ADVANCES IN RF TECHNOLOGY FOR CYCLOTRONS

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ABSTRACT

The wide number of cyclotron applications and the different physics requirements have produced a variety of machine designs, especially of the RF cavities which have to support the Dees, and depend strongly on the magnet design. In this paper few recent RF systems are discussed with emphasis on the cavity design improvements, mainly based on new ideas, designer's imagination and advances in allowable technology. Some suggestion on the way to make profit from the use of computer are also given, together with some general ideas on how to design the control electronics and the RF power amplifiers.

1. INTRODUCTION

In the cyclotron history many cases can be found in which the RF system was considered just when the general machine design (that is mainly the magnet) was practically frozen. As a consequence a number of RF systems suffer the fact that some of the imposed constraints, which limited the possible solutions and sometime the best envisaged performances, were not strictly necessary. In these cases a minor modification of the machine design would possibly have produced a much performing RF.

In this paper I will describe few recent RF systems which were designed with discussed boundary conditions, that is whose parameters have been optimized together with the general machine parameters. To do that the RF designer must have a serious knowledge on beam dynamics and techniques related to magnetic field design, while the project leader must have a good competence on RF related problems.

I am convinced that most of the RF performances are dominated by the cavity design[1,2], including the coupling element. In fact few companies can deliver a very good amplifier, the problem being eventually the price. Again modern electronics allows to design performing controls which match phase and amplitude stability requirements and can be operated via computer. But in the case of meson factories, with very strong beam loading, electronic controls can be considered like cyclotron independent. This concept means that, adapting the frequency range and the software compatibility, a good electronic control, designed for a multi-cavity machine, can in principle be used for any other cyclotron whose cavities have no major limitations.

In the next paragraph I will briefly discuss five recent cavities, pointing out the major design choices together with the solutions adopted, based on the development of original designs for critical components and on the use of special technologies, which could be widely applied in cavity realization to improve the system reliability and performance. The eventual impact on the overall machine cost is discussed too.

In the third paragraph few comments and personal opinions are given on the way to make profit from a proper use of the allowable computer codes and more generally from the computer itself.

Finally in each of the last two paragraphs one example will be given, respectively of control electronics and RF amplifier. These two examples can be considered as a reference, in the sense that they include most of the important, or just useful, choices which would have to be done when a RF system is designed.

2. CAVITY DESIGN EXAMPLES

Among all the built cavities, I have chosen few recent examples to discuss the most interesting technologies applied or developed together with the design criteria, related to the machine specs and constraints. I will also use these examples to sketch how design, ideas and technical solutions are going together all over the time of the machine construction; so that most of the comments expressed for a specific RF system have to be considered as general comments referred to most of the RF systems.

2.1 The AGOR Cavity

The superconducting cyclotron AGOR[3,4] has three vertical and identical cavities, symmetrically placed with respect to the machine median plane. The conceptual design of this cavity has been conceived together with the magnet design, with the aim to obtain the best compromise from the machine point of view. Particularly, with respect to the other three sectors superconducting cyclotrons[5-8], the chosen frequency range is considerably higher (24 to 62 MHz), asking for a different harmonic operation. In this case the majority of ion energies per atomic mass unit (10 to 72 MeV/amu) are accelerated using the 3rd harmonic instead of the 2nd

(LNS/Milano) or the 1st, like in the others cases. The use of the 4th harmonic for energies below 10 MeV/amu increases the minimum RF frequency up to 24 MHz.

The major impacts on the magnet and RF designs produced by the chosen frequency range can be summarized as in the following:

a) Each magnet pole has three very large (Φ=500 mm) vertical holes, tangent to the hill profile, but no other holes are supplied for coupling and fine tuning. A careful design of the valley shimming[3] was necessary to compensate for the big holes. In the other similar machines this magnet design has not been accepted or proposed. A schematic drawing of the AGOR pole face, where the large RF holes are visible, is presented in Fig. 1.

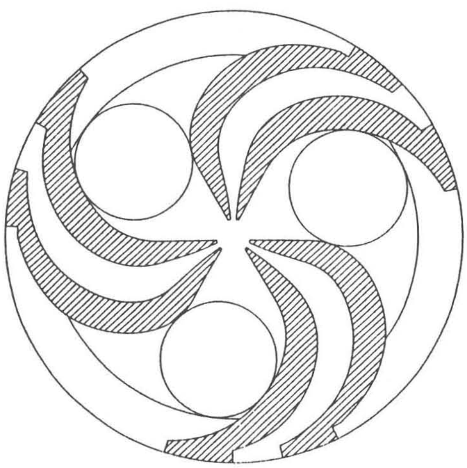

Fig. 1. Schematic drawing of the AGOR pole face with the large RF holes tangent to the hill profile.

b) The RF cavities can be much shorter (~ 2 m) and no ceramic insulator between the HV electrode and the outer coaxial line is supposed to be needed[9]. For a lower RF power and Dee voltage, a compact and performing sliding short has been developed, able to slide under power and vacuum, and to include variable inductive coupling and fine tuning[10]. Very tight general tolerances and external multi-axis adjustments are needed too.

Once defined the frequency range and the general design criteria - based on the previously mentioned compromise supported by first order calculations and technological considerations - as for the other machine components, the RF boundary conditions become practically frozen and the detailed design starts, including the items and the fabrication technologies which need to be implemented or developed. In the case of the AGOR RF system I will list in the following the major characteristics of the cavity design[9,10] and technology, pointing out the most interesting solutions, which could be eventually applied for other machines.

• Because of the absence of the mechanical support given by the ceramic feedthrough, the cavity length has been minimized at low frequency, while increasing the minimum distance of the sliding short circuit from the beam plane. These two effects have been together obtained maximizing the characteristic impedance of the coaxial part (just limited by mechanical rigidity and current density considerations), while reducing the impedance of the dee-liner region, by a careful shaping of the HV electrode and of the valley part of the liner. The reduction of the impedance of the dee-liner region slightly increases the average current density on the sliding short, the effect being screened by a more homogeneous distribution[10].

• Coarse tuning, fine tuning and variable inductive coupling are performed via two symmetrical multi-function sliding shorts, one carrying the coupling loop. A schematic drawing of the multi-function sliding short carrying the coupling loop is presented in Fig. 2. Particularly: coarse tuning is accomplished by mean of a symmetrical and rigid movements of the two sliding shorts; the coupling loop is matched varying the distance between the two concentric rings, in which the short is split; fine tuning is done and maintained acting (during operation via a feedback system) on the position of the outer ring of the sliding short not involved in the coupling loop matching.

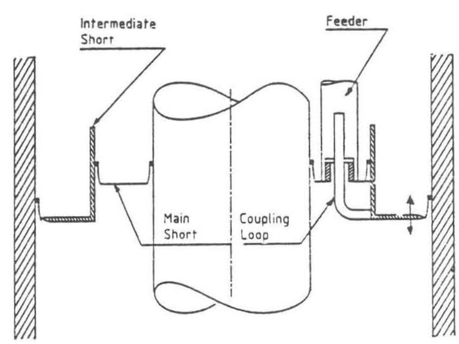

Fig. 2. Schematic drawing of the AGOR cavity sliding short which carries the coupling loop.

• Many technologies have been used to fulfil the tight requirements on the general mechanical tolerances and stability against induced vibrations and thermal deformations. Moreover the very compact solution chosen for the sliding short contacts (based on the developments of carefully optimized finger contacts), while supporting the needed current density (~ 40 A/cm @ 60 MHz), with a 50% safety margin[10], asks for overall tolerances between the two coaxials of the order of ± 0.5 mm. As a consequence, compared to the other cavities for similar cyclotrons[5,6,11], this one needed more engineering and the total cost has been higher. Each dee half is EB welded to the inner coaxial and can not be disassembled. Again numerically controlled multi-axis machining has been widely used (together with EB welding) to guarantee the mechanical tolerances needed for the dee position (central region, extraction and lip plane) and for a safe operation of the sliding contacts all over the frequency range.

2.2 The LNS/Milano Cyclotron Cavity

While the operating diagram of the LNS/Milano cyclotron is very similar to that of AGOR, the general design is quite different[7,8]. As mentioned above the majority of ion energies per atomic mass unit (8.5 to 100 MeV/amu) are accelerated using the 2nd harmonic instead of the 3rd, the RF frequency range being 15 to 48 MHz.

The compromise between magnet and RF has been different: for a less sophisticated coil design, the large holes (Φ = 500 mm) on the pole valleys have been accepted just up to a minimum distance of 600 mm from the median plane. As a consequence the 3rd harmonic, with frequencies up to 72 MHz was impossible, and we decided to put all the efforts to have a 2nd harmonic operation covering almost all the operating diagram up to 100 MeV/amu. Moreover the 2nd harmonic (with respect to the 3rd) has the advantage to reduce the phase precession problem at the extraction, for a 13 % lost of the peak dee voltage.

Among these discussed boundary conditions, the cavity was designed to fulfil the specs with a reasonable cost and development[11-14]. In the following I will list the rationals of some choices, together with the conceptual design of few special items, trying to sketch how they are sometime dictated by theory and experience, and sometime by personal feeling, optimism or imagination.

• Dee shape has been defined with the aim to minimize the overall capacitance and reduce the high field regions to those considered unavoidable (at the centre and at the extraction; see the photograph of Fig. 6). An aluminium bulk structure has been chosen for the dee to minimize its volume and weight for the same stiffness A copper cone, which can be disassembled, assures the connection to the dee stem, while housing the cryopump cold head. A brazing technique had to be developed to connect the Cu cooling pipes to the Al dee.

• Being the hole shape in the magnet yoke a boundary condition (see Fig. 3), the transition region, between the valley part of the cavity and the uniform coaxial part, was designed to get the maximum required frequency (48 MHz), while optimizing (see below for the criteria) the insulator region in the allowable space. Once understood and taken into account the behaviour of the cavity characteristic impedance into this strongly perturbed region and how it affects the overall cavity parameters (maximum frequency, power dissipation, etc,), the main criteria to perform the optimization of the insulator region can be summarised in a careful control of the following three parameters:

- maximum electric surface field on the corona ring; ≤ 30 kV/cm for a dry controlled atmosphere.
- maximum electric surface field at the ceramic edges: ~ 2 kV/cm, to strongly simplify the vacuum tight ceramic to Cu connection (done by a simple Viton OR seal)
- maximum power dissipation inside the insulator: ~ 200 W, together with a proper distribution to minimize the insulator equilibrium temperature (a minimum insulator Q = 5000 is in this case accepted).

After measurements on the cavity prototype a second order optimization has been performed (see § 3) using the computer code SUPERFISH, which was implemented for this purpose. A maximum frequency of 49.5 MHz was reached for the cavity supporting the most capacitive dee (that is the dee between the two electrostatic deflectors), instead of 47 MHz, as measured on the cavity prototype (one MHz below the computed value). A drawing of the upper half of the LNS/Milano cavity is presented in Fig. 3.

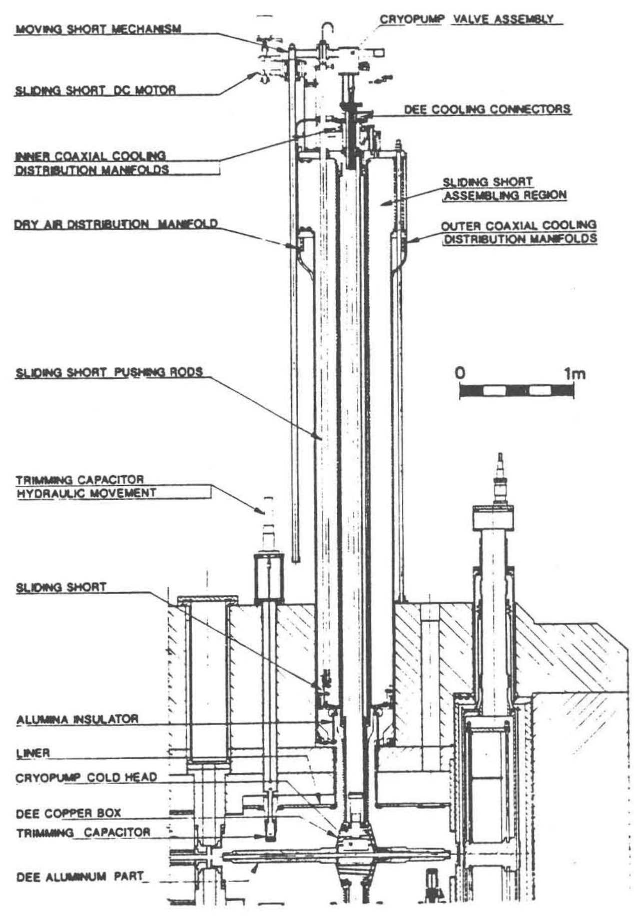

Fig. 3. Schematic drawing of the upper half of the LNS/Milano cavity fitted into the magnet.

• The characteristic impedance of the uniform coaxial part of the cavity, which does not appreciably affect the maximum frequency and the maximum dissipated power (in such a cavity being always associated to the highest frequency), has been determined as a compromise between the cavity length and the maximum current density to be accepted by the sliding short contacts. I want to point out that a rms current density of more than 40 A/cm @ 50 MHz, together with reasonable mechanical tolerances (greater than ± 1 mm to limit the cavity cost), was at that time already optimistic and well above the existing technology. Nevertheless, if the high performance ball based sliding short[15] was at that time already developed, a different optimization would have been done, reducing the cavity length (and the sliding short stroke) of at least half a metre!

• A drawing of the high performance ball based sliding short, which was developed to fulfil the specs, is presented in Fig. 4. Being the item designed around a completely new idea[15], its performances, as optimistically expected, resulted to be much higher than needed. Since a more detailed discussion on the basic idea, experimental results and technologies involved is available in Ref. [15], in the following I will just list the major performances and characteristics of the actual sliding short, as a reference for other projects on what can be reliably done today. In particular its characteristics are:

- Maximum current density (rms, @ 50 MHz)	> 200 A/cm
- Accepted mechanical tolerances	± 2.5 mm
- Sliding distance before ball maintenance	> few km
- Under vacuum operation (~ 10^{-7} mbar)	allowed
- Sliding at full current	allowed

• The last interesting item I want to mention is the coupling capacitor, whose drawing is presented in Fig. 5. Its main peculiarity are:
- The inner conductor is coaxially water cooled up to the edge of the cylindrical alumina insulator;
- The coupling head has a stroke of 50 mm;
- An especially designed tee (6 1/8") is used for a reliable access of water pipes and rotary actuator ceramic staff.

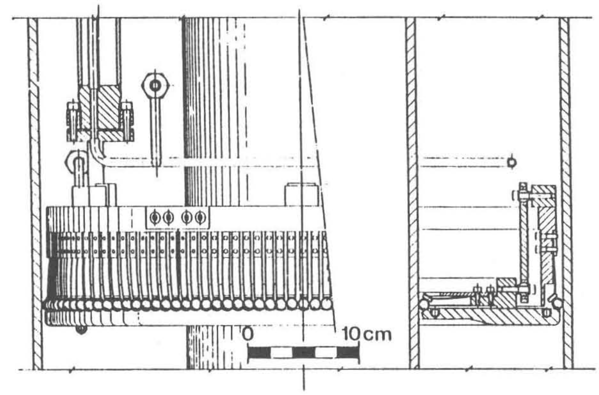

Fig. 4. Drawing of the very high performance, ball based, sliding short of the LNS/Milano cavity.

A thin layer of Ti (~ 60 Å), deposited on the insulator surface exposed to vacuum, can be used to prevent damages from static charges, like usually done in SC cavity main couplers[16]. This technique has not been already adopted for the couplers of cyclotron cavities, but it would improve their reliability.

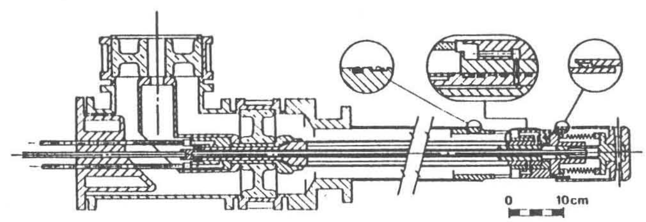

Fig. 5. Schematic drawing of the variable, coaxially cooled, coupler of the LNS/Milano cavity.

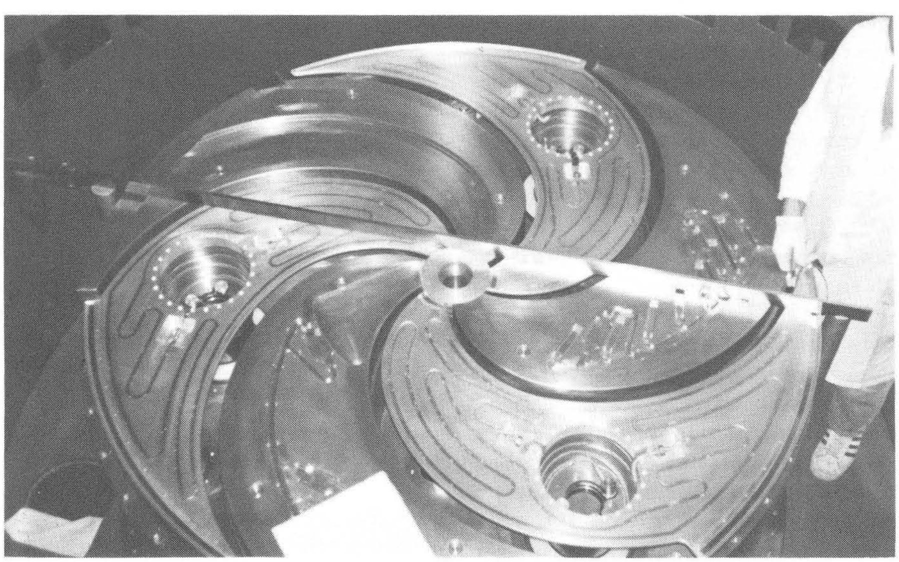

Fig. 6. Picture of one of the LNS/Milano liners covering the magnet pole, the three alluminum dee halves being assembled in their final position. On the top of the hills the special groves carved for beam dyagnostic and stripper are also visible.

Among the unusual technologies adopted to solve some critical feature[11], I want to mention:
- Electroforming of outer coaxials, to have together tolerances, thickness and surface quality;
- EB welding of the major Cu components of the coaxials, to be not limited on their thickness (that is on the general cavity stiffness);
- Inner coaxial cooling by coaxial stainless steel tubes, the external one supporting an especially shaped rubber joint, helically placed with a variable pass (see Fig. 11);
- TIG welding (with a proper He-Ar atmosphere) of the two Cu-OFHC liners, composed of thin (3 mm) sheets for the vertical parts and thick (18 mm) sheets for the horizontal ones (hill and valley covering). This solution, presented in Fig. 6, while mechanically stiff, gives the possibility to locate beam probes into special groves (carved into the hill covers) and to precisely work (with a numerically controlled machine) all the critical parts like the dee lining and the vacuum tight connections with the outer coaxial, the trimmer, the coupler and the central plug. A similar technique has been adopted for the AGOR liners, which have to support atmospheric pressure[10].

2.3 The GANIL SSC Cavity

I want to mention the GANIL SSC cavity[17-19], also if its design is not very recent, because it is an example of imagination to better fulfil the machine requirements, discussed in advance, with a reasonably compact and quite reliable structure. In this case, for an envisaged frequency range very low and wide (6.4 to 14.2 MHz), a dee voltage almost proportional to the frequency was required. Again, to have a favourable phase compression, a dee voltage increasing with the machine radius was strongly recommended. Conversely the only limitation imposed by the magnets was to fit in the region between two sectors.

With these requirements, a cavity of the coaxial type (tuned by sliding shorts) is not a good solution; in fact the usual behaviour of such a cavity type would produce these major effects:
- a dissipateed power strongly increasing with the frequency (dee voltage being a constant), that is with a behaviour opposite to that suggested by dee voltage vs frequency required low;
- the need of a vertical symmetrical structure, because of the required voltage vs radius behaviour,
- an enormous vertical dimension for a power dissipation which is negligible at low frequency, with respect to that required at high frequency.

So that the GANIL SSC cavity, whose schematic drawing is presented in Fig. 7, while being symmetrical with respect to the beam plane, is more similar to a lumped circuit than a coaxial cavity. In fact, referring to Fig. 7, the two folded (to reduce the vertical dimension) dee stems behave like two parallel inductances, resonating with the dee capacitance. Starting from the highest one, frequency range is covered increasing the dee capacitance, by mean of a very large wave panel. As a result, at the price of an almost constant power dissipation, in spite of the dee voltage vs frequency low, a very compact and reliable cavity has been realized.

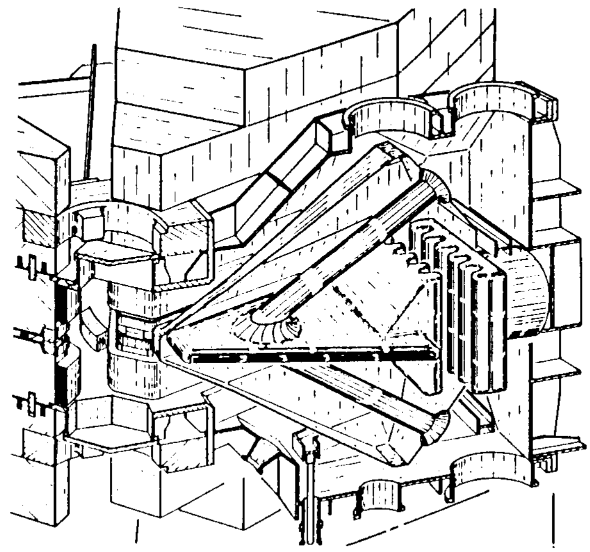

Fig. 7. Pictorial view of the GANIL SSC cavity in its operational position between two magnet sectors.

I want to mention a possible problem which comes with this type of structure, that is the existence of a strong, radial and high Q high order mode, involving the dee, the capacitive panel and its stem. In the case of the GANIL cavity, this mode, which was computed and measured, can be excited by the 3rd harmonic of the fundamental, the last being tuned at a frequency closed to 9 MHz. Nevertheless, in the GANIL operation, this parasitic mode has never been a limitation, because of the combination of the weak coupling performed to this mode by the main coupler and of the good harmonic rejection performed by the RF amplifier output circuit, together with the matching line.

2.4 The RIKEN Ring Cyclotron Cavity

Among the many cavities designed and constructed for large separated sector cyclotrons I want also to quote the cavity of RIKEN[20,21], because of its unusual and very interesting design which could be taken as a reference when a high (with respect to that of GANIL) and wide RF frequency range is required, for a frequency independent peak dee voltage. Particularly, for the RIKEN cavity, the frequency range is 20 to 45 MHz, for a dee voltage of 250 kV. A sketch of the movable box RIKEN resonator is presented in Fig. 8.

As can be evinced from the drawing of Fig. 8, the cavity is a vertical half-wavelength (that is two time $\lambda/4$) coaxial resonator, the tuning being performed by two symmetrical, very low characteristic impedance, movable boxes, instead of by sliding shorts, as usual and envisaged in the preliminary design. The effect of the low impedance boxes[22] can be understood thinking that the effect of a characteristic impedance jump on the length of a $\lambda/4$ coaxial resonator depends on the standing wave longitudinal phase at the jump position, according to the first order equation[22]:

$$\Delta\alpha = \frac{Z_{0o} - Z_{0i}}{2\, Z_{0i}} \sin 2\alpha_i$$

where: $\Delta\alpha$ is the phase advance due to the jump (in the direction from the open edge to the shorted one), Z_{0i} and Z_{0o} are respectively the characteristic impedance before and after the jump and α_i is the phase just before the jump. Because a box produces two opposite jumps at two different phase positions, that is weighted by two different values of $\sin 2\alpha$, the effect of the box movement, which has a fixed geometrical length, is that to tune a constant length cavity all over a frequency range. We note that, in this case, the effect of the dee to box cpacitance is also important to compute the cavity behaviour.

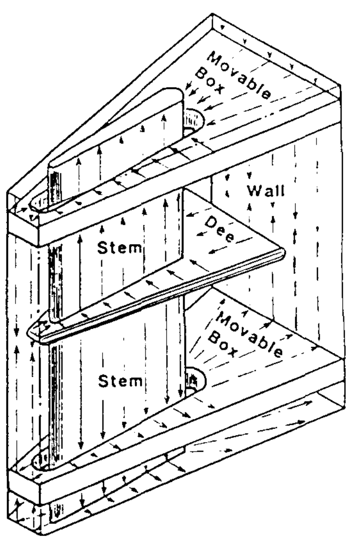

Fig. 8. Schematic drawing of the box tuned cavity for the RIKEN ring cyclotron. The arrows show the RF surface current behaviour.

Once optimized the box dimensions, the main advantages of this tuning system, with respect to the use of symmetrical sliding shorts, are:

- the overall cavity length is reduced,
- the demands on the box sliding shorts are much less severe and so the position of the dee stem can be set for a radial increase of the dee voltage, to take advantage of the induced beam phase compression,
- the stroke of the box is smaller with respect to an equivalent sliding short.

Conversely the most important disadvantage is that of the total power dissipation which, for a wide tuning range, is significantly increased all over the frequency range.

2.5 The Tritron SC Cavity

Tritron is based on a quite original concept, very promising for compact accelerators[23]. As discussed in Ref. 23, this machine is called Tritron because it has typical features of a cyclotron, a syncrotron as well as a linac. In particular, the beam performs separated orbits, guided by 238 superconducting magnetic channels, for a total of almost 20 turns. Radial and axial focusing are produced by the alternating gradient of the channels, while, as in a conventional cyclotron, the condition of isochronism is fulfilled by the radial dependence of B_z. Also longitudinal focusing will occurs in this machine.

Concerning the accelerating system, the Tritron concept asks for very compact, and properly shaped, superconducting cavities, able to fit the magnetic channels structure, while supplying to the beam an accelerating voltage per turn ranging from 1.4 to 3 MV, at injection and extraction respectively. Conversely, the use of high harmonic numbers (harmonic number h ranging from 14 to 55), allowed because of the longitudinal focusing, sets the cavity frequency to 170 MHz. A drawing of one of the six Tritron cavities is presented in Fig. 9.

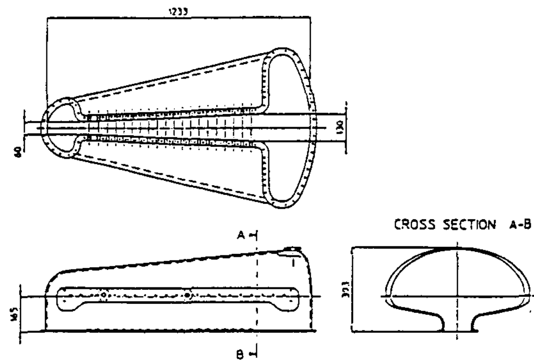

Fig. 9. Drawing of the 170 MHz superconducting cavity for the Tritron cyclotron.

Since all the details are available in Ref. [24], I want just to mention two very unusual and promising technologies which have been developed to fulfil the cavity specs and could be considered for other new machines, namely:

- Electroforming of the Cu cavity halves. The major steps of this technique are: a solid plastic model of the cavity inside, a mold which encloses the model exactly, a number of fibreglass shells (one for each cavity half) sprayed with a conducting layer, electroforming of the cavity halves, final machining of the symmetry planes.
- Electroplating of the superconducting PbSn layer (4 at % Sn). This was performed by the Tritron group with a commercially available bath, the electrodes being made by a set of platinum plated titanium roads.

As a result six superconducting cavities have been realized, able to hold an accelerating voltage higher than the design value (250 kV at the injection and 530 kV at the extraction), for a heat dissipation well below 6 W.

3. COMPUTER CODES IN CAVITY DESIGN

The need of a very large 3D electromagnetic code is not felt by most of the cyclotron community. In fact, as can be understood from the above examples (but the TRITRON CAVITY), the geometry of a cyclotron cavity is usually very complex and completely three dimensional. Moreover to define the general behaviour of the fundamental, accelerating, mode the design method based on the transmission line schematization and model measurements[1] is well established and can give very good results: the limit of a cavity usually being determined by technological problems. Thus the design of good existing cavities would probably have been almost the same even if a large electromagnetic code had been used.

The use of large electromagnetic codes (2D and 3D) is eventually useful if an envisaged (or built) structure has serious problems coming from the excitation of high order (parasitic) modes by the harmonics of the fundamental. One example of two computed dangerous high order modes[25], standing inside the accelerating electrode of the TRIUMF cavity, is presented in Fig. 10

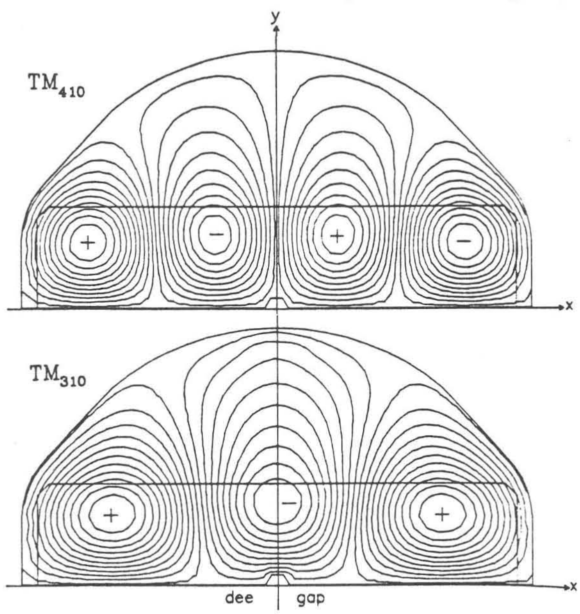

Fig. 10. Two computed dangerous high order modes, standing inside the accelerating electrode of the TRIUMF cavity.

In variable frequency machines, the excitation of high order modes by harmonics of the fundamental takes place at some specific frequency and usually can not be avoided all over the frequency range.

Nevertheless, with a careful design of the cavity and its coupling element, the effect on the beam, produced by the eventual excitation of some parasitic mode, becomes negligible (see § 2,3). Particularly, using a proper electromagnetic code, the position and the field shape of the critical modes (for the beam dynamics or for the cavity) can be evaluated, together with a rough estimation of their frequency.

Usually minor modifications of the cavity design and a proper position and shape of the main coupler have the effect to strongly reduce the coupling between harmonics and parasitics. A very general and also useful design criterion is, for example, that to limit the vertical dee aperture to the value strictly necessary for the beam, having in mind that each centimetre is paid with an increase either of the RF power and of the coupling of possibly dangerous high order modes.

Finally, a good direct way to simplify the parasitic induced problems is that to design a RF amplifier (possibly in class B) with a very low harmonic content (see § 5).

In the recent cyclotron cavities, computers play an important role in the transmission line method[1]. In particular existing codes are used or new more performant codes have been written[26]:

- to manipulate the line equations;
- to compute the characteristic impedance of unfamiliar sections (via a 2D electrostatic code), together with the expected current distribution;
- to speed up the comparison of different cavity shapes which could be used;
- to speed up the optimization of a cavity, whose shape has been already decided, including the eventual modifications dictated by mechanical problems;
- to speed up the iteration procedures for fixed length cavities;

Nevertheless I want to point out that, using the transmission lines approach for cavities of unusual shape (see for example the cavities presented in Figs 3, 7 and 8), most of the errors are introduced at the level of the choice of the line schematization, which must be done by the RF designer according to the envisaged shape and position of the wave propagation surfaces[1]. Moreover a careful correction of the current distribution in each constant impedance section, according to the current previous history, is mandatory for a good estimation of the power dissipation and a good design of the cooling system.

In two peculiar cases[6,11] - both referring to cavities for superconducting cyclotrons - a 2D electromagnetic code (SUPERFISH) has been widely used to perform a second order optimization of an already designed and tested cavity[27,28] (see § 2,2). In the following a brief description of the work performed for the LNS/Milano cyclotron to increase the maximum frequency of the cavity prototype[11] (47 MHz instead of 48 MHz) ant to improuve the design of the ceramic insulator region, is given.

As can be seen in Fig. 3, the cavity has a cylindrical geometry (i.e. a 2D geometry), but in the dee region. The basic idea[27,28] is that to find, by trial and error, a 2D model for the 3D region, able to produce for the cylindrical part of the cavity the proper boundary conditions over the frequency range. It is worthwhile that the matching surface (between the model and the real cavity) has to be a propagation surface where the field is that typical of a cylindrical transmission line. In such a way the whole structure can be studied by means of 2D finite element procedure such as the code SUPERFISH, which performs a discretization of the Helmoltz equation over an irregular triangular mesh.

It is important to point out that an a priori knowledge of the cavity frequency behaviour is required in order to check the simulating 2D model throughout the frequency range. In the present case the measurements on the cavity prototype of the frequency versus the sliding short position have been used for this purpose.

Since a more detailed discussion is available in Ref. [28], only a few computer outputs are presented here to give an idea of the use of this procedure in improving the understanding of the cavity behaviour.

An enlarged view of the ceramic insulator region before (left - cavity prototype) and after (right - final cavity) the optimization is presented in Fig. 11.

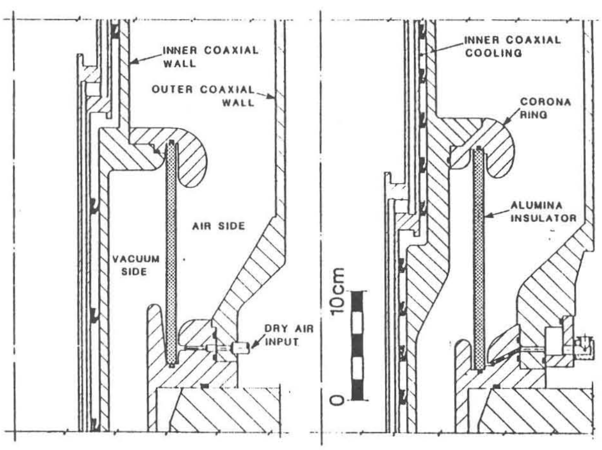

Fig.11. Enlarged view of the ceramic insulator region before (left) and after (right) the optimization.

The plot presented in Fig. 12 (which refers to the cavity prototype @ 47 MHz, see Fig. 11) is based on the Slater theorem which, in a perturbative approximation, gives the frequency shift, Δf, due to the removal of a small volume, ΔV, from a cavity of volume V, according to the formula:

$$\frac{\Delta f}{f} = \frac{\int_{\Delta V} (\mu H^2 - \varepsilon E^2)\, dV}{\int_{V} (\mu H^2 + \varepsilon E^2)\, dV} = \frac{\int_{\Delta V} (\mu H^2 - \varepsilon E^2)\, dV}{4W}$$

where W is the total stored energy. The numbers shown on the lines give the shift of the resonant frequency [kHz/cm^2] due to a 1 cm^2 reduction of the cavity area in the r-z section. This system of lines is very useful to evaluate quickly the effect on the resonant frequency of any tapering applied to the cavity, simply adding the contribution of each elementary square in which the tapering can be subdivided. All the numbers in the plot of Fig. 12 are positive because, at that frequency, the region is inductive ($\alpha > \pi/4$).

In Fig. 13 a comparison between the boundary of the ceramic insulator region of the cavity prototype (dashed line) and of the optimized cavity (solid line) is given. The volume reduction, which mainly determines the frequency increase from 47 to 49.5 MHz, is clearly visible. The sliding short, shown on the right side of Fig. 13, is in both cases at the minimum distance from the corona ring.

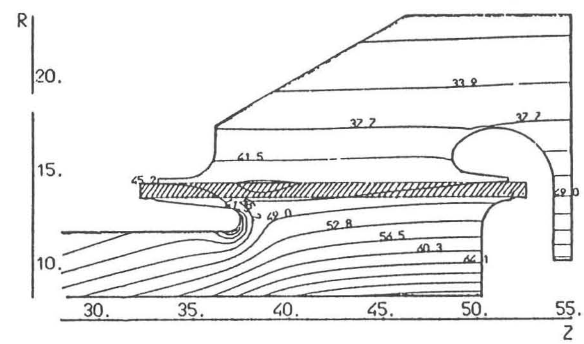

Fig.12. Plot @ 47 MHz, referring to the cavity prototype and based on the Slater theorem (see text for details).

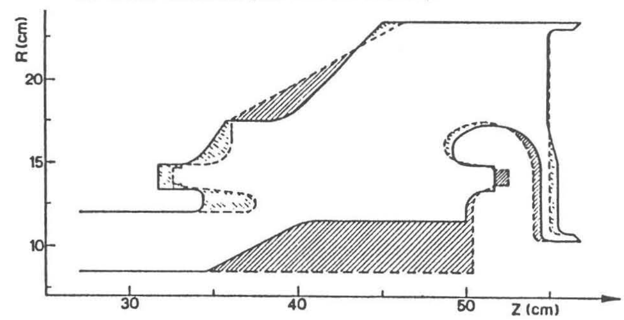

Fig.13. Comparison between the boundary of the ceramic insulator region of the cavity prototype and of the optimized one.

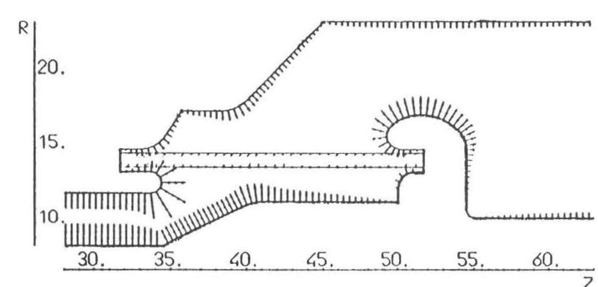

Fig.14. Electric field on the surface of the two coaxial in the region close to the ceramic insulator (@ 15 MHz, worst case).

The electric field on the surface of the two coaxials in the ceramic insulator region (@15 MHz) is shown in Fig. 14. The arrows represent just the electric field vectors on the surface; each segment marked by the scale on the arrows represents a field value of 10 kV/cm. Because the electric field amplitude on the surface can not be computed precisely by SUPERFISH, a new routine has been added to have a better numerical solution of the equation:

$$|E| = \frac{\sqrt{\mu_o/\varepsilon_o}}{k\,\varepsilon_r}\,\frac{\partial(rH)}{r\,\partial l}$$

where: $k=\omega/c$ and l is the path coordinate along the cavity boundary. This routine is very useful to optimize the metal to ceramic connection and the voltage holding capability of that critical region. Particularly, limiting the electric field to less than 2 kV/cm at the ceramic to copper connection, no metallization and brazing was needed, a conventional vacuum sealing (by Viton O-ring) being sufficient and fully reliable. A similar solution has being adopted for the main coupler (~ 600 kW) to be realized for the new high power cavities of the PSI ring cyclotron[29].

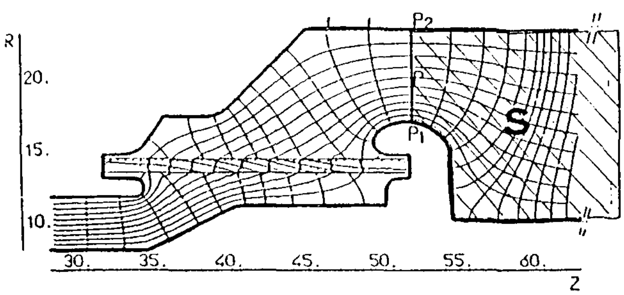

Fig.15. Plot of electric field lines and "equipartitional lines". S is the surface used to compute the voltage (see text for details).

A very interesting field pattern is presented in Fig. 15 (for the usual example @ 32.2 MHz) where two orthogonal systems of lines are plotted. The first one consists of the electric field lines[28], spaced at a constant increase of the voltage between the two coaxials (as calculated along an electric field line). The second one consists on the "equipartitional lines", which connect the points of the electric field lines having the same voltage fraction, with respect to the total voltage difference as computed along the field line itself. To have a precise value of the electric field integral (voltage) along a field line, the Stokes's theorem is applied, the computing surface for the magnetic field flux being that limited by the coaxials, the short circuit and the electric field line itself.

This way to present the electromagnetic field of a resonant coaxial cavity has a lot of interesting properties, among them I mention:

- The lines of the two systems are orthogonal to each other, like field lines and equipotentials in an electrostatic field.
- The ratio V_P/V corresponds, in the dynamic case, to the electrostatic potential;
- Each curvilinear rectangle links the same magnetic flux.
- The ratio between the dimensions of each curvilinear rectangle is related to the local impedance of the cavity.
- A cavity limited by any two "equipartitional lines" has the same resonant frequency as the actual cavity.

All these properties should offer the possibility of a very powerful definition for the generalized characteristic impedance along the cavity, as a function of the wave phase advance.

4. CONTROL ELECTRONICS

As mentioned above, the block diagrams of the RF control electronics for multi-cavity cyclotrons are now very similar[30,34], major differences being at the level of the internal layout of a single block. Since this topik is extensively discussed in a dedicated papar at this conference[35] - where a special enphasis is given to the more diffilcult problem related to the very high beam loading, typical for a mason factory - I will just present in Fig. 16, as a typical example, the block diagram of one chain of the RF control electronics, designed for the operation of each cavity of the LNS/Milano cyclotron.

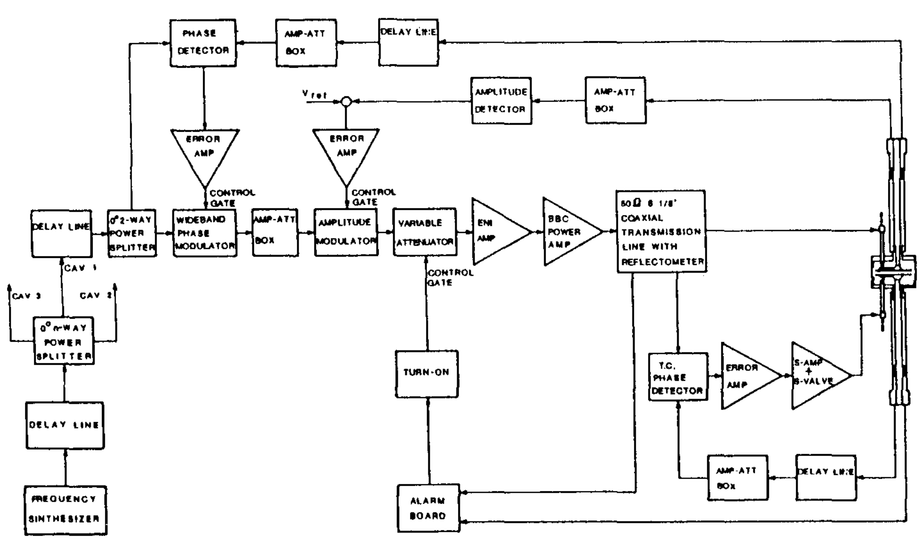

Fig.16. A typical example of RF control electronics block diagram (LNS/Milano SC cyclotron).

5. RF POWER AMPLIFIER

This very short paragraph is just to mention a number of general considerations which are important when a new machine has to be designed.

Because the RF power amplifiers are usually purcased and their cost is not negligible, often some money is saved reducing the specs required to those which are strictely necessary (i.e. output power and frequency range), with a less enphasis on the other characteristics. In particular, according to my experience, I will give in the following some suggestions which, while increasing a bit the RF amplifier cost, are very usefull and would improve the overall RF system performances and reliability. In particular:

- Grounded grid configuration is strongly preferred for the power stage to overcome neutralization problems.
- Class B operation is also preferred, because of better lineariry (the coltrol electronics becomes easier) and of lower harmonic content (the risk to excite cavity parasitic modes is reduced)
- To have both, L and C, separately tunable in the output tank circuit is usefull to easily suppress eventual parasitics (this is really helping if the frequency range is wide).
- A Class B driver, with a broad band input, relaxes the power requirement (that is the price) for the broad band solide state pre-amplifier, the total number of tunable elements staying constant.

The scheme of a well designed amplifier, which fulfil the specs given above, is presented in Fig. 17.

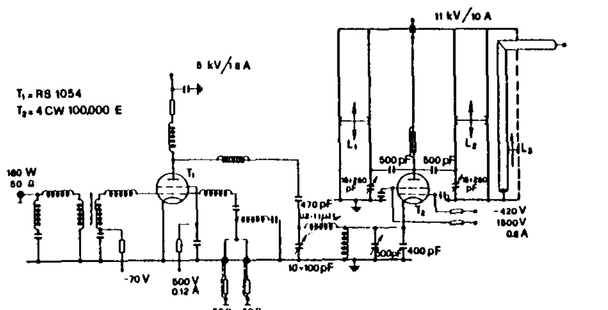

Fig.17. 90 kW, class B, two stages (final grounded grid) RF power amplifier for the LNS/Milano SC cyclotron (made by BBC).

6. CONCLUSIONS

As a conclusion I want to remember that, being the cyclotron the first of the circular accelerators, since 1930 more than one hundred of different machines have been built and others are under construction. Cyclotron RF system performances are dominated by the cavity design and technology, choices being mainly based on the machine parameters, on the designer's imagination and on the allowable money and/or man power. Nevertheless, the support, on money and man power, given to the other ancillary equipments, like amplifiers and control electronics, is also very important for a good and reliable RF system. In particular, while for a good amplifier money is enough (few companies being qualified to deliver excellent RF amplifiers), for a good control electronics competent peoples are needed.

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