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A 600 MeV Cyclotron for Radioactive Beam Production

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Abstract

The magnetic field design for a 600 MeV proton cyclotron is described. The cyclotron has a single stage, a normal conducting magnet coil and a 9.8 m outside yoke diameter. It has 8 sectors, with a transition to 4 sectors in the center region. The magnetic field design was done using 1958 Harwell rectangular ridge system measurements and was compared with recent 3-dimensional field calculations with the program TOSCA at NSCL. The center region 4-8 sector transition focussing was also checked with TOSCA.

I. INTRODUCTION

The report on the IsoSpin Laboratory (ISL) [1] describes a "benchmark" reference design for a facility for the production of radioactive nuclear beams in North America. The primary accelerator is required to produce protons at an energy of .5-1.0 GeV and an intensity of 100 μA, while a secondary accelerator will accelerate radioactive beams from the target to about 10 MeV/u. The primary accelerator can be a cyclotron such as the PSI ring or TRIUMF. Because of the high beam power an essential requirement for this cyclotron is that of minimizing the beam lost at high energy inside the cyclotron, to prevent component damage and reduce radiation exposures during maintenance. This in turn requires very high extraction efficiency either by good turn separation at extraction or by use of negative ions. This paper presents the magnetic field design of a primary cyclotron which minimizes cost while maintaining high extraction efficiency.

II. GENERAL FEATURES

The design choices are described in a previous paper [2]. The present design uses positive ions with very high extraction efficiency. This design has the advantage over a negative ion design of preventing the stripping loss activation of vacuum tank material, and using a higher magnetic field and thus a smaller radius. The advantage compared to a separate sector design is that the compact magnet requires only one main coil, and eliminates the injector stage. The choice of pole diameter size is a compromise between better turn separation for a large radius and lower cost for a small radius at higher magnetic field. The dees are placed in valleys so that the hill gaps can be made small, giving acceleration out to near the edge of the magnet, easier extraction and low magnet power. Dees in the valleys at this energy require the resonators to be in the valleys also, since the radial length of the dees is the order of 1/4 wavelength. The highest acceleration is required near extraction, so additional auxiliary dees are added there. The sector number can be 6 or 8 to get to 600 MeV. 8 is chosen to allow a transition from 8 to 4 sectors in the center with 2 main dees. The 4 sector center region gives better acceleration transit time factor and magnet flutter than an 8 sector design.

III. 4-8 SECTOR CENTER REGION

A magnetic field having a transition between different numbers of sectors has to be evaluated for adequate flutter to give axial focussing. Such a transition between 8 and 4 sectors was used by the Analogue II electron model [3] in 1961 at Oak Ridge, as pointed out by H. Blosser. The use of a transition from 6 to 3 sectors was proposed by AEG in 1962 [4], as pointed out by Joho.

To check the feasibility of a particular geometry of a 4-8 sector design, the magnetic field of a simple sector magnet representing the center region was calculated by F. Marti with the 3D program TOSCA [5]. The magnet is shown in Fig. 1. With a .1 meter gap in the hills, the pole radius is .75 m, compared to 3.4 m for the full 600 MeV beam. In Fig. 2 the magnetic flutter is plotted, showing the fast rise of the 4 sector region at the machine center, and the transition to the slower rising 8 sector region further out. The flutter drops at large radius due to the usual pole edge effect. The value of the axial focusing frequency Nuz is also plotted in Fig. 2, showing that there is adequate focusing from this configuration. Nuz could be increased at larger radius by having the transition further out. Nuz was calculated with the equilibrium orbit code CYDEG, a general form of the 88-Inch Cyclotron program CYDE, developed by J. Moehlis.

IV. MAGNETIC FIELD DESIGN

The present design for 600 MeV protons is shown in Fig. 3. As mentioned above it is a compact design using a single main coil. The maximum radius is about 3/4 of that of the PSI ring design. The average magnetic field was assumed to be 12 kG at 600 MeV. The transition of 4-8 sectors can be seen in the center region.

For preliminary design one can use the simple formula for the axial focusing:

$$Nuz^2 = FSQ\,(1 + 2\tan^2 Eps) - \mu'$$

where Nuz is axial frequency, FSQ is flutter, Eps is spiral angle and μ' is average field gradient. μ' is determined by the energy. To produce a Nuz of .3-.4 we need to have enough spiral and flutter at each energy to overcome the defocusing of the average field. In the previous paper [2] a sharp edge was assumed, with a valley field of zero. A better estimate is tested in this paper. It uses some systematic magnetic field measurements on rectangular ridge systems by P. F. Smith of Harwell [6]. This work by Smith calculates the flutter and average gap for a range of average magnetic field of 6-20 kG, a range of ratio of hill width, p, to (hill + valley) width, lamda, of .35-.80, and ranges of hill gap and hill depth. A design was tested using a p/lamda of .5 at 600 MeV and using a spiral angle Eps sufficient to make Nuz = .35. At lower energies p/lamda was reduced to produce the proper isochronous field and Eps was reduced to leave Nuz = .35. This calculation required considerable interpolation and extrapolation. The Smith measurements are on rectangular parallel ridges, but the correction suggested by him was used to calculate the spiral ridges used here. This consisted of measuring p and lamda perpendicular to the edges of the spiral to give and effective reduced value. The valley depth was set at the coil height to make a simple design. Deeper valleys don't increase the flutter much.

The resulting hill shape is shown in Fig. 3. Spiral is required only at the outer radii. In Fig. 4 the values of Eps and p/lamda are shown. It was decided in this test to keep p/lamda at .35 or larger, since this was the minimum value in the Smith report. Eps is 0 below 100 MeV, slightly over half radius.

A TOSCA calculation was done on this design by F. Marti [5] to compare the values of average field and flutter with those predicted by Smith. Fig. 5 shows the comparison of average field. The field for the Smith case used the calculated average gap, and assumed the field is inversely proportional to the gap. In the Smith calculation the average gap depends on the field, so this comparison used the TOSCA field to calculate gap. The agreement is about .5 kG out of 10 kG, or 5%. The disagreement at the largest radius is due to the edge effect of the pole. An additional TOSCA run showed that the average isochronous field could be extended by increasing the hill radius, as expected. This field is approximately isochronous for the outer 1/3 of the radius. Inside that coils would have to be used to correct up to 3 kG error in the center. Alternatively the p/lamda could be further reduced and the gap increased at smaller radii.

A similar comparison is shown for flutter, FSQ, in Fig. 6. There are two Smith curves. The one at small radius uses an approximation for small hill width to depth ratio, which applies at the center region. The last outer point of the Smith curve is again due to edge effects. The agreement of TOSCA and Smith are good enough for preliminary design.

The conclusion is that the Smith data can be used for first design, before running TOSCA, and can provide a guide to the hill geometry which can provide a required amount of axial focussing. However it needs interpolation and extrapolation to make use of the tables of data, and has some limitations of parameter range. The configuration used here and shown in Fig. 3 is just an example for evaluating the Smith data. For a final design we need up to 10 degrees more spiral at 300-600 MeV for focussing, a hill extension outward of about .1 m, and some adjustment of the average field in the smaller radii to reduce trimming coil power.

V. OTHER DESIGN FEATURES

The main dees operate at harmonic 4, 44 MHz, and extend in to the center. 1/4 wavelength of rf is 1.7 m, only about 1/2 the extraction radius, so the resonators must be in the valleys, with vertical dee stems. 2 more dees can be added to reduce the number of turns from 2000 to 1000, at a dee voltage of 100 kV. Small auxiliary dees, indicated near extraction radius in Fig. 3, increase the energy gain/turn there and give the option of flat-topping for better turn separation. For acceleration they can operate at harmonic 8. For example, 4 dees at 250 kV, harmonic 8, would give about 2 MV/turn.

The ion source is assumed to be external, with an injection energy of about 50 kV. An external source allows bunching into the required phase width for turn separation at extraction.

VI. ACKNOWLEDGMENTS

The author wishes to extend thanks to W. Joho and H. Blosser for helpful discussions, and to Felix Marti for the TOSCA calculations of magnetic fields.

VII. REFERENCES

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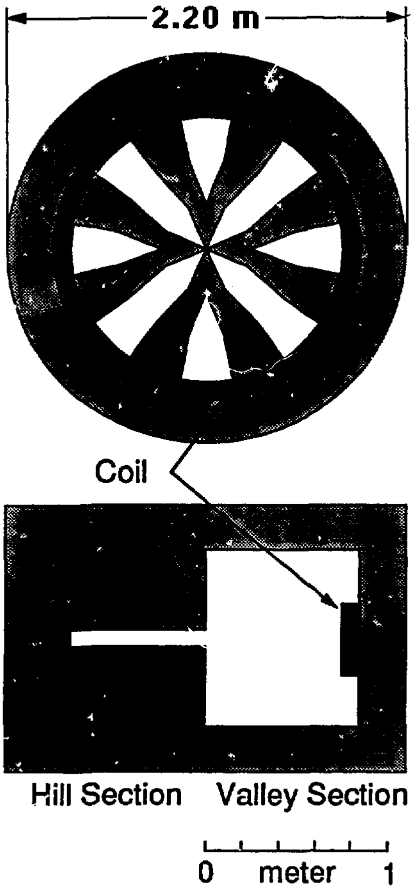

Figure 1. Magnetic model with 4-8 sector transition, for TOSCA calculation.

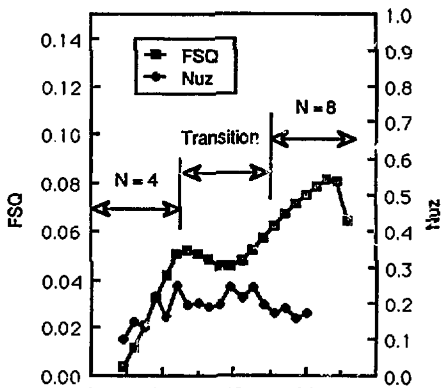

Figure 2. Flutter, FSQ, and axial focusing, Nuz, for 4-8 model using TOSCA calculation.

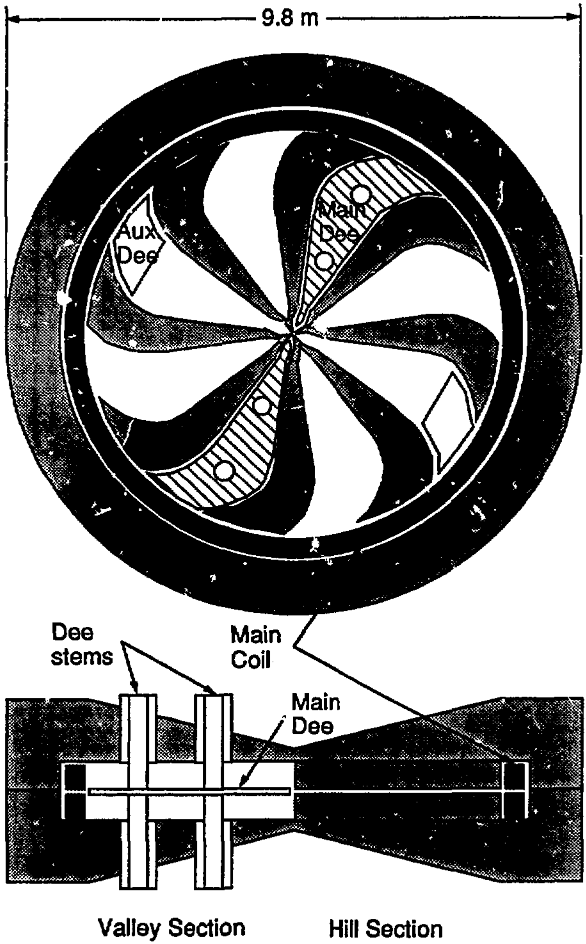

Figure 3. 6?0 MeV proton cyclotron, plan and elevation views.

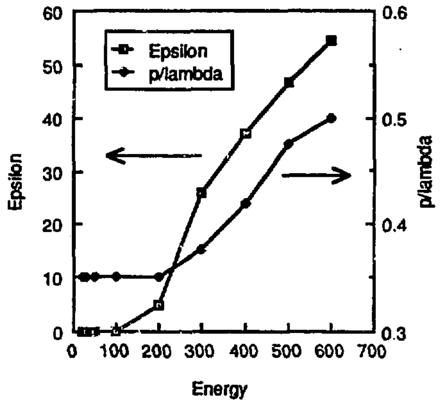

Figure 4. Spiral angle, epsilon, and hill fraction, p/lamda for 600 MeV cyclotron.

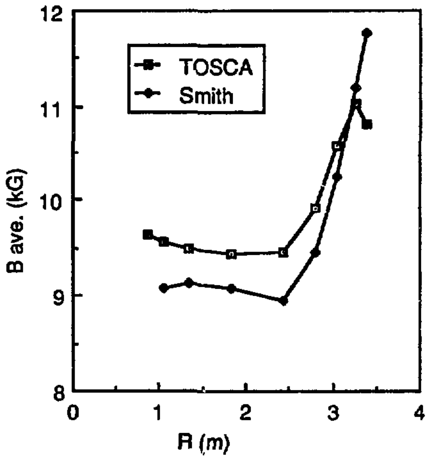

Figure 5. Average magnetic field, B ave., calculated by Smith tables and TOSCA.

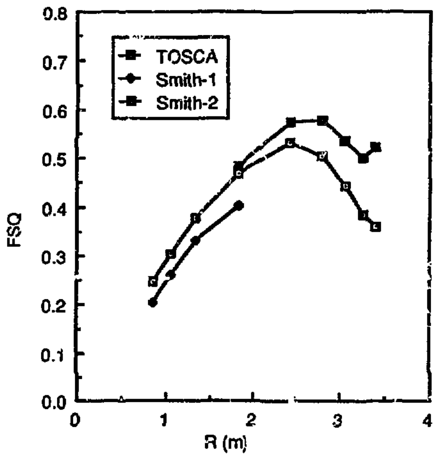

Figure 6. Flutter, FSQ, calculated by Smith tables and TOSCA.