RF SYSTEM FOR HIGH BEAM INTENSITY ACCELERATION IN THE CERN PS

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Introduction

Heavy beam loading is encountered in the main RF system of the CERN Proton Synchrotron (PS) [1]. This consists of 11 ferrite loaded cavities, each one capable of developing 20 kVp between 2.6 and 10 MHz. Harmonic 20 is normally used for acceleration, and feedforward compensation has been used in the past to suppress beam loading instabilities. This technique could not satisfy the stringent requirements of the antiproton production beam for the Antiproton Collector (AC).

RF feedback around the final amplifier and the cavity has been implemented. All power amplifiers have been rebuilt, adding amplification stages and auxiliary equipment, but keeping the same high power tetrode to drive the cavity (RS 1084 with 80 KW plate dissipation). The installation was completed as scheduled for February 1988, and many different types of beams have been successfully handled since, including a record intensity of 2.34 e13 protons per pulse. Various hardware improvements were subsequently implemented and extensive beam measurements accumulated. The present hardware status, together with the experience gathered over 1 year of operation, are described in this paper.

Beam loading in the ferrite cavities

High beam intensities are regularly accelerated in the PS when injecting into the SPS running fixed target physics (> 2.2 e13 protons per pulse), and for pbar production (> 1.5 e13 ppp). Letting I_b and I_0 be the peak RF components of the beam current and of the resistive current flowing into a cavity, relative beam loading can be defined as $Y = I_b/I_0$ [2]. Characteristic values of Y experienced in the PS are listed in table 1.

Operation	Protons (in ppp)	Y during inject.	trans.	RF gym.
SPS fixed target	2.3 e 13	2.5	1.5	2.5
Pbar prod. for AC	1.5 e 13	1.6	1.	4.

Table 1 : Relative beam loading in a "naked" cavity during typical PS cycles.

At these levels of Y, a fast instability [2] develops because of the cross-coupling introduced by the beam between the various feedback loops of the RF system (Cavity voltage and tuning servos, Beam Control loops).

Feedforward techniques [4] have been used until recently to compensate for the h=20 beam current component of the beam in the cavities. It performed adequately between 800 MeV and 26 GeV, and helped achieve, in the past, an intensity record of 2.2 e 13 ppp for the SPS fixed target operation. It was unfortunately not suited to handle the conditions expected during the RF gymnastics envisaged for the pbar production beam of the Antiproton Collector (A.C.) [3], as several different harmonic numbers are employed (10,12,14,16,18,20). Moreover, the relative beam loading being roughly doubled, feedforward gain and phase adjustments would have been very delicate and machine time consuming.

The RF feedback scheme

Fig. 1 illustrates the scheme actually applied [4]. The cavity and the final amplifier are included in an RF closed loop. According to standard feedback system theory, and provided that the loop stability conditions are met, the response to any perturbation is reduced by the factor $1/(1 + G_{0L})$ (G_{0L} is the open loop gain. $|G_{0L}\ (@\ f_{res})| >> 1$). The impedance Z "seen" by the beam being nothing else than the response to a 1 Amp. current perturbation into the cavity, it becomes : $Z = Z_0/(1 + G_{0L})$ (Z_0 is the naked cavity impedance).

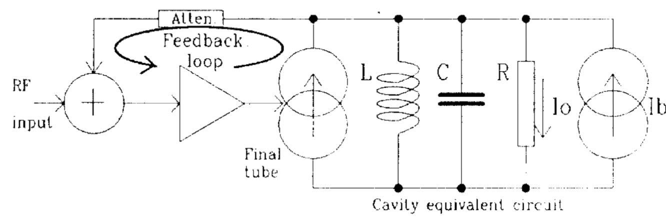

Fig. 1. RF feedback principle.

The equivalent resistive current in the cavity can be now expressed as :

$$I_0' = I_0 * (1 + G_{0L}\ (@\ f_{res}))$$

Consequently, the relative beam loading, for a given beam current, is transformed into:

$$Y' = Y/(1 + G_{0L}\ (@\ f_{res}))$$

Complementary features

Apart from the fundamental effect described above, the RF feedback scheme introduces side-benefits of major importance: (i) independence from the harmonic number. The installation is adjusted to work over the frequency range of the cavity tune, and does not depend on the harmonic number being used. (ii) no need of machine time for adjustment. Each amplifier is properly adjusted on the bench, and full performance is immediately obtained after installation in the machine. (iii) excellent long term stability. Closed loop behaviour guarantees compensation against any drifting parameter. (iv) the low level RF is in control of the voltage developed in the cavity. Phase shift of the amplification chain being stabilized (for instance against cavity detuning and beam current action), setting-up of RF gymnastics is considerably simplified, and independent of beam intensity.

PS system design

Goals

Considering the relative beam loading levels listed in table 1, taking into account the experience gained with the feedforward scheme (which, at the most, reduced the cavity impedance by a factor of 5), and estimating the hardware difficulties, we aimed at an open loop gain of 10 at the cavity resonance. This comfortably covers the high intensity operations, and includes some room for improvement. The resulting maximum equivalent impedance experienced by the beam is lower than 1 kOhms.

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Amplifier design

To reduce cost and development time, the existing high power amplification stage [5] has been kept. It is made up of an 80 KW plate dissipation tetrode (Siemens RS1084) operating in grounded cathode mode and housed in the cavity base.

A 3 tube (Siemens YL1056) driver has been added to the final amplifier plug-in, according to the description in ref. [6]. An up-dated drawing of the installation is presented in Fig. 2.

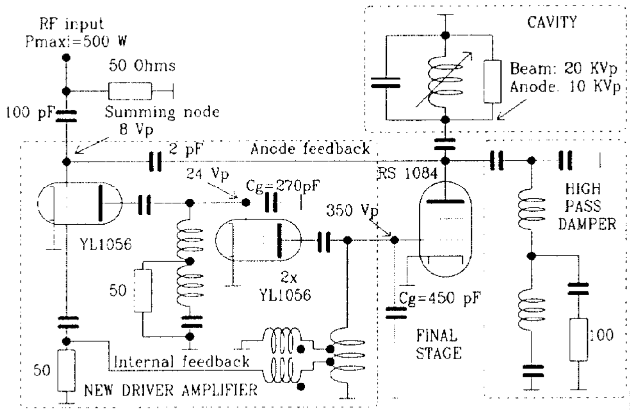


Fig. 2. Schematic of the cavity amplifier plug-in.

Grid 1 of the first YL1056 tetrode is the capacitive summing node where feedback from the cavity drive voltage and input signal are added. Both signals are fed from low impedance voltage generators through series capacitances, so that a flat transfer function is obtained over all the frequency range.

A tunable low Q resonator (<3 @ 10 MHz) on the grid of the high power tube helps develop the required voltage on this predominantly capacitive electrode. The Q is achieved by the combined actions of a 50 Ohms damping resistor and internal feedback around the driving stages. Loop stability is improved by this circuit, as well as the rejection of harmonics of the input signal.

A photograph of the rear of a complete plug-in is shown in Fig. 3. The new driver amplifier is housed in an hermetic enclosure (right of the figure) which channels the cooling air flow around the tubes. Cool air enters through the central hole and goes out through the lower and upper ones. The tubes are installed upside down to minimize the connection lengths.

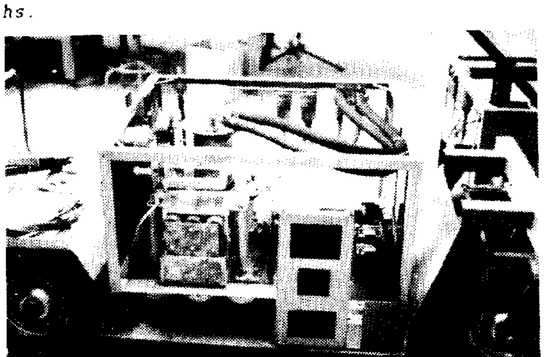


Fig. 3. Rear view of amplifier plug-in.

Auxiliary equipment

Various low power electronic modules have also been developed to : (i) bias the grid inductance properly with respect to the total cavity tuning current. Each inductance has been measured on a computer controlled measurement system, and the algorithm for optimum control programmed into an EPROM. (ii) make the cavity fine tuning loop insensitive to beam loading and to harmonics of the drive. Final tube grid and plate probe signals are heterodyned to 10.7 MHz. and processed to provide a tuning error proportional to the relative reactive power delivered to the cavity [7]. (iii) protect the hardware against self-oscillations as well as wrong control parameters.

The complete set-up is sketched in Fig. 4.

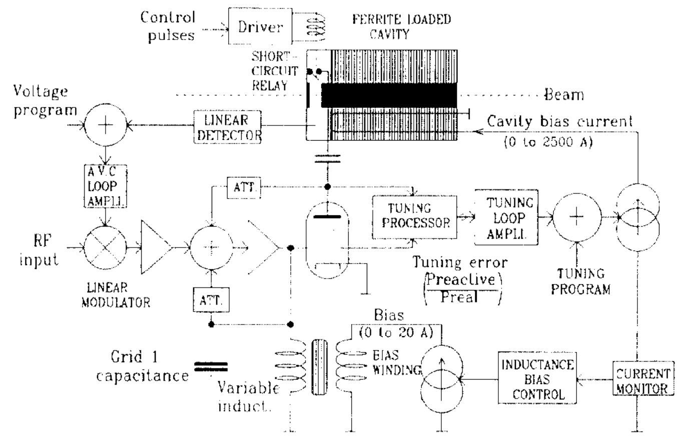
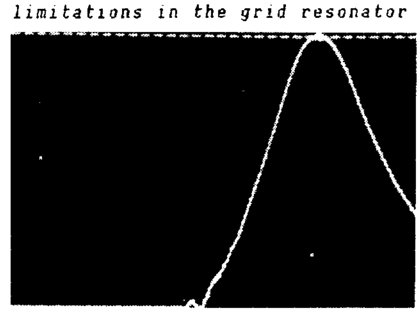


Fig. 4. Cavity and amplifier servo systems

Electrical performance

Fig. 5 shows a typical closed loop transfer function measured between input and cavity gap. Gain and 3 dB bandwidth are constant for a cavity tune frequency between 3 and 10 MHz. A slight degradation is observed below 3 MHz (Gain: +2 dB), due to limitations in the grid resonator tuning range.

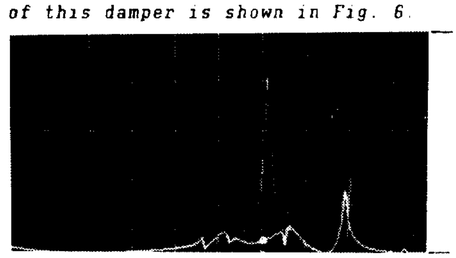


Tuning current 2500 A
Resonance freq.: 9.6 MHz
Vertic. axis : 3 dB/div.
Horiz. axis.: 1 MHz/div.

Fig. 5. "Typical" closed loop transfer functions.

An harmful cavity resonance at 34 MHz was detected during the testing when some plug-ins proved unstable in closed loop. A high pass damper has then been added to the anode of the final tube (Fig. 2), to provide a near 100 Ohms damping resistance above 30 MHz, and a negligible load below 10 MHz. The effect of this damper is shown in Fig. 6.

0.9 K Ohms



Marker @ 34.2 MHz
|Z| = 57 Ohms

0 K Ohm

Fig. 6. Anode impedance with/without damping circuit (10 - 50 MHz).

Operational hardware experience

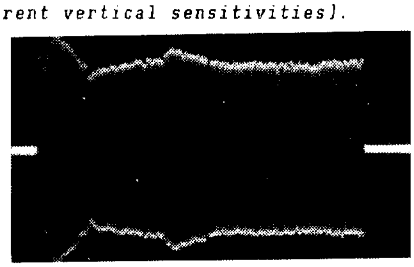
Although bench results were fully satisfying on all 15 plug-ins, difficulties were experienced after machine start-up and the early fault rate of the installation was a high 2.7% (1/2 h. down time per day). At the end of the year, after many corrective actions, that figure has been brought down to a more usual 0.7%, without any compromise in performance.

The troubles belonged to various categories : (i) design weaknesses (air filters, cooling water pipes, 34 MHz anode damper,...) (ii) burning-in of new hardware (power supplies,...) (iii) faults in the old hardware (anode choke, power supplies, tuning circuit,...)

Special mention must be made of the natural tendency of the system to use all of its power capabilities to correct any perturbation, be it a step in the input frequency or a short circuit through an electric arc... The appropriate protection electronics were included from the start, but triggering them properly proved delicate.

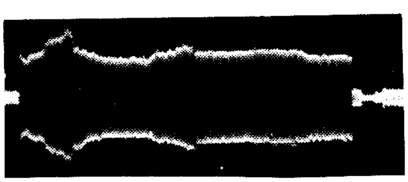
Beam results

The expected improvements concerning beam loading at the cavities resonance have been actually measured. Figs. 7 and 8 illustrate the factor of 10 ratio for beam induced voltage in an idle cavity with and without powering the RF feedback (note the different vertical sensitivities).



Vertical axis : 50 mV/div.
Horiz. axis : 100 ms/div.

Fig. 7. Beam induced voltage without RF feedback.



Vertical axis : 10 mV/div.

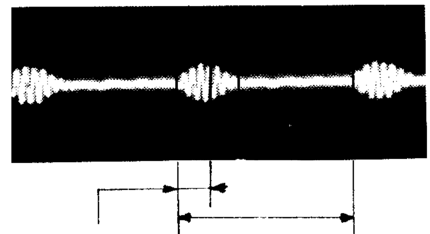
Fig. 8. Beam induced voltage with RF feedback.

Adjustment of the beam control for high beam intensity acceleration was rather easy and a record of 2.34 e13 ppp has been delivered to SPS running fixed target physics [8].

Moreover, the sophisticated process envisaged for pbar production [3] was set-up and operationally exercised at up to 1.5 e13 ppp, providing a 10% increase in the pbar stacking rate. Typical transient beam loading is then observed in the cavities, induced by the 5 bunches, filling 1/4 of a circumference (see Fig. 9).

Even low intensity beams profit from these modifications (for instance for the p/pbar bunch length compression), thanks to the better tracking between input and gap voltage during transients.

However the thresholds for many coupled bunch mode instabilities is lower than during the preceding years, and beam stabilization is obtained at the cost of higher longitudinal emittances.



Horiz. axis: 500 ns/div.

Fig. 9. Transient beam loading.

Conclusion

Hardware specifications have been met on time, old beam manipulations have been eased and new ones made possible, up to the point where a meaningful improvement was measured by the users of the PS beams.

More work is yet needed to decrease further the fault rate, as well as to find the source of the present beam instabilities at high intensity.

Acknowledgements

We are indebted to the many people from the PS/RF group who contributed efficiently to the successfull operation of this new equipment, and it is impossible to do justice here to all of them. However, special thanks has to be given to those who helped us to solve quickly unexpected problems when the system was in operation, especially P Marchand, D. Grier, A. Susini, P. Gourcy, and R. Hohbach.

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