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THE TRANSVERSE FEEDBACK SYSTEM FOR THE CERN PS BOOSTER

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Summary

With the operational beam intensity in the PSB continuing to increase, transverse stability will soon become a limiting factor. To damp transverse instabilities, a wide band feedback system has been designed and built, and it is being installed at present. It consists of eight independent systems (four rings, two planes), based on the usual scheme (position sensor, and deflector located at an odd number of betatron quarter wavelengths). Specific features of the PSB system are: large bandwidth (> 50 MHz), limited by easily modifiable filters; continuous and automatic delay tracking (by digitally controlled delay lines) coping with the proton velocity variations ($\beta \approx 0.31$ to 0.84); automatic suppression of the closed-orbit induced signal, allowing considerable savings in the power rating of the output amplifiers. The paper describes the system and its characteristics.

General Description

The system consists of eight identical subsystems (one per ring and per plane). Design parameters were provided from computer studies and machine experiments conducted by H. Schönauer using an experimental damper[1] similar to the final subsystem. Figure 1 shows the basic structure of a subsystem.

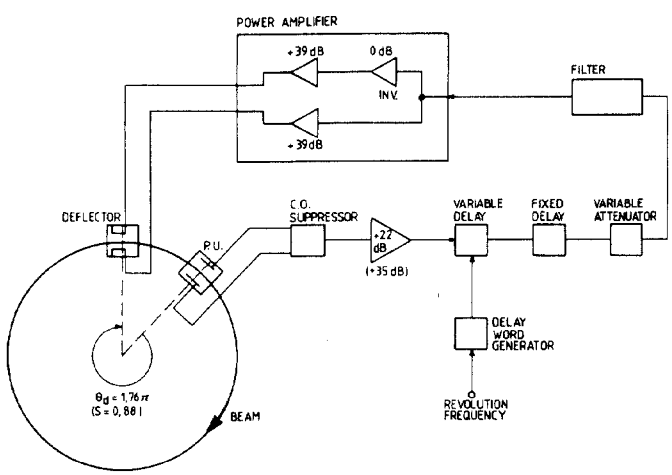

Fig. 1 - Basic system arrangement

An electrostatic sensor (Pick-Up electrode) detects the transverse position of the beam. A Closed Orbit Suppressor subtracts from the position signal the component due to the stable beam position at the PU location. The remaining components represent deviations due to instabilities. They are amplified and applied to a deflector so as to correct these deviations. PU and deflector positions are chosen as to have, for all realistic tune regions (at least approximately), the correct betatron phase difference of an odd multiple of $\pi/2$. The dynamically programmed working tune of the PSB induces a swing in this phase difference of about $\pi/3$ which puts unusually tight restrictions on the electronics response.

The transit time of the beam from PU to deflector must equal that of the signal through the electronics, so that the correction will affect the same portion of beam that produced the error signal. An artificial delay line in the electronics allows the two propagation times to be matched.

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Because of the low β at injection in the PSB, the delay circuit must automatically track[2] the strongly varying flight time during acceleration.

The required information is derived from the accelerating radio frequency. For the system to behave like a pure delay, the phase shift must be linear across the bandwidth of interest. All components are designed for a much wider bandwidth and the global response is shaped by a band limiting filter. The filter is designed for linear phase up to a frequency corresponding to more than 40 dB of attenuation.

The rest of the system consists of amplifiers, gain control attenuators, and auxiliary circuitry (not shown in Fig. 1) for monitoring the operation, opening and closing the loop, and injecting test signals for beam response measurements (Photograph A).

Pick-Up Electrode and Amplifier

- Type of sensor : electrostatic, horizontal and vertical combined in the same unit (Photograph B)
- Length: mechanical = 177 mm; electrical = 160 mm
- Capacitance : 550 pF/plate
- 3 dB bandwidth (PU + preamplifer):from < 5 kHz to > 200 MHz
- Differential PU sensitivity: $9.3 \times 10^{-16}\ N_p/B_f$ [V/mm]
  where: N_p = number of protons per ring; B_f = bunching factor
  For : $N_p = 5.10^{12}$, $B_f = 0.29$, this corresponds to a sensitivity of $\approx$ 16 mV/mm peak to peak.

Closed Orbit Suppressor[3,4]

The basic diagram is shown in Fig. 2. The signals e_1 and e_2 from two opposite plates are applied through voltage controlled attenuators to a difference amplifier. The output e_s is a bunch-shaped carrier modulated by the closed orbit (D.C. or very low frequency), plus the instabilities (wide band; the lowest frequency, depending on the fractional part of Q, will be higher than 30 kHz in the PSB).

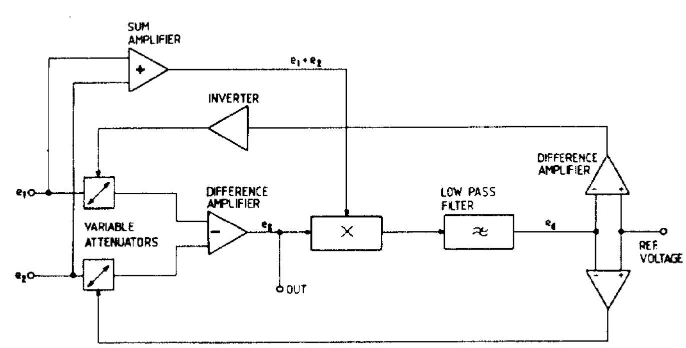

Fig. 2 - Diagram of closed orbit suppressor

A signal e_d proportional to the closed orbit is obtained by synchronous detection techniques and controls differentially the attenuators in such a way that e_d is minimized. It can be shown[3] that this in effect removes from e_s the modulating components within the pass band of the synchronous detector. i.e. the closed

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orbit components, leaving the rest of the spectrum essentially unaffected.

The degree of suppression depends critically on the phase relationship between e_1 and e_2. Propagation times from PU plates to C.O.S. must be carefully matched.

The closed orbit component is normally, by far, the largest in the PU signal. It generally determines therefore, with the system gain, the power that the output amplifier must handle. A good degree of suppression is hence important.

For a B_f of ≈ 0.3, at 800 MeV (8 MHz radio frequency) closed orbit rejections of more than 60 dB have been obtained.

Amplifiers and Filters

Low level

The loop gain is distributed in several places along the chain, to match at each point the dynamic range of the various elements. Global parameter values are given here.

- Gain : + 22 dB (optional + 35 dB)
- 3 dB bandwidth : < 5 kHz to > 200 MHz
- Deviation from linear phase shift : ± 5° from 10 kHz to 100 MHz.

Band limiting filter[5]

- Type : equi-ripple group delay, 9th order (low pass)
- 3 dB cut-off frequency : 13 MHz
- Deviation from linear phase : ± 5° from 0 to 40 MHz
- Attenuation at 40 MHz : $\approx$ 40 dB.

Alternative values of the cut-off frequency might be adopted after system evaluation.

Deflector

- Type : twin 50 Ω transmission line (Photograph C)
- Length: mechanical = 377 mm; electrical = 240 mm

Vertical and horizontal combined in one unit.

The two transmission lines are driven in phase opposition. Power, fed at the downstream end, travels in a direction opposite to the beam in order to benefit from the addition of the electrostatic and electromagnetic effects. Their relative and absolute influence depend on beam energy. The deflection sensitivity for a centred beam is: $S_d \approx 3.4 \times 10^{-8}$ rad/V at 50 MeV; $S_d \approx 4.1 \times 10^{-9}$ rad/V at 800 MeV, referred to the voltage between plates, i.e. twice the transmission line voltage.

Automatic Delay Circuit

The principle of operation is similar to the one used at FNAL[2,6,7]. The signal goes through a set of delay cables, with propagation times in binary progression. Each cable can be switched in or out of the signal path by an analogue signal gate[8], and the gates are controlled by a binary delay word, representing the value of the required delay as a multiple of the shortest cable delay. A counter continuously measures the required delay and updates the delay word. To avoid transients, the signal is gated off for 2 µs just before each updating.

If $S = \theta_d/2\pi$ is the fraction of circumference from PU to deflector, f the accelerating frequency, h the harmonic number (f/h = revolution frequency), the proton flight time is $T_1 = (Sh/f)$. If T_2 is the fixed delay (cabling, filter, electronics), then the variable part must be $T_1 - T_2 = (Sh/f) - T_2$; if T is the delay unit (shortest cable in the binary set), then the delay word must be $n = (T_1 - T_2)/T$. To have n positive, one must have $T_2 \leq (Sh)/f_{max}$. One obtains n by the arrangement of Fig. 3. Preset counters 1 and 2 start together and count respectively N_1 radio-frequency periods and N_2 periods of a reference frequency f_0. Counter 3 counts f_0 between the stop of 2 and that of 1. Its count will be $N_3 = (f_0 N_1/f) - N_2$. If one selects $N_1 = (Sh)/Tf_0$ and $N_2 = (T_2)/T$, one obtains $N_3 = (T_1 - T_2)/T = n$. At the end of the count N_3 is loaded into a latch memory and a new measurement begins.

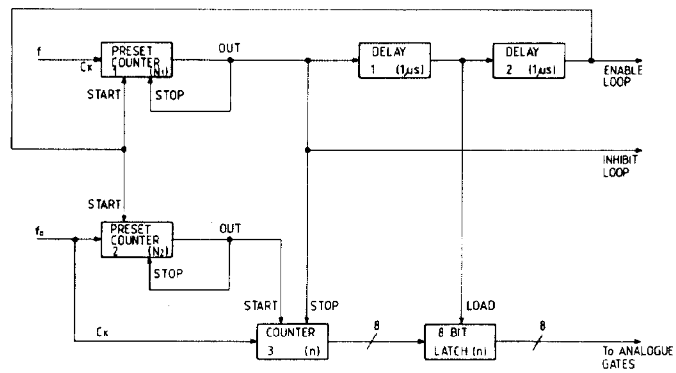


Fig. 3 - Diagram of delay control

In the PSB, S = 0.88; h = 5; T_1 = 1470 ns at 50 MeV and 550 ns at 800 MeV, a variation of 920 ns. With T = 4 ns and an eight bit delay word, we have 1020 ns. T_2 must therefore be between 450 and 550 ns. As the electronics delay is shorter, fixed delay cables have been added to bring T_2 up to 500 ns. With f_0 = 2 MHz, one must have N_1 = 550, N_2 = 125.

Fine tuning of the delays can be made by varying N_2 and/or N_1.

Gates

The analogue gates[8] that switch the delay cables must not introduce delay errors, gain variations or impedance mismatching. They consist therefore of twin gates, arranged so that from input to output the signal goes either through one gate or through one gate plus one delay cable. The two gates are matched very carefully in gain and delay, and buffers are provided to isolate input from output impedances. All signal paths are properly terminated at all times, and the total number of gates traversed by the signal is always 9, independent of the delay word. The entire switching system can be considered as a unit, with the following characteristics:

- Gain : 0 dB
- 3 dB bandwidth : from < 5 kHz to > 100 MHz
- Deviation from linear phase : ± 15° from 10 kHz to 50 MHz.

System Open Loop Gain

The definition of loop gain in the usual way G = response/stimulus (e.g. G = deflection caused by deflector/beam angle error at the deflector) is not straightforward for a bunched beam, because G would be a function of beam intensity and longitudinal distribution, varying along the bunch. It would also depend on proton energy (deflector efficiency) and Q (position to angle transformation from PU to deflector).

With several simplifying assumptions we estimated G at 50 and 800 MeV, for an unbunched beam of $N_p=5.10^{12}$ protons per ring, with typical values of betatron tune. The corresponding e-folding time of the strongest instabilities that one would expect to be able to damp has also been estimated (the reduction in loop gain from 50 to 800 MeV is partially compensated by the increase in revolution frequency).

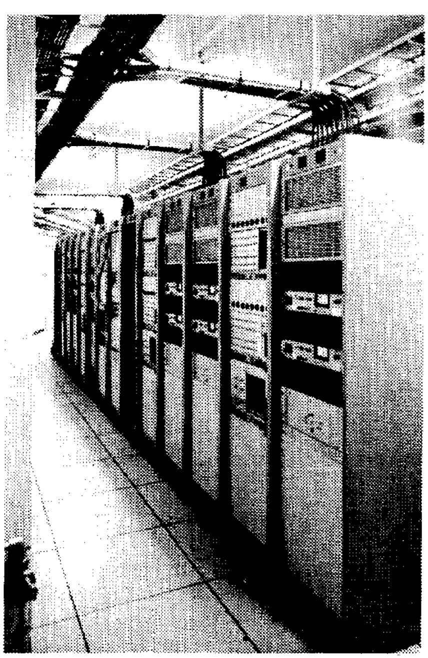
Energy [MeV]	Plane	Q	G	τ [ms]
50	H	4.3	$2.1\ 10^{-3}$	0.80
50	V	5.45	$1.6\ 10^{-3}$	1.05
800	H	4.2	$2.5\ 10^{-4}$	2.50
800	V	5.25	$1.4\ 10^{-4}$	4.35

Conclusion

The system is at present in the final phase of installation. Pilot tests with beam on a prototype proved the feasibility of the scheme and provided information for the design. Commissioning tests will begin in the near future. The figures given in this paper are the result of laboratory measurements (without beam). In some cases (e.g. deflector efficiency) they are design figures.

Acknowledgements

We wish to thank all the persons that have contributed to the construction and installation of the various elements of the system.



A - Rack arrangement in auxiliary Booster Tunnel. Three racks contain the damping systems for one Booster ring; delay cables overhead.

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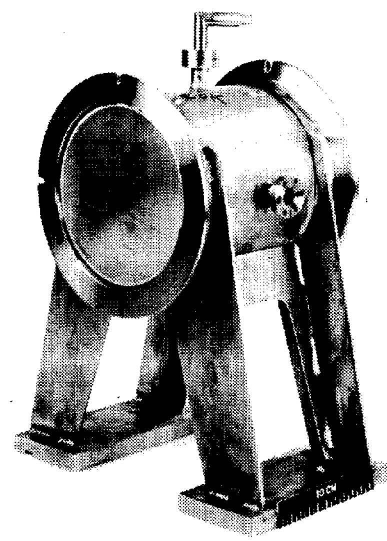
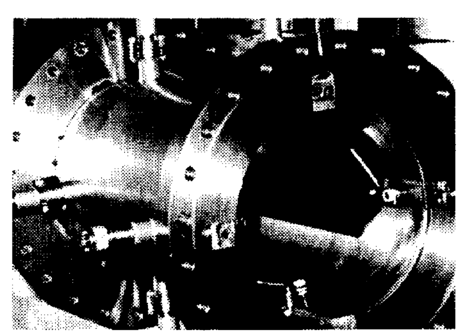


B - PU electrode for horizontal and vertical planes.



C - Transmission line deflector for horitzontal and vertical planes.