FIRST OPERATIONAL EXPERIENCE WITH THE RF SYSTEM OF THE LNS SUPERCONDUCTING CYCLOTRON

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ABSTRACT

The RF system of the LNS Superconducting Cyclotron, whose prototype was successfully tested at Milano in 1985, has been finally tested in operational conditions during a few weeks in the last year. In this paper we present the experimental results obtained so far together with a discussion on the experienced reliability of the major components. The few modification we have planned to perform in the near future are also presented.

1. INTRODUCTION

The RF system of the LNS Superconducting Cyclotron has been described elsewhere in a number of review and status papers [1-5], in which the design criteria and the solutions adopted for the critical components have been presented and discussed. Particularly, the initial design is given in [4] and references, while in the paper [5] the system, once realized at the level of the first cavity prototype, is discussed on the basis of the experience gained during the preliminary low level and power tests.

In the context of the Tokyo International Cyclotron Conference (1986) we discussed, in a dedicated paper [6], the RF system performance as deduced by long term full power tests, performed on a half cavity; moreover few minor modifications already tested, or to be included in the final design, and their rationales where also presented and discussed [7,8].

By the end of 1987 the six identical half cavities where assembled at Milano and ready to be installed and tested into the cyclotron.

Once transferred to LNS (Catania) and installed in the cyclotron magnet, the whole system of three cavities has been finally tested, for the first time, in August-September '93 and, after the magnetic measurements, it has been operated in May-June '94 during the first acceleration tests [9].

In the following we discuss the experience gained so far, the major problems we had, and finally the solutions we decided to adopt to improve the system reliability.

1. CAVITIES AND TUNING

Each of the three $\lambda/2$ resonators is tuned by two sliding shorts, symmetrically placed with respect to the beam plane, their stroke being limited by the corona ring of the dee stem insulator from one side and by the cavity edge from the other. Each sliding short can be smoothly moved independently and its position is read by an encoder whose resolution is less than 0.1 mm.

One interesting measurement we want to quote was that to find, for each of the three cavities, the optimum em symmetry condition, while plotting the frequency vs. sliding short position curve. This has been done making use of the HP 8753A Network Analyzer (NA) with the S-parameters test-set. Port 1 of the NA was connected, through a cone adapter (Spinner), to the main coupler transmission line, while Port 2 was connected to one of the three pick-up loops installed in each sliding short. This simple set-up allows to determine the em symmetry condition as that giving the maximum loaded Q factor. For a given frequency, the last is measured moving the two sliding shorts, while keeping the matching point in the center of the Smith Chart. Slightly different positions (up to 0.5 mm) for the up and down sliding shorts have been found to get a precise em symmetry. We quoted this measurement because its sensitivity is quite good and usually much better than needed for acceleration. In our case the system symmetry is good enough to use geometrical symmetry for sliding short positioning, the axial component of the electric field being in any case smaller than the critical value.

As expected the three resonators have slightly different parameters due to different dee capacitance. This is a consequence of the resonant extraction [1] mechanism which asks for different dee radial extensions. In particular the dee before the first electrostatic deflector (dee 1) must not interfere with the extracted beam, while the dee placed after the second deflector (dee 3) has to give to the beam the last energy gain. This design choice, together with the interface with the magnetic components of the extraction system, produces the difference between the capacitance of the three dees.

An upper frequency slightly above 50 MHz has been measured for the three cavities (as predicted in ref. [8]) wile the lower frequency is close to 15 MHz. So that the operational frequency range fits that of the power amplifiers, being helpfully a little wider than strictly required (15 to 48 MHz).

All the other cavity parameters (Q factor, shunt impedance, etc.) are very close to the expected values.

2. COUPLING CAPACITOR

In spite of the difference among the cavity parameters, the three couplers are identical and their design is presented in Fig 1 (right side). For a stroke of 50 mm, the coupler matches the transmission line to the cavity exactly to 50 Ω, within the 20÷50 MHz frequency range. Below 20 MHz its capacitance was found to be a little to small for a perfect matching. In particular, for the more capacitive cavity, the mismatch reaches (at 15 MHz) a value of 1.45, once expressed in VSWR. That is at 15 MHz for 100 kV dee voltage [10], a 6% (2.4 kW) reflected power is expected. This value, while tolerable, can be easily reduced adapting each coupler head to its proper cavity, wile preserving a perfect matching at 50 MHz, where, for 100 kV dee voltage, the required power reaches a value of 87 kW.

The multipactoring problems which has been encountered during power tests are discussed in section 5.

3. SLIDING SHORTS AND TRIMMING CAPACITOR

According to the experimental results obtained during the power tests at Milano, the sliding short is a very reliable component, being able to support a current density, at 50 MHz, of the order of 200 A/cm, that is 5 time more than needed. Again it can be moved at full power [6,7]. This peculiarity, together with its smooth displacement, allows to set a cavity to the operational frequency, within 1 kHz, and to eventually tune it, once in power, for the frequency shift induced by the magnetic field (few kHz).

Moreover we could install just one narrow-band trimming capacitor per cavity, having a shape similar to that of the coupler, in order to compensate for the asymmetry induced between the two half cavities which, once connected, behave like a $\lambda/2$ cavity. For a stroke of 50 mm (the head mechanism is that of the coupling capacitor), the band covered by the trimmer ranges from 17 kHz at 15 MHz to 110 kHz at 50 MHz. At any frequency this band is larger than that needed to compensate for the thermal detuning, due to the high cavity stability.

4. DEE-TO-DEE COUPLING

Since the cyclotron can be operated in three different harmonic modes (1, 2 and 3), the three cavities must support dee voltages either in phase (harmonic 3) or out of phase of $\pm$ 120 degrees (harmonics 1 and 2). In the last two cases, as it was pointed out elsewhere [11], the crucial point is the mutual parasitic coupling. In fact, to operate the three cavity system with the required phase relations, an eventual coupling capacitance of more than 10^{-2} pF has to be compensated with a very complex external tool [11].

Facing this problem, the central post needed for the tandem injection (that is the operation mode we have selected for preliminary beam tests) has been designed for a very good shielding, and the mutual capacitance between any two cavities has been carefully measured, as mentioned in the following.

Starting from two cavities tuned at the same frequency, the two coupler being set at the matching position, the two ports of the Network Analyzer were connected to the transmission lines through cone adapters. So doing we have verified that our cavities are really uncoupled, because the insertion loss $|S_{21}|$ has a minimum value of 55 dB at 50 MHz. This value corresponds to a mutual capacitance between dees 1 and 3 of the order of $2 \cdot 10^{-4}$ pF, that is 50 times smaller than acceptable [11].

Also if the central region for axial injection will be more capacitive, we are confident to be able to menage the problem with no compensation tools.

5. MULTIPACTORING AND CONDITIONING

The system was conditioned with the magnetic field on and a vacuum of few 10^{-6} mbar. Being the amplification chain quite linear (class A and class B amplifiers), the input power can be set to any value from the watt level and the control electronics allows to choose the pulse duty factor and shape.

During the tests we noted that the cavities are not very sensitive to the chosen conditioning procedure. The lowest levels of multipactoring, which are situated in the region of the dee gaps, are the most critical to be passed and occur for dee voltages ranging between 60 and 200 V. After a long shot down which includes a machine opening, these low voltage multipactoring levels need for conditioning 2 or 3 hours, the time being rather independent either from the power used to pulse the cavity or from the pulse shape and duty cycle. A low power conditioning (10÷50 W) is than preferred.

The second group of multipactoring levels which has to be passed is situated, for all the three cavities, between 2 and 4 kV. To pass these levels a pulsed input power of few kW is preferred to reduce the conditioning time to less than one hour, with respect to the longer time (2 or 3 hours) needed if the power is maintained slightly above the value that is strictly required by the dee voltage.

Looking at the high voltage conditioning, according to the experience gained on the prototype [6], no conditioning time is needed up to 60-70 kV, while to get a stable operation at 100 kV at least 5 hours are required. These tests have been done, cavity by cavity, in August-September 1993.

We note that the amplitude of the dee voltage, defined as in ref. [4], is measured by one of the six loops installed into the sliding short plate (three each) - once calibrated with the Network Analyzer - according to the cavity shunt impedance given in ref. [10]. An absolute dee voltage calibration, measuring the x-ray spectrum [6], is foreseen in autumn.

6. POWER TESTS AND COUPLER FAILURES

During the two runs at high power (August-September 1993 and May-June 1994), the magnetic field being on, we had a total of four coupler failures, limited to cavity 1 and 3, all these failures looking similar. The damaged coupler showed a metalized region on the ceramic insulator, while the failure was detected as a sudden pressure increase into the vacuum chamber, caused by a water leak in the ceramic cooling circuit.

The possible weakness of our coupler design was somehow expected and a possible solution envisaged [12], also if no failure has been observed during the one year tests performed at Milano on the prototype [6], the only significant difference being the presence of the magnetic field. The experience of the other laboratories which had used similar couplers for similar machines (Texas A&M University and NSCL) was the reason of this fear.

Unfortunately, in a superconducting cyclotron which has to operate at any frequency included in a wide frequency range, with different values for the dee voltage and the magnetic field, many dangerous conditions exist. Moreover, being the phenomena a resonant discharge across the coupler ceramic insulator (matched for 50 Ω), the effect produced on the cavity tuning is very small (VSWR goes from ~1 to 1.7) and, if it is not suddenly and independently detected, it is automatically compensated by the trimming capacitor! The effect of the magnetic field is that to focalize and stabilize the resonant beam of electrons which can carry a significant power (in one case we have estimated a power of the order of 70 W). As an example, at 27.5 MHz, with a magnetic field of 3 Tesla, this dangerous condition is reached for a dee voltage of the order of 30 kV, that is a typical "safe value" at which one stays to properly set the control electronics circuits.

As a conclusion we decided to modify the coupler design in a way similar to that proposed and successfully tested by the two laboratories mentioned above. Figure 1 shows the actual coupler design (right side) compared with the new modified version (left side). With few modifications the insulator position and orientation have been changed, to annul the effect of the magnetic field. We expect to have the new couplers by the end of the year.

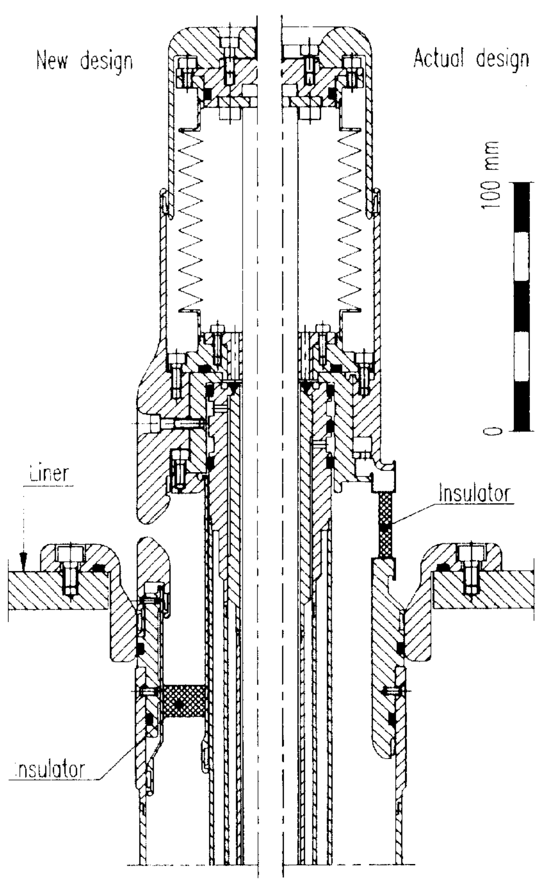

Fig. 1 Schematic drawings of the two couplers: the actual one (right) and the new modified version (left).

7. CONTROL ELECTRONICS

The control electronics that has been used during power tests and first beam runs [9], is an improved version of that used in the first power tests [6] and its features have been already reported [13].

As expected, during tests the control electronics performed according to the specs and tuning and setting were possible via computer.

Nevertheless, because of the significant progress of RF electronics components, computers and control software in the last eight years, we decided to dedicate some effort to update the system. We expect to gain both in reliability and maintenance time, because of the reduction of the total number of components, while conserving the general lay-out and philosophy.

Thanks to the modularity of the system, its updating will not interfere with the general cyclotron program, and we expect that it will be completed by next spring.

8. CONCLUSIONS

Despite that the RF system of the INFN LNS Superconducting Cyclotron has been conceived, designed and built few years ago [4-6], its general behavior during power tests has been very satisfying, showing that all the major components are reliable and performing, the coupler weakness being expected and under control.

Moreover we are confident that the few improvements we plan to realize to update the system (coupler and control electronics) shall not interfere with the general schedule for cyclotron commissioning and they will be completed in less than one year from now.

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