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RF SYSTEM OF THE MILAN K800 CYCLOTRON

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Introduction

The main characteristics of the Milan Superconducting Cyclotron are extensively reported elsewhere[1-4]. For the sake of completeness we just recall that the machine has a K=800 and a 3 sectors geometry, with an average magnetic field ranging between 22 and 48 kG. The accelerating structure of the cyclotron consists of 3 spiral dees, in the valleys, each dee being the high voltage part of a symmetrical coaxial resonator[5].

The accelerator design calls for an RF frequency range between 15 and 48 MHz for harmonic operation from h=1 to h=4 and 100 kV peak dee voltage in the injection and extraction regions. Depending on the harmonic used, the three dee voltages can be either in phase or $\pm 120^\circ$ out of phase. The design phase stability is $\pm 0.2^\circ$ for an AM noise on the accelerating voltage better than $1\cdot10^{-4}$.

While the other RF parameters are similar to those of the MSU K500, we note that the frequency range is very different. The rational of this choice, which complicates the RF design because of the higher frequency, is that to accelerate all the ions from 100 MeV/n to 8.5 MeV/n with just one harmonic and particularly h=2. This is important because, when the machine operates with internal ion source or axial injection, the center region is strictly connected to the harmonic in use and to change harmonic means to open the cyclotron.

This paper presents the main components of the Milan RF system, its present status and the results of the tests carried out so far.

RF cavity

A vertical cross section of the RF cavity fitted into the cyclotron is presented in Fig. 1, where all its main parts are sketched. The resonator consists of two $\lambda/4$ half cylindrical cavities tied together at the center and symmetrically placed about the median plane. For the whole length of the short circuit movement the cavity is in air. Separation between air and vacuum is made by an alumina insulator, which is designed to require only normal viton seals. Also the air part of the cavity is tight, enabling a dry air operation with a cooling flow at the insulator edge.

To obtain an upper frequency of 48 MHz, the high voltage insulator, which limits the sliding short movement, is placed inside the magnet yoke at 620 mm from the median plane. This solution strongly reduces the insulator dimensions and makes quite critical the design of the insulator region.

Each sliding short, to cover the frequency range, moves from 0.85 to 3.5 m from the median plane. A 4.2 m length has been chosen for the cavity to have a margin in case of reduction of the lower frequency and to have a region at the edge which can be opened for sliding short assembling.

The coupling capacitor is placed below the median plane to simplify the lifting of the yoke upper cap. The respective position of the trimming and coupling capacitor has been reversed with respect to the previous design[5] because of the 6 1/8" coaxial line connecting the coupling capacitor to the power amplifier. The hole in the magnet yoke opposite to the coupling capacitor is actually free. It will be probably used for the 3 phases operation neutralizing network, which has been not designed yet.

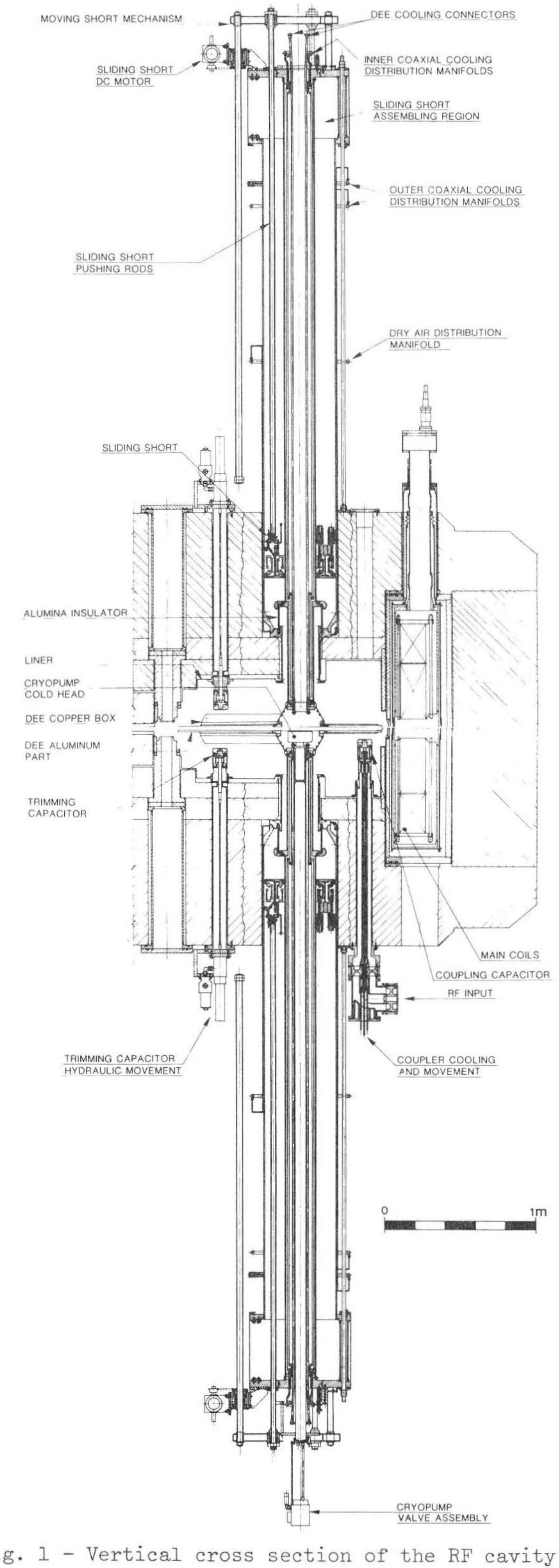

Fig. 1 - Vertical cross section of the RF cavity fitted into the cyclotron.

A free region inside the dee is guaranteed for high vacuum pumping system[4]. In Fig. 1 the splitted cryopump which is now under test is sketched.

Some detail of the main components of the cavity is presented in the following.

Coaxials

The two coaxial copper tubes, along which the sliding short moves, have a thickness of 8 mm and an outer diameter respectively of 208 mm and 486 mm, the last being dictated by the hole in the magnet yoke (ø500mm). They have been manufactured by Kabelmetal, Germany, in two different ways. The small one has been cold-drown, using an oxygen free copper billet and, after that, it has been machined and polished. The big one has been electroformed using a patented procedure which guarantees mechanical properties close to those of cold-drown copper.

While the outer coaxial is cooled by copper pipes soft soldered on the outside, the inner tube has a coaxial cooling system. The water flow is guided by a properly shaped rubber seal (refer to Fig. 2).

High voltage insulator

In the high voltage insulator region the geometry of the coaxials is strongly modified. Fig. 2 shows a vertical cross section of the upper half cavity insulator region.

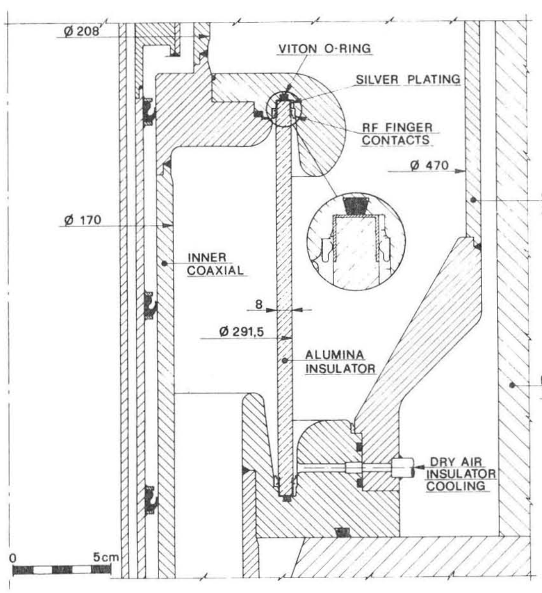

Fig. 2 - Vertical cross section of the upper half cavity insulator region. Dimensions are in mm.

The shape of the upper and lower nose and the tapering of the outer coaxial have been optimized using a finite elements computer code. This code called MACSPE[6], originally written for mechanical structures calculation, was modified for electrostatic problems. The optimization was carried out in order to have a very low voltage gradient at the insulator edges and an almost uniform electric field in the central part of it. With the actual design the maximum power dissipation on the insulator would not exceed 200 W. Moreover with a voltage of 100 kV on the upper nose, the maximum field on its surface exposed to the air is below 30 kV/cm. We are confident that this field value is reasonable because the whole air part of the cavity is tight and a controlled atmosphere is used.

The pure alumina (99.7%) insulator is symmetrical and the two edges have an U shaped silver plating having a thickness of 0.4 mm. The rational of this choice is to avoid the use of metallic seals which need for tightness very large pressure ($\geq$ 40 kg/cm). In the expanded detail of Fig. 2 the silver plated upper insulator edge fitted into the high voltage nose is presented, together with the viton O-ring and the RF contacts on both sides. Silver plating and RF contacts, modifying the RF current path, protect the viton seal. Large plating thickness is needed for a proper heat conduction.

In the picture of Fig. 3 the insulator during assembling into the cavity is shown. An air cushions system is used for this purpose in order to gently insert the insulator between RF finger contacts.

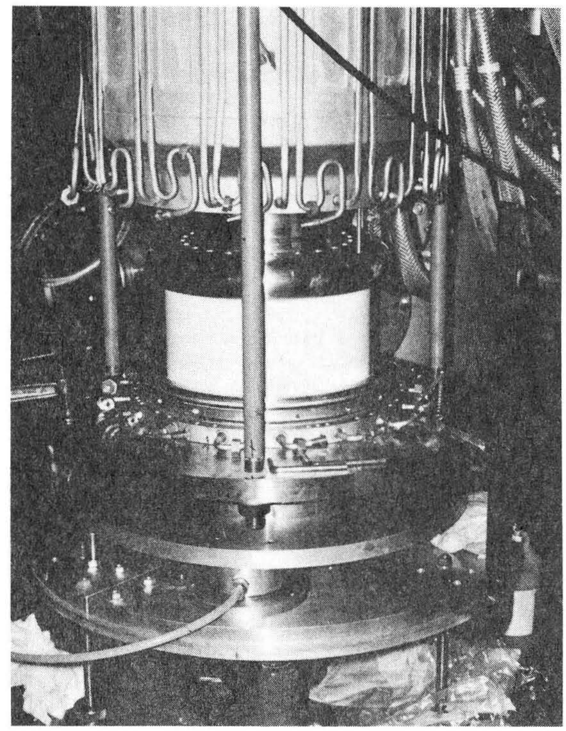

Fig. 3 - Upper dee stem insulator during assembling. Air cushions system is also shown.

Dee

The dee is splitted in two halves, symmetrical with respect to the cyclotron median plane, electrically connected at the extraction region. Another connection will be supplied according to the center region requirements.

Each half dee is composed by two separated copper and aluminum parts which can be easily disassembled. A picture of the upper half dee is presented in Fig. 4.

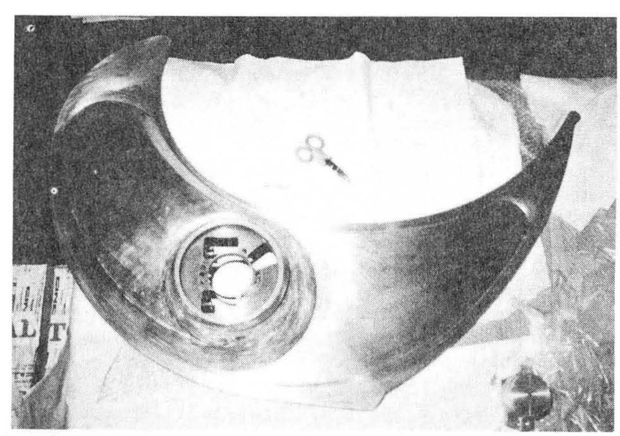

Fig. 4 - First cavity upper half dee.

The copper part, connected to the inner coaxial, is an internally beaded box made from 2.5 mm thick soldered

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copper sheet. Its main purpose is to contain the high vacuum pumping system[4]. The second part is a solid pure aluminum piece machined with a numerically controlled milling machine.

This design has in our opinion a certain number of advantages. Namely:

- any modification of the center region geometry is simple and reliable;
- shape of the high voltage profile of the dee can be optimized;
- activation of the dee during cyclotron operation is strongly reduced.

The main problem we had for a proper dee manufacturing was related to the connections between aluminum and copper. The solution was to spray a copper layer on the aluminum piece upon all those limited regions in which RF contacts or soft soldered water pipes are needed. A picture of the dee seen from the median plane side, showing copper piping, water connectors and sprayed copper (left side), is presented in Fig. 5.

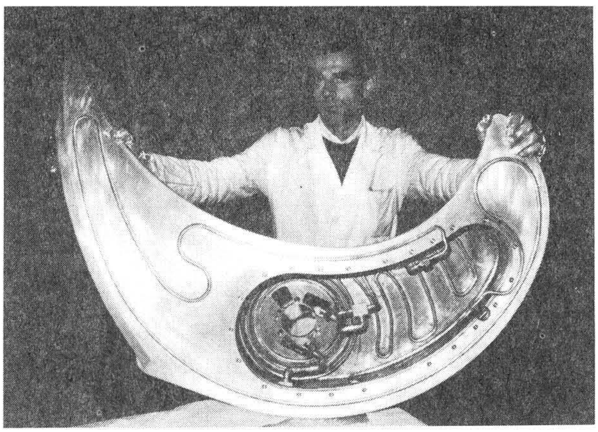

Fig. 5 - Upper half dee seen from the median plane side.

Sliding short

Because of an expected current density on the short plate of 50 A/cm at 48 MHz, the design of a reliable sliding short was one of the RF system major problems. We decided for a rather new design in which the contact between coaxials and short plate is obtained using small silver-graphite spheres (10 mm in diameter). A picture of the sliding short fully assembled on the dummy coaxials support is presented in Fig. 6.

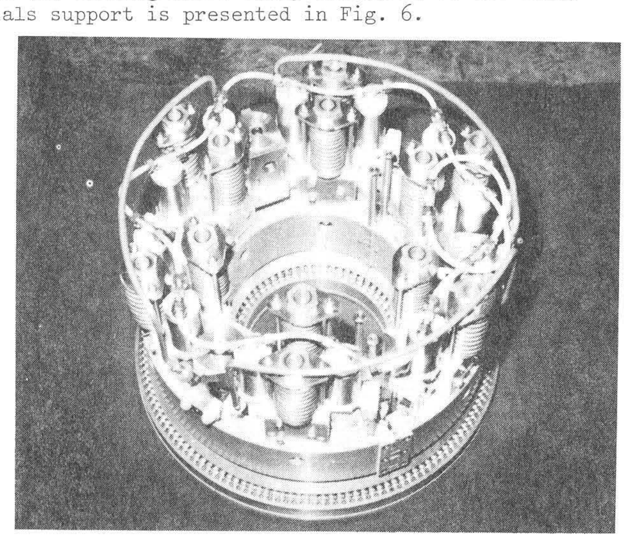

Fig. 6 - Sliding short fully assembled on the dummy coaxials support.

There are 144 and 63 balls respectively for the two coaxials, each one being pressed with a force of 2 kg against coaxial and short plate. A set of 12 air cylinders is used to reduce the force on the contacts during the movement.

For the final insertion into the cavity, the sliding short fully assembled is splitted in three parts, the spheres being sustained by proper thin aluminum sectors. In the picture of Fig. 7 the short reassembled into the cavity is presented.

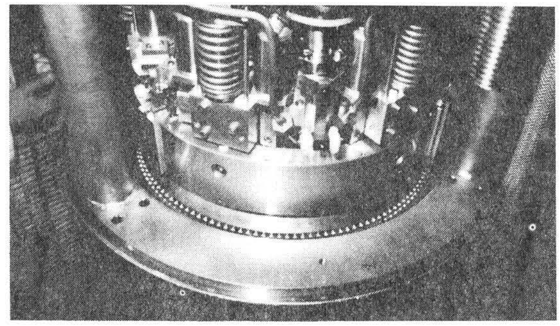

Fig. 7 - Sliding short assembled into the cavity.

To give an idea of its internal structure, two of the three sectors which compose the short are presented in the picture of Fig. 8 during assembling.

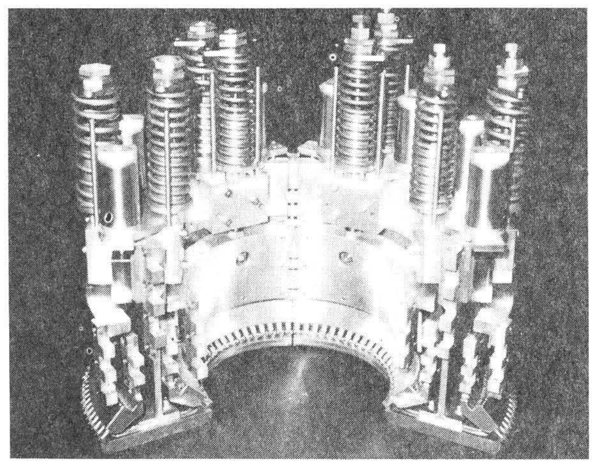

Fig. 8 - Two sliding short sectors during assembling.

Referring to the picture of Fig. 8, both rings which press the spheres for contact can move freely in order to compensate radial forces induced by an eventual defect on the coaxials straightness. The sliding short can accept overall defects of the coaxials walls position within ± 2 mm.

Since the use of balls for contacts is quite unusual, a set of tests with 50 Hz current was performed using a single 10 mm sphere on a water cooled prototype. A current up to 1500 A was carried reliably, the limit being dictated by the current wires. At this current level the temperature on the sphere was 260 °C

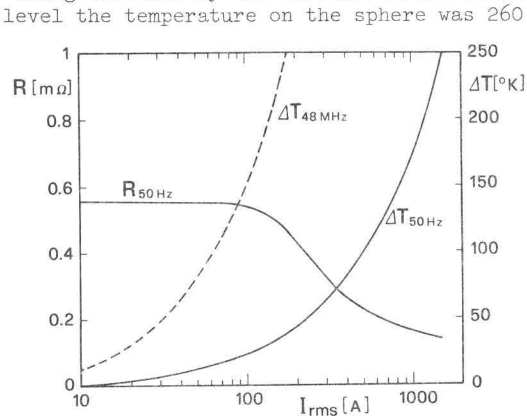

Fig. 9 - Single sphere performances.

and the total power dissipated in the two contact regions more than 300 W.

Fig. 9 shows the experimental results on the prototype together with an extrapolation of the performances of a single sphere carring a 48 MHz RF current. ΔT is the temperature of the sphere referred to the cold walls temperature, R being the overall resistance of the sphere and contact regions.

Coupling capacitor

The RF design calls for a coupling capacitance ranging between 2 and 5 pF, depending on the frequency. We adopted a solution based on the same type of insulator used in the new SIN injector cyclotron. A cross section of the actual coupling capacitor is presented in Fig.10.

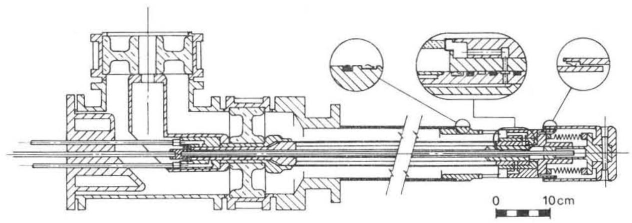

Fig. 10 - Coupling capacitor cross section.

Only a few comments are in order:

- finger contacts on the coupling head protect the bellow from the RF field;
- head stroke is 50 mm;
- a cylindrical alumina insulator (86 mm in diameter) with U shaped metallic edges is used, the edge closer to the coupling head being water cooled (refer to the central expanded detail in Fig. 10);
- a modified 6 1/8" tee (manufactured by Spinner, Germany) is used for a reliable access of water pipes and rotary actuator ceramic shaft.

A picture of the coupling capacitor head (left) together with the tuning capacitor and the upper dummy liner (for first cavity tests) is presented in Fig. 11 during assembling. A linear hydraulic actuator drives the trimming capacitor, the measured small signal unity gain bandwith being 25 Hz.

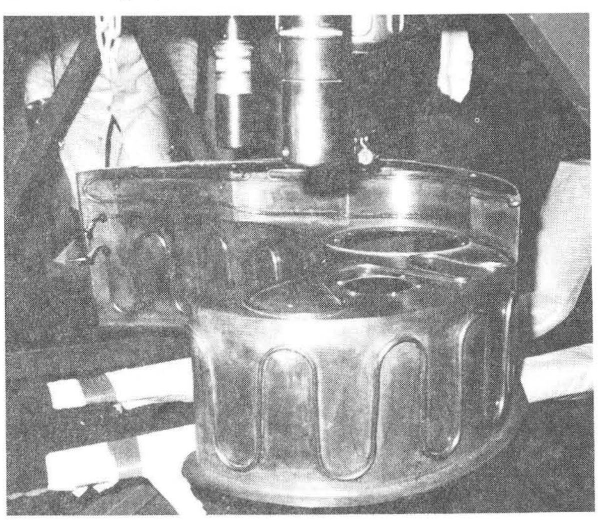

Fig. 11 - Coupler, tuning capacitor and upper dummy liner during assembling.

Power amplifier

The RF power system of each of the three cavities consists of a two stages power amplifier, driven by a commercial solide state broad band amplifier. The power amplifiers were expecially designed and manufactured by Brown Boveri Co., Switzerland, according to our specs.

The first amplifier was extensively tested for acceptance on a 50 ohm dummy load. Particularly it was tuned continuously from 15 to 50 MHz at 90 kW output power, looking with an high quality spectrum analyzer into the power tube tank circuit. No parasitics were detected. The main features of the power amplifier are listed in Table I.

Table I - Power amplifier main features

Frequency range	= 15 ÷ 50 MHz
Output power on 50 ohm load	= 0 ÷ 90 kW
Class	= B
Gain variation from 10 mW to 90 kW output power	≤ ± 1.5 dB
Efficiency at full power	= 67%
Maximum input power (on broad band 50 ohm input)	= 60 W
Residual amplitude and phase modulation at full power	≤ - 60 dBc
Harmonic distortion at full power	More than 40 dB below fundamental
Tuning	Automatic - 6 motors

In the picture of Fig. 12 the power amplifier RF cubicle with the door open is shown. The final stage has a grounded grid configuration, the power tube being an EIMAC 4CW 100.000E. Both capacitance and inductance of the output tank circuit are separately tunable. The output coupling is inductive. A pi circuit, with three tunable elements, connects the driver tube anode with the cathode of the power one. The driver grid circuit has a 50 ohm broad band input impedance.

One of the three identical units which were delivered one year ago has been installed at the present cyclotron laboratory and it is now connected to the cavity and to the 50 ohm soda water dummy load, via a motorized coaxial switch.

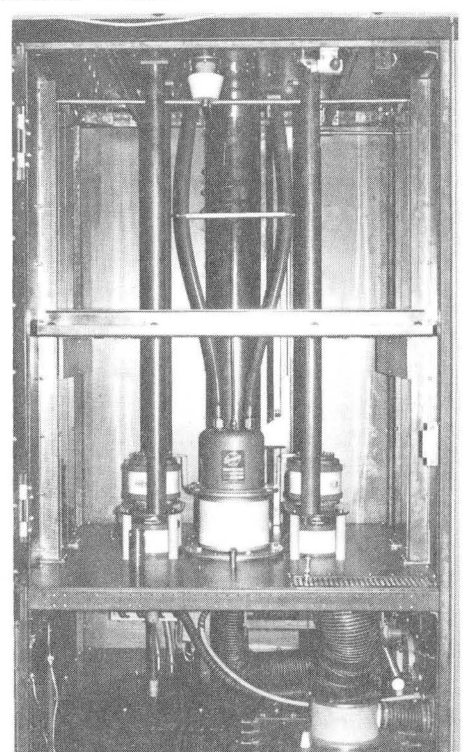

Fig. 12 - Power amplifier RF cubicle.

Control electronics

The present control electronics for the first cavity power tests is composed by the turn-on and the fine tuning systems[7]. These two systems are intended to provide easy and reliable full power operation of the RF resonator. Particularly:

- The turn-on system modulates the amplitude of the RF voltage fed to the resonator in order to break through multipactoring in minimum time; it also detecs any potentially dangerous condition and cuts off the RF driving signal (~3 μs).
- The fine tuning system continuously keeps the RF cavity tuned by adjusting the position of the trimming capacitor.

Both systems are now operative during power tests on the RF cavity. Fig. 13 shows the general block diagram of the systems.

Prototypes of phase and amplitude controls of the accelerating voltage have been designed and assembled. In the near future they will be tested on the cavity.

Low power tests

Due to a significant delay in the construction of the new building which will house the cyclotron, the original tests program has been modified and the first cavity has been assembled in the machine shop where it has been constructed (Zanon, Schio). The assembling was carried out in order to perform a preliminary set of electrical measurements for checking the computed data. These measurements were important because we can install in the present cyclotron building only one half of the cavity. This installation,while adequate for power tests on the system components, cannot provide informations on the resonant frequency and power dissipation of the whole cavity.

In September 1983, the cavity was assembled and ready for tests. Electrical measurements have been carried out exciting the cavity in a non perturbative way. Small probes have been installed on the two symmetrical sliding shorts, coupling and trimming capacitors. Dummy sliding shorts and dummy trimming and coupling capacitors were used for this set of measurements. In the picture of Fig. 14 the cavity fully assembled is shown.

Fig. 15 shows the experimental results relatively to the short circuit distance from the median plane and the Q factor. Also total power dissipation is presented like an extrapolated figure. Few comments are in order:

- the maximum frequency is 47 MHz instead of the calculated 48 MHz;
- the Q factor is smaller by about 10% and the power dissipation is therefore greater than expected.

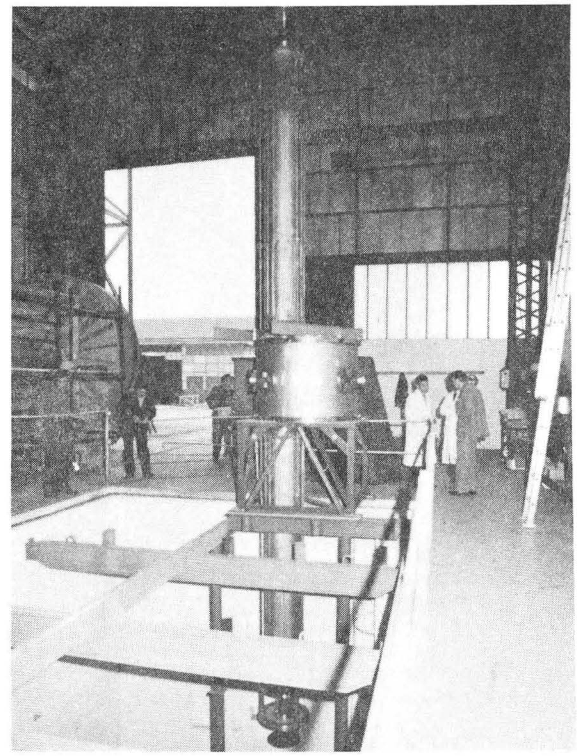

Fig. 14 - RF cavity assembled in the machine shop where it has been constructed.

We think that these results are rather successfull, looking at the complexity of the cavity geometry and consequently at the number of approximations introduced in the computer code.

Looking at the RF requirements of the Milan Superconducting Cyclotron, the two main discrepances quoted above have a different weight. The lower Q factor is probably due to poor polishing of the cavity and ineficent contacts on the provisional components. Therefore we expect an increase of it and in any case the RF power amplifier can supply the power we need. Concerning the maximum frequency we plan to modify the insulator region, slightly reducing the characteristic impedance. This will be done when the dee geometry, including the center region, will be frozen. We point out that the dee which has been tested is the most capacitive, namely that which is placed between the two electrostatic deflectors.

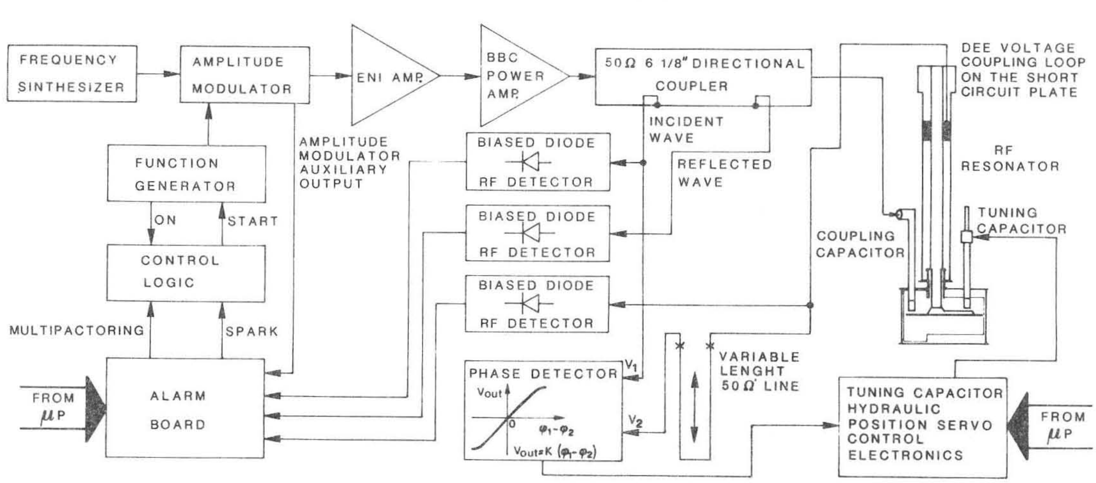

Fig. 13 - General block diagram of the operating control electronics.

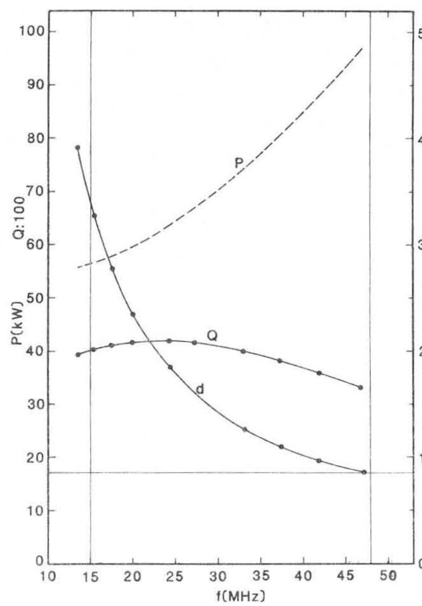

Fig. 15 - Experimental results relatively to the short circuit distance from the median plane (d) and Q factor. Also total power dissipation(P) is presented like an extrapolated figure.

Preliminary high power tests

In the picture of Fig. 16 the upper half cavity fully assembled in the present cyclotron laboratory is presented together with the power amplifier and control electronics. By the end of February 1984 the system was considered ready for a first power test, the vacuum being poor ($1\cdot10^{-4}$ mbar) due to a leak in the water piping. The turn-on circuit broke through the multipactoring and a dee voltage of 35 kV at 15 MHz was obtained, the first multipactoring level being at less than 100 V.

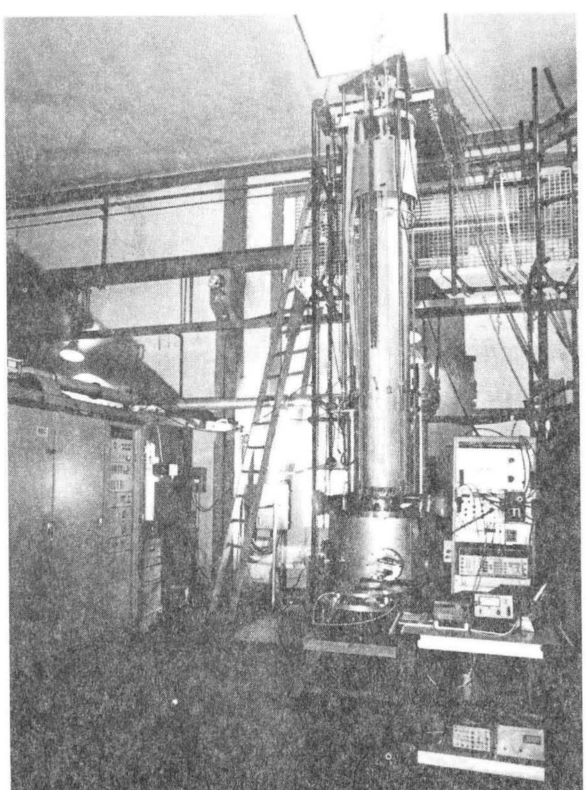

Fig. 16 - Upper half cavity, power amplifier and control electronics during power tests.

After that the cavity was partially disassembled to repair water piping in order to improve the vacuum by at least a factor ten for reliable testing.

A second set of power tests was carried out at a medium dee voltage (~30 kV) in order to check frequency range and coupling capability. A frequency range from 13 to 39 MHz was measured for the half cavity. During these tests the tuning capacitor servo system was sucessfully tested and the alarm board controlled attenuators calibrated via the microprocessor.

By the end of March the whole system, including control electronics, was ready for cavity conditioning up to the full power. Unfortunately, when the resonator was running at 65 kV dee voltage, the frequency being 15 MHz, the high voltage dee stem insulator broke.

Since the high voltage insulator should be in principle a reliable component of the RF cavity, we decided to stop power tests in order to investigate the problem. Opening the cavity, first look was that of an intact insulator, but a grazing light carefull observation showed a number of branched circumferential cracks in the insulator median region.

A complete set of tests is now under way, the insulator having been repaired with a cyanoacrylate adesive (Loctite IS407). Up to now mechanical stresses induced by the cavity have been excluded, while a strongly anomalous insulator heating was observed. Particularly, operating the cavity at 15 MHz with the repaired insulator, the dee voltage being 50 kV, in few minutes the pressure rised up to $3\cdot10^{-4}$ mbar. Ten minutes were enough to recover a pressure of $2\cdot10^{-5}$ mbar and start again: the same effect on the vacuum was observed. During this test the insulator temperature went up to 150 °C, to much for the power involved, to low to justify insulator break.

During May we plan to complete insulator tests and to take a decision. Nevertheless, while there was no indication of high power problems in the rest of the structure, we are confident to be able to start the whole RF system final construction before spring 1985.

Acknowledgements

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