Innovations in isochronous cyclotrons *

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ABSTRACT

Since the last International Conference on Isochronous Cyclotrons, three major projects have been approved: the 585 MeV proton cyclotron of the Swiss Institute for Nuclear Research (SIN) to be built at Villigen near Zurich; the 500 MeV H^- cyclotron of the Tri-University Meson Facility (TRIUMF) at Vancouver, British Columbia; and the 200 MeV variable energy cyclotron of the Indiana University. A much smaller but unique project has been successfully brought into operation, the cyclograaff at Duke University which combines a small cyclotron with a tandem accelerator in a way which enhances the desirable characteristics of both. Finally, the most important happening since the last conference has been the renewed interest in accelerators for very heavy ions. In the United States alone, there will be more than ten major proposals. This paper reviews the activities and progress of the past several years and discusses some of the important innovations accomplished or foreseen.

1. INTRODUCTION

Since the last International Conference on Isochronous Cyclotrons, we have left one era and entered a new one. The years 1963–1966 saw the end of the meson factory competition. In the United States, the contest for meson research facilities was resolved by the decision to build the Los Alamos Meson Physics Facility. In Europe, the cyclotron project of the Swiss Federal Technical University was approved and for a time it was the only project in the energy range that is attractive for meson production. Later, in Canada, the H^- cyclotron concept gained favour and the TRIUMF project at Vancouver, British Columbia was proposed and recently approved.

There was brief interest in the so-called neutron factory idea in the United States at Oak Ridge and in Canada at the Chalk River Nuclear Laboratories. This was stimulated by the possibility of obtaining extremely high currents of protons at high energy with the separated orbit cyclotron. The effort and interest in the

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neutron factory concept was short lived–it yielded to the realities of high cost without correspondingly strong scientific justification. The idea was probably ahead of its time and its resurrection may await the success of some more advanced acceleration concept.

The Indiana University cyclotron project, which was approved last year, represents the first cyclotron in the United States in an energy range below the meson factory level to depart from conventional design. It will be a variable-energy, multi-particle cyclotron of the ring (separated magnet) type with a maximum proton energy of 200 MeV; for heavier particles, the maximum energy is $\sim 240\, q^2/A$.

More recently at the Triangle Universities Nuclear Laboratory, Duke University, the Cyclograph achieved successful operation. A 7 MV tandem is used as the post-accelerator for the beam from a fixed-energy 15 MeV H^- cyclotron. The combination will provide continuous quick energy variability over a wide range of energy up to 30 MV.

This year has seen renewed interest in high energy cyclotrons. A new era characterised by an intense interest in research with heavy ions is just now beginning. We have had ions as heavy as argon for a long time, but the possibility of a new region of nuclear stability near $Z = 114$ has escalated the requirements for heavy ion accelerators. Very heavy projectiles are needed. A proposed production method for the new elements is to bombard uranium with uranium, or perhaps lead with lead, hoping the new species will be formed as a product of the fission of the resulting super-size compound nucleus.

This paper characterises the status of several of the new projects underway or in operation and reviews the several U.S. proposals for large cyclotrons with the view of emphasising their differences rather than their similarities.

2. NEW MAJOR PROJECTS

2.1. *The Swiss Institute for Nuclear Research (SIN) 585 MeV Cyclotron*

The basic plan for the 585 MeV Cyclotron was developed by the Swiss Federal Technical University (E.T.H.) in 1963. Since that time the design of the machine has been essentially completed. The project is now fully approved and the first beam is due late in the year 1973. The cyclotron laboratory is to be built about 35 km from Zurich at Villigen near the Swiss Federal Institute for Reactor Research.

The cyclotron is an eight-sector fixed-energy machine with slight spiral. The final energy is to be 585 MeV, an increase over the former value of 525 MeV. This increase in energy has necessitated that the operating path pass twice through the resonance $\nu_r = 2\nu_z$ but computer studies show that the increase in axial oscillation amplitude will be very small.

A change since earlier plans is the increased flexibility of the injector cyclotron. Earlier, the ring cyclotron was provided with a fixed energy proton cyclotron as the injector, but the new plan is to use a variable energy multi-particle cyclotron. Its capabilities of variable energy and of accelerating a variety of particles will greatly enhance its value as an independent accelerator for nuclear research. It is planned that the injector cyclotron will provide a proton current of over $100\,\mu$A.

2.2. *TRIUMF*

In Western Canada, the University of Alberta, Simon Frazier University, the University of Victoria, and the University of British Columbia have combined forces to plan and build an accelerator for 500 MeV negative hydrogen ions. The facility will be called the Tri-University Meson Facility (TRIUMF), and will be located at the University of British Columbia. It will provide proton beams of low energy-spread over the range 150-500 MeV and will be able to simultaneously deliver beams of different energies to separate research areas. Initially there will be two independent beams–later there may be as many as six; this is a unique feature of the negative hydrogen ion accelerator. The price paid for it (at least in the TRIUMF design) is lack of flexibility; it is not possible to accelerate other particles. The accelerator was proposed in 1966; the project has been funded since about May, 1968. Impressive progress has been made. Notable changes made since the original proposal include an increase in injection energy from 150 kV to 300 kV, the use of cryo-pumping, and a slight increase in magnet size. The latter came as a result of the need to lower the magnetic field slightly in recognition of the result of a new measurement of the lifetime of H^- ions in magnetic fields.

According to the present schedule, the cyclotron will be completed in the spring of 1973.

2.3. *The Indiana University Cyclotron*

In 1968, the Indiana University proposed the construction of a 200 MeV cyclotron capable of variable energy and the acceleration of a variety of particles. The project has received final approval and design of the cyclotron is progressing rapidly. Notable features of the machine include the use of an injector cyclotron with design so similar to that of the large accelerator that it can almost serve as a model, the use of d.c. injection at several hundred kilovolts, and the plan to use auxiliary rf cavities to provide a second harmonic voltage to give the effect of a flat-topped accelerating voltage waveform. Both cyclotrons will have four separated sector magnets with small gaps. The rf accelerating structures are placed in the spaces between the magnet sectors. In this way, a rather large rate of energy gain can be achieved with a modest rf power requirement. Because of the relatively large turn spacing it is not necessary to use special means to enhance the turn separation.

The concept of flat-topping to improve the phase acceptance and/or energy resolution is not a new one. I can remember T. A. Welton and M. M. Gordon discussing the virtues of the use of third harmonic in connection with the possibility of getting perfect turn separation at the $\nu_r = 2$ resonance for beam extraction. That was in 1959–60 when the studies of the Mc^2 cyclotron were in progress.

The use of second harmonic seems to be original with Martin Rickey and associates at Indiana University. The use of an optimum combination of fundamental and second harmonic gives constant voltage gain over approximately twice the phase width that can be obtained with the combination of fundamental and third harmonic but the gain in phase width of the flat-top is at the expense of a larger reduction in the maximum energy gain per turn. The peak accelerating voltage is reduced by the amount of the harmonic amplitude. The optimum amplitude of the second harmonic is 25% and about 10% for the third harmonic. Second harmonic cavities have been adopted in both the Argonne National Laboratory and Oak Ridge heavy ion cyclotron proposals.

3. THE CYCLOGRAAFF

In terms of energy per unit cost, the Van de Graaff is a poor bargain. A cyclotron with 40 MeV proton output and extremely good energy resolution would not cost more than $2 000 000, whereas a tandem Van de Graaff would cost at least $5 000 000 if obtained commercially. The only clear advantages of the tandem would be the continuous beam and the very easy variation of the beam energy.

Professor Henry Newson of Duke University first appreciated the versatility of a tandem Van de Graaff combined with the cyclotron. By the addition of a relatively inexpensive cyclotron, ($360 000) to a small tandem (a $1 200 000 HVEC model FN) he is able to have smoothly variable energy over a wide range. Negative ions are accelerated in the cyclotron, extracted at 15 MeV as negative ions, and injected into a tandem. The ions emerge from the tandem with energy $E_{cyclotron} + 2\ eV_{tandem}$. With the present arrangement, a resolution of 20 keV is reported. With improvement in the cyclotron and the analysis system, it is hoped that the energy resolution of the combination can be made to match that of the tandem alone.

Advances in the performance of cyclotrons since the Cyclograaff was conceived suggest that in the future the cyclotrons might properly be somewhat more elaborate and smaller tandems might be used. It appears that comparable energy resolution can be obtained with a cyclotron. Henry Blosser of Michigan State University reports an energy spread of 0·04%, about 13 keV, in the 34 MeV raw beam from his cyclotron. Recognising that even better performance will be achieved with future cyclotrons, there seems no good reason for the use of a tandem except to give smooth adjustment energy over a small range or to set the energy exactly to a prescribed value. Achieving the equivalent with a cyclotron may require a computer control system, but seems entirely practicable.

4. HEAVY ION CYCLOTRON PROPOSALS

Prompted perhaps by the method of heavy ion acceleration proposed at Orsay[1] and by the paper by Professor V. P. Dzhelepov,[2] a large number of proposals have been prepared that propose the use of multi-stage acceleration. Many of these involve the use of potential drop accelerators (tandem Van de Graaffs) together with sector-focusing cyclotrons. Although most proposed cyclotrons are of the separated sector variety, there are substantial differences among them. Table 1 lists the main characteristics of the several U.S. proposals for heavy ion accelerator facilities. Generally, the proposal of each laboratory reflects the local combination of research programmes and accelerator experience and interests as well as the results of optimisation studies. Laboratories with a tradition in low energy research with beams from Van de Graaff accelerators will usually wish to extend their work to higher energies; hence, will prefer a large tandem as the ion injector. Laboratories without a low energy research background may prefer to use a smaller tandem with resulting lower q/m for the final stage heavy ion acceleration.

Table 1. CHARACTERISTICS OF SOME PROPOSED HEAVY ION CYCLOTRONS

	Argonne National Laboratory	*Indiana University Type*[1]	*Maryland University*[2]	*Michigan State University*[3]	*Oak Ridge National Laboratory*
Number of Sectors	6	4	4	6	4
Sector angle, degrees	20°	36°	Conventional Cyclotron	~24°	45°
Spiral	none	none		weak	none
Uranium Ion Energy (MeV/a.m.u.)	10	~6	~10	~9	7·5
$K, T = Kq^2/A$	420	240	185	720	330
Proton Energy (MeV)	350	200	140	600	300
Injector	16 MV tandem	tandem	Cyclotron + 9 MV tandem	9 MV tandem or Cyclotron	16 MV tandem
Injected Ions	negative only	negative only	negative only	negative only with tandem	positive or negative

[1] Modified versions primarily for the acceleration of heavy ions are being proposed by Los Alamos Scientific Laboratory, the University of Rochester, and Brookhaven National Laboratory.
[2] Injector cyclotron will be a duplicate of the present machine.
[3] To be proposed also by Florida State University.

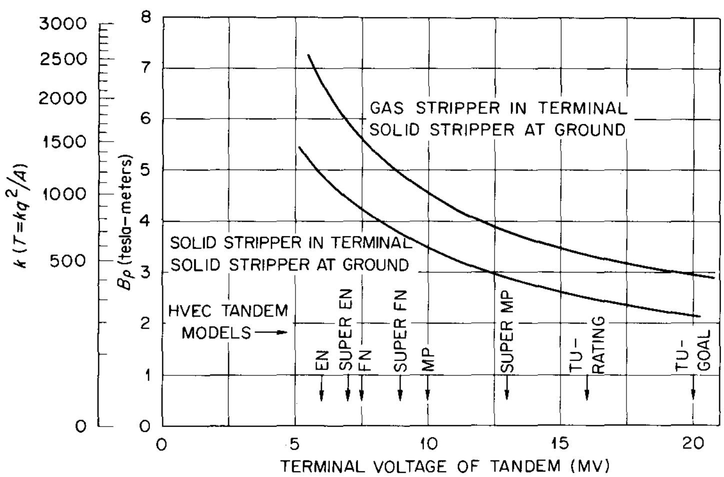

Fig. 1. The Bρ *and energy constant of a cyclotron to accelerate uranium ions to 7·5 MeV/a.m.u., as determined by the terminal potential of a tandem Van de Graaff injector*

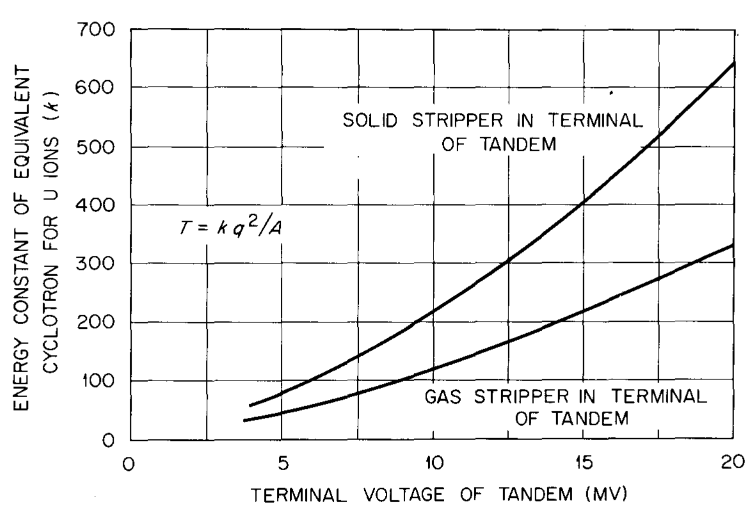

Fig. 2. The Bρ *and energy constant of an injector cyclotron that would replace a tandem*

This choice leads to a larger cyclotron and a higher proton energy capability is realised.

Fig. 1[3] shows the variation of the required cyclotron $B\rho$ and energy constant, k (the k in the equation $E = kq^2/A$) with the terminal voltage of the tandem Van de Graaff used as the injector. The cyclotron is sized to achieve a final energy of 7·5 MeV/a.m.u. for uranium ions. Fig. 2 gives the cyclotron $B\rho$ and energy constant, k, needed of a cyclotron to replace a tandem as the injector. It is assumed that the cyclotron would accelerate U^{10+} ions (q/A = 0·042).

For example, Fig. 1 shows that a 16 MV tandem as an injector requires a second-stage cyclotron with a $B\rho$ of 2400 tesla-meters (kG-cm) and an energy constant of about 300 MeV to achieve 7·5 MeV/a.m.u. final energy for uranium ions if solid strippers are used both at the tandem terminal and just before the ions are injected into the cyclotron. If gas stripping is used in the tandem terminal, the cyclotron $B\rho$ required increases to 3300 tesla-meters and the energy constant is ~500 MeV.

Referring to Fig. 2, we may see that if the tandem with 16 MV terminal is to

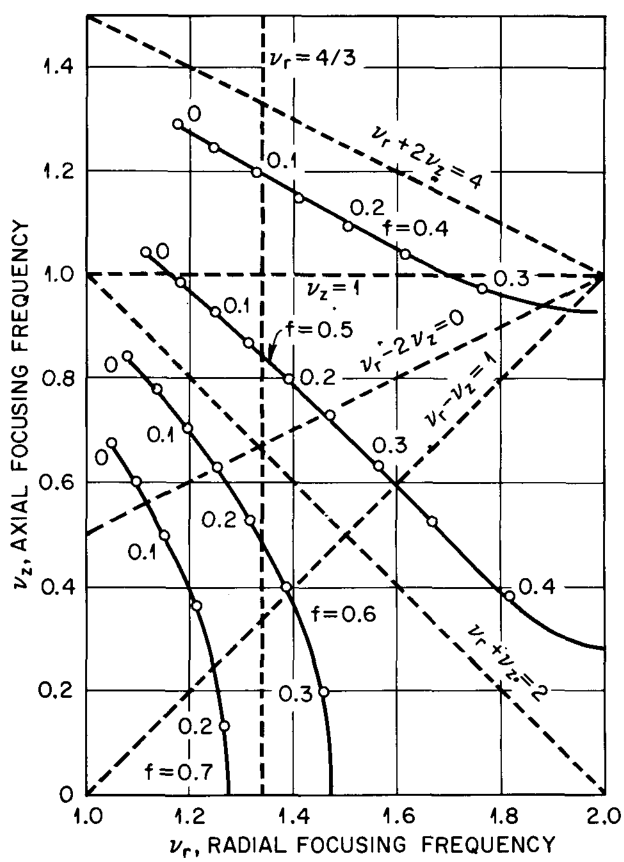

Fig. 3. The radial and axial focusing frequencies for a four-sector separated magnet system without spiral. The parameter f *is the fractional width of a magnet sector;* f = *0·5 corresponds to 45° magnets. The dots on the curves are labelled with the corresponding kinetic energy in units of* m_0c^2

be replaced by a cyclotron, the energy constant required for the cyclotron would be 230 MeV for the gas stripper case and about 430 MeV if the tandem was used with a foil stripper in the terminal.

These data illustrate that for the acceleration of lightly charged heavy ions the tandem d.c. accelerator is equivalent in effectiveness to a very large cyclotron.

The comparative total costs of systems with high and low injection energy have been the subject of many studies. The studies at Argonne National Laboratory[4] show that the total cost for a two-stage accelerator with tandem first stage is nearly independent of injector voltage at least in the 10–15 MV range. This result suggests that the choice of injector voltage may depend heavily on factors other than cost.

The choice of injection energy influences the magnet configuration as well as its size if the full proton energy capability is to be utilised. The possibility that

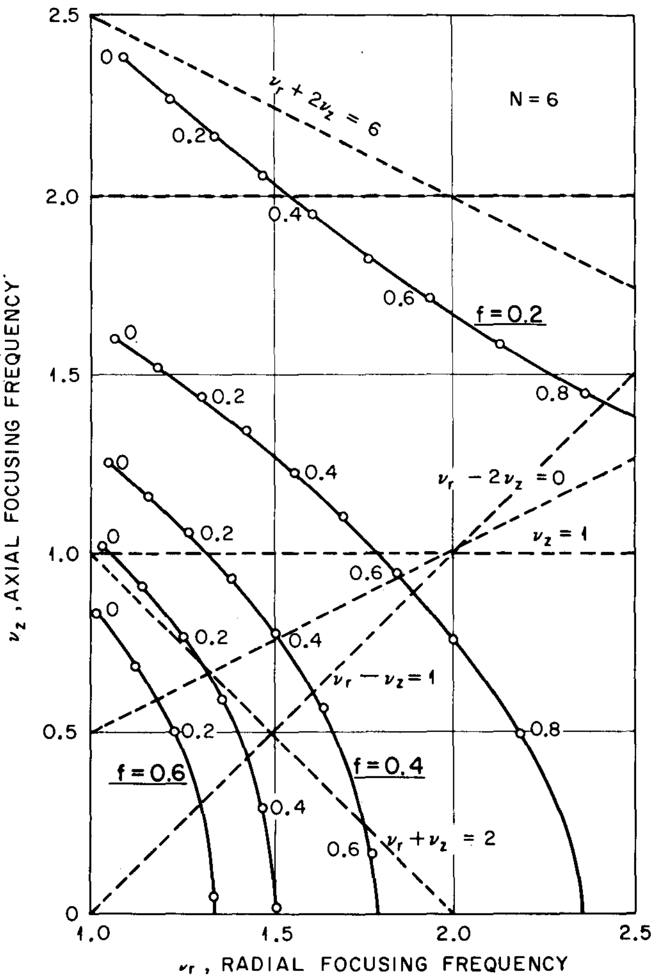

Fig. 4. The radial and axial focusing frequencies for a six-sector separated magnet system without spiral. The parameter f *represents the fractional width of the sector magnets;* f = *0·5 corresponds to 30°. The dots on the curves are labelled with the corresponding energies in units of* m_0c^2

resonance crossings will produce undesirable effects on the particle motion must be considered. In general, the higher the proton energy, the more difficult it becomes to completely avoid resonances. Figs 3 and 4 give the resonance diagrams for four and six sector cyclotrons without spiral, from the work of Gordon.[5] A similar analysis for magnets of more general form has been made by Schatz.[6] For the acceleration of heavy ions, almost any non-spiraled magnet configuration will do. In magnets of constant configuration, i.e. the same value of flutter at all radii, both ν_r and ν_z are nearly constant when heavy ions are accelerated. On the other hand, the variation in the focusing frequencies during proton acceleration may be quite large. ν_r will increase according to the increase in γ (the ratio of total energy to rest energy) and ν_z will decrease with energy as a result of increasing radial gradient of the rising magnetic field required to maintain isochronism. The avoidance of serious resonances during proton acceleration is a principal factor in determining the magnet configuration.

The imperfection resonance that is most important is the axial resonance, $\nu_z = 1$. Passage through it places extremely tight tolerances on the median plane symmetry of the magnetic field, or requires that a system be provided to precisely compensate the first harmonic component in B_r on the median plane of the magnet. To avoid the resonance, the operating line (the locus of the particle in $\nu_r - \nu_z$) space must remain wholly above $\nu_z = 1$, or wholly below it. The six sector, 350 MeV, Argonne National Laboratory design, and the four sector, 200 MeV, Indiana University Cyclotron, are designed so that the operating path is always comfortably above $\nu_z = 1$. The Argonne Cyclotron uses six sectors rather than four because there is not enough room above $\nu_z = 1$ to accommodate 350 MeV protons without crossing or getting uncomfortably close to $\nu_r = 2$, an extremely strong resonance in a four-sector cyclotron. There is no similar problem in the Indiana design because the proton energy is lower. In the Oak Ridge design with four sectors of 47° width, the operating path remains always below $\nu_z = 1$, but the $\nu_r - 2\nu_z = 0$ resonance is crossed.

In the six sector, 600 MeV, Michigan State Cyclotron, the $\nu_z = 1$ resonance is crossed but a set of adjustments will be provided to correct possible errors in the median plane magnetic field. It is necessary for $\nu_z = 1$ to be crossed because there is no resonance-free region wholly above or below $\nu_z = 1$ that will accommodate 600 MeV unless extremely narrow hills are used.

Designs like those of Oak Ridge National Laboratory and Michigan State University that require resonance crossings will, of course, need detailed orbit studies to assure that the required beam quality and/or magnet perfection can be readily achieved. Cyclotrons that use absolutely safe paths that are free of all significant resonance crossings all require narrow sector angles with resulting lower average field. They will generally prove more expensive, all other considerations being equal.

5. CONCLUSIONS

First, the new cyclotrons of the separated sector type that are being planned will have unprecedented flexibility and research utility. This is because the large inter-sector spaces provide the necessary space for powerful and efficient variable rf systems. Also, the power requirements for magnetic field trimming are modest, making it easy to provide variable energy and multi-particle capability at energies beyond the capabilities of conventional design.

Second, the recent progress toward improving the energy spread and beam quality of cyclotron beams suggests that in the future, cyclotrons can be expected to compete on even terms with d.c. accelerators in all respects except perhaps the microstructure of the beam. The advanced cyclotron will be able to do high resolution research at energies unattainable by d.c. accelerators. The application of computer control can be expected to make a cyclotron almost as easy to operate as a small tandem Van de Graaff.

6. ACKNOWLEDGMENTS

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REFERENCES

1. Bieth, *et al, I.E.E.E. Trans. on Nuclear Science,* **NS-13,** 182-190, (1966)
2. Dzhelepov, V. P., *et al, Proc. Sixth Intl. Conf. on High Energy Accelerators,* Cambridge, Mass. (1967)
3. Figs 1 and 2 are based on charge-exchange data from Betz, H. D., *et al, Phys. Letters* **22,** 643, (1966)
4. *Proposal for a Regional Accelerator Facility,* Argonne National Laboratory Report, ANL 7582 (1969)
5. Gordon, M. M., *Ann. Phys.* **50,** 1571, (1968)
6. Schatz, G., *Nucl. Instr. Meth.* **72,** 29-34, (1969)