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CONTROL ELECTRONICS FOR HIGH POWER OPERATION OF THE MILAN SUPERCONDUCTING CYCLOTRON RF CAVITIES

Servizio Documentazione
dei Laboratori Nazionali di Frascati

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ABSTRACT

This paper presents the control electronics which has been developed for the full power tests of the first cavity of the Milan Superconducting Cyclotron(1). According to the successful results, three identical systems are now under construction for the cyclotron operations.

1.- INTRODUCTION

A control electronics for the full power operations of each Milan Superconducting Cyclotron RF cavity[2] has been developed and successfully tested at our Laboratory. Its main tasks are the following:

a) to turn on the cavity

b) to protect the cavity against dangerous sparks

c) to keep the cavity tuned.

Referring to these tasks, a few comments are in order.

a) To turn on the cavity means to lead the resonator from a zero voltage to the voltage required for beam acceleration, namely 100 kV peak. Due to the high vacuum in the acceleration region, the main problem is to punch through the multipactoring[3]. Particurarly the low level RF input signal, to the linear amplification chain, is amplitude modulated with a trapezoidal envelope. This is to force through the multipactoring barriers with the minimum required power and then to go linearly to the desired dee voltage. The system resets itself and tries again, if multipactoring is not completely punched-through, until all the critical voltages are overcome, permitting to reach the working voltage.

b) At the occurence of any dangerous conditions (sparks, etc.) during power operation of the RF system, input power must be switched off in a few μs, in order to minimize the energy involved into the phenomenon.

c) The cavity geometry changes due to Joule effect during power operation, i.e. the resonance frequency changes too. Because of the high cavity Q factor[4] a closed loop geometrical compensation is necessary. This is done by a trimming capacitor, controlled by the fine tuning network.

2. - RF SYSTEM PROTOTYPE STRUCTURE

The block diagram of the RF system is presented in fig. 1.

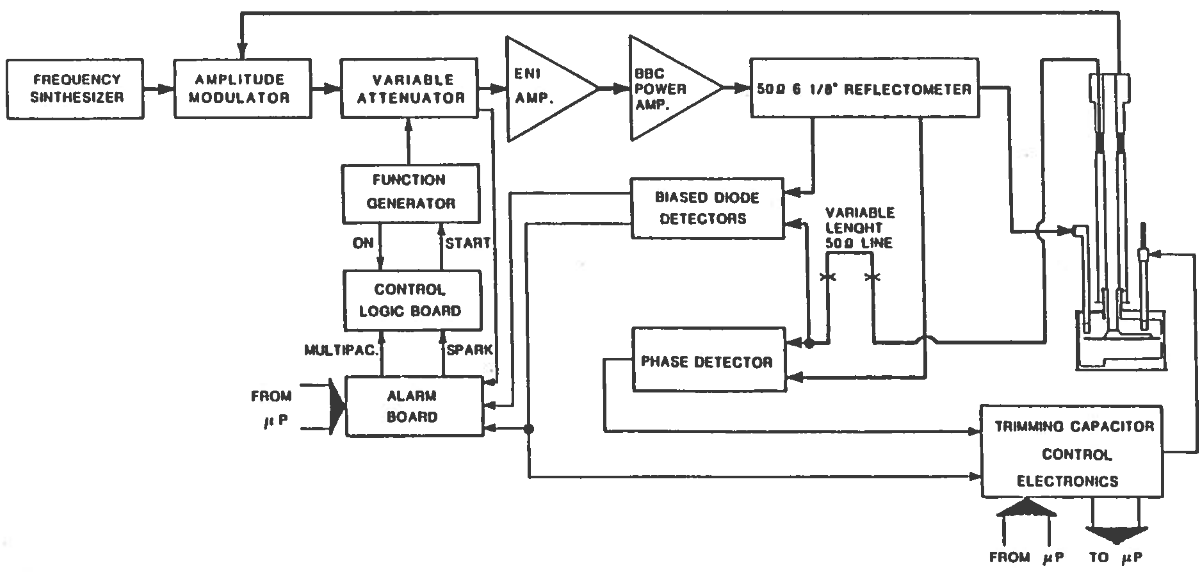

FIG. 1 - RF system prototype block diagram.

The RF power is driven by a HP 8662A frequency synthesizer, whose output is directly connected to the amplitude modulator of the amplitude stabilization loop[5]. When the system starts, the variable attenuator modulates the signal with a trapezoidal envelope generated by the function generator. The control logic guides the start/stop procedures, while the alarm board has the task to test the whole system and to send alarm signals to the control logic board. The variable attenuator output signal is amplified by a two linear amplifiers chain. The first one is a 200 W broadband amplifier (55 dB gain), while the second is a two stages, class B, power amplifier(BBC) specially designed and manufactured by Brown Boveri,according to our specs[6].

The BBC output power(up to 90 kW) feed the cavity via a 50 ohm coaxial line. The cavity is capacitively coupled with a tuned coupler in order to have 50 ohm input impedance,all over the frequency range(15 ÷ 48 MHz).

A reflectometer is inserted between the BBC and the cavity to sample the incident and the reflected power, while the dee voltage is sampled by inductive pick-ups installed on the short circuit plate. The RF sampled signals are demodulated and transmitted to the alarm board.

Samples of incident power and dee voltage are sent to the phase detector of the fine tuning system. The RF cavity electronic boards are controlled by a microcomputer.

3. - VARIABLE ATTENUATOR

The variable attenuator is used, as explained above, to amplitude modulate the RF input signal, to switch on the cavity. The block diagram of this element is shown in fig. 2. The first block is the function generator that produces the trapezoidal envelope, its output being the control signal for a current controlled variable attenuator (MCL PAS-3). The system is closed in a feedback loop in order to stabilize its working point. The feedback branch is constituted by a RF fet input amplifier (to partially compensate the MCL PAS-3 attenuation), a biased Schottky diode amplitude detector and a low frequency amplifier(to correct the non idealities of the amplitude detector).

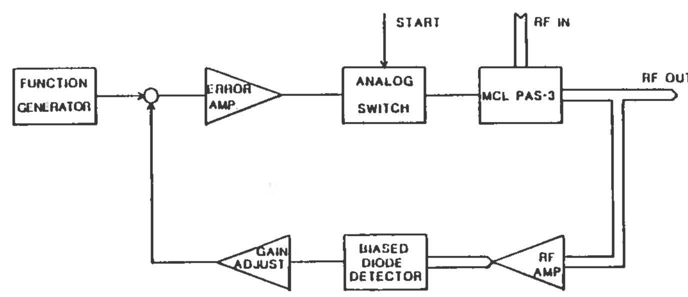

FIG. 2 - Variable attenuator board block diagram.

The difference between control voltage and fed back signal (i.e. the error) is amplified by a high gain error amplifier. The analog switch, between the error amplifier and the MCL PAS-3, blocks the RF power until it receives a logic enabling signal from the control logic board.

4.- CONTROL LOGIC BOARD

The control logic board allows to send the START logic signal to the variable attenuator board, while the later sends back the negative logic signal ON when the ramp between V_{in} and V_{fin} (of the trapezoidal envelope) starts; this indicates that a pulse has been passed to the amplification chain. Moreover it receives the logic alarm signals MULTIPACTORING and SPARK sent by the alarm board.

The control logic board can work either in manual or in automatic mode. In the manual mode the operator, pushing the START button, enables the variable attenuator to transmit RF power to the amplification chain. The transmission lasts until the operator wants to stop it or until the alarm board sends an alarm signal. On the other hand, in the automatic mode, after a switch off, a new start signal is given, delayed by a proper time (hundreds of milliseconds) to guarantee that any cavity ionization is self extinguished.

The control logic board has been designed with C-MOS logic circuits (74C family). The system block diagram is shown in fig. 3.

When the operator pushes the START button on the control panel, the flip flop FF1 output goes high and sends the start signal to the analogic switch of the variable attenuator board. If the alarm board sends an alarm signal on the MULTIPACTORING or SPARK lines FF1 goes low opening the switch and stopping the RF power transmission to the amplification chain.

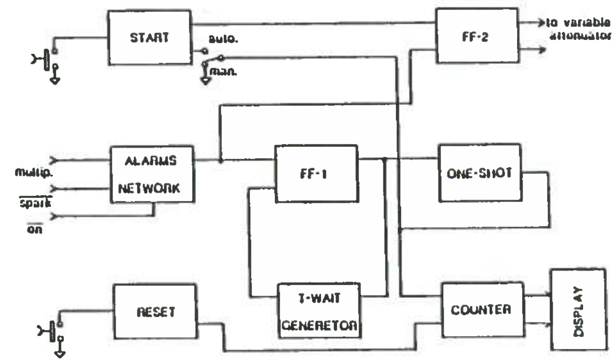

FIG. 3 - Control logic board block diagram.

In the automatic mode the system remains off for a certain time "t_1" set by the operator. The optimization of this "wait" time between a turn off and a new turn on is done by setting, via panel, a binary counter. When the "wait" time is passed, the counter output goes high and then also the flip flop FF2 goes high, starting the system again.

A particular remark has to be done on the MULTIPACTORING channel. In fact the control board is not sensible to alarm signals on this channel for a certain time "t_2" after the start (set by the operator), due to a logic signal transmitted by the variable attenuator board when the linear ramp between V_{in} and V_{fin} starts. This system insensitiveness let the RF power on for the time "t_2" under multipactoring conditions, to contribute to the self extinguishment of the secondary electron currents. The number of alarm signals is detected by a binary counter and shown on the panel display.

5.- ALARM BOARD

The alarm board detects any dangerous condition which can occur during the resonator power operation. Namely the alarm board input signals are:

- amplitude of the RF dee voltage, sampled by a small coupling loop on the resonator short circuit plate and detected by a biased diode RF detector;
- amplitude of the cavity input power, sampled by a 6 1/8" bidirectional coupler (close to the coupling capacitor) and detected by a biased diode RF detector;
- amplitude of the RF signal fed to the amplification chain (from the auxiliary output of the amplitude modulator);
- signals coming from the vacuum meters auxiliary output.

The alarm board gives a pulse on the SPARK line everytime the dee voltage falls with a time constant faster than the resonator time constant, or the level of the auxiliary output of the vacuum meter is higher than a safety threshold. Conversely the alarm board gives a pulse on the MULTIPACTORING line when the amplitude of the dee voltage is lower than expected, compared with the amplitude of the RF signal fed to the amplification chain (that means that the cavity shunt impedance is lowered by the multipactoring phenomenon), or the reflected power is larger than a threshold safety level. Originally the alarm board was provided with an input for a logical signal coming from photo-transistors placed in the most crucial parts of the RF cavity. The occurrence of such a logic signal, caused by a spark, would have generated a pulse on the SPARK line. Experience showed us that we do not need such an alarm, since other protections are sufficient to avoid cavity damages.

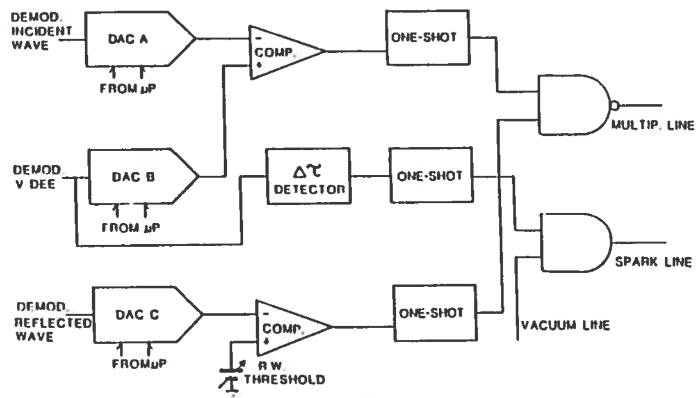

FIG. 4 - Alarm board block diagram.

The input signals specified above pass through three digitally controlled attenuators (multiplying DACs) and then go to a set of fast comparators (Schmitt triggers). The attenuators are controlled by a microcomputer in order to perform automatically the calibration of the alarm board. This calibration is necessary to compensate the frequency dependance of the directional coupler output and of the dee voltage sensing loop coupling attenuation. The block diagram of the alarm board is presented in fig. 4. The electric scheme of the time constants comparation circuit, which is the most important of the alarm board, is shown in fig. 5.

The input signal is splitted in two branches. One branch goes directly to OP10 (summing point), while the other goes to OP8 (very high input impedance amplifier), charging the capacitor C. In normal operation the output voltage is zero, and this is true also during switching off, because the capacitor discharge time constant is set (via front panel) equal to the cavity time constant. Nevertheless, in case of sparks, the cavity time constant is lowered by a localised short circuit and so the output voltage becomes different from zero, enabling an alarm signal to be sent just when the spark starts. For the sake of completness we show in fig.6 a sketch of the shape of the input and output signals of the time constants comparation circuit.

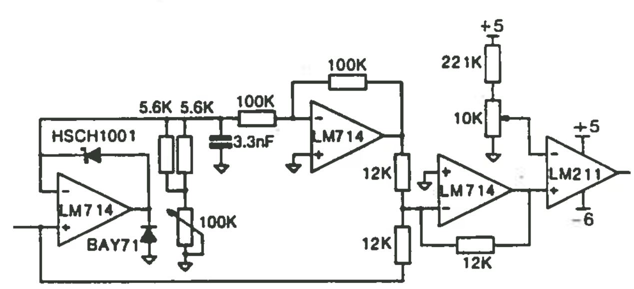

FIG. 5 - Time constants comparation circuit.

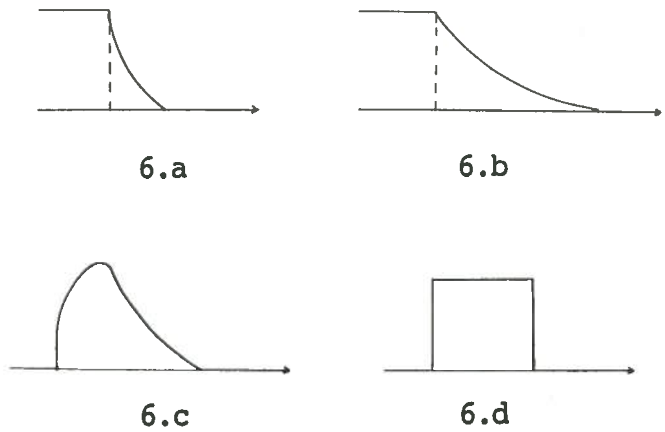

FIG. 6.a - Dee voltage sampling during a spark.

FIG. 6.b - Capacitor discharge with the set cavity time constant.

FIG. 6.c - The two signal summed.

FIG. 6.d - Comparator output.

6.- FINE TUNING SYSTEM

Fine tuning of the resonator is accomplished by means of a trimming capacitor just above the dee. The movable head is actuated by an hydraulic piston servo with a stroke of 50 mm. The position of the trimming capacitor can be set either manually or automatically. The capacitor in the manual mode is moved by setting its position with a microcomputer keyboard placed on the front panel, while in the automatic mode the system is included in a feedback loop, where the command signal is proportional to the phase error. The fine tuning system detects any resonance frequency drift looking at the phase angle between the incident wave and the dee voltage. When the resonator is properly tuned and matched to the transmission line, the phase angle at the phase detector input is set to zero.

The block diagram of the fine tuning system is shown in fig. 7. Referring to the block diagram, the hydraulic position servo is composed by an hydraulic linear actuator servovalve and a position transducer. By the analog switch either manual or automatic mode of operation can be choosen.

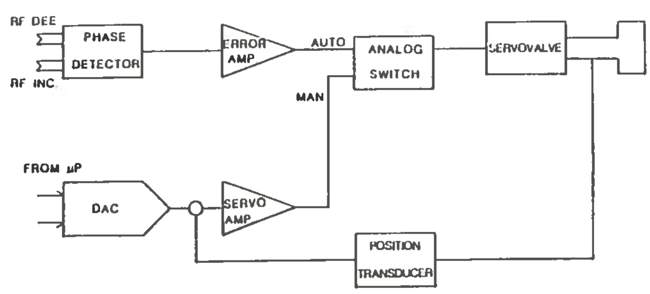

FIG. 7 - Fine tuning system block diagram.

We want to point out that the system must have very high loop gain at very low frequencies, also if the piston behaves as an integrator(7) and the servovalve has a low frequency pole. In fact the transfer function of the servovalve is the following:

$$T_v(s) = \frac{Q}{i} = \frac{K_1}{(1+s\cdot\tau_v)}$$

where:

Q = oil flow $\quad i$ = control current $\quad \tau_v$ = servovalve time constant

while for the piston:

$$T_p(s) = \frac{X}{Q} = \frac{K_2}{A\cdot s}$$

where:

A = piston area X = piston position

A good compromise between high DC gain and loop stability has been obtained by a system whose loop gain Bode plot is presented in fig. 8.

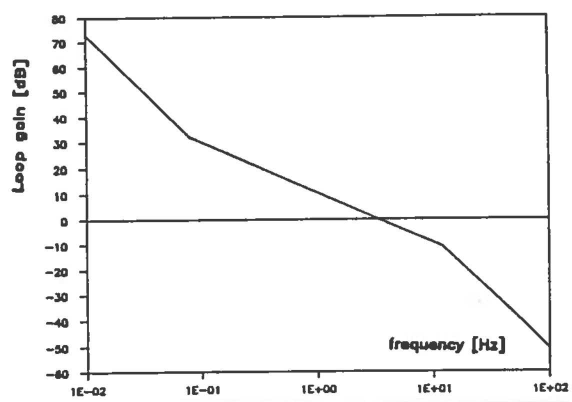

FIG. 8 - Bode plot of the fine tuning system loop gain.

In order to obtain this loop gain an error amplifier has been developed and its scheme is presented in fig. 9.

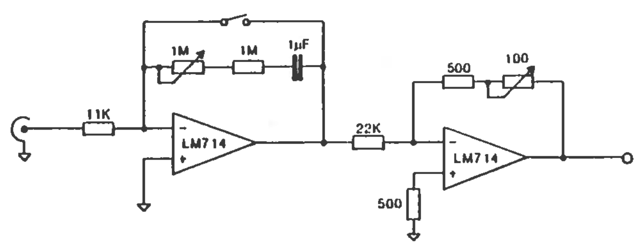

FIG. 9 - Error amplifier.

The phase detector is the most critical electronic component of the fine tuning system. In fact it must detect very small phase errors together with wide RF input bandwidth and input dynamic range. The purpose of the phase detector is to detect any phase difference between the incident wave and the dee voltage. In fig.10 the phase detector scheme is shown.

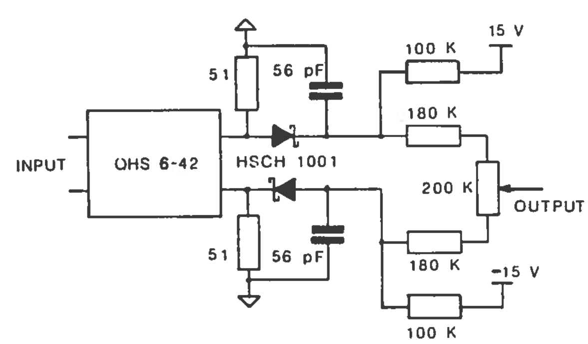

FIG. 10 - Phase detector.

The phase detector has been designed around the 3 dB quadrature hybrid Merrimac QHS-6-42. This device splits an input signal into two output signals of the same magnitude but with a phase difference of 90 degrees. The QHS-6-42 device is a four ports network, whose functional block diagram is shown in fig. 11.

When the two signals applied at ports one and four are in phase, independently from their amplitudes, the output signals at ports two and three have the same amplitude while if the two input signals are out of phase the output amplitudes are different.

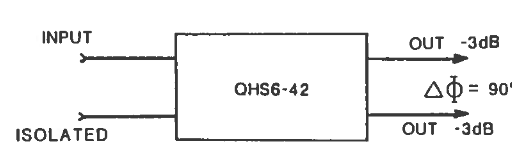

FIG. 11 - QHS-6-42 functional diagram.

The ports two and three are followed by two biased Schottky diode amplitude detectors. The first one detects the positive peak and the other the negative one. The two demodulated signals feed the terminals of a symmetric (with respect to the sampling point) resistive network. If the two DC signals are of the same amplitude the sampled voltage is zero, otherwise it is proportional to the phase difference and it has the same sign. The $\Delta\phi$ signal is then buffered and sent to the input of the fine tuning system integrator.

The experimental characteristics of the phase detector are presented in fig. 12.

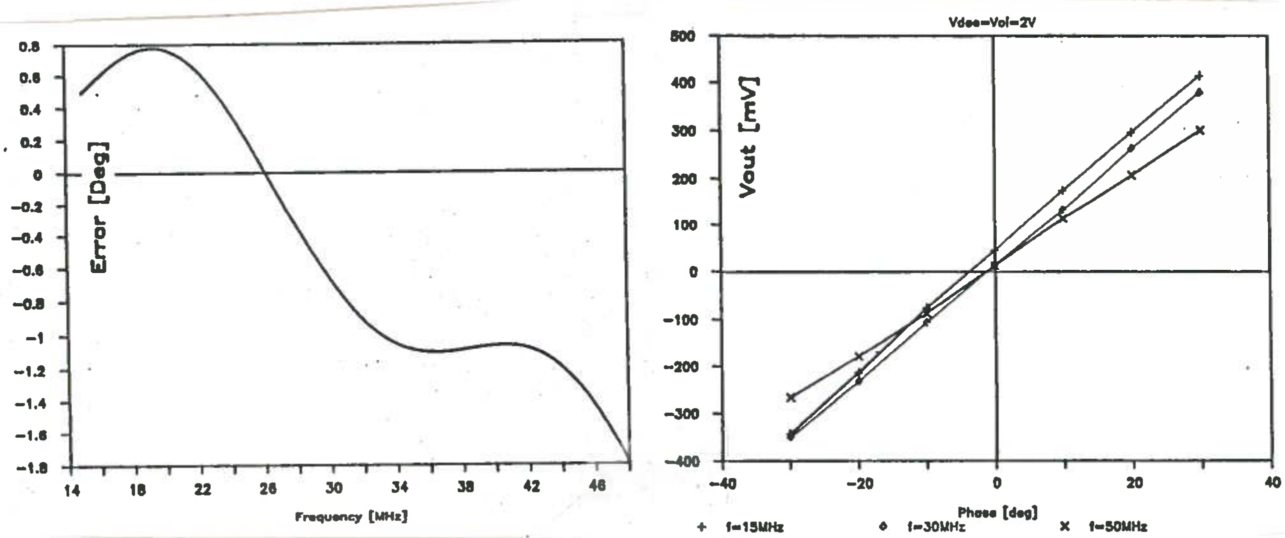

FIG. 12.a - Phase error vs. frequency.

FIG. 12.b - Phase detector output at various frequencies.

7.- CONCLUSIONS

The control electronics, discussed in this note, has been successfully tested since summer 1984, during power tests of the first RF cavity for the Milan Superconducting Cyclotron, together with a provisional microcomputer(based on a 8085AH microprocessor).

Since the results of the power tests will be presented elsewhere[(1)], we want just to point out that the system, with minor modifications, has been considered adequate for a reliable cyclotron operation and we are now ready to start the assembling of the three final systems.

Looking at the provisional microcomputer, its functions will be included into the RF station of the C.S. computer control.

The first RF cavity under power tests is shown in fig. 13, while a picture of the control electronics racks connected to the cavity is presented in fig. 14.

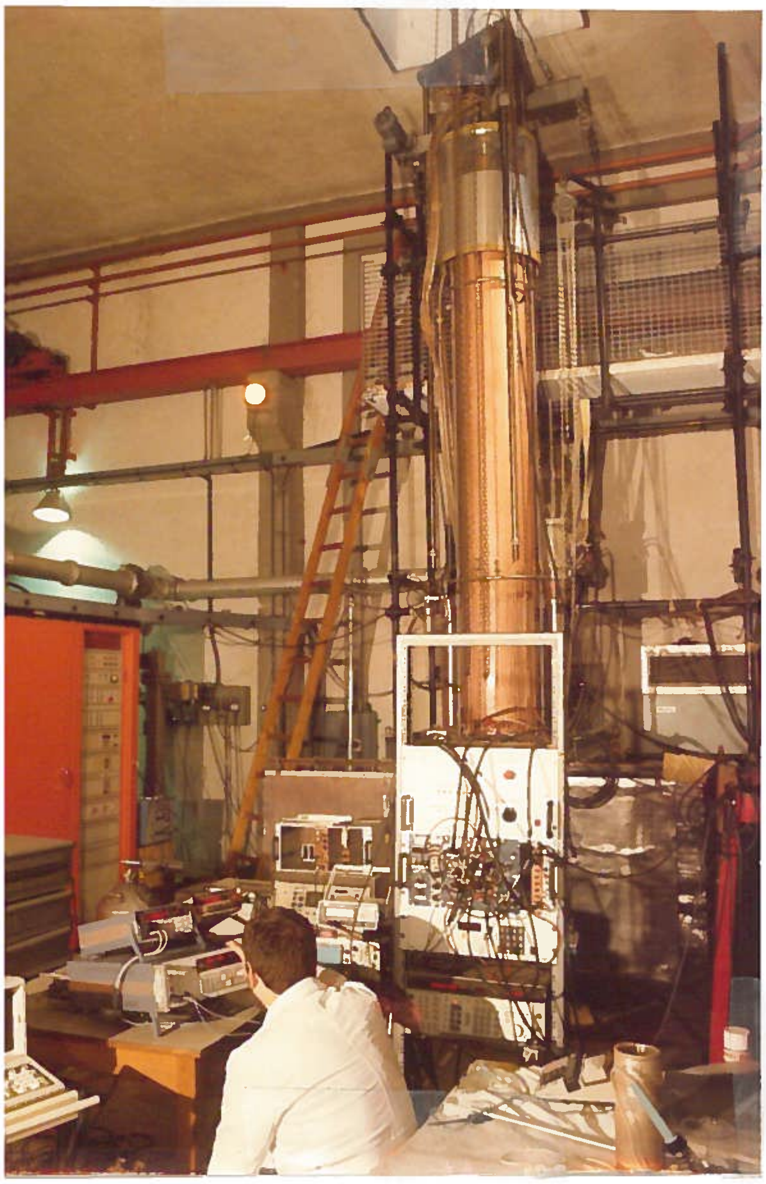

FIG. 13 - The first RF cavity (upper half) under power tests, connected to the control electronics.

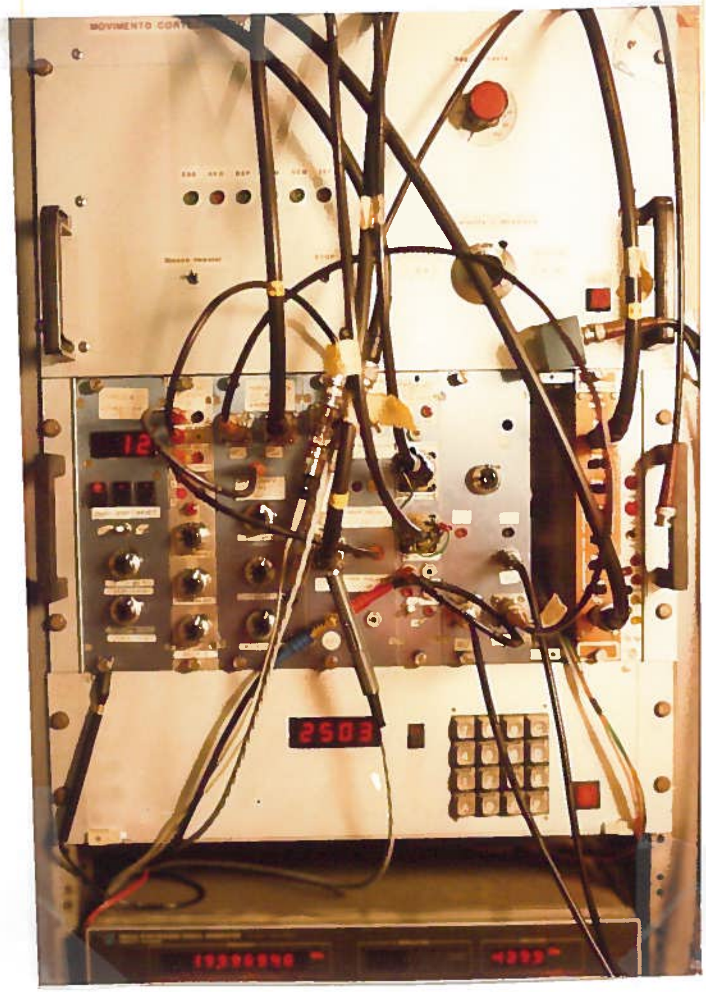

FIG. 14 - The control electronics modules connected to the cavity.

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