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THE MARYLAND UNIVERSITY SECTORED ISOCHRONOUS CYCLOTRON

MUSIC

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I - Summary

This paper describes the main features of the "Music" cyclotron machine as they appear after completion of the basic studies and initiation of the procurement of the components.

Music is funded by the United States Atomic Energy Commission. Studies, engineering, procurement and construction are performed by Raytheon Company and CSF under control of Pr HOLMGREN of the University of Maryland, and important contributions from Dr Reiser, Dr Kim and Ken Jenkins, in all phases of computation or design.

Music is a variable energy cyclotron of nominal energy 100 MeV protons using a four sectors magnet and two 90º dees connected to two panel tuned RF cavities. The conventional ion source will be mounted through a hole in the frame. Axial injection from an external source is also envisaged. Extraction will use electrostatic and electromagnetic deflectors.

The cyclotron general arrangement is similar to the Grenoble machine. It has been designed to accelerate protons up to at least 100 MeV, deuterons up to 70 MeV, alpha particles up to 140 MeV and He_3 up to 190 MeV. In order to ensure the 100 MeV proton value, the magnetic field was designed for 114 MeV and it turns out how that with the help of the installed flutter coils (hill an valley coils) somewhat higher proton energies could be made stable up to extraction radius.

II - RF system

The RF system incorporates two frequency tunable cavities each feeding one 90º dee, and powered by an RF chain terminated by a power tube, one mounted on each cavity. Servo systems, activated by phase discriminators are used to keep the cavities and drivers tuned to the same resonant frequency.

The cavities are similar to those of the Grenoble cyclotron, comprising a circular cylindrical sector in which a tuning panel rotates about 60º to control the frequency (fig.4).

Tuning with one panel only gives a rather large frequency band. With some improvements in the details of the shape of dee and liner, it could be pushed from 9.5 to 20.5 MHz with a corresponding Q factor of 2,700 to 1,300 and a shunt impedance of 56.000 Ω to 20.000 Ω in the same band, but the quality drops down rather abruptly on the high frequency side of the band.

A factor 2 in frequency bandwidth is sufficient to cover all energies for all particles on harmonics 1, 2, 3, 5 ... etc. Actual overlapping (19 - 20.5 MHz) is considered sufficient and gives the possibility of going to higher proton energies, as far as focussing and extraction will permit.

General dimensions

- dee aperture	1.57 in
- dee to liner clearance	1.7 in
- max dee voltage	90 kV
- RF tuning range	9.5 to 20.4 MHz
- RF total power	2 x 200 kW
- power supply	600 kW
- length of cavity	75 in
- width of cavity	82 in
- of panel	55 in
- angle of rotation	60 º
- panel area	20 sq feet
- panel to liner dist.	0.8 in

hinge : thin sheet of copper : 60 cm wide, water cooled.

The shape of the region of the hinge turned out to be very critical to attain the highest frequency, and also good mechanical behavior of the hinge itself is a problem. The hinge is made of a long and wide thin sheet of copper. The minimum radius of curvature being about 20 cm ; so that it is cooled by water pipes directly welded under it.

The axis of the panel goes through the wall of the cavity in a low field region, and shielding of the ball-bearings is no problem.

The whole RF chain (fig. 3) will consist of a frequency synthetizer followed by a divider amplifier including phase controls. The outputs of this amplifier will be fed by two Marconi distributed amplifiers working at a power of about 1 kW. The frequency adjustment will deliver reference voltages to preset the driver tuning ; the cavity panel tuning and the fine tuning will be achieved through phase discriminators controls.

The power tubes selected are the Machlett LPT 27 W which can deliver 225 kW at 13 kV RF with 375Ω load impedance. The very low power required in the neighbourhood of 10 MHz, i.e. 50 kW leaves the possibility of small mismatch for the power tube, a perfect match being set for 20 MHz.

These power tubes require about 8 kW max, RF drive power, and a model has been built for this driver. It uses a 4 C x 5000 A tetrode and requires only one variable capacitor tuning.

III - Magnet system

The four sectors magnet and the two 90º dees have been chosen to avoid undesirable resonances and also because it allows a rational distribution of different elements of the cyclotron (fig. 1 and 2). The basic difficulty of the Music magnet design was lying in the compromise between vertical stabilities for high energy protons and low energy heavy ions. Besides, the four sectors geometry leads to a rather low flutter in the center and therefore to severe requirements for the central magnetic bump which must achieve the vertical focussing in the center region.

These contengencies lead to a focussing factor (in smooth approximation) slightly slower than 0.25 for the iron field. With such a geometry a small amount of flutter correction given by suitable hill and valley coils is able to insure ν_z below 0.5 for heavy ions and still acceptable for high energy protons. It appears in this case that the resonances $\nu_z = 0.5$ and $\nu_r = 1$ are likely to occur in the same region. But this point is basically an extraction problem.

In order to achieve this focussing factor, the compromise between flutter and spiral angle has been made in the scope of a very simple design with a magnet as small as possible. In this way the magnet gap has been chosen rather small to ensure a flutter in the vicinity of .36 with coils of acceptable dimensions and a not too high power consumption. The lower gap value is determined by RF voltage requirements and by the size of extraction components. In this case, the spiral angle reaches 50º to ensure the right value of the focussing factor.

A fine study of these requirements has shown that hills could be made with flat top (no steps) and with edges made by one circle in each side. Neverthless in the center region, hill tips are machined with small chamfers and slope on the top.

Small trimming shims can be added on the full size magnet to adjust control and extraction region after final measurements which are planed from July 1967.

A large scale (0.322) magnet model has been used to ensure that enough precision was obtained so as to minimize possible modifications on the final "Music" magnet. The objectives of the study program were to provide a system ensuring vertical focussing of protons up to 110 MeV, acceleration of heavy ions below the $\nu_z = .5$ resonance with minimum power in the trimming coils and with a central magnetic bump as defined by injection studies.

The first model using four sectors with spiral angles close to 50º at the extraction radius was designed to focus the 110 MeV protons through the help of flutter coils. The iron field alone had very good focussing properties but the extraction radius was rather small compared to hill radius and the average field was too high for a good compromise between proton and heavy particles fields. The second model was corrected accordingly and the spiral angle was slightly increased at the extraction radius to keep ν_z at a safe value of 0 .1.

It turns out, after extensive model measurements, that a rather simple shape of hills can give the required iron field for heavy ions as well as for protons up to 100 MeV with correction of isochronism by use of trim coils only. However the flutter coils will be maintained and will permit to go to higher proton energies. Besides, they may be necessary for fine trimming of the flutter in the extraction region since the extraction of 100-120 MeV protons is a delicate problem.

The focussing factor in smooth approximation, ($\nu_z^2 + k$), is for the iron alone near 0.23 in the extraction region. Nevertheless, it is possible to handle protons at energies in the neighbourhood of 110 MeV with a field slightly different from isochronous field in the extraction region. This possibility is limited by the phase shift which must be kept in a suitable range for normal beam acceleration. Fine computation shows that for the best compromise for trimming coils adjustment, a positive value of ν_z can still be achieved up to 110 MeV. The field is isochronized beyond the radius 1.12 m where the spiral angle reaches its maximum, and then matches smoothly to to the iron field.

Figure 5 shows the iron field made approximately halfway between the proton and 12 C^{4+} isochronous fields, and the amount of trimming coils correction required to achieve these fields. The corrections are approximately balanced and the effect of most coils is cumulative, minimizing power requirements.

The magnet can also be used at higher fields for heavy ions acceleration, and future improvement of Music has been provided by installation of flutter coils which will procure the flutter needed to accelerate protons with this high field. Rough model measurements and computation have shown the possibility of accelerating protons at energies higher than 120 MeV but measurements on the final magnet are necessary to predict the exact limits.

In the curves of fig.6 for the 110 MeV proton field, the ν_z value in the extraction regions depends of the transition between the iron and isochronous field and can be moved by trim coil action as well as in the center region at the transition between the central bump and the isochronous field. Computation of the effect of trim coils were based on their air field. Therefore, the exact phase shift and values will be known only after measurements on the final magnet. Spiral angle and flutter for the 110 MeV proton field derived from the fourth harmonic phase are shown on fig.6.

The vicinity of the $\nu_z = 0.5$ and $\nu_r = 1.0$ resonances in the extraction regions can lead to some difficulties. The extraction studies which are starting now can show the necessity of some shimming in the fringe field.

The model measurements lead to the following parameters :

- Pole diameter	105 in (2,67 m)
- Hill diameter	101.5 in (2,58 m) (four sectors)
- Hill gap	7.244 in (0,184 m)
- Valley gap	18.346 in (0,465 m)
- Frame overall length	228 in
- Frame overall width	120 in
- Frame overall height	117 in
- Frame weight	360 tons

and for 110 MeV protons

- Extraction radius	45.25 in (1,15 m)
- Average field at extraction radius	13.46 kG
- Flutter at extraction radius	0.056
- Spiral angle at extraction radius	47º
- Frequency	18.6 MHz

From model computations the main coils must provide 382.000 A.t. The choice of conductor size has been made to comply with the selected water head loss of 120 psig. Each coil is made of four double pancakes, three of 26 turns and one of 24 turns with space in the latter for the median plane correction coil. The conductor is square hollow copper of 1 x 1 in cross section with 9/16 in dia. cooling duct.

- Number of turns	2 x 102
- Max. intensity	2000 A
- Ampere turns	404,000
- Power	360 kW

All auxiliary coils will be in primary vacuum, a thin wall separating the coils and the RF gap. This copper thin wall is used as a platter for assembly of trimming and harmonic coils. It is thus efficiently cooled by the coils water circulation.

Trimming coils :

- Number	16
- Intensity	200 to 800 A
- Number of turns	4 to 8
- Conductor size :	1/4" x 1/4" to 3/8" x 3/8" copper
- Total max power	130 kW

Harmonic coils : 4 in the center and 4 on the outer radius on each pole, each coil has two turns 180º, 1/4" x 1/8" copper conductor, 40 A max current, cooled by conduction to the neighbouring trimming coils.

Flutter coils :

- 8 hill coils 3/8" x 3/8" copper conductor 1200 A max.
- 8 valley coils 3/8" x 3/8" copper conductor 1200 A max.
- Total max power : 400 kW

The power supplies are solid state, water cooled units. To avoid harmonic generation no silicon controlled rectifiers are used. The current is controlled by series transistors. The current stability of the main power supply is 10-4.

IV - Injection

The ion source will be installed axially in the cyclotron. Two 8" diameter holes are machined through the frame and two similar mechanisms provided in these holes to use either the top or bottom hole for the ion source and also for future use of an external source and axial injection. The change in geometry from push-pull to push-push RF cavity operation, first to third harmonic, is too great to be made with an acceptable puller of a simple enough shape.

Two pullers will be used to achieve the best possible control of the injected beam for any particle or mode of operation as a result of the detailed studies of Dr Reiser (U.M) and Dr Dupont (CSF). The two pullers can easily be exchanged and the shift over harmonics 1, 2, 3 of the fundamental frequency can be considered as one operation.

In the hypothesis of constant orbits injection, computations gave a starting geometry for an electrolytic tank model and showed the minimul RF voltage to be about 60 kV. The electrolytic tank models were built at the University of Maryland on a design similar to that used at Michigan State University.

The measured electric fields were used to make computer runs in the six main modes of operation : 60 and 90 kV and 3 harmonics, and the data was used to design a better geometry for further computation of ion source positions and beam parameters. This led to the final geometry which appears in fig. 7 in the cases of N = 1 and N = 2.

The conclusions of these studies are summarized in the following table.

Harmonic	N = 1		N = 2		N = 3	
	60kV	90kV	60kV	90kV	60kV	90kV
Ion source slit abscissa in.	0.76	0.87	0.16	0.23	0.19	0.12
Ion source slit ordinate in.	0.13	0.39	1.16	1.33	1.70	1.90
Ion source slit plane angle	8º	16º	71º	64º	94º	88º
Ion source to puller distanc.	0.35	0.63	0.35	0.63	0.35	0.63
Beam duty fact.	40º	28º	30º	25º	15º	6º

The conclusions are that injection with 60 kV dee voltage only is possible in the fourfold symetry of the center. The betatronic amplitudes are related to the duty factor and we can expect 1.2 in. for 40º (protons). The duty factor is less than 70º in all conditions, the best being for N = 1 and 60 kV, the betatronic amplitude is then greater than .2 in.

The puller shape is different for each mode. In order to avoid unreliable complex mechanisms it is planned to use the two different interchangeable puller systems with only limited motions : translation along the dee axis and rotation of 15º max. They will be removable through the dee stem.

The magnetic bump in the center of the cyclotron was assumed to give $\nu_z = 0.2/\nu_r$ to compensate space charge effects on the first turn, and this was obtained on the model magnet. The remaining problem is the rate of variation of $\Delta B/B$ when the magnetic field is varying. For a constant orbit injection the phase shift due to the magnetic bump is given by :

$$\sin\phi - \sin\phi_0 = K\int\frac{\Delta B}{B}\,r\,dr$$

and if $\Delta B/B$ increases, the phase shift increases. At 110 MeV protons, the field bump gives a phase shift of 30º. This field bump will increase 2.5 times with a fixed center plug in the best possible design and the phase shift will increases up to 75º when the main field is reduced to its lowest value. As this is unacceptable a movable plug has been chosen.

It is also thought that one of the dummy dee tips will be movable to give enough clearance between it and the puller in the N = 1 and 90 kV mode of operation.

The focussing needed to inject beams with a high space charge requires a very sharp bump, in the range of 4% of the central field for all fields, as in a four sectors geometry flutter starts relatively far from the center. The highest gradient required is of the order of 250 gauss/inch and the bump meets the isochronous field at a radius of 8 in. approx. (see fig. 5)

To provide this bump, model studies showed the need of an iron-cobalt steel movable plug in the center. The severe mechanical requirements for the ion source, which must be displaced between radii .8 and 1.9 in. in a 90º sector, involves rotation of the center plug and an inner radius of hill tips of 3.1 in.

The design of the center plug was determined by successive model studies to minimize its vertical motion for a constant relative bump. The best system gives this result with only half an inch displacement. The gradient was obtained by shaping the plug and modifications on the center tips of the hills as chamfers and sloping top. Two imperfections remains. The flutter starts farther from the center than desirable due to the four sectors geometry and the transition region to isochronous field is not perfect but this can be corrected by the trimming coils.

V - Extraction

Extraction of the 110 MeV beam shows an unexpected difficulty, which would not exist for much higher energy, because of the existence of the $\nu_z = 0.5$ resonances right in the region of extraction.

This comes from the fact that the field index for 110 MeV protons is 0.235 and must be overcome by the focussing factor. Second, the rigidity of the beam is such that it is not possible to extract it without using the $\nu_r = 1$ radial resonance.

But the focussing power of the flutter does not decrease very rapidly and it turns that the three relations $\nu_r = 1$, $\nu_z = 0.5$, $\nu_r = 2\nu_z$ occur within a few millimeters distance. As Dr KIM (U.M) has shown any means of exciting the $\nu_r = 1$ resonance to get an acceptable turn separation, feeds enough energy into the axial movement through the coupled resonance and the "index" resonance, to destroy beam quality.

The problem is not yet solved completely. Some means of separating the resonances are envisaged either by increasing flutter by use of the flutter coils, to push $\nu_z = 0.5$ inside, or decreasing abruptly the spiral angle by change of shape of the iron on the edge, which pushes $\nu_z = 0.5$ outside.

Changes of 5 mm in its position seem possible.

The extraction set up is conventional : electrostatic channel at about 120 kV /cm, max magnetic channel (-3500 gauss) and steering and gradient correcting magnet.

It is not yet clear which of a field bump of a few gauss, or a magnetic regenerator will be used to excite the $\nu_z = 1$ resonance. (Electrostatic regenerator cannot be envisaged in the actual geometry, and the peeler scheme has been rejected because of lower performance).

After computation it appears that the best design for beam quality and emplacements for the extraction components leads to a beam rotation in the same direction as the hill spiral.

VI - <u>Conclusion</u>

The design of the Music cyclotron should make it a very flexible machine and preserve the possibilities of interesting improvements for the future. The choice of the 100-120 MeV range leads to new basic difficulties mainly in extraction but goods solutions are possible.

The fabrication is now will under way, the magnet frame being delivered on the site. The machine is to be commisionned at the end of 1968.

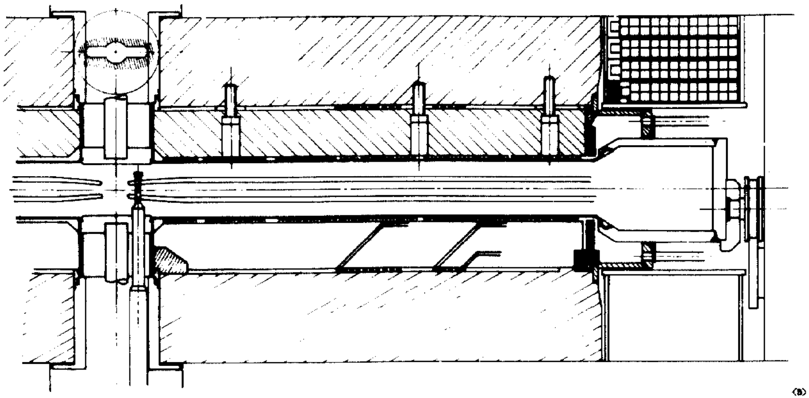

Fig.1 - A detailed side view of the magnet gap showing correction coils, center plug, vacuum box and dee.

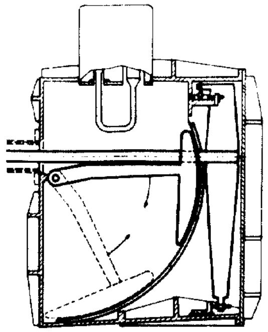

Fig.4 - RF cavity

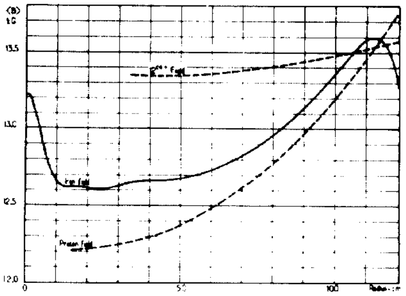

Fig.5 - Graph of average B

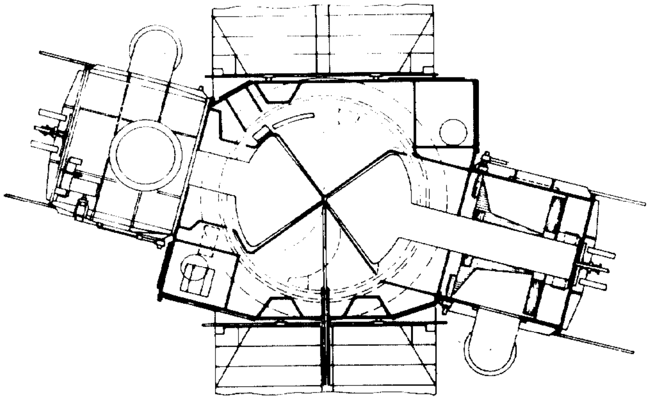

Fig.2 - General layout of the cyclotron

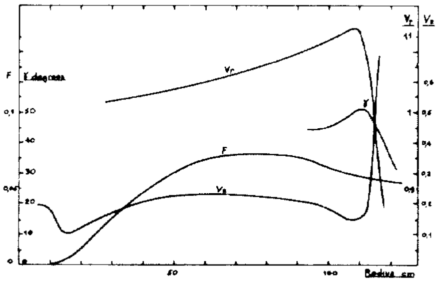

Fig.6 - Graph of

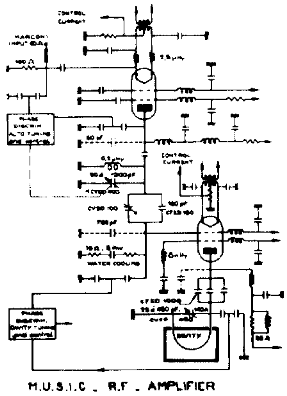

Fig.3

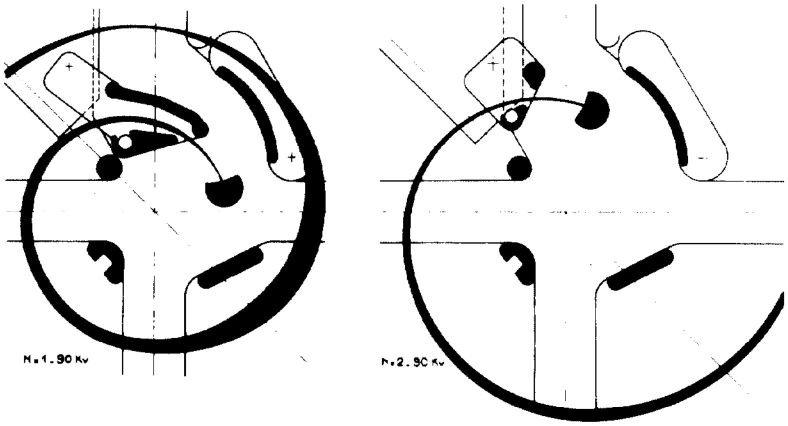

Fig.7 - Two examples of beam injection showing the two pullers