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SURVEY OF ISOCHRONOUS CYCLOTRON TECHNOLOGY

Invited Paper

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Introduction

There are presently 22 isochronous cyclotrons in operation with energies ranging from 8 to 130 MeV (α, p). There are at least as many being constructed, designed or seriously proposed. I will restrict myself to the existing and proposed machines in the indicated energy range. Furthermore, I hope you will forgive me for using the title of this paper freely and for not making an attempt to cover the overwhelming number of clever ideas which have been proposed and/or investigated. It is not my purpose to present new ideas but, I hope by choice of emphasis, to contribute to the discussion leading to improved research tools.

Experimenters Specifications

For many years the designers of isochronous cyclotrons were concerned whether or not their machines would be successful and useful; even though their expectations were modest as compared with today's standards, particularly in beam quality. Many of the basic ideas leading to good designs were suggested quite early. Two electron models and two ion machines had proved the sector focusing principle to be sound by the time of the Sea Island Conference (1959). But there still was considerable doubt whether these machines would become as widely accepted as research tool as they are today.

We have learned in the meantime to understand these machines; hence their performance and limitations become predictable. These are the reasons for the overwhelming number of excellent computer codes which have evolved in the past few years. No machine builder would attempt a design without consulting the computer extensively.

A logical consequence of the increased understanding is the favorable response to the experimenters continuing request for more versatility and more reliable performance of our machines. It might be useful to review the present set of specifications. In this context I define specifications as a mixture of wishful thinking and known technology. It is no longer enough for an experimenter to just receive a beam of certain particles and energy. In addition he specifies:

a) to receive the desired beam quickly and reliably.

b) an energy spread $\Delta E/E \leq 100$ keV for the unanalyzed beam, and as low as a few keV for a highly analyzed beam.

c) excellent optical beam properties. Emittance in both planes of 10 mm-mrad (normalized to 50 MeV).

d) a stable but variable pulse length.

e) low background radiation.

Furthermore, experimenters desire sufficient flexibility to incorporate new developments.

If we combine the best results of the machines presently operating and visualize them incorporated into one ideal machine we can fulfill just about any wish.

a) During a data collection period of 70 hr 120 energy changes have been reported from the Berkeley 88-Inch. Similar results are obtained on other machines.

b) An energy spread of 50 keV (50-MeV p) is reported from MSU. Several other machines are capable of delivering unanalyzed beams with energy spreads around 100 keV. The beam preparation magnets of the University of Michigan can select a monochromatic beam within 5 keV (40-MeV d) and in several other facilities beams can be analyzed to 50 keV and better.

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c) The fraction of the full beam contained within 10 mm-mrad (normalized to 50 MeV) varies from 70% (Amsterdam, Phillips, in both planes and ORIC in the axial plane) to not less than 20% in most machines..

d) Pulses of less than 10^{-9} seconds have been achieved in the 3ω machine built by AEG in Karlsruhe. A duty cycle of 15% could be reach by most isochronous cyclotrons.

e) Should it become routine to extract negative ions by electric or magnetic fields as has been done at the University of Colorado the necessary slits for magnetic analysis could be made very thin to avoid slit scattering. By this method a few groups hope to produce an exceedingly clean beam.

To decide whether it is a reasonable venture to incorporate all possible specifications in one machine, I leave up to your judgment. A first-rate facility only emerges if the experimenter's needs and the ideas on machine building and the engineering techniques go hand in hand. Excellent results have been achieved where possible changes of specifications were anticipated in the design. In our first generation of isochronous cyclotrons (i.e., the machines in operation at the Geneva Conference, 1963) we have learned that this cannot be done in a cheap way.

Operation

We understand how to obtain a good quality beam, now preparations are well underway to make changes in particles, energies, and beam characteristics fast and reliable. The automatic setting of machine parameters as described by Dave Struthers (Session F), and a commercially available computer from Philips to do the same job, indicate the direction we are heading. For the groups who propose negative-ion extraction by stripping, as well as for those proposing negative-ion injection into tandem Van de Graaff's, the fast change of energy without changing cyclotron conditions is a significant consideration. For the same reason constant orbit operation has been adopted by several groups. This implies a dee voltage proportional with the final energy and no change of center region or deflector hardware. This scheme has distinct attractions; it is limited, however, by saturation effects and dee voltage range.

Once an experimenter has decided on what he wishes to do, he wants to have his equipment and a beam trimmed to specification immediately. In this context, the contribution of a well trained, well organized support group is of vital importance. Particularly, the machines above 50 MeV cannot be exploited without an integrated support group.

The fact that residual activity in and around the machine is not discussed much anymore shows that we have learned to partly avoid it, or at least to handle it effectively. For a facility used intensively, a substantial arsenal of spare parts is needed. From ion source cones, beam probes, septums, electronic components, oscillator tubes, and assemblies up to spare dees and deflectors are held ready for exchange. Those groups having been substantially delayed because of a failure of a vital component appreciate the necessity for spare parts.

Construction, Startup

The length of the construction period, or at least the schedules thereof, become shorter and shorter. This forces the machine builder to freeze certain parameters before he has fully investigated all implications. Hence a number of components might become an afterthought. Often the instrumentation which is needed for the starting period of the cyclotron and for development suffer from a tight construction schedule. Defining the starting period as the time from the first internal beam to full operation for experimental use, an interval close to a year is usually necessary. This is a substantial fraction of the construction time and needs, therefore, careful consideration early in the basic layout.

Good water-cooled probes with precise positioning mechanisms, multichannel recorders, in short, good instrumentation eases the life of the operation staff during this demanding period. Viewing ports at the vacuum tank and even through the magnet yoke, as in the Harwell machine, proved to be of great help.

Magnetic Guide Field

Considering all the effort which is required from the planning stage for a cyclotron facility to a successful experiment, one wonders why machine builders try to save on the magnet, in diameter and gap. High average fields make an electrostatic beam deflection harder, by about the square of the field. Furthermore, saturation effects, even though in principle they could be used to aid shaping the field, usually cause difficulties. The cost of the magnet rarely exceeds 20% of the machine costs, or about the annual operating budget. I am aware this has been said before, but I repeated it because more than one machine suffers from faults of this kind.

The objective of a machine builder is to deliver a beam into a beam handling system consisting of elements with constant field gradients. During acceleration every effort needs to be made to keep the beam in as linear a field as possible. Even so, the invariance of phase-space area remains valid in any field configuration. The beam handling system in general cannot correct for non-linear distortions. Hence, in practice, non-linear distortions mean an increase of phase-space area, and hence a loss in density. For the designer this implies that the betatron-oscillation amplitude must be kept very small compared with the magnet gap. The values for incoherent betatron-oscillation amplitudes in a well-built well-tuned machine vary from 1.5 to 3 mm (normalized to the betatron frequency $\nu = 1$).

Inhomogenieties of the material and machining errors are more likely to show up in a small gap. Also, access to the center region and to the deflector is favored by a relatively large gap. Unless the dees are embedded in the valleys, the dee-to-ground capacity also sets a lower limit for the gap.

It is impressive how precisely cyclotron magnets have been built. Typically, the gap is uniform to 0.004" (~0.1 mm), with the hills placed to an equal accuracy. The first-harmonic contents of such magnets is only a few parts in 10^4. It appears that this is the standard for a good cyclotron in the energy region under consideration. The magnetic field is rather sensitive to the quality of the steel pole tips, therefore, the pole pieces are cut and forged from the same ingot. For the yokes, however, less homogenious steel seems to suffice. Amazing are the magnets where the yokes can be lifted and put together again without exceeding tolerances, even with auxiliary coils in place. (AEG, Karlsruhe; CSF, Grenoble; Manitoba; and Michigan State University)

Due to the well built magnets, an assumed linearity within the beam envelope over the isochronous part of the guide field of most machines is a good approximation.

Auxiliary Coils

In any design one wishes to minimize the contribution of the auxiliary coils to the main field. This is usually done by choosing a field shape for the uncorrected field that is intermediate between the isochronous field for the most relativistic particle and that for the least relativistic particle.

Circular trim coils are the rule for isochronous field shaping. There are, however, designs using only the hill coils to shape the field. In addition, this makes it possible to use the same coils as AVF coils for the 1st harmonic and, if powerful enough, for flutter. In higher energy machines it is a virtue to save on auxiliary coils, because the power of the auxiliary coils can exceed the power of the main coil. In some designs the contribution of auxiliary coils have been minimized by using saturation effects. NRDL, San Francisco, uses the saturation of iron with magnetic induction, whereas Orsay uses different magnetic alloys, and Manitoba uses temperature-controlled Invar-bars.

Everyone engaged in designing as complex a magnetic field as is required for a sector-focusing cyclotron knows that these remarks cannot do justice to the effort required.

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Careful mapping of the field with and without auxiliary coils, is certainly a prerequisite for the meaningful use of computers. That this procedure works has been demonstrated by the several groups using only computed coil settings to obtain a specified beam. A good example is the MSU cyclotron.

Magnetic Field Regulation

The best designed magnet serves little purpose if not excited by a highly regulated power supply. It is a pleasure to report that power supplies have been built with a current regulation of 10^{-5}. Considering the long time constant of the main magnet (~20 sec) the short-time stability of the field will be a substantial factor better. It should be pointed out, however, that the regulation requirement on frequency and magnetic field increases with the square of the number of turns, whereas the need for dee voltage regulation increases linearly.

The regulation of the auxiliary coils should be somewhat better than their contribution to the main field indicates, because they lack the large time constant of the main magnet. An investigation at the Berkeley 88-Inch showed that frequencies around 1c/sec were particularly disturbing.

On-Center Acceleration - Center Region

It is probably an understatement to say all machine builders agree that one should accelerate on center. In this context on-center acceleration is fulfilled if the center of gravity of the r-pr phase space (center spread) coincides with the magnetic center of the guide field; in other words, coherent radial oscillations are avoided. The dominant reason is the so-called precessional mixing. When a coherent oscillation is present the center spread of the beam precesses around the magnetic center of the guide field. The number of turns for a full precession is given by $1/(\nu_r-1)$. For (ν_r-1) positive, the center spread precesses opposite to the particle rotation, inversely for (ν_r-1) negative. Particles with different energy gain per turn experience a different number of precessions to full radius. If the number of precessions for the leading and the lagging particles started simultaneously at the ion source differs by at least one, complete precessional mixing occurs. This means all coherent radial oscillation has become incoherent. The beam is now centered, but the incoherent amplitude has increased by the coherent amplitude. Also, with an entirely centered beam but non-circular center spread, precessional mixing takes place. (Dimension of center spread in units of length: r, pr(1/Be) where B is the magnetic field and e the charge of the ion in question.

It is very easy to induce a coherent oscillation at the center of the machine. But as soon as ν_r deviates from unity, which means it is no longer in resonance with a first harmonic of the guide field, a change of the coherent amplitude becomes difficult.

These are the dominant reasons why several groups have invested a substantial effort in central region studies. These investigations by MSU, Philips, and others paid off. Not only did they yield many valuable computer codes and insights but they are also in very good agreement with experimental results. Hence, we can consider these problems basically solved.

It should be pointed out here that with a small number of turns, small phase width, and also with ν_r-1 small, the effect of precessional mixing is not severe. Inversely, with a large number of turns and large ν_r, which implies high energy, good beam quality can only be preserved by accelerating on-center with a circular center spread. Already at the Sea Island Conference in 1959 it was pointed out that ion source puller and slit arrangements, together with their relative position to the center, determine the incoherent radial oscillations (center spread). Hence, the concept of emittance of an ion source in a cyclotron which implies ion extraction from the source by an rf field, is only meaningful in connection with the first few turns of acceleration.

Care should be taken to avoid phase bunching in the radial plane. In the vertical plane, where the focusing due to the electric field is significant and rf-phase dependent in the first few turns, an effective phase selection can be accomplished with vertical slits, as has been

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pointed out by H. L. Hagedoorn. Because of this phase dependence of the vertical electric focusing, a practical upper limit for the phase width is approximately 80°.

I am afraid that for good beam quality in higher energy machines, we will have to live with a rather elaborate center region. The tendency will be, therefore, to operate with constant orbits, at least over certain energy intervals.

It is remarkable that the Oak Ridge type ion source developed more than a decade ago, generally adopted with few modifications, still meets most needs of cyclotron operation. Granted that some of the undesired beam needs to be clipped off. But it appears that for up to 100 μA of CW operation, space charge effects are small. Hence, the phase-space density is determined by other factors than the ion source output. Metal chimneys have some advantages in lifetime and operational convenience over carbon chimneys. However, for most machines still employing carbon chimneys, routine operation doesn't seem to be restricted.

Polarized Particles

The majority of the groups using, building, or planning a cyclotron facility hope to incorporate polarized particles. The successful realization of these plans depends on a reliable ion-injection mechanism. Fortunately, a number of groups have reported work on various schemes; even so, the electrostatic mirror and the axial injection of the cyclotron in Birmingham (England) is working well. A comparison of the relative merits of these schemes can only be made after they are fully investigated.

Much attention has been paid to three- versus four-fold symmetry of the magnet pole tip configuration. The three-fold symmetry was originally preferred because of its faster rising flutter with radius, and the space available for AVF coils at small radii. The present point of discussion is the depolarization of polarized particles. Resonance occurs, using H. Kim's formalism, if $(1/2\ g-1)\gamma = \pm \ell N \pm m\nu_z \pm n\nu_r$ where ℓ, m, n are integers and N is the harmonic of the guide field. For deuterons $1/2\ g-1 = .143$ and for protons $1/2\ g-1 = 1.79$. Of all the possible resonances only two shall be considered here. The resonance at $\nu_z = 0.143$ for deuterons cannot be avoided by either configuration, but can be made harmless. A resonance for polarized protons at $N - (\nu_r+\nu_z) = 1.79$ can be avoided by choosing a four-sector machine in the energy range under consideration. However, except for unfortunate changes of the values of $(\nu_r+\nu_z)$ with radius, the depolarization for this resonance is predicted to be small.[1, 2]

RF Systems

In principle, the rf systems employed are shorted quarter-wave coaxial lines. The large variety in actual design gives rise to discussions concerning multipactoring and operational and reliability considerations which I feel unqualified to judge. General agreement remains restricted to the statement that a reliable, well-regulated, rf system is essential. It is, therefore, quite understandable that the group in Harwell chose a commercial transmitter which doesn't seem to have the usual startup difficulties. Since operation demands it, all these various designs will eventually work reliably.

Regulation of the frequency to 10^{-6} doesn't seem to be a serious problem. Most rf systems, self-excited or employing a power amplifier, use a crystal, controlled frequency synthesizer as reference. The importance of good dee voltage regulation has been widely recognized. A regulation of 10^{-3} is achieved in several systems.

The dee's are expensive and a delicate structure, therefore they are carefully protected with carbon blocks to avoid accidents due to axial blow-up and activation.

For access to the deflector parts and operational convenience a single dee is hard to beat. There is obviously a certain machine size where the dee-to-ground capacity, as well as structural difficulties, makes a single 180° dee impractical. This limit appears to be above 100-MeV protons. For harmonic acceleration of low energy or not fully ionized particles, a frequency range of at least 3:1 has to be provided.

In a two-dee system and with the proper accelerating modes (push-pull and push-push) the even harmonics of the orbital frequency can be used. Hence the frequency ratio needed is only 2:1. Such a system, in connection with a four-fold symmetry of the pole-tip geometry, avoids also the gap-crossing resonance described by M. M. Gordon.[3] It should be noted, however, that for a 180° dee in a three-sector magnetic field, the coherent radial amplitude induced by the gap-crossing resonance is small compared with the incoherent radial amplitude.[6] It becomes more pronounced if ν_r is close to unity.

Vacuum

It is a fact of cyclotron operation experience that machines with good vacuum (a few x 10^{-6} mm Hg) are running well. In addition, acceleration of negative or otherwise not fully stripped ions requires even better vacuum, depending on the number of turns and the tolerable losses. It is, therefore, amazing that a number of machines still operate above 10^{-5} mm Hg. External ion injection brings some improvement in pressure. One should keep in mind that good pumping speed is an important operational convenience and adds little to the cost of the accelerator unless the machine is conductance limited, or has a lot of virtual leaks. Good examples are the MSU and the Harwell cyclotron which not only have excellent operating pressures, but can go up to air and back to operation in an extremely short time. On these machines, as well as on ORIC, operation can be resumed in less than one hour.

Several groups use epoxy resins in substantial quantities exposed to the high vacuum. I am personally somewhat surprised how well it works. AEG proposes a new organic hot-curing insulation material from DuPont for their auxiliary coils, with substantially lower vapor pressure.

The discussion concerning organic versus metal seals has settled down in favor of organic seals, primarily because the beam lost inside the machine is far less than anticipated. This is partly due to excellent control of beam stabilities, and partly because the average beam needed for experiments is at least an order of magnitude less than the specifications called for. Last, but not least, more reliable data is available on radiation damage to organics suitable for high-vacuum seals.

Under certain circumstances, e.g. near the exit port of the vacuum chamber, radiation damage becomes an important factor. An exposed vacuum seal should therefore be designed with the possibility of replacement in mind.

Extraction

Given a properly shaped and regulated guide field, a well centered beam with smallest possible betatron oscillation amplitudes, and a stable rf system, we have all the prerequisites for successful acceleration and subsequent extraction.

For reasons of structural simplicity, essentially all isochronous cyclotrons employ an electrostatic channel to start beam extraction.

Since the radial gain due to energy gain is typically below 0.050 in., most operating machines use, in one way or another, by plan or by default, the natural occuring resonance $\nu_r = 1$ at the beginning of the fringe field. All these schemes use a small first harmonic to induce a displacement of the center spread. There are now two possibilities.

In the first, which I call precessional extraction, the natural properties of the fringe field with its rapid decrease of ν_r with radius are used. This results in a precession of the center spread around the magnetic center of the machine, coherent radial oscillation.

For example, at $\nu_r = .85$, the phase advance of this precession per turn is ~1 radian; and hence the separation of the centers of two consecutive turns is approximately the coherent amplitude. The radial increase due to the precessing center spread clears the septum.

The second possibility is to use a regenerator, which forces the average ν_r to remain unity. This eliminates precessions and pushes the center spread of the beam radially out. The radial gain per turn is determined by the strength of the regenerator. And the direction of the center spread motion is given by the azimuthal position of the regenerator elements. Therefore, the extraction parameters are relaxed and less dependent on machine conditions. Whereas, direction and radial gain of the precessional extraction depend on machine tuning.

This is certainly correct for particles having all made the same number of turns, and hence remain bunched in time (separated turns). It holds true also for particles which, due to a finite phase width, have a spread in time relative to the starting point (continuum). In a continuum, however, the center spread, by inducing a coherent oscillation, will remain a continuum, as has been pointed out by H. G. Blosser. This implies that the maximum extraction efficiency is given by the radial gain per turn divided by the effective radial extent of the septum. Therefore, extraction of 100% of the beam is impossible, but 60 to 80% is quite common.

Both extraction schemes, due to the resonant exitation of the coherent amplitude, give rise to the energy compression described in Session B by H. L. Hagedoorn and H. Kim.

In the regenerative system the excitation of the axial amplitude in the $\nu_z = 1/2$ resonance has to be avoided.

In the precessional extraction, in order to gain substantial phase advance per turn, a ν_r appreciably different from unity is required. This applies in general to passing through the coupling resonance ($\nu_r = 2\nu_z$). Passing this resonance with an excessive total radial amplitude results in transforming the radial amplitude into vertical amplitude inversely proportional to the betatron frequencies.[4, 5] This not only deteriorates the optical properties of the beam but can constitute a severe beam loss, depending on axial obstructions.

The designer of such an extraction system is restricted by two opposing conditions. For good extraction efficiency the coherent amplitude needs to be somewhat larger than the incoherent amplitude. To avoid coupling, however, the sum of both remains restricted. It is evident that this points to as small an incoherent amplitude as possible.

This entire extraction mechanism relies on a decreasing guide field with radius. This in turn implies a phase shift of the accelerated particles relative to the rf. Careful field shaping is therefore important to maintain good energy resolution, especially for wide phase width. Qualitatively, one tends to enter the fringe field with the particles leading the rf so as to minimize the maximum phase excursion in the fringe field.

With all these restrictions the stringent requirements on the mechanical adjustments for the electrostatic channel are not surprising. The precision ought to be as good as the tolerances on the magnet pole pieces (a few mils, ~.1 mm).

If one chooses, instead of accelerating through the resonances, to extract with the aid of precessions before $\nu_r = 1$, a coherent amplitude needs to be maintained throughout the acceleration. It is easy to induce the necessary coherent amplitude in the center of the machine and very difficult as soon as ν_r differs from unity.

To maintain the coherent amplitude, precessional mixing has to be avoided. This implies a small number of precessions and a small phase width.

To obtain the necessary turn separation to clear the septum a coherent amplitude several times as large as the incoherent amplitude is required, unless a very high energy gain per turn is available. With increasing ν_r the coherent amplitude can be reduced, provided the energy gain per turn increases proportionally to clear the beam associated with the previous precessional turn.

One possible way to avoid these difficulties is to use a regenerative system which permits acceleration on center and forces ν_r to become unity before entering the resonances of the undisturbed fringe field. And then the extraction mechanism is as described above.

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Septums

The septum of the electrostatic channel presently limits the external beam intensity of most machines. The materials used for septums are mainly radiation-cooled tungsten or water-cooled copper. Radiation-cooled carbon can be used where relatively low VE-numbers (voltage x gradient) and modest power density can be tolerated. Septums now in use located outside of the resonances can stand the necessary beam power to produce up to 3 kW of external beam. Since the axial focusing rises sharply with radius in the fringe field, the power density for the same beam rises too, namely with the square root of the axial betatron frequency.

Computations and experiments by W. B. Powell predict a large increase in power dissipation capability for properly designed water-cooled tungsten septums.[7]

Most septums have a slot at the entrance in the median plane to distribute the dissipated power. This slot is essential for large currents. However, recent investigations by D. Clark indicate a distortion of the orbits preceding extraction due to the electric field leaking through the slot. I hope that it is obvious to every machine builder that precaution must be taken to design the septum so that it can be removed rapidly, even though it might be distorted or damaged.

Fringe Field Passage

An important point is the radial focusing in the fringe field. By keeping the beam small in radial width, non-linear distortions can be minimized. Even by choosing the best possible path (i. e., the most linear fringe field) the beam, without radial focusing, becomes so wide that a constant gradient would not be a good assumption over the width of the beam.

Iron channels, coil arrangements, and shaped electrostatic electrodes are used to not only extract but also to provide radial focusing. Since the vertical focusing in the fringe field is strong, the drift spaces together with the radial focusing devices can be thought of as an alternating gradient system.

Neglecting the radial focusing in the fringe field will not change the energy resolution of the unanalyzed beam, but the optical properties of the beam will be adversely affected. When a certain acceptance for the experimental use of the beam is prescribed this results in a net loss.

Cyclotron Development

The evolution of isochronous cyclotrons over the past few years has brought, to some extent, a standardization in design of cyclotron components. There is a lot of virtue, if one wants to do nuclear research, to copy a proven design that fills the need. This might not be very original, but there is plenty of room left for necessary and essential developments.

The benefits of machine development are threefold: 1) it enables the operational staff to stay in step with the fast-changing demands of vigorous experimental groups, 2) the understanding of the characteristics of a machine will be enhanced if thought is given to improvements. There is no substitute for understanding even if the demands on the machine deviate only slightly from the most standard operation, and 3) even modest development stimulates interest and advances the cyclotron technology as a whole.

There is no other type of machine presently available which can seriously compete in the upper energy region of presently operating cyclotrons. However, from discussions among experimental groups, which are in the market for an accelerator, one can easily gather that higher energy is an important but not a priori the decisive factor. Therefore, the machine builders are grateful when experimenters express their wishes, even if they seem entirely out of line. It is only by this stimulus that even better machines can be conceived.

Acknowledgement

I would like to express my thanks for the vast amount of information which I received directly or via status reports from many groups. I am particularly thankful to Dr. R. S. Livingston and the Organizing Committee for encouraging me to brush up on the latest cyclotron technology.

References

The primary references are private communications I enjoyed with several machine builders and users. In addition:

a) The progress and status reports submitted to this conference.

b) Nuclear Science series Report No. 26 (1959) (Sea Island Conference on Sector Focusing Cyclotrons).

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2. T. K. Khoe, L. C. Teng 63-19, 118 (1963) CERN.
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DISCUSSION

LIVINGSTON: Will you comment further on the results of the discussion between three- and four-sector machines in the region up to 100 MeV?

GRUNDER: There are two questions under consideration here. The one is depolarization of protons in the resonance, as I described it, where N, the dominant field harmonic, is the fourth harmonic; it is this, $N - (\nu_r + \nu_z) = 1.79$. You can see if N is 4, up to 100 MeV, ν_r will not exceed 1.12, and ν_z is of the order of 0.2, so you can reach 1.79. So, in principle a four-fold symmetry would avoid this resonance in the energy region up to the energy you quoted. This merely says the resonance as such is avoided; it doesn't say anything about the depolarization effects. With Teng's or Kim's formalism, it shows that the depolarization is of the order of 10^{-4}, for instance, the Berkeley 88-Inch Cyclotron.

The other question is the so-called gap resonance, described by Gordon, which has more complications than just 180° vs the symmetry of the pole tip. It also depends on whether you actually have 180°, or whether you have another configuration, such as Michigan State has. The gap-crossing resonance, as described by van Kranenburg, is equivalent to a few parts in 10^4 as long as you stay away from ν_r very close to unity; if you are in resonance with unity it is small. If I quote van Kranenburg correctly, it amounts to something like a millimeter, or so. Is this correct?

VAN KRANENBURG: Yes.

BLOSSER: I would like to make another comment on that gap-crossing resonance. You know, it is 1 millimeter if you are very careful. Another figure which can be quoted is that, given the configuration in our machine, and the way it operates N = 3, it produces an amplitude of nearly an inch. So, it can also be catastrophic if you get the wrong set of circumstances together.

GRUNDER: Yes, this was essentially included in what I said before. N = 3 means in your machine a very low relativistic particle, so you remain relatively long to unit, and since it is harmonic, the effect is obvious.

HAGEDOORN: You just mentioned all the things against three-fold symmetry. There is also one thing against four-fold symmetry, in the central region you have weak particle focusing. This means that the maximum current of the total internal beam will be less, because if your focusing forces are small, your dee is acting as a smaller diaphragm that limits the total current internally.

GRUNDER: I am in entire agreement; I am myself more inclined to three-fold symmetry. In pointing out the disadvantage of three-fold symmetry, I was merely not being prejudiced!