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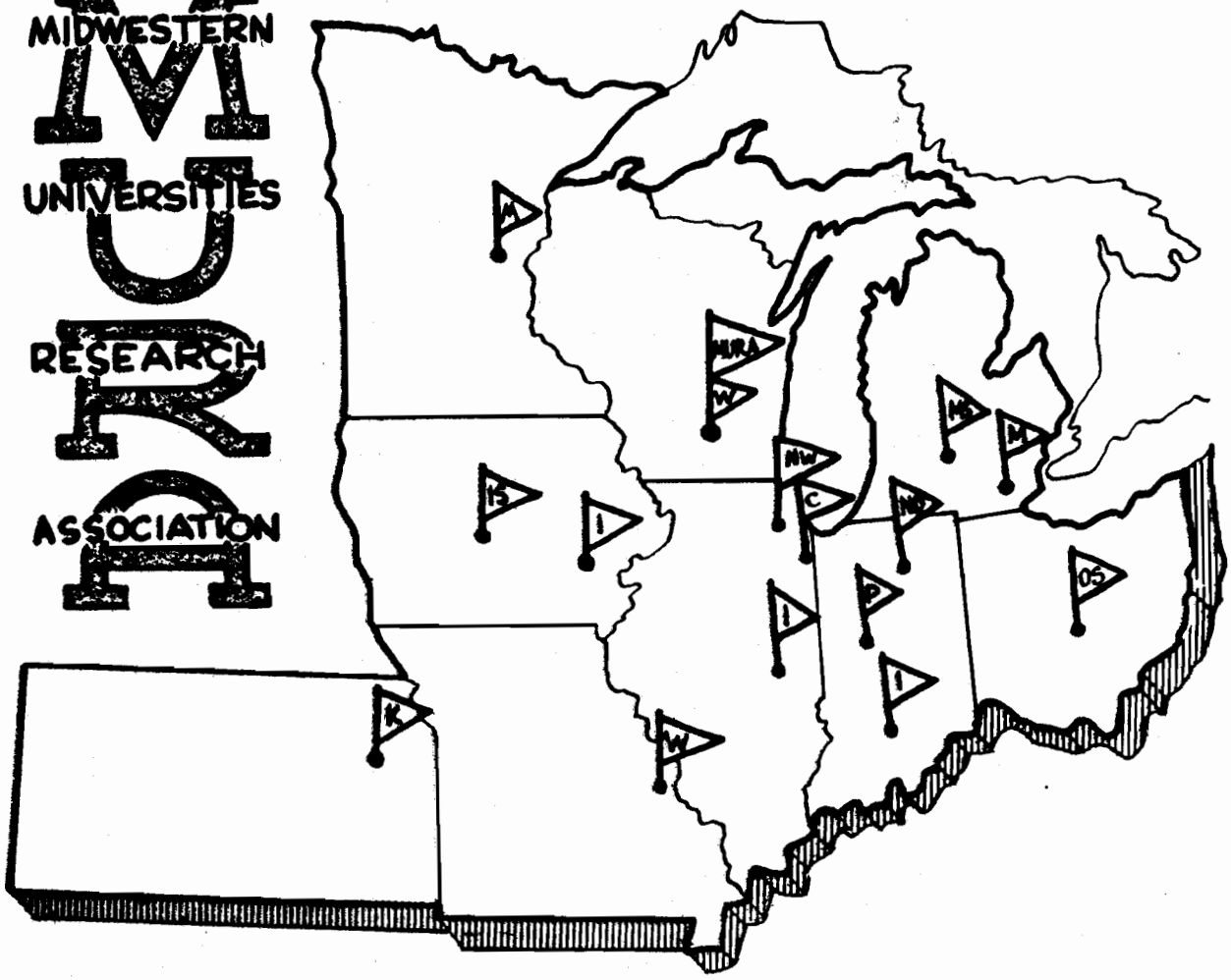

ON THE ADVISABILITY OF INJECTION FROM A CYCLOTRON

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ON THE ADVISABILITY OF INJECTION FROM A CYCLOTRON

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ABSTRACT

A survey of some of the factors which determine the properties of a cyclotron beam is given. An effort is made to determine the characteristics of a beam as far as injection is concerned, and it is indicated why a 50 Mev cyclotron is at the present inferior to the 50 Mev linac. An 850 Mev cyclotron, however, is shown as a possible replacement for the 50 Mev linac injector.

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I. INTRODUCTION

The last two years witnessed an enormous growth in the understanding of the operation of a cyclotron. The revived interest in the field was demonstrated at the meeting on sector-focusing cyclotrons, which took place at Sea Island in February of this year. Most of the problems, however, and especially those which are essential to the use of a cyclotron as an injector, are still far from being understood. The reason for this late wave of renewed interest (about a generation after the invention of the cyclotron) might be blamed on the good performance of the so-called "conventional cyclotron."* Most conventional cyclotrons yielded more intensity than was needed for most experiments, and better energy resolution (1-2 per cent) than the natural resolution of most detectors, which were used in the investigation of nuclear reactions; phase space considerations did not seem relevant; and the energy output for protons approached the calculated limit of 15 Mev.**

The discovery of the principle of strongfocusing initiated the efforts to increase the output energy, while the improvement of the detecting equipment (to energy resolution of .1 per cent) raised the question of the improvement of beam quality and intensity. A major improvement of energy, quality, and intensity of cyclotrons is needed before cyclotrons can effectively compete with linacs as injector into a synchrotron or an FFAG high energy accelerator. (We will later refer to the FFAG or the synchrotron as accelerator.)

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*The term conventional will be used here to describe a weak-focusing cyclotron, i.e., a cyclotron with $k \equiv \frac{r}{B} \frac{dB}{dr} < 0$.

**This limit, which is due to the phase shifts between the rf and the ion motion will be discussed in the next section.

An effort will be made in the following pages to state and discuss some of the features of the cyclotron performance, and especially those which are important for injection. Since only a month was devoted to the study, it is obvious that this report will be incomplete, and some of the facts stated might unfortunately be non-representative. An attempt was made, however, to survey the literature, and it is felt that the references[1-6] do present a consistent picture. It is the writer's belief that any possible value of this report lies in its presentation of the problems, rather than in its attempt to give quick answers.

The opportunity will be used in this report to elaborate on the problem of phase space beyond the expected scope of this report. This will be done for two reasons: It is felt that it is not understood by many who start working in the field (the writer included); and it is hoped that the little understanding which was achieved in the present study, together with the still existing misconceptions which might be displayed, would serve as a catalyst to the clarification of this problem. The question of resonances, integral and non-integral, essential and imperfection, etc., is another example of a field which can stand some clarification and standardization for the benefit of the "newcomer" to the field of high energy accelerators.

It seems that the choice of an injector for the MURA accelerator depends on a variety of considerations. There are some requirements, such as intensity, energy, energy resolution, phase density, etc., which are primarily dictated by the accelerator; on the other hand, there are such questions as size and cost which can be considered independently to a great extent. The next six

sections will be devoted to the discussion of these requirements; the discussion will be summed up and some conclusions will be drawn in the last section (Section VIII). A comparison with an equivalent linac will be given in several cases, although the present study was devoted to cyclotrons only.

II. INJECTION ENERGY

It can be said simply that the higher the energy of the injector the better. The space charge limit of the accelerator is determined by the energy of injection; the range-of-frequency modulation can be reduced for higher injection energy; magnetic field errors in the low field end become less critical; and the repetition rate can be increased. At the present it is accepted to consider 50 Mev linacs for injection. For the acceleration of H_2^+, however, which might be needed for transparent inflection (see Section IV), 100 Mev H_2^+ are required to yield 50 Mev protons.

It was impossible to accelerate protons to such energies with conventional cyclotrons because of the relativistic mass increase, which causes phase shift between the (fixed frequency) rf and the particle motion. A simple-minded calculation, using a flat field (which is the limiting case of a conventional cyclotron) and a continuous acceleration given by $\frac{dT}{dn} = 2\,e\,V\cos\phi$ yields for the maximum kinetic energy T:

$$T = \sqrt{\frac{2}{\pi}\, e\, V\, E_o} \quad ,$$

where n is the number of revolutions, e is the electron charge, V is the peak dee-to-dee voltage, ϕ is the phase shift, and E_o is the rest mass

of the accelerated particle. This expression is for particles which start "in phase" ($\phi = 0^{o}$) and end "out of phase" ($\phi = -90^{o}$).

For V = 200 kv, this expression yields

$$T \simeq 11 \text{ Mev} .$$

If electrical defocusing and other difficulties are overcome, and the particles start at $\phi = +90^{o}$, the energy can be raised by a factor $\sqrt{2}$.

With the introduction of focusing with azimuthally varying fields, it became possible to make $\bar{k}(r) \equiv \frac{r}{\bar{B}} \frac{d\bar{B}}{dr} > 0$ (where $\bar{B}(r) \equiv \frac{1}{2\pi} \int_0^{2\pi} B(r, \theta)\, d\theta$) and thus to achieve isochronism between the rf and the particle motion up to indefinitely high energies. A group at Oak Ridge[2] suggests an 850 Mev isochronous* cyclotron. The problem in their proposed machine, which has 12 magnetic sectors and 4 accelerating gaps, seems to be crossing of the resonances rather than isochronism. They believe, and they have performed some calculations and model experiments to support their belief, that neither the quality nor the intensity should be much affected by the acceleration to such a high energy. As a matter of fact, they have found the interesting phenomenon that due to non-linear forces, some resonances act as filters. They transmit particle with small amplitudes of betatron oscillations almost unaffected, but filter out those with large amplitudes.

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*The term isochronous means in effect no phase shift. Since the cyclotron equation is $\omega(\text{orbit}) = \frac{e\bar{B}}{m} = \frac{e\bar{B}}{m_o \gamma}$, isochronism which means that $\omega(\text{orbit}) = \omega(\text{rf}) = \text{constant}$, will be achieved if $\bar{B}$ will vary with the radius as $\bar{B}(r) = B(o)\,\gamma = \frac{B(o)}{\sqrt{1 - \frac{\omega^2(\text{rf})\, r^2}{c^2}}}$.

III. INTENSITY

All existing reports (see for instance Table I in Section VII) indicate that the internal beam is 1-3 ma and can probably be increased to 5 ma. On the other hand, only 10-20 per cent of this intensity is extracted so that a practical number at the moment is 200 μamp. although the number might be raised with some effort up to 1 ma. Only 100 μamp. out of these 200 are transmitted[5] through 0.2 per cent slits.

In the 1958 MURA Proposal[1] the expected injected current from a linac is 10 pulses per second, each lasting 750 μsec. with instantaneous intensity of 5 ma. The time-average injected intensity is therefore

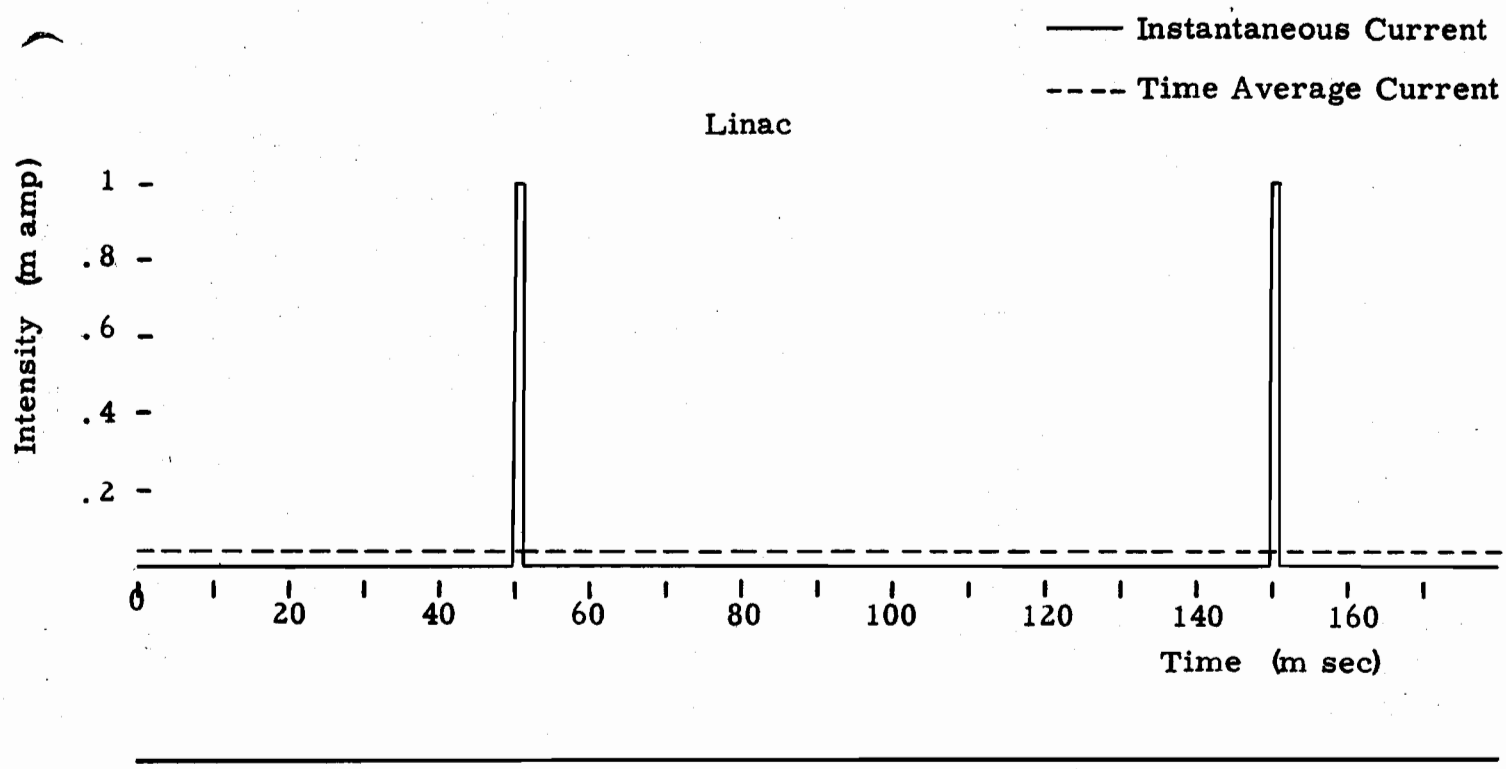
$$\bar{I}_t = 5000 \times 10 \times 750 \times 10^{-6} = 37.5\,\mu\text{amp.}$$

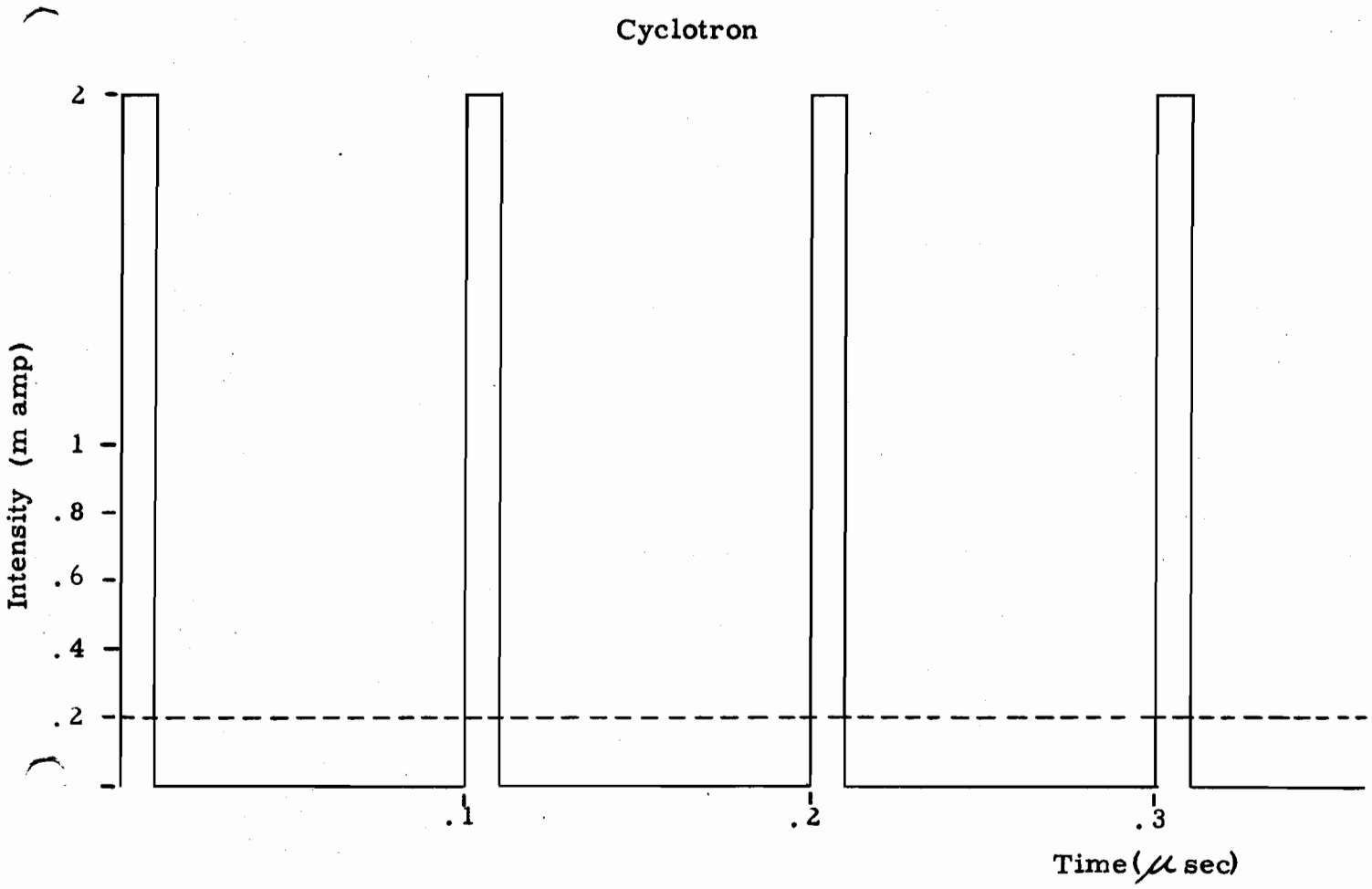
This means that the expected and adequate time-average intensity needed is only 20 per cent of present-day extracted beams from cyclotrons. The expected increase in cyclotron internal beams and efficiency of extraction is expected to compensate for the loss of intensity in the energy defining slits, so that this ratio of 5:1 seems reasonable.

Intensities as functions of time are plotted qualitatively in Fig. 1 for both a linac and a cyclotron. Note that the intensity scales are the same, but the time scales are different. Time-average intensities are also plotted, with the ratio of 5:1 in favor of the cyclotron indicated. It should be noted however, that 100-turn injection will last $\sim$ 750 μsec., after which it is at the moment impossible to inject, since it takes the rf of the accelerator 65 m sec. to complete the acceleration, 10 m sec. to be turned off, and 25 m sec. to fly back. This means that it is ready for injection less than

Fig. 1

Intensity vs. Time





1 per cent of the time, or just the length (which is adjustable) of the linac's pulse, so that the ratio 5:1 in favor of the time-average intensity of the cyclotron is only of academic interest at the present. Any further improvement in the repetition rate of the accelerator will enhance the importance of the continuously high time-average current of the cyclotron.

The linac's pulse is constant in intensity throughout the 750 μsec. of injection due to the use of a debuncher; the cyclotron beam however consists of 7500 pulses during the 750 μ sec. of injection. During the period of injection, the cyclotron has at the present two disadvantages, it has a lower time-average intensity and the current is strongly bunched (a factor of 10), an effect which tends to lower the space charge limit of the accelerator.

It should always be kept in mind that the ideal is a single-turn injection with a uniform charge distribution. About .2 amp. are needed for the proposed MURA machine so that all present injectors are at least two orders of magnitude below this requirement. Since the accelerator is ready for injection only 1 per cent of the time, it would be interesting to investigate the possibility of storing the injector's beam for 100 m sec., and injecting it 10 times a second.

IV. OUTPUT PHASE SPACE

The strongest objection to using a cyclotron for injection is its large beam spread especially in the radial direction. Although nobody has ever measured it, the general feeling is that the betatron oscillation phase space in the cyclotron is at least ten times larger than that of the linac. Since the injector's output phase space defines the minimum admittance of the accel-

erator, it is obviously important to keep this phase space small. It is also essential to keep this space small (or equivalently--to keep the phase density high) in order to increase the number of possible injected turns (Ref. 1, p. 48).

It might be profitable to pause here and discuss this last statement, since it is felt that it is by no means "self evident." Let us rephrase the statement and put it in the mouth of person M:

M - Let the injector's phase space be A_i and the accelerator's admittance be A_a; $n = \frac{A_a}{A_i}$ is then the maximum number of injected turns.

S (Sceptic) - Instead of "painting" the space A_a with small-space high-density spots, I would like to use large-space small-density spots and achieve the final density by overlapping the spots.

M - Overlapping spots, or parts of spots, increases the phase density and this violates Liouville's theorem.

S - Do you measure the density of phase space by looking at a certain beam cross section at a given instant?

M - An injected particle sees a certain phase space density in its neighborhood, measured by the number of neighboring particles. This number cannot change after injection because of Liouville's theorem.

S - It is wrong to consider phase space as the actual neighborhood of a particle. If you want to associate phase space or orbits with particles, you should consider the neighborhood of a particle at each instant as consisting of all orbits of all particles which are emitted by the ion source from $t = -\infty$ to $t = +\infty$. Since the ion source is capable of

emitting infinite density, a smart physicist should be able to paint A_a indefinitely without violating Liouville's theorem.

M - You ignored the following practical point. Let us suppose that you fill up A_a in n turns, injecting at a definite point in the accelerator. If you want now to inject turn (n + 1) into same A_a, the first turn should physically return to the same location and hit this inflector. The way to beat this difficulty is to make a so-called "transparent inflector." One possibility is to inject H_2^+ ions and dissociate them upon their leaving the inflector, so that the inflector will not be in their way when the two protons return.

S - This argument is sound. It seems that an alternative way might be the dissociation of the ions after n turns, but before they return to hit the inflector.

The preceding imaginary discussion illustrates three points: (a) there are many misconceptions in regard to phase space limitations; (b) it is important for an injector to have a small phase space output (or large phase density); and (c) the number of injected turns can be increased by any scheme which uses a transparent inflector. Such a scheme was described by Moon,[4] who suggested the use of H_2^+ ions and then dissociate them by collision with hydrogen-gas molecules.

The question which is often asked is: why is the cyclotron phase space large? It seems that it is a combination of factors which results in this large phase space. The electric field which pulls the ions out of the source, together with the initial velocity distribution and the finitude of the apertures in the

chimney and puller introduce a certain initial width. Upon emergence, space charge gives the particles transverse acceleration. Since the axial aperture is severely limited by the dees, high intensities are achieved in cyclotrons due to the large radial acceptance. The proposal for a Southern Regional Accelerator[2] sums the situation up in this way. "The cyclotron beam apparently occupies an inordinately large area in the radial phase space and has an inordinately low density in the axial phase space. This combination is not exactly suited for efficient handling at extraction. The above difficulties are multiplied by the fact that $\nu_x = 1$ is an integral and half-integral resonance so that residual magnetic field errors may magnify the already large radial amplitudes." The existence of a second harmonic in the electric field also tends to blow the beam up. In spite of these arguments, the Oak Ridge people believe that with the help of four (instead of two) accelerating gaps, with focusing grids, and with the azimuthally varying field extending clear to the center, "the cyclotron will supply a beam of between one and ten milliamperes with a quality of 2×10^{-4} centimeter-radians in both the radial and axial direction." They thus think that there is no reason why a cyclotron should be inferior to a linac with respect to beam quality, but they add, "needless to say, some further calculations as well as experimental work on this question are very much in order."

It is appropriate to ask at this point whether phase space is really such a great handicap, or whether there are other factors, such as space charge, etc., which limit the injected intensity even before the phase space

factor becomes critical. The question of space charge will be discussed in the next section.

V. SPACE CHARGE

The 1958 MURA Proposal[1] states that "with multi-turn injection, the maximum current which can be injected is limited not by properties of the injector, but by space charge effect within the accelerator."

Since $I \sim (\beta \gamma)^3$, it is clear that it is advantageous to raise the energy of the injected beam. Since $I = Q \times f$ where Q is the total injected charge and f is the frequency of revolution, it is possible to use the data of p. 111 of the Proposal in order to calculate the maximum injected current for the proposed machine which is set by space charge limitation:

For 50 Mev Injector $I = 0.65$ amp.

For 200 Mev Injector $I = 2.81$ amp.

For 500 Mev Injector $I = 7.94$ amp.

These numbers clearly show that although a 100-turn injection of 5 ma will not reach the space charge limit for 50 Mev, it comes very close to it. This limit seems at the moment to be of a limited significance as far as a cyclotron is concerned unless either the output intensity of the cyclotron is increased by two orders of magnitude, or the phase density output is increased, or a multi-turn scheme is devised which uses some kind of a transparent inflector.

The bunching of the cyclotron beam was mentioned in Section III, where it was estimated that this bunching ($\sim 36^\circ$ out of 360° within the cyclotron)

lowers the space charge limit by a factor of ten. It should be realized, however, that this effect can be appreciably, though not completely, reduced by choosing the cyclotron frequency ω (cyclotron) such that

$$\omega \text{ (cyclotron)} = (m \pm 0.1) \quad \omega \text{ (accelerator)},$$

where m is an integer. This choice will enable successive injected turns to fill up the empty spaces between bunches, so that in ten turns the whole circumference of the accelerator will be filled up uniformly. The possibility of a debuncher for the cyclotron is not ruled out as well; it will be of extreme importance if and when the way will be found to inject .2 amp. in one turn.

IV. ENERGY RESOLUTION

When the participants of the Sea Island Conference were asked what energy resolution $\left(\frac{\Delta E}{E}\right)$ they were getting from their cyclotrons, it turned out that almost no one had made a good measurement. The reasons for this situation were explained in Section I, and suffice it to say here that in most cases a good energy resolution was not needed, and whenever it was needed, analyzing magnets were used to improve the energy resolution on the expense of the intensity. The only number which was quoted at Sea Island was 1-2 per cent.*

The proposed MURA accelerator requires an injector which has the lowest possible energy spread. The reason is simple. Particles which are injected at energy E_1 with a spread ΔE_1 occupy in synchrotron phase

*By F. H. Schmidt from the University of Washington.

space an area $A_1 = 2\pi \frac{\Delta E_1}{f_1}$, where f_1 is their orbital frequency. When these particles are stacked at energy E_2, their phase area is $A_2 = 2\pi \frac{\Delta E_2}{f_2}$. Liouville's theorem says that $A_2 \geqslant A_1$, so that $\Delta E_2 \geqslant \Delta E_1 \frac{f_2}{f_1}$ or for the MURA accelerator $\Delta E_2 \geqslant 3\ \Delta E_1$. For .1 per cent - 50 Mev injection this means $\Delta E_2 \geqslant 150$ Kev.

This lower limit is very small when only one bucket is used. If stacking is considered, the maximum number of injected turns becomes

$$n_p = \frac{A}{A_1} = \frac{\Delta E}{\Delta E_1} \frac{f_1}{f_2} \simeq \frac{1}{3} \frac{\Delta E}{\Delta E_1} ,$$

where A is the available phase area and ΔE is the tolerated energy spread in the stacked beam. A required 1 per cent energy resolution of the stacked 15 Bev beam yield $n_p = 1000$ for a .1 per cent injector and $n_p = 100$ for a 1 per cent injector, which means that the present-day 1 per cent cyclotron can stack only one-tenth of the beam which can be stacked when the expected linac is used.

Before an attempt is made to improve the energy resolution of the extracted beam from the cyclotron, the reasons for its poor performance should be spelled out. Since the gain per turn δE for the last orbits in a conventional cyclotron is at most 100 Kev, 1-2 per cent energy resolution means that at least 5-10 orbits are extracted by the deflector. Since $E \sim r^2$, $\frac{\delta r}{r} = \frac{1}{2} \frac{\delta E}{E}$. If E = 50 Mev, δE=200 Kev, r = 30", then δr = 1/16". An electric deflector which has a thin (preferably 1/16" if only possible)septum is now introduced, but it is impossible to extract only one turn because of the radial betatron oscilllations. Since the radial betatron amplitudes are

about one order of magnitude larger than δr, and since precession of orbits is caused by the inequality $\nu_x \neq 1$, ten orbits on the average enter the deflector and are extracted.

The solution to this unfortunate situation lies mainly in the feasibility of extraction of a single orbit. The scheme which is generally used in these cases is the Le Couteur scheme of regenerative deflection.[7] An efficient extraction of a single orbit will yield energy resolution of less than $\frac{\delta E}{E} \simeq \frac{.2}{50} = .4$ per cent.

VII. SIZE AND COST

The cyclotron is undoubtedly superior to a linac as far as size is concerned. Even the 850 Mev cyclotron magnet is only about 40 feet in diameter, and the dee-stems and rf assembly do not occupy too much room, especially if the cyclotron is kept vertical. There are two advantages to this compactness: (a) it is easy to place even the largest cyclotron inside the accelerator, and (b) there should be some savings in cost for the injector housing.

It is hard to arrive at a reasonable estimate of the total cost of a 50 Mev injector. Michigan State estimates that their 40 Mev cyclotron will cost $\$1.5 \times 10^6$; this estimate however is for a variable energy multi-particle cyclotron. The data in Table I, which were taken from Howard's Report,[6] may serve as a guide for making some sort of an educated guess as to the cost of a 50 Mev cyclotron injector. A word of caution about this Table should be added. The quoted costs represent estimates taken at various countries for cyclotrons which were built at various dates. Some estimates include

TABLE I. COST OF FIXED FIELD CYCLOTRONS

	Energy (Mev)	Fixed or Variable	Weak or Strong Focusing	Internal Beam (μa)	External Beam (μa)	Cost ($)
Brookhaven	3	F	W	1000 - 2000	800	110,000
Birmingham, Ala.	4	F	W	?	?	120,000
Oak Ridge	5	F	W	$\leq$ 1,000	?	100,000
St. Louis	5	F	W	?	300	750,000
Osaka, Japan	6	F	W	30	5	100,000
Zurich	7.2	F	W	150	30	$\sim$ 100,000
Pretoria, S. Africa	7.5	F	W	?	?	280,000
London	7.5	F	W	?	?	420,000
MIT	7.55	F	W	?	50	100,000
Carnegie Tech.	8	F	W	120	10	250,000
Canberra, Australia	8	F	W	3,000	10	50,000
N. S.A. Cleveland	10	F	W	?	80	1,000,000
Pittsburgh	10	F	W	200	40	200,000
Argonne	10.8	F	W	350	125	1,790,000
Seattle	11	F	W	1,000	300	900,000
Stockholm	11	F	W	?	?	> 500,000
Saclay	11	F	W	100	10	600,000
Melbourne	11	F	W	750	30	98,000
Livermore	15	V	W	200	15	1,000,000
Tokyo	15	V	W	600	80	650,000
Oak Ridge	25	F	W	2,000	40	> 700,000
Colorado	30	V	S	?	?	750,000
Michigan State	40	V	S	1,000	200	1,500,000
N.R.D.L. San Francisco	70	F	S	?	?	1,515,000
Oak Ridge	75	V	S	?	?	3,000,000
Florida	400	F	S	?	?	5,000,000
Oak Ridge	850	V	S	?	100	5,300,000

buildings and accessory equipment, whereas others do not. With this understanding in mind, a plot of energy vs. cost is presented in Fig. 2. A rough interpolation yields $\$(1.8 \pm .5) \times 10^6$ for a 50 Mev proton cyclotron. This number is only slightly lower than the $\$2.2 \times 10^6$ which was Brobeck's cost estimate for the 50 Mev linac injector at Brookhaven.

VIII. CONCLUSIONS

Very little is known at the moment about the actual performance of an azimuthally varying field cyclotron. The data given in Table II, which was assembled from publications by U. C. L. A.[8] and Oak Ridge[2] present a clear view of the expected performance of the A. V. F. cyclotrons which are at the present either running, constructed, or studied.

There are several serious disadvantages to using a cyclotron for injection. Its time-average intensity for the duration of injection is low, and the current is bunched so that the space charge limit is lowered. It has an energy resolution 5-10 times worse than the linac unless an effective way is found to extract most of the beam from one orbit. The worst disadvantage concerns phase space. It is clear that unless this quality is improved, a cyclotron cannot be used as an injector, especially when multi-turn injection is considered.

There are many features of the cyclotrons which need a better understanding, which, so it is hoped, would lead to an improved performance. The ion source region is one of the most important areas. The research should go in the direction of increasing the intensity and decreasing the phase

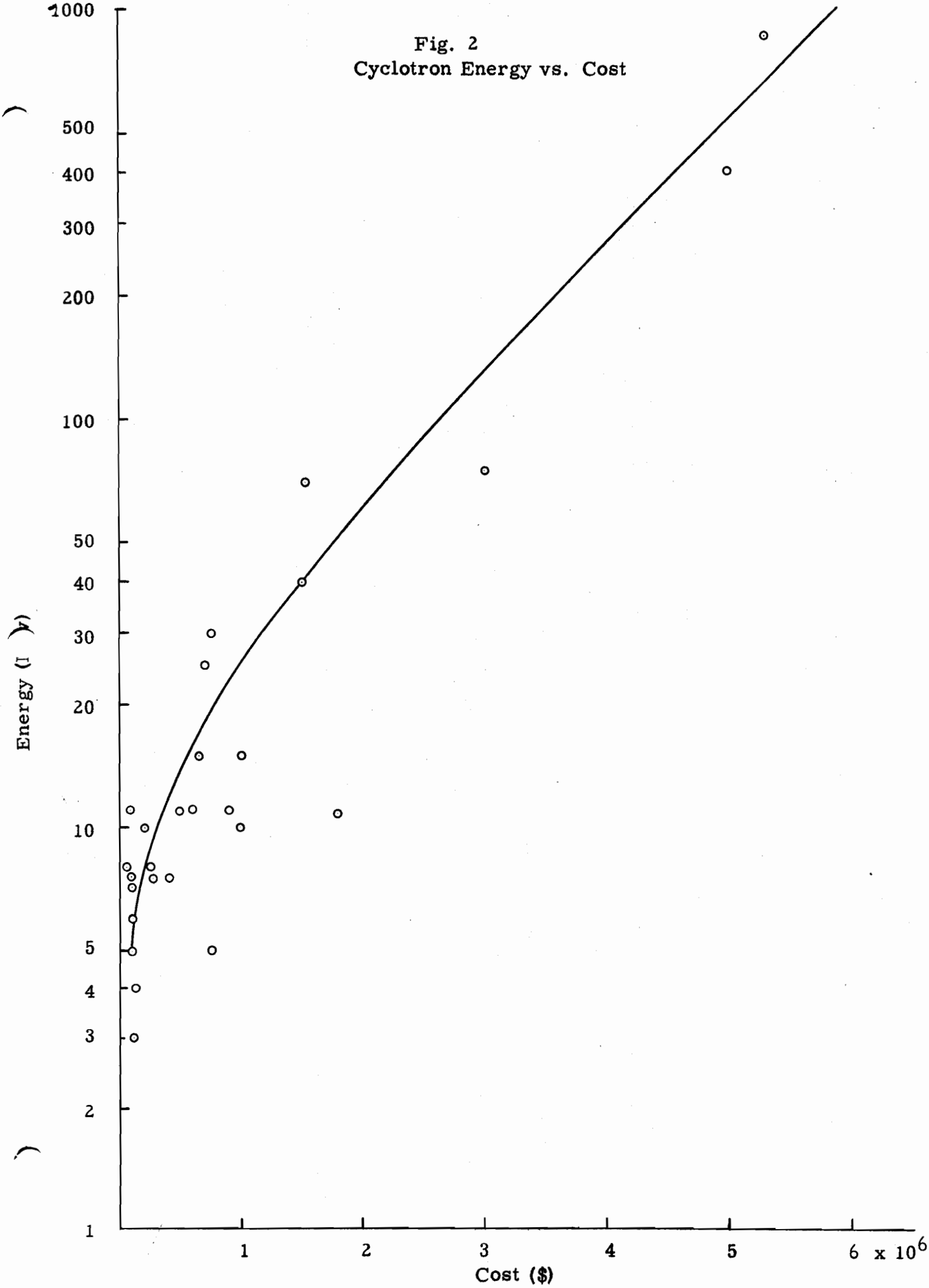


Fig. 2
Cyclotron Energy vs. Cost
Energy (MeV)
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
1
2
3
4
5
6 x 10^6
Cost ($)

TABLE II. SECTOR FOCUSING CYCLOTRONS

	Status	Completion Date	Frequency Ratio	No. of Hills	Hill Field (KG)	Valley Field (KG)	Max. Spiral Angle (Deg)	Max. Orbit Radius (inch)	No. of Dees	Dee to Ground Voltage	Internal Beam Current (ma)	Proton Energy (Mev)
Los Alamos	Running	1954	$\sqrt{3}$:1	3	18	16.4	0	19	2	70	2	9
UC Davis	Const.	1961	2:1	4	22	16	0	10	2	30	0.5	12
Illinois	Debugging	1959	2:1	4	17.6	14.4	66	18.5	1	50	1	15
Colorado	Const.	1961	3:1	4	16	10	40	24	1	75	1	30
Michigan	Proposal	1962(?)	$\sqrt{2}$:1	4	15 (Average)		73	33	2	100	1	40
MSU	Design	1962(?)	$\sqrt{2}$:1	3	18	8	5	26	2	70	1	40
UCLA	Const.	1959	Fixed	4	25	16	47	21	2	50	0.1	50
ORNL	Const.	1961	3:1	3	21	7	20	31.5	1(?)	70	1	75
NRDL	Study	?	?	4	22	13	45	31	2	100	1	80
Harwell	Design	?	Fixed	4(?)	23	16	78	50	1	50-75	0.05	240
Florida	Study	?	3:1	6	23	?	65	82	4	185	0.1	400
ORNL	Study	?	Fixed	12	22	?	?	205	12 cavities	(250)	0.1 (external)	900

space of the beam from the ion source. Space charge and radial blowup effects due to $\nu_x = 1$ at the center should be investigated. Attempts should be continued to calculate and construct field configurations which will result in maintaining the same beam intensity and quality throughout the acceleration process.* The possibility of storing the beam during the 99 per cent of the time when the accelerator is not ready for injection should be looked into. An effective single orbit deflector should be devised for the sake of improvement of the energy resolution. A scheme should be found for extraction of the beam from the region of the fringing field without worsening its quality. As far as multi-turn injection is concerned, all possibilities of transparent inflection should be studied. Disregarding momentarily the problem of the availability of physicists for such a research, it is felt that MURA could be of great help in the field in providing its facilities for a "Cyclotron Improvement Group" headed by a senior theorist and a senior experimentalist.

Any attempt to compare a cyclotron with a linac for injection stands the risk of comparing existing cyclotrons with ideal linacs or vice versa. No sincere attempt of comparison is tried here since only a little amount of time has been devoted to the study of cyclotron characteristics and no time has been devoted to linacs. It is also feared that conclusions based on few facts stand a great chance of being misleading. Nonetheless, it is felt that it is possible to come to at least tentative conclusions on the question of the

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*Preliminary measurements in the remodeled cyclotron of the University of Illinois (which has a field which rises with radius, and 7/8" spiral shims) show that all the internal beam which reaches the region of strong focusing (from r = 6") can be accelerated up to the deflector.

advisability of injection from a cyclotron.* Two possible injection energies are considered in this report: 50 Mev, and 850 Mev (some mention is made of 100 Mev for H_2^+). The advantage of a 50 Mev cyclotron over a linac seems to be limited at the moment to one-feature size, and probably cost, although the difference is small. The 850 Mev, if its performance fulfills the hopes of its designers, has a tremendous advantage over either the 50 Mev cyclotron or the 50 Mev linac. Since it is difficult to conceive of an 850 Mev linac which will serve as an injector, it seems that the $\$5.3 \times 10^6$ - 850 Mev cyclotron, if built, could be of great use to all accelerators, with or without stacked beams.

Unless and until a further study indicates a major improvement of 10-100 Mev cyclotrons, it is strongly felt that it is not advisable to use them for injection. The 850 Mev cyclotron, however, has a tremendous potentiality and should therefore be seriously considered before a final decision on the kind of injector is made.

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*The conclusions will be presented in terms of a comparison with a 50 Mev linac for reasons of ease of presentation.

REFERENCES

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