N \cdot e \cdot f \cdot b \quad e = 1.6 \cdot 10^{-19} \text{As}, \; f = 43.3 \text{kHz} $$

For a cosine shaped bunch of length $T$ measured at the base of the bunch, the Fourier component $b$ at 200 MHz is given by

$$ b = \frac{2 \cos \left( \frac{\pi T}{5 \text{ns}} \right)}{1 - (2 \frac{T}{5 \text{ns}})^2} $$

The bunch length of fixed target beams is about 3 ... 4 ns. For single bunches p/p, the bunch length shrinks during acceleration from 5 ns to 1 ns. Electron bunches are very short $\sim 0.1$ ns.

The Fourier component $b$ of a cosine shaped bunch of length $T$ amounts at 200 MHz to:

<table>
<thead>
<tr>
<th>$T$ [ns]</th>
<th>0.1</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>2.00</td>
<td>1.93</td>
<td>1.72</td>
<td>1.41</td>
<td>1.04</td>
<td>0.67</td>
</tr>
</tbody>
</table>

The signal voltage $U$ and the power $S$ of the electrostatic pick-ups BPH amount for a fixed target beam of $5 \times 10^{13}$ ppp injected in two batches and a bunch length of 3 ns:

$$ U = 1.1 \; Z_t \cdot N \cdot e \cdot f \cdot b = 3.55 \text{V} $$

$$ S = \frac{U^2}{50 \Omega} = 0.25 \text{Watts} \approx 24 \text{dBm} $$

At the arrival in the auxiliary building at the input of the homodyne receiver, the sum signal of the pick-ups is attenuated by $-27 \text{dB} \approx k = 0.045.$

| hybrid ring | + 3 dB |
| cable CK-50 | - 20 dB |
| calibrator  | - 6 dB |
| bandfilter  | - 4 dB |
| attenuation  | - 27 dB |

The signal level of $-3 \text{dBm}$ at the mixer input is just below mixer saturation. At $+1 \text{dBm}$ RF-input and $+7 \text{dBm}$ LO, the signal compression is $-1 \text{dBm}$.

For single bunches, the peak voltage $\hat{U}$ of the RF-burst at the bandfilter output is given by:

$$ \hat{U} = Z_t \cdot N \cdot e \cdot f \cdot b \cdot k / f \cdot w $$

whereas $w = 175$ ns which represents the width of the RF-envelope measured at 50% of the peak amplitude. The factor $f_w = 1/132$ represents the duty-factor of the signal for single bunches. The duty-factor for double batch injection is $2 \times 5/11$.

An antiproton bunch of $N = 10^9$ ppb and $T = 5$ ns bunch length provides at the bandfilter sum output a peak signal $\hat{U}$:

$$ \hat{U} = 0.18 \text{mV}_{\text{rms}} $$

$$ \hat{S} = \frac{U^2}{50 \Omega} = 0.66 \cdot 10^{-9} \text{Watts} \approx -62 \text{dBm}. $$
At this low antiproton intensity \( N = 10^9 \) ppb, an amplifier gain of 56 dB is needed in the homodyne receiver, which has 5 stages of 14 dB fixed gain (5x), see fig. 1.

The electron and positron intensities foreseen for the SPS are in the range \( 0.4 \ldots 2.0 \times 10^{10} \) epb. At \( 10^{10} \) epb the peak signal at the band-filter sum output amounts to:

\[
\hat{U} = 5.4 \text{ mV}_{\text{rms}}
\]

\[
\hat{S} = 0.58 \times 10^{-6} \text{ Watts} = -32 \text{ dBm}
\]

The amplifier gain needed for \( 10^{10} \) electrons/bunch is 2 x 14 dB.

3. Functional description of synchronous receiver

The homodyne receiver consists of 3 elements: the programmable RF-amplifiers, the zero crossing detector and the mixer with a low-pass filter and operational amplifier, see fig. 1.

The programmable 200 MHz amplifier consists of 5 stages with a fixed gain of 14 dB each. Three miniature relays put in parallel with the amplifier modules allow to switch the gain in steps of 14 dB between 0 dB and 70 dB. The gain of the sum and difference channel is equal and depends on beam intensity. The gain must be as high as possible, but shall not saturate the RF-input of the mixer (< -3 dBm).

Taking into account a signal attenuation of 20 ... 32 dB between the electrostatic pick-ups and the input of the calibrator, the following beams can be measured if sufficiently bunched at 200 MHz:

<table>
<thead>
<tr>
<th>RF gain</th>
<th>Fixed target intensity</th>
<th>Single bunch intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 batches, bunch 3 ns</td>
<td>bunch length 5 ns</td>
</tr>
<tr>
<td>0 dB</td>
<td>( 1 - 5 \times 10^{13} ) ppm</td>
<td>( 1.7 - 8.8 \times 10^{11} ) ppb</td>
</tr>
<tr>
<td>14 dB</td>
<td>( 0.2 - 1 \times 10^{13} )</td>
<td>( 0.35 - 1.7 \times 10^{11} )</td>
</tr>
<tr>
<td>28 dB</td>
<td>( 0.4 - 2 \times 10^{12} )</td>
<td>( 0.7 - 3.5 \times 10^{10} )</td>
</tr>
<tr>
<td>42 dB</td>
<td>( 0.8 - 4 \times 10^{11} )</td>
<td>( 1.4 - 7 \times 10^9 )</td>
</tr>
<tr>
<td>56 dB</td>
<td>( 1.6 - 8 \times 10^{10} )</td>
<td>( 2.8 - 14 \times 10^8 )</td>
</tr>
</tbody>
</table>

If the gain needs to be changed during a supercycle between \( 5 \times 10^{13} \) protons and \( 1 \times 10^{10} \) electrons/bunch, only one DPDT-relay needs to be switched in every RF-amplifier. The miniature relays HI-C are very reliable and are guaranteed for a life-time of \( 10^7 \) operations minimum.

The zero crossing detector consists of 4 stages of the famous hard limiter SL 532 C from Plessey. Two RF-transistors are used to drive the LO-input of the mixers. The propagation delay of the zero crossing detector needs to be adjusted exactly to 5 ns between the RF- and LO-input of the mixer.
The RF-signals of the sum and difference channel are demodulated by the mixers, which provide the sum and difference frequency of the RF- and LO-signals. The sum frequency is 400 MHz and is filtered out by the low-pass filter. The difference frequency is a DC-signal which has half the amplitude of the RF-signal. The RF- and LO-signals of the mixer are in phase for the sum channel. Small phase errors $\varphi$ cause very little amplitude errors $\epsilon$ for the homodyne receiver.

$$\epsilon = 1 - \cos \varphi = \varphi^2 / 2$$

The RF- and LO-signal of the difference channel are not necessarily in phase\(^3,4\). The mixer of the difference channel provides at its output only that component of the RF-signal which is in phase (0° or 180°) with the LO-signal and with the sum RF-signal. The orthogonal RF-component of the difference signal is completely rejected.

Broadband noise picked up in the difference channel (CK-50) is filtered out by the low pass filter. This method called synchronous detection allows to measure the centre position of the beam with the utmost accuracy of 0.5% of the half aperture of the monitors, i.e. 0.4 mm for BPH and 0.2 mm for BPV.

For single bunches $p\bar{p}$ and $e^+e^-$, the homodyne receiver works as envelope detector of the 200 MHz burst generated by the bandpass filter at the passage of a single bunch (Dirac excitation)\(^5\).

The demodulated signals are amplified by operational amplifiers with an adjustable gain for a full scale voltage of 1 V. Depending on the cable attenuation CK-50, the gain is adjusted between 14 -- 60 x, so that the demodulator output of the sum signal is 0.500 VDC for all pick-ups, if a 200 MHz CW-signal of -4 dBm is applied to the B-input of the hybrid ring in the tunnel and if the gain of the programmable RF-amplifier is set to 28 dB.

4. Receiver Noise

The programmable RF-amplifiers in front of the mixers are 300 MHz-wideband low noise amplifiers. The monolithic amplifier SL 560 from Plessey has a gain of 14 dB and a noise figure $NF = 4.5$ dB when used in common base configuration. The noise factor $F$ of 4 amplifiers in cascade is given by \(^6\).

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \frac{F_4 - 1}{G_1G_2G_3} = 3.26$$

\(^4\) C. Boccard, J.P. Papis, V. Rossi, Evaluation de l'importance de la phase dans la mesure de position, to be published.

whereas:

\[ F_i = \text{noise factor of stage } i, \quad F_i = 10 \left( \frac{NF}{10} \right) = 2.82 \]

\[ G_i = \text{gain factor of stage } i, \quad G_i = 5 \]

The noise power \( N_i \) referred to the receiver input is proportional to the receiver bandwidth\(^6\) \( f_i = 200 \ldots 300 \text{ MHz} \):

\[ N_i = 4kT F f_i, \quad \text{whereas } 4kT = 1.62 \cdot 10^{-20} \text{ Joule} \]

\[ N_i = 1 \cdot 10^{-11} \text{ Watts} \]

The signal-to-noise ratio \( S_i/N_i \) in the RF-amplifier of the sum channel amounts for an antiproton bunch of \( 10^9 \text{ ppb} \) and \( 5 \text{ ns bunch length} \):

\[ S_i/N_i = 0.66 \cdot 10^{-9}/10^{-11} = 66 \]

The noise of the RF-amplifiers exceeds the trigger threshold of the zero crossing detector, if the amplifier gain is set to 56 dB or 70 dB. In the absence of beam, the noise can be measured at the output of the LP-filter (fig. 1). If the receiver is set to a gain 56 dB, i.e. \( G = 625 \), the noise at the output of the LP-filter with a bandwidth \( f_o = 5 \text{ MHz} \) amounts to:

\[ N_o = N_i G^2 f_o/2 f_i = 4.9 \cdot 10^{-8} \text{ Watts} \]

The sum signal \( S \) of an antiproton bunch of \( 10^9 \text{ ppb} \) and \( 5 \text{ ns bunch length} \) amounts at the LP-filter output

\[ \hat{S}_o = S_i G^2/4 = 6.5 \cdot 10^{-5} \text{ Watts} \]

\[ \hat{U}_o = \sqrt{\frac{S_o}{100 \Omega}} = 80 \text{ mV} \]

The signal-to-noise ratio at the sum output of the LP-filter is improved by the smaller bandwidth \( f_o = 5 \text{ MHz} \):

\[ \hat{S}_o/N_o = 1320 \hat{=} 31 \text{ dB} \]

In the difference channel the signal-to-noise ratio is better by 6 dB since there is no signal splitting in the calibrator as for the sum signal (-6 dB). The convolution of the difference noise with the zero crossing signal reduces the noise by another 3 dB, since only half of the noise signal is in phase with the zero crossing detector, the other half being orthogonal. The signal-to-noise ratio of the difference channel is better by 9 dB and amounts at the receiver output to:

\[ \Delta/N = 40 \text{ dB, for } x = a \]

if the beam were positioned on the vacuum chamber of the monitor, i.e. \( x = a \).

The error caused by receiver noise to the center position of a single turn measurement of an antiproton bunch of \( 10^9 \text{ ppb} \) 5 ns long is therefore 1% rms of the "radius" \( a \) of the vacuum chamber (\( a = 82 \text{ mm} \) for BPH, \( a = 46 \text{ mm} \) for BPV).

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6) Reference data for radio engineers, ITT (1972), p. 27-7

7) R. Bossart, Beam position monitors for antiprotons, SPS/ABM/RE/Report 78-8
The accuracy of the position measurement is furthermore improved by integrating the sum and difference signals in the acquisition system during a time $T$. For the closed orbit measurement the scaler gate (see chapter 7) is opened during $T = 1\text{ ms}$, which reduces the noise error by a factor

$$\sqrt{T \cdot 43 \text{ kHz}} = 6.5.$$ 

With the help of the synchronous detector and the scaler acquisition $T = 1\text{ ms}$, the noise of the closed orbit measurement is reduced to $0.005 \cdot a$ for an antiproton bunch of $3 \times 10^8 \text{ ppb}$ $5\text{ ns}$ long.

5. **Calibrator and bandfilter $200 \pm 2\text{ MHz}$**

There is no modification necessary for the electronic equipment in front of the homodyne receiver. The plug-in unit SPS 2202 from LTT can be used furthermore at its present place. The calibrator allows to calibrate the zero offset and the gain of the electronic equipment. The zero offset of the electronics can be calibrated with an accuracy of $10^{-3}$, i.e. $0.08 \text{ mm}$ in the horizontal plane and $0.04 \text{ mm}$ in the vertical plane. The relative error of the calibration is $1.7\%$ typically, $4\%$ maximum of the beam position.

The bandfilter $200 \pm 2\text{ MHz}$ serves for two purposes. For fixed target beams, the higher harmonics $400\text{ MHz}$, $600\text{ MHz}$ etc of the beam signal must be filtered out. For single bunches, the pick-up signal is reduced in amplitude and stretched in time: a Dirac pulse at the input of the bandfilter $200 \pm 2\text{ MHz}$ excites at its output a $200\text{ MHz}$ burst of about $500\text{ ns}$ duration$^8)$. The envelope of the $200\text{ MHz}$-oscillation is the same as for a $2\text{ MHz}$ low pass filter. The peak amplitude and the integral of the RF envelope are both proportional to the pick-up signal. $1\mu\text{s}$ after the signal peak the transient response of the bandfilter decays to $2\%$ of the peak amplitude.

The attenuation of the coaxial cables CK-50 varies between $10$ and $30\text{ dB}$. RF-attenuators have been put in series with the short cables for a minimum attenuation of $20\text{ db}$ necessary for beam intensities up to $5 \times 10^{13}\text{ ppb}$. For 5-batch injection of $5 \times 3 \times 10^{13}\text{ ppb}$, the sum signal of the pick-ups must be attenuated by $30\text{ dB}$ in order to avoid saturation of the receiver.

6. **Gated Peak Detector**

The gated peak detector holds the peak signal of the single bunch until the next bunch arrives. Two sample-hold amplifiers (S/H) are used for the sum and difference signal, see fig. 2.

The peaking of the sum signal is detected by a slope discriminator. During the rise of the sum signal, the output of the discriminator is high. Immediately after the peaking of the beam signal, but at least after half of the delay time between the two comparator inputs, the comparator output goes low. The transition of the comparator triggers the flip-flop FF into the hold mode. The flip-flop controls the mode of the sample-hold amplifiers for single bunches. For fixed target beams, the sample-hold amplifiers are permanently in the tracking mode.

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8) R. Bossart et al., Beam position measurement for proton-antiproton operation in the SPS, Proc. XIth Int. Conf. on High Energy Accelerator 1980, p. 486.
The single bunch to be measured is selected by the timing system at every beam revolution. The two bunch selectors for the positive and negative beams are common for all pick-ups of the same sextant. The individual delays between the pick-ups and the sample-hold amplifiers are adjusted by two variable one-shots (OS) in every peak detector module. The mode flip-flop (FF) is set to the tracking mode by a clear from the one-shots briefly before the bunch arrives. It is important that the clear of the flip-flop covers the first 10% of the signal raise, otherwise the flip-flop can be triggered by noise. The slope discriminator triggers on the peak with a time delay of 20 ... 60 ns for peak amplitudes $E = 0.3 ... 10 \text{ Vpk}$. If necessary the time lag of the sampling can partly be compensated by delay lines $\sim 40$ ns put at the input of the sample-hold amplifiers.

It is not possible with electrostatic pick-ups to measure the beam position of colliding beams in the intersection zone. A minimum time interval of 0.5 $\mu$s between positive and negative single bunches is required for a proper measurement. This constraint for colliding bunches is imposed by the transient response of the bandfilter $200 \pm 2 \text{ MHz}$ and by the slew-rate of the sample-hold amplifiers. The gated peak detector will be mounted in a plug-in module and installed at the place of the demodulators SPS 2205 actually in use. The synchronous receiver plug-in modules will be installed in place of the superheterodyne receivers SPS 2203.

7. Signal Acquisition

The existing signal acquisition consists of a voltage-to-frequency converter (10 V - 5 MHz) and a CAMAC-scaler (16 bits), both for the sum and difference channel. This system has proven to be reliable and excels by its high accuracy and resolution. The beam position (Pos.) is calculated by the computer from the sum $\Sigma_1$ and difference $\Delta_1$ measurements taking into account the calibration measurements $\Delta_3$, $\Delta_2$ and $\Sigma_2$:

$$
\text{Pos} = C \times \frac{(\Delta_1 - \Delta_3)}{\Sigma_1} \times \frac{\Sigma_2}{2(\Delta_2 - \Delta_3)} \\
\text{aperture factor} \quad \text{measurement} \quad \text{gain cal.} \quad \text{factor}
$$

The details of the calibration procedure are described in the blue instrumentation manual, chapter 1.9) and also in 10).

A new software package will be written in order to calibrate all electronic equipments sextant by sextant during one single machine cycle.

9) V. Rossi, SPS beam position measurement, 1.C2.7, 1.D.1.17
10) R. Bossart and M.C. Crowley-Milling, Technical specifications for electronic equipment of beam position monitors, Lab II-CO/SPEC/73-21
Due to the gated peak detector, closed orbits as well as single turn trajectories can be measured without any modification of the existing acquisition system consisting of V/F converters and CAMAC scalers. The single turn measurement will be used at injection to minimize the injection errors and to measure the integer value of Q. The single turn measurement allows also to check the betatron functions in the low-beta insertions.

The stability of the V/F converters is $3 \times 10^{-5}$/hour and can be fully exploited only if the closed orbit is measured during 20 ms. If the scaler gates are opened for 20 ms, the resolution of the acquisition system is $2 \times 10^{-5}$ and the reproducibility of the beam position measurement is $10^{-4}$, i.e. 8 μm in the horizontal plane and 4 μm in the vertical plane.

8. Performance Summary of synchronous receiver

a) accuracy of center position $\frac{0.005 \cdot a}{\text{max.}}$
   accuracy of horizontal center position $\frac{0.4 \text{ mm}}{\text{max.} \ (a = 82 \text{ mm})}$
   accuracy of vertical center position $\frac{0.2 \text{ mm}}{\text{max.} \ (a = 46 \text{ mm})}$

b) resolution of position with gate 1 ms $\frac{4 \times 10^{-4} \cdot a \text{ max.}}{}$
   resolution of position with gate 20 ms $\frac{2 \times 10^{-5} \cdot a \text{ max.}}{}$

c) reproducibility of position with gate 1 ms $\frac{4 \times 10^{-4} \cdot a \text{ max.}}{}$
   reproducibility of position with gate 20 ms $\frac{10^{-4} \cdot a \text{ max.}}{}$

d) linear error of position measurement
   $(y = \text{beam position})$
   $\frac{0.017 \cdot y \text{ rms}}{}$
   $\frac{0.04 \cdot y \text{ max.}}{}$

e) dynamic range of receiver
   200 MHz CW beam 3.5 ns at base $70 \text{ dB max.}$
   single bunch 5 ns at base $2 \times 10^{10} \ldots 6 \times 10^{13} \text{ ppp}$
   $3 \times 10^{8} \ldots 9 \times 10^{11} \text{ ppb}$

f) receiver input noise, $N_i$
   $1 \times 10^{-11} \text{ Watts}$
   minimum intensity for 0.5% of a closed orbit error caused by noise:
   - 200 MHz CW beam 3.5 ns with gate 1 ms $2 \times 10^{10} \text{ ppb}$
   - single bunch 5 ns with gate 1 ms $3 \times 10^{8} \text{ ppb}$

Distribution list:

ABM Group
Scientific Personnel SPS
LEP Instrumentation Group