FUTURE CYCLOTRONS*

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ABSTRACT

This paper reviews future trends in cyclotron design, first briefly from the point-of-view of cyclotrons now in construction and second from the point-of-view of design features. The topics covered include the choice of a conventional or separated-sector magnet, the use of dees or cavities for acceleration, possible flat-topping of the rf wave, the impact of new technologies on design and operation, and extensions of the cyclotron concept to higher energies.

INTRODUCTION

From the earliest times humans have derived pleasures from listening to the pronouncements of enlightened prophets regarding what lies ahead. The pleasant sensations are particularly keen and meaningful if the prophet is a person with convincing super-natural power. To be convincing it helps to refer to tangible evidence—tea leaves, lines in the hand, and crystal balls have been widely used. In addition the prophet enjoys an important credibility advantage if his view of the future is pleasant. In this paper I will employ these time-tested techniques. A proper substitute for tea leaves at a cyclotron conference is obviously to study the mystic patterns of orbitry from the great God DigiComptus. And in order to have an optimistic picture of the future I will specifically exclude all references to money, thus clearly leaving only pleasant things to consider. With these stipulations understood, let us go on to a happy hour of dreams.

Thinking of how to look at the future, two different, mutually interesting perspectives occur. One is to look from the point-of-view of projects—machines being built or proposed. The other is to look from the point-of-view of design features—what are likely to be the main features of new cyclotrons, how will they resemble present machines, how will they differ? Many other papers at this conference present material telling us about the future as seen from the project point-of-view; the main emphasis of this paper will therefore be on design features. To begin with though it is useful to take a brief look at projects since many of the things I want to consider in the discussion of design features have their origins in present projects.

PROJECTS IN PROGRESS

Isochronous cyclotrons with proton energy of 100 MeV or greater are listed in Table I. Four of these are nearing completion—one

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Table I: Major Cyclotrons 1972 (Proton Energy $\geq$ 100 MeV)

Laboratory	Proton Energy (MeV)	Features
Maryland Louvain	100	CSF design, conventional 4 sector magnet, two 86° dees, 1st, 2nd, and 3rd harmonic acceleration, multiparticle, variable energy.
Indiana	200	3 stage (2 cyclotrons and Cockcroft-Walton), 4 sector magnet, radial separated-sector design, two 36° dees, 4th-8th harmonic acceleration, multiparticle, variable energy.
TRIUMF	500	H^- acceleration, 6 sector moderate spiral magnet, axial injection, two 180° dees, 5th harmonic acceleration, variable energy.
SIN	585	2 stage, 8 sector magnet, moderately spiralled separated-sector design, cavity acceleration (4 gaps—2 MeV/turn), 6th harmonic, fixed energy.

is operating. These machines incorporate a broad spectrum of interesting design features.

The similar machines at Maryland[1] and Louvain[2] are good illustrations of what we now refer to as "conventional" isochronous cyclotrons. In such cyclotrons the pole tips mount from a single picture-frame yoke, the vacuum chamber spans the whole pancake-shaped region containing the orbits, and particles are accelerated from essentially zero velocity up to the maximum. A major virtue of this type of cyclotron is its striking compactness, particularly as compared with so-called open-sector designs such as employed at the Schweizerisches Institut fur Nuclearforschung (SIN) project[3] and the Indiana University project.[4] Other major advantages of the conventional approach are the simplified control system—one accelerator to control instead of several—and the proven technology—most design features have been employed in operating cyclotrons for many years and weak spots or problems have been ferreted out and eliminated.

At the opposite end of the compactness spectrum is the TRIUMF project[5] which most of us will be visiting during this conference. The fundamental premise of the TRIUMF design is to minimize the problem of extracting the high energy beam by accelerating negative ions and using stripping extraction. Additional bonuses of this approach are: 1) the energy can be varied with almost trival ease and 2) there is an easy capability for running multiple beams. The negative ions, however, force the machine to be very large since the magnetic field must be kept at levels low enough to avoid electric disassociation of the negative ion.

The SIN and Indiana projects, as already indicated, are of the "separated-sector" type, i.e. the magnet is composed of a set of individual magnets arranged in a ring with essentially field free regions between the magnets. The structure shows clearly in Fig. 1 which is a recent photograph of the SIN cyclotron. Both SIN and Indiana also use the two-stage approach, replacing the relatively unused central part of the large accelerator with a more compact injector stage. The SIN project in addition involves a novel acceleration system, namely a set of four large cavities operated in the transverse electric mode replacing the conventional dee structure. In tests, the SIN cavity system has performed exceptionally.[6] More than 600 kilovolts has been obtained in a single cavity which would give an energy gain per turn of about 2.5 MeV for the four cavity array which will be employed.

As each of these new projects comes into operation in the coming years the new features of the designs will be tested and debugged and in this process novel ideas will gradually change to proven technologies. But what about machines not yet started? Let us go on to consider what some of their major features might be.

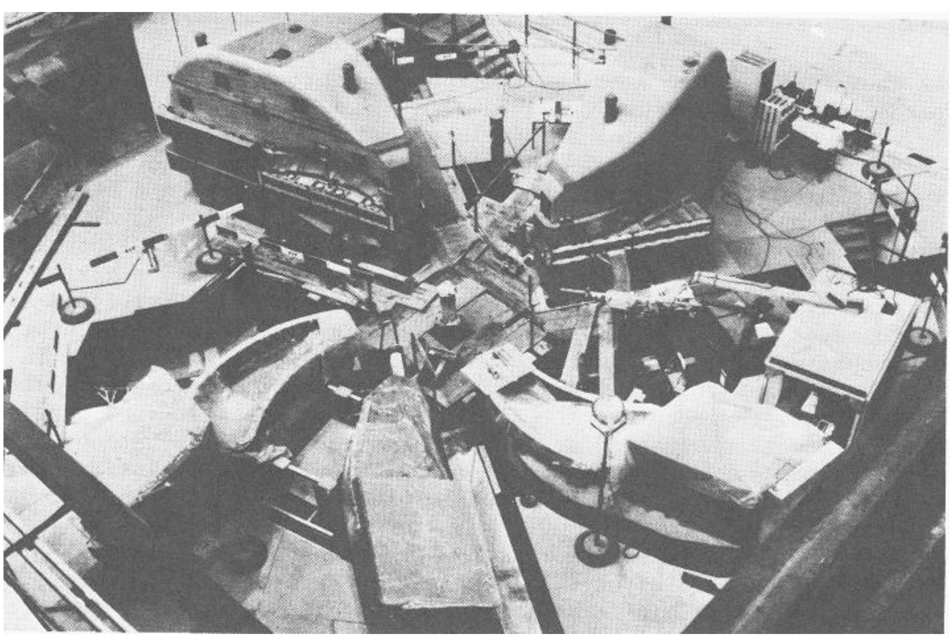

Figure 1 Photo of the separated-sector magnet of the 585 MeV SIN cyclotron in process of assembly.

MAGNETS—OPEN-SECTOR OR CONVENTIONAL

As has long been recognized, open-sector magnets become essential at very high proton energies in order to obtain the high flutter necessary to override the strong defocussing effect of an isochronous average field. The relevant factors are shown in Fig. 2 which graphs results from the smooth approximation equations:[7]

$$\nu_r = \sqrt{1+k}, \quad \nu_z^2 = -k + \frac{1}{2} f^2 (1+2\tan^2\alpha), \tag{1}$$

where

$$\nu_r = \omega_r/\omega_o, \quad \nu_z = \omega_z/\omega_o, \quad \omega_o = \frac{q\langle B\rangle}{m_o\gamma}, \quad k = \frac{r}{\langle B\rangle}\frac{d\langle B\rangle}{dr}, \quad \langle\ldots\rangle = \frac{1}{2\pi}\int_o^{2\pi} \ldots \, d\theta$$

$$B(r,\theta) = B_o(r)(1+f \sin N(\theta-\zeta(r))), \quad \tan\alpha = r\frac{d\zeta}{dr}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}. \tag{2}$$

From these equations it follows that ω_o=constant implies $k=(p/m_oc)^2 = (\beta\gamma)^2$ and hence if p/m_oc is large, $f \tan\alpha \simeq p/m_oc$. Thus at high energies the flutter amplitude times the tangent of the spiral angle must approximately equal the final momentum p/m_oc. Since very large spiral angles introduce delicate problems of linearity and stability, there is a strong impetus to make the flutter amplitude f as large as possible. Conventional magnets, even with very thick pole tips such as at MSU, seldom give flutter factors greater than 0.3. Open-sector magnets in contrast rather naturally give a flutter amplitude of around 1.0 for hills and valleys of equal width; if the valleys are widened relative to the hills the flutter amplitude increases proportionally so that in effect one can make the flutter as large as desired at the expense of increasing machine radius.

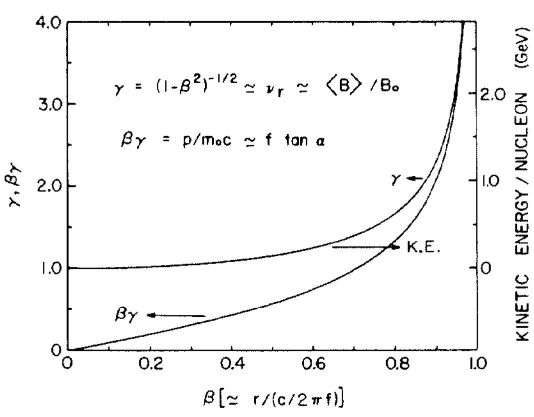

Fig. 2 Plot of γ and $\beta\gamma$ versus β. The γ curve shows the approximate radial variation of the magnetic field and the radial focusing frequency. Similarly the $\beta\gamma$ curve gives the approximate radial variation for the axial focusing term, $f \tan \alpha$.

At the opposite energy extreme—the low energy-per-nucleon limit—the conventional type magnet has many advantages. In this energy range there is no need for high flutter and the conventional yoke is a great asset in positioning pole tips to the accurate tolerances characteristic of isochronous cyclotrons. In addition one obtains a very compact accelerator; the MSU 50 MeV conventional type cyclotron is for example smaller than the Indiana 15 MeV separated-sector injector.

What is the energy where one should change from a conventional to an open-sector magnet? The answer, like most major design questions, involves complicated inter-relationships with project objectives and other design features. If, for example, project objectives are compatible with the selection of ions available from an internal ion source (or from low energy external sources), the conventional structure remains attractive up to rather high energies; in a separate paper at this conference[8] Gordon describes a design study for a 200 MeV conventional isochronous cyclotron using a magnet with a pole diameter of 123 inches. The proposed structure encompasses all of the classical virtues of conventional designs, namely, compactness, ease of control, and proven technology. The major missing feature of this design as compared with an open-sector cyclotron for the same purpose is reduced flexibility as regards acceleration of exotic heavy ions (W, Au, U, etc.). For such ions one gains greatly by using an intermediate stripping point to increase the charge, since the final energy will go as the square of the ion charge. With a two-stage accelerator it is natural to strip in the stage-to-stage transfer and with the stripper thus outside of both accelerators, exotic devices can be employed to deal with the subtle problem of constructing a stripping system which is both reliable and efficient. A further important advantage of the open-sector magnet concept is greater flexibility in the choice of accelerating systems as is discussed in the following section. It may be in fact that a special accelerating system is a great advantage in meeting design objectives in a particular situation and this system may require separated-sector magnets to be used at much lower energies than those where one would otherwise think of such a magnet structure.

An interesting independent thought on the matter of magnet design for a heavy ion accelerator was put forward by Wright,[9] namely to construct a two-stage accelerator using vertically displaced gaps in the same magnet structure. A beam is accelerated in a low charge state in one gap, extracted, stripped, reinjected at the appropriate smaller radius in the second gap, and again accelerated to full radius. With this idea the cost of the iron is reduced by nearly a factor of two as compared with two independent cyclotrons for the same function. Cost estimates for heavy ion cyclotrons usually indicate the iron to be the single most expensive item, amounting typically to about one-third of the total accelerator cost.

ACCELERATING SYSTEMS

Two major innovations in cyclotron accelerating systems are in process, one to substitute high-Q cavities for dees and the other the introduction of flat-topped rf waves. Both are old ideas.[10]

The major virtue of the cavity accelerating structure is higher voltage. Dee-type accelerating structures normally run at less than 100 kilovolts per gap; the 600 kilovolts obtained in the SIN cavity tests is therefore a 6-fold increase. The Q's of the cavities are moreover sufficiently higher than Q's of typical dees for this voltage to be obtained with about the same power input as a typical dee system. The SIN cavities as presently designed are for fixed frequency operation; arrangements for a variable frequency cavity are however conceptually clear. The top and bottom panels of the cavity would need to move up and down with some sturdy contact arrangement not unlike that found on present day sliding shorts.

Cavity type accelerating systems require separated-sector magnets and in many cases this is not the most attractive magnet design as was indicated in the previous section. Why select cavity acceleration if a more difficult magnet fabrication problem is involved? Equivalently, what are the advantages of high energy gain-per-turn? Perhaps the most important advantage comes from reduced space charge in the accelerator; if single turn extraction is desired or (at high energies) necessary, the so-called longitudinal space charge effect becomes the limiting factor on beam current. This phenomenon, which has been studied in detail by Gordon,[16] smears the energy spectrum of individual turns and at high currents this smearing is large enough to cause the energy spread of different turns to overlap making single turn extraction impossible. A high energy-gain-per-turn accelerating system hence opens the way to 100% extraction even with external beams in the milliamp range. A design of this type[11] is in fact in many ways the middle ground between the separated orbit cyclotron (SOC) concept of Russell[12] and the normal 10 to 20 microamp cyclotrons of today. Orbits would be sharply defined and separated in such a machine just as in a SOC but the magnet and vacuum chamber would be a continuous structure as in present cyclotrons. (Interest in milliamp beams is of course a strong function of the intended use of the cyclotron —the vast majority of nuclear physics experiments cannot handle currents beyond the 1 microamp range. On the other hand if secondary particles—neutrons, mesons, residual radioactive nuclei, etc.—are the primary interest then there is an immediate major benefit in higher current. The SIN project may well in fact be the first machine to move into this beam range using a second generation injector designed for 1 milliamp operation.)

The second main rf innovation, flat-topping, is an idea which appears to go back to the earliest days of cyclotrons. The concept was patented by Rossi in 1954[10] and in 1957 a mock-up rf system resonating at both first and third harmonic frequencies was constructed by Goodman.[13] In spite of these early efforts and in spite of a number of obvious advantages of flat-topping no operating cyclotron has yet utilized such a system. Why? One difficulty lies in the sensitive phasing requirement between harmonics[14] illustrated in Fig. 3. Unless the relative phase is maintained at just the right value the benefit of the flat-top is lost. Control techniques now appear, however, to have advanced to the point where this requirement can be met with appropriate careful work.[15] A second difficulty with flat-topping is that the requirements on the accuracy of the magnetic field increase by an order of magnitude. This comes from the fact that the beam phase group must stay in the flat-top region of rf phse throughout the acceleration. An ordinary sinusoidal wave in contrast allows cancelling of time spent on the leading side of the wave by shifting the beam for a corresponding time to the tailing side of the wave due to the effective linearity of the derivative of a sine wave over a wide phase region. (At MSU a quick technique for using this property of sine wave acceleration has been in use for many years; the beam itself is used to sense the cancellation between rising and falling sides of the wave and the optimum operating point is selected by minimizing the energy spread in the external beam.) With a flat-top on the other hand, the beam must be maintained at essentially zero phase throughout the acceleration process and a point by point presetting of the field or a point by point sensing and correcting of the phase is necessary. The array of trim coils for correcting the magnetic field must have a much greater capacity for making precisely detailed corrections and much greater control accuracy. A third problem in utilizing flat-topping comes from the gap-crossing resonance. If the third harmonic acceleration comes from an independent rf system with gaps at a different azimuthal location than the main gaps, a phase dependent disturbance of the radial betatron oscillation can easily result, depending on the detailed geometrical relationships of the betatron oscillation form

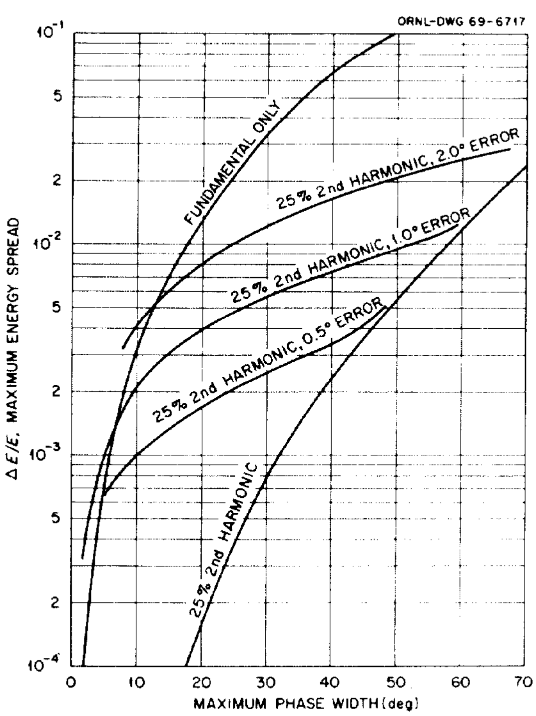

Figure 3 The energy deviation (E_{max}-E_{min})/$E_{av.}$ versus phase width for 25% second harmonic amplitude and several values of the phase error (referred to the fundamental). From Ref. 14.

factor and the two accelerating systems. For example, several years ago at MSU we did a design study of a system which included a third harmonic dee in the 40° dummy-dee region between our two 140° main dees. An extended series of computer studies soon made it clear that the gap-crossing resonance in this arrangement was so severe that the beam in all circumstances became radially unstable at the inner $\nu_r=1$ resonance transition, and spiralled out of the machine on a spurious orbit. A very attractive arrangement for circumventing this type of difficulty is planned at Indiana[4] where a second harmonic dee will mount inside the main dee and on the same center line. This arrangement also eases the difficulty of maintaining the correct phase between the two dees since the correct relative phase is 0° which is easier to actually determine than say a 60° or 90° phase displacement.

TECHNICAL FEATURES

The attention of cyclotron builders, or at least of the papers at a conference such as this, seems always to be dominantly focussed on the "big" picture—what kind of magnet, what kind of rf, how many stages, etc. Historically, however, it is clear that the success of a project depends at least as much on treatment of details as it does on the big picture and that through the years at least as much progress has come from technical improvements of details as from innovations in the structure of major components. Things such as reliable vacuum-tight welds in aluminum, the availability of epoxies for bonding and insulation, the introduction of hollow conductor, the series transistor regulator bank, and a host of other innovations have had enormous impact on the characteristics of modern cyclotrons. What does the future hold in terms of developments of this type?

An immediate first thought in this direction is superconductivity, a technology under intensive study by our linac and synchroton brethern. The virtues of using superconducting elements in cyclotrons are however much less clear than in either of these other applications. Synchroton interest in superconductivity for example is for the purpose of making the machine smaller since the size of the new large synchrotrons has reached the proportions of a critical problem. The size of cyclotrons is however much less of a problem and the virtues of making cyclotrons smaller are at best mixed. On the positive side there would be savings in building and shielding costs, both tending to go as the square of the size. On the other hand reducing the space available for the beam is a definite disadvantage—space charge effects are increased, extraction is more difficult, and the design of the central region (or the inflection mechanism) is more difficult. Use of super conducting elements in the accelerating system is likewise a mixed blessing. Cavities such as those at SIN could presumably be enclosed in a cryostat but the large size would certainly imply a large refrigeration cost. And the SIN cavities are not excessive consumers of electric power as is the case in linacs. It hence seems likely that the electric power saving would off-set the refrigerator costs.

Making smaller cavities is similarly not attractive since such cavities would run at a higher frequency giving a higher harmonic number and therefore tightening tolerances on magnetic field and phase control. Superconductivity then seems unlikely to make a contribution to cyclotrons in the foreseeable future primarily because there is no overriding problem which would thereby be solved such as is the case for synchrotrons and linacs.

A much more likely area of important technical progress in cyclotrons is computer control. Computers are in fact already essentially in use as a sophisticated intermediate link between operator and accelerator; all three of the large new projects, i.e. Indiana, TRIUMF, and SIN, employ such a system. A major further step which control computers are likely to bring about is the realization of so-called light-bulb operation, i.e. an accelerator with a simplicity of control and reliability comparable to that of the light-bulb and the wall switch. Progress of this type can be of great benefit across the whole spectrum of cyclotrons from the smallest to the largest—in fact it may well be of most benefit for small cyclotrons which are increasingly likely to be in the hands of biologists, M.D.s, and others who lack technical training in handling such equipment. The effectiveness of cyclotrons in the hands of such a broad spectrum of users hinges heavily on how simple and reliable the machines can be made. Unfortunately the problem of real computer control is tricky and subtle. On Friday the afternoon session of this conference will be devoted to this problem. The desire is to fully replace the human operator by a computer which means trying to take account of as many as possible of the enormous number of logical processes which may go on in the brain of a sophisticated operator. Each of these processes must be formalized into an appropriate block of computer instructions and in addition, decision making must be studied and codified in order to determine when to use a particular operation or block of instructions. This problem is difficult but certainly not insurmountable; work is going on in a methodical way at many laboratories including ours at East Lansing to gradually shift decision making from the human operator to the control computer, and the next few years should produce impressive accomplishments.

A less dramatic but nevertheless important line of technical innovation is the increased use of aluminum and alumina in cyclotron accelerating systems. Aluminum is a vastly better structural material than copper, the material normally employed for cyclotron rf components; it is less costly, much easier to fabricate, and has negligible residual radiation. Its disadvantages are that the resistivity for rf is 15% higher and it is alledged to have poor sparking characteristics. This last assertion is difficult to verify and yet is a point which has great influence on designers. The only really adequate test of the point is of course to use aluminum dees in cyclotrons and verify performance characteristics. Such dees have been in use in the Julich cyclotron for several years with good results and it hence appears that the sparking resistance of aluminum is not as bad as had been feared.

Increased use of alumina, i.e. increased use of insulators, can lead to both design simplications and improved performance. One of the main performance limitations in cyclotrons emphasizing beam precision comes from thermal motion of the dee structure. Mounting dees on insulators from the pole tips would both eliminate these motions and greatly simplify the design of the dee. Work at Columbia using Freon cooled alumina insulators offers promise of insulators able to stand the voltage and other hazards of the interior of a normal cyclotron. At Michigan State in about 6 months we will have a test assembly of this type in operation in which the source puller geometry is fixed by Freon cooled alumina insulators. If this experiment is successful a further major improvement in machine precision and stability will result.

An interesting question for the nuclear physics user relates to the improvements in beam precision which can be expected in the future since resolution is always a frontier for the nuclear physicist. What are the prospects of having an energy homogeneity of 1 in 10^5 in a cyclotron beam? Clear requirements are a magnetic field stable to 1 part per million, rf amplitude stable to 1 part per 200,000, and either a flat-top rf wave or a very precise phase selection system (capable of selecting 0.5° out of 360°). None of these requirements seem prohibitively difficult, or from another point of view, each represents an improvement on present practice by a factor which is smaller than the same factor for the improvement in the past ten years. It will of course be necessary in the detailed design of such a machine to look very carefully at coupling phenomena between axial, radial, and longitudinal motion and work out a design which is very precisely linear. Again, however, there appears to be no prohibitive barrier in achieving the necessary orbit characteristics. In total then it seems very likely that a well motivated group could design and construct a cyclotron to achieve an energy homogeneity of 1 in 10^5. Would such a machine make an important contribution in nuclear physics? Would qualitatively new phenomena turn up or would the result be simply a modest extension of the realm of present spectroscopic information? These are obviously difficult questions and also obviously, they are best left hanging in this paper with the hope of evoking discussion and comment from nuclear experts.

HYBRID ACCELERATORS

At Duke University a cyclotron is used as a negative ion injector for a tandem Van de Graaff[17] and at Orsay a linear accelerator is used as a heavy ion injector for a cyclotron.[18] Both of these arrangements are examples of a large class of possible hybrid accelerator systems involving cyclotrons. And recently, there has been much discussion and interest in hybrid accelerator system for heavy ions employing a tandem electrostatic accelerator as the injector for an open-sector cyclotron.[19] What are the general advantages and disadvantages of such hybrid systems?

Two obvious basic problems occur in a hybrid accelerator system, namely 1) the technical problem of shifting the time structure of the beam to match the widely differing requirements of the different accelerators, and 2) the personnel problem which arises from the fact that a staff is needed with very broad expertise, sufficient to develop and operate a system involving two very different kinds of accelerators. The timing problem typically requires some form of bunching system or else beam transfer is very inefficient. Conceptually feasible systems can be laid out in a reasonably straight forward manner; complete calculations including allowances for variations in flight time in the transfer line have apparently not yet been made. The problem seems clearly soluble; nevertheless a substantial additional degree of complexity is added to the total accelerator system and added demands are placed on design and operating staff. The broad staff expertise required to handle a hybrid accelerator system is clearly very difficult to weigh in any quantitative fashion. It is an important factor but obviously depends heavily on conditions at a given lab and so no general guideline can be drawn.

What are the attractions of hybrid acclerator systems? In many situations there is the simple overriding attraction of having an existing accelerator whose useful range can be greatly augmented by a hybrid modification. Thus the Duke project started from an existing Van de Graaff and the Orsay project from an existing cyclotron and many proposals[19] have emphasized the economies which would result from incorporating an existing accelerator into a broader system.

More generally interesting is the question of the optimum accelerator configuration in the case of a new project so that constraints arising from the presence of existing equipment are eliminated; project goals of course have a great influence. Thus if the primary objective is the acceleration of light ions (hydrogen and helium) a straight cyclotron configuration seems the clear choice. From 5 MeV to 500 MeV the composite virtues of cyclotrons (precision, flexibility, intensity, economy, ...) are at present significantly ahead of any other form of accelerator. For these light ions, hybrid systems thus seem attractive only where the situation is that of augmenting an existing accelerator.

If the primary project objective is acceleration of heavy and very heavy ions the optimum accelerator system is much less clear. Cyclotron systems, electrostatic systems, linac systems and hybrid systems all seem possible and are advocated by various groups; design and development has not yet proceeded to a point where definitive judgements can be made regarding the most advantageous system.

The basic scaling laws for cyclotrons and electrostatic accelerators are for the case of heavy ions much more alike than for light ions. This arises from the fact that the charge state for the final acceleration from terminal to ground in an electrostatic accelerator will be approximately proportional to the terminal voltage. The final energy then also increases roughly as the square of the terminal voltage and hence approximately linearly with cost. This is a much more favorable cost formula than results when electrostatic machines are considered as proton accelerators. The final energy of a heavy-ion cyclotron is given by the well known formula $E=E_c(Z^2/A)$ where E_c is an energy characterizing the maximum bending capability of the cyclotron magnet and Z and A are the charge and mass of the accelerated ions. A reasonable cost formula for cyclotrons is a linear dependance on E_c. The key point though is that the final ion energy varies as Z^2/A and the effectiveness of a cyclotron is hency very sensitive to the charge of the ion. The energy of a singly charged Uranium beam would for example be down by a factor of 200 from the nominal energy maximum E_c, a charge 15 Uranium beam would match the nominal maximum and a charge 30 Uranium beam would go to an energy of 4 times the nominal maximum. The Z^2 dependance then focusses great interest on the question of ion source development. Interestingly the classic internal cyclotron ion souce is one of the most effective sources of highly charged ions, as we will hear more of on Thursday in the papers from Dubna[20]. Cyclotron ion sources can seemingly work reliably at least up to Z=15 for ultra-heavy ions and perhaps higher. In order to obtain reaction energy for Uranium on Uranium from a cyclotron of the size of the SIN machine a further doubling of the charge from 15 to 30 is required. Since the cyclotron is incompatible with charge change during the acceleration it is necessary to use two or more stages with charge change between the stages as at Dubna. Tandem electrostatic accelerators in contrast can in principle use several charge changing points although significant technical problems remain to be solved in achieving adequate life-times for stripping foil. Comparison of pure electrostatic and pure cyclotron configurations is hence at present very cloudy since each depends sensitively on a rapidly changing technology (ion sources for the case of the cyclotron and stripping foils for the case of the electrostatic accelerator). Linacs are likewise at present an area of substantial technical uncertainty; if superconductivity can be successfully adapted to heavy-ion linacs the traditional linac deficiencies of high initial cost and prodigious power consumption may well be eliminated.[21] Hybrid systems are substantially more difficult to evaluate than the one accelerator systems; it is thus in my view not possible at this time to establish a clear advantage for any of the approaches. The detailed work now in progress at many laboratories will of course fill in technical details in the coming months and years and a more accurate comparison of the respective advantages of the several approaches will become possible. I am sure we can look forward to a great deal of new information in this area at the next conference.

LIMITATIONS OF CYCLOTRONS

The principle parameters characterizing an accelerator are its energy, energy variability, maximum beam current, duty cycle, and the homogeneity and density of the final beam. It seems appropriate to conclude this paper by considering whether there are any clearly defined limitations on the capabilities of cyclotrons in one or another of these attributes.

The matter of maximum beam current was referred to in a previous section. Repeating briefly, it is clearly necessary at very high currents to have single turn extraction with ≈100% efficiency which means that the rf voltage must be sufficiently high to keep the longitudinal space charge effect from smearing out the turn structure in the internal beam energy spectrum. This does not lead to any definite limitation on current, however, since if a design current is specified, an rf voltage adequate to avoid turn smearing quickly follows from relatively simple calculations. Economic factors will of course come into play; rf systems with 10 MeV per turn or 100 MeV per turn may well be viewed as economically prohibitive even when the most efficient techniques are employed. The axial space charge effect must also be considered in a high current cyclotron but is certainly a much less pressing problem than the longitudinal effect. Many present cyclotrons for example have axial space charge limits in the range of a few milliamps and raising the limits to much higher values would be relatively easy since the current limit increases as the square of the axial focusing frequency ν_z.

The requirements for an energy homogeneity of 1 in 10^5 were looked at briefly in a previous section and seemed quite consistent with modest extrapolations of present achievements. As regards spatial precision the capability of cyclotrons in producing beams of the highest quality has already been clearly demonstrated. The emittance of the external beam of the MSU cyclotron for example is now estimated to be 0.2 mm-mrad for particles of given energy[8] and the inferred beam density is essentially just that estimated for the ion source. This shows that the accelerator proper is near the theoretical limit allowed by Liouville's theorem, namely that it produces no detectable dilution of the phase space density. The inferred phase space density is also high in an absolute sense indicating that the normal cyclotron source is one of the better ion sources.

The question of variability of cyclotron beams hinges largely on the implementation of more modern control techniques. The energy variability of present cyclotrons is well known; experiments are run at a broad spectrum of energies in nearly every laboratory and a number of laboratories have on occasion studied excitation functions with very fine steps in energy. The goal of easy energy variability is nevertheless not yet really here in the sense of the proverbial one-knob control so frequently cited by electrostatic accelerator enthusiasts. This picture should rapidly change however as computer control systems come into real use. In a few years it seems reasonable to expect cyclotrons to fully match electrostatic accelerators on the matter of easy energy variability.

The one area in which cyclotrons have a solid deficiency is in the matter of duty cycle. Cyclic accelerators are inherently pulsed devices. Flat-topping of the rf wave should produce important improvements but it seems unlikely that cyclotrons will ever do better than 10% to 20% on duty cycle which must be compared with the presumed 100% duty cycle of a good electrostatic accelerator. Nevertheless flat-topping is a major step forward from the small duty cycles characteristic of present cyclotrons (2-5%). (If energy homogeneity comparable to that of an electrostatic accelerator is required, present cyclotron duty cycles are in fact much more typically ≈1%.[22]) The duty cycle disadvantage of cyclotrons is of course also substantially offset by the ease with which timing measurements can be made. This can be a great advantage in many circumstances and pulsing systems are frequently installed on electrostatic accelerators to obtain these benefits.

Finally let me consider the question of the energy limitations of cyclotrons. The SIN project as noted previously will yield a beam of 585 MeV protons. This is an effective energy for the production of intense fluxes of π-mesons and so the label "meson factory". What if one wanted a k-meson factory? Would it be reasonable to think of a cyclotron for such an application? Recently at MSU we have looked into a few of the technical details of such a machine and in a technical sense the idea appears surprisingly realistic. Figure 4 for example shows a magnet structure for such a machine computed by Gordon[23] using the hard-edge approximation. The assumed injection energy is 590 MeV approximately matching the final energy of the SIN meson factory. The 22 meter diameter of the 2.4 GeV orbit was selected to give an orbital frequency of one-half that of the SIN machine and a maximum magnetic field of 16.3 kilogauss in the hard-edge magnets. The spiral was set in the calculation to give a ν_z of about 0.8 for the whole energy range. ν_r of course increases more or less like the relativistic mass factor γ, and passes integral resonances at ν_r=2 and ν_r=3. In earlier days such resonance crossings would have been considered extremely difficult or prohibitive. Today however it seems reasonable to assert that such resonance transitions are routine; nearly every small cyclotron regularly passes the ν_r=1 resonance either once or

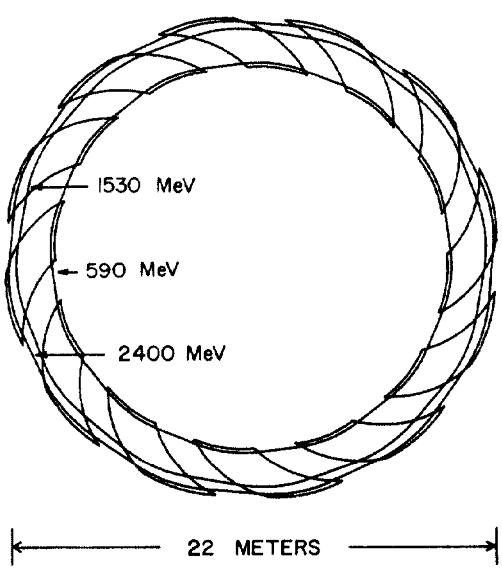

Fig. 4 Hard edge magnet pattern and three typical orbits for a 590-2400 MeV isochronous cyclotron. At the radii of the 590 and 2400 MeV orbits the magnetic field in the hills is 7.4 and 16.3 kilogauss respectively. The orbital frequency is 4.15 Mhz.

twice in the acceleration process, and the Oak Ridge Cyclotron Analogue II demonstrated that $\nu=2$ could be easily passed[24]. The whole matter of integral resonances is now in fact a well understood, bread and butter business of meeting tolerances and providing correcting elements and with requirements which are completely compatible with careful application of present technology. Referring back to Fig. 2 one notes that the average field <B> would increase rapidly with radius in such a Kaon factory. Specific calculations show however that the radial gradient does not exceed 200 gauss per centimeter even in the hills of the magnets of Fig. 4; this is then certainly not a severe technical problem. In conclusion, it seems reasonable to assert that cyclotrons are at present far from any clear-cut energy limitation. If intense beams were desired at energies appropriate for the production of k-mesons the cyclotron would be a likely choice for the most effective accelerator.

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DISCUSSION

RICKEY: With respect to the 2500 MeV machine, I wonder about the cavities--they are at quite an angle and they would add considerable radial component. Muller, I believe now at Karlsruhe, formerly with AEG, did some calculations that showed there was some quite bad radial driving from non-parallel components of the electric field. Did you run any orbit studies on that?

BLOSSER: No, that wasn't put into the calculations but obviously if I go to 12 cavities, it's O.K. It seems that six is also likely to be O.K. since the harmonic of this RF driving term is still high enough not to get in trouble with resonances.

RICKEY: One more thing just quickly: on the size of the various machines something that is curious and sort of interesting is the little machine in Bloomington now; it is reasonably comparable to the old machine which we wrecked out, in terms of energy, in terms of the maximum rigidity. Its magnet weighs less, and it takes significantly less floor space. That is because the coils are so much smaller. Iron runs 60 tons in the little machine whereas it was 75 tons in the old machine. The RF takes so much less space that the net floor space is actually quite a bit smaller.

BLOSSER: What is the orbital frequency?

RICKEY: 8.5 MHz.

BLOSSER: So it is two or three times as big as a standard 20 MHz cyclotron of the same energy.

RICKEY: That is on the magnet pole tip but the flux return is closer in--the flux return is better divided, and the big thing that makes the difference is the RF tanks. The RF frequency is now 35 MHz whereas the old one was 11 MHz, and the RF tanks took up much more room than the magnet did.

BLOSSER: How far is it across the machine--all across the yokes?

RICKEY: 16 ft diagonally.

BLOSSER: Our 55 MeV cyclotron is 12 ft in its maximum dimension versus your 15 MeV in 16 ft. I really think the open sector machines are like a factor of two bigger any way you slice it.

MALLORY: The heavy ion open sector machine design for the second stage is not justified because of the injection system. It seems to fall naturally out of the stripping characteristics for solid foils. You strip up roughly twice the ion source change state. If you had a conventional cyclotron, you just would not use the B_ρ that is possible for normal excitation of the magnet.

BLOSSER: I don't understand that. I just make the radius smaller and use it that way.

MALLORY: But that is when you really run into injection problems. Also, you've got to look at the synchronous solutions.

BLOSSER: Right, but whatever you have for the ring, couldn't I just make it a factor of two smaller, run it around twice as fast, and keep the same charge?

MARTIN: In the particular case of the NHL design, it is a good match to the ORIC because of the characteristic of the stripping. The ion charge is doubled. If you doubled the field in the second stage, then the harmonic number in the second stage accelerator would be half as large.