FULL POWER TESTS OF THE FIRST RF CAVITY FOR THE MILAN K800 CYCLOTRON

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Introduction

The main characteristics of the Milan K800 RF system have been extensively reported elsewhere[1], together with preliminary tests results. We want just to recall that, due to building problems, we decided to carry out just low power measurements on the full cavity, limiting to the upper half cavity the high power tests for system reliability.

At the time of the MSU Conference, the low power measurements were completed and results have been reported[1,2], showing that the maximum frequency was one MHz less than needed and the Q factor about 10% lower than expected. Moreover, at the beginning of the full power tests, when the resonator was running at 65 kV dee voltage, the frequency being 15 MHz, the high voltage dee stem insulator broke.

A complete set of tests was then decided with a new insulator and a repaired one to comprehend the rationale of this failure. As a result we could demonstrate that the quality factor of the alumina cylinders was more than one order of magnitude lower than the minimum value guaranteed by the the factory. So that, a new set of insulators was ordered to Wesgo, whereas a fully compensation was asked and finally obtained by the previous supplier.

A delay of about one year was caused by this trouble. Moreover we had to abandon the U shaped silver plating at the insulator edges and slightly modify the connection between ceramic cylinder and copper cavity. The most critical consequence was to accept that the viton vacuum seals were no more protected from the RF field, being directly pressed between alumina and copper. This was accepted because of the expected very good cooling of the viton ring.

Waiting for full power tests, we anticipated some design modification of cavity components, according to the experience accumulated during assembling and preliminary measurements. Particularly:

- Coupling capacitor: the movable head diameter has been reduced and its central position displaced due to an over coupling at the highest frequencies.
- Sliding short: being very confident on the reliability of our balls based contact system, we developed a new mechanically simplified version, to strongly reduce the assembling procedure[3].
- Cavity assembling philosophy: we decided to study the possibility to fully equalize the two naturally symmetrical half cavities, to simplify the assembling procedure and reduce time and spare parts for future maintenance.

In the same time we started a complete analysis, based on an implemented version of the computer code SUPERFISH, of the cavity insulator region for an eventual second level optimization, including the recovery of the design frequency range[4].

Full power tests results

By may 1985 the cavity was ready for power tests with the new ceramic insulator. A 24 hours conditioning procedure was needed to obtain a stable operation at 100 kV dee voltage, the frequency being 15 MHz. After that, the test was stopped to install around the cavity high voltage region a 6 mm thickness lead sheet, to stop the very high X ray emission observed above 70 kV.

During the following ten months, a complete set of tests was carried out to verify cavity performances and mainly to check the reliability of all the RF system components on their extreme working conditions. As a synthesis, we can say that the system has been full power tested for a time exceeding 500 hours and no failures of the main components was observed, excluding some trouble for vacuum leaks and control electronics prototypes.

Fig. 1 presents a picture of the cavity under power test, connected to the amplifier, control electronics and measurement instruments.

The main half cavity characteristics are shown in Fig. 2, where, as a function of the frequency, the measured value of the power dissipated into the cavity, for a dee voltage of 100 kV, and the Q factor are given. The sliding short distance from the cyclotron median plane is also shown.

These curves, which are well reproducible, are very close to the computed ones (see the reference 4 at this conference for details) and so they give us good confidence on the expected behavior of the final cavities, including the small modifications decided for upper frequency increasing. The expected performances of the more capacitive of the three final cavities, i.e. the cavity supporting the dee placed between the electrostatic deflectors, are also presented in Fig. 2, as dotted lines.

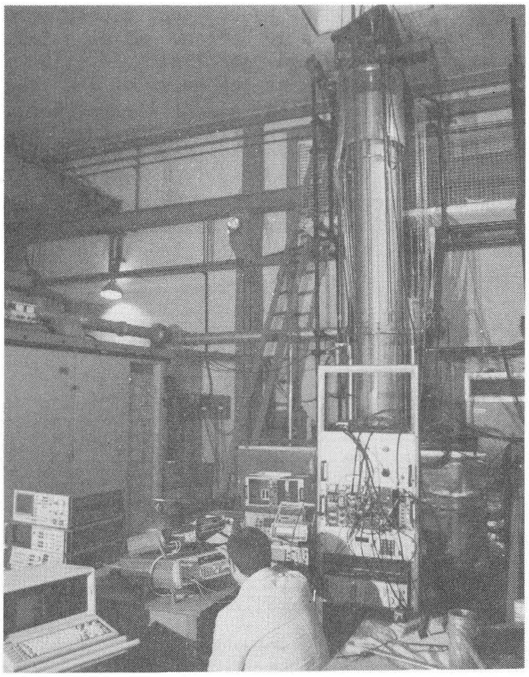

Fig. 1 - Full power tests set-up.

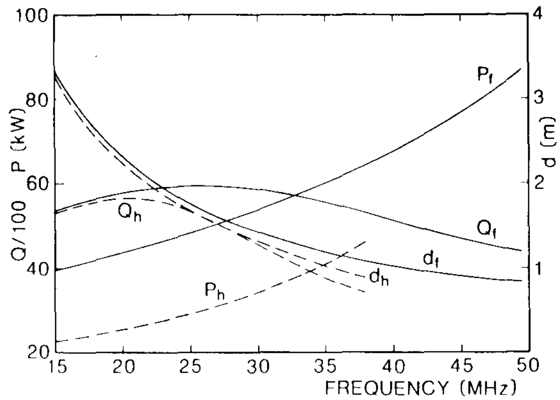

Fig. 2 - Main half cavity characteristics and final cavity expected performances (dotted lines).

Table I presents the best results obtained during the tests concerning some critical parameters.

Table I. RF critical parameters best tests results

Dee voltage at the extraction	124 kV
Short circuit current density (rms)	200 A/cm
Ceramic insulator dissipation	300 W
Coupler VSWR over the freq. range	1.05
Residual amplitude mod. index	$3 \cdot 10^{-5}$
E_{max} on the insulator corona ring (air)	30 kV/cm
Vacuum into the test chamber	10^{-6} mbar

A few comments are necessary on each of these results to comprehend its eventual limits of validity and how it can be extrapolated to a complete two time λ\4 cavity fitted into the Milan cyclotron.

Maximum dee voltage

Testing just the upper half cavity, no limits are imposed by the power amplifier, the only limit being the voltage holding capability of the structure in the dry air part and/or in the vacuum one, depending on the operation frequency. As expected, after a few hours conditioning, the maximum dee voltage (124 kV) was obtained at 25 MHz, while at the edges of the frequency range the voltage holding capability was reduced to about 110 kV and 118 kV respectively. So that, being no limited elsewhere, we expect that the maximum dee voltage will be dictated by the voltage holding capability of the central region. The actual design for h=2 axial injection seems to be adequate to ensure a dee voltage of 100 kV all over the frequency range[5].

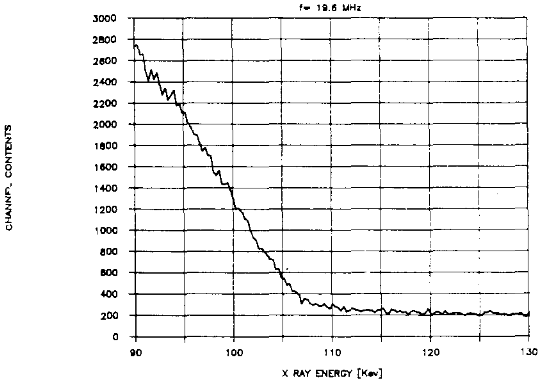

Fig. 3 - High energy side of a typical X ray spectrum used for dee voltage calibration.

We want to point out that, since the voltage on the dee is strongly dependent from the position and this dependence increases with the frequency, we call dee voltage the average voltage on the two dee gaps at the extraction radius. A computed coefficient is used for setting the dee voltage meter, starting from the result of the end point measurement carried out using a Ge-Li X ray detector connected to a multichannel. A typical example of the high energy side of the X ray spectra we use for dee voltage calibration is presented in Fig. 3. We estimate a dee voltage accuracy better than 2% for tensions greater than 80 kV. Dee voltage is sampled by a small very stable inductive pick-up fixed into the sliding short plate.

Short circuit current density

The previous version of our balls based sliding short has been extensively tested for few months, demonstrating its very good reliability. During these tests the maximum rms current density was 69 A/cm, corresponding to the inner coaxial current density at 38 MHz (the maximum half cavity operation frequency) for 115 kV dee voltage. On these testing conditions the short circuit has been successfully moved inside the trimming capacitor range. No damage or anomalous heating was never observed.

How was anticipated in the introduction, a second version of the sliding short has been designed and tested into the same testing conditions. The same encouraging results were got, but with a strongly simplified mechanics and so an even better reliability.

Since the sliding short is described in another paper of this conference[3], we want just recall the extreme test we did. Two spheres over three were taken away from the inner contact ring, together with their pushing elements, and the short so modified was tested and moved at 38 MHz with 115 kV on the dee. No damage was observed, while the temperature on the pushing springs never exceed 60 °C. Because we have one sphere/cm in the inner contact ring, this result has been summarized in table I as a tested current density of 200 A/cm, four time more than that we expect to have in the full cavity at 48 MHz.

Dee stem insulator power dissipation

According to the MSU K500 experience, a good quality alumina insulator seems to be a reliable component as expected by the computer data. In fact in our application, supposing a safety quality factor of 10 thousands, the power dissipated inside the ceramic insulator[4] will never exceed 230 W, for a maximum temperature well below 100 °C. During power tests, conditions worst than expected have been reached without any problem.

Nevertheless the full power tests were considered very important to verify the criteria adopted for the insulator region design. Particularly we were interested at the following critical points:

- reliability of the greased (using Fomblin Y VAC 3 grease) viton seals at the insulator edges, not protected by the RF field;
- adequacy of the edges cooling, mainly at the inner coaxial connection;
- adequacy of the maximum design value of the axial electric field (2 kV/cm) at the alumina to copper connections.

From tests results we judge satisfactory the seals design and the electric field level, while we decided to improve the inner coaxial corona ring cooling (see Fig. 7), the maximum detected temperature being 70 °C at 38 MHz, which can be extrapolated to 90 °C for the full cavity at 48 MHz.

Coupling capacitor

How it was mentioned above, we had to redesign the coupler head because the previous one was too capacitive and so it was not able to cover all the frequency range. The new one, with an adjustment of its central position, was well adapted to our requirements and we expect that it will be also adequate for the full cavity. In fact the coupling capacitance range is very similar in the two cases and the small 10% difference can be easily canceled or slightly magnified by the distributed effects which are relevant in such a coupler design. Moreover this coupler is rather wide band and a small adjustment of its central position is always possible.

The standing wave ratio at the cavity input for two extreme and two intermediate head positions is presented in Fig. 4. The coupler head distances from the cyclotron median plane are also shown (d_j). These curves show that an almost perfect adaptation is possible all over the frequency range and also that a few presetted positions are fully adequate to guaranty a VSWR better than 1.1 at any frequency. We consider this last result very important in order to simplify the RF system tuning procedure.

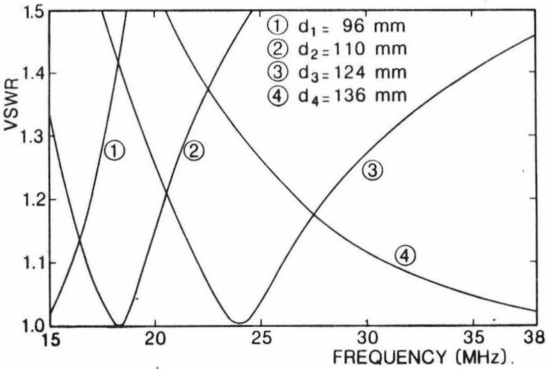

Fig. 4 - Coupler performances (see text for details).

Looking at the coupler reliability under power, we can say that no damage was observed, excluding a water leak in the air part of the cooling system. Due to this leak, we decided to slightly modify the mechanical design substituting everywhere soft soldering with TIG welding. Waiting for the new item, we continued the power tests with the leaking one, which was just air cooled, without any problem. As expected the TIG welded coupler behaves like the previous one being, in our opinion more reliable.

Amplitude and phase control loops

Control loops for amplitude and phase stabilization of the accelerating voltage have been tested and results were in agreement with the design goals. As expected we obtained good performances with rather conventional designs, mainly because of the high quality of the BBC power amplifier output signal together with the very linear behavior of the amplification chain. As an example, Fig. 5 shows a typical spectrum of the dee voltage amplitude modulation with and without feedback. A feedback with a loop gain of 40 dB at 50 Hz was used.

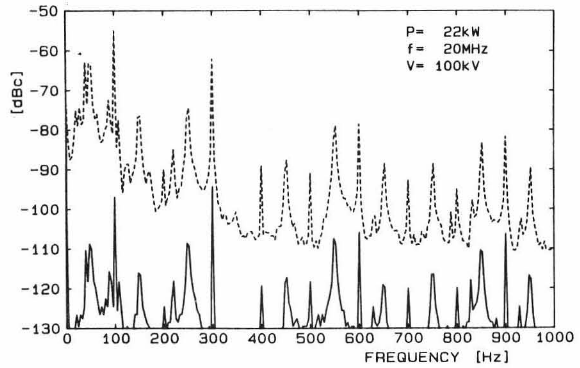

Fig. 5 - Typical spectrum of the dee voltage amplitude modulation with and without feedback.

Air side voltage holding capability

The air side of the cavity is tight to allow a controlled atmosphere in the high voltage insulator region. In fact, being the insulator inside the magnet yoke, no margin can be taken. Good results have been obtained with a modest dry air flow (≃1.5 m³/hour) from the insulator bottom edge. Particularly, at the low frequency sparking limit, the maximum value of the computed electric field on the inner coaxial corona ring was very close to 30 kV/cm.

Test chamber vacuum

All the power tests were carried out with a vacuum ranging from one to few 10^{-6} mbar, one order of magnitude more than expected inside the cyclotron but completely reasonable for our purposes. This poor vacuum was mainly due to the large amount of soft soldering that was used for water piping together with an insufficient cleaning procedure.

A maximum pressure of $2 \cdot 10^{-5}$ mbar was accepted during multipactoring punching through, while, as expected, a strong increase of the hydrogen partial pressure was observed during cavity conditioning up to maximum voltage.

Other informations from power tests

In this chapter we will discuss few useful informations coming from power tests, which can be extrapolated to the behavior of the complete RF system, together with few comments on electronic controls.

Multipactoring and turn on procedure

As expected the multipactoring was a real problem just at the beginning of the cavity operation and probably to have most of the dee in pure aluminum increased the trouble. At that time to have a good turn on system was very important[6].

Particularly, a variable attenuator has been used to amplitude modulate the RF input signal, with a trapezoidal envelop given by a function generator, in order to force-through the multipactoring barriers with the minimum required power, leaving on the phenomenon for few hundreds of milliseconds, to accelerate the surfaces conditioning. Five hours have been necessary the first time to punch-through all the multipactoring levels, ranging from less than 100 V to few kV dee voltage.

The strongest of the multipactoring levels was placed in the dee-liner region at a voltage of about 1 kV, while the second was placed in the coupler region at about two time this voltage. In the first few days of operation the phenomenon was practically extinguished, being the surfaces, in the critical parts of the cavity, conditioned to an electron emission coefficient below unity. Nevertheless, to strongly reduce the conditioning procedure, we made some encouraging experiments using low pressure Argon glow discharge[7]. So that, we planned to adopt this technique for a preliminary conditioning of the Milan cyclotron accelerating structure.

System tuning procedure

Few words must be spent about the tuning procedure because it is very simple and reliable, due to a number of decisions taken at the design level. Particularly the power amplifier works in class B and it behaves very linearly from few milliwatts to full power. Moreover it has an automatic tuning system and a coaxial switch is provided at the output, in order to feed the power into the cavity or into a 50 ohm soda water dummy load. So that, the system tuning procedure can be summarized in this way:

- amplifier is properly tuned on dummy load at the required power level and then the tuning setting is fixed;

- coupler is presetted, via a measured coupling curve, because of its rather wide band performance (Fig. 4);
- during amplifier tuning on dummy load, the sliding short can be moved and cavity tuned, using the small parasitic power coming from the switch open way (40 dB less than the other).

This tuning procedure is completely adequate for a safe cavity turn on and damages or sparks on feeder and amplifier have never been observed. Starting from this tuning point, fine adjustments can be done on power, via the trimming capacitor loop, which fixes the phase relation between the input power (from a reflectometer close to the coupling capacitor) and the dee voltage (from a field pick-up in the short circuit plate)[6].

System protections

Since this argument has been already reported[6], we want just to recall some criteria which have been adopted. Namely:

- The power amplifier is internally self protected and, particularly, the protection against load mismatching is obtained via reflected power measurement (from a reflectometer at the amplifier output), the switch-off threshold being externally adjustable up to 20 kW. This design choice, together with a relatively slow (>100μs) switch-off time, is very useful for cavity conditioning and makes the amplifier insensible to promptly detected cavity sparks.
- The cavity is mainly protected by a fast (few μs) time constant comparison circuit, which detects sparks comparing the natural cavity time constant (presetted) with the actual one.

The block diagram of the cavity alarm board is presented in Fig. 6. The output signals of this board command the switch-off of the input RF signal to the linear amplification chain, the multipactoring line signal being delayed, at the turn-on time, for multipactoring punching-through.

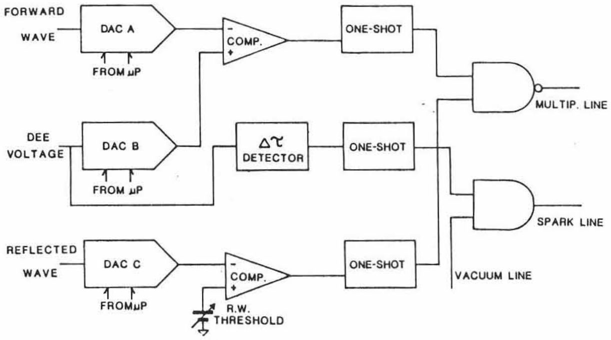

Fig. 6 - Block diagram of the cavity alarm board.

Final cavities improvements

As anticipated above, according to the tests and calculations results, few improvements have been included in the final RF system design. The most important modifications are discussed in the following.

Resonator geometry

According to the optimization carried out with the computer code SUPERFISH, the ceramic insulator region has been slightly modified[4] to increase the maximum frequency from 47 MHz to 49.5 MHz. Figure 7 presents the previous and the actual design, together with the mechanical modifications to improve the upper corona ring cooling. With this design the maximum expected temperature at 48 MHz, for 100 kV dee voltage, is 70 °C, 20 °C less than with the previous design.

The new design gives also a 6% reduction of the maximum electric field in the air side, leaving practically constant the full cavity and the dee stem insulator power dissipation.

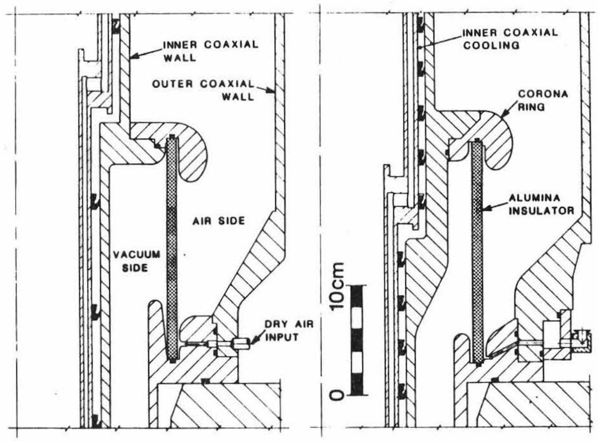

Fig. 7 - Previous and actual design of the dee stem insulator region. The main mechanical improvements are also shown.

Technological aspects

Because of outgassing problems and overall reliability, almost all soft soldering has been substituted with other technologies. Particularly: the connections between the main copper coaxial parts are now obtained by electron beam welding, small flanges are used for piping connections and a stainless steel gasket has been designed for the outer coaxial cooling in the region of the liner connection.

The only soft soldering left is the connection of the dee cooling pipes, which is supposed to be done under low pressure controlled atmosphere.

Cavity symmetry and assembling procedure

The two half cavities, which are naturally symmetrical with respect to the cyclotron median plane, excluding the dee, are now identical. So that they can be indifferently fitted above or below the median plane. One proper tooling has been designed to turn the fully assembled half cavity (including the sliding short and its movement), the dee stem insulator being pressed with a force of 3 tons by loaded springs.

Conclusions

All the final components of the Milan K800 Cyclotron RF system are now completed or under construction. Particularly we expect to be able to fully assemble the cavities during spring 1987, to be ready for their fitting into the cyclotron. More details on the Milan Project status, including RF system, can be found in a proper paper at this Conference[8].

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