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CONCEPTUAL DESIGN OF THE ELECTRONIC CONTROLS FOR THE RF CAVITY OF THE MILAN SUPERCONDUCTING CYCLOTRON

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ABSTRACT

This paper presents the conceptual design of the RF phase and amplitude control systems. A new approach is proposed and its major features are briefly discussed.

1. - INTRODUCTION

The Milan Superconducting Cyclotron accelerating structure consists of three dees placed in the valleys(1, 2, 3). Each dee is the high voltage inner part of a coaxial resonator which consists of two $\lambda/4$ cavities tied together at the center and placed symmetrically about the median plane.

Two alumina insulators, placed at 630 mm from the median plane, connect mechanically the coaxials. To tune the resonators in the 15 to 48 MHz frequency range two sliding shorts move along the cylindrical walls of the cavity.

The accelerator design calls for a peak dee voltage of 100 kV in the injection and extraction regions. Depending on the harmonic used, the three dee voltages can be either in phase or ± 120° out of phase. The design phase stability is ± 0.1° for a residual amplitude modulation of the order of 5×10^{-5}.

A low level splitted signal from a high spectral purity synthesizer feeds three high-linearity independent amplification chains. A 50 ohm coaxial cable connects each amplifier to its cavity via a coupling capacitor.

This paper presents the phase and amplitude control loop and its expected performances. A low frequency digital control loop, not yet designed, will provide the long term phase relation between the three cavities, while three trimming capacitors will accomplish tuning of the cavities in a ± 5° phase range.

2. - LOOP DESIGN APPROACH

Our starting point for the specification of the phase and amplitude loop gain will be a spectral analysis of the detected phase and amplitude noise. On the basis of the detected noise we will shape the loop gain in order to meet the closed loop phase and amplitude stability specs with satisfactory transient response(4).

Nevertheless, at present, we can anticipate that:

- On the basis of reasonable predictions we expect important phase and amplitude noise components up to frequencies of the order of 600 Hz.
- We wish a constant 20 dB/dec slope to avoid stability problems when changing RF voltage level: that is to have maximum flexibility during preliminary operations with no sophisticated loop gain control electronics.

Therefore we design our electronic components with a flat frequency response up to 1 MHz, the rationale for this design choice being that the more flexible the electronic building blocks are, the larger is our freedom in optimizing the loop gain.

Proceeding this way the major limit to the feasibility of large loop gain at low frequencies will be represented by the poles introduced by the RF power amplifiers.

Preliminary calculations, based on information supplied by the manufacturer, show that they should allow a gain-bandwidth product of the order of 150 KHz. A better figure will be available after a set of measurements on the amplifiers during the acceptance tests. These tests are planned for September 1982.

3. - PHASE AND AMPLITUDE CONTROL LOOP

A new approach to phase and amplitude controls of the RF voltage is proposed. It should perform larger bandwidth and therefore larger d. c. accuracy than a conventional design. The idea underlying the presented approach is easily summarized in a few points:

- The RF voltage fed to the power amplifiers is obtained by combining to 90° out of phase low level RF voltages which pass through two voltage controlled attenuators.

- The components of the phasor corresponding to the RF cavity voltage are detected by means of coherent amplitude detection.
- The detected low frequency signals, each subtracted from a d. c. reference value, are fed back to control the voltage controlled attenuators.

The diagram in Fig. 1 illustrates the above stated points. A schematic vector representation of the effects of amplitude and phase modulation on the RF phasor is shown in Fig. 2.

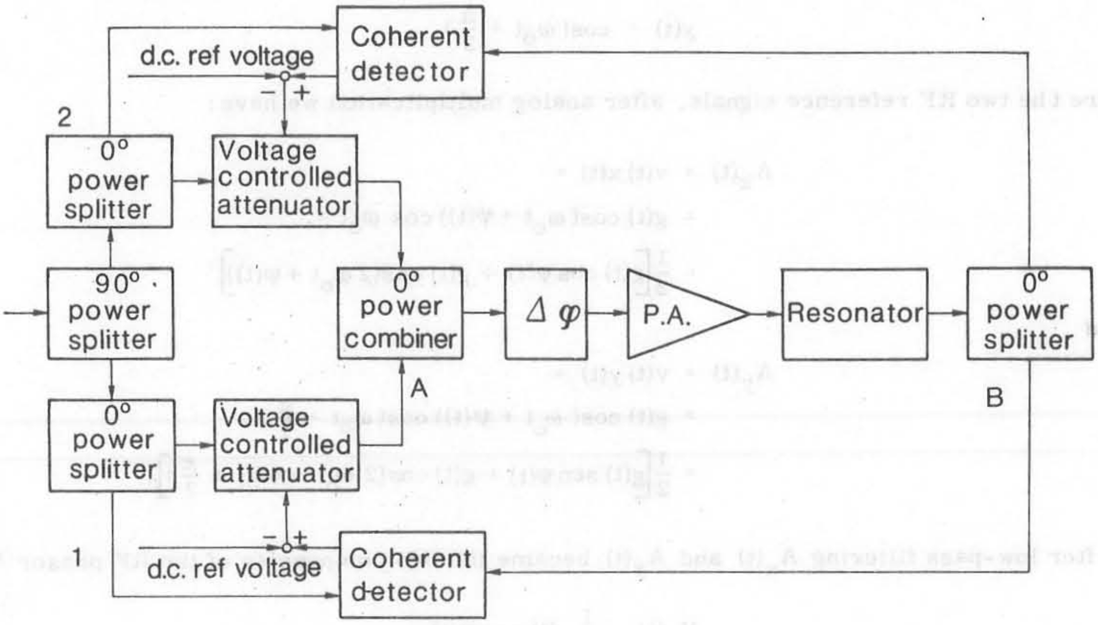

FIG. 1 - General block diagram of the proposed system.

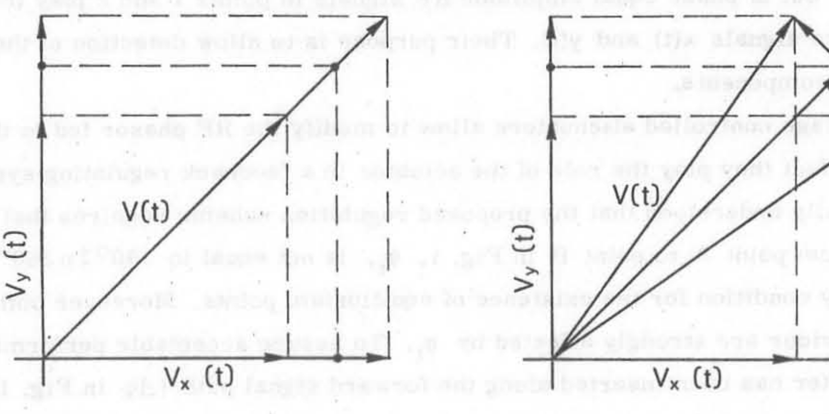

FIG. 2 - Vector representation of amplitude (left) and phase (right) modulation.

The RF phasor is easily detected by means of coherent amplitude detection, that is analog multiplication with an equal frequency reference signal followed by low-pass filtering. If

$$v(t) = g(t)\cos(\omega_0 t + \psi(t))$$

is the RF signal and

$$x(t) = \cos \omega_0 t \ ,$$

$$y(t) = \cos(\omega_0 t + \frac{\pi}{2})$$

are the two RF reference signals, after analog multiplication we have:

$$\begin{aligned} A_x(t) &= v(t)\,x(t) = \\ &= g(t)\cos(\omega_0 t + \psi(t))\cos \omega_0 t = \\ &= \frac{1}{2}\left[g(t)\cos\psi(t) + g(t)\cos(2\,\omega_0 t + \psi(t))\right] \end{aligned}$$

and

$$\begin{aligned} A_y(t) &= v(t)\,y(t) = \\ &= g(t)\cos(\omega_0 t + \psi(t))\cos(\omega_0 t + \frac{\pi}{2}) = \\ &= \frac{1}{2}\left[g(t)\,\mathrm{sen}\,\psi(t) + g(t)\cos(2\,\omega_0 t + \psi(t) + \frac{\pi}{2})\right]. \end{aligned}$$

After low-pass filtering $A_x(t)$ and $A_y(t)$ became the two components of the RF phasor $V(t)$:

$$V_x(t) = \frac{1}{2}\,g(t)\cos\psi(t) \ ,$$

$$V_y(t) = \frac{1}{2}\,g(t)\,\mathrm{sen}\,\psi(t) \ .$$

Let us now return to the block diagram of Fig. 1:

- The two 90° out of phase equal amplitude RF signals in points 1 and 2 play the roles of the RF reference signals $x(t)$ and $y(t)$. Their purpose is to allow detection of the RF cavity voltage vector components.
- The two voltage controlled attenuators allow to modify the RF phasor fed to the power amplifiers, in fact they play the role of the actuator in a feedback regulating system.

It is easily understood that the proposed regulation scheme requires that the total RF phase shift from point A to point B in Fig. 1, φ_t, is not equal to $180^{\circ} \pm n\,360^{\circ}$; in facts this is a necessary condition for the existence of equilibrium points. Moreover both static and dynamic behaviour are strongly affected by φ_t. To assure acceptable performance a variable phase shifter has been inserted along the forward signal path ($\Delta\varphi$ in Fig. 1).

In Fig. 3 a block diagram is shown, the signals manipulated by the blocks are the x and y components of the RF voltage phasor.

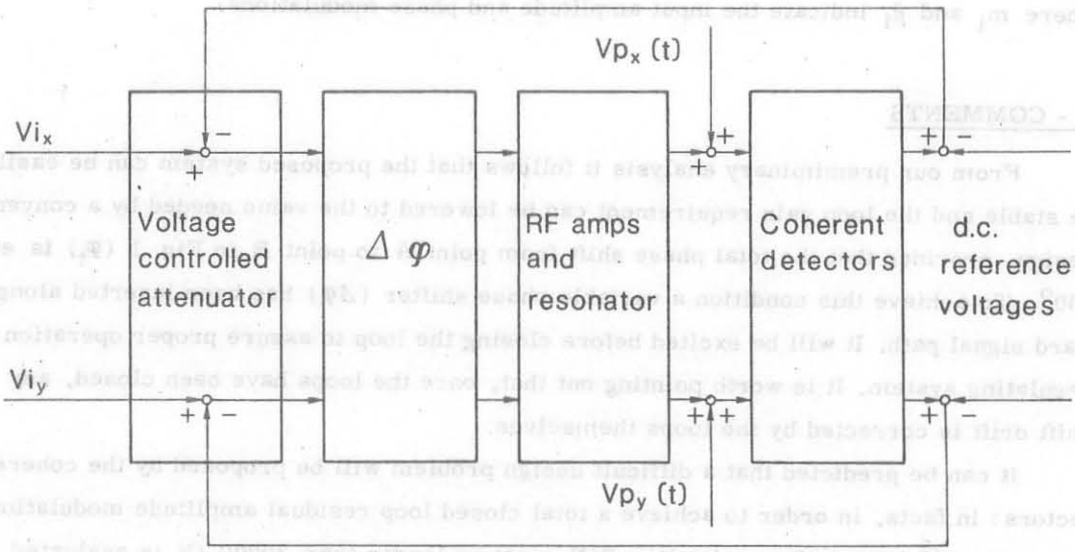

FIG. 3 - Block diagram. The input signals to the blocks are the x and y components of the RF voltage phasor.

From our analysis of the proposed system it follows that:

- The cavity RF voltage amplitude is:

$$\left| V(t) \right| = \frac{V_{o,\mathrm{ref}} \sqrt{2}}{\left(1 - \frac{2G(1 - \cos \varphi_t)}{(G+1)^2}\right)^{1/2}}$$

and its phase:

$$\arg V(t) = \mathrm{artg} \frac{\frac{\mathrm{sen}\ \varphi_t}{G + \cos \varphi_t}}{1 - \frac{\mathrm{sen}\ \varphi_t}{G + \cos \varphi_t}} =$$

$$= \frac{\pi}{4} + \mathrm{artg} \frac{\mathrm{sen}\ \varphi_t}{G + \cos \varphi_t} \simeq \frac{\pi}{4} \quad \text{if } G \gg 1$$

where G is the loop gain and $V_{o,\mathrm{ref}}$ is the d. c. reference voltage.

- The total closed loop amplitude and phase perturbation (m_o and β_o) are:

$$m_o = \frac{m_i \cos \varphi_t + \beta_i\ \mathrm{sen}\ \varphi_t}{\sqrt{G^2 + 2G \cos \varphi_t + 1}} ,$$

$$\beta_o = \frac{m_i\ \mathrm{sen}\ \varphi_t + \beta_i \cos \varphi_t}{\sqrt{G^2 + 2G \cos \varphi_t + 1}}$$

where m_i and β_i indicate the input amplitude and phase modulations.

4. - COMMENTS

From our premiminary analysis it follows that the proposed system can be easily made stable and the loop gain requirement can be lowered to the value needed by a conventional design, provided that the total phase shift from point A to point B in Fig. 1 (φ_t) is equal to 360°. To achieve this condition a variable phase shifter ($\Delta\varphi$) has been inserted along the forward signal path. It will be excited before closing the loop to assure proper operation of the regulating system. It is worth pointing out that, once the loops have been closed, any phase shift drift is corrected by the loops themselves.

It can be predicted that a difficult design problem will be proposed by the coherent detectors : in facts, in order to achieve a total closed loop residual amplitude modulation of the order of 10^{-5}, the analog multiplier S/N must be larger than 20000 (N is evaluated over a 1 MHz bandwidth). Moreover to get an extremely stable RF cavity voltage amplitude, the two RF reference voltages x(t) and y(t) must hold an equally stable phase relation ; this last problem is not encountered in designing a conventional regulating system.

On the other hand our system should perform a large bandwidth as a result of a simple design : in facts no phase stable limiting amplifiers are necessary and only one kind of detector has to be developed.

5. - CONCLUSIONS

According to the previous analysis the proposed system seems to be very promising ; the only unusual and critical block being the analog multiplier. Nevertheless, before making the final choice of the amplitude and phase regulating system, we plan to proceed as follows:

- To design a low frequency model of the proposed system to better understand its eventual limits.
- To complete the theory of the proposed control loop, looking at the results of the tests performed on the low frequency model.
- To improve the S/N of our analog multiplier prototype.

We are confident that, by the end of the year, we shall be able to design the amplitude and phase control system that will be tested on the cavity prototype by next spring.

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