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

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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).

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}+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.](image)

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.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop gain</td>
<td>≥ 12 dB at f_{rF} ± f_{Rev}</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>415 kHz to 480 kHz</td>
</tr>
<tr>
<td>Harmonic number (h_{rF})</td>
<td>10 to 20 (continuous variation)</td>
</tr>
<tr>
<td>RF frequency</td>
<td>4.15 MHz to 9.6 MHz</td>
</tr>
<tr>
<td>High power system</td>
<td>~ Cascade of 2 resonators with 1 MHz &amp; 2 MHz 3 dB bandwidth</td>
</tr>
</tbody>
</table>

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
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, \( \tau_{\text{overall}} \), smaller than the revolution period, \( T_{\text{REV}} \). In fact,

\[
\tau_{\text{overall}} = T_{\text{REV}} \left(1 - \frac{1}{n_{\text{RF}}} \right) \tag{1}
\]

Amplitude

[10 dB per div]

2 MHz to 14 MHz

Phase

[60 deg per div]

[0.5 MHz per div]

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

\[
C(z) = \frac{a}{(1 - (1 - a)z^{-80})} \tag{2}
\]

with \( a = 2^{-4} \).

Notch filter

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

\[
N(z) = \frac{1 - z^{-4}}{(8/7 - z^{-4})} \tag{3}
\]

Figure 6: Notch filter layout.

Automatic delay compensation.

The overall electrical delay of the full loop is stabilized at

\[
\tau_{\text{overall}} = T_{\text{REV}} \left(1 - \frac{1}{n_{\text{RF}}} \right) \tag{4}
\]

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.
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.

![Beam induced voltage in a cavity.](image)

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 PSI[4], a record intensity of $1.85 \times 10^{13}$ ppb has been achieved with an acceptable beam quality, while $1.7 \times 10^{13}$ ppb was routinely obtained in operation.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES


