DAΦNE Longitudinal Feedback

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Abstract

A preliminary assessment of the growth rate of the longitudinal multibunch instabilities in DAΦNE has evidenced the need for a powerful active feedback system. In this report we present a preliminary design of a mixed analog/digital feedback system employing DSP techniques, which can be used with 30 bunches and is upgradable to 120 bunches, capable of a damping time of 0.1 - 0.2 ms.

1. INTRODUCTION

DAΦNE is a high-luminosity Φ-factory based on two intersecting storage rings. Details of the project are given elsewhere in these proceedings [1].

Calculations [2] and simulations show that the resistive impedance of undamped HOM's in the accelerating cavities can drive coupled-bunch (CB) modes of oscillation with unmanageably fast rise-time. Although a small frequency shift can in principle reduce by a large amount the growth rate, damping of at least two orders of magnitude of the HOM may prove more viable [3]. Even so, the rise-time of CB modes can be much faster than the natural (radiation and Landau) damping time; moreover the probability for a damped HOM to cross a CB mode frequency is larger, due to the wider bandwidth. An all-mode feedback system capable to damp all the CB modes and the injection transients is thus necessary. The system proposed for DAΦNE is a bunch by bunch, time-domain feedback. This approach is common to other factories with intense beams and a large number of bunches. In fact, a collaboration has been set up with the B-Factory group at SLAC, where considerable R&D on feedback systems for the next generation of electron colliders [4,5] is being carried out.

2. FEEDBACK BASICS

In Table I we list the machine parameters relevant to the feedback.

Table I

Energy E_0 (MeV)	510
Revolution frequency f_{rev} (MHz)	3.07
Harmonic number h	120
Average current/bunch (mA)	44
Number of bunches B	30 -> 120
Bunch spacing (ns)	10.9 -> 2.7
RMS Bunch duration σ_z (ps)	100
Synchrotron tune Q_s	~ 1/80
Momentum compaction factor α_c	0.017
Synchrotron damping time τ_s (ms)	17.8

The damping rate α_{FB} [sec^{-1}] provided by a longitudinal feedback system is

$$\alpha_{FB} = \frac{1}{\tau_{FB}} = \frac{1}{2} f_{rev} * \frac{\Delta U_{FB}}{\Delta E}$$

where ΔU_{FB} is the energy correction/turn by the feedback kicker and ΔE is the energy error.

The following scheme can be applied: detect the individual synchrotron phase error with a longitudinal pick-up, rotate the signal in the synchrotron plane by means of an appropriate filter, amplify and give an energy kick with a longitudinal kicker. The differential equation governing the synchrotron phase ϕ of a bunch is then, in the smooth approximation:

$$\frac{d^2}{dt^2}\phi + \alpha\frac{d}{dt}\phi + \Omega_s^2\phi = \text{feedback forcing term} =$$
$$= -2\pi f_{RF}\frac{\alpha_c}{E_0} f_{rev}(\mathbf{g}\,\phi)\ ,\ \text{with}\ \mathbf{g} = \frac{\Delta U_{FB}}{\Delta\phi}\ ,$$

where α is the combined damping (or antidamping) rate from radiation and HOM excitation, f_{RF} is the RF frequency, Ω_s the synchrotron angular frequency and $\mathbf{g}(\Omega)$ [eV/rad] is the (complex) feedback gain

$$\mathbf{g}(\Omega_s)\,\phi = |g|\,(\underbrace{\phi\cos\theta}_{\text{in-phase}} + \underbrace{j\,\phi\sin\theta}_{\text{quadrature}}) \approx$$
$$\approx |g|\,(\phi\cos\theta + \frac{\dot{\phi}}{\Omega_s}\sin\theta)\,.$$

The overall damping time is determined by the quadrature component of the feedback forcing term:

$$\frac{1}{\tau} \approx \frac{1}{2}\left(\alpha + 2\pi f_{RF}\frac{\alpha_c}{E_0}\frac{f_{rev}}{\Omega_s}|g|\sin\theta\right).$$

On the other hand, the in-phase component contributes to a small shift of the synchrotron frequency, but not to the damping. Therefore the optimum damping effectiveness is achieved when $\theta = \pi/2$.

It is worth noting that, in order to maintain the optimum phase-shift, the filter should be tuneable in the range of the allowable synchrotron tunes and that it is necessary to replicate the filter B times in order to damp independently B bunches. The phase detector and the kicker do not need to be replicated, provided that their bandwidth is such to detect the phase and kick individual bunches with no "memory" of the adjacent ones.

With a maximum B of 120, however, the above basic approach can become very complex, if not prohibitive at all. A different solution, still based on individual detection and correction of the different bunch phases will be discussed in the following section.

3. ANALOG - DIGITAL FEEDBACK

Available electronic technology allows the realization of a mixed analog/digital system employing Digital Signal Processors (DSP) as filters. With reference to Fig. 1, the front-end is a phase detector followed by a fast (bandwidth 1.2 GHz) digitizer capable of sampling the phase signal of individual bunches at full rate with 8-bit resolution [6]. The DSP's run at some lower frequency than the digitizer, thus a digital demultiplexer is needed to convey to different units the digitized phase. The DSP's perform the filtering algorithm, after which the feedback correction information from different parallel processors is multiplexed into a fast digital to analog converter [7], then amplified with a power amplifier and fed to a longitudinal kicker.

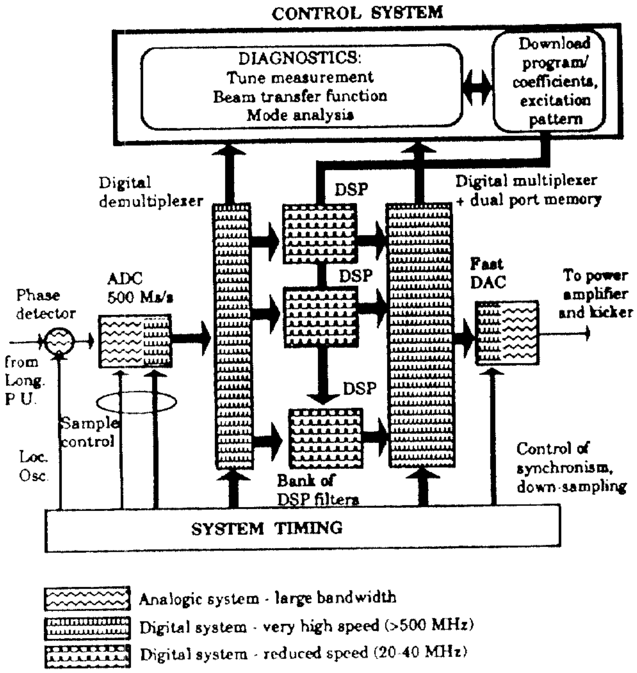

Figure 1. Analog-digital feedback.

The main advantage of such a system is that the same DSP can serve as a filter for several different channels, thus reducing the overall complexity. Indeed, the use of programmable devices allows also the flexibility to program the gain and to *tune* the frequency response of the filters on-line, according to the beam current intensity and to machine parameters which affect the synchrotron motion. Moreover, the digital system can be programmed in such a way as to maintain the correction signal just below the saturation limit of the power amplifier, so that, even in the presence of large phase excursions (i.e. at injection), the final power amplifier never goes into saturation, an undesirable condition during which the effective feedback gain is considerably reduced and whose recovery could take a time longer than the bunch to bunch spacing.

3.1. Phase Detector

We need to measure the single bunch phase with no signal feed-through by the preceding bunches. The use of a narrowband tuned detector is thus precluded.

A coherent burst of bipolar pulses can be produced by time-shifting and summing the output of a longitudinal stripline pickup. The phase of this pseudo-sinusoidal burst is compared, by means of a double balanced mixer (DBM), to that of a local oscillator (LO) locked to a harmonic of the ring RF. The output of the DBM phase detector is fed to a fast digitizer and processed by the DSP system.

A laboratory test, based on that described in [4], has been set-up at SLAC, with which it has been possible to characterize the performance of the front-end detector.

In this test (see Fig. 2) we send two narrow pulses of ~100 ps FWHM, produced by step-recovery diodes, into the inner conductor of a 3" coaxial line, to simulate two bunches spaced at 2.7 ns in the accelerator pipe.

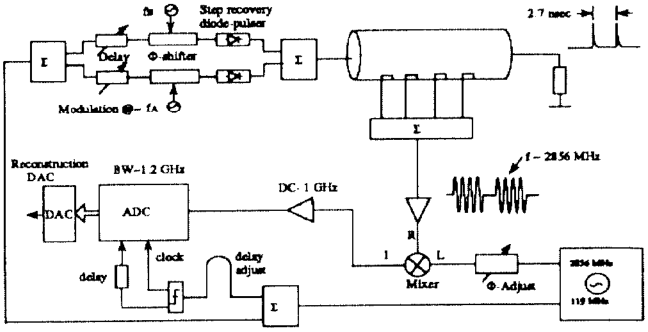

Figure 2. Schematic layout of the front-end test.

The output of four -36 dB stripline couplers in the coaxial line are combined to form a coherent burst in correspondence to the passage of each pulse (Fig. 3).

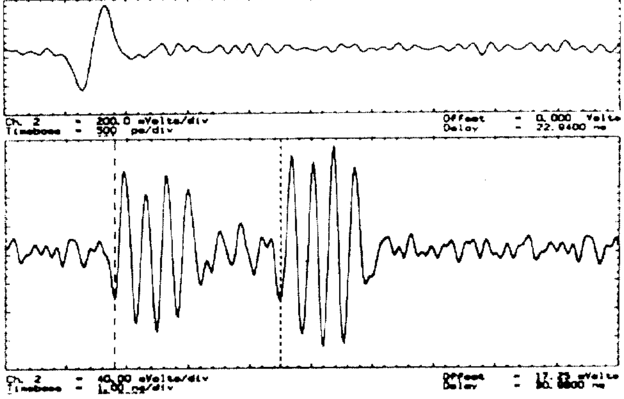

Figure 3. Pickup signal and coherent burst in the bunch simulator.

We modulate the time position of the pulses with two sinusoids at slightly different frequencies. The detected phase of each burst is digitized by gating the ADC on either one or the other bunch. The ADC output is converted back into analog by a reconstruction DAC and the output measured with a spectrum analyzer. The feed-through of one modulating frequency on the detected phase of the other bunch is a measure of the bunch to bunch isolation. The measured isolation is ~ -30 dB; an improvement can be expected by choosing a DBM with a better isolation of the LO port at the carrier frequency. The full scale range in the phase measurement is ± 15° and the measured rms noise is comparable to the least significant bit (1/128 of FSR) of the ADC.

3.2 Digital Filter

The correction signal is calculated by a discrete-type non-recursive digital filter with *N*-taps. In such a filter the output signal y_n at the instant t_n is computed as the convolution sum of *N* prior values of the input signal ϕ_{n-i} :

$$y(t_n) = G * \sum_{i=1}^{N} \phi(t_{n-i}) \bullet h_i ;$$

$G*\{h\}$ is the *N*-samples reconstruction of the desired pulse response of the filter, a sinusoid in our case.

The period of the synchrotron oscillation is ~80 revolution times, but to reconstruct it in the digital filter we can use a smaller number of points by sampling at a rate D (down-sampling factor) times slower than the revolution frequency [8]. The number of taps in the filter is then $N \sim 1/DQ_s$ and the number of multiply-accumulate (MAC) cycles in each DSP filter is reduced accordingly. The total number of operations/second is reduced by $1/D^2$ because the number of MAC's is reduced by $1/D$ and the rate at which the correction kicks are computed is reduced by the same amount.

The main advantage of down-sampling is that the number of digital processors can be limited to a number much smaller than in a system sampling at full rate. On the other hand, a fast dual-port memory register is necessary to hold the last computed correction kick for each individual bunch and to provide a correction signal to the kicker, synchronously with each bunch passage.

According to simulations, the feedback system performs satisfactorily with a number of taps as small as 5. A preliminary estimate of the number of DSP's needed for 30 bunches is ~5, assuming a DSP with an instruction time of 50 ns [8].

3.3 Longitudinal Kicker

The energy correction, in terms of the output power P_0 of the final amplifier is

$$\Delta U_{FB} = \sqrt{2 P_0 (R T^2)} \ ,$$

where (RT^2) is the kicker shunt impedance, corrected by the transit time factor. The bandwidth required to damp all bunches separately is roughly ≥1/2 the bunch frequency Bf_{rev}. The kicker resonant frequency f_r and the bandwidth must be such to encompass with a substantial value of the shunt impedance all possible CB mode frequencies. The optimum resonant frequency is at

$$f_R = (p + 1/4)\, B\, f_{rev}$$

with p an integer.

The present choice for the kicker is a structure of three $\lambda/4$ striplines with full coverage, broadly resonating at ~1.2 GHz, series-connected with $\lambda/2$ delay lines [9]. With such arrangement, a peak shunt impedance of up to 900 Ω and a half-power bandwidth in excess of 1/2 the bunch frequency are achievable. Proper design of the kicker electrode is crucial in reducing the power demand on the final stage of the feedback system and mismatches at the power port must be minimized to reduce reflections.

4. SIMULATION STUDIES

We have used the simulation code developed at SLAC [5] to assess the system performances in a realistic context. All simulations are performed in the time domain taking into account the interaction between the beam, the offending HOM's and the correcting action of the feedback, including noise and bunch to bunch coupling in the detector circuit, the implementation of the digital filter and independent adjustment of the filter gain and saturation and the kicker power.

The conditions under which we have tested most feedback configurations are :

- nominal intensity of the bunch current;
- number of bunches B = 30, 25 ("gap" of five RF buckets);
- initial time offset of 100 ps of one injected bunch;
- *dummy* HOM (see [2])
  R/Q = 20 Ω, Q = 250, 500
  $f_{HOM} = (12{*}30 + 1 + Q_s) f_{rev} \sim 1.1$ GHz;
- number of taps in the digital filter = 5, 20
- feedback gain ~ 20 KeV/rad;
- kicker voltage = 400, 500 V.

Under all the above conditions we have consistently measured a damping time of ~ 100 μs with no HOM's, and an overall damping of all the bunches even in the presence of a dummy mode with 10 KΩ shunt impedance at the frequency where the fastest growth rate occurs. The maximum time offsets of 30 bunches tracked over 3000 revolutions in the presence of such HOM are reduced from ~ 700 ps without feedback, down to ~ 12 ps with feedback (5 taps).

5. CONCLUSIONS

From the results of this preliminary study we are convinced that a longitudinal feedback system largely based on digital techniques is feasible and works well according to the initial performance specifications that we aim to (damping time of 0.1 - 0.2 ms, 30 bunches).

Down-sampling to a level of a 5-taps digital filter is acceptable. The number of DSP's needed is *modest*.

Although many components in the system are the state of art of electronics, all the required hardware, from the front-end to the power amplifiers, is market-available. Expected improvements of the performances of future DSP's can furtherly reduce the complexity of the digital system.

A power amplifier of ~500 W is enough to damp transients of 100 ps with 30 bunches at the full design current. The number of power amplifiers-kickers will be increased four-fold when we run DAΦNE with 120 bunches.

The performances are not affected in the case of an asymmetric fill.

6. ACKNOWLEDGEMENTS

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