Damping of Coherent Synchrotron Oscillations Occuring at Injection of 7.5 GeV Protons into PETRA II

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Abstract

First operational experience with a dedicated phase loop for damping coherent synchrotron oscillations of protons in PETRA II is described. Without the loop the synchrotron oscillation is smeared out by Landau Damping within 4 to 6 periods. With the loop being active complete damping within less than one synchrotron period is achieved.

Introduction

Prior to injection into HERA (1) protons are preaccelerated to 7.5 and 40 GeV/c in the synchrotrons DESY III and PETRA II respectively (2). RF noise and timing imperfections during transfer of protons from one machine to the next one are likely to cause synchrotron oscillations which, if not damped properly, may lead to an increase of beam emittance. Therefore a phase loop acting on the RF phase such as to damp these oscillations of the proton bunches could become a necessary component of the low level RF system of a synchrotron. The PETRA II Proton RF system which consists of two 52 MHz cavities, each with a closely coupled RF amplifier chain and a fast feedback loop of gain 50, has been described in more detail in (3). In this article we want to describe a dedicated phase loop for damping synchrotron oscillations of the protons in PETRA II.

Loop Bandwidth

The maximum number of bunches is 11 in DESY III and 80 in PETRA II so that 8 DESY III cycles are needed to fill PETRA II. If synchrotron oscillations due to injection timing errors arise all bunches of the corresponding batch are expected to oscillate coherently. Therefore one single correction signal can damp the bunch oscillations in that batch and in total up to eight such signals are needed, one for each batch. This phase loop is a batch-to-batch rather than a bunch-to-bunch feedback. The correction of expected errors of about two degrees in the injection phase, however, has to be applied within the 96 ns separating the last bunch of batch n from the first one of batch n+1. Due to the fast feedback of gain 50, the RF system is capable of performing phase changes of the order of 1°/100 ns which should be sufficient for damping synchrotron oscillations also in multi batch mode of operation.

The Phase Detector

A block diagram of the phase loop instrumentation is shown in fig. 1. Each bunch passage generates a signal in the inductive beam monitor. A passive LC filter of 8 MHz bandwidth filters out the 52 MHz

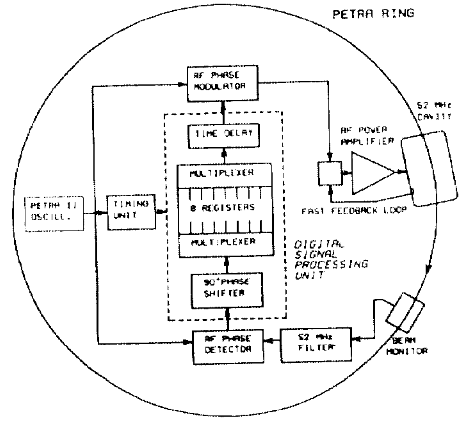

Fig. 1. Block diagram of the PETRA II phase loop. In the phase detector synchrotron oscillations of the bunches are detected by comparing the filtered 52 MHz component of the beam to the 52 MHz RF reference source. An averaged phase signal for each of the eight batches of 10 bunches is phase shifted by 90° with respect to the synchrotron frequency, stored in it's register and properly multiplexed to the phase modulator acting on the RF drive signal.

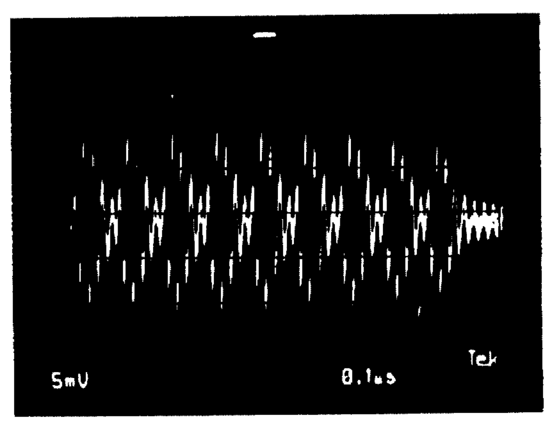

Fig. 2. Filtered signal of a batch of 9 proton bunches circulating in PETRA. The bunch spacing time is 96 ns.

component. The ringing time is comparable to the bunch spacing time as is shown in fig. 2. Amplitude fluctuations of this signal are reduced to ± .5 dB in a limiter of 40 dB dynamic range. So the amplitude dependence of the synchrotron phase measurement between the bunch signal and the 52 MHz RF source signal is minimized. The phase detector has a sensitivity of 10 mV per degree. Inserting a low pass filter ($f_{max} \leq 1$ MHz) one can directly observe the synchrotron motion of the bunches at the phase detector output.

This is shown in fig. 3 for one batch of 9 proton bunches circulating in PETRA II with the momentum of 7.5 GeV/c a few ms after injection. The observed synchrotron period T_s = 5 ms agrees with the expected value for the actual RF voltage of 50 kV.

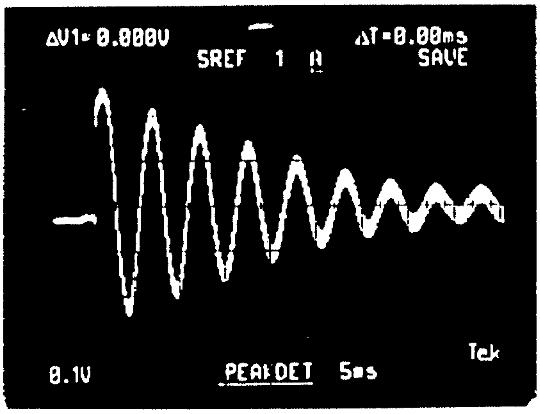

Fig. 3. The synchrotron oscillation measured at the phase detector output a few ms after injection of a batch of 9 proton bunches into PETRA II. It is smeared out by Landau damping after some periods. The damping loop is not active.

The Analogue Synchrotron Frequency Phase Shifter

A feedbackloop can damp the synchrotron motion if, as is shown in fig. 1, the synchrotron phase signal is shifted by -90^0 relative to the synchrotron frequency f_s, delayed properly and fed into a phase modulator acting on the 52 MHz RF drive signal. The necessity of the -90^0 phase shift relative to f_s can be seen from the equation of damped harmonic motion: $\ddot{x} + a\dot{x} + bx = 0$ with the solution $x = A\sin(\omega_s t - \phi)e^{-at}$. The damping term ax is proportional to the time derivative of the solution x, i.e. a phase shift of -90^0. The correction signal will coincide with the corresponding batch in the cavity if the delay $\tau = t_f + nT_{rev}$, where t_f is the transit time from the beam monitor to the cavity, n an integer, and T_{rev} = 7.7 µs is the particle revolution time in PETRA. Since $T_s \gg T_{rev}$ a delay of even more than one turn (n>1) would be uncritical.

For the first run with protons in PETRA II in November and December 1989 essentially single batch operation was foreseen. Therefore, in a preliminary version of the phase loop only one single RC differenciator network was present to perform the -90^0 phase shift. Due to the increasing gain of a differentiator as a function of frequency,the risk of introducing phase noise with this setup seemed substantial, and alternatively an integrating network was built. The latter had no high frequency noise but, for frequencies around 1 Hz, it's gain increased to more than 10 times of the value at f_s, and in this configuration large amplitude longitudinal beam oscillations were indeed excited by the loop at low frequencies. The differentiator network, on the other hand, did not cause any instabilities.

Results

The performance of the loop using the differentiator network is demonstrated in fig. 4. The beam intensity is displayed by the upper trace of the storage scope and the phase detector output by the lower one. Complete damping of the synchrotron oscillation is achieved within less then one period. This corresponds to a damping time of less than 4 ms, and no significant change of beam intensity is observed. If the loop is operated in the antidamping mode, the beam is lost within some ms.

In this run the proton lifetime in the PETRA II flat bottom was limited by other factors to typically 20 s. No effect on this lifetime by the phase loop could be observed.

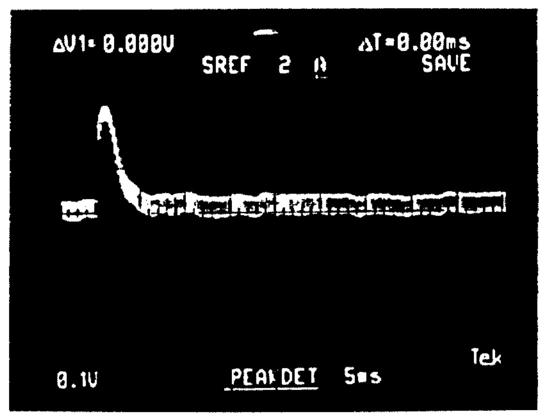

Fig. 4. Same as fig. 3 but with the phase loop active. The synchrotron oscillation is completely damped within half a synchrotron period of 5 ms.

The Projected FIR Filter as a Digital Phase Shifter

As we pointed out above, a simple RC integrator or differentiator network as a 90^0 phase shifter is not without problem. In addition one has to note that during injection, acceleration and compression of the bunches the synchrotron frequency varies in the range from 200 to 350 Hz. Therefore a digital solution with a software controlled phase shift is very attractive. Storing and multiplexing the eight correction signals for each of the eight possible batches in PETRA II can also be realized most comfortably on the digital side. The phase shifter has been built up as a three coefficient digital FIR (Finite-length Impulse Response) filter according to

$$g_\mu = \sum_{k=0}^{2} h_k f_{\mu-k} \qquad (1)$$

with an amplitude response

$$H(\omega) = \sum_{k=0}^{2} h_k e^{-ik\omega T_B} \qquad (2)$$

where f and g are input and output data respectively. Using the coefficients $h_0 = \frac{2}{\pi}\sin\phi$, $h_1 = \cos\phi$, $h_2 = -\frac{2}{\pi}\sin\phi$ one obtains a phase shift which, in the frequency range of interest 200 HZ $\leq f_s \leq$ 350

Hz, deviates by less than ± .4 from the nominal value $\phi = -\pi/2$ in accordance with equs. 1 and 2. The frequency dependence of the phase shift is mainly due to the delay in the filter which is of the order of 1 ms, i.e. two sampling periods. It can always be corrected by software, if necessary. The amplitude response is constant within a few percent for all frequencies.

A block diagram of the filter is shown in fig. 5. The synchrotron phase information of the eight batches is sampled at intervals T_s = .5 ms and passed through eight times three shift registers. The three coefficients are stored in ROMs and are appropriately combined with the phase information. So, the first filter output is available after three sampling periods and is then renewed every .5 ms.

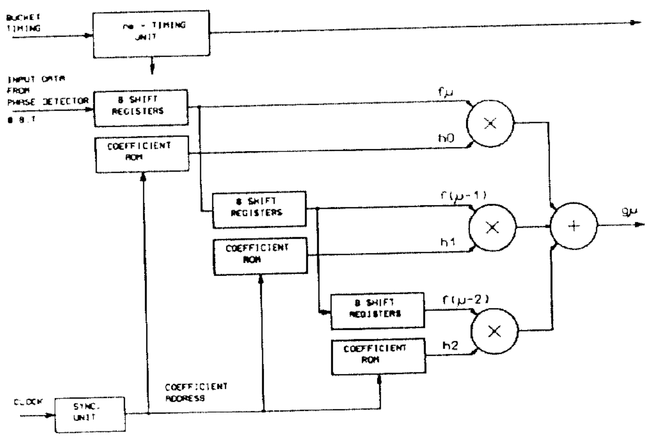

Fig. 5. Block diagram of the FIR filter. From three successive sampling periods the averaged phase signals for the eight proton batches in PETRA II are stored in shift registers and combined with the three coefficients which are stored in ROMs. The first phase shifted output is avilable after three sampling periods of .5 ms and is renewed every sampling period.

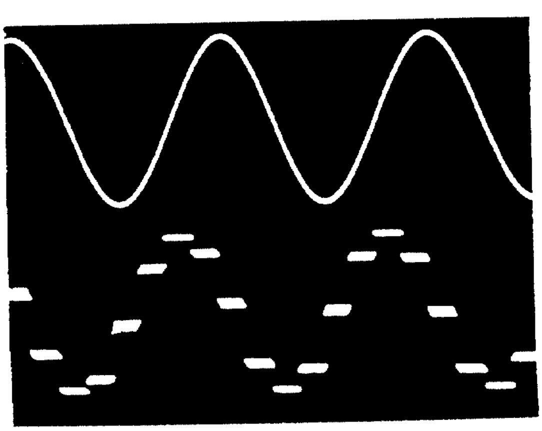

Fig. 6. Oscilloscope photograph of a 250 Hz input signal and the phase shifted output signal (lower trace) of the digital filter. Here the sampling time structure of .5 ms is clearly visible.

A prototype of the complete filter has been built and successfully tested in the laboratory. In fig. 6 we show an oscilloscope photograph of input- and phase shifted output signals at 250 Hz.

We plan to use this filter in the PETRA II phase loop during the next proton run sheduled for May 1990.

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