Multibunch Phase Detection in DESY III

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Abstract

To detect individual bunch phase oscillations a standard toroidal intensity monitor with about 30 MHz bandwidth is used. The bunch selection is done with track & hold devices. At DESY III the revolution frequency changes by a factor of 3 due to the momentum change. To manage this variation, the beam signals are converted up to a fixed intermediate frequency of 60 MHz. Crystal filters for noise suppression are used to optimize resolution for longitudinal dipole oscillations. Quadrature detectors in conjunction with low pass filtering deliver analog phase signals from each of the 11 bunches.

1 INTRODUCTION

After multiturn injection of H^- ions into DESY III through a stripping foil eleven proton bunches are created due to the harmonic number $h = 11$ of the RF system. Although a phase loop is closed across the frequency control, damping the average of the dipole mode, the bunches start individual longitudinal oscillations during acceleration at intensity levels above 50 mA. The design intensity is about 160 mA. A resistive wall monitor shows typical bunch motion at 7.5 Gev/c and about 100 mA. See Fig. 1. The longitudinal phase space matching with PETRA at single transfer of 10 bunches was correspondingly poor.
This has motivated a phase detector design for individual bunches to be used in a longitudinal feedback system for DESY III. A block diagram is shown in Fig. 2.

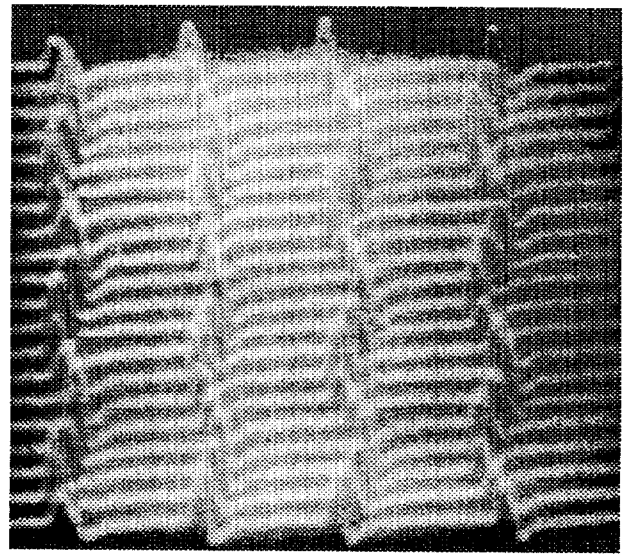

Figure 1: 'Mountain range' display of a resistive wall monitor showing longitudinal bunch motion at a synchrotron frequency of about 200 Hz. The horizontal distance of the bunches is 96 ns.

2 THEORY OF OPERATION

The beam current of one bunch, executing coherent synchrotron oscillation, observed at a fixed azimuthal location can be expressed as [1]

$$I(t) = e \sum_{n=-\infty}^{+\infty} \sum_{j=1}^{N} \delta\left(t - nT_0 + A_j \cos\left(\omega_s t + \phi_j\right)\right) \qquad (1)$$

N = Number of particles in the bunch.
$T_0 = 2\pi/\omega_0$ is the revolution time and A_j and ϕ_j are the amplitude and phase of the synchrotron oscillation of the j th particle. The synchrotron frequency ω_s is assumed to be constant for all particles, ignoring non-linearities. The periodic function of each particle can be expressed by its Fourier expansion. Averaging over all particles in the bunch, it can be written [1]

$$I(t) = \sum_{nk} I_{nk} e^{i(n\omega_0 + k\omega_s)t} \qquad (2)$$

Introducing the phase-space distribution $\psi(A, \theta, t)$ and its Fourier expansion with components $R_k(A)$, i.e.

$$\psi(A, \theta, t) = \sum_{k=-\infty}^{\infty} R_k(A)\, e^{-ik(\theta - \omega_s t)} \qquad (3)$$

with θ the phase angle and t the time variable, by which the phase-space distribution rotates. The sideband components of the beam current signal in Eq. 2 can now be calculated [1].

$$I_{nk} = \frac{eN}{T_0} i^k \int_0^\infty A\, dA J_k(n\omega_0 A)\, R_k(A) \qquad (4)$$

$J_k(z)$ = Bessel functions of the first kind.
$k = 0$ gives the average strength of the revolution line,
$k = 1$ ...the coherent dipole mode,
$k = 2$ ...the coherent quadrupole mode and so on.

A purely phase modulated sinewave signal at frequency Ω_0 has components with constant envelope [2].

$$S_k = S_0 i^k J_k (\Omega_0 A) e^{ik\phi} \qquad (5)$$

From Eq. 4 it can be seen, in general, the envelope of the revolution line and its sidebands is not constant. That means, it is phase and amplitude modulated even in the case of small and purely dipole mode oscillations.
Applying a bandfilter with low distortion to all significant Bessel components and removing all harmonics different from $n\omega_0$, one has the ability to employ a limiting amplifier with low phase shift, to produce a purely phase modulated signal from the components I_{nk}. The frequency ω_0 changes by a factor of 3 in DESY III due to the momentum change of the protons during acceleration. Therefore the beam signal Eq. 2 has to be converted to any constant frequency ω_{IF} before applying a bandfilter. This can be done using a reference signal with a frequency $h\omega_0 + \omega_{IF}$, available from the RF source. See Fig. 2.
The mixer produces components at the difference of both signals with carrier frequency ω_{IF}. These components can be extracted using a bandfilter and fed into the limiting amplifier. The amplitude modulation, mainly from quadrupole mode oscillations, is suppressed at the output signal but the phase information is preserved.
At this point it is important to mention, that the resolution for phase detection is related to the sensitivity of the detector which is degraded by the noise figures of the amplifiers and the noise bandwidth installed in the detector path [2](Q). Therefore, in addition to good selectivity the IF filter should posses both low noise bandwidth and low distortion due to the variation of the group velocity in the pass band.
The output signal $S(t)$ now is purely phase modulated.

$$S(t) = S_0 i^k J_k (h\omega_0 <A>) e^{ik<\phi>} e^{i(\omega_{IF} - k\omega_s)t} \qquad (6)$$

with $<A>$ and $<\phi>$ the average amplitude and phase of the coherent bunch oscillation.
And $S(t)$ is appropriate to be input into a quadrature phase detector (see Fig. 3) using a reference signal at frequency ω_{IF}. A phase shifter device is used in the reference signal path to adjust the phase offset $<\phi>$. The baseband signals from the phase detector are

$$A_s = A_0 \sin\alpha(t) \text{ and } A_c = A_0 \cos\alpha(t) \qquad (7)$$

with $\alpha(t) = h\omega_0 < A > \sin\omega_s t \approx A_s$ for small amplitudes we get the phase information of the coherent oscillation.
In general $\alpha(t)$ must be calculated from

$$\alpha(t) = \tan^{-1}\left(\frac{A_s}{A_c}\right) \qquad (8)$$

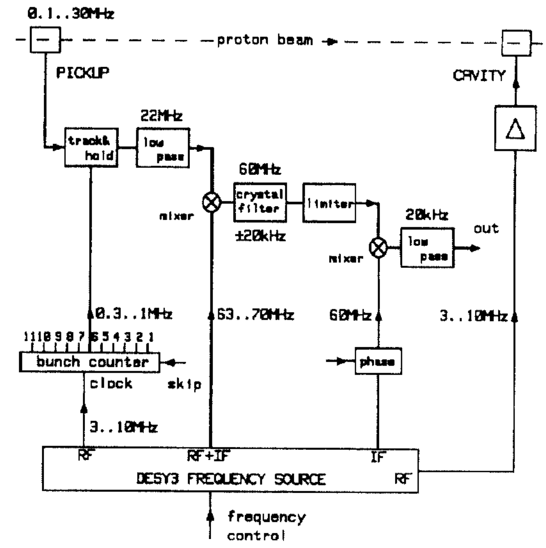

Figure 2: A Block diagram of the multibunch phase detector and its connection to the DESY III frequency source is shown for one bunch signal e.g. The bunch counter device is used additionally as a DESY III bunch marker.

3 HARDWARE

3.1 RF section

The bunch signals from the beam current monitor must be well separated in time to apply analog gating techniques. This means the bandwidth of the monitor has to be large enough to avoid signal pile-up.
A toroidal ferrite current transformer with a bandwidth of about 30 MHz is well suited. In addition the coupling to transverse beam signals is rather small for such a device.
To avoid switching transients due to the dc offset in the monitor signal, track&hold devices[1] are chosen. The track mode is switched on for exactly one cycle of the RF frequency $t_{on} = 2\pi/h\omega_0$ adjusted by cable to the propagating time of the bunch signal.
The clock signals are produced from a bunch counter device connected to the DESY III frequency source (Fig. 2).
During hold mode, the signal path is well decoupled from other bunches by more than 80 dB.
To suppress unwanted signal harmonics in the 60 MHz IF band a low pass filter[2] is installed in every bunch channel with a cut off frequency at 22 MHz and low distortion at 3 to 10 MHz signal band.

[1] AD9100 Analog Devices
[2] BLP-21.4 Mini-Circuits

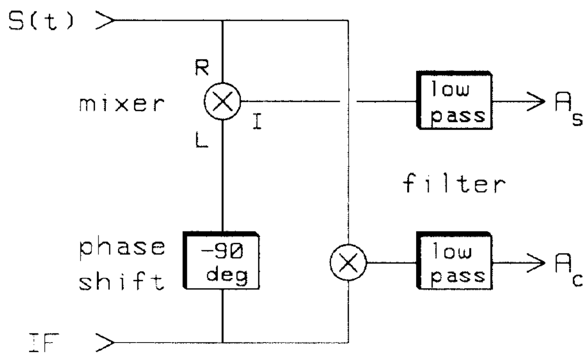

Figure 3: The principle of conventional quadrature phase detection is shown. The mixer may behave as a multiplier with $I = R \times L$. The input signal is $S(t) = A_0 \cos(\omega_{IF} t + \alpha(t))$ and the reference signal is $IF = 2\cos\omega_{IF} t$. Simply using the theorem $\cos(x+y) = \cos x \cos y - \sin x \sin y$ for the input signal and multiplying with the reference signal, taking the phase shift into account, we get $A_s = A_0 \sin\alpha(t)$ and $A_c = A_0 \cos\alpha(t)$ if we neglect frequency components cut from the low pass filter.

3.2 IF section

Signal conversion is done with double balanced mixers[3] using quartettes of selected Schottky-barrier diodes with about -6 dB of conversion loss.
The bandfilter for the IF band is realized by a crystal filter[4] with a bandwidth of ±20 kHz, a variation of the group velocity of about 2μs and a selection for harmonics of the revolution frequency of about 70 dB at ±300 kHz.
The bandwidth needed for phase modulated signals can be calculated from the Carson formula [2].

$$BW = 2\,(h\omega_0 < A > +1)\,\omega_s/2\pi \qquad (9)$$

For synchrotron frequencies up to 3 kHz the amplitude of the phase modulation can be as high as 2π.
The limiting amplifier[5] used behind the crystal filter has a 40 dB input dynamic range with low phase shift 0.14 degree per dB of compression at 60 MHz.
It can be seen, that the harmonics of the revolution frequency suppressed by the crystal filter are re-installed due to the compression factor of the limiting amplifier to a level of about -30 dBm at 0 dBm output level.

3.3 AF section

Low pass filters combined with operational amplifiers suppress the distorting harmonics of the revolution frequency and deliver a fixed 10 V amplitude A_0 for the sine and cosine output signal (Eq. 7). The purpose of the cosine output is not just for more precise phase measurement (Eq. 8) but, furthermore to simplify the phase adjust with the reference signals. Due to the frequency change in DESY III the phase changes by about $7 \times 2\pi$ in 200 m of transmission cable.
The resolution of the phase detector is considerably influenced by electrical noise. With ±20 kHz of bandwidth, the input noise level from the beam current transformer is of the order of -120 dBm taking just thermal noise into account. This level is shifted due to 60 dB gain required in the IF path against the 0 dBm output level of the limiting amplifier. About 60 dB remains for signal to noise ratio in good agreement to the measured noise level of about ±25 mV.
From this value, using Eq. 7 with $A_0 = 10\ V$ the resolution can be estimated to be ±0.15 degree.

4 ACKNOWLEDGEMENT

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5 REFERENCES

[1] S. Krinsky, "Measurement of longitudinal Parameters ..", Proceedings of the US-CERN School on Particle Accelerators, Anacapri,Isola di Capri,Italy, October 1988, pp.150-166.
Berlin Heidelberg New York: Springer Verlag, 1989.

[2] Meinke - Gundlach, Taschenbuch der Hochfrequenztechnik, Berlin Heidelberg New York Tokyo: Springer Verlag, 1986.

[3] ZLW-1-1 Mini-Circuits
[4] TQF-60 TeleQuarz
[5] UDL-503 Avantec