ACCELERATING VOLTAGE AMPLITUDE AND PHASE STABILIZATION FOR THE MILAN SUPERCONDUCTING CYCLOTRON.

A. Bosotti, A. Caruso, M. Di Giacomo, V. Lovati,
C. Pagani, G. Varisco, F. Zibra.
Istituto Nazionale di Fisica Nucleare and Universita' di Milano, Milano, Italy.

ABSTRACT

Two feedback loops are employed to control the phase and the amplitude stability of the Milan Superconducting Cyclotron accelerating voltage.

In this paper we describe the main features of these systems together with the experimental results obtained during the full power tests of the first RF cavity.

In particular we obtained, all over the frequency range, a phase stability better than $\pm$ 0.2° and an amplitude modulation noise below $5 \cdot 10^{-5}$ at 100 kV peak dee voltage.

INTRODUCTION

The Milan Superconducting Cyclotron accelerating system consists of three dees, placed into the valleys. Each dee is the high voltage inner part of a coaxial resonator which consists of two $\lambda/4$ half cavities tied together at the center and symmetrically placed with respect to the accelerator median plane [1,2].

The cyclotron design calls for a peak dee voltage of 100 kV in the injection and extraction regions, the three dee voltages being in phase or $\pm$ 120° out of phase depending on the harmonic in use [3].

The design phase stability is below $\pm$ 0.2° for an amplitude modulation noise better than $5 \cdot 10^{-5}$ in order to introduce a minor contribution to the beam energy spread, which is assumed to be of the order of 10^{-3}. Because both the amplitude and the phase of the accelerating voltage have slow and fast variations well above these limits, two high d.c. gain feedback loops are needed to reach the design goals.

The accelerating voltage is amplitude modulated by the 50 Hz and its harmonics (in particular 100 and 300 Hz) coming from the ripple of the RF amplifiers power supplies. The power supply ripple also affects the phase modulation, but with a percentage smaller with respect to the amplitude modulation.

The phase is strongly affected by the cavity thermal drifts, due to Joule effect. In fact a temperature change leads to a cavity geometry variation and this means a detuning of the resonator. Due to the high Q of the resonator, a small detuning leads to a considerable phase shift. A similar effect, but much smaller, is related to the thermal detuning of the power amplifiers tank circuits, which have a two orders of magnitude lower Q factor.

The last cause of the amplitude and phase noise is related to the small mechanical vibrations, of the cavities and tank circuits components, induced by the water and air cooling systems and by the moving piston of a special refrigerator cryopump assembled inside the accelerating structure [4].

As a synthesis, we have two different kinds of phase and amplitude variations: a periodic one, due to the amplifiers power supplies and the mechanical vibrations, and an aperiodic one, slower than the former, due principally to the thermal drifts of the cavities. We control all these modulations using two feedback loops based on amplitude and phase modulators, while a trimming capacitor, faced to the dee (and inserted in another phase control feedback loop), controls each cavity geometry change, to maintain the phase shift well inside the phase modulator dynamic range. The trimming capacitor movement causes a slow modulation which is well corrected by the two stabilization loops.

Besides the phase and amplitude loops have a reciprocal influence, i.e. the amplitude loop gives a phase modulation and vice versa the phase loop. We will see that, while the amplitude loop phase modulation is important, the phase loop amplitude modulation is negligible (of the order of 10^{-4}).

AMPLITUDE LOOP

As we told before, the amplitude loop must ensure an amplitude modulation noise below $5 \cdot 10^{-5}$. The block diagram is shown in fig. 1.

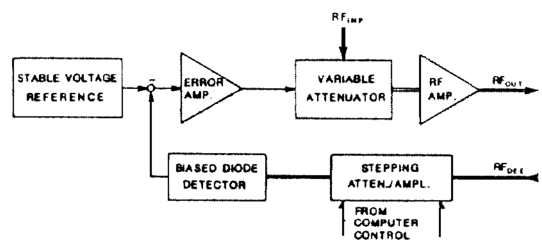

Fig. 1 - Amplitude loop block diagram.

The amplitude modulator, which is the most crucial part of this system, is a double balanced mixer variable attenuator (MCL ZAS 3), driven by a high gain error amplifier. The error is the difference between a high stability voltage reference (AD 584 LH), which controls the dee voltage, and a demodulated sample of the dee voltage, picked-up by a loop placed on the short circuit plate [2]. A conceptual scheme of the error amplifier is shown in fig. 2.

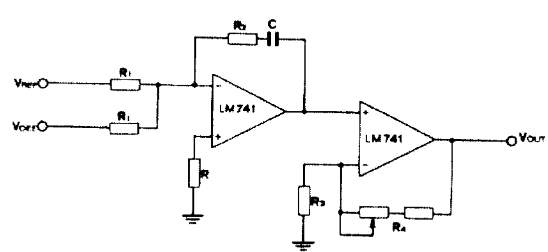

Fig. 2 - Conceptual scheme of the error amplifier.

Its transfer function is the following:

$$T_1(s) = \frac{1 + sR_2C}{sR_1C} \times \frac{R_4}{R_3}$$

The rationale of the choice of such an error amplifier is that it ensures a very high dc gain, controlled by the second stage, and it places a zero at a proper frequency ($\simeq$ 1.5 kHz), lower than the frequency of the cavity pole, in order to control the error bandwidth. In fact the cavity, from the point of view of the amplitude loop, behaves as a low pass filter, with a cutting frequency f_T given by:

$$f_T = f_o/2Q$$

where f_o is the cavity frequency and Q is its quality factor. Finally, due to the relatively low Q (< 100) of the tank circuits of the power amplifier, its dominant pole does not affect the loop stability, having a frequency of some hundred of kHz.

The optimized Bode plots of the amplitude feedback loop gain, at two different frequencies, are presented in figure 3, for a phase margin of 45°. In the same figure the displacement of the cavity and power amplifier poles, as a function of frequency, can also be seen. Inside the operational frequency range, the loop gain plots are limited by the two presented curves.

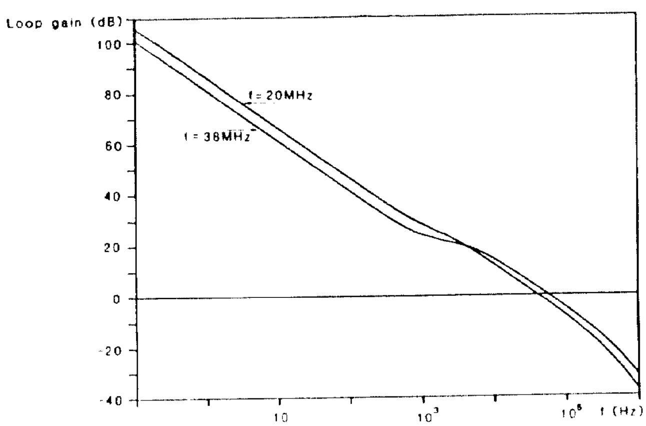

Fig. 3 - Bode plot of the amplitude feedback loop gain (see text for details).

The amplitude loop working point must be chosen in such a way that the loop will be stable for each frequency and amplitude of the accelerating RF voltage, together with the higher possible loop gain.

Nevertheless either the loop components or the pick-ups used to take samples of the dee voltage are strongly influenced by the signal frequency and amplitude. In particular we have that the coupling between the inductive loops and the field increases with the frequency, and so we have different input voltages to the amplitude detector and the variable attenuator that lead to a change in the loop gain. In the same manner the loop gain is changed for different dee voltages. So that, to have an optimum loop gain in spite of the working parameters, we developed a stepping attenuator/amplifier in order to keep the loop gain independent from the amplitude and the frequency of the sampled signals. This component is a computer controlled device designed to control the amplitude of the RF power in a range of ± 20 dB with 1 dB step.

As an example two spectra (with and without feedback) of the measured amplitude noise are shown in fig. 4, for a typical setting of the cavity operation parameters. Comparing the spectra with closed or open loop, it is apparent that the loop gain has the frequency dependence presented in fig. 2, the residual noise being below the design values.

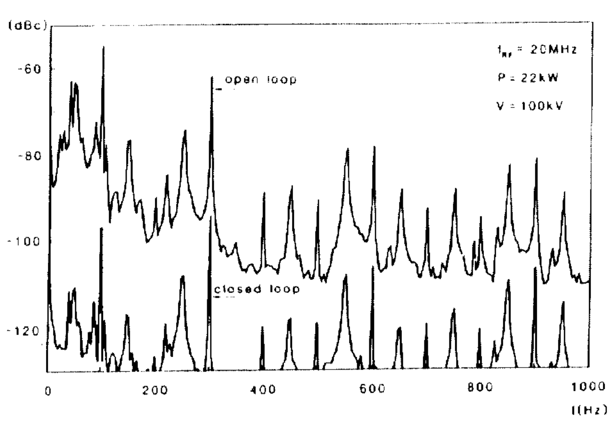

Fig. 4 - Measured amplitude noise spectra, with and without feedback, for a typical setting of the cavity operation parameters.

PHASE LOOP

Like for the amplitude, a phase loop is used to reduce the phase modulation below ± 0.2°. Its block diagram is presented in fig. 5.

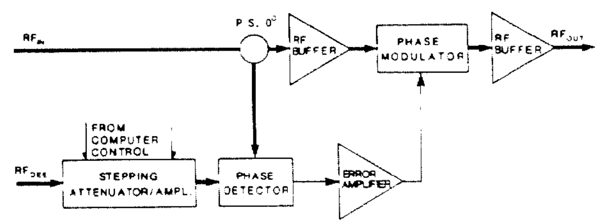

Fig. 5 - Block diagram of the phase stabilization loop.

The phase modulator, which is the most crucial part of the phase control system, performs a vector modulation acting on the two orthogonal components of the input RF signal, obtained by means of a 3 dB quadrature hybrid.

A high gain amplitude loop keeps constant the total power, giving a phase modulation proportional to the output signal of a phase detector. The phase modulator block diagram is presented in fig. 6.

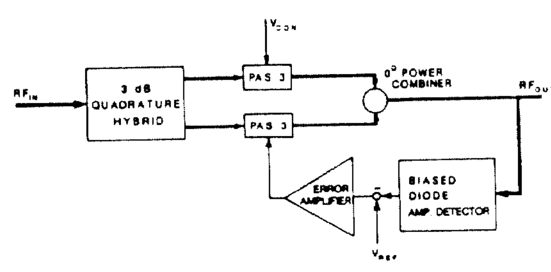

Fig. 6 - Phase modulator block diagram.

In order to ensure a very low coupling between the amplitude and the phase loops, the phase modulator is designed to have a very small residual amplitude modulation. This task is mainly accomplished by the phase modulator amplitude loop and by the RF buffers (see Fig. 5), used for a proper impedance matching. An example of a typical residual amplitude modulation of the phase modulator is shown in Fig. 7.

The phase detector is a XR 2208 analog multiplier. The output signal V_f is given by: $V_f = K\cos\Delta\phi$, where $\Delta\phi$ is the phase difference between the two input signals and K is a parameter that depends on the amplitude and the frequency of the input signals, one

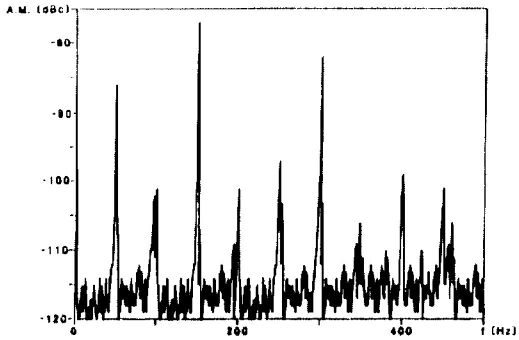

Fig. 7 - Residual amplitude modulation of the phase modulator.

of which is the phase reference signal, while the other one is a sample of the dee voltage. It follows that the two input signals of the phase detector, in order to give a constant contribution to the loop gain, must have a phase difference $\approx 90°$ at any frequency and their amplitude must be kept constant, in spite of the setting of the accelerating voltage amplitude and frequency.

A stepping attenuator/amplifier, similar to that described for the amplitude loop, is used for signals constant amplitude, while a programmable delay line is used to preserve 90° phase difference. This device is a modular six bits computer controlled stepping line (1 ns step for 63 ns maximum delay) together with a continuously variable length line used for fine adjustment in between two adjacent steps. A picture of this device connected to the delay lines control logic circuit is shown in Fig. 8.

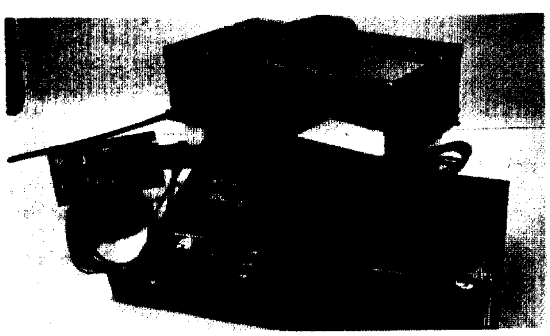

Fig. 8 - Computer controlled delay line phase shifter.

The problem of the system stability is very similar to that of the amplitude loop, and for this reason the error amplifier is analogous to that used for the amplitude loop.

FINE TUNING SYSTEM

As we told before the cavity geometry changes due to Joule effect during power operation, and so the resonance frequency changes too. Because of the high cavity Q, a small detuning leads to a consistent phase shift, according to the following equation:

$$\Delta f = \frac{f_o}{2Q} \Delta\phi$$

where $\Delta\phi$ is the phase shift due to a detuning Δf from the resonance frequency f_o. A closed loop geometrical compensation is necessary to keep the detuning well inside the dynamic range of amplitude and phase loops. This is done by a fine tuning system accomplished with a trimming capacitor placed just above the dee [5]. For the sake of completeness the fine tuning system block diagram is presented in Fig. 9.

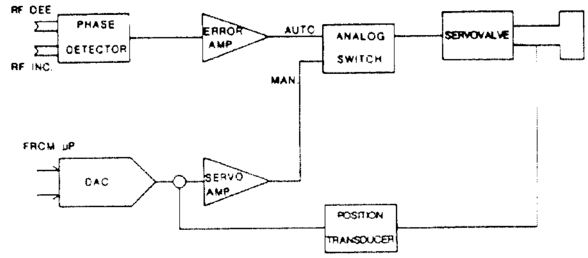

Fig. 9 - Fine tuning system block diagram.

CONCLUSIONS

The electronic systems presented in this paper are the final version of the prototypes extensively tested since 1985 [2]. Because of the significant delay of few major components of the Milan Superconducting Cyclotron [6], these systems, together with all the others circuits of the RF control [5], have been redesigned, in order to increase reliability and simplify the maintenance procedures. Moreover, all the settings, needed to operate the cyclotron RF system at a certain frequency and dee voltages, are now fully computer assisted [7].

The picture of Fig. 10 shows a typical rack with the different electronic sub-systems assembled. Each sub-system has a separate cabinet with a mimic diagram on the front panel, including test points and status signals. All the input/output cables, connecting the cabinets, are in the rear panels.

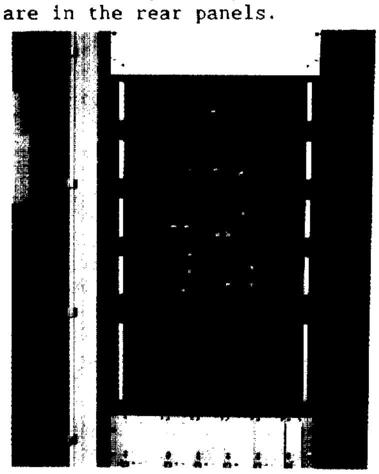

Fig. 10 - Typical RF rack with different electronic sub-systems assembled (see text for details).

REFERENCES

1 - C. Pagani, RF System of the Milan K800 Cyclotron, Proc. X Int. Conf. on Cyclotrons, East Lansing 1984, IEEE cat. N. 84CH 1966-3, pag. 305.

2 - C. Pagani et al., Full Power Tests of the First RF Cavity for the Milan K800 Cyclotron, Proc. XI Int. Conf. on Cyclotr., Tokyo 86, IONICS Pub., pag. 271.

3 - A. Acerbi et al., The Milan Superconducting Cyclotron Project, Proc. X Int. Conf. on Cyclotr., East Lansing 1984, IEEE cat. 84CH 1966-3, pag. 251.

4 - P. Michelato et al., Operational Experience and Tests of the Milan K800 Cyclotron System, paper presented at this conference.

5 - A. Bosotti et al., Report INFN/TC-86/6, 1986.

6 - A. Acerbi et al., Status Report of the Milan Superconducting Cyclotron, paper presented at this conference.

7 - A. Bosotti et al., Computer Control for the Milan K800 Cyclotron RF System, paper presented at this conference.