Improved Impedance Reduction in the CERN SPS Superconducting Cavities for High Intensity Proton Operation

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I. INTRODUCTION

Two four cell superconducting cavities are installed in one bimodule in the SPS accelerator to provide accelerating voltage for leptons. The four 3,5 GeV-20 GeV lepton cycles are interleaved with a 14 GeV-450 GeV fixed target high intensity proton cycle, the composite supercycle being 14.4 s long. The extremely high impedance of the superconducting cavities is unacceptable for the high intensity proton beam and to maintain beam stability the resonances in the main cavity passband must be heavily damped. This damping is produced by an RF feedback system [1]. The limitations for this feedback system are due mainly to the proximity in frequency of the two upper resonances in the cavity and the loop delay. Typically a final, operationally reliable, impedance of ≈ 400 KΩ/cavity can be obtained. Measurements on the proton beams at high intensity have shown that with two cavities in the machine this impedance produces coupled bunch instabilities when $\approx 3\times10^{13}$ protons/pulse are accelerated. As there are plans to increase the proton intensity beyond this value, and since the possibility also exists of installing a second bimodule for lepton acceleration, it has become very important to study possible methods of further reducing the total impedance. Two methods have been studied, built and tested in machine development periods, both of these acting as a supplement to the existing RF feedback system. The first consists of a feedforward loop injecting a beam current signal into the feedback loop and the second consists of an additional feedback loop around the first, acting only at harmonics of the revolution frequency.

II. THE BIMODULE AND EXISTING FEEDBACK

Each superconducting cavity consists of four coupled cells producing four resonances in the main passband at 347, 349, 351 and 352 MHz. The latter, the π mode, is used for acceleration and has an R/Q of 230 Ω; the others interact to a much smaller extent with the beam. The extremely high Q_{ext} of each resonance, $\approx 3\times10^7$, is reduced by the RF feedback during proton operation to $\approx 2\times10^3$ giving an impedance on the π mode of ≈ 400 kΩ. This feedback is shown schematically in Fig. 1a. The detailed design and functioning of the loop have been described previously [1]. For the present purposes, the transfer function of the ensemble from point A to point B is given by:

$$X(s) = \frac{Z(s)G_1(s)\, e^{-s\tau'}}{1 + Z(s)G_1(s)\, e^{-s\tau}}$$

where Z(s) is the transfer function in-out of the cavity (V(s)/Ig(s)), τ the total loop gain, τ' the measurement path delay and $G_1(s)$ the amplifier gain (≈ constant for the upper two modes). The amplitude response of this closed loop is given in Fig. 2.

III. FEEDFORWARD COMPENSATION

A. Implementation

The principle is to cancel the voltage induced in the cavity by the beam current by injecting an equal and opposite current via the power amplifiers. The implementation is shown schematically in Fig. 1b. A signal proportional to the beam current is derived from a wideband monitor situated close to the superconducting cavity. Provision is made for adjusting both the phase and amplitude of this signal and a gate is incorporated to allow switching during the proton cycle. Since the bandwidth of the amplifier is significantly wider than that of the cavity, care must be taken to avoid loading the power amplifier unnecessarily. For this reason a bandpass filter is added in the chain. The bandwidth is a compromise between the amplifier requirements and the need for minimum delay since any delay in the feedforward path reduces the efficiency of the feedforward compensation at frequencies away from the centre. In practice the filter had a 2.8 MHz bandwidth (delay ≈ 150 ns).

The effective impedance of the cavity with feedforward is defined as:

$$Z_{eff}(s) = \frac{V(s)}{I_b(s)} = \frac{Z(s)\left[1 - G_2(s)e^{-s\tau''}\right]}{1 + Z(s)G_1(s)e^{-s\tau}}$$

where τ'' is the total delay in the feedforward path; i.e the electronic delay from monitor through to cavity plus the beam delay cavity to monitor (which may be negative). $G_s(s)$ is the gain in the forward path.

B. Results with Beam

The phase and gain were adjusted using the signal of the beam induced voltage in the cavity. A spectrum analyzer was used to observe a few revolution frequency lines centred on the π mode, the feedforward being switched on just after transition energy during the proton cycle and switched off again just before extraction at 450 GeV. Fig. 3 shows a typical result, a reduction in impedance of ≈10 dB being obtained. Observation on a much wider frequency bandwidth covering the two modes in the passband of the filter gives results shown in Fig. 4. The reduction in signal on the π mode is accompanied as expected by the emergence of the signal on the lower mode. Even for a perfect feedforward correction on the π mode, the observed signal V(s) does not vanish completely at 352 MHz, because of the contribution of the other mode. Precise phase and amplitude settings of the feedforward path (which are independent of the RF feedback gain) are better adjusted with high Q separated resonances (low RF feedback gain). The total delay in the feedforward path was ≈ 530 ns. It is clear that with this delay the injected current changes phase by π between 351 and 352 MHz, thus limiting the efficiency of the feedforward. However it will be improved significantly (reduction of 230 ns) by replacing the existing monitor by a dedicated monitor upstream of the cavity. Another limitation of the method is the residual R/Q of the other modes which cannot be corrected.

IV. ONE TURN DELAY FEEDBACK

IV.1 ONE CAVITY

B. Implementation

The delay in the main feedback loop combined with the proximity of the resonant frequencies forces a limitation in gain of the system and hence of impedance reduction. If we look at the transfer function on a network analyzer and unravel the response with a delay correction, negative, we see that the four cavity resonances can all be superimposed in the right half of the complex plane (Fig. 5a) and that therefore if such a delay could be inserted in series, a secondary feedback loop could be used to further reduce the impedance. In a synchrotron the frequencies where loop gain is beneficial occur at multiples of the revolution frequency, f_{rev}. If $f_{rev}>>f_s$, the synchrotron frequency, then only a small bandwidth at each harmonic is important. A comb-filter in the feedback path can be used to select these bands and the total delay of the loop can be increased to $\tau_{rev}=1/f_{rev}$ to rotate the phase by 2π between each harmonic [2] [3]. This produces, for these bands, the same result as the negative delay mentioned above. The cavity impedance with this extra loop is defined as:

$$Z_{eff}(s) = \frac{Z(s)}{1 + G_1(s)Z(s)e^{-s\tau} + G_1(s)G_3(s)Z(s)e^{-s(\tau + \tau'')}}$$

τ'' is the "one-turn" loop delay and $G_3(s)$ is the loop gain which includes the comb-filter response:

$$H(s) = \frac{(1-k)e^{-s\tau_{rev}}}{1-k\,e^{-s\tau_{rev}}}$$

The layout is given in Fig. 1c for this particular implementation. The signal at 352 MHz is mixed down in two stages to 5MHz, after which it is digitised. The signal then passes through the comb filter and delay, (bandwidth 0-->10MHz), both realised in digital form [2], and then, after the DAC, is remixed to 352 MHz. Phase and amplitude adjustment are provided plus an RF switch and following amplification the signal is reinjected into the main loop. The delay phase and gain are adjusted in open loop using the network analyzer (the delay tolerance is found to be ± 25 ns). The two upper resonances are shown with delay correction in Fig. 5b and after the comb-filter in Fig. 5c. What remains is the non-linear phase response of the system. The closed loop response is given in Fig. 6. Here the "tails" on the response are due to these residual errors, which could be compensated if necessary using an equalisation filter. The spacing of the four resonances is not exactly the 1 MHz and 2 MHz quoted and consequently it is impossible to "place" all four resonances one on top of the other. With the delay optimised for the upper two, the lower two would seriously reduce the maximum loop gain possible. For this reason, the lower two are rejected by notch filters [1].

B. Results with Beam

The combination of loops implemented on one cavity was tested using beam. The second cavity in the bimodule was used to render the beam unstable at top energy by reduction of the main feedback gain. The difference in gain values on this cavity for instability threshold when the single-turn feedback on the other cavity is ON or OFF gives a measure of the effective impedance reduction. A reduction of 5 x in impedance has been reliably obtained.

IV.2. TWO CAVITIES

A. Implementation

A one-turn feedback system can be used independently on each cavity in the bimodule. A more economic system is to make the vector sum of the signals from the cavities and correct via a single cavity. This is shown in Fig. 1d. Again provision is made for independent phase and amplitude control. The easiest way to adjust this was found to be to use a difference hybrid and set the controls for minimum beam-induced signal at the output. The introduction of 180° delay then produces the required sum signal. One point to note is the increased power requirement on the power amplifier used for feedback. Performance is limited by inaccurracies in the summation [4].

B. Results with beam

This technique has been tested on the SPS and its efficiency estimated by reducing the main feedback gain and searching for the instability threshold. An impedance reduction of ≈ 3 x is estimated.

V. CONCLUSIONS

It has been shown experimentally that a feedback system around a multi-cell cavity can be complemented in two ways by feedforward and single.turn feedback. It has also been shown that the impedance of two multi-cell cavities can be reduced by using the vector sum of the two as reference for the single turn feedback loop.

VI. REFERENCES

[1] RF feedback Applied to a Multicell Superconducting Cavity. D. Boussard, H. P. Kindermann, V. Rossi. EPAC Rome 1988

[2] Reduction of the Apparent Impedance of Wideband Accelerating Cavities by RF feedback, D. Boussard, G. Lambert, IEEE 1983 PAC Santa Fe

[3] Design and Operational Results of a "One-Turn Delay Feedback" for Beam Loading Compensation of the CERN SPS Ferrite Cavities. F. Blas, R. Garoby, IEEC 1991 PAC San Francisco

[4] RF Cavity Feedback, F. Pedersen, CERN PS/92-59

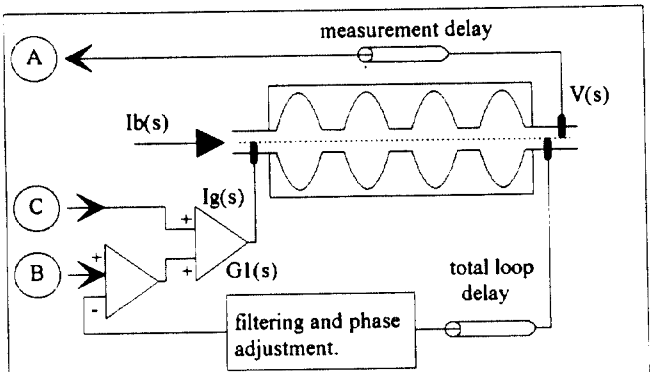

Fig. 1a RF feedback, normal operation.

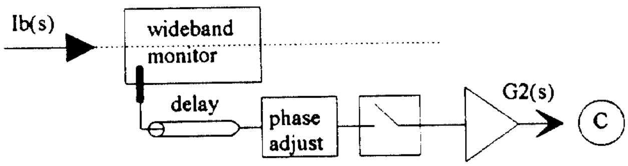

Fig. 1b Addition of feedforward.

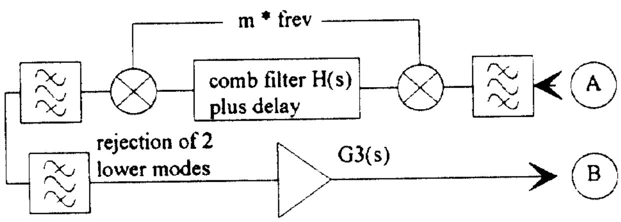

Fig. 1c Addition of one-turn feedback.

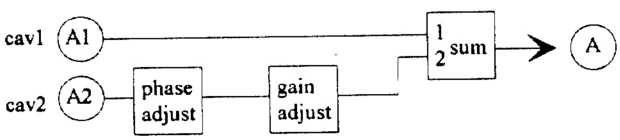

Fig. 1d Addition of 2 cavities to one turn feedback.

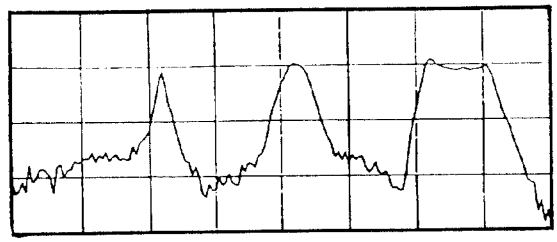

Fig. 2 4 resonances of damped cavity
349 MHz ± 4 MHz (H); 10 dB/div (V)

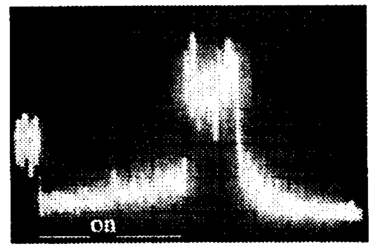

Fig. 3 Effect of feedforward
0.5 s/div (H)
5 dB/div (V)

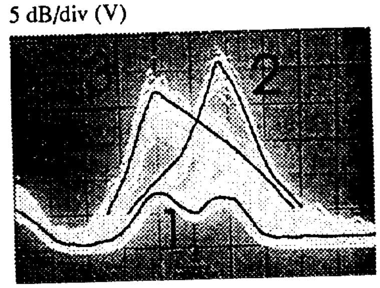

Fig. 4 Spectrum of feedforward
500 KHz/div (H)
5 dB/div (V)
1. System noise
2. Feedback off
3. Feedforward on

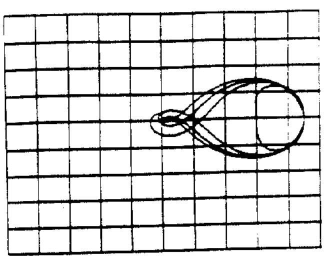

Fig. 5a Calculated response
4 resonances with delay correction

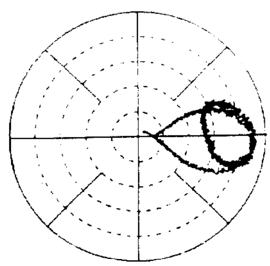

Fig. 5b Measured response
with delay correction, upper two modes

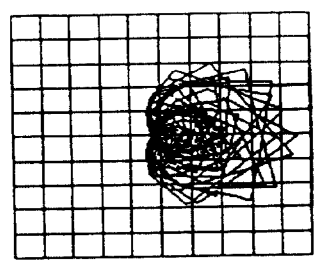

Fig. 5c With comb filter

Fig. 6 Response with and without one turn feedback