THE HERA-P BPM READ OUT SYSTEM

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Abstract: A beam position monitoring read out system has been developed for the 820 GeV HERA Proton Storage Ring Accelerator. The electronics provides position, intensity and further information about a selected bunch on a turn-by-turn basis. The analogue and digital parts of the electronics are described in detail.

Introduction

HERA [1], now under completion at DESY in Hamburg, is a pair of storage rings in which 820 GeV protons will collide with 30 GeV electrons. The beams will consist of 210 bunches each spaced by 96 ns. The beam position measurement system for the proton storage ring is based on directional coupler antennas both in the cryogenic and ambient termperature parts [2] of the proton ring [3]. The 395 mm long antennas are well matched to the 0.3 m (at 820 GeV) to 2.7 m (at 40 GeV injection energy) long bunches and yield signals with a broad frequency content around 100 MHz. Under optimal conditions at luminosity storage operation the pick ups deliver pulse signals with peak amplitudes up to 100 V (corresponding to 10^{11} p/bunch) at a 96 ns repetition rate, while during injection studies single pass pulses of a few hundred millivolts (corresponding to 10^9 p/bunch) have to be processed. To keep the quench probability low during runs with high beam currents, an early warning for orbit movements is envisaged. It has turned out in other [4] accelerators to be useful to be able to analyse consecutive measurements of a given bunch at several positions in the machine. In particular, a history of the beam position shortly before a beam abort might be very useful in identifying the cause of the fault.

The electronics for the beam position monitor system is divided into two parts: an analogue module - which is split into an (almost) passive input section and an active analogue electronics section - and a digital module. While the first two parts are fast enough to cope with the 10.4 MHz rate at no extra cost, most digital modules are limited to accept one measurement per revolution (i.e. 48 KHz) because of memory space. The electronics is built up of bipolar devices to insure a higher immunity against radiation.

Analogue Modules

The BPM-signal electronics measures the position of the proton beam with respect to the vacuum chamber's centre processing analogue the directional coupler pick up signals [2]. This beam position information is converted to an 8 bit digital data word and passed to a digital module for further treatment. The electronics together with the trigger system [5] selects a single selectable bunch (out of 210). The measurement is repeated once per revolution (21 μs).

For diagnostics purposes the electronics measures additionally with 8 bit resolution either the sum (Σ) or the difference (Δ) of the pick up signals. These signals are proportional to the beam intensity or (alternatively selectable) the product of beam position and intensity.

In order to achieve a beam position measurement under the various HERA-p beam conditions we choose the phase measurement principle [6]. Together with the pick up stations it enables a single bunch position measurement with submillimeter resolution for centred beams and moderate resolution towards the chamber walls. The dynamic range is sufficient to ensure the operation, under all machine conditions without the need to switch elements (attenuators, amplifiers, etc.) in the signal lines.

Figure 1 sketches the schematics for a single frequency (the "operation" frequency) with two sine wave generators as equivalent circuits for the signals of the two adjacent electrodes of the dual directional coupler pick up.

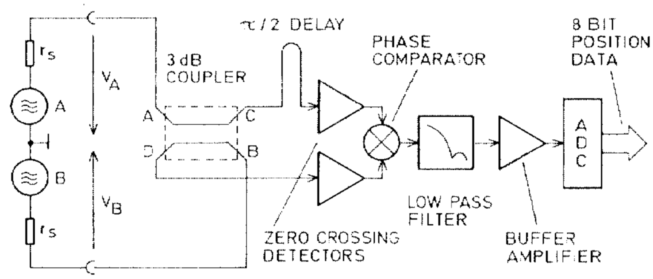

Fig. 1 Principle of the beam position measurement

Their amplitude ratio $|V_A|/|V_B|$ is a function of the beam position and is approximately given by

$$\frac{|V_A|}{|V_B|}\,[\mathrm{dB}] \approx 20\ \lg\left[\frac{f(\varepsilon_x,-\varepsilon_z,\phi_o) - f(\varepsilon_x,-\varepsilon_z,-\phi_o)}{f(-\varepsilon_x,\varepsilon_z,\phi_o) - f(-\varepsilon_x,\varepsilon_z,-\phi_o)}\right] \qquad (1)$$

$\varepsilon_x = x/R$ norm. horizontal beam position

$\varepsilon_z = z/R$ norm. vertical beam position

$R = 27.65$ mm vacuum chamber radius

$\phi_o = 0.628 \mathrel{\hat{=}} 36°$ angle corresponding to the pick ups' electrode width

$$f(\varepsilon_x,\varepsilon_z,\phi_o) = \arctan\left[\frac{\{(1+\varepsilon_x)^2+\varepsilon_z^2\}\tan(\phi_o/4)+2\varepsilon_z}{1+\varepsilon_x^2-\varepsilon_z^2}\right] \qquad (1a)$$

for a horizontally sensitive pick-up[2]. A 3 dB directional coupler (hybrid) running at π/2 electrical length converts the $|V_A|/|V_B|$-ratio at its A and B inputs into a phase ratio between its C and D outputs:

$$\psi_{C-D} = \frac{\pi}{2} - 2\mathrm{arccot}\left(\frac{|V_A|}{|V_B|}\right) \qquad (2)$$

while the amplitude at the output ports is now the average of the two input signal amplitude.

So the 3 dB coupler acts at its centre-frequency (π/2 - electrical length) as an amplitude ratio to phase difference converter (Fig. 2).

1) on leave from Weizmann Inst., Tel Aviv

2) for a vertically sensitive pick up the indices x and z have to be exchanged.

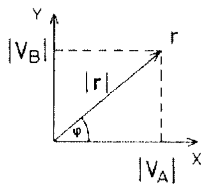

Fig. 2 Principle of the 3 dB directional coupler as amplitude ratio to phase ratio converter

In an orthogonal plane x and y correspond to the pick up electrode signal levels[3] $|V_A|$ and $|V_B|$, where $|r|$ is the beams intensity and ρ his position. A π/2 delay line matches the phase range (ψ_{C-D}) with the phase detector's range. The two zero crossing detectors (analogue comparators) at the phase detectors inputs limit the C and D signals to a constant amplitude. A low pass filter separates the quasi DC-component representing the beam position information. As the phase detector characteristic is linear, (it is a digital mixer based on a GaAs-EXOR-gate), the overall characteristic of the beam position measurement is the product of (1) and (2) with some constants. The mapping of this signal range to the 8 bit binary scale of the following ADC limits the position resolution to approximately 150 µm for a centred beam in the HERA-p vacuum chamber (Fig. 3).

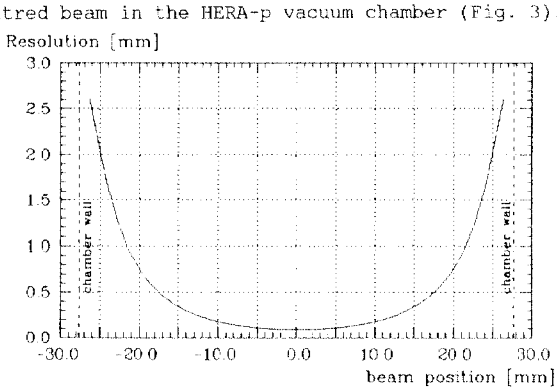

Fig. 3 Theoretical resolution limit versus beam position due to 8 bit digitalization

This 1 bit is equivalent to 8 mV at the ADC input corresponding to a phase difference of $\psi_{C-D} = 1.125°$ (or 30 ps). For a 150 µm beam displacement from the centre the pick up signal ratio is 0.186 dB for 1 bit.

Measurements on a prototype show a (short time) phase jitter of < 0.1° (≙ 2 ps), which corresponds to a 12 bit resolution.

To apply this phase measuring principle on the HERA proton bunch signals two pulse-forming filter networks are needed at the electronics inputs A and B to excite a sine-wave-like burst signal. The bursts frequency ("operation" frequency) is chosen to be 104.1 MHz (2200 times the revolution frequency) where the convolution of the bunch spectrum with the pick up transfer function has a broad maximum [2]. The bursts envelope approximates a trapezoid to produce a sine-wave-like response. This results in minimum phase jitter and constant peak amplitude during the measuring interval (which is 60 ... 80 ns, because of the 96 ns bunch-bunch spacing), and minimum ripple for times > 96 ns. The poles and zeros of the normalized low-pass-equivalent transfer function were synthesized by minimizing [7]

$$\int_{t=0}^{\infty} [r(t) - a_o(t)]^2 \, dt \overset{!}{=} \min. \qquad (3)$$

where r(t) is the ideal normalized trapezoidal time domain response and

$$a_o(t) = \sum_{\nu=1}^{n} \mathrm{Res}_\nu [W(s), s_{o\nu}] \, e^{t \cdot s_{o\nu}} \qquad (4)$$

the normalized impulse response of the network with n poles, in which

$$W(s) = \frac{1}{k} \, \frac{\prod_{\mu=1}^{m} (s - s_{\infty\mu})}{\prod_{r=1}^{n} (s - s_{or})} \qquad (n \geq m)$$

the normalized transfer function appears (Fig. 4).

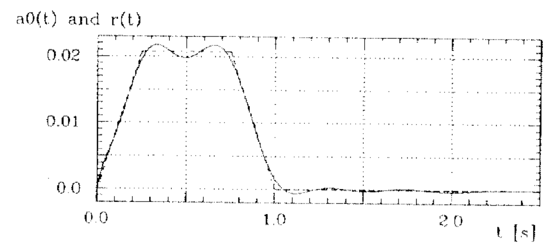

Fig. 4 Synthesizing the trapezoidal impulse response r(t) by $a_o(t)$

The result of the practical realization with n = 6 and m = 4 of the input bandpass pulse former is shown in Fig. 5. Some decrease of performance due to the needed Norton impedance transformation of the input resonator circuit and series production problems produce a higher ripple for t ≥ 96 ns. Measurements on the whole system show nevertheless (because of the amplitude-to-phase conversion) a sufficient bunch separation, the influence of a previous bunch of the same intensity as the bunch under position measurement being ≤ 50 µm on the measurement accuracy.

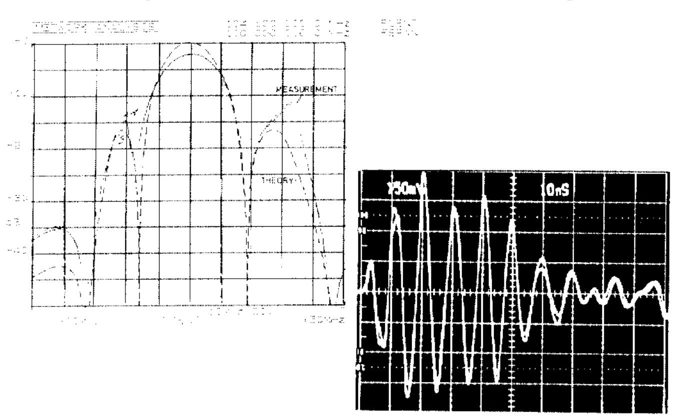

Fig. 5 Time and frequency domain (magnitude) response of a matched bandpass pulse former pair

The pulse forming of the input signals requires slightly more sophisticated DC component filtering behind the phase comparator. We apply the theorem of the time bandwidth product [8] for a low pass pulse former with seven poles and four zeros.

Both filter networks, those trapezoidal band pass pulse formers at the input and the low pass filters behind the phase comparator, result in a

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3) these signals have to be approximately in phase

measurement interval of ≈ 20 ns for the analog-to-digital conversation, in which the signal to be digitalized is constant within 0.4 %. The dynamic range of the beam position measurement electronics is limited by the zero crossing detectors to at least 48 dB. The overall frequency-dependent characteristics and the linear attenuations in the system (including pick up and beam) result in a signal range between - 36dBm ($\hat{=}$ 10^9 protons/bunch, 2 m bunch length) and + 12 dBm ($\hat{=}$ > 10^{11} protons/bunch, 0.3 m bunch length). At the lower end, i.e. injection studies and machine commissioning, the absolute resolution will be reduced to ≈ 1 mm (for a centred beam).

The intensity or intensity-times-position measurement is based on 60 dB (in some modules 40 dB) detector logarithmic amplifiers, sensing a Σ or (selectable) Δ signal. This measurement branch allows a rough single-bunch intensity measurement as well as a high resolution measurement for the relative beam position under stable machine conditions.

Digital modules

Figure 6 sketches the main features of the digital module. Two identical channels are housed in one double width NIM-type module. Inputs from the analogue module are routed over the upper backplane connectors. The lower connectors are used for the interface to a backplane bus which makes the connection via a crate controller with a computer. Both channels share a command logic block (mainly PAL's). Each channel contains one 8 bit input for intensity information and one 8 bit input for a position measurement. The timing is based on an independent timing system [5] and insures the measurement of one preselected bunch at all monitors of the accelerator. The position information is stored in a 8 bit wide, 1024 deep circular buffer and simultaneously the average over 128 measurements is calculated. 256 averages (or alternatively 256 single measurements) are stored in a shorter buffer.

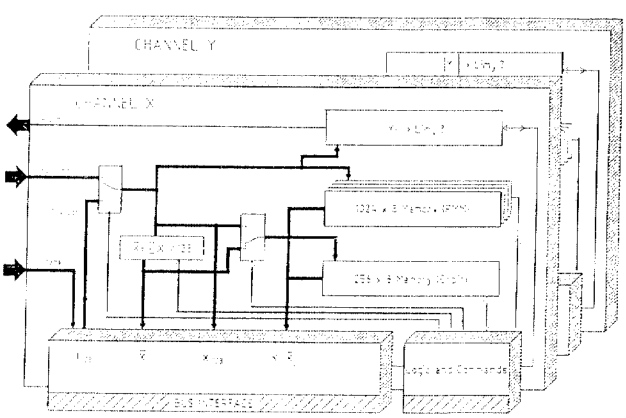

Fig. 6 Schematics of the digital modules

To be able to identify a single turn and to synchronize readings of distributed monitors the following scheme was implemented. Once the continuous string of synchronous trigger pulses is interrupted in all modules a 32 bit counter for synchronization and identification is reset. From now on all modules show the same content in this counter at the time at which the selected bunch is passing by. After 128 turns a new average is calculated everywhere and simultaneously a read out flag is raised. The output registers are not changed for a settable read out time (should be the same everywhere and is synchronized by the timing signal). The output registers contain intensity, position and several flags. Available is also on request the content of the shorter memory containing averages or single positions, depending on the operating mode. The sampling time interval should be set properly to allow the read out of this memory, otherwise synchronization will be lost temporarily. The long memory is always updated and not readable during normal operations. In case an external interrupt is issued, the identification counter is saved and all memories are frozen. Now the long memory can be accessed for fault diagnosis (post mortem) or special tests (transient recorder feature). The interrupt can be caused by an operator, an external trigger signal, and is issued automatically whenever a quench has happened or is likely to happen because the beam orbit is at several places in the machine close to the beam pipe wall. The latter alarm is based on the limit detector. All position measurements that enter the post mortem memory are checked against a settable limit provided the intensity is above pedestal. If the limit is passed a signal is sent to an alarm module which collects the information around the ring. (In future also loss monitors will contribute to this collection line.) If a settable number of alarm requests is reached, an interrupt is issued, stopping the memories and causing a beam abort. The list of normal operating modes is complemented by several test modes, either with hardware or software generated data. Moreover the limit feature and the synchronization can be switched off.

A preseries of 15 sets of analogue modules and all digital modules have been delivered. They are tested and mounted in their respective crates. Fifteen modules are in operation, waiting for the first proton beam injection into the first octant of HERA.

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