DESIGN OF THE CENTRAL REGIONS FOR THE MSU 500 MeV SUPERCONDUCTING CYCLOTRON*

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Abstract

Different central regions for the MSU 500 MeV superconducting cyclotron are designed and extensively studied in order to find central regions which would yield desired beam qualities for the wide variety of ions and energies which we plan to accelerate. Coupled operation of the 500 and 800 MeV superconducting cyclotrons is included in this study.

1. Introduction

The requirements of a good central region for the MSU 500 MeV superconducting cyclotron are more stringent than those for a cyclotron using conventional magnets. A good beam quality is desirable for the large variety of particles and energies for which the 500 MeV superconducting cyclotron should operate, both as a stand-alone accelerator and as an injector to the 800 MeV superconducting cyclotron.

The high magnetic field strength of the superconducting magnet, which is about three times higher than in conventional cyclotrons, influences the design of the central region. Particles with high charge to mass ratios will bend very strongly during the first revolution, thus leaving only a very small free space for an ion source. As will be seen later, special attention has been required to overcome the clearance problems close to the ion source, especially in the first harmonic mode of acceleration.

Instead of the constant orbit geometry applied in the MSU 50 MeV cyclotron, the new 500 MeV cyclotron will make use of a fixed dee voltage (100 kV) and variable turn number, ranging from 45 to 535. Due to a 3-fold dee structure (3 dees and 3 dummy-dees) and 3-phase operation of rf voltage, the electric field is very complicated in the centre of the cyclotron where a strong electric focusing is needed. The dees are so "thin" in azimuth that there is practically no electric field free area in the first few turns. Therefore all orbit calculations in the central region have to be based on realistic electric fields. The 3-dimensional electrolytic tank measurements of electric fields have been an essential part of this study.

In the course of development, the frequency range of the 500 MeV cyclotron has changed considerably from the originally proposed range of 27-84 MHz, in which it was intended to operate in the 3rd and 9th harmonic modes of acceleration. Detailed studies of this frequency range revealed two relatively serious sources of difficulties, namely that the large physical size of the dees causes a severe voltage gradient to occur along the dees when operated at high frequencies, and transit time problems between the ion source and puller were shown to exist on the higher harmonics. This second difficulty would force the use of a dc bias on the ion source, which is not desirable due to the expected maintenance problems. To overcome these problems a much lower frequency range was introduced, 9-32 MHz. This frequency range is excellent for coupled operation of the 500 and 800 MeV cyclotrons, but it will require 1st harmonic acceleration in the stand-alone use of the 500 MeV cyclotron for the most interesting high-energy light heavy ions.

The operational requirements for the central region are so extensive that it is obvious more than one central region is needed to fulfill all these conditions. On the other hand, one likes to keep the number of central regions as small as possible.

2. Electrolytic Tank Measurements of Electric Fields

The electric fields are measured using a full-scale 11 inch diameter electrolytic tank model of the center of the cyclotron. The three dees and three dummy dees are represented by copper plates set 1/2 inch below water surface to correspond to the one inch dee height. To simplify construction and data-taking, the mirror image of the electrode system relative to the median plane is omitted; placing the water surface at this plane imposes the proper boundary condition. A photo in Fig. 1 shows a model which is built for the first harmonic mode of operation.

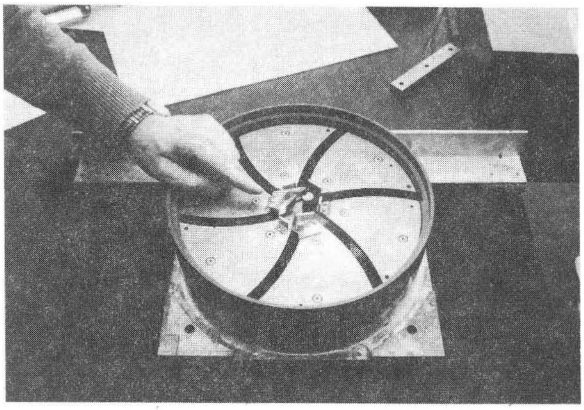

Fig. 1. Photograph of three dimensional electrolytic tank used to obtain central region electric field maps. The forefinger points to the extraction electrode (the "puller") on dee #1 and the cylinder near the puller represents the source. The top surface of the central electrodes corresponds to the median plane of the system. Electrodes in the tank are full size and the electrode system in the photo is set up for cyclotron operation on the first harmonic mode.

The gap between each dee and its neighboring dummy dee is 1/2 inch. In order to decrease field penetration on the first turn both the gap and the dee height are reduced, and the posts extend through the median plane. It takes about six hours for one complete measurement with a 140 by 140 mesh in 0.04 inch steps. The measurement system shows a very small r.m.s. of one part in one thousand from a check with a parallel geometry.

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3. Source - Puller Calculations

Due to the high magnetic field of the superconducting magnet, one can expect the transit time effect between the ion source and puller electrode to be a serious limiting factor in the design and operation of the 500 MeV cyclotron. Therefore it was necessary to study the properties of source-puller trajectories in more detail.

The first approach was to study an ideal situation applying homogeneous electric and magnetic fields in order to find the extreme conditions where particles still can reach the puller. A dimensionless parameter χ, used e.g. by Reiser,[1] is very useful for this purpose. χ is defined as

$$\chi = q/m \; \frac{B^2 \cdot d^2}{V}$$

where q/m is the specific ion charge, B the magnetic field strength, d a reference length, and V is the applied rf voltage. The usefulness of the χ-parameter is based on the fact that the ion trajectories in two ion optical systems are similar if they have the same χ-value. In Fig. 2 the maximum values of χ were calculated as a function of the starting time for different harmonic numbers. If the χ_{max} is multiplied by the harmonic number h, one finds a useful approximation, namely that

$$h \; \chi_{max} \simeq \text{constant}$$

As a practical limit one should keep $h\;\chi \simeq 1$, which is also an easy rule to remember. One should also use the lowest possible harmonic mode of operation.

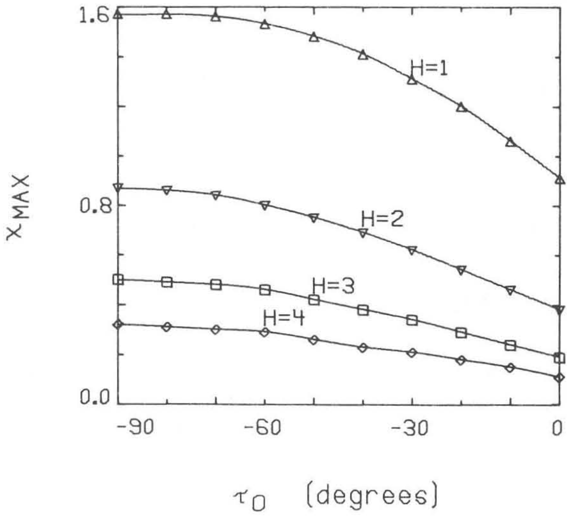

Fig. 2. The maximum value of χ is plotted as a function of the starting time from the ion source for the h = 1, 2, 3 and 4 harmonic modes of acceleration. The zero starting time is the time of the peak voltage. These curves are valid for the homogeneous magnetic and electric fields. χ is defined in the text.

A 2-dimensional source-puller model in 6:1 scale was built for the MSU electrolytic tank facility, and an electric field map was measured. Two circular posts in front of the ion source formed the puller electrodes in this model. The dimensions were scaled so that the minimum surface-to-surface distance is 10 mm to hold the required 100 kV dee voltage. The measured electric field, together with realistic magnetic fields was then used in the source-to-puller part of the revised MSU orbit program CYCLONE.[2] A few typical trajectories in the maximum magnetic field are plotted in Fig. 3 for different particles, specified by their charge to mass ratio q/m, and for starting times representing the selected central rays. As can be seen in Fig. 3, all particles clear the puller easily in the h = 1 case, but in the h = 2 and 3 modes of operation the particles with higher q/m-ratios are bent back before reaching the puller.

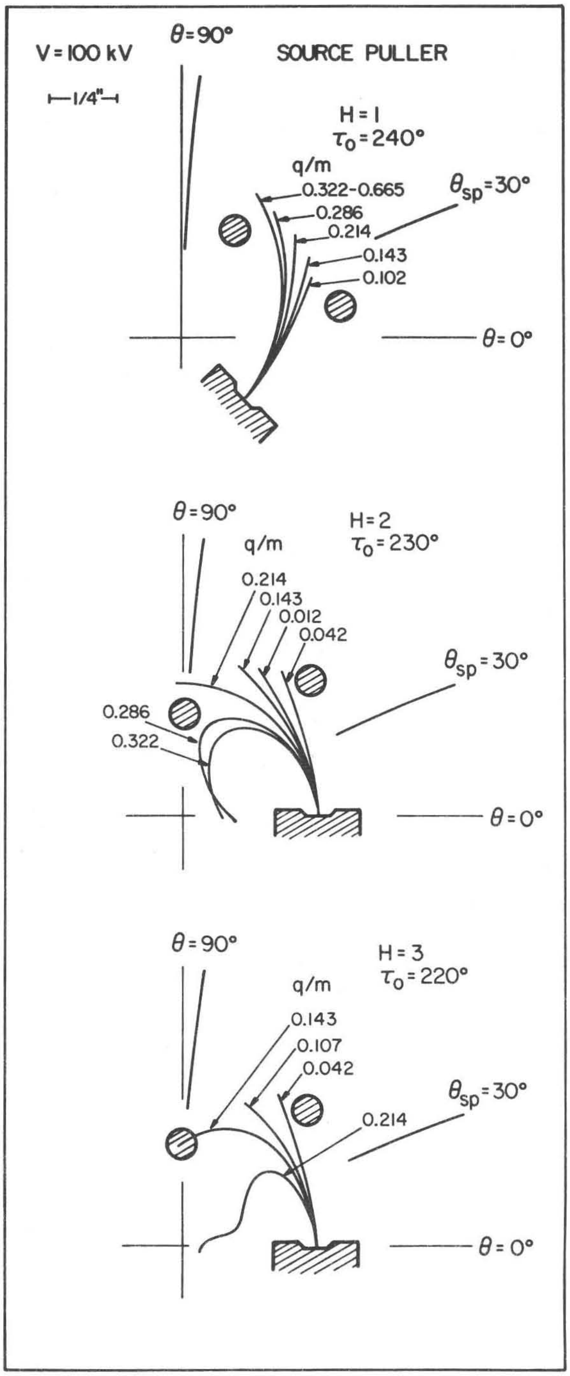

Fig. 3. Ion trajectories between the source and the puller for the h = 1, 2 and 3 harmonics in the maximum magnetic field of the 500 MeV superconducting cyclotron. θ_{sp} denotes an acceleration gap at a spiral angle of $\theta_{sp} = 30^o$.

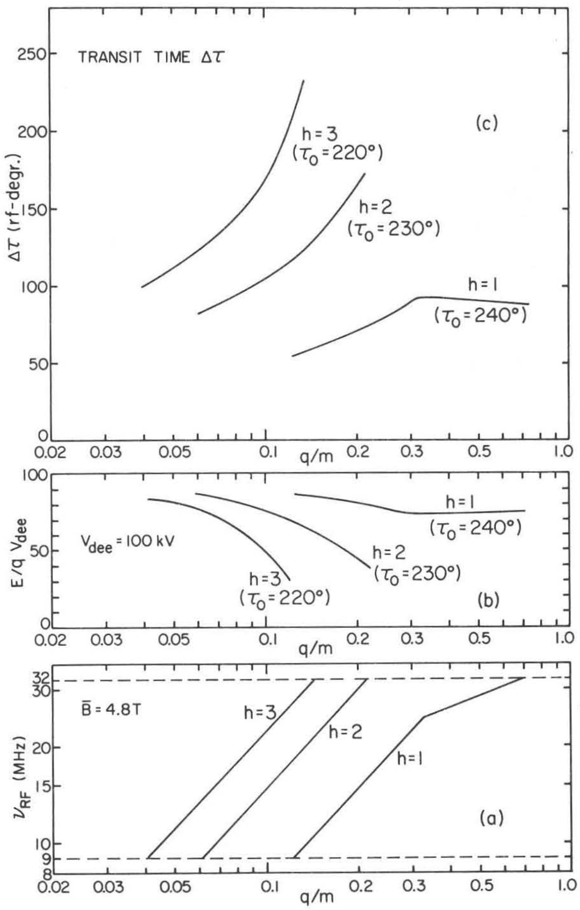

Fig. 4. (a) The required rf frequencies, (b) the energy gain and (c) the transit times in the gap between the ion source and puller are plotted as a function of charge to mass ratio, q/m for the first, second and third harmonic acceleration of particles in the 500 MeV cyclotron operating with the maximum magnetic field. For details, see text.

The results of the source-puller calculations are collected in Fig. 4, together with the required rf frequencies of the 500 MeV cyclotron for maximum energies in h = 1, 2 and 3 operation as a function of the charge to mass ratio. The 9 MHz and 32 MHz frequency limits are also displayed in Fig. 4(a). (The change in slope of the h = 1 line in Fig. 4(a) is due to the fact that the 160 MeV focusing limit[3] of the 500 MeV superconducting magnet is exceeded for $q/m \geq 0.3$ at maximum energies.) Fig. 4(b) and (c) show the energy gain and transit times, respectively, for those particles which have been able to reach the line between the centers of two puller electrodes. As one can see, the 9-32 MHz frequency range is very nicely matched with the transit time effect. There are practically no limitations in the first and second harmonic operation, and in the 3rd harmonic mode of operation the transit time effect only prevents the use of the highest frequencies with q/m between 0.12-0.145. In all cases there is a large frequency overlap between the adjacent harmonics.

A feature worth noting is that in the h = 1 mode of operation (see Fig. 4(c)) the transit times are nearly constant for q/m > 0.3. This is due to the fact that the focusing limit of the 500 MeV magnet forces the use of lower magnetic fields for these particles at highest energies. Therefore the χ-values and trajectories of these particles are nearly identical (see Fig. 3.) This allows the design of a central region with a fixed source-puller geometry in the h = 1 operation.

4. Central Region

The first central region studies for the 500 MeV cyclotron were made in 1977 for the 3rd harmonic mode of operation, when the 27-84 MHz rf frequency range was under consideration. An electrolytic tank was built and a complete set of electric field maps was measured. This set of electric fields is used in many orbit calculations with the CYCLONE program, which is capable of handling the 3-phase operations. Although this first central region might only have academic interest in real applications, it has served well as a first approximation, on which all later revisions are based.

The introduction of the lower rf frequency range naturally shifted the design efforts to a central geometry suitable for 1st harmonic acceleration {see Fig. 3(a)}. The orbit calculations showed, however, that the basic central geometry was not well matched for the 1st harmonic beams. Only a marginal clearance was left between the source and dee for holding the required dee voltage of 100 kV. (Building of two separate rf systems was already considered as a solution to this problem. Besides the "long" rf system, a "short" system was planned to cover rf frequencies from 32 to 60 MHz. Thus, 1st harmonic operation would not be needed in the stand-alone use of the 500 MeV cyclotron.)

An effort was made to design a new central region to overcome the clearance problems. A new electrolytic tank model was built (Fig. 1), with the dummy dee between dees #1 and #2 cut shorter to allow locally higher energy gain and then also higher radial gain near the calculated position of the ion source. Electric fields were mapped, orbit calculations were repeated and adequate overall clearances and other desirable beam qualities were obtained. As an example, the calculated central-ray orbits for q/m = 0.322 particles are drawn in Fig. 5 together with the superimposed equipotential contour lines. The position of the ion source was adjusted so that particles will have a positive phase of about 10° when they arrive at the 1st acceleration gap at 90°, thus obtaining strong electric focusing in this gap. The starting conditions indicated in the figure produce well-centered orbits. Also the centering error due to the different starting times was found to be reasonably small. The orbits of particles having lower charge states were also checked and the electrodes designed so that these undesirable beams can be stopped as early as possible, normally during the first turn. The h = 1 geometry was also studied using our other "standard" beams:

$^{14}N^{4+}$(q/m=0.286, E=41 MeV/A), $^{2}H^{1+}$(q/m=0.498,

E=81 MeV/A) and $^{3}He^{2+}$(q/m=0.666, E=107 MeV/A).

All of these particles produced well-centered beams having the same starting conditions as in Fig. 5. (The success with the h=1 geometry has now removed the need to build the second "short" rf system.)

5. Coupled Cyclotron Operation

The coupled operation of the 500 and 800 MeV cyclotrons requires that the 500 MeV cyclotron should

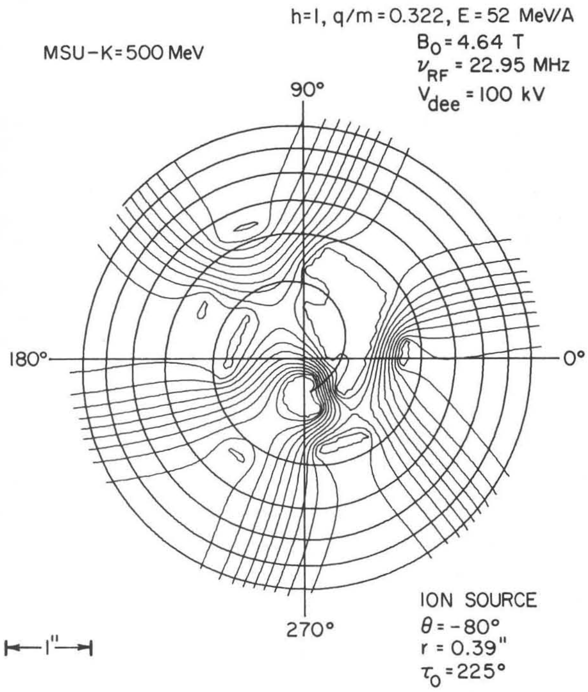

Fig. 5. Equipotential contours of the central region designed for the first harmonic operation of the 500 MeV cyclotron, together with calculated central-ray orbits of the q/m=0.322 ions.

mainly operate in h=3 and 4 modes. The use of an rf extracted ion source may be restricted only for beams with low q/m values (if max. B-field is used) due to the transit time effect. On the other hand, beams with low q/m-values will have only a very small number of turns in the 500 MeV machine, e.g. 44 turns for $^{238}U^{10+}$ and 110 turns for $^{75}As^{8+}$ (with V_{dee} = 80 kV). These low turn-number beams will require the ion source to be placed at a relatively large radius (r = 1.0" — 1.8"), causing an undesirably large dip in the magnetic field. To overcome these problems different solutions are being considered. One can use a grid on the ion source in order to solve the transit time problem, but the grid will not help for the large starting radius. A dc-extracted ion source in the center of the magnet is one possibility. The expected intensity problems with this type of ion source can be serious, however. Axial injection is also an open possibility. Studies of these various options are continuing.

6. References

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