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THE NEVIS SYNCHROCYCLOTRON CONVERSION PROJECT [1]

R. Cohen

Columbia University, New York, New York

I. Introduction

Since 1950 when Columbia University's 385-MeV synchrocyclotron first went into operation, the physicists here at Nevis have concentrated in and contributed greatly to the fields of pion and muon physics and to the field of time-of-flight neutron spectroscopy. Among their notable achievements were: the discovery of muonium and its use to measure the fine structure constant α; the first quantitative measurements of muonic x-rays; the first counter experiment to measure the mu-capture rate in hydrogen; the discovery of parity violation in the $\pi \rightarrow \mu \rightarrow e$ decay; the most precise measurement of the muon magnetic moment; etc. etc.

It has become obvious that if the high quality of the research is to be continued here at Nevis, the intensity and the quality of the beams available from the cyclotron would have to be increased greatly. Within the limitation of keeping our present basic magnet structure, there were several possible ways in which we could improve our beams, from building a completely isochronous cyclotron to making minor improvements in the beam transport system, arc source, the rf, etc. It became clear at a fairly early stage of our planning, that a fully isochronous machine using the present magnet would probably have an energy of only 250-300 MeV, which would be entirely too low for our purposes. Our studies showed that we could convert to a partially isochronous cyclotron, that is, one in which the average magnetic $\langle B(r) \rangle$ increases with radius but not fast enough to operate isochronously. This machine would have many of the advantages (and disadvantages) of both the isochronous and the synchrocyclotron. For example, the machine will have the advantage of having phase stable orbits so that field-shaping will not be as critical as for fully isochronous cyclotrons; it will employ strong focusing spiral ridges so that much more intense proton beams may be accelerated before space charge causes beam blowup; the spiral ridges present the possibility of efficient beam extraction; it will have a much smaller frequency swing than a conventional synchrocyclotron, thus easing the design requirements of the rf system and allowing a much higher repetition rate; (we plan to use a repetition rate of about 300 cps).

II. Theoretical Studies

Since the machine is not going to be operated in a fully isochronous manner, certain parameters can be chosen that would otherwise be determined. We are thus able to use somewhat arbitrary functions for the values of the average magnetic field $\langle B(r) \rangle$ and the vertical oscillation frequency $\nu_z(r)$ vs r. Using these values of B and ν_z, the Smith and Garren[2] equations for the flutter factor F were solved by numerical integration and the radial oscillation frequency ν_r was calculated. Dr. S. Ohnuma of Yale University has been studying the resonances which are likely to be serious for various configurations and his work has been most valuable in showing whether the parameters chosen were feasible. A computer program to calculate orbits was developed by Dr. Rainwater of Columbia University with which we were able to check whether the fields as calculated by the Smith and Garren equations really gave the correct radial and vertical oscillation frequencies. These frequencies agreed to better than 1%. The studies showed that a magnetic field of the form

$$\langle B(r) \rangle = B_o \exp[(r^2/5) - r^{40}/100]$$

where r = 1 corresponds to the maximum useful radius of the machine (80 in.), a spiral angle $\tan\gamma = 2r^{1/4}$ and reasonable values of the flutter factor should give values of ν_z and ν_r that do not cross any of the most bothersome resonances. The magnetic field chosen increases with r about 40% of the amount needed for full isochronism.

III. Model Magnet

A one-fifth scale model of our present magnet has been constructed as one of the basic tools to be used in our design studies and a measuring device has been designed and built which automatically measures the field with a Hall-effect probe at a predetermined set of points and punches the valves of the radius, azimuth and Hall output voltage on IBM cards. It is possible to set the machine to scan the entire field or just a single sector.

We have measured the model magnet field using the iron configuration of the present machine. This will serve the dual purpose of checking our computer programs using a field whose properties

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we are familiar with, giving us a better insight into the operation of the synchrocyclotron. This could well lead to improvements being effected before the major modifications are made.

Figure 1 shows the first trial spiral shims, $\tan\gamma = 2r^{1/4}$, which our calculations showed should be a good first trial. They are mounted on an aluminum backing plate together with the auxilliary coils in place. This entire assembly is mounted in the model magnet with the aluminum plate toward the median plane as a unit greatly facilitating the alignment procedures. The coils have been designed to provide up to one-half the number of ampere-turns of the main coils and this should increase the final proton energy from our present 480 MeV to 600 MeV in the new machine. The first set of measurements will show how much flutter can be produced by this configuration, but obviously the average field will decrease with radius rather than increase as desired. In order to increase the field with radius and still keep the maximum of flutter, the thickness of the shims near the center will be reduced (with smaller reductions at larger radii), by cutting away the iron nearest the pole face. Thus the distance between the face of the shims nearest the median plane and the median plane remains constant. Similar iron shims with the same spiral angle but with four-fold symmetry rather than six-fold have been made. They will be mounted in the model and the field configuration measured while the six-fold are being machined to produce the correct B(r) vs r.

IV. The Central Region

The central region studies have two basic aims, the first of capturing the largest number of ions into phase stable orbits and the second which is at least as important is to have these orbits geometrically well-centered with minimum vertical and radial oscillations. Dr. Ohnuma tells us that the extraction efficiency that can be obtained is directly dependent on how well the second aim is accomplished. One means of avoiding large oscillations is to use a closed arc source with a puller electrode and defining slits. This of course implies fairly large rf voltages near the center so that the ions do not hit the ion source on the first revolution.

MacKenzie[3], Lawson[4], and Rainwater[5] have studied the effect of space charge blowup in cyclotrons and synchrocyclotrons and these studies show that beam intensities can be considerably increased by additional focusing in the central region. One method of doing this, as suggested by Rainwater, is to place iron spiral ridges in the central region within two or three inches of the median plane (our basic pole pieces are 36 in. apart). In this way, values of $F \sim 0.2$ should be quite feasible. If the spiral angle used is between zero and one, one can get the value of ν_z^2 between 0.04 and 0.09 which implies a space charge limit of between 60 and 180 μamps assuming a repetition rate of 300 cps.

To study the central region experimentally a vacuum system has been built for the model magnet and an rf system with a small amount of frequency modulation is being designed and built capable of putting 20 kV on the dees. The system will be quarter wavelength, run at an average frequency of 22 mc/sec with a frequency swing of 2% to 3%, probably be ferrite turned, and run at a peak power of 50 kW but only at about a 2% duty cycle. Three- and four-fold flutter plates have been made for this model. One of the flutter plates will be both above and below the dee skin and so will be at rf potential. Thus we will have a low energy operating synchrocylotron which should be very useful for extraction as well as central region studies.

V. Shielding and Residual Activity

Since this is a conversion of an existing cyclotron, we will be somewhat limited in the space available for the additional shielding which the increased intensity will require. The most practical solution to this problem seems to be to use mostly iron for the shielding except at points where this is likely to interfere with the magnet field. It is planned to have part of the meson beam transport system in the shielding walls using the iron of the wall as the return path for the flux.

One of the most serious problems for this accelerator (and any other high intensity machine) is residual activity inside the chamber. Our present machine has an internal beam of the order of 1 μamp and it is still possible to do work inside the vacuum chamber if one waits long enough, usually two to three weeks. In the light of our experience with our present machine we feel we could lose up to 10 μamps inside the new machine provided the basic pole structures are protected by sufficient marble or carbon, and provided we are clever enough to have made provision to do any conceivable work inside the chamber by remote control.

Figure 2 is a plan view of the old cyclotron building and its new addition. The external proton beam will be brought out into a special target room. We are fortunate in having a steep high hill behind this room where it will be a fairly simple matter to dump the residual beam safely.

References

[1] A more complete account is available in Columbia University Nevis Report R-536, J. Rainwater, "Modification Program for Nevis Synchrocyclotron" (1966).

[2] UCRL Report 8598, "Orbit Dynamics in the Spiral-ridged Cyclotron", Lloyd Smith and Alper A. Garren (1-12-59).

[3] K. R. MacKenzie, Nucl. Instr. and Meth. 31, 139 (1964).

[4] J. D. Lawson, Nucl. Instr. and Meth. 34, 173 (1965).

[5] J. Rainwater, Rev. Sci. Instr. 37, 262 (1966).

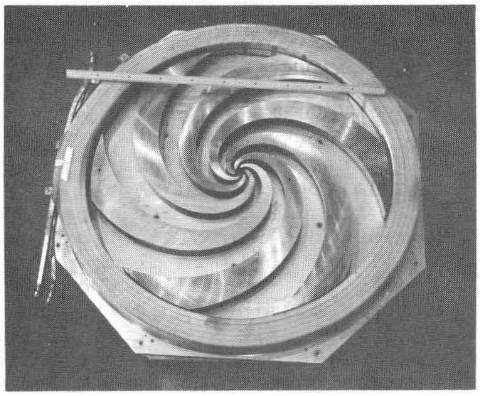

Fig. 1 First Trial Spiral Shims

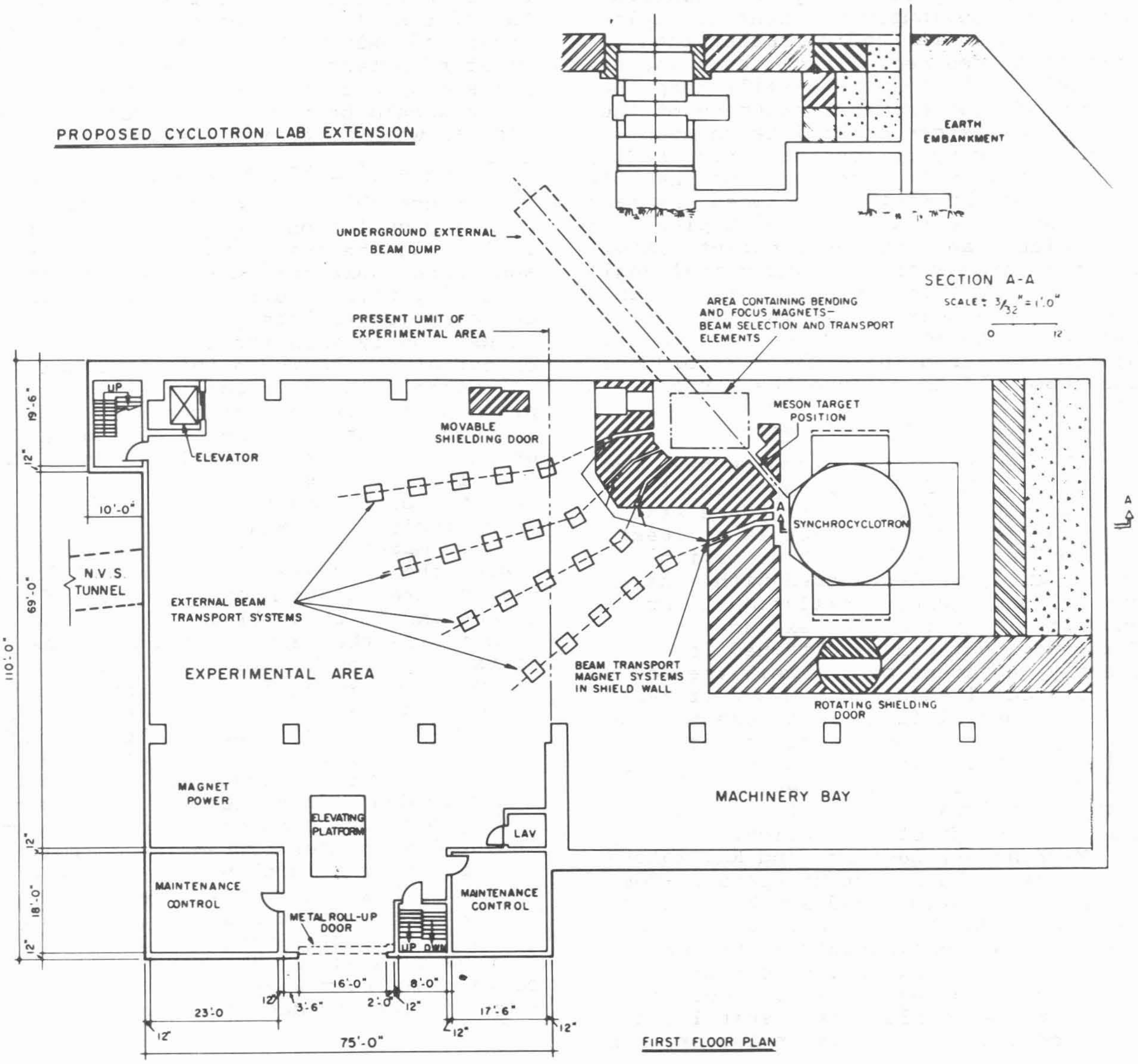

Fig. 2 Cyclotron Building and New Extension

DISCUSSION

RICHARDSON: Do you traverse the $\nu_r = 4/3$ resonance?

COHEN: We hope not to.

BLOSSER: Your slide of the pole tips struck me with how tight the spiral is. How large are your radial stability limits?

COHEN: We expect it to be reasonably good. Dr. Ohnuma is working these out. From his preliminary investigations we find no trouble.

WRIGHT: How much beam can you afford to lose internally, without getting the machine overly radioactive?

COHEN: We have had a lot of experience with this. Our present beam is about 1 μA; we are able to operate quite comfortably with it. With just a week-end shutdown we can do major repairs inside the chamber. We have a lot of carbon and marble on the iron, and we feel we can lose up to 10 μA in the chamber, if we are clever enough in being able to design remote control equipment to do anything we have to do in the chamber, and if we are able to line the chamber itself with enough marble. I would say about 10 μA.