NEVIS SYNCHROCYCLOTRON IMPROVEMENT PROGRAM[1]

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Introduction

The Columbia University "Nevis Laboratories" Synchrocyclotron has been in operation since 1950. The research program has fully and effectively utilized this facility for pion, muon, and neutron research during this period. Only internal proton beams of ~1 μA at 385 MeV have been used on internal targets to produce the secondary beams of interest. We have been increasingly aware that its time of obsolescence is approaching unless major improvements are made in the machine effectiveness.

About 1964[2] we began to make a serious study of the feasibility of a major improvement program. To keep costs down, it was decided that we should attempt to retain the major parts of our present magnet and building, instead of requesting financing to start over with an entirely different machine and building complex. By January 1966 the major outlines of the plans had been established as described in a report by J. Rainwater.[3] The plan is to use iron spiral ridges to produce an azimuthally varying magnetic field, keeping the present cyclotron yoke and excitation coils. The azimuthal average field <B(r)> is to increase by ~ 20% from center to ~ 80 in. (~ 2 m) radius. This is much less than for full isochronism, but enough to reduce considerably the rf frequency swing required. It also seems to be capable of yielding a value of (<B>r) corresponding to ~ 500 to 600 MeV proton energy at a radius ~ 2 m where $\nu_r \sim 1$ and <B> ~ 19 to 20.5 kG.

During the past year we have mainly concentrated on model magnet studies of numerous spiral ridge iron configurations in an attempt to produce a median plane Nfold symmetrical magnetic field configuration corresponding to a suitably shaped <B(r)> , ν_z , and ν_r vs r . While a final configuration has not yet been achieved, results to date have shown that such a configuration giving 500 to 600 MeV protons is quite feasible. Some of the measured results are close to the form which we have tried to match.

Space Charge Considerations

The pioneering work of MacKenzie[4] showed that the beam currents achieved in synchrocyclotrons are essentially those expected from space charge considerations near r = 0 to 10 cm. Further theoretical analyses[3] support this conclusion and this aspect of the problem has dominated our thinking since early 1965. The result is that the synchrocyclotron space charge controlled current limit should be proportional to the vertical focusing strength ν_z^2 near the center as one factor. The magnetic focusing is proportional to -(r/B)(dB/dr) for an azimuthally symmetrical magnetic field, so ν_z^2 is quite small for r < 10 cm. We plan to use a 1- to 2-in. (2.5 to 5-cm) median plane spacing between the spiral ridge iron for r ~ 1 cm to 50 cm to achieve $\nu_z^2 \sim 0.05$ to 0.10 starting at a few cm radius. The iron at the azimuth of the dee would be supported on alumina insulators and be enclosed within the dee skin at rf potential.

Since the time average current should also have somewhat stronger than linear dependence on the dee voltage (and proportional FM repetition rate), we plan to raise both ~ five times above their present values to ~ 300/sec and 50 kV. The increasing <B(r)> vs r implies a much reduced rf frequency modulation swing which is comparable to that now used for existing lower energy (<200 MeV) synchrocyclotrons which presently operate at similar or greater repetition rates than our planned value. The use of ~ 50 kV peak dee voltage will permit an arc source and central region geometry similar to those for isochronous cyclotrons, but with much stronger magnetic vertical focusing at small r. The space charge current limit is expected to be >> 10 μA.

Magnet Studies (One-Fifth Scale)

Our model magnet studies assume that we shall use the present magnet excitation coils, plus new "inside the vacuum chamber" auxiliary coils similar to those used with the Berkeley 184-in. cyclotron for the past decade. A basic 170-in. (432-cm) pole diameter and ~ 35-in. (90-cm) pole tip spacing is planned, with spiral ridge hill shims plus 360° iron shims to produce a suitable B(r,θ). A maximum $\nu_r \sim 1.15$ is expected, decreasing to $\nu_r \sim 1$ at extraction. The one-fifth scale model studies have ruled out N = 6 as unable to achieve sufficient field flutter and ν_z^2 . Our subsequent studies have been for N = 4, but N = 3 is not excluded from consideration.

Present thinking favors the use of radial shims (no spiral) for about the first one-third of the radius, followed by an increasing spiral angle with $\tan\gamma \lesssim 2$ at large radii. The required magnetic field flutter $F \sim 0.2$ over most of the region will be produced by "floating iron" spiral hill shims of $\sim$ 5 to 7 in. thickness and vertical separation about the median plane, followed vertically by $\sim$ 4-in. (10-cm) rf gap, in turn followed by a combination of spiral ridge and 360° pole tip iron shims.

We have a priori selected approximate values for the desired shape of $\langle B(r)\rangle$ vs r (and thus $d\langle B\rangle/dr$), $\tan\gamma$ vs r and ν_z^2 vs r . We have as variable parameters the azimuthal angle $\varphi_1(r)$ subtended by the "floating" spiral ridge hill iron shims, the thickness vs r of the 360° pole tip iron shims, and the thickness and angular extent $\varphi_2(r)$ of the pole tip spiral ridge iron (hill) shims. The values of the "floating" spiral ridge iron spacing, their thickness, and their spacing from the iron mounted to the pole tips are only adjustable to a limited extent due to considerations associated with the rf system and the installation and servicing of the hill iron support insulators.

The fraction of the volume between the pole tips occupied by iron must increase monotonically from r = 0 to 85 in. to have $\langle B(r)\rangle$ increase with r in the presence of a normal strong tendency for B to sag at larger r (near the edge). A relatively high field flutter F is obtained by accomplishing this rise in $\langle B\rangle$ by using a relatively large total iron ridge (hill) thickness and have $\varphi(r)$ increase strongly with r near the edge. Use of 360° pole tip or floating shims at larger r to accomplish this rise in $\langle B(r)\rangle$ would give smaller F values. A judicious combination of the two methods seems capable of simultaneously yielding proper $\langle B(r)\rangle$ vs r <u>and</u> F and $\tan\gamma$ vs r to maintain suitable values of ν_z^2 . For $\langle B(r)\rangle_{max}$ values in the neighborhood of 19 to 21 kG variations of shim geometry near the edge have shifted the r for $\langle B\rangle_{max}$ from $\sim$ 75 in. to 84 in. bracketing the a priori choice of 80 in.

Further Considerations

We expect to use the one-fifth scale magnet to produce an operating cyclotron to study central region problems. A one-tenth scale model magnet is nearly ready for use for continuing iron geometry studies when the one-fifth scale model becomes unavailable for that purpose. A modulated rf system for the central region studies has been built and tested. The model vacuum chamber and pumping system is finished and vacuum tested.

For the final full-scale cyclotron, the dee will consist mainly of the alumina supported iron ridge shims at the dee azimuth, with joining copper skins at rf and ground potential over the full dee region. For r < 75 cm the dee will subtend 180° (two of the N = 4 shim regions) to avoid beam orbit center walking when ν_r is very near 1. The orbit center displacement for a < 180° dee is proportional to $(\nu_r - 1)^{-1}$ times the radius gain per turn. Beyond $r \sim 75$ cm this should be small enough to permit a gradual reduction to $\sim$ 120° for the dee azimuthal extent. Where the dee boundary cuts the hill ridge spiral (in a near radial direction) a narrow vertical cut can be made (N = 4 symmetrically) in the floating ridge iron. Similarly, when the floating ridge iron central spacing increases from the 1- to 2-in. value at small r to the 5- to 7-in. spacing at larger r, the two region floating iron masses can be electrically separated, with the azimuthal extent of the central shim gradually reduced to zero, and that of the outer shim increased in a compensating fashion to maintain a smooth transition over the radial extent of the transition region.

The copper dee and ground skins are expected to be continued to a transmission line, rotating capacitor system of the $\lambda/4 - 3\lambda/4$ type used successfully on so many existing synchrocyclotrons (Berkeley, CERN, Chicago, Carnegie Tech, etc.) The detailed design for this should be straightforward and will be subcontracted to one of the industrial experts in this field if project support is obtained.

The beam extraction will occur where $\nu_r \approx 1$ where an unstable growth in the radial oscillation amplitude using a peeler regenerator can probably be accomplished with high efficiency ($\gtrsim$ 50%) and a long duty cycle. A detailed study of this aspect of the system can continue after most other aspects of the design must be "frozen". We expect to achieve a long duty factor 500 to 600 MeV external proton beam of 5 to 40 μA time average value. The extraction at $\nu_r = 1$ should be easier than for ordinary synchrocyclotrons ($\nu_r < \sim 0.9$) or high energy isochronous cyclotrons ($\nu_r > 1$). The freedom from the isochronism requirement is expected to simplify greatly many aspects of the design and permit a much higher proton energy, for the given magnet size, than would otherwise be possible.

References

References

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[2] M. Bardon, Proceedings of the Conference on High Energy Cyclotron Improvement, College of William and Mary, Williamsburg, Va., February 6-8, 1964, pp. 138-142.

[3] J. Rainwater, "Modification Program for the Nevis Synchrocyclotron", Nevis Report 144, Columbia University preprint (1966).
See also J. Rainwater, Rev.Sci.Instr.37 262-267 (1966).

[4] K. R. MacKenzie, Nucl.Instr.Methods 31 139 (1964).