Design and Operational Results of a "One-turn-delay Feedback" for Beam Loading Compensation of the CERN PS Ferrite Cavities

F. Blas, R. Garoby
PS Division, CERN, CH-1211 Geneva 23

Abstract

The periodic transient beam loading in the CERN PS ferrite cavities was diagnosed in 1989 to be the source of performance limitations for the antiproton production beam [1]. A project was then launched to lower the transient beam induced voltage by a factor of four, with a "one-turn-delay feedback" system reducing the equivalent cavity impedance on the first 3 revolution frequency side-bands around the cavity tune frequency. The design is able to cope with a wide frequency range due to particle acceleration (15 % velocity variation) and choice of harmonic number (h=10 to 20). Loop gain is above 0 dB in the vicinity of revolution frequency harmonics over an instantaneous bandwidth of 3 to 4 times the 3 dB bandwidth of the original RF system. Fast digital electronics is applied extensively, resulting in a very reliable and compact implementation. The various functions are described, closed loop performance of a cavity is shown and measurements with beam are presented.

I. INTRODUCTION

After the implementation of a fast feedback around each high power amplifier and cavity system [2], the full set of RF gymnastics proposed in 1983 for the antiproton production beam in the PS was put into operation in 1988 [1]. Performance was then limited by the periodic transient beam loading induced in the cavity because of the partial filling of the machine with particles. Troubles were especially obvious at transition and whenever the voltage was supposed to be reduced continuously to zero on a cavity (as in figure 1 with 1.7 10^{13} protons).

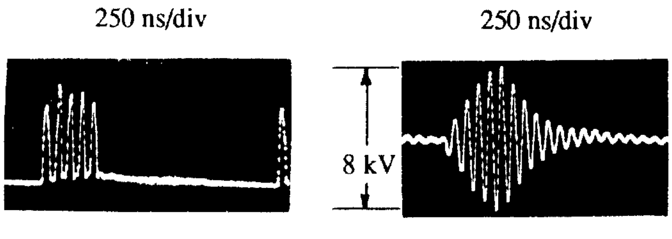

Figure 1 : Beam current and beam induced voltage in a cavity.

The first 3 revolution frequency harmonics of the beam current on each side of the RF are responsible for the cavity voltage shown. The loop gain of the fast feedback having already been pushed to its practical limit, no further increase by a factor of four (12 dB) could easily be expected, so that a complementary system was needed to help reduce the cavity impedance.

II. PRINCIPLE OF ONE-TURN-DELAY FEEDBACK

The beam current spectrum is localized in narrow frequency bands (~10 kHz) centred around revolution frequency harmonics ($f_{RF} \pm 3\ f_{REV}$). Moreover, no other feedback loop is active other than at the RF frequency. A total electrical delay of one revolution period is then tolerable in the feedback loop, since high loop gain is only needed over a limited bandwidth and the phase can be correct simultaneously at each revolution harmonic. Such a "one-turn-delay feedback" system has already been designed and applied to wide-band cavities [3]. Figure 2 shows the basic block diagram with the fundamental functions.

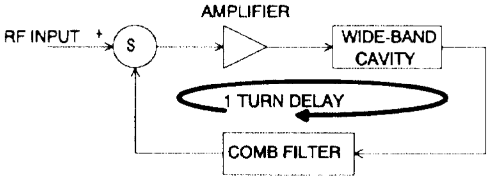

Figure 2 : Block diagram of a one-turn-delay feedback system.

Apart from the requirement for a total electrical delay of one machine turn, a comb filter with gain maxima at harmonics of the revolution frequency is necessary.

III. PRACTICAL REALIZATION

Special features

Table 1 : Feedback specifications.

Loop gain	≥ 12 dB at $f_{RF} \pm f_{REV}$
Revolution frequency	415 kHz to 480 kHz
Harmonic number (h_{RF})	10 to 20 (continuous variation)
RF frequency	4.15 MHz to 9.6 MHz
High power system	~ Cascade of 2 resonators with 1 MHz & 2 MHz 3 dB bandwidth

Table 1 lists the requirements and figure 3 presents the overall system set-up. All the processing is done digitally using ECL circuits after analogue-to-digital conversion (8 bits) at the base-band without heterodyning. The comb filter and the "automatic delay compensation" have a clock frequency of 80 f_{REV}, so that their useful bandwidth extends comfortably to more (~ h=28) than the highest line to be compensated (h=23).The notch filter, clocked at 4 f_{RF}, is needed to reduce the loop gain around the RF frequency and to avoid any

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interference of this new feedback with the many other existing loops (AVC, tuning, beam phase loop, etc.).

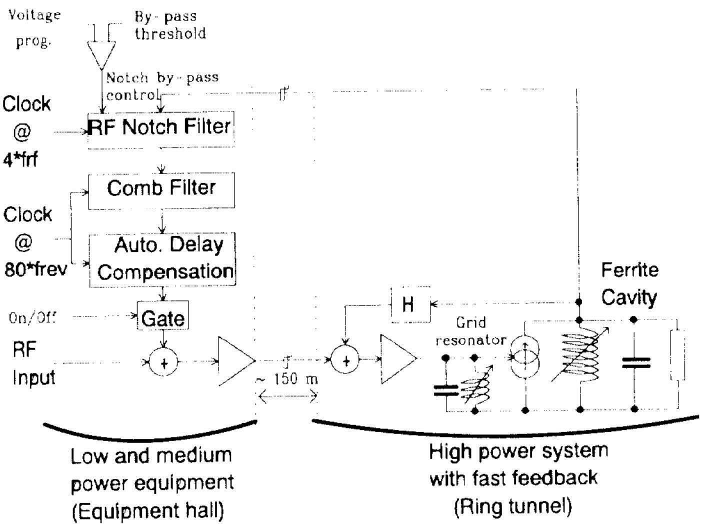

Figure 3 : Block diagram of the practical realization.

Auxiliary functions are included for on/off control of the loop and to cancel the action of the notch filter when the cavity is left idle with a voltage program at 0 V.

The transfer function of the high-power RF system is shown in figure 4. The 3 dB bandwidth is limited to 1 MHz and the phase shift is 270° over a 3 MHz frequency band, due to the low-Q resonator in the grid of the final tube (figure 3) [2]. Loop stability is preserved by making the overall electrical delay, τ_{total} , smaller than the revolution period, T_{REV}. In fact ,

$$\tau_{total}=T_{REV}(1-1/h_{RF}) \qquad (1)$$

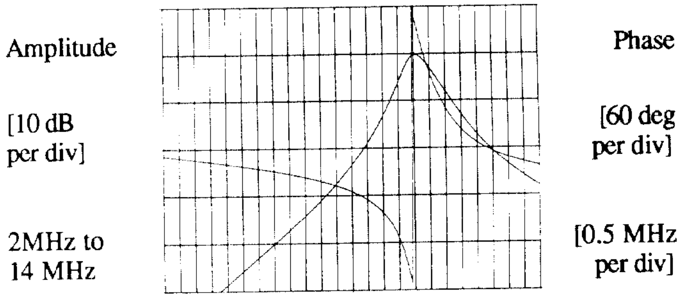

Figure 4 : Transfer function of the high-power RF system.

Comb filter

This is realized as a single-coefficient recursive filter (figure 5) [3]. Its transfer function is given by the z transform

$$C(z)=\frac{a}{\left(1-(1-a)z^{-80}\right)} \qquad (2)$$

with $a=2^{-4}$.

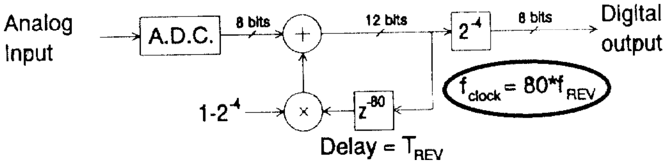

Figure 5 : Comb filter lay-out.

Gain maxima of 0 dB are obtained at all harmonics of the revolution frequency with a 3 dB bandwidth of 15 kHz. Gain minima of -30 dB are located at (n+1/2) f_{REV}. The 8-bit output is fed directly in digital form into the "automatic delay compensation unit".

Notch filter

The notch filter is also recursive (figure 6) and its transfer function is given by :

$$N(z)=\frac{\left(1-z^{-4}\right)}{\left(8/7-z^{-4}\right)} \qquad (3)$$

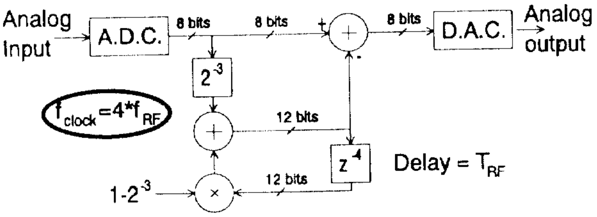

Figure 6 : Notch filter layout.

The output is converted back into analogue form before being sent to the next modules. The open-loop gain resulting from the cascade of the comb and notch filters with the high-power RF system is shown in figure 7.

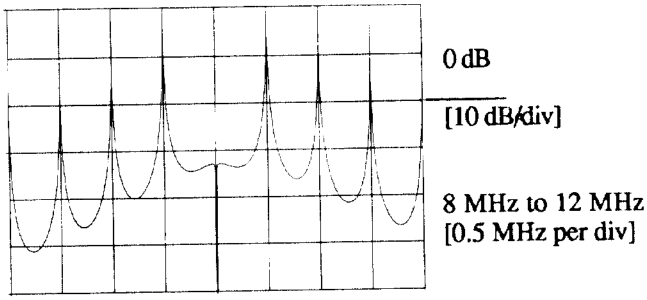

Figure 7 : Open-loop gain

Automatic delay compensation.

The overall electrical delay of the full loop is stabilized at

$$\tau_{total}=T_{REV}(1-1/h_{RF}) \qquad (4)$$

by the action of the automatic delay compensation. The system is based on a "first-in-first-out" register (FIFO), whose clocks are connected as described in figure 8.

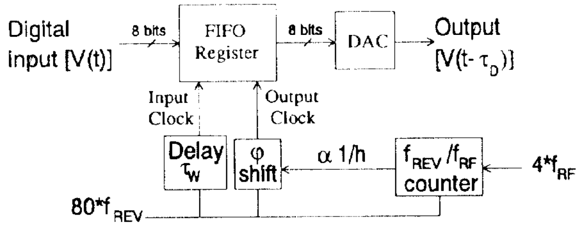

Figure 8 : Block diagram for delay compensation.

The FIFO is preset with n_0 cells at a clock frequency f_{C0} (period T_{C0}) and the delay in the unit is

$$\tau_{D0}=\tau+n_0 \cdot T_{C0} \tag{5}$$

where τ is a constant group delay. At constant RF harmonic number h_{RF} when the clock is at f_C, the number of cells in the FIFO has changed by

$$\Delta n=(f_{C0}-f_C)\tau_W \tag{6}$$

and τ_D has become

$$\tau_D=\tau+(n_0+f_{C0}\cdot\tau_W)T_C-\tau_W. \tag{7}$$

Noting that $(n_0+f_{C0}\cdot\tau_W)T_C$ is a constant phase shift for all harmonics of the revolution frequency ($T_C=T_{REV}/80$), τ_D behaves as a negative delay $\tau-\tau_W$, which can compensate for the large electrical delay in the full RF system (~2 μs).

On top of this, a phase shift proportional to $1/h_{RF}$ is applied to the output clock to obtain the result quoted in equation (4). $1/h_{RF}$ is measured in real time, counting the length of T_{RF} in units of $T_{REV}/80$.

IV. RESULTS

Closed-loop transfer function

A typical closed-loop transfer function measured between the low-level RF input and the cavity gap, with the feedback on or off, is shown in figure 9.

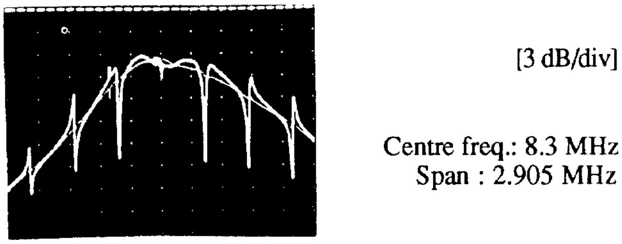

Figure 9 : Closed-loop transfer function (RF notch active).

The gain decreases as required by 12 dB on the first 2 revolution side-bands, the gain at the following ones being approximately at the same absolute level, so that the beam sees an equivalent resonator with a Q lowered by a factor of four.

Results with beam

A reduction factor of 3.3 is measured, by comparison with the situation without feedback, for the peak voltage induced in an idle cavity (figure 10). The successive bunches now experience the same transient beam loading voltage.

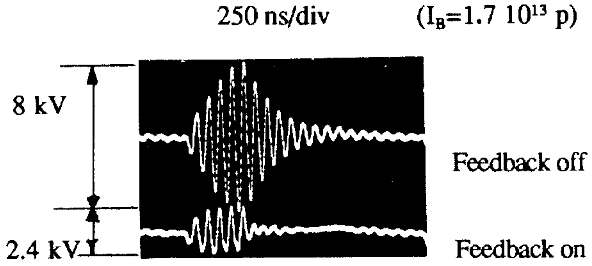

Figure 10 : Beam induced voltage in a cavity.

The full installation on the ten ferrite cavities was put into operation in September 1990. The expected improvements [1] were indeed observed : the 3% loss when crossing transition has almost disappeared as well as most of the bunch shape oscillations triggered by the various gymnastics. However, the coupled bunch instabilities thresholds have not been clearly reduced, which indicates that the disturbing impedance is not due to the cavities. Consequently, the intensity of the antiproton production beam could be raised by 10%. Using the RF dipole in the 1 GeV transfer line between PSB and PS[4], a record intensity of 1.85 10^{13} ppp has been achieved with an acceptable beam quality, while 1.7 10^{13} ppp was routinely obtained in operation.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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