THE UPGRADED CONTROL OF THE LNS SUPERCONDUCTING CYCLOTRON RADIO-FREQUENCY SYSTEM

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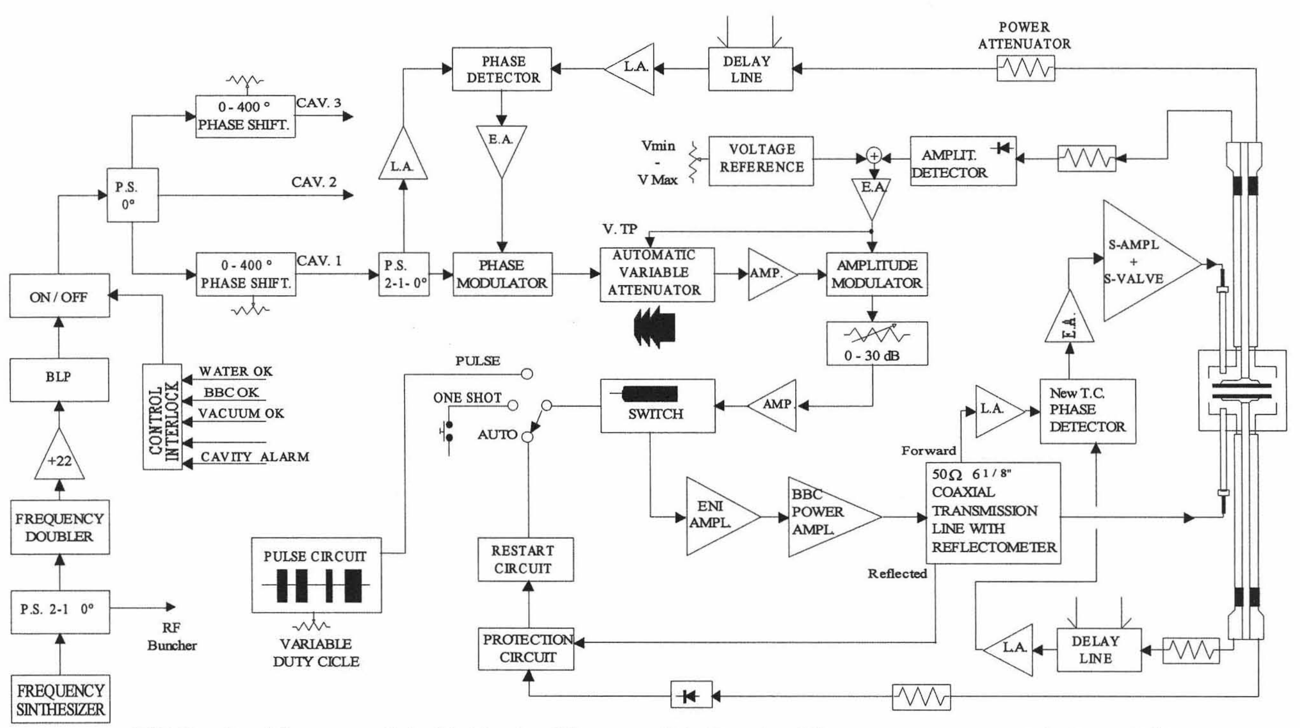
During the beam operation of the LNS Superconducting Cyclotron, many of the elements in the designed RF system had to be modified or re-designed. The main modifications were introduced to the RF Control System and Coupling Capacitors. The modified circuits were: the run-up circuits, which are on during the conditioning - multipactoring period, the phase and amplitude loops, the breakdown loops which automatically bring back the RF system into operation after a breakdown. The operational features of these circuits are presented as follows:

1 INTRODUCTION

The electronic control system of the cyclotron's RF cavities is a natural evolution of the first power tests on the half prototype cavity, carried out with the RF group based in Milan [1]. These tests were done without a magnetic field, mutual coupling of the other cavities and, of course, no beam to accelerate and therefore to extract. Starting from the positive result of the electronic control system prototype, we have projected all the RF control system to assist, not only a half cavity, but the three cavities of the C.S. We developed a system fully assisted by computer control where the concept remained the same as the philosophy of the prototype. Most of the procedure was in the hands of the computer, so a lot of the electronic hardware was thought up with that in mind. Four racks were realised, one for each RF cavity and another for the control interlock system; a kind of electronic supervisor [2, 3]. Unfortunately, we tested the four racks once again, with a half cavity, the current one, with only a couple of hundred watts. The cyclotron was still not available. Again, functional tests were carried out with good results [4]. It is pointless to say that in these conditions many of the problems discovered when the R.F. system underwent acceleration tests, did not emerge.

Fig. 1 shows the block diagram of the RF electronic control system inclusive of all the new devices that we developed during the commissioning of the LNS Superconducting Cyclotron. The most significant improvements and changes have taken place in the amplitude and phase stabilization control-loops and in the turn-on system. These devices are to be presented in the following pages of this report.



BLP: Low Pass Filter L.A.: Limiting Amplifier E.A.: Error Amplifier P.S.: Power Splitter

Fig.1 - Block diagram of the electronic RF-system.

2 NEW TURN-ON SYSTEM

We noticed, during the first power tests, the necessity to pulse the RF signal at very low power, just inside the multipactoring levels. A pulse modulator was developed and installed for each cavity, so independently we now have the possibility to choose the way and the pulses lenght for a long or short conditioning time. After we have tuned the cavity, moving the coupling capacitor up to optimise the VSWR, by increasing the RF signal a little bit more, we can be sure of staying within the first level of the multipactoring. As a consequence, the VSWR increases and the RF dissipated in the cavity remains nearly constant even if we increase the signal. The "conditioning time" has come. Now, still at very low power, the pulse modulator begins its work: it is a sort of "electronic massage". In fact, thanks to a variable attenuator placed before the pulse modulator, we can increase the RF in the cavity, following the way the shape of the modulated square wave RF changes.
According to Tab.1, the envelopes grouped in the Fig.2 are the three different steps into seeing the start, the growth and the end of the multipactoring phenomenon, when RF power increases [7].

Table 1- Observed multipactoring levels.

Level	dis-tance [mm]	Area	Vmin0 [Volt]	Vmax0 [Volt]	Vexp [Volt]	P [Watt]
1	85	Dee-Coupler or	329	390		
	110	Dee-Trimmer	552	654	850	2
2	266	Dee - Liner	3225	3823	2700	20
	275		3447	4086	5400	80
3	700	Dee - Main Ins.	27020	22656	26900	2000

There will be a moment when the transmitted power is enough to go beyond the multipactoring. Now we can stop the pulsing and with a "one shot pulse" bring the cavity to the right high power (Fig.2). With the VSWR<1.5, the protection circuits are inserted and the trimming, phase and amplitude loops are closed.
Generally, in a couple of hours of "conditioning", we exceed the multipactoring level, but it may be that we need different times for each cavity. In this case, three independent turn-on circuits, become essential one for each cavity. The heart of pulse modulators are high isolation RF switches of Mini Circuits. The most important requirements are great isolation and a very low switching time. It means an isolation>65 dB, a switching time<T, a pulse frequency<1/T, with the cavity's constant factor of time T ≈ 65 µsec at 27.5 MHz. Through this summarised condition, our switch can execute a sort of by-pass of the dangerous multipactoring level [7].
Our pulse modulator has three different ways of working:
the pulse mode: where it is important to adjust the frequency, always under T, and duty-cycle of the square wave, so as to reduce the final power dissipated into the cavity through the coupling capacitor;
the one-shot mode: where we can decide when to start or stop the transmission of the RF power in the cavity;
the auto mode: where, in view of a dangerous situation, a protection device will stop, automatically. The same device will start up again as soon as the danger has passed.

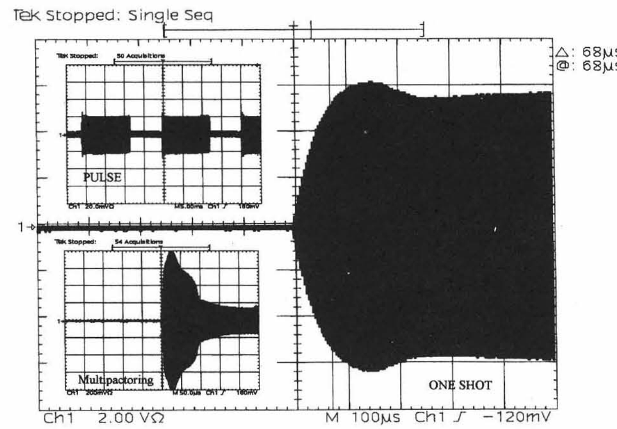


Fig.2 - The sequence of start-up envelopes.

3 PHASE LOOP

The superconducting cyclotron operates in harmonic mode h=2, so each resonant cavity has a difference in phase with the others of 120°. We take the second cavity as a reference and we move the third at −120° and the first at +120°. All the cavities need a phase stability, no greater than ± 0.2°. To avoid undesirable phase shift from that projectual limit, we require an automatic control loop to maintain the right differential phase between the cavities inside the limit seen above. Residual amplitude modulations of the phase amplitude loop are shown in Fig.3.

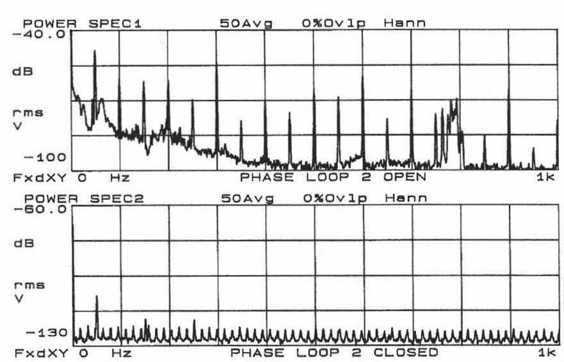


Fig. 3 - The open and closed phase-loop signals.

To move the cavities in the right difference of phase we have placed, for the first and the third, two manual continuous delay lines, which will be computer-controlled in the near future. At the moment we are making use of the "continuous phase shifters 0-400° " from Chalk River

Atomic Center. We have used them to impose the phase shift of +120° and -120°. The phase detector and phase modulator have remained close to the first version[2]. The most important find has been the insertion of two limiting amplifiers in the inputs of the phase detector. They are very useful because when the input signal changes inside the range of the limiting amplifier, the output remains constant. We have the maximum linearity of the phase detector, when the two inputs have the same amplitude and a difference in phase of 90°. Using the limiting amplifiers we can obtain the first objective and thanks to a programmable delay-line, we impose the second. Now we are ready to close the loop.

4 AMPLITUDE LOOP

It is a high d.c. gain feedback loop that ensures an amplitude modulation noise of the voltage on the dee below $1*10^{-4}$.
In comparison with the first prototype we have changed a lot of the initial structure, although conceptually it remains similar [1, 2]. The block diagram is shown below :

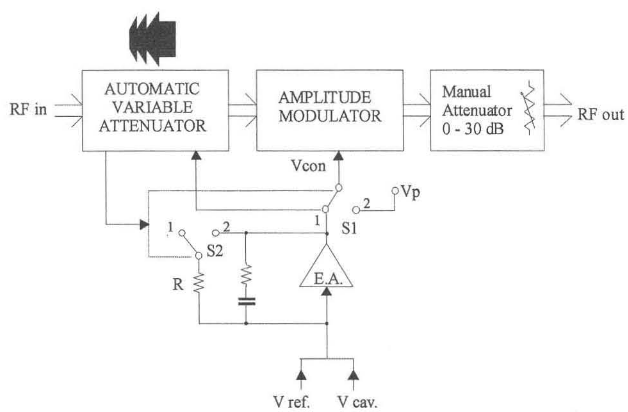


Fig. 4 - Block-diagram of the amplitude-loop.

In order to reduce the manual operation, we developed an analogue automatic amplitude loop system. When the voltage on the dee Vcav equals the Voltage reference Vref, the error amplifier output voltage is around -2 volts, necessary in permitting the amplitude modulator to work in the linearity zone of its characteristic curve. A window comparator, placed inside the variable automatic attenuator (Fig.4), just around that voltage value of -2 volts, through the dotted line, turns switch S1 from pos.1 to pos.2 and, after a few msecs. of delay, switch S2 from pos.2 to pos.1. The amplitude loop is closed. We introduce the above-mentioned delay , because the resistor R smoothes the initial transient response of the capacitor just when the loop is closed. After the delay, the capacitor is connected to ensure a proper high d.c. gain and stability of the voltage on the dee, like the spectrum shown in Fig. 5. The graphs show how the error amplifier works to obtain the graph below, where the residual modulation of the voltage on the dee is under -85dBc, according the limit above. Great care was taken in choosing the electronic components. We are using a high-speed Burr-Brown precision op. amps. for the error amplifiers inserted in the accurate system of shielding, grounding and assembling of the cabinet (Fig. 6).

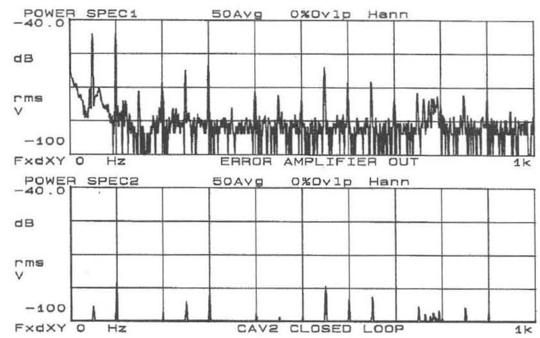


Fig. 5 - The driving and the resulting signals of the am-loop.

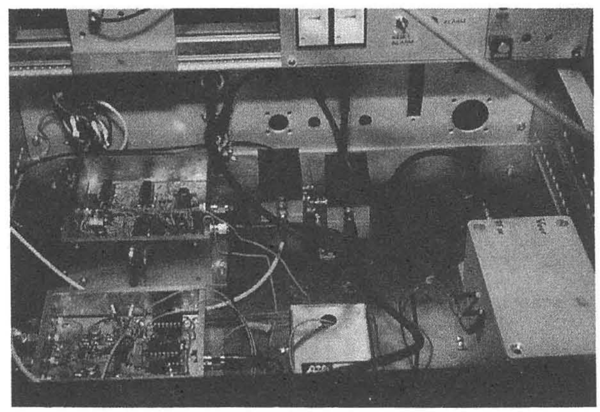


Fig. 6 - Amplitude loop rack.

Thanks to a fixed x-rays measuring system, we can read and plot on-line the exact value of the voltage on the accelerating electrodes. An operative example is given in the Fig. 7.

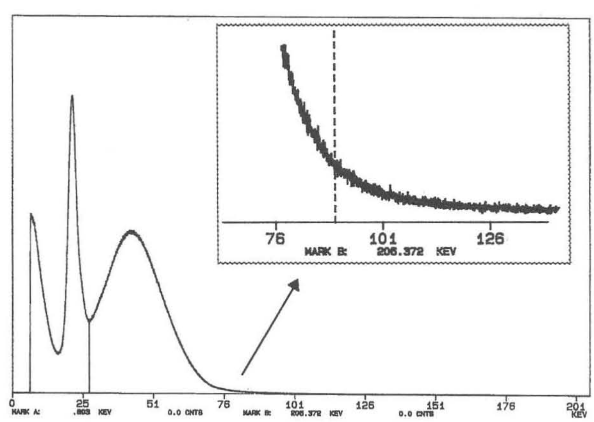


Fig. 7 - x-rays spectrum

In short, we read the x-rays emission from the dee-surface when the RF is switched-on. For example, from the x-rays spectrum we read 90 kV on the dee, while VSWR <1.1 and

RF power from the amplifier of about 22 kW, we calculate the shunt resistor of 181kΩ ($R= V^2/2P$) at 27.5 MHz [6, 8].

5 COUPLER AND TRIMMING CAPACITORS

One of the most important modifications in the RF system has been the re-designed coupling capacitors. Thanks to collaboration with MSU, Texas A&M University and LASA, we manufactured new couplers with disc insulators[5]. These couplers have been working reliably since December '94 without fail. Long-term operation using full power allowed us to come to the actual modified control system. In the picture below a disassembled coupler is shown.

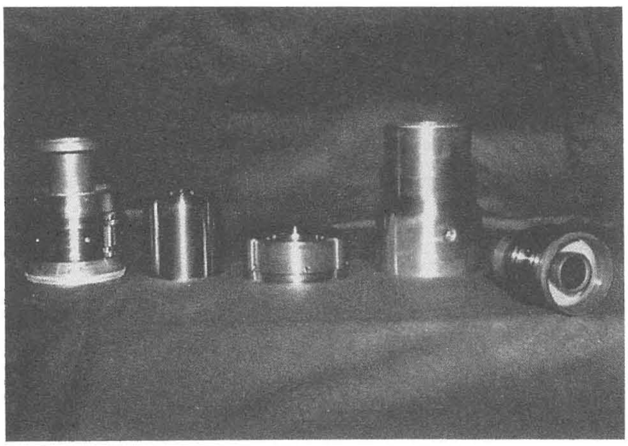


Fig.8 - Parts of the disassembled coupler.

The tuning system remains similar to the first version[1, 2]. It maintains the resonance frequency inside the range of trimming (about 40 kHz) when the cavity geometry changes due to the Joule effect during power operation. The phase detector has been redesigned. In order to improve the sensitivity response of the tuning-loop, a RPD-1 of Mini-Circuits has been used with two limiting amplifiers before inputs, to ensure the same amplitude value for each different dee-voltage. A detector-comparator, sensitive to the dee-voltage, opens the loop if an accidental or intentional turn-off occurs. It is very useful, because trimming does not follow the cavity discharge and remains next to the right position of tuning, ready to restart RF power.

6 RF COMPUTER-CONTROL

The actual architecture of the RF computer-control is a hierarchical master-slave structure[4]. The I/O operations are performed from microcontrollers INTEL i44/10 and i44/20. A personal computer called "Main Console", with a Bitbus Network Master inside, is able to co-ordinate, through messages-exchange (order-reply), all the operations. The computer control sets and reads some parameters of the RF system: all the phase shifts introduced into the different delay-lines, trimmers, couplers and sliding-shorts position, loops status, threshold protection level and, the parallel bus GP-IB (IEEE488) reads the instruments too. In the near future we will be introducing full control of each main parameter of the RF system. In particular, we are thinking about the possibility of arranging an on-line connection with the C.S. console. Thanks to a PC, we will be developing a parallel console, called "Remote Console", located in the CS control room which will be able to perform (only when allowed from the main console) the monitoring of the parameters, the variation of amplitude accelerating voltage and cavity phases. Moreover, the most dangerous alarms will be sent to the C.S. console.

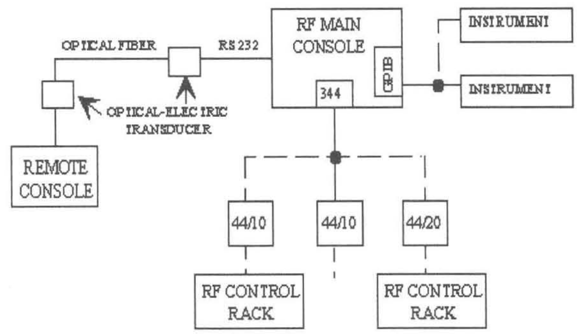


Fig.9 - Block diagram of the RF Computer-Control

CONCLUDING REMARKS AND ACKNOWLEDGEMENT

This work has been done with a frequency of 27.5 MHz and an RF power of about 25 kW for each cavity. This has given rise to an accelerated and extracted beam of ^{58}Ni (June '95)[8]. At the moment experiments are in progress on the beam-line available in L.N.S.

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