DESIGN OF R. F. SYSTEMS FOR COMPACT CYCLOTRONS

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Summary

A review is presented of the RF system designs in use or under construction at the several superconducting cyclotron projects. The three phase RF system used by most of the facilities is treated in detail since it has the unusual characteristic of being in a state of unstable equilibrium. Emphasis is placed on the use of computer analysis to evaluate design concepts. These techniques are of particular value since detailed quantitative examinations of the electromagnetic fields in complex resonator structures are possible.

Introduction

For the purposes of this paper the term "compact cyclotron" refers to those machines having large magnetic fields produced by superconducting coils. The small diameter magnets of these machines have energy constants comparable to or exceeding the physically larger conventional cyclotrons. They are then not to be confused with those cyclotrons manufactured commercially for very special low-energy purposes.

A review of existing compact cyclotron RF systems is helpful in considering the general design characteristics. Systems which are already operational as well as those being constructed or designed are included.

Most of the designs use a three dee configuration with a three-phase driving scheme to produce the correct phase of accelerating voltage on each dee. The three-phase system presents unique challenges and has special characteristics which are discussed in detail. The exception to this is the four dee arrangement of the Chalk River machine. Its special features present a useful contrast in design.

The nature of the compact cyclotron design is such that large voltages and electric field gradients must be impressed on the dee elements and resonator structures. A review is presented of some computer analysis techniques which are available to evaluate these special problems. Examples of results which can be obtained from these programs are included along with some caveats about their use.

Present System Designs

Presented here is a brief list of the various systems and their parameters. (Errors of omission are strictly those of the author.)

1. NSCL K500, Michigan State University, U.S.A.
   $K_b = 510$
   Resonators: half-wave in vacuum/air
   Frequency = 9 to 32.4 MHz
   Dee Voltage = 100 kV
   RF Power = 250 kW

2. NSCL K800, Michigan State University, U.S.A.
   $K_b = 1200$
   Resonators: half-wave in vacuum/air
   Frequency = 9 to 27.5 MHz
   Dee Voltage = 200 kV
   RF Power = 600 kW

3. Chalk River, Atomic Energy of Canada, Ltd.
   $K_b = 520$
   Resonators: quarter-wave in vacuum
   Frequency = 31 to 62 MHz
   Dee Voltage = 100 kV
   RF Power = 100 kW

4. University of Milan, Italy
   $K_b = 800$
   Resonators: half-wave in vacuum/air
   Frequency = 15 to 48 MHz
   Dee Voltage = 100 kV
   RF Power = 180 kW

5. Cyclotron Institute, Texas A&M University, U.S.A.
   $K_b = 500$
   Resonators: half-wave in vacuum/air
   Frequency = 9 to 32.5 MHz
   Dee Voltage = 100 kV
   RF Power = 210 kW

6. University of Jyvaskyla, Finland
   $K_b = 800$
   Resonators: half-wave in vacuum/air
   Frequency = 15 to 48 MHz
   Dee Voltage = 100 kV
   RF Power = 180 kW

7. IPN Orsay Project, France
   $K_b = 600$
   Resonators: half-wave in vacuum
   Frequency = 24 to 62 MHz
   Dee Voltage = 100 kV
   RF Power = 240 kW

8. Kyoto University, Japan (design study)
   $K_b \sim 60$ (estimated)
   Resonators: half wave in vacuum
   Frequency = 100 MHz
   Dee Voltage = 30 kV
   RF Power = 60 kW

The above list omits the SuSe project because of its uniqueness in both design and size. The NSCL superconducting medical cyclotron design is omitted since it will be described at this conference.

Most of the systems listed above have an insulator which splits the resonator into an untuned vacuum insulated section and a tuned air insulated section. This dee-stem-with-insulator design for the compact cyclotrons was pioneered by the MSU group and gives rise to some unique characteristics for the resonators.

The Chalk River[1] four-dee design is the simplest of the tunable RF structures. The resonators are straight coaxial lines of uniform impedance. This geometry is a classical resonator design that is well known and well behaved in terms of possible interfering modes. It has the beauty of simple mechanical construction because opposing pairs of dees are mechanically connected and attached to a single resonator. A possible difficulty with this design is that the sliding shorts must operate in vacuum. The detailed design of these sliding shorts is published elsewhere in these proceedings. A unique feature of the design is that only quarter-wave resonators are used. If this same technique were employed in the three dee case there would be a net vertical force on the beam resulting from the electric field at the dee lip being distorted by the presence of only one resonator. This effect is eliminated in the four-dee design by extending the two resonators above and below the median plane. This four dee, two resonator design avoids the three-phase problem and takes advantage of the stable 0 and π mode operation of coupled resonator pairs.

The simplest RF system design is that of the Kyoto University[2] model study for a medical cyclotron. A three-dee half-wave structure is used for a fixed frequency of 100 MHz. No sliding shorts are required and the resonators are sufficiently short so they are totally contained in the vacuum chamber. The system is designed to operate with a third harmonic beam only so the three-phase problem is avoided entirely with the dees being mechanically connected together.

The proposed Orsay[3] design is for a half-wave system with the resonators in vacuum. The unique features are the unusually large space (500mm diameter) given to the resonators and the method of coupling the RF power into the resonators through a double sliding short arrangement.

The balance of the machines included in the list above (NSCL, Jyvaskyla, Milan, Texas A&M) all use the three dee, three-phase design and the dee-stem-with-insulator resonator. The special characteristics of this design technique is to be treated in detail.

The Three-phase Problem

This problem was discusssed in detail by the Lawrence Berkeley Laboratory group working on the Cloverleaf[4] cyclotron project (circa 1952). At that time the difficulties with operating a three dee three-phase RF system were described and workable solutions were found. However, there were some shortcomings to the solutions because the Cloverleaf cyclotron was a fixed frequency machine and no attention was given to the needs of a machine that had a wide tuning range. This problem has been resolved by the NSCL group and a successful three-phase RF system which tunes over a large frequency range has been built and operated. To the present time little effort has been made to describe the nature of the problem in a more fundamental way. Some comments presented here hopefully will lead to a better understanding of the problem and may eventually give some insight into other solutions.

The simplest possible resonator for a cyclotron has a dee with capacitance to "ground" and physical dimensions which are relatively small when compared to the wavelength of operation. This capacitive dee is then connected to a coaxial line structure which is less than a quarter wavelength long to form a complete resonator. The modes of this structure are well known and well behaved and unless the coaxial line has some unusual irregularities then the resonant frequency is easily and accurately predictable. The frequency of such a system is found from the following:

$$1/2\pi f C_d = Z_0 \tan \beta l \qquad (1)$$

where: C_d is the capacitance of the dee,
Z_0 is the characteristic impedance of the line,
β is $2\pi f/c$ (c = velocity of light), and
l is the length of the line.

If two such simple resonators are connected together with a capacitive element then a two dee system is formed which has an interesting characteristic. If the voltages on the dees are in phase, the 0 mode, then the resonant frequency of the structure remains the same as given in the case for a single dee. There is no effect from the coupling capacitor when equal voltages appear on both plates. If the voltages on the two dees are exactly opposite in phase, the π mode, then a lower frequency of operation is obtained because the effective capacitance of each dee, C_d', is now given by:

$$C_d' = C_d + 2C_c \qquad (2)$$

where: C_c is the coupling capacitor.

This value for the effective capacitance is found by computing the total energy stored in the three capacitors at the peak applied voltage. The assumption is then made that the energy is shared equally by the two resonators. C_d' represents a single capacitor of such value that one half of the energy will be stored on it at maximum voltage. A capacitor of this value is assumed to be connected to each coaxial line with no capacitance connecting the two systems.

A feature of this design is that the RF signal may be introduced into only one resonator. The system will automatically assume the correct mode of operation, 0 or π, for the frequency of the driving signal,

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provided of course that the frequency is one of the two allowed.

Construction of a complex system from a collection of simple resonators can be continued with the addition of one more resonator to yield a three dee system. The dees are again coupled with capacitive elements which, for the sake of simplicity, are taken to be equal. As in the two dee case, there is a resonant frequency for the system, a 0 mode, which is equal to that of the single dee resonator. This mode can also be excited by introducing power into only one resonator with the resulting dee voltages being of equal amplitudes and 0 phase difference.

For the three-phase case the dee voltages are assumed to be equal in amplitude and at a phase of 120 degrees relative to each other. By the same reasoning as in the two dee case the value of the effective dee capacitance is found to be:

$$C_d' = C_d + 3C_c. \qquad (3)$$

A new resonant frequency can be calculated with this capacitance in the same manner as in the two dee case. However, if a signal of the correct frequency for three-phase operation is applied to one resonator of the system the result is not a nicely phased set of equal amplitude dee voltages. Rather, the dee of the driven resonator will attain a voltage of some amplitude. The other two dees will have a voltage of one-half that amplitude and a phase of 180 degrees relative to the driven dee. (This result is very similar to the two dee case so it will be referred to as a "paired-π" mode.)

The effective capacitance seen by each coaxial line can be computed for this array of voltages and phases. The computation is again made by considering the stored energy only. The resonant frequency of each individual resonator will be found to be identical to the one calculated for the three-phase voltage array. This result can be verified with a small system made up of coaxial cables or by using a circuit analysis program such as SPICE.[5]

Further analysis with SPICE shows that if the system is perfectly balanced with respect to component values and a driving signal of the correct amplitude, frequency, and phase is applied to each resonator then the system appears to be stable. However, any imbalance in the component values or driving signals results in the system trying to revert to the same paired-π mode as when only one driving signal is applied. This result is identical to that of the LBL analysis.

The solution to this problem is to "neutralize" the effect of the coupling capacitors so that the three resonators operate independently. This technique was used by LBL and a tunable form suitable for use over a wide frequency range was developed by the NSCL group. Neutralization is accomplished by introducing a coupling link between the resonators at some location which, for mechanical reasons, is at a point some distance away from the dees. This link causes a small amount of energy of the proper phase to be coupled between the resonators to just cancel the energy being coupled through the dee-to-dee capacitance. The physical location of the links causes this not to be a true neutralization which is generally taken to be frequency independent, e.g., the neutralization of the interelectrode capacitance of a tube. However, this technique works and requires only that the designer find a suitable location for the links.

If the stored energy for the two modes is compared, the three-phase mode stores twice the amount of energy of the paired-π mode. The system appears to simply seek the lowest energy state and considerable effort must be expended to maintain it in the three-phase mode. The neutralization technique destroys the three-phase system as a "system" by making the resonators independent. An equally effective technique would be to fully shield the dees from each other. This is a difficult task but is the solution adopted by the Orsay design.

Computer Analysis

The small spacing between elements and required voltages in the compact cyclotron lead to electrical gradients which approach the limits of accepted sparking criteria. It is necessary to carefully evaluate all portions of the dee and resonator structure to insure that these limits are not exceeded Further, the dee-stem-with-insulator design is sufficiently different from a uniform coaxial line that careful evaluation of its behavior over the expected frequency range is needed.

Several computer programs exist today to aid the designer in making quantitative decisions about design choices. The programs which have been found to be of use in the project at Texas A&M are: MSUDS, TDS, POISSON[6] and SUPERFISH[7,8]. Short summaries of these programs are given below along with some example results.

MSUDS was written by J. Riedel of MSU and models the dee and resonator structure of the K500 RF system. It can be adapted to model any similar resonator system. The modeling is done with sections of line using well-known transmission line equations. The modeling of the dee using special shapes of transmission lines overcomes the difficulty of the unusual dee shape. The program is very fast and gives the designer a quick look at the RF performance of the structure.

TDS was written by Sven Knudsen of Texas A&M. It models a coaxial line with a fixed outer conductor and tapered inner conductor to allow the designer to evaluate the use of a tapered line as a resonator element. This technique is useful in looking for designs which save power or as a way of minimizing discontinuities.

POISSON is one of a group of field analysis programs which are available from Los Alamos Scientific Laboratory. This is a two-dimensional magnetostatic and electrostatic program which accepts cylindrical symmetry. It is useful in careful evaluation of static electric gradients and can produce plots which help the designer visualize the problem areas.

SUPERFISH, also from LASL, is an RF program which finds resonant frequencies, voltage gradients and current densities in a resonant structure with axial symmetry. Some designers have made some very special geometric arrangements of models to allow this symmetry limitation to be overcome in special cases.

Figure 1 shows a dee stem section of the Texas A&M resonator. The design of this line section made use of all four of the above programs. Because of the unusual shape of the dee in the K500 cyclotron, MSUDS was used to evaluate the effective capacitance of the dee as a function of frequency. This data provided the capacitance values to be input into TDS to evaluate various impedance tapers. Once a taper was chosen POISSON was used to find the gradients in the area around the insulator so that proper dimensions could be chosen. Figure 2 is an equipotential plot in the insulator region. (The hardcopy plot is from a Tektronix program which was converted to operate with a Printronix printer.) Figure 3 is a plot of data from POISSON for the high gradient area on the surface of the corona ring.

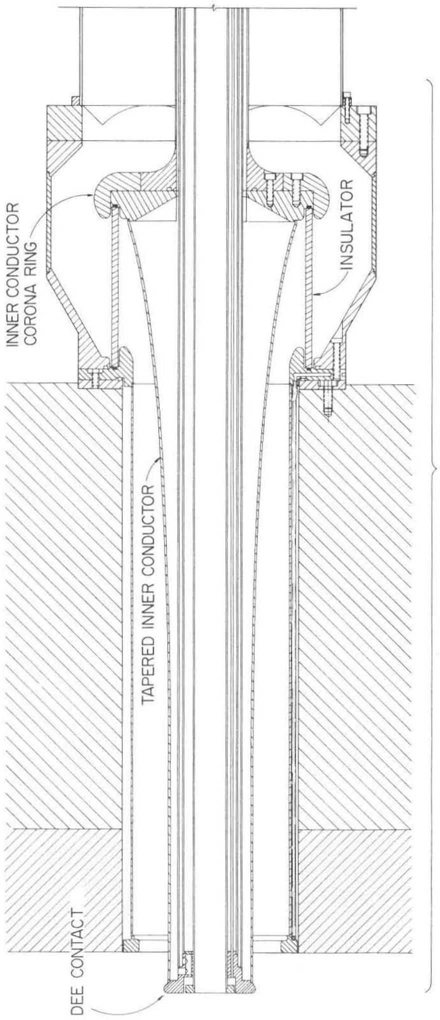

Fig. 1. View of the tapered dee stem of the Texas A&M resonator.

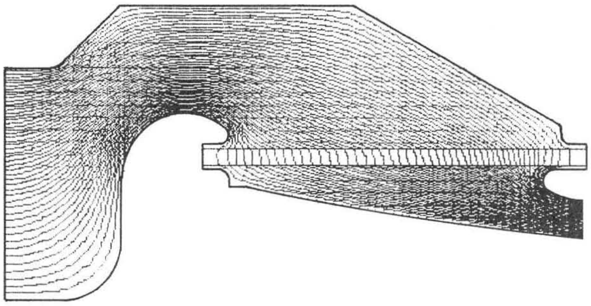

Fig. 2. Equipotential plot of the corona ring area from POISSON.

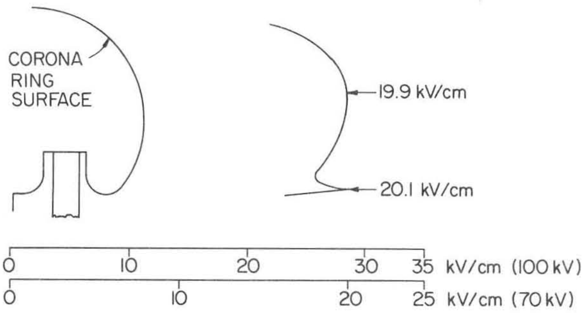

Fig. 3. Plot of the electric field gradient along the surface of the corona ring. Indicated maxima are for the 70 kV voltage.

The RF performance of the resonator was evaluated with SUPERFISH. One of its useful qualities is the ability to look for possible mode problems. Figure 4 shows a plot of the three-quarter wave mode for the first line taper chosen. There is an interference between this mode and the third harmonic of the fundamental at about 28 MHz so this taper was discarded. Figure 5, shows the performance of the three-quarter wave mode in the accepted design. Figure 6 and Figure 7, show representative quarter wave and three-quarter wave plots of the fields in the resonator structure. Table 1, is a summary of the RF characteristics of this final design as computed by SUPERFISH. (In the calculation results the input data were "calibrated" by first using the known characteristics of the NSCL K500 resonator performance. This provided a way to properly model the dee shape in a cylindrical geometry.)

With careful use, both POISSON and SUPERFISH are excellent tools which provide valuable data for the designer. The written documentation for the programs is somewhat meager. Both programs have good internal checks, such as the ability to plot the mesh being used for calculation, which are needed to assist the user in setting up the input data correctly. SUPERFISH has some difficulty in convergence so that selecting the proper starting frequency comes with experience rather than from any internal help from the program.

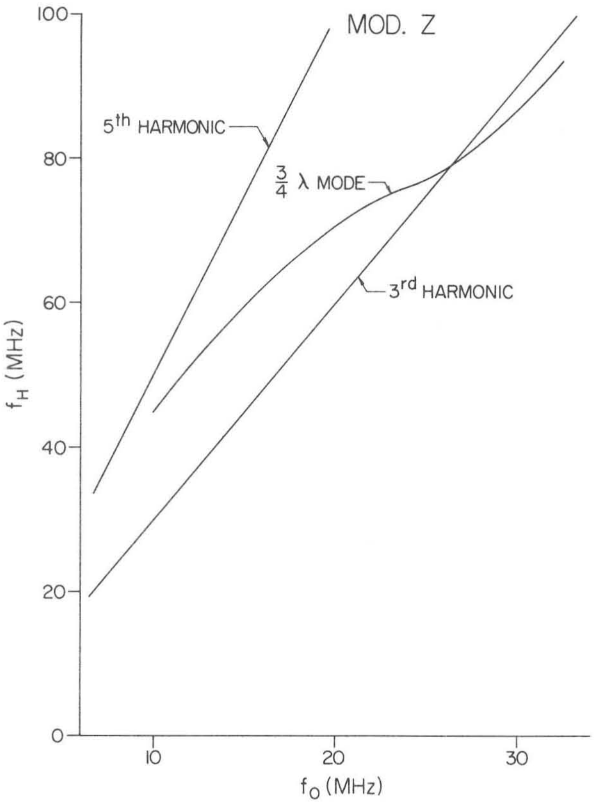

Fig. 4. Plot of the 3/4λ mode showing an interference with the 3rd harmonic.

Final Notes

The matter of the sliding shorts for the resonators is very important because the short circuit current density is of the order of 80 to 100 A/cm. Some important results[9,10] of recent tests are reported in these proceedings.

A design for the amplifiers that would allow mounting close enough to the resonators so that no anode tuning would be required would be helpful in reducing the number of tuned elements. A simpler operation would also result with only one resonator per amplifier. In addition, the design of an untuned technique for coupling the energy into the resonators should be sought.

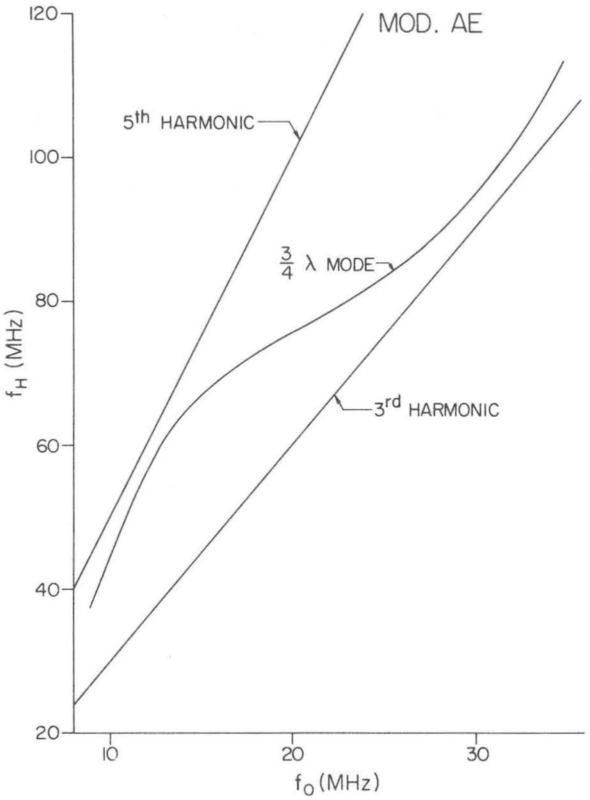

Fig. 5. Plot of the 3/4λ mode for a different taper with no interference.

Fig. 6. An electric field line map produced by SUPERFISH for the 1/4λ mode.

Fig. 7. The electric field map for the 3/4λ mode.

Table 1

Superfish Calculation Results for the Texas A&M RF System Resonator Design

f(MHz)	8.8551	9.9779	12.517	15.022	17.495	20.056	22.433	25.068	27.560	30.026	32.535	35.001
I_{SC}(A)	1257	1333	1507	1681	1847	2010	2148	2283	2392	2479	2545	2584
P_T(kW)	34.7	35.6	38.0	40.9	44.1	47.6	51.2	55.4	59.6	63.9	68.5	73.3
W_T(J)	2.82	2.68	2.43	2.26	2.12	1.98	1.87	1.75	1.65	1.56	1.47	1.39
Q	4519	4721	5044	5226	5289	5242	5143	4987	4799	4595	4372	4184
f(3/4λ)	37.337	44.346	58.804	66.982	71.579	75.375	78.865	83.220	88.221	94.494	102.891	113.403

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