SECTORED CYCLOTRONS†

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Summary. Conventional fixed frequency cyclotrons evolved from the pioneering work of E. O. Lawrence and M. S. Livingston[1]; typical performance characteristics include fixed output energy, fixed e/m of the accelerated ions, energy less than 10 MeV/nucleon[2], poor beam quality and poor duty cycle. In recent years a series of new concepts have revolutionized the fixed frequency cyclotron. These new concepts include (a) sector focusing, (b) variable frequency rf systems, (c) resonant extraction, (d) programmed orbits, and (e) acceleration of negative ions. The resulting machines, referred to herein as "sectored" cyclotrons[3], have essentially ideal properties as compared with the classical cyclotron, i.e., variable energy, variable e/m, arbitrary final energy, good beam quality, and greatly improved duty cycle. The initial section of this paper reviews fundamentals of modern sectored cyclotrons with illustrative examples drawn from the present generation of such machines; the final section considers possible features and design problems of future machines of this type.

New Concepts

Sector Focusing

Conventional cyclotrons utilize axially symmetric magnetic fields and fixed frequency rf systems. At an early date Bethe and Rose[4] pointed out an essential incompatibility between these two features namely that an axially symmetric magnetic field must decrease with radius to provide axial focusing whereas, if particles are to remain synchronous with a fixed frequency accelerating voltage, such a magnetic field must increase with radius to compensate the relativistic mass increase of the accelerated particles. (This incompatibility follows directly from the fact that the axial focusing force in an axially symmetric field is derived entirely from the $v_\theta B_r$ term of the Lorentz force.) The difficulty can be relieved, as was first pointed out by L. H. Thomas[5], by introduction of azimuthal variations in the magnetic field, giving a median plane field of form:

$$B(r,\theta) = B_o(r)(1 + f(r)\cos N\theta) \qquad (1)$$

The functions $B_o(r)$ and $f(r)$ are referred to as the "average field" and "flutter" and N is the sector number.

Such azimuthal variations produce a "scalloping" of the particle orbits, the instantaneous radius of curvature increasing and decreasing as the particle moves from weak to strong field regions. The scalloped orbits have a radial component of velocity which oscillates with the same periodicity as the field; the product $v_r B_\theta$ is therefore of constant sign (since B_θ is of course also oscillatory with the periodicity of the field) and in the direction to provide focusing. Since the scalloping of the orbits and the strength of the B_θ field component are both directly proportional to the flutter amplitude, f, the resulting focusing force is proportional to f^2. If, in addition to the flutter, a "spiral" is introduced in the field, i.e.,

$$B(r,\theta) = B_o(r)[1 + f(r)\cos N(\theta - \zeta(r))] \qquad (2)$$

a further enhancement of the focusing results due to introduction of alternating gradient focusing thru the $v_\theta B_r$ term in the force.

Smooth Approximation. Focusing effects of both flutter and spiral are conveniently summarized in the "smooth approximation" equations[6] for the focusing frequencies, ν_r and ν_z, namely

$$\nu_z^2 = -k + \frac{1}{2} f^2 (1 + 2\tan^2\alpha) \qquad (3)$$

$$\nu_r^2 = 1 + k \qquad (4)$$

and for the rotational frequency

$$\omega_o = \text{const} \rightarrow \nu_r = \gamma = 1 + \frac{E}{E_o} \qquad (5)$$

where

$$k(r) = \frac{r}{\bar{B}}\frac{d\bar{B}}{dr}, \quad \tan\alpha = r\frac{d\zeta}{dr} \qquad (6)$$

Orbit Codes. The smooth approximation equations are in most cases not of sufficient accuracy to form the basis for a complete design. A variety of orbit integration routines have therefore been developed with varying degrees of sophistication and special features. When furnished with a field description such routines rigorously compute the various orbit properties of interest. The smooth approximation equations nevertheless, as a result of their simplicity, remain of great use to the designer and are customarily used both to obtain a starting point or initial configuration for a magnet study and to gauge the size of required field corrections as the study proceeds from cycle to cycle.

Azimuthal Waveform. Simple sinusoidal azimuthal dependence of the magnetic field such as indicated by Eqs. (1) and (2) is, of course, extremely difficult to obtain in an actual magnet, even in reasonable approximation. Great effort was expended on this problem in early model studies.[8] Designers have since realized that the specific azimuthal waveform is of minor importance and modern designs therefore revert to easily fabricable shapes for the azimuthal form of the pole tips. For such fields Eq. (3) is generally modified by replacing $1/2\ f^2$ by F where

$$F = \overline{(B(r,\theta) - \bar{B}(r))^2/\bar{B}(r)^2} \quad (7)$$

All averages are with respect to θ. For fields of form (1) and (2), $1/2\ f^2 = F$, as is easily verified.

Design Features. Sectored cyclotrons are customarily subgrouped into spiral-sector and radial-sector categories. As can be seen from Eq. (3), introduction of spiral gives a reduced flutter factor for given k and ν_z^2; hence machines with spiral sectors will have shallower valleys and a consequent economic advantage (since shallower valleys give smaller average magnet gap and therefore reduced ampere turns). Advocates of radial sectors, on the other hand, point out that the actual dollar savings resulting from use of spiral sectors is small compared to the cost of the cyclotron and the spiral sectors involve somewhat greater non-linear effects on the particle motion and consequent poorer beam quality. As a result of the offsetting advantages, spiral and radial sector designs are both widely used.

Figure 1 is a photograph of the pole tip configuration employed in the Berkeley 88" Cyclotron illustrating a typical spiral-sector design, while Fig. 2 shows the radial sector pole tip configuration for the M.S.U. cyclotron, the design being a refinement of a similar pole tip arrangement employed in the Oak Ridge Isochronous Cyclotron (ORIC). (As is seen in the figure the M.S.U. pole tips, as a fabricational convenience, have one straight edge and one curved edge and as a result, in a strict sense, are slightly spiraled. The spiral is, however, negligible with respect to other terms in Eq. (3) and the design is, therefore included in the radial-sector category.)

In a variable-energy cyclotron with fixed extraction radius the magnetic field must be adjusted in strength to match the momentum of the accelerated particle. Saturation effects leading to changes in the field shape are a troublesome problem and designers endeavor to minimize such effects to as great an extent as possible. The rounding and beveling of the pole edges seen in Figs. 1 and 2 and the patterns of holes (voids) in the valleys of the Berkeley magnet are all for the purpose of achieving a more constant flux density in the magnet, so as to minimize changes in field shape due to saturation.

A variable-energy and/or multi-particle cyclotron must include a network of correcting coils capable of shaping the average field in accord with the requirement of Eq. (5) for all particles and energies and also with provision for overriding any residual saturation shifts in field shape. The more refined the pole tip design, the less is the load placed on the corrective windings. Typically these windings take the form of a pancake of separately excited circular turns placed on the surface of the magnet pole tips. A variety of computer routines have been developed for computing ampere turns required in the various coils.[9,10]

Independent ν_z. One of the major advantages of the sectored cyclotron lies in the substantial decoupling of ν_z from B_o. From Eqs. (4) and (5) it is seen that the logarithmic derivative, k, must be positive in an isochronous machine and hence of wrong sign to provide z focusing. Furthermore, as implied above, if variable-energy or multi-particle operation is desired, k varies widely in magnitude. The flutter term in Eq. (3) is however essentially independent of B_o and hence if the field is designed to make the flutter term dominant, an approximately constant ν_z can be obtained—independent of energy or particle accelerated. Variable-energy, multi-particle cyclotrons can therefore be constructed without difficulties from either inadequate space charge limits or resonances which occur at low and high values of ν_z, respectively. Figure 3, as an example, shows computed ν_z curves for a variety of particles and energies in the M.S.U. cyclotron. All of the curves lie predominantly above $\nu_z = 0.15$, corresponding to a space charge limit of 1.4 ma. Except in the extraction region, which will be discussed later, ν_z is also well away from possible resonances.

Resonances. One of the most troublesome of the cyclotron designer's various headaches results from the occurrence of "resonances", i.e., regions in which the radial or axial focusing oscillation is synchronous with some component of the electric or magnetic field leading to coherent and large excitation of the focusing oscillation and to consequent loss of the beam. As is well known such resonances occur when

$$k\nu_r + \ell\nu_z = m \quad (8)$$

where k, ℓ, and m are integers. The resonances are most severe for small $|k| + |\ell|$ and when $m = pN$ where p is an integer and N the sector number. (Resonances with $|k| + |\ell| > 4$ are routinely neglected.) As indicated by Eq. (5) the radial focusing frequency in a cyclotron is determined by the requirement that the field be isochronous. In a fixed frequency machine this isochronism requirement is extremely stringent—a uniform field error of 1/4n where n is the total number of turns will shift the beam to decelerating rf phase. Since n is typically of order 250-500, deviations from isochronism of less than 0.1%-0.05% are implied. The radial focusing frequency is therefore effectively beyond the control of the designer (with the exception of minor changes obtained thru manipulation of the flutter gradient or carefully gauged deviations from isochronism). Thus, in marked contrast to the synchrotron, where the operating point can be carefully selected to be as far as possible from all resonances, the cyclotron designer is forced to live with a prescribed operating point which moreover starts exactly on an integral resonance ($\nu_r = 1$) and will often involve direct passage thru several major resonances ($\nu_r = 1$, $\nu_r = 2\nu_z$, $\nu_z = 1/2$, etc.). In a synchrotron such resonance transitions would be disastrous—in a cyclotron due to the much smaller number of turns, resonance transitions can be accomplished but at the expense of careful design study and careful field control. While the problem is of too complex a character to be treated in detail in a review paper, a partial insight into some of the complexities and problems can be inferred by reference to Fig. 4 which shows three "phase plots" of the radial motion in the M.S.U. cyclotron, the three plots differing only in the azimuth at which a 1% first harmonic field component is positioned. The general complexity of the phase plots, reflecting large non-linear terms, as well as the extreme sensitivity to the small first harmonic component, reflecting the necessary proximity of the operating point to $\nu_r = 1$, are both indicative of the sensitive problens which the designer must consider and handle.

The strength of various resonances is, of course, greatly influenced by both the number of sectors and by the amount of spiral in the field. Variations in these parameters from one design to another reflect both differences in boundary conditions, (resulting from different final energies) and differing opinions of designers as to the severity of particular resonances or as to the difficulty of achieving particular field tolerances.

Variable-Frequency Rf Systems.

In cyclotrons with fixed extraction radius the orbital frequency is directly determined by the final velocity of the ion. In variable-energy cyclotrons a frequency variation is therefore implied proportional to the square root of the energy (neglecting relativistic effects which are customarily small). For multi-particle operation, an additional variation in rotational frequency directly proportional to the range of e/m values results. Combining these two effects a variation in orbital frequency over a range of as much as ten to one is typically desired.

Harmonic Acceleration. Tunable high-power, high-Q rf systems pose an exceedingly complex design problem, the difficulty increasing rapidly the wider the tuning range. This range can be greatly reduced by use of harmonic acceleration, in which the rf operates at an integer multiple of the particle rotational frequency. Such acceleration, is obviously possible when the harmonic is an odd integer. In two dee cyclotrons, acceleration on even harmonics is also possible provided the dees subtend an angle of less than 180^o. (Also, for even harmonics the dees must be operated in push-push or in-phase mode.)

Depending on whether all harmonics or only odd harmonics are employed, an arbitrary range of rotational frequency can be continuously covered by an rf tuning range of 2:1 or 3:1, respectively. Acceleration on even harmonics makes the design of the cyclotron central region considerably more difficult; the 3:1 range, using odd harmonics only, is therefore the most common design choice. Techniques for covering the required tuning range with the accelerating cavity divide into two major classes known as "sliding short" and "moving panel" tuning, respectively.

Sliding Short. The accelerating structure in a cyclotron can be considered as a shorted transmission line with the dee as a capacitance at the open end; usually the systems are designed for operation in the quarter wavelength mode. The resonant frequency of such a system can obviously be varied by adjusting the length of the shorted line. While the technique is electrically straight forward, it involves the complex mechanical problem of loosening, moving, and retightening major rf joints each time the frequency is changed. Mechanisms for accomplishing this become quite complicated as can be seen in Fig. 5 which is a photograph of the movable shorting plane mechanism in the ORIC cyclotron.

Moving Panels. The resonant frequency of a capacitively loaded shorted line also varies if the characteristic impedance of the line is changed. Figure 6 is a view of the tuning panel arrangement on the Berkeley 88" Cyclotron which makes use of this principle, the panels moving close to or far away from the dee stem to obtain high and low frequencies, respectively. In such a system, breaking and reclamping of current carrying joints is avoided by the use of flexible foils at the hinge positions. Such systems have the disadvantage of relatively low Q at the high frequency position which is unfortunately also the position of maximum power dissipation.

Dee-in-Valley Designs. The cyclotron designer is in a continuous struggle to find room in the magnet gap for the innumerable objects which must go there. The valley regions, as a result of their larger magnet gap, are generally much less congested. Dee-in-valley designs, such as employed at U.C.L.A. and elsewhere, utilize this space by shaping of the accelerating structure so that it will fit into the valley areas. Such designs also permit large reductions of the magnet gap in the hill regions since the space usually alloted to dee insulation and dee structure can now be omitted; large reductions in excitation requirements therefore result with very substantial economic advantage as compared with conventional designs. Principle problems in this type of design result from basic incompatibilities in rf and magnet structure requirements on the valley shape. Figure 7 is a photograph of the dees and lower pole of the U.C.L.A. cyclotron.

Resonant Extraction.

As was indicated above, resonances have the effect of producing a coherent increase in the amplitude of the associated focusing oscillation. Such an increase in amplitude can be of tremendous assistance in accomplishing extraction of the beam as has been generally realized since the first such arrangements, known as regenerative extraction systems, were evolved by Tuck and Teng[11], and LeCouteur[12] for synchrocyclotrons. Resonant extraction is generally somewhat easier to accomplish in sectored-cyclotrons than in synchrocyclotrons since one of the naturally occurring resonances can be used rather than having to artificially construct a resonance.

In medium energy cyclotrons the $\nu_r = 1$ resonance is utilized for extraction. From Eq. (5) one sees that for machines of 100 MeV and down one is never far from this resonance and as the average field turns over at the edge, the operating point will quickly shift from the value indicated by Eq. (5) into a rapidly falling ν_r which quickly passes thru $\nu_r = 1$. The essential resonance at this point is either 3/3 or 4/4 for three and four sector machines, respectively. Since the resonance transition is very rapid, there is a marked tendency for the beam to pass thru the resonance without an appreciable disturbance if the essential resonance alone is relied upon to excite the oscillation. (Also if the 3/3 resonance is utilized alone the beam will in many circumstances split into three sub-beams, one emerging on each of the three sectors.) Addition of a small first harmonic to the field gives a superposition of the 1/1 resonance onto the 3/3 or 4/4, which both imparts a unique directional bias to the oscillation amplitude and makes the resonance arbitrarily strong. First harmonics of order 2 to 4 gauss will, for example, excite an amplitude of 5 to 10 millimeters. Such small first harmonics have essentially no effect on the orbits when ν_r is away from the resonant value; since ν_r is rapidly changing near the resonance the effect of the bump is therefore sharply localized regardless of its actual spatial extent.

Single Turn Extraction. The resonance functions only to produce a coherent oscillation where the coherence is in the sense that maximum amplitude will occur at specific phase, minimum amplitude at specific phase, etc. There remains the separate question of whether turn separation can be induced, i.e., whether one can achieve alternate current-carrying and current-free radial bands in the edge region of the magnetic field. If such bands can be induced, the septum of the extraction device can be placed in a current-free region; the beam will be extracted on a single turn with 100% efficiency and very low energy spread. From general arguments one concludes that separation of coordinates cannot be induced in systems with coordinates originally continuous—a discontinuity in one coordinate can, however, be translated into a discontinuity in some other coordinate, as occurs, for example, in analyzing magnet systems in which separation in the energy coordinate is transformed into a separation in spatial coordinates. Resonant extraction systems have very similar properties to magnetic analysis systems. The small-amplitude focusing frequency is determined only by the energy of the particles —when the energy reaches the $\nu_r = 1$ value, the focusing oscillation becomes coherent with the driving terms and the amplitude builds up. If particles in the cyclotron have a discreet energy spectrum, that is, if a plot of a number of particles with given energy vs. energy is a series of peaks rather than a continuum, the resonance will convert the discreet energy spectrum into a spatially separated series of groups all having the same energy. Therefore, the problem of achieving turn separation reverts to the question of whether a discreet energy spectrum can be achieved.

For a fixed initial starting phase the energy spectrum has the desired character (neglecting coupling effects) since the discreet accelerating gaps impart quantum-like jumps to the particle energy at each gap. On the other hand, if a distribution in rf phase is considered, the energy structure tends to wash out since the sinusoidal accelerating voltage gives a different acceleration to particles with different phase. In addition, fluctuations in the amplitude of the rf voltage or in the strength of the magnetic field contribute smearing effects which have much the same effect as a change in the initial phase. To achieve a discreet energy spectrum it is therefore necessary to (a) limit the distribution in phase of the accelerated beam, (b) properly stabilize the amplitude of the accelerating voltage and (c) properly stabilize the strength of the magnetic field. Each of the resulting tolerances is inversely proportional to the number of turns; single turn extraction is therefore markedly harder to achieve as the number of turns increases.

Since the separated turns each correspond to a distinct energy group, single turn systems have the important advantage of greatly reducing the energy spread in the beam as it leaves the cyclotron; in fact, the necessary condition to achieve good turn separation is that the energy spread in a given turn group must be less than approximately 1/4 of the energy gain per turn, which, for a cyclotron of 250 turns, gives a spread in energy of less than one part per thousand.

At the time of writing, single turn extraction as contemplated herein has, to the author's knowledge, not been successfully accomplished. The orbit computations, which are of a rigorous nature, leave no doubt, of course, as to the basic validity of the mechanism. The question remaining is whether the requirements on field stability, voltage stability, and phase spread, presumed in the computations, can be experimentally achieved. Preliminary results from initial tests of the M.S.U. cyclotron indicate that the required criteria are satisfied; more definitive experimental studies are now in progress.

Statistical Extraction. At the opposite extreme from single turn systems, resonant extraction is employed (as in a synchrocyclotron regenerative systems) simply as a mechanism for enhancing the radius gain per turn. This, of course, gives an important improvement in extraction efficiency as compared with non-resonant systems since for given septum thickness increased radius gain per turn leads to a greater fraction of particles entering the channel. In such systems the energy spread is determined by the magnitude of the incoherent radial amplitude originally present in the beam.

Post-Resonance Acceleration. In machines with sufficiently large energy gain per turn, acceleration can be continued for a considerable number of turns beyond the $\nu_r = 1$ resonance before the particles finally slip out of phase with the rf voltage. During such acceleration the amplitude induced at $\nu_r = 1$ will undergo precessional oscillations just as in conventional cyclotrons and will periodically pass thru positions at which the radius gain per turn due to the oscillation adds coherently to the radius gain per turn due to energy gain. At any of these positions the septum and extractor can be inserted. Advantages of accelerating beyond the resonance are two-fold, namely, (1) a magnet of given size can produce particles of appreciably higher energy and (2) the extraction system, which carries the particles to the fringe field of the magnet, can have more relaxed parameters or, for fixed parameters, the beam will spend less time in the highly non-linear fringe field with consequent improvement in optical properties.

Axial Motion. As a result of basic features of the field shape, the $\nu_r = 2\nu_z$ resonance normally follows closely after $\nu_r = 1$. The effect of $\nu_r = 2\nu_z$ must be kept small since this resonance converts radial amplitude into axial amplitude and, due to spatial limitations, an increase in axial amplitude leads directly to beam loss. If post-acceleration is employed the beam passes directly thru this resonance—the radial amplitude must therefore be sufficiently small to avoid beam blowup in the transition. The amount of amplitude which can be tolerated will be larger the higher the accelerating voltage or the sharper the edge of the field, both of which enhance the speed with which the resonance is traversed. In the M.S.U. cyclotron, as an example, the voltage gain per turn is high but the field edge is not particularly sharp—the coupling resonance gives in this machine a limiting radial amplitude of order 4 to 6 millimeters. Such an amplitude is, of course, quite adequate to induce full turn separation at the septum entry.

When post-acceleration is not employed, the coupling resonance nevertheless places a limit on the amount of radial amplitude which can be induced, as a consequence of the fact that both ν_r and ν_z are amplitude dependent for large amplitudes, and shift to the resonant value for sufficiently large amplitude. In this circumstance amplitudes of 1 to 2 centimeters can normally be achieved before the resonance leads to instability. A system of this type is employed on the ORIC cyclotron; transmissions of up to 70% have been achieved.[13]

Extractor Hardware. Once the particles pass the septum and enter the extractor the hardware employed is strikingly similar to that used on conventional cyclotrons, i.e., customarily an electrostatic deflector gives the particles an initial outward impulse thru the fringe field—sometimes this electrostatic deflector is followed by a backup magnetic deflector inserted whenever sufficient turn separation is achieved. While considerable progress has been made as regards the detailed design of these components[14], they are not in principle different from the systems employed on conventional cyclotrons and will not be considered further here.

Programmed Orbits.

Orbit programming is an attempt to eliminate at the center of the cyclotron those particles which would ultimately strike the extraction device thereby reducing background radiation, residual activity, and power dissipation problems. While the concept of programming of orbits relates to single turn extraction systems, the concept can also be applied to statistical systems in which case in the following discussion attention would center on averages over rf phase rather than on individual orbits.

The extractor is, like any ion optical device, characterized by an admittance function specifying the combinations of initial coordinates (i.e., the volume in phase space) which gives orbits passing thru the extractor. With the aid of orbit integration programs this admittance function can be transformed backward thru the cyclotron (which is simply another ion optical device) to determine the admittance function at any previous point corresponding to transmission thru the extractor. "Orbit programming" then refers to sets of defining structures (usually placed on the first turn) which preferentially transmit the particles lying within the admittance function of the extractor and absorb those not in this area.

On the early turns, details of the electric field configuration are unfortunately of great importance and so more complicated codes and field measuring systems must be employed. In the extreme, the electric field is mapped in essentially the same detail as the magnetic field utilizing three dimensional electrolytic tanks.[15] The orbit integration routines are then furnished with maps of both fields.

As an illustration, Fig. 8 shows the arrangement of the central region of the M.S.U. cyclotron with superimposed orbit integration results showing the behavior of particles on the first turns. The various structures serve both to shield the orbits from undesired transverse electric fields and to absorb particles whose coordinates do not conform to the desired values. The orbit patterns obtained in initial operation of the cyclotron are in complete agreement with the calculated patterns.

Figure 8 also displays an important feature of central region design first introduced by Smith[16]; namely, an adjustment of the length of the first half turn to shift particles into an electrically focusing region of rf phase. (As can be quickly seen from inspection of the field lines, conventional accelerating gaps give a large focusing or defocusing impulse depending on whether the voltage is falling or rising—this phenomena is usually referred to as first order electric focusing.) In Fig. 7 the source and puller electrodes have been positioned to lengthen the first half turn as is necessary for operation in any odd harmonic to shift the particles to focusing phase. For operation on even harmonics, the first half turn must be shortened to shift particles to the focusing phase.

Phase Selection. Single turn extraction as indicated previously requires selection of a very narrow interval of rf phase,—for 200 turns this interval, for example, must be 7^o or less. Such a selection by means of radial slits is quite impractical since the energy gain varies as the cosine of the phase, and a shift of 7^o corresponds to an energy difference of no more than one in one thousand,—to make such a selection on a turn of 1" radius would require a source and selector slit each with aperture of order one mil, which would lead to vanishing small currents. Hagedoorn[17] has suggested the use of the axial motion to accomplish phase selection. The strong first order electric focusing varies as the sine of the rf phase and a difference of 7^o can make a large difference in the axial motion. Such a selection system is incorporated in the design of the M.S.U. cyclotron, the axial slit being positioned at the midpoint of the second turn.

As has been pointed out by Garren and Smith[18], the phase width of an internal beam can be quite accurately inferred by slightly detuning either field or frequency so that the beam slips out of phase before reaching full radius—the width of the radius interval over which the current changes from full beam to no beam, can, in conjunction with the results of orbit computations, be unfolded into a determination of the phase width. Studies of this type on the internal beam of the M.S.U. cyclotron verify that the desired phase spread of 7^o has been achieved.

Negative Ions.

The acceleration of H^- ions in a cyclotron, which had been considered by Wright,[19] was first successfully accomplished in 1962 by the group at the University of Colorado,[20] and since then has become an increasingly standard cyclotron technique. Acceleration of H^- ions has two major advantages; namely, (1) installation of a stripping foil in the path of the beam gives a trivially simple extraction system or (2) if the beam is extracted by conventional means, the jaws in downstream defining slits can be replaced by thin foils and therefore slit scattering can be effectively eliminated.

Stripping Extraction. Use of the stripping technique as the extraction mechanism has the important advantages of being in every situation a 100% efficient extraction mechanism—particles which miss the foil continue to circulate, eventually reaching the foil radius and are thereupon extracted. Such a system has the advantage of allowing external beam operation prior to installation of more complex and difficult conventional extraction systems (as is presently the situation at M.S.U.) and also, in contrast with systems based on the turn separation concept, permit extraction of internal beams occupying a broad range of rf phase which can be of great importance in many coincidence experiments where duty cycle is normally a limiting factor. As an example, with stripping extraction, microscopic duty cycles of as high as 30% can be routinely achieved and mechanisms have been proposed to extend this figure to 60% (The macroscopic duty cycle is, of course, always 100% in a sectored cyclotron.)

Thin Slit Experiments. The large range of medium energy protons makes design of conventional slits a very difficult problem and slit scattering an important limiting factor in most experiments. Protons at 55 MeV, for example, have a range of 1/8 inch in Tungsten which is the densest material readily available. If a slit of 1 mm aperture is desired, the thickness is already such as to make the structure more like a tunnel than a slit and hence with consequent large slit scattering. With a negative beam, extremely thin foils can be substituted for slits—particles passing thru the opening between foils remain negative, particles penetrating the foils are converted to positive and therefore at the next magnet the two groups are cleanly separated by bending in opposite directions. If a magnet is interposed between the final slit and the target, to image the slit on the target, the technique can be repetitively utilized thru the complete optical system from accelerator to target. (Reaction products will, of course, always be positively charged and a thick slit must, therefore, be used to define the acceptance angle of the reaction product analyzer. Kinematic situations, however, typically allow use of a larger aperture at this point which therefore again works to make slit scattering a negligible effect.) Such systems can be utilized as a mechanism for obtaining extremely high precisions out of relatively simple magnet systems merely by going to small slit openings. As an example, it has been estimated that the M.S.U. cyclotron can work at resolutions up to 1 in 10^4 in energy using slits of quarter millimeter aperture and still have counting rates of reasonable intensity.[21]

Future Sectored Cyclotrons

In the United States additional new sectored cyclotrons are in construction at the Naval Radiological Defense Laboratory, at the Naval Research Laboratory, at the University of California—Davis, at Texas A & M, and at the University of Maryland; a large number of projects (regretably too numerous to list) are also underway in other countries. Of the U.S. projects, the N.R.D.L. and Maryland machines involve new designs; the others listed are based on existing Berkeley and Oak Ridge designs with improvements. Due to the impetus of important problems in nuclear physics[22] a continuing trend to higher proton energies exists. The Maryland machine will be designed to achieve 100 MeV protons—preliminary consideration of machines of even higher proton energy is in progress at several institutions.

The trend to higher energies leads to severe design problems in a number of areas which will tend to lead to rather different design features than found in the past generation of sectored cyclotrons. Major problem areas and possible resulting design features are reviewed in following sections.

Energy Homogenity.

Many of the most interesting nuclear physics problems[22] in the energy range from 100 to 200 MeV require energy resolutions at least as good as the best expected in the present generation of machines. Single turn extraction systems offer the only real hope of achieving such resolutions with reasonable beam intensity. As indicated previously, the various tolerances which must be met to achieve such extraction are all inversely proportional to the number of turns and therefore in a higher energy machine one must either successfully work with tighter tolerances, i.e., better control circuits, or must achieve a higher energy gain per turn. The latter option immediately leads to difficult problems since the increase in dee capacity which results from the increased size of the machine, leads to lower Q cavaties and resulting severe economic problems such that even the matching of present dee voltages (typically 70 KV dee to ground) is a formidable problem. The most promising new approach appears to be a shift to 90° dees. Such a system will be employed in the cyclotron now in construction at Grenoble.[23] As compared with 180° dees, 90° dees give 0.7 of the energy gain per turn (on the first harmonic) but have only one half the capacity and hence approximately only one quarter the power requirement. In addition, 90° dees are naturally adapted for acceleration on even harmonics so that tuning ranges of greater than 2:1 are unnecessary to consider.

Gap Crossing Resonance.

An undesired increase in the amplitude of radial focusing oscillations can be induced as pointed out by Gordon[24] via a phenomenon known as the gap crossing resonance. This effect is the generalization of a phenomena well known in flat-field, 180° systems in which the orbit center executes a stepwise back and forth motion with a continual damping in amplitude. When one considers the general situation in which dee angles differ from 180° and azimuthal variations are added to the magnetic field, very drastic increases in amplitude can occur as a result of incompatibility between the basic symmetries of the magnet and accelerating structures. Each accelerating gap produces a stepwise change in the radial betatron amplitude. In the normal situation the effect of one gap tends to be cancelled by the effect of the next and so there is little accumulation in amplitude. With sector focusing, variations in the betatron form factor can greatly unbalance the effects of successive gaps if these gaps lie at different positions with respect to the sector structure of the magnet. In addition, since the particle angular velocity also has an oscillatory component resulting from the period of the sector structure a phase difference between successive gaps, will always be present. The effect is further compounded if dee angles other than 180° are considered since particles now do not enter and leave a dee at the peak of the voltage wave and therefore small variations in phase give large variations in energy gain per turn and hence in radial amplitude.

As an example, of the cumulative effect of all of these phenomena, orbit code studies for the M.S.U. cyclotron which has a three sector magnetic field and two 140° dees, indicate a radial amplitude of 1" for third harmonic particles starting on the equilibrium orbit in the intermediate radius region of the cyclotron and were it not for the very large stability limits in this cyclotron, third harmonic acceleration would not be possible. For 90° dees, the gap crossing resonance would be even more severe than the M.S.U. case and therefore on qualitative grounds one presumes that third harmonic acceleration in a three sector machine with 90° dees would be impractical. Therefore 90° dees and multi-particle operation will undoubtedly lead to four sector machines rather than the currently popular three.

Flutter Adjustment.

As seen from Eq. (3) the positive focusing contribution in a sectored cyclotron comes entirely from the flutter term. This focusing term must equal the sum of ν_z^2 and k. Since energy and k are related thru Eqs. (4) and (5), Eq. (3) can be used to determine the strength of the required focusing term for any desired value of ν_z. Figure 9 is a graph of the resulting focusing term vs. energy with curves for three different values of ν_z. In a multi-particle cyclotron the energy per nucleon will vary as the square of the variation in e/m; the envelope of operating points in such a cyclotron will therefore be essentially a horizontal line in a graph of the form of Fig. 9. One immediately sees that 110 MeV is the maximum energy in which a horizontal line can fit between the $\nu_z = 0$ and the $\nu_z = 1/2$ lines and a practical design must, of course, always allow some margin of error away from limiting values. Multi-particle machines in the 100 to 200 MeV region must therefore include either a means of adjusting the strength of the focusing term or must pass thru the $\nu_z = 1/2$ resonance. Adjustment of the focusing term is a major economic and engineering problem, since one is here required to change major features of the field, under the press of severe spatial limitations.

The alternate solution, passing $\nu_z = 1/2$, has not previously been seriously considered, primarily due to the fact that passage of this resonance was not a point of concern in machines built to date. In a recent theoretical study,[25] Gordon has derived expressions for the width of the stop band associated with $\nu_z = 1/2$, as follows:

$$(\nu_z^* - \tfrac{1}{2})^2 = (\nu_z^o - \tfrac{1}{2})^2 - \Delta^2 \qquad (9)$$

where

$$\Delta^2 = \frac{R^2}{4B_o^2}\left[\left(\frac{dh_1}{dr}\right)^2 + \left(\frac{dg_1}{dr}\right)^2\right]. \qquad (10)$$

ν_z^* and ν_z^o are the values of ν_z in the actual field and in a perfect field, respectively, and the functions h_1 and g_1 give the amplitude of cosine and sine components of the first harmonic field, i.e.,

$$b_1(r,\theta) = h_1(r)\cos\theta + g_1(r)\sin\theta. \qquad (11)$$

Equation 9, in conjunction with orbit code data on the rate of change of ν_z^o with energy, leads directly to a stopband width; a safe limit is obtained by requiring that this width be less than the energy gain per turn. Applying Eq. (9) and the above criterion to the M.S.U. cyclotron leads, for example, to a tolerance on the first harmonic gradient of approximately 30 gauss per inch which is two orders of magnitude larger than actual first harmonic gradients in the field— $\nu_z = 1/2$ should therefore be completely negligible in this cyclotron. (Experimental studies of this resonance are now in progress; for these studies the trimming coils in the cyclotron are readjusted to produce a transition thru $\nu_z = 1/2$. Results will be reported when available.)

Since the $\nu_z = 1/2$ field tolerance implied by Gordon's analysis is trivially easy to satisfy, multi-particle operation in the 100 to 200 MeV region will presumably be most economically achieved by going above $\nu_z = 1/2$ for low energy particles or heavy ions rather than by attempting flutter adjustment.

Conclusion

Design of the next generation of sector focused cyclotrons will not be routine—intricate and challanging problems must be faced and resolved. The impressive successes of the present generation of these machines, however, argues well for the future. Designers will undoubtedly press on with zest and enthusiasm.

Since sectored cyclotrons exist primarily for the purpose of doing nuclear physics research, it is appropriate to conclude by referring to Fig. 10 which shows a reaction products spectrum[26] taken with 12.5 KeV resolution at the University of Michigan cyclotron. This figure, more directly and succinctly than any other argument, evidences the outstanding success of the sectored cyclotron.

References

1. E. O. Lawrence and M. S. Livingston, Phys. Rev. 37, 1707 (1931).
2. The Oak Ridge 86" Cyclotron is a notable exception; by virture of an extremely high dee voltage this cyclotron achieves 23 MeV per nucleon. R. S. Livingston, Nature 170, 221 (1952).
3. These cyclotrons are also variously referred to as FFAG, AVF, Sector-Focusing, Spiral Ridge, etc.
4. H. A. Bethe and M. E. Rose, Phys. Rev. 52, 1254 (1937).
5. L. H. Thomas, Phys. Rev. 54, 580 (1938).
6. Symon, Kerst, Jones, Laslett, and Terwilliger, Phys. Rev. 103, 1837 (1956).
7. Arnette, Blosser, Gordon and Johnson, Nuc. Instr. and Meth. 18, 19, 343 (1962).
8. Kelly, Pyle, Thornton, Richardson and Wright, Rev. Sci. Instr. 27, 492 (1956).
9. Young, Kenney and Garren, Nucl. Instr. and Meth. 18, 19, 323 (1962).
10. N. F. Verster and H. L. Hagedoorn, Nuc. Instr. and Meth. 18, 19, 327 (1962).
11. J. C. Tuck and L. C. Teng, Phys. Rev. 81, 305 (1951).
12. K. J. LeCouteur, Proc. Roy. Soc. (London) B64, 1039 (1951).
13. W. R. Smith and W. H. White, Jr., (Private communication).
14. B. H. Smith and H. A. Grunder, CERN 63-19, 304 (1963); R. E. Berg and H. G. Blosser (Paper in these proceedings).
15. M. Reiser and J. Kopf, Rev. Sci. Instr. (To be published).
16. W. I. B. Smith, Nuc. Instr. and Meth. 9, 49 (1960).
17. H. L. Hagedoorn (Private communication).
18. A. A. Garren and L. Smith, CERN 63-19, 18 (1963).
19. B. T. Wright, Archiv. f. Math. Nat. B. Liv. Nr. 2 (1957).
20. M. E. Rickey and R. Smythe, Nuc. Instr. and Meth. 18, 19, 66 (1962).
21. H. G. Blosser and J. W. Butler, CERN 63-19, 138 (1963).
22. Holmgren et al., Proposal for an Intermediate Energy Nuc. Phys. Fac., Dept. of Physics, Univ. of Maryland (1963).
23. LeBoutet, Aucouturier, and Schnuriger, CERN 63-19, 262 (1963).
24. M. M. Gordon, Nuc. Instr. and Meth. 18, 19, 268 (1962).
25. M. M. Gordon (Private communication).
26. The author is indebted to Professor W. C. Parkinson for making this data available prior to publication.

† Work supported by National Science Foundation.

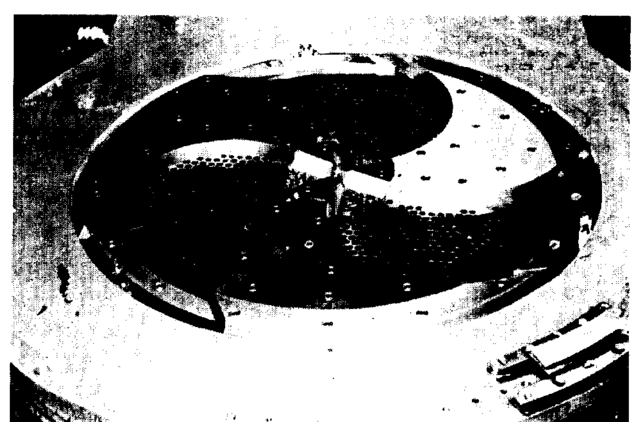

Fig. 1. View of lower half of model magnet for the Berkeley 88" Cyclotron showing typical spiral-sector design. Holes in magnet valleys assist in achieving a more uniform flux density throughout the magnet.

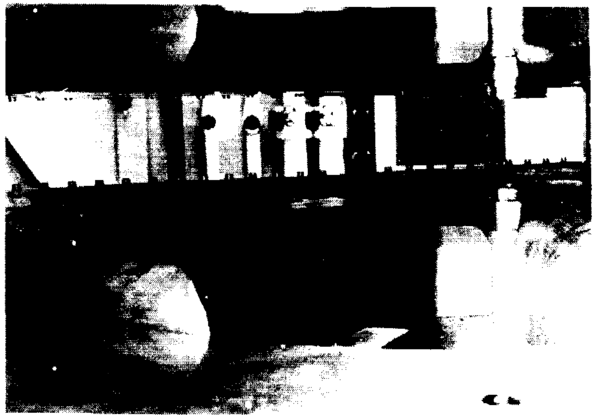

Fig. 2. View into the magnet gap of the M.S.U. cyclotron, showing deep valleys and rounded edges of the pole tips. Cylindrical plugs at the right (top and bottom) mark the center of the magnet.

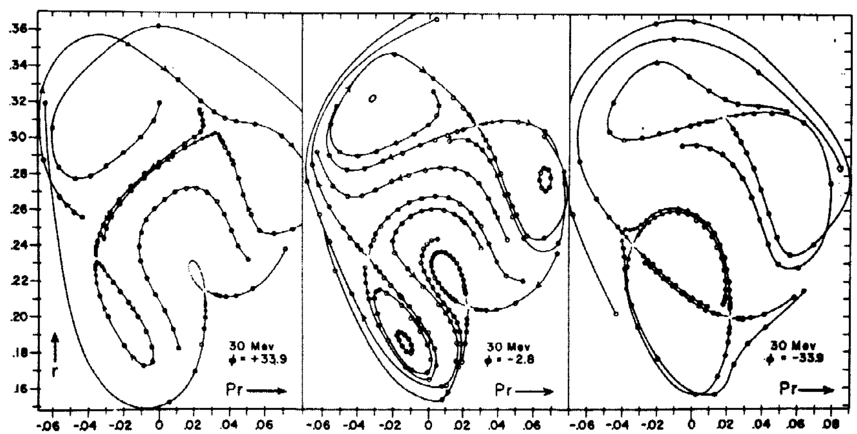

Fig. 4. Phase plots of radial motion in the M.S.U. cyclotron. ("Phase plots" are obtained by plotting radius against the radial component of momentum at a specified azimuth—points representing a given trajectory on successive revolutions are connected by lines with arrows to denote the sequence with which the points occur for an orbit integrated forward in time.) The three graphs are identical except that a 1% first harmonic field component is shifted in azimuth as indicated by the quantity, ϕ.

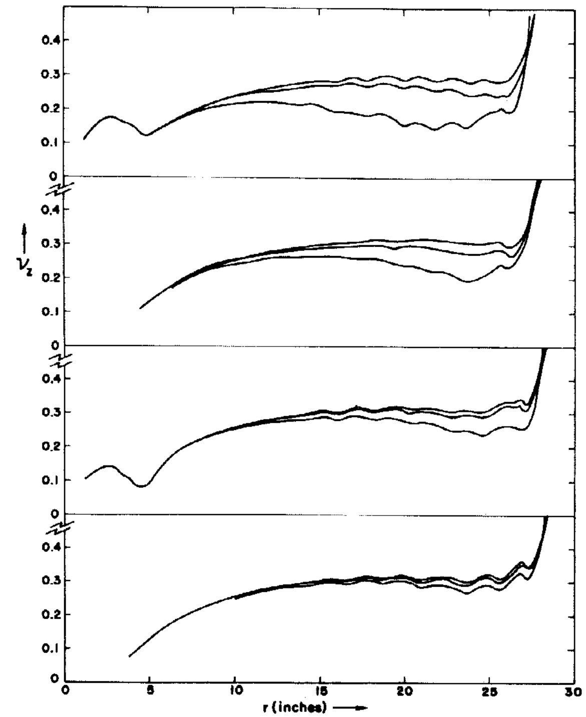

Fig. 3. Plots of ν_z vs. radius for the M.S.U. cyclotron. The four different ν_z scales correspond to four different excitations of the main magnet and cover the full range of field strengths. For each excitation of the main magnet three curves are given which, in ascending order, are for protons, deuterons, and heavy ions. Only two of the curves have been extended to small radii; other curves would be similar in this region.

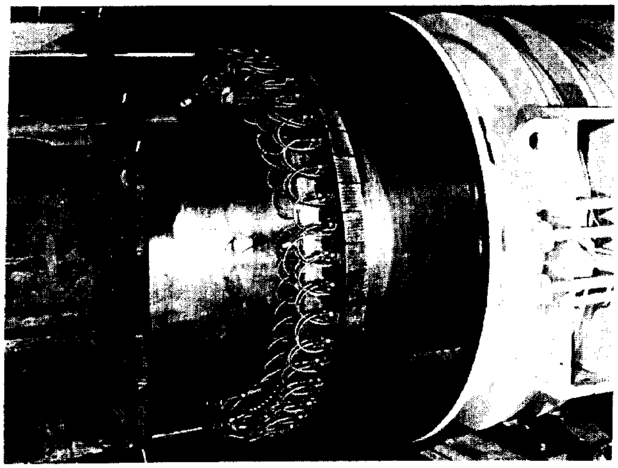

Fig. 5. View of the shorting plane being installed in the Oak Ridge Isochronous Cyclotron. The dee stem of this cyclotron is 50" in outside diameter while the outer tank is 75" in inside diameter. The shorting plane contains 48 pressure-actuated segments to achieve adequate clamping action for carrying the high rf currents.

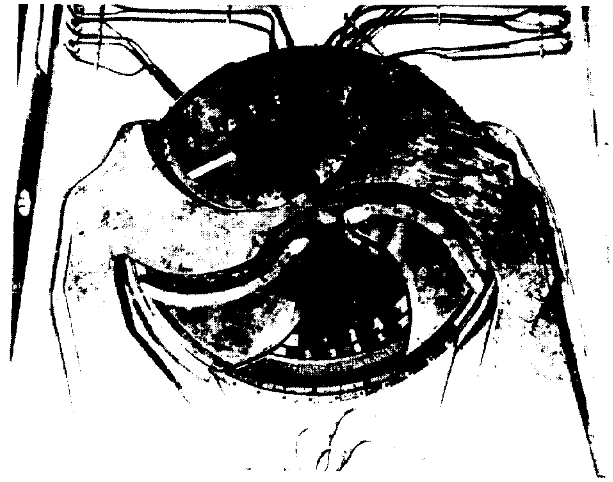

Fig. 7. View of the lower pole tip and dee assembly of the U.C.L.A. cyclotron. The dees, which have been figuratively described as "kissing sea horses", are at the right and left, respectively, of the cyclotron center. The four-sector pole-tip arrangement is also clearly visible.

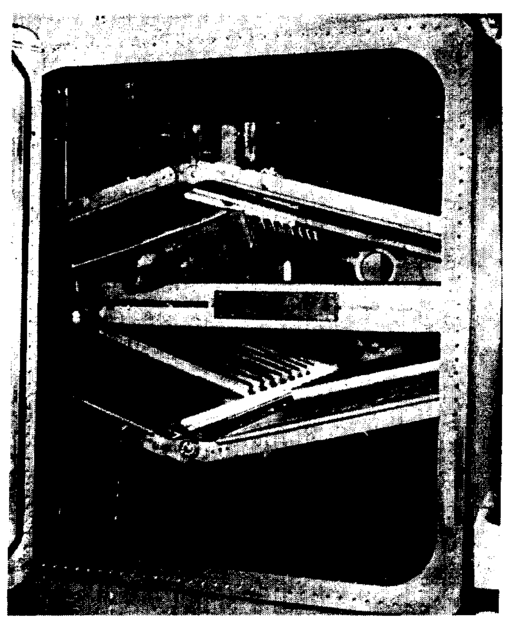

Fig. 6. View of the dee stem and tuning panel arrangement in the Berkeley 88" Cyclotron, the dee stem being the horizontal structure at the center of the picture. The panels move close to or away from the dee stem to achieve high and low frequency operation, respectively. Ridges on the panels mesh with mating ridges in the dee stem to give increased tuning range.

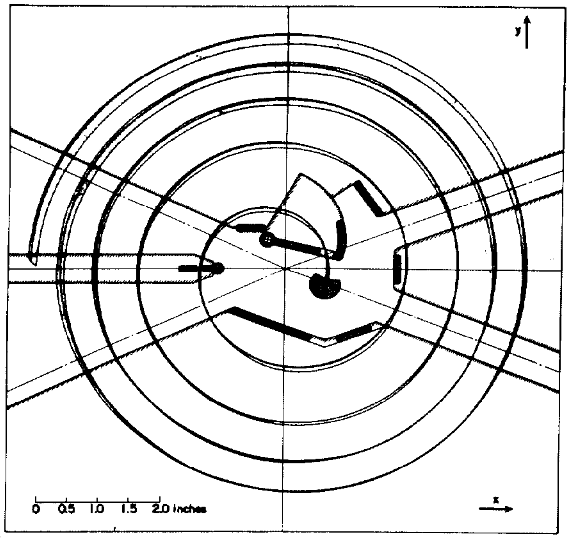

Fig. 8. Drawing of the central region of the M.S.U. cyclotron showing 140° dees (top and bottom), dummy dees (right and left), and slit structures (slant-hatched areas). Computer results for a family of orbits are also shown, orbits being obtained from integration of rigorous equations using detailed maps of both electric and magnetic fields.

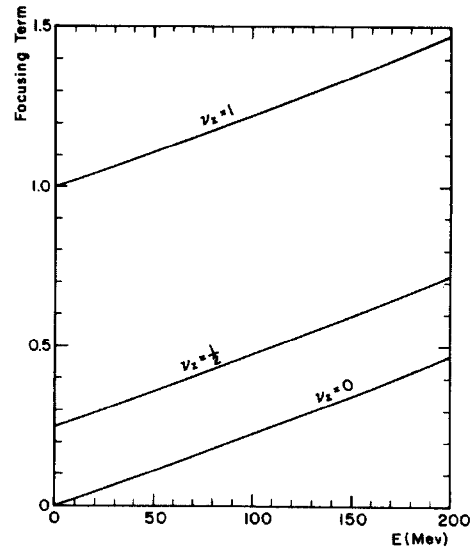

Fig. 9. Graph of the focusing term from Eq. (3) vs. energy for three values of ν_z, the focusing term being defined as the quantity $\nu_z^2 + k$, where k is presumed to have energy dependence as specified by Eqs. (4) and (5).

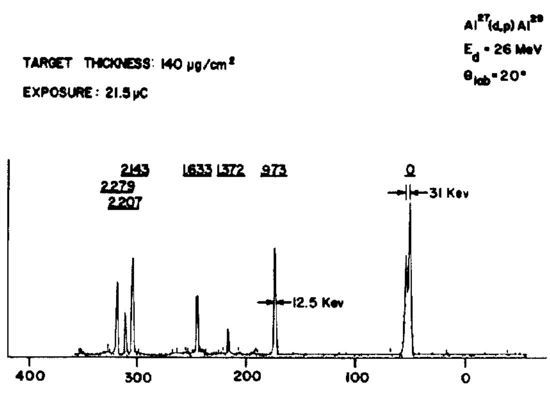

Fig. 10. Reaction product spectrum taken at 12.5 KeV resolution at the University of Michigan 83" Cyclotron. The cyclotron and related ion optical equipment will ultimately work at energy resolutions as high as one part in ten thousand.