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I. INTRODUCTION

Particles accelerated in A.V.F. cyclotrons are usually confined in a phase interval, with respect to the r.f. which is of the order of 15° to 45°, FWHM. These phase widths are further reduced to 5° - 10° if good quality and energy resolution of the external beam are required. Thus, when beams from d.c. external sources are injected into the cyclotron, low injection efficiencies are obtained. This issue is an important one when polarized ion sources are used, since they produce only small d.c. currents.

To obtain better matching of the d.c. external source to the cyclotron a beam bunching system[1] can be used, which concentrates the particles initially spread over an entire r.f. period into the narrow phase range accepted by the cyclotron. The main advantages thus obtained will be: 1) An intensity increase for phase bunching into the 30° - 45° range. 2) An improvement in beam quality if one succeeds in bunching down to 5° - 10°. Klystron-type bunchers, which apply a sinusoidal energy modulation to the d.c. beam are by now in operation at various Van de Graaff and tandem accelerators.[2,3] They are generally used to produce short beam pulses, in the nanosecond and subnanosecond range, for time-of-flight work. In these systems the beam is first chopped and then bunched, since the emphasis is on small pulse width rather than on maximum transmission. Several cyclotrons have used klystron-type bunching with external injected beams, including the Birmingham and Saclay cyclotrons. Where intensity increase is the main goal, it seems that sinusoidal-type bunchers are limited in their phase acceptance, which is of the order of 180°. Also it is difficult to obtain the 5° - 10° phase width necessary for best quality. The reported intensity gain, at Birmingham, is about 2.2, which points out that different operation modes should probably be used in order to get higher current gains. Among the possible improvements are use of several acceleration gaps with various harmonic sine-wave frequencies, or use of a sawtooth voltage wave shape. In this report a scheme of a sawtooth wave buncher, to be used in the axial injection system at the 88" cyclotron, is discussed, together with the limitations which can be envisaged at the present stage of the project.

II. BUNCHER MATHEMATICS

As is well known, bunching of d.c. ion beams is done by controlling the acceleration at one or more gaps, according to the crossing time. Later particles are accelerated relative to early particles and then allowed to drift to the place where bunching is required.

In order to obtain a fully bunched beam the velocity change at the gap should increase linearly with time. This fact leads naturally to the choice of an accelerating gap driven by a sawtooth oscillator, having the same frequency as the cyclotron. The bunching system we propose is shown schematically in Fig. 1. The sawtooth voltage wave is applied to a drift tube of length $\underline{s}$, the accelerating gaps being at A and B. After B particles travel a distance $\underline{d}$ to the cyclotron center, where we require the maximum amount of bunching.

We derive now a few formulas characterizing the buncher operation, under the following simple assumptions:

a) Peak accelerating voltage small compared to the injection energy, so that the velocity change is proportional to the voltage at the gap crossing.

b) Narrow gap at A and B, i.e. we disregard transit time effects in this section.

c) Equal length trajectories between A and the cyclotron center.

d) Monochromatic injected beam.

e) No space charge effects.

More realistic assumptions will be taken into account later and their consequences evaluated for our specific case. Suppose the incoming beam has an energy E_o, velocity v_o, the cyclotron being operated at a frequency $f = 1/\tau$.

The particles to be bunched, within each r.f. period, cross the gap A at times $0 \leqq t \leqq \tau$ their velocity being increased by (see Fig. 2):

$$\Delta v(t) = \Delta v_p \frac{t}{\tau} \quad . \tag{1}$$

Let us assume as a reference particle, around which all others will be bunched, the one which crosses gap A at t=0. We further require its energy to be unaffected even by the second gap at B, thus providing the relationship:

$$s/v_o = n\tau \quad , \tag{2}$$

n being an integer.

All other particles, initially spread over the r.f. period τ, will be partially bunched while travelling over the distance s, and at B will fill a time interval given by

$$\Delta t_B = \tau + \frac{s}{v_o + \Delta v_p} - \frac{s}{v_o} = \tau - \frac{s\Delta v_p}{v_o(v_o + \Delta v_p)} \tag{3}$$

and using Eq. (2),

$$\Delta t_B = \tau \left(1 - \frac{n\Delta v_p}{v_o + \Delta v_p}\right) \tag{4}$$

or

$$\Delta t_B/\tau = 1-n\Delta v_p/(v_o + \Delta v_p) = K < 1 \tag{5}$$

At the second gap B, due to the asymmetry of the wave, a debunching effect will occur. With the present choice of the zero line, gap A is accelerating for all particles, and gap B is decelerating. The velocity decrease at B, as a function of crossing time, follows a law exactly analogous to (I). However, due to the bunching effect from A, the deceleration at B will be less than the acceleration at A, thus leaving a velocity spread in the beam which allows a further bunching action in the flight path d.

From Eq. (4) we observe that the last particle in the bunch crosses the gap B at a time:

$$\Delta t_B = \tau \left[1-n\Delta v_p/(v_o + \Delta v_p)\right]$$

after the reference particle. It experiences a velocity decrease given by:

$$-\Delta v_p \frac{\Delta t_B}{\tau} = -\Delta v_p \left[1-n\Delta v_p/(v_o + \Delta v_p)\right]$$

As a consequence, the particles will have, after B, velocities in the range between v_o and

$$v_o + \Delta v_p - \Delta v_p \left(1 - \frac{n\Delta v_p}{v_o + \Delta v_p}\right) = v_o + \frac{n(\Delta v_p)^2}{v_o + \Delta v_p} \tag{6}$$

or using Eq. (5)

$$v_o \leqq v_B \leqq v_o + \Delta v_p(1-K) \tag{7}$$

The bunch width at B, Δt_B, will then reduce to zero after the distance d if it equals the difference in flight times:

$$\Delta t_B = \frac{d}{v_o} - \frac{d}{v_o + \Delta v_p(1-K)} = K\tau$$

Solving for d we get:

$$d = \frac{K\tau v_o[v_o + \Delta v_p(1-K)]}{\Delta v_p(1-K)} \tag{8}$$

For small values of Δv_p, Eq. (8) is well approximated by

$$d = \frac{K\tau {v_o}^2}{\Delta v_p(1-K)} \tag{9}$$

The dependence of d upon s is explicitly obtained inserting K from Eq. (5)

and s from Eq. (2) in the formula above, and assuming $\Delta v_p \ll v_o$ we get:

$$d = \left(1 - \frac{s\Delta v_p}{\tau v_o^2}\right) \frac{(\tau v_o^2)^2}{s(\Delta v_p)^2} \qquad (10)$$

Putting

$$\alpha = \frac{\tau v_o^2}{\Delta v_p} = \frac{s}{1-K} \qquad (11)$$

we finally get

$$d = \frac{\alpha^2}{s}\left(1 - \frac{s}{\alpha}\right) = \frac{sK}{(1-K)^2} \qquad (12)$$

We see that d tends to infinity for $s \to 0$, which means physically that for small s the accelerating and decelerating gaps will have nearly zero net effect, requiring a long drift distance for bunching.

III. MATCHING THE CYCLOTRON REQUIREMENTS

The formulas derived above can now be used in order to estimate a reasonable set of values for d, s, and Δv_p. However we have still to consider the requirements the buncher has to meet in order to match the cyclotron for both variable energy and particles.

In the injection transport system the magnetic field increase near the median plane acts as a strong focusing lens or "hole lens".[4] It is convenient to have constant orbit geometry through this lens, as stated in requirement (1) below. In our present axial injection system the particles are injected along the magnet axis for all cases. As a consequence it is necessary to scale properly the injection energy and the dee voltage, at the various magnetic field settings, in order to keep the orbits centered at all times. This is described by requirement (2) below.

The two requirements are:

1) Constant orbit geometry through the injection magnetic field B, for optimum injection optics. This requires an injection voltage $V_i \propto \frac{QB^2}{M} \propto \frac{f^2 M}{Q}$ where M and Q are particle mass and charge.

2) Centering of the cyclotron orbits. This requires a dee voltage $V_D = KV_i$ where K = .2-.3.

So $V_D \propto V_i \propto QB^2/M$ from 1) above. This means constant cyclotron orbit geometry during acceleration. An upper limit $V_D \leq 60$ KV on the available dee voltage sets an upper limit $V_i \leq 20$ KV on the injection voltage for injection on the magnet axis.

The restriction on parameters set by the buncher are as follows. A fixed geometry, i.e. constant <u>d</u> and <u>s</u>, would be preferable to avoid many construction problems. If <u>s</u> has to be constant we get from Eq. (2):

$$v_o \propto \frac{1}{n\tau} \propto \frac{f}{n} \tag{13}$$

where we allow for possible variations of the interger <u>n</u>. In terms of injection energy we get:

$$E_o = QV_i \propto Mv_o^2 \propto M \frac{f^2}{n^2} \propto \frac{E_f}{n^2} \tag{14}$$

where E_f is the full energy of the accelerated beam, and for injection voltage:

$$V_i \propto \frac{M}{Q} \frac{f^2}{n^2} \qquad (15)$$

We see that the buncher requirement matches the requirement (I) of the cyclotron above.

If also d has to be constant we have from (12) that α is constant and from (11) we find the requirement for the modulating voltage:

$$\alpha = \frac{\tau v_0^2}{\Delta v_p} = \text{constant}, \qquad \Delta v_p \propto \tau v_0^2 \propto \frac{v_0^2}{f} \qquad (16)$$

and from (16), (13):

$$\Delta v_p \propto \frac{f}{n^2} \qquad (17)$$

From (17), (13) we get for the ratio of modulating to injection voltage:

$$\frac{\Delta V_{ip}}{V_i} \propto \frac{\Delta v_p}{v_0} \propto \frac{1}{n} \qquad (18)$$

Therefore we conclude that:

a) The proposed buncher can in principle match continuously, at constant geometry, the cyclotron requirements, by proper variation of the injection energy (14) or voltage (15).

b) The modulating voltage applied to the gaps is a fixed fraction of the injection energy as given by (18).

c) The additional cyclotron requirement of orbit centering then implies constant orbit geometry during cyclotron acceleration.

IV. TYPICAL BUNCHER PARAMETERS

We turn now to a preliminary design of the buncher, according to the formulas derived above, for the 88" cyclotron axial injection system. For use with the polarized ion source we confine ourselves to the proton and deuteron cases. For α particles the operating parameters are the same as for deuterons, but with twice the energy. The range of the cyclotron operating frequencies is $7 \leq f \leq 16$ MHz for protons with final energy $10 \leq E_f \leq 55$ MeV, and $5 \leq f \leq 13$ MHz for deuterons with $10 \leq E_f \leq 65$ MeV.

Restrictions on the injection energies come from orbits through the magnetic plug and cyclotron orbit centering. Possible values of the parameters d and s are determined by the geometry of the injection line.

The injection energies could reasonably be in the range between 20 keV and 2 keV, with peak dee voltages from 60 to 10 kV, which fits quite well the capability of the 88" r.f. system.

The axial injection system, Fig. 3, allows the insertion of the buncher, up to a cavity length s of 45 cm, in between the electrostatic triplets which are the basic elements of the transfer line optics. The choice between the available positions of the buncher along the line is determined by the following arguments:

a) It is useful to have the buncher as near to the cyclotron center as possible (small d), in order to minimize debunching effects like those coming from the energy spread in the injected beam.

b) A small $\underline{d}$ requires more modulating voltage (Eqs. 12, 11), making a saw-tooth wave buncher more difficult to build.

c) The energy spread necessarily introduced by the buncher should be kept low, a few percent, if good quality beam is to be accelerated in the cyclotron.

It turns out that in our case the energy spread given by the polarized ion source could run as high as 1% (see Sec. VD), so that we are forced to accept higher modulating voltages and to put the buncher at the minimum distance from the cyclotron. Typical values could be $\underline{s}$ = 45 cm; $\underline{d}$ = 100 cm. From (12) we get α = 93.5 cm and K = 0.5. Recalling (11):

$$\frac{\Delta v_p}{v_0} = \frac{v_0 \tau}{\alpha} = \frac{s}{n\alpha}$$

we have that the peak modulating voltage ΔV_{ip} is given in terms of the injection voltage by

$$\frac{\Delta V_{ip}}{V_i} = 2\,\frac{\Delta v_p}{v_0} = \frac{2s}{n\alpha} \tag{19}$$

Choosing an $\underline{n}$ value of 5 one has ΔV_{ip} = 19.3%. After the second gap traversal the total energy spread is then reduced to (1-K) times this, or 8.5%, according to (7). A useful parameter is also the "beam wavelength" $\lambda = v_0\tau = \frac{s}{n}$ = 9.0 cm. This is the distance traveled by the injected beam in one r.f. period. The scaling law for the injection energy of the particles is provided by (2), yielding

$$E_0 = QV_i = \frac{1}{2} M \frac{s^2}{n^2} f^2 \tag{20}$$

The tabulated results are presented in the graphs of Fig. 4, as a function of the cyclotron frequency and the final energy, for several ions. It is seen that the injection voltage varies between 1 and 16 kV, the peak to peak modulating voltage of the buncher being correspondingly in the range from 200 to 3300 volts.

This choice of parameters is close to those of "Mode 1", UCRL-18016, chosen to optimize beam transport through the yoke. It seems a reasonable one for the sawtooth system. The main effects which are likely to affect the buncher performance are shortly reviewed in the following section.

V. SURVEY OF EFFECTS LIMITING THE BUNCHER OPERATION

A fair estimate of the buncher performance can be obtained only if more realistic assumptions than those considered in Section II are taken into account.

A. Finite Transit Time Effect

We give here only a qualitative picture of the thick gap crossing, which is, however, sufficient for evaluating the effect involved. For an order of magnitude estimate let us assume a gap length G = 2 cm, which is rather reasonable for ungridded electrodes, on the basis of the transverse beam dimensions.

For the proposed scaled operation of the buncher the beam "wavelength" $\lambda = v_0\tau$, has the constant value $\lambda = \frac{s}{n} = 9$ cm. Thus we see from $\frac{G}{\lambda} = \frac{2}{9} = 22\%$, that the transit time amounts to 22% of the buncher period.

As a consequence, the real wave seen by the particles will rather approach the dashed curve depicted in Fig. 5, which is the result of averaging the original sawtooth wave over the transit time T. We conclude in turn that the required linear velocity increase is experienced only by particles entering the gap at times $0 \leq t \leq (\tau - \frac{G}{v_0})$.

Complete bunching action, in the sense of the formulas derived so far, can thus be obtained only for these particles, which constitute 78% of the total in this example. For constant n operation, λ is constant, so the same fractional amount of beam can be bunched at all frequencies. However, the transit time effect can be reduced by using gridded gaps, which are desirable also in order to reduce unwanted focusing effects. In this case the gap length could decrease to about 4 mm, with a corresponding transit time of only 5% the accelerating period. The bunched beam could in turn increase to 95% of the d.c. beam.

B. Non-Linear Velocity Increase

The ideal wave shape is a linear increase of velocity with time. This is approximately the same as a linear increase of voltage with time. For the accelerating voltages ΔV_{ip} plotted in Fig. 4 corresponding to $\frac{\Delta V_{ip}}{V_i} = 19.3\%$ the difference is easily shown to be small, as follows. From

$$\Delta v_p = v_0 \left(\sqrt{1 + \frac{\Delta V_{ip}}{V_i}} - 1\right),$$

by series development we get

$$\Delta v_p = v_0 \left[\frac{\Delta V_{ip}}{2V_i} - \frac{1}{8}\left(\frac{\Delta V_{ip}}{V_i}\right)^2 + \dots\right]$$

Assuming the law

$$\Delta V_i(t) = \Delta V_{ip} \frac{t}{\tau}$$

we have

$$\Delta v(t) = v_0 \left[\frac{\Delta V_{ip}}{2V_i}\frac{t}{\tau} - \frac{1}{8}\left(\frac{\Delta V_{ip}}{V_i}\right)^2 \frac{t^2}{\tau^2} + \dots\right]$$

If ΔV_{ip} is now adjusted in order to yield the desired Δv_p at $t = \tau$, the maximum discrepancy between the real velocity increase and the desired overall linear behavior will occur at $t = \tau/2$. For $\Delta V_{ip}/V_i = 19.3\%$, the correction is of the order of 0.1%, which is negligible with respect to all other factors affecting the buncher operation. Even if the effect were larger, the voltage could be shaped to give a linear velocity change.

C. Effect of Beam Divergence

We recall that for the proposed buncher the distance between the last gap and the cyclotron center is $\underline{d}$ = 100 cm, the cavity length being $\underline{s}$ = 45 cm. Recalling that we assumed in our calculations equal length trajectories, we inquire whether the path difference for the particles of a finite emittance beam, transmitted through the quadrupole array of Fig. 3, could play some role in the ultimate bunch width obtainable. We assume an emittance of 200 mm mrad, shaped to a waist of 4.75 mm halfwidth and θ_m = 14.2 mrad halfdivergence in the line but with a larger θ_m on entrance to the cyclotron. The path difference between the central and the outer rays is approximately $(1 - \cos \theta_m)(s + d)$. For the proposed transfer line optics the maximum path difference, in the beam, should be of the order of 0.7 mm. The fraction of a cycle is then correspondingly given by $\frac{0.07 \text{ cm}}{9 \text{ cm}} = 0.8\%$, or 3 degrees, i.e., a rather small effect. It could however, be considerably larger, if the transfer line is not designed in order to keep the beam as parallel as possible, or if the beam quality is appreciably worse than assumed above.

D. Consequences of the d.c. Beam Energy Spread

The energy spread $\Delta E/E_0$ of the d.c. beam is by far the most serious effect one has to consider for a polarized ion source, whose energy spread could run[5] as high as ±1% or more. The effect of the energy spread is to introduce a spread in the times of arrival of the particles to the center of the cyclotron, thus producing an overall bunch width which can be much larger than that estimated for a monoenergetic beam. It is quite obvious that the effect is more pronounced the longer the distance between the buncher and the cyclotron center.

Using Eqs. (2), (3) we can show that the phase width $\Delta\phi$ or time spread Δt_f at the median plane is $\Delta\phi/360^\circ = \frac{\Delta t_f}{\tau} = \frac{1}{2\lambda}\left[s + d + \frac{\Delta v_p\, sd}{v_0 \lambda}\right]\frac{\Delta E}{E_0}$. Assuming the values $\underline{s} = 45$ cm, and $\underline{d} = 100$ cm, from Section IV, we calculated the resulting full bunch width $\Delta\phi$ for a beam of energy $E = E_0(1 \pm \epsilon)$ and corresponding velocity $v = v_0(1 \pm \frac{\epsilon}{2})$. To a good approximation the result is:

$$\Delta\phi = 38 \text{ degrees}/\% \text{ energy spread}$$

$\Delta\phi$, when expressed in degrees is not dependent upon the frequency and the injection energy, due to the scaled operation of the buncher.

One can then estimate the overall intensity increase of the accelerated beam due to the buncher for various cyclotron phase acceptances, as a function of the energy spread of the d.c. beam. The results are shown in Fig. 6. A Gaussian distribution for the d.c. beam intensity vs. energy spread is assumed, the parameter 2ϵ representing the corresponding FWHM. The three cyclotron phase acceptances chosen as examples are 18^o, 36^o, and 54^o. The upper value, namely 54^o, is close to that measured for the internal beam of the 88" cyclotron, in normal operating conditions. The lower values are in turn more desirable if good beam quality and extraction efficiencies are wanted.

We might point out that for energy spreads beyond ±1% the intensity gain is not very sensitive to the cyclotron phase acceptance, being almost unity (d.c. conditions) for ϵ of the order of ±4%. The advantage of the buncher is quite evident for 2ϵ less than 1%, the gain being higher the less the cyclotron phase acceptance.

For the purpose of comparison we have plotted on the same Fig. 6 the points corresponding to the expected performance of a single frequency, single or double gap buncher. The effect of the d.c. beam energy spread is much the same for both systems, so that the efficiency behavior vs. energy spread is quite similar. Limiting thus the comparison to the monochromatic beam, we see that the sawtooth buncher allows an intensity increase of about a factor of 2 for cyclotron phase acceptances of 54^o and 36^o, and about 3 for $\Delta\phi = 18^o$, with respect to the simple sinusoidal buncher.

VI. CONCLUSIONS

Although some consideration has been given, by some authors[6,7] to the sawtooth buncher, none has been developed at the present time, at least to our knowledge. On the other side, sinusoidal bunchers with more than one gap and multiharmonic operation have been designed.

From the present study one can conclude that, for the axial injection in the 88" cyclotron, the resulting buncher parameters as far as the voltage and frequency range are concerned seem reasonable enough for the consideration of a sawtooth buncher as a real possibility. The expected improvements in beam intensity and quality are high enough to justify the proposed system, whereas a sinusoidal multiharmonic buncher would be of design almost as complex as the present one.

REFERENCES

1. W. B. Powell, Ion injection from external sources, IEEE Trans. Nucl. Sci. 13, 147 (1966).
2. C. D. Moak, et al., Nanosecond pulsing for Van de Graaff accelerators, Rev. Sci. Instr. 35, 672 (1964).
3. J. H. Anderson, et al., Klystron bunching of the ion beam of a 5.5 Van de Graaff, Nucl. Instr. Methods 41, 30 (1966).
4. A. Luccio, Axial injection studies on the 88-inch cyclotron hole lens, University of California Lawrence Radiation Laboratory Report, UCRL-18016, January 1968.
5. M. K. Craddock, Polarized ion sources, IEEE Trans. Nucl. Sci. 13, 127 (1966).
6. L. Grodzins, et al., Proposed methods for producing intense pulsed beams of monoenergetic neutrons, Nucl. Instr. Methods 36, 202 (1965).
7. See J. H. Neiler and W. H. Good, Chap. IV.A. in Fast Neutron Physics, Part I, ed. by J. B. Marion and J. L. Fowler, (Interscience, a division of John Wiley and Sons, New York, 1960) for a comprehensive survey.

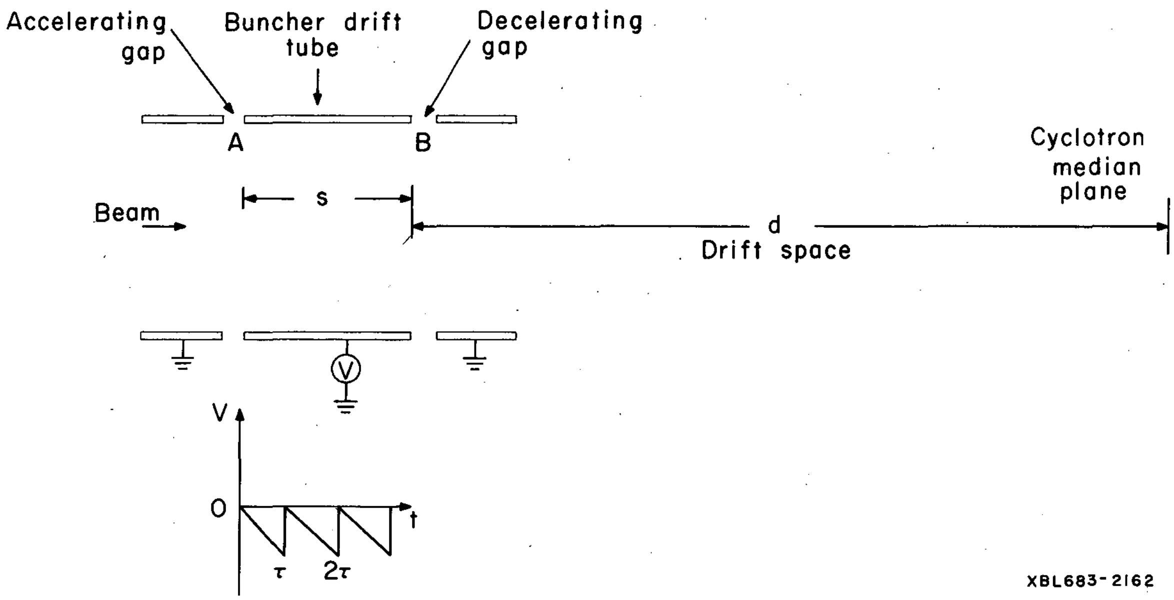

Fig. 1. Proposed drift tube buncher driven by a sawtooth voltage wave, V. Beam is velocity modulated at gaps A and B, to give space bunching at cyclotron median plane after drift distance, d.

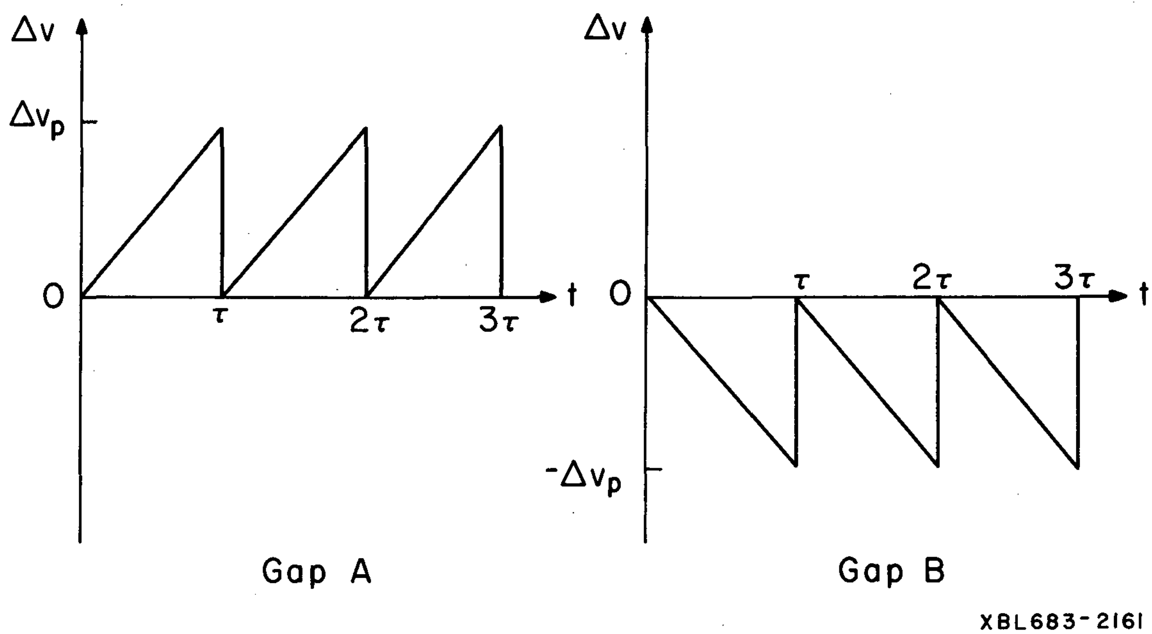

Fig. 2. Velocity modulation, Δv, given to particle at gap crossings A and B. Gap B partially cancels out the effect of gap A.

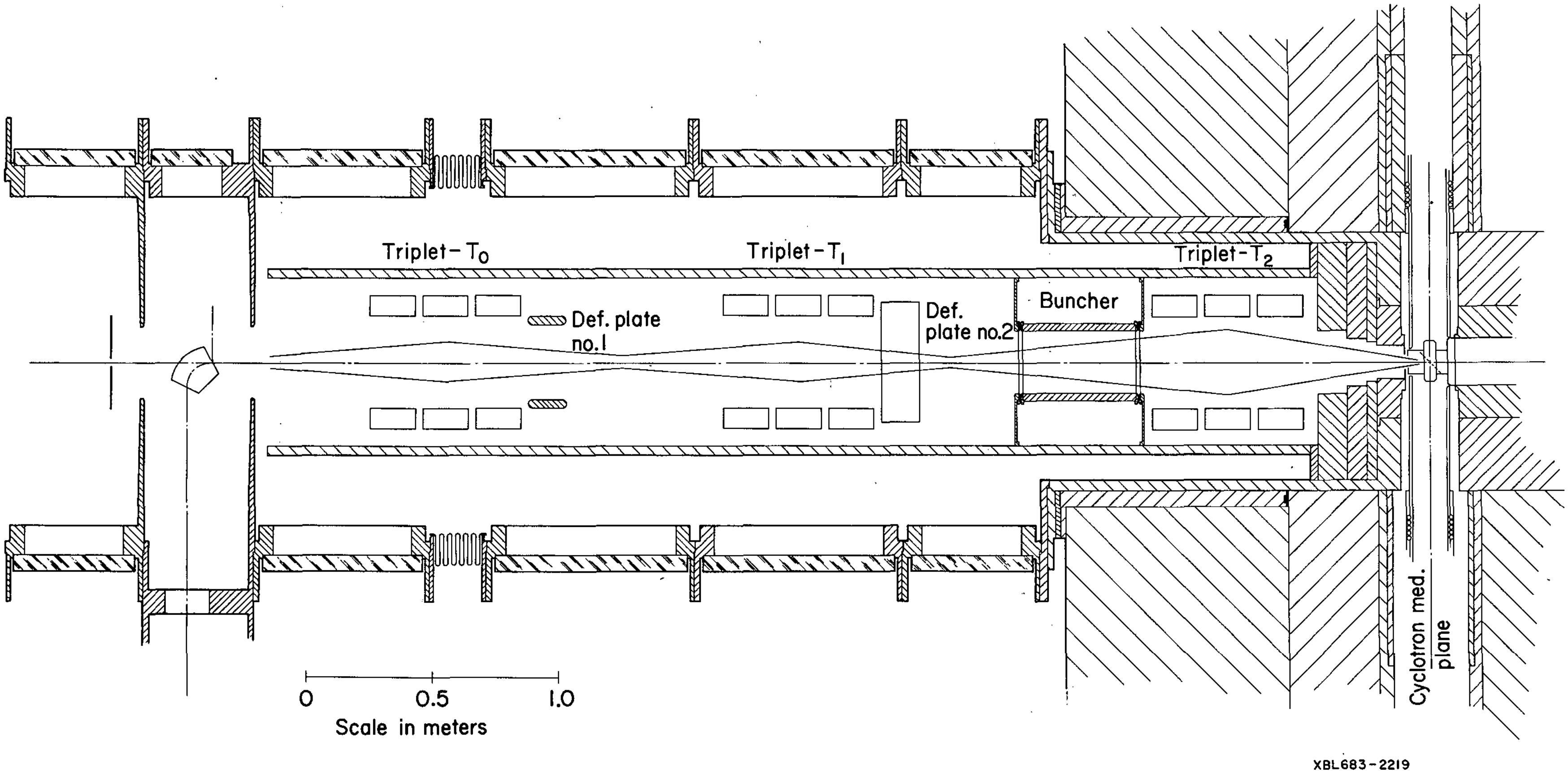

Fig. 3. Schematic drawing of proposed 88-inch cyclotron axial injection system showing electric quadrupole triplet lenses, steering plates, buncher, cyclotron median plane, and beam profile.

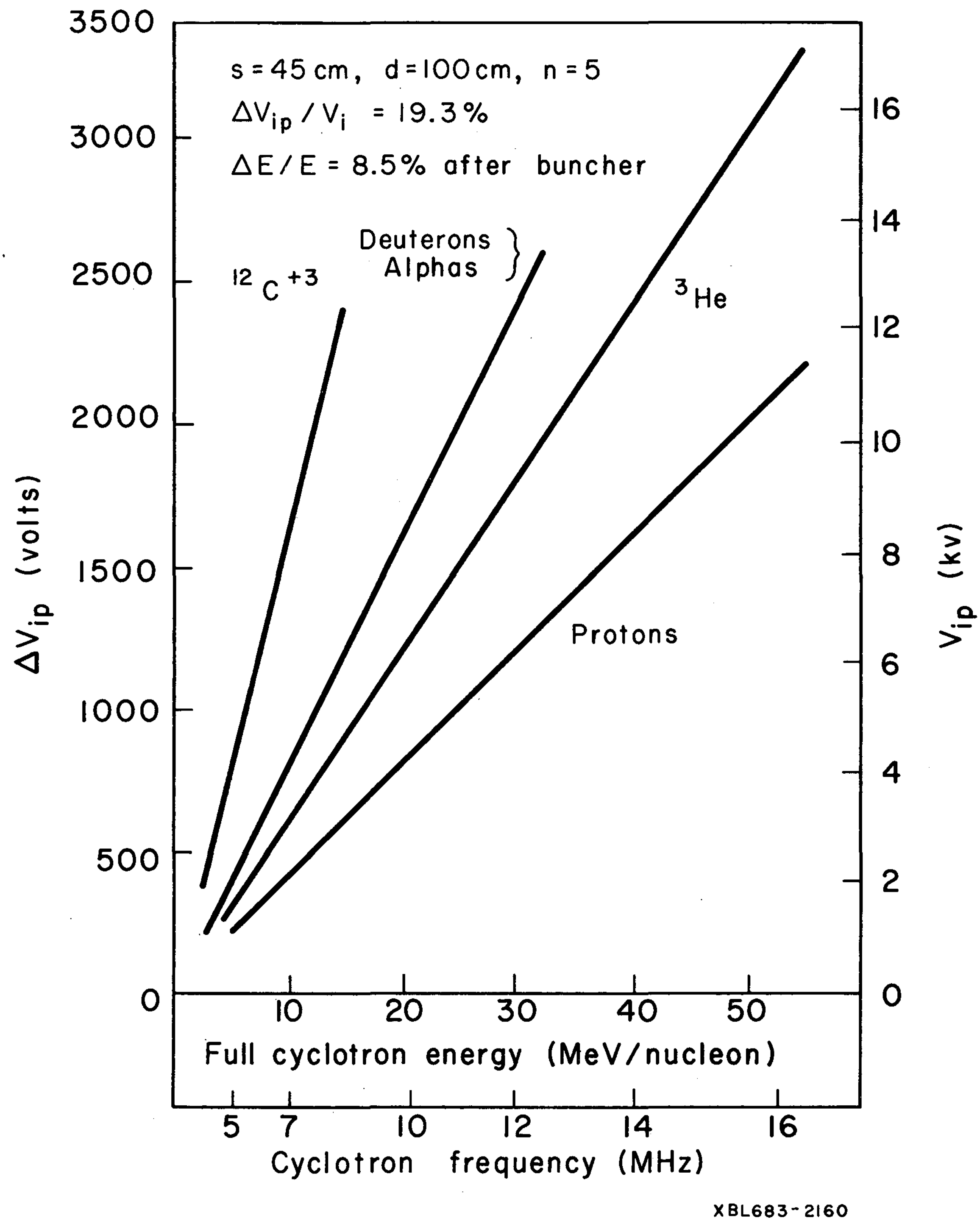

Fig. 4. Buncher voltage ΔV_{ip} required for various cyclotron operating energies and particles, using scaled injection energy V_i. Buncher parameters for this typical case are shown.

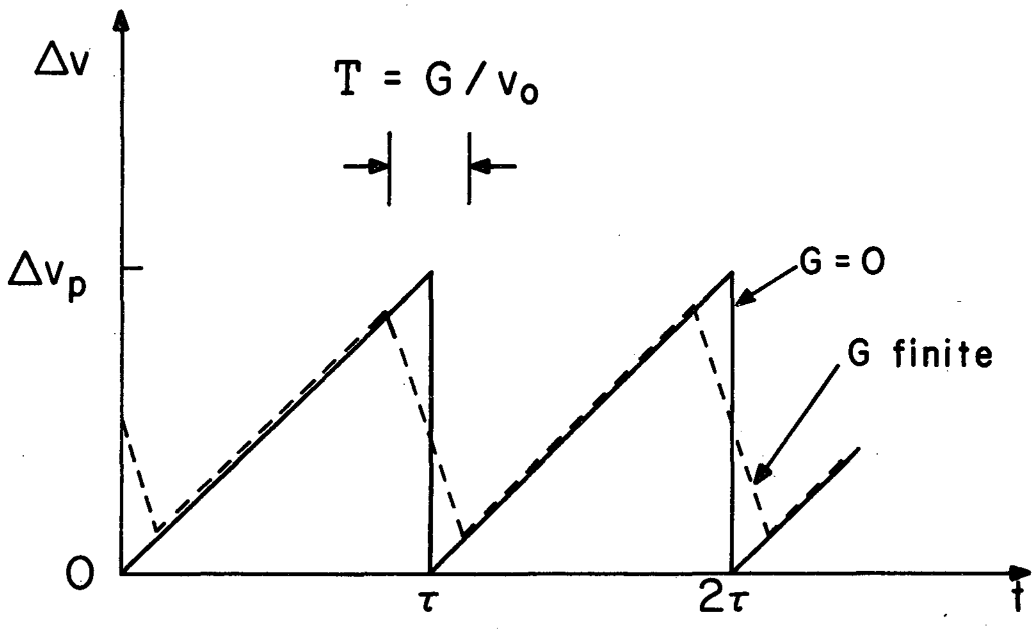

Fig. 5. Comparison of velocity modulation, Δv, at buncher gap for cases of zero gap width and gap width G.

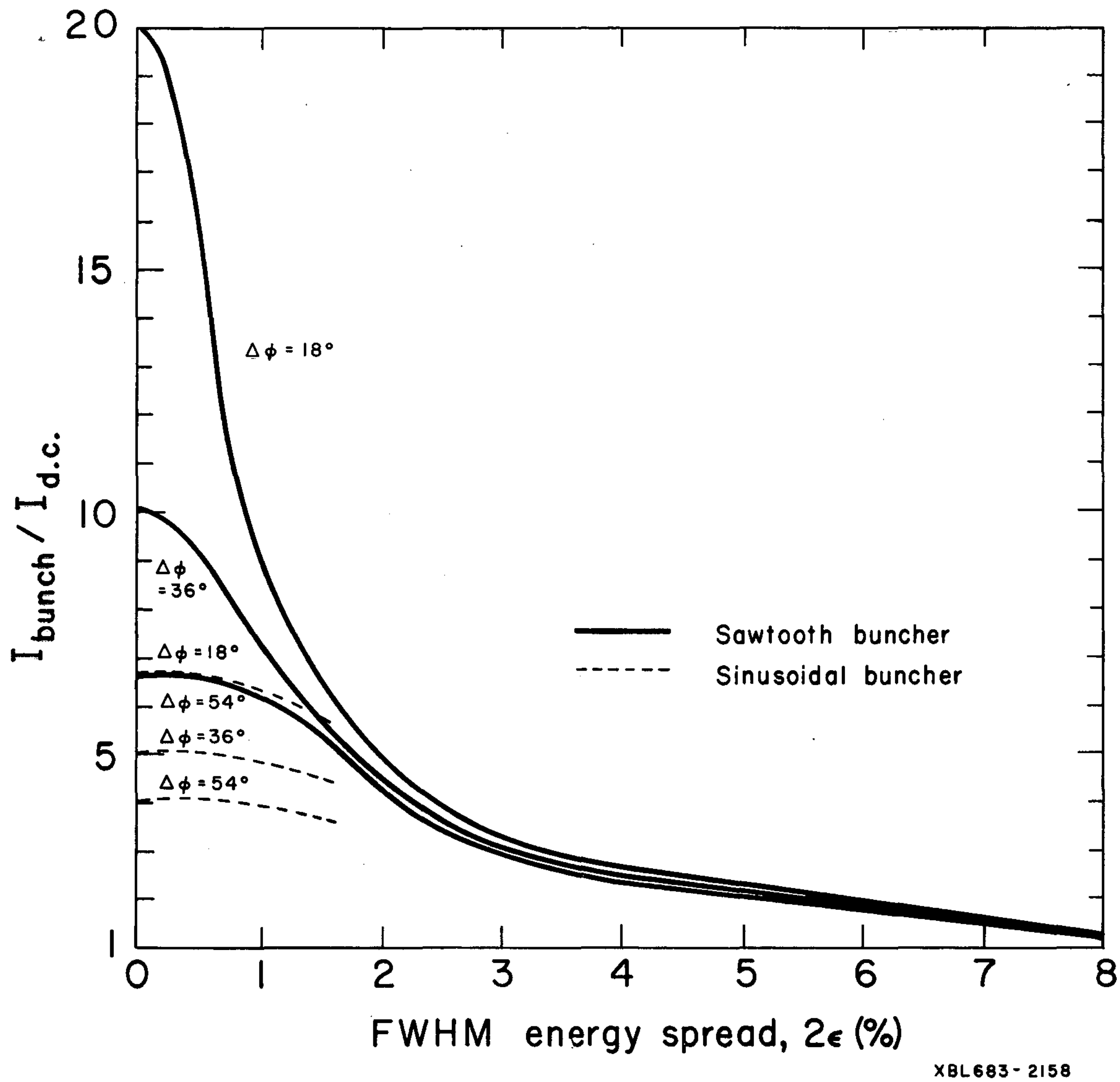

Fig. 6. Ratio of current accelerated by cyclotron for bunched and unbunched cases, $I_{bunched}/I_{d.c.}$, for $\Delta\phi$ full width phase acceptance, for equal d.c. beam from the ion source. Abcissa is the FWHM energy spread 2ϵ. Comparison is given between sawtooth and sinusoidal wave shapes.