The status of the Columbia University Nevis Synchrocyclotron modification program is presented. The machine will be converted to a three-fold symmetry spiral sector focussing AVF synchrocyclotron, having a long duty factor 550 MeV external proton beam. The time average external beam intensity is expected to be between 5 μA and 40 μA. The reasons leading to the particular approach of this conversion program are given.

I. Status of the Conversion Project

The Columbia University Nevis Synchrocyclotron Conversion program is now reaching the stage where orders for the major components are being placed. The conversion will change the machine, which now produces - 2 μA time average internal beam of 380 MeV protons, to a 550 MeV machine having a long duty factor (5 to 40 μA time average) external beam facility. The building extension was finished last year.

The plans call for retention of the basic 2,000 ton steel magnet and the present main current excitation coils. Pole iron within 30 in. of the median plane will be replaced by new iron which will provide a 3-fold symmetrical azimuthally varying field (AVF) for the beam. The system will remain a synchrocyclotron rather than become a fixed frequency (RF) machine. The azimuthal average magnetic field \(<B>\) will increase from \(\sim 17\) kG near the center to \(\sim 20\) kG near 80 in. radius. This implies an FM frequency range from \(\sim 26.5\) MHz to \(\sim 18.5\) MHz for the additional field excitation will be provided by the addition of new "auxiliary" magnet coils between the main coils and outside the 170-in. pole diameter. These coils will carry about half as many ampere turns excitation as the main coils. Due to their position, these coils will be much more effective, per ampere turn, than the main coils in producing a high magnetic field at large radius.

The original plans envisaged mounting the auxiliary coils in vacuum inside the new larger cyclotron vacuum chamber. We have, however, arrived at a chamber design which has donut shaped recesses, top and bottom, on the outside of the chamber so the coils will be topologically outside (Fig. 1). The detailed chamber design has been completed, with help from W. M. Brobeck Associates. It is ready to be sent out for bids. The auxiliary coils were ordered last year.

We will operate at higher total yoke flux and will add a 10-in. thick steel band around the outside perimeter of the magnet yoke to lower its magnetic reluctance. This band of iron was also ordered last year.

The azimuthal field variation will be produced using spiral ridge sector iron having three-fold symmetry. We can control the shape of the \(<B>\) vs \(r\) curve by varying the azimuthal extent of the spiral hill iron, and by using a radial variation of the pole face gap. It changes from a 44 in. gap near the center to a 16 in. gap from 80 to 85 in. radius. Since one of our objectives is to achieve strong magnetic axial focussing starting at \(r < 2\) in., we shall have a small median plane gap between top and bottom sector iron pieces. The gap spacing will be 1 in. near the center (\(r < 1\) in.) and increase to a few inches at larger radii. This does not leave space for an accelerating dee electrode between the sector hill iron (Fig. 1). We will, therefore, divide the top and bottom sector iron each into two parts. One lies within about 7 in. of the median plane, and the other part is further than 10 in. from the median plane. The pieces within 7 in. of the median plane are called "floating shims." One of the three sets of floating shims will be mounted on ceramic insulators and will form part of the RF dee structure. The three-inch gap regions from 7 to 10 in. from the median plane will represent the "dee to ground" RF drop for the hill part of the dee structure in Fig. 1.

The dee structure will subtend 180° azimuth at small radius, decreasing to about 120° azimuth near the 85 in. radius. It will clear the other two hill iron sectors which will be at RF ground potential. The 3 in. gap regions of the
other two sectors (between 7 and 10 in. from the median plane) will be used for sector current coils to correct for any residual \( \cos \theta \) or \( \sin \theta \) type error field. Details of the RF system are given in an accompanying paper.

A major problem in the mechanical design was the need for the ceramic insulators which support the massive floating sector iron at RF potential. A major part of our effort has been devoted to these insulators. Early tests showed that \( Al_2O_3 \) insulators could not be relied on to carry intermittent heavy loads under tension, but they can carry over 100,000 psi in compression. The high purity \( Al_2O_3 \) and BeO insulators have RF loss \( \tan \delta \sim 0.0001 \) near room temperature, but their loss factors increase rapidly with temperature. Since significant RF power is dissipated in the ceramic bodies, it is essential that the insulators have effective cooling to keep them near room temperature and avoid a "run away" loss-heating situation leading to insulator failure. We have favored the use of high purity BeO because of its high thermal conductivity near room temperature (slightly better than aluminum metal). Because of the high beam currents and radiation levels, it is essential that all designs be reliable enough to keep the need for servicing to an absolute minimum. In any event, quick remote handling replacement methods will be required.

Recently we have arrived at a superior solution to the RF support insulator cooling problem. We intend to use a hollow cylinder insulator design which has vacuum tight end pieces of metal sheet brazed to the metalized insulator ends. We shall then circulate Freon C51-12 dielectric coolant fluid through the insulators. Tests under more severe RF field conditions than we will use have shown that satisfactory results can be obtained. This is described in more detail in an accompanying paper.

The main vertical magnetic forces on the floating sector iron pieces have been balanced by using a rigid "tuning fork" metal structure connecting the top and bottom floating iron pieces beyond the 85 in. radius. This is illustrated in Figs. 1 and 2, which are suggestive rather than final scale drawings. The main support insulators, under compressive loads only, are beyond the 85 in. radius and act on the massive metal structure. Our central region studies indicate that the first ion orbit turn, for \( > 30 \) kV RF on the dee, will have a 1 in. diameter. We will therefore, probably use a non-iron brace to resist the magnetic forces which tend to close the 1 in. gap. The brace structure through the median plane would be inside the first orbit. The ion source would be positioned in the valley region at a small radius. We expect to pulse it to a value between + 5 kV and + 20 kV during injection.

The rotating capacitor and RF drive system are discussed in detail in an accompanying paper. We expect to operate using a \( \sim 300 \) Hz repetition rate with the RF off for \( \sim 60\% \) of each FM cycle. During this time the long duty factor beam extraction occurs. The details of the extraction system planning are presented in an accompanying paper.

II. Theoretical Considerations for our Conversion Approach

It may be noted that our choice of a conversion to an AVF synchrocyclotron is unique to our program. Conversion plans for the CERN and Berkeley synchrocyclotrons envisage retention of their magnets with no magnetic field changes. Those involved in AVF isochronous cyclotron design tend to regard any other approach as some kind of blasphemy. We shall attempt to indicate the logical considerations which have led to our choice, and discuss developments from our studies which relate to its feasibility.

The discussion should be related to the orbit theory in an AVF situation. The Smith-Garren formulas\(^1\) provide relatively precise expressions for the vertical (axial) focussing terms \( v_z \) and the radial oscillation frequency \( v_r \). The radial orbit precession frequency is \( v_{prec} = v_r - \frac{1}{2} \). For three-fold symmetry, the main terms in the Smith-Garren equation can be written

\[
v_z^2 = -k + P^2(1.111 + 2.111 \tan^2 \gamma) + 0.1234(rP')^2 + 0.1111(rP'')^2 + 0.125(rP')^2 + 0.125(rP'')^2 \tag{1}
\]

\[
v_r^2 = (1 + k) + 0.675 P^2(1 + \tan^2 \gamma) + 0.2(rP')^2 + 0.925 rP' + 0.125 r^2P'' \tag{2}
\]

where \( k = \langle \overline{rB} \rangle / \langle \overline{B} \rangle \), \( d = \overline{B} / r \),

\[
r = \left( \overline{d \overline{B}^2} \right)^{1/2} / \langle \overline{B} \rangle^2 \tan \gamma = r \left( d \overline{B}^2 / \langle d \overline{B}^2 \rangle \right) / \langle B \rangle^2
\]

The primes represent derivatives with respect to \( r \), and \( \langle \cdot \rangle \) is the magnetic field azimuthal spiral angle. The \( \langle \cdot \rangle \) imply an azimuthal average.

For an isochronous machine, \( \langle \overline{B} \rangle \) must be proportional to the total proton...
energy. For a 550 MeV proton machine, \( \langle B \rangle \) would increase by the factor \((1490/940)\) from injection to full energy. In this case k becomes large and positive. It contributes a strong axially defocusing term which must be more than counteracted by the subsequent focusing terms involving the field flutter factor F and its derivatives. In practice, such a design for our magnet diameter would require very large F values and as a consequence, a much lower \( \langle B \rangle \) at full energy would result. An attempt to achieve full isochronism with our magnet would probably yield about half the 550 MeV energy which we shall obtain. It would be much more meaningful to start over, with an order of magnitude more expensive "Meson Factory" program implied.

The CERN and Berkeley synchrocyclotrons produce 600 MeV and 750 MeV protons respectively. These energies are in the region of efficient and practical magnet production towards which we strive. Since our plan includes an increase of energy from 380 MeV to 550 MeV, we must alter our magnet. In the process, it is worthwhile to avail ourselves of the benefits achieved by the use of AVF.

An ordinary synchrocyclotron is a very "weak focusing" machine. For an azimuthally symmetrical magnetic field, \( v_2 = -k \) and \( v_2 = (1+k) \). A gradual monotonic decrease in B vs r introduces weak axial focusing (\( v_2 \) positive) and has \( v_r = 1 - v_2/2 \). The precession frequency \( v_{\text{pre}} \) usually varies slowly and monotonically over most of the radial region. The space charge beam current limit is determined by the ability of axial focusing terms to counteract beam space charge axial repulsion. It tends to be proportional to \( v_2^2 \) at small radius and increases slowly and monotonically with generation frequency, and to some power of the dee RF voltage near injection. The precession frequency should be reasonably large to counteract the tendence of the orbit center to "walk" laterally, or to have a large growth in the radial oscillation amplitude due to "walking force effects". These include (a) residual imperfection cos \( \theta \) or sin \( \theta \) Fourier magnetic field components, (b) the unbalanced net impulse force when \( <B> \) vs r is used, and (c) the particularly undesirable resonance effects for a \( <B> \) vs r which is a low order multiple of the charge oscillation frequency. The slow continuous increase of \( v_{\text{pre}} \) for an azimuthally symmetric field makes ordinary synchrocyclotrons particularly vulnerable to this last effect.

The approach which we have adopted represents an attempt to utilize the strong focusing features of AVF, starting near the center, to (a) introduce and maintain strong vertical focusing to counteract space charge limit terms, (b) permit us to introduce a moderate increase in \( <B> \) at large radii while reducing the RF frequency range required. By limiting the value of field flutter required at large radius, we find that it is feasible to achieve \( <B> = 20 \text{ kG at 80-in. radius.} \)

The value of \( f^2 \) will probably be \( \geq 0.05 \) starting at \( r \) between 2 and 3 in. radius, to \( r = 70 \) in. radius. Recent studies using a 1 in. median plane gap spacing of the sector iron vs radius, including the starting radius for the sector iron, (d) the choice of the boundary division position for separating the sector iron into portions nearest to the median plane ("floating iron") and that mounted on the pole tips, (e) the choice of a gap vs radius between the pole 360° iron and the sector iron nearest to the 360° iron. (f) the choice of the azimuthal angle to be subtended by the sector iron vs radius, and (g) the spiral angle shape of the sector iron vs radius. For a machine with an azimuthally symmetrical field, only the parameters (a) and (b) are involved.

Most of our model studies have investigated the gross aspects of the variation of these parameters. We have, however, collected a considerable amount of model study results where factors (a) and (b) are in their essentially final form. We devoted considerable time to a study using a 1 in. median plane gap at small radii, and 6 in. gap at larger r. Figure 3 shows one of these studies. While we could probably achieve the desired \( <B> \) vs r and beam stability with the 6 in. basic gap at large r, the values of P and \( B_{\text{max}} \) (hill value) are lower than we would like. Recent studies using a 4 in. median plane sector iron gap at large r yield considerably larger P and \( B_{\text{max}} \) values at large r. We have even achieved \( <B> > 21 \text{ kG at 80 in. radius.} \)

By varying parameter (f) above we are rapidly approaching the desired \( <B> \) vs r,
Fig. 1 Side view of the iron configuration for the modified Nevis Synchrocyclotron (suggestive).

Fig. 2 Top view of the iron configuration for the modified Nevis Synchrocyclotron (suggestive).

Fig. 3 One set of field parameters giving stable orbits at all radii.
with indication that the other parameters will be satisfactory for beam stability and for beam extraction. We should soon be ready to purchase our final 360° sector iron. We plan to have the central region and one edge of the "floating" sector iron pieces removable to do a final "touch up" after installation in the main magnet before attempting operation. Model results should speed up this final touch up process.

An automated electrolytic tank has been used for central region electric field studies. We will also use our 1/5 scale model magnet as a working 34 in. pole diameter AVF cyclotron. It uses "floating" spiral ridge iron with three-fold symmetry having a 1 in. median plane gap, and ~ 1 3/8 in. RF gap between the sector iron and the flat 360° poles. The dee includes two of the three iron sectors at RF potential. We have a vacuum chamber and pumping system, an RF drive system, an ion source and various probes completed. Operation of this model, which will give >10 MeV proton energy, should begin soon. It will use ~20 kV dee voltage with very low duty factor pulsed RF operation to minimize radiation problems. It is expected to be a valuable testing device for ion sources and central region geometry studies. Figure 4 shows the initial orbits computed for this system using the tank study results and computer orbit calculations. The cases treated are for a range of gap crossing phases, which yield strong electric axial focussing for the first few turns. We expect to pulse the arc to a value between +5 kV and +20 kV during injection. Figure 4 shows the situation for +5 kV on the ion source.

Conclusion

Our time schedule calls for a test and "de-bugging" of our final RF system in our final chamber with final sector iron, etc., mounted in the chamber before stopping present operation for the change-over. The shutdown should come during 1970, and operation with the revised system should begin by late 1970, or during 1971. Since the present cyclotron is still running, and being fully utilized, we would like to have the shutdown for the conversion as short as possible.

References

3. J. D. Lawson, Nucl. Instr. and Meth. 34, 173 (1965).

Fig. 4a Computed initial orbits for the 34-in. cyclotron from measured electric and magnetic fields with a pulsed ion source.

Fig. 4b Range of axially focussing phases for successive gap crossings and centered orbits.