Design of the 4000 ton magnet for the TRIUMF cyclotron

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ABSTRACT

The containment of the accelerated H^- beam in the TRIUMF isochronous cyclotron presents some unique design problems.

The electric dissociation of the H^- ion as it travels through a magnetic field requires that the maximum field be limited to 5·76 kG to maintain a relatively low activity level inside the vacuum chamber. This results in an overall magnet diam. of 71 ft. Two scale models were built to aid in the design of the 6-sector magnet; a 20:1 scale model of the whole magnet and an 8:1 scale model of the centre region. The models were fabricated in a way that was consistent with the eventual construction of their full-scale counterpart.

Computer analysis of the measured fields has confirmed that a focused beam of H^- ions can be isochronously accelerated to 500 MeV with a total beam loss due to H^- stripping of 6·5%. The vertical focusing frequency, ν_z, is well within the design limits of 0·35 ± 0·10.

The effects on the magnetic field of the magnet support structure, bolting array and vacuum chamber supports have been measured and have been accounted for to a first order.

The main coil is to be made of extruded aluminium plate and will be assembled in six separate sections for convenience in manufacturing and handling and to maintain the exact six-fold symmetry of the magnetic field. The final size description is: 500 MeV radius, 312 in; coil radius, 348 in; outside radius, 426 in; gap, 20·8 in; overall height, 197 in; weight, 4200 tons.

1. INTRODUCTION

The design of the TRIUMF cyclotron magnet is based on the results of magnetic measurements done on a 20:1 scale model and 8:1 scale centre region model. The results indicate that the original design aim of the cyclotron can be exceeded.

**On leave from UCLA*

2. DESIGN THEORY

The basic objective of the TRIUMF cyclotron is to extract[1] a 100 μA CW beam of 500 MeV protons by accelerating H^- ions. The basic reasons for choosing these limits for the cyclotron are covered in another paper.[2] The magnetic design criteria are the following.

(1) The requirement that the cyclotron activity be limited to an effective beam loss of 20 μA at 500 MeV sets the maximum magnetic field to 5·76 ± 0·02 kG. This limit is based on the lifetimes of energetic H^- ions in a magnetic field measured by Stinson *et al.*[3]

(2) The isochronism condition demands that the magnetic field increases with radius as γ. This essentially determines the radial variation of the maximum magnetic field and the change in the angular width of the pole piece.

(3) The achievement of a real vertical focusing frequency over the whole energy range is made more difficult because of the radial increase in the average field. The number of vertical oscillations per ion revolution (ν_z) is obtained from the approximate expression:

$$\nu_z^2 = -\frac{r}{\bar{B}}\frac{d\bar{B}}{dr} + F^2(1 + 2\tan^2\epsilon)$$

The first term is defocusing as $dB/dr > 0$ to satisfy the isochronism condition. Assuming that the average field is isochronous, this expression reduces to:

$$\nu_z^2 = -(\gamma^2 - 1) + F^2(1 + 2\tan^2\epsilon)$$

F^2 is the flutter ratio and ϵ is the spiral angle of the field. Out to a radius of about 180 in the flutter ratio dominates the expression; for $R \geqslant 200$ in the spiral angle becomes more and more important, and at 500 MeV it reaches a maximum value of 70°. Fig. 1 summarises these various focusing terms as measured on the 20:1 scale model.

3. DESCRIPTION OF MODEL

Most of the magnetic field data has been produced with a 20:1 scale model powered by a 150 kW (50 V 3000 A) supply regulated to 1×10^{-5}. Great care was taken in modelling the actual construction of the full-size magnet. Since the magnet was envisaged as being made from rolled plate, the model was made of scaled-down plate (see Fig. 2).

The centre region of the magnet is of special interest because of the axially-injected beam. An 8:1 scale model magnet was built in order to look at the magnetic properties of the first 40 in radius of the cyclotron.

The field measurement system consists of a temperature-controlled Hall probe mounted on a rotating channel. The Hall probe temperature is maintained at approximately 10°C above room temperature with a thermocouple-controlled oven. The temperature control is better than ±0·05°C. The probe's position anywhere in the model was known to be within ±0·02° and ±0·002 in. The relative accuracy of the field measurements was ~0·5 G. The absolute accuracy,

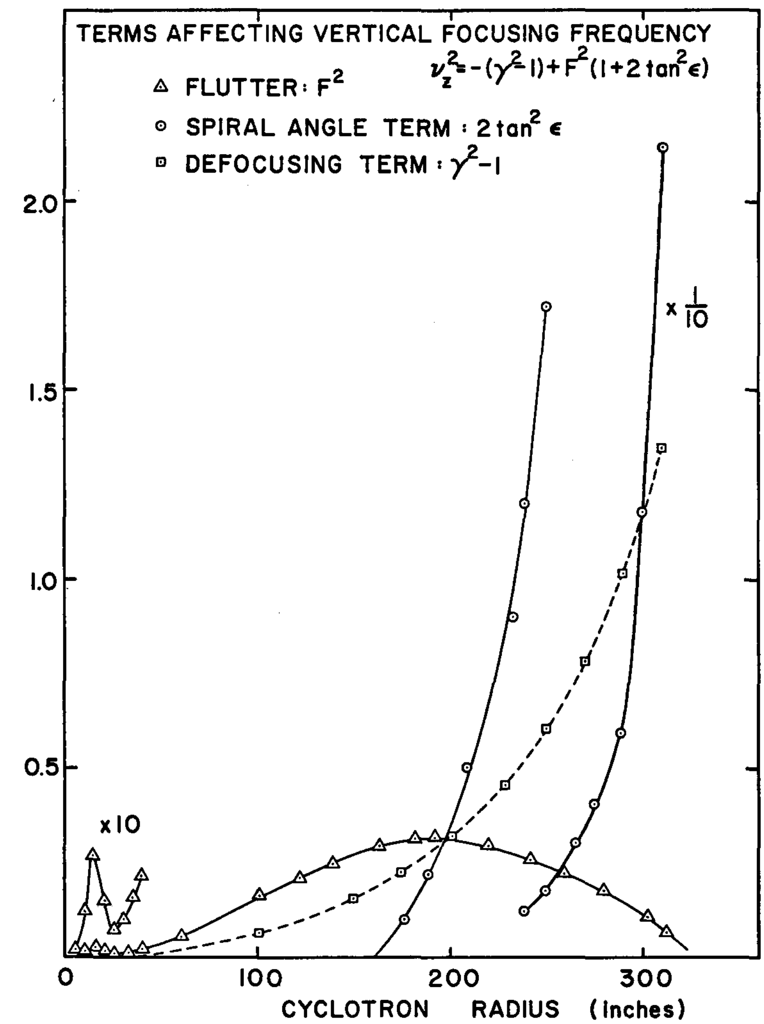

Fig. 1. Terms affecting the vertical focusing frequency ν_z

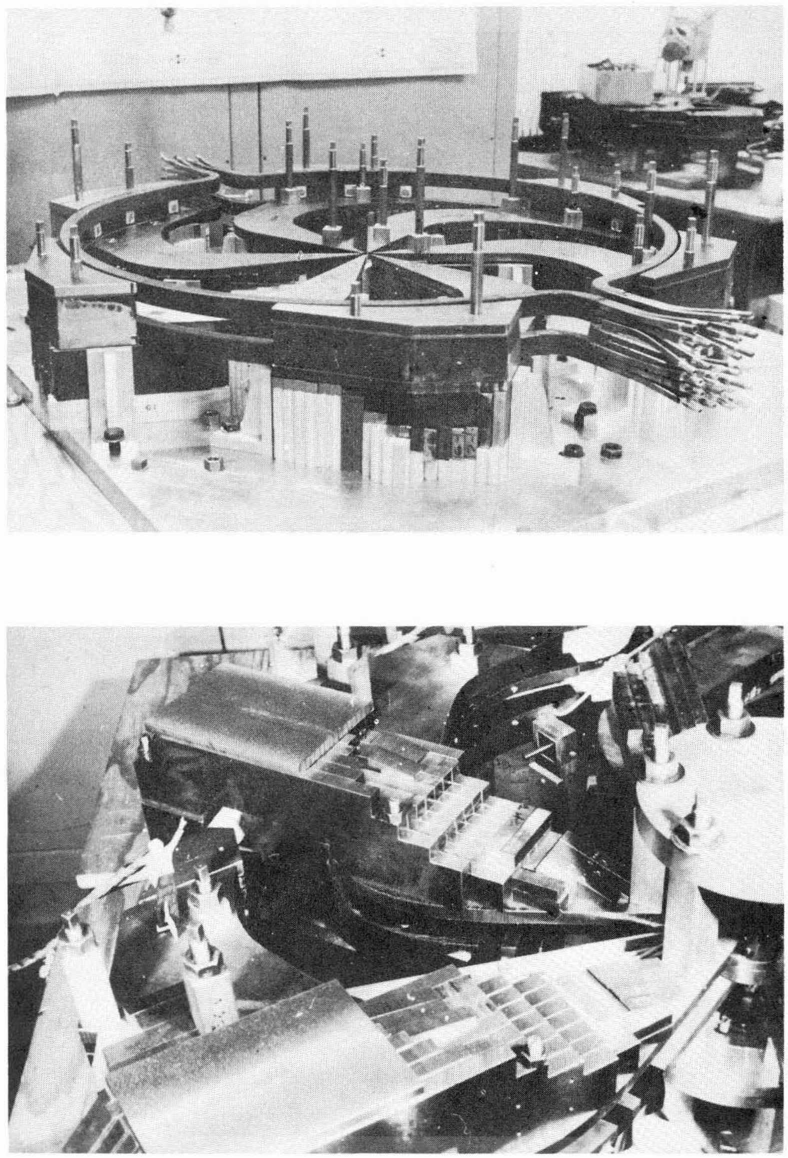

Fig. 2. (a) 20:1 scale model showing spiral pole pieces and coil;
(b) 20:1 model showing return yoke and plate construction

using a polynomial calibration curve with respect to NMR gaussmeter, was ~2 G. Measurements were made over a 128° interval but field analysis was done over a selected 60° portion.

The analysis and beam orbit codes were modified versions of POLICY and CYCLOPS.[4]

4. RESULTS

The magnetic field tailored in the 20:1 scale model has the following properties (see Fig. 3). The average field deviates from the isochronous field by less than 100 G. The vertical focusing frequency falls within the design limitation of 0·35 ±0·10. The maximum field is approximately 5·74 kG. The beam loss due to H^- electric dissociation is 6·5% if the field is set to give the 500 MeV equilibrium orbit at an average radius of 312·5 in. This is the maximum radius

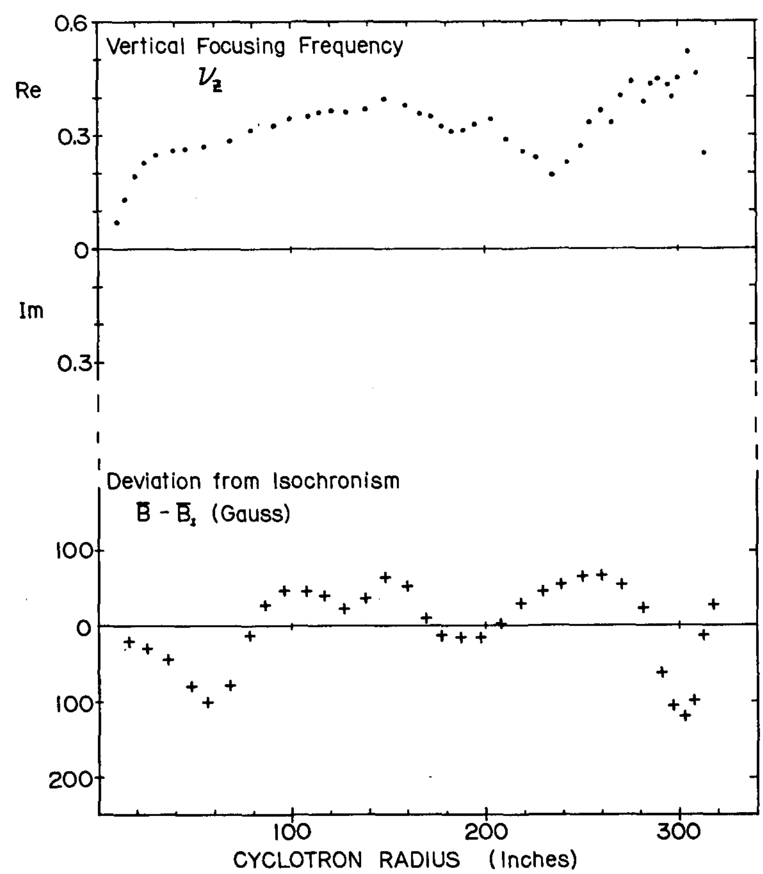

Fig. 3. Properties of tailored magnetic field measured in the models

at which the necessary forces are sufficient to keep ν_z real. If the magnetic field is increased, the following happens.

(1) The radius for 500 MeV is decreased and the beam loss increases.
(2) The maximum energy that can be accelerated before $\nu_z^2 < 0$ increases.
(3) The overall value of ν_z decreases.

All of these points are summarised in Fig. 4(a), (b), (c).

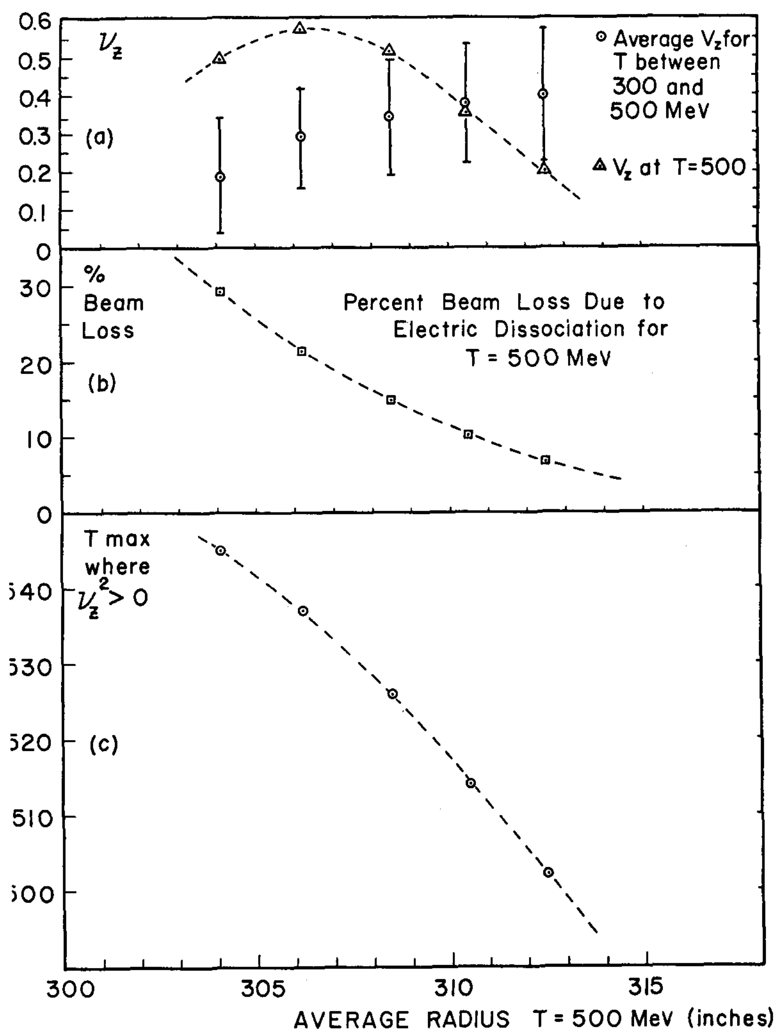

Fig. 4. (a) The variation of ν_z with the average radius of the 500 MeV beam;
(b) Percentage beam loss at 500 MeV as a function of the 500 MeV radius;
(c) Maximum energy of stable acceleration

Fig. 4(a) shows the average of ν_z over the energy range $T = 300$ to 500 MeV and the value of ν_z at $T = 500$ MeV, plotted against the average radius at 500 MeV. The error bars are the rms deviation from the mean. As the magnetic field is increased such that $R_{(500)} < 304$ in, ν_z becomes imaginary near radius 280 in.

Fig. 4(b) shows the percentage beam loss due to electric dissociation integrated to 500 MeV. By choosing the 500 MeV radius to be 312·5 in, the total current that could be accelerated would be in the order of 200 μA. This would be consistent with an acceptable activation level mentioned in design criterion (1).

Fig. 4(c) shows the increased energy available if the magnet induction is increased. The maximum energy available can be increased above 500 MeV, thus

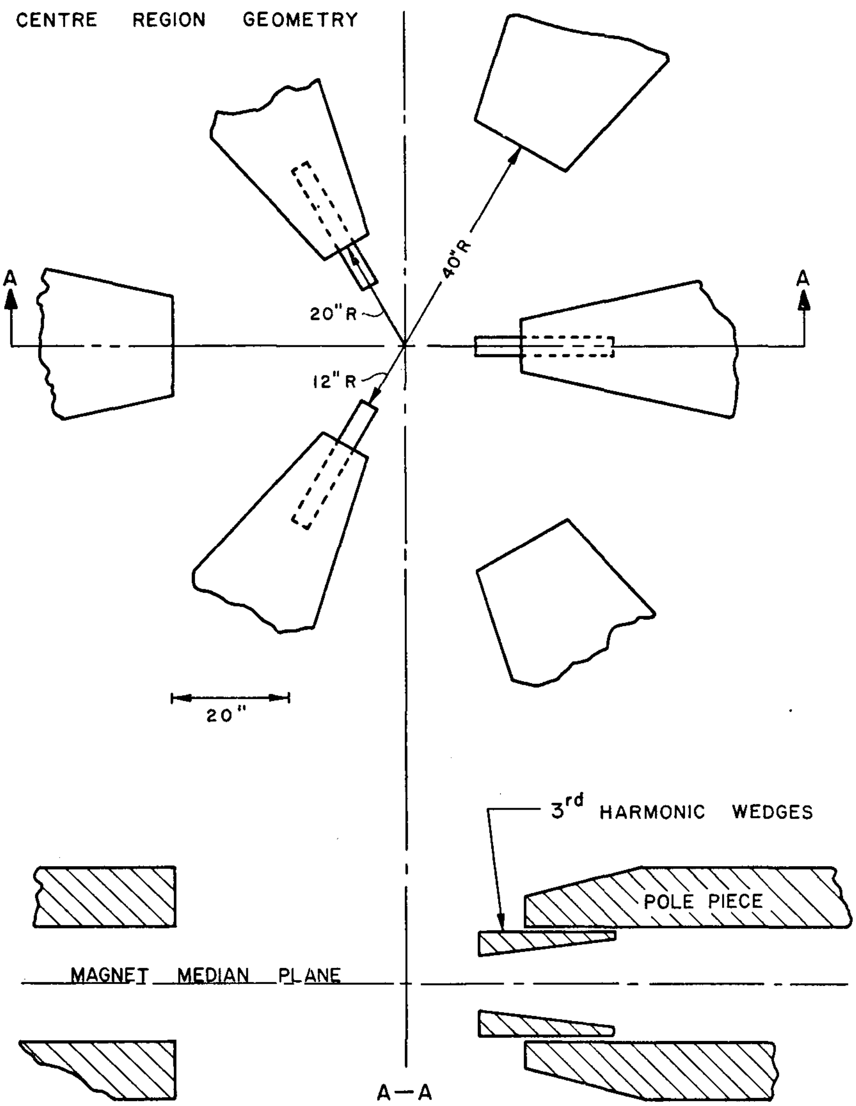

Fig. 5. Details of the magnet centre region showing the cut back sectors and wedges

making 300 MeV pions an easy objective. To satisfy the activity criterion, the beam intensity will be reduced to the order of 10 μA.

To achieve the necessary magnetic focusing over the first few turns of acceleration, the magnet sectors have been cut back as shown in Fig. 5.

This suppresses the sixth harmonic amplitude in favour of the third, increasing the flutter and hence the vertical focusing frequency ν_z.

ν_z can be further increased by adding small wedges to the remaining sectors (Fig. 5). The effect on ν_z from these various changes is shown in Fig. 6.

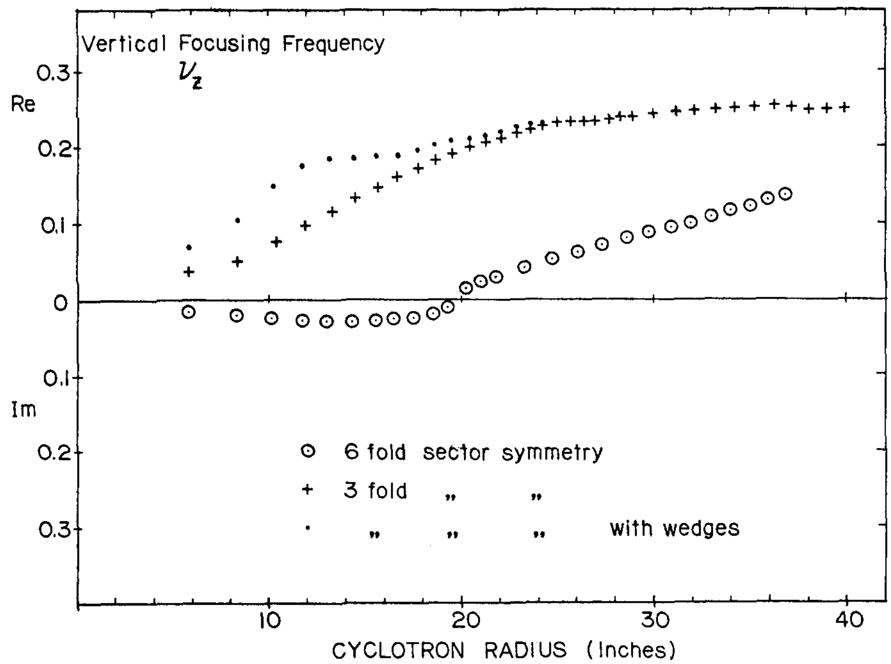

Fig. 6. Changes in ν_z due to the changes in the centre region geometry

Table 1

Number of sectors	6
500 MeV radius	312
Width of sector at 312 in	36·4°
Width of sector at 160 in	25°
Mean spiral angle at 312 in	70°
Average magnet field at 312 in	4·56 kG
Average magnet field at 0 in	2·98 kG
Magnet gap	20·8 in
Pole plate radius	338 in
Main coil radius	348 in
Main coil cross-section (aluminium conductors)	20 x 20 in
Main coil excitation	720 000 amp turns
Main coil power	2500 kW
Magnet weight	4200 tons

There is a phase dependent electric focusing effect due to the relatively long time the low energy H^- ion takes in crossing the rf accelerating gap. By introducing the third harmonic central field the phase acceptance has been increased by 50%.[5]

5. MAGNET PROPERTIES

Table 1 describes some of the features of the TRIUMF magnet.

The support structure associated with the magnet causes the average field to change by the order of 50 G and a magnetic median plane shift of 0·10 in. The yokes are penetrated by tie rods which support the vacuum tank and provide adjustment for the resonator positions. The effect of porosity caused by these holes and also by the non-flatness of the vertical plates has been measured and allowed for in the final yoke sizes specified. A high quality steel (AISI hot rolled, silicon killed) and uniformity of manufacture have been specified to achieve consistency between sectors. Final adjustment of the field will be made by adding or removing shims to achieve a uniformity between sectors of better than 5 G.

A series of 54 trim and 72 harmonic coil pairs will be brazed to the top and bottom of the vacuum tank to achieve final uniformity and to obtain the required mode of operation. The design aim is to achieve a first harmonic uniformity between sectors of ±0·2 G.

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