Proceedings of the 9th International Conference on Cyclotrons and their Applications
September 1981, Caen, France

THE EFFECTS OF NOISE AND BUNCHER NONLINEARITIES IN THE PRODUCTION OF VERY SHORT BEAM BUNCHES

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Abstract. - The coupling of electrostatic accelerators to compact superconducting cyclotrons often requires the production of very short beam bunches. The random energy spread (noise) of the beam as well as buncher nonlinearities can both be limiting factors in the production of the required beam bunches. Techniques for alleviating these problems are presented.

1. Introduction.-One of the problems associated with compact superconducting cyclotrons is that in general the acceptance phase space is very small. This is a direct result of reducing the mean radius of the cyclotron by a factor of 5 to 10. For the Chalk River Superconducting Cyclotron project,[1,2] the longitudinal phase acceptance of $\pm 1.5^{o}$ RF requires the production of beam bunches with FWHM of the order of 115 ps or physical bunch lengths $\sim$ 1.2 mm FWHM. In situations such as this, ion source noise becomes a limitation in some cases even without the much more severe problem of the noise introduced by the straggling of the beam passing through the stripper in the high voltage terminal of the MP tandem injector. Without the use of special techniques, to be discussed in this paper, the bunch lengths produced at the cyclotron are many times wider than the acceptance phase of the cyclotron

In this paper, the theory of beam bunching including noise will be presented along with a description of techniques to alleviate the problems of ion source noise and the effects of buncher nonlinearities.

2. Basic Bunching Theory.-Although the theory of beam bunching has been described by a number of authors,[3] the basic equations will be repeated here to establish the notation. The dynamics of beam bunching are shown schematically in fig. 1. We impose a velocity (or momentum) distribution $\delta_\beta = \frac{\Delta P_\beta}{P_o} = \frac{\Delta v_\beta}{v_o}$ (non relativistic) by modulating the velocity distribution of the d.c. beam (having mean velocity v_o and momentum P_o) with the triangular buncher voltage wave form V_β as shown; the particles in the region $-\ell_o$ must be speeded up and the particles in the region $+\ell_o$ must be slowed down in such a manner that they all arrive at s_1 at the same time. We see that $\pm\ell_o = \frac{\pm\pi}{\omega} v_o$ where ω is the angular frequency of the buncher wave form.

In general the effective drift distance, L, is:

$$L = L_o + \ell(x_o,\theta_o,y_o,\phi_o,\ell_o,\delta_o) \quad (1)$$

where L_o is the length of the central trajectory and the second term, ℓ, the differential path length is in general a function of the position of a particle in both the transverse (x,y) planes and the longitudinal coordinates; here the notation of Brown[4] is used; $x_o,\theta_o,y_o,\phi_o,\ell_o,\delta_o$ are the initial coordinates of the particle under consideration.

The time of arrival of a particle at s_1 is T=L/v where v is its velocity and the time difference between this particle and the "central" particle or ray is:

$$t_1 = T - T_o = \frac{L}{v} - \frac{L_o}{v_o} \quad (2)$$

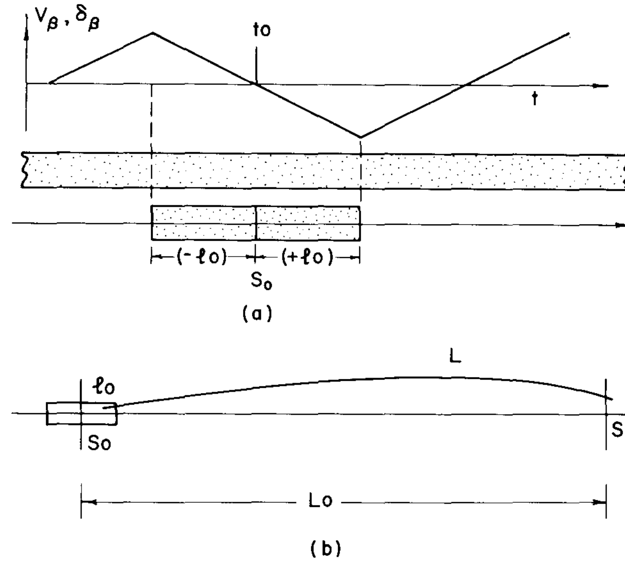

Fig. 1: (a) Triangular buncher voltage V_β imparts a velocity (momentum) distribution δ_β on a segment of a uniform d.c. particle beam. (b) Coordinates used to specify the propogation of a beam bunch of length $2\ell_o$ through a section of an optical system; $L_o = S_1 - S_0$ is the length along the central trajectory. L is the effective length that a representative particle travels through the system.

The bunch length at s_1 is:

$$\ell_1 = v_o \left[\frac{L}{v} - \frac{L_o}{v_o}\right] \quad (3)$$

In the non-relativistic limit[5] $\delta_o = \Delta P/P_o = \Delta v/v_o$ and hence

$$v = v_o(1 + \delta_o) \quad (4)$$

Thus
$$\ell_1 \approx L(1 - \delta_o) - L_o \quad (5)$$

Substituting eq. 1 into 5 leads to[5]

$$\ell_1 = [\ell(x_o,\theta_o,\delta_o) - \ell_o - L_o\delta_o] \quad (6)$$

where the dependence on ℓ_o is shown explicitly. If we assume a non dispersive system for convenience, then eq. 6 reduces to $\ell_1 = -(\ell_o + L_o\delta_o)$ (7)

and we see that the beam bunch can be minimized by setting

$$\delta_{\beta_o} = \delta_o = -\ell_o/L_o \quad (8)$$

This is only true for non-relativistic beams. For relativistic beams[5] the term $L_o\delta_o$ in eq. 6 becomes $\gamma^{-2}L_o\delta_o$ where $\gamma^{-2} = (1 - \beta^2)$. Thus a Klystron buncher of the type assumed here will not bunch a highly relativistic beam.

3. Linear Bunching Theory with Noise.-In the previous section, we saw (see Fig. 1) that 50% of a uniformly distributed beam could be perfectly bunched by a triangular wave if we assume first order paraxial optics and a nondispersive system. The effects of the addition of a randomly distributed velocity distribution in the d.c. beam will now be discussed.

Let us assume that the noise distribution is Gaussian. That is, the probability of finding a particle with velocity $v_o + \delta v_n$ has a Gaussian distribution given by

$$P_n(\delta) = G(\delta,\delta_n) = \frac{1}{\sqrt{2\pi}\,\delta_n}\exp\left[-\frac{1}{2}\left(\frac{\delta}{\delta_n}\right)^2\right] \tag{9}$$

where δ_n is the standard deviation of the noise. We see also from section 2, that our ideal, linear buncher produces a uniform distribution function, U,

$$P_\beta(\delta_\beta) = \frac{L_o}{2\ell_o}U[\delta_\beta] \quad\text{and}\quad \delta_\beta = -\ell/L_o \tag{10}$$

Hence the probability of finding a particle with velocity v or $\delta = v/v_o$ is just the convolution integral of the two distribution functions:

$$P_T(\delta) = \int_{-\infty}^{\infty} P(\delta_\beta)P(\delta' - \delta_\beta)d\delta_\beta$$

$$= \frac{1}{4\delta\beta_o}\left\{\text{erf}\left[\frac{\delta + \delta\beta_o}{\sqrt{2}\delta_n}\right] - \text{erf}\left[\frac{\delta - \delta\beta_o}{\sqrt{2}\delta_n}\right]\right\} \tag{11}$$

The variance of δ, a quantity we will need later is

$$\delta_T^2 = \int_{-\infty}^{\infty}\delta^2 P_T(\delta)d\delta = \delta_n^2 + \frac{(\delta\beta_o)^2}{3} \tag{12}$$

That the variance of the convoluted distributions is the sum of the variances of its components is a general result of convolution integrals and will be useful later[6]. $\frac{(\delta\beta_o)^2}{3}$ is the variance of the uniform distribution function for δ_β integrated from $-\ell_o$ to $+\ell_o$. In an exactly analogous manner, we can find the spacial distribution of the particles in the beam bunch for any distance $\bar{s}$ along the optic axis, where $\bar{s}$ is the mean position of the bunch. Once again we see (Fig. 1) that the initial particle distribution is uniform and is given by

$$P_u(s) = \frac{1}{2\ell_o}U\left[\frac{s-\bar{s}}{\ell_o(\bar{s})}\right] \tag{13}$$

If the buncher is set such that $\delta\beta_o = -\ell_o/L_o$ then

$$\ell_o(\bar{s}) = \ell_o(1 - \bar{s}/L_o) \tag{14}$$

so $\qquad \ell_o(\bar{s}) \to 0$ as $\bar{s} \to L_o$.

The noise distribution function $P_n(\delta)$ is the same as before, but we must make the change of variable $\delta' = \delta\bar{s}$ in order to do the convolution integral with $P_u(s)$. Thus,

$$P_s(s) = \int_{-\infty}^{\infty} P_u(s')P_n(s-s')ds' \tag{15}$$

$$= \frac{1}{4\ell_o(1-\bar{s}/L_o)}\left\{\text{erf}\left[\frac{s+\ell_o(1-\bar{s}/L_o)}{\sqrt{2}\bar{s}\delta_n}\right] - \text{erf}\left[\frac{s-\ell_o(1-\bar{s}/L_o)}{\sqrt{2}\bar{s}\delta_n}\right]\right\}$$

It is easily shown that in the limit as $\bar{s} \to L_o$

$$\text{that}\quad \lim_{\bar{s}\to L_o} P_s(s) \to \frac{1}{\sqrt{2\pi}L_o\delta_n}\exp\left[-\frac{1}{2}\left[\frac{s - L_o}{L_o\delta_n}\right]^2\right] \tag{16}$$

so that at the "time focus" the bunch has a Gaussian spatial distribution function with spatial variance

$$\text{Var}(s) = \ell_s^2 = (L_o\delta_n)^2 \tag{17}$$

and a momentum distribution given by eq. 11 with variance δ_T^2 given by eq. 12.

We see from eq. 16,17 that at the time focus the bunch width is a function of two parameters, the noise δ_n and the drift length L_o. Reducing either δ_n or L_o shortens the bunch. Thus, for a given noise component δ_n, the bunch length can be reduced by shortening L_o and increasing δ_β. Note, however, that the total energy spread of the beam is increased as given by eq. 12 and although δ_β does not appear explicitly in eq.16 its presence could have unpleasant consequences if the beam passes through dispersive elements.

The "dark current" produced by the debunching phase of our triangular wave is easily found by noting that eq. 14 becomes

$$\ell_o(\bar{s}) = \ell_o(1 + \bar{s}/L_o). \tag{18}$$

Substituting eq. 18 into eq. 15 we obtain the dark current distribution function. At the time focus this reduces to, setting $\bar{s} = L_o$.

$$P_D(s) = \frac{1}{8_o}\left\{\text{erf}\left[\frac{s + 2\ell_o}{\sqrt{2}L_o\delta_n}\right] - \text{erf}\left[\frac{s - 2\ell_o}{\sqrt{2}L_o\delta_n}\right]\right\} \tag{19}$$

The total distribution function at the time focus is the normalized sum of the two functions eq. 16 and 19, which in this case is just

$$P(s) = \frac{1}{2}P_s(s) + P_D(s) \tag{20}$$

The factor of 1/2 in front of the first term results from extending the range from $\pm\ell_o$ to $\pm 2\ell_o$ in order to include one complete cycle of the buncher waveform.

The dark current becomes a uniform distribution under the bunches in the vicinity of the time focus for a triangular bunching waveform.

4. Phase Ellipse Formalism.-A more convenient way of looking at the problem discussed in section 2 is to use the phase ellipse formalism developed by Brown[7] and extended to second order in the longitudinal domain by Davies[5]. For convenience, we will once again restrict the discussion to non-dispersive systems.

In a non-dispersive system, the longitudinal phase space is decoupled from the transverse phase space and can be written as a 2 x 2 matrix[7,2] having the form

$$\sigma_o = \begin{bmatrix}\sigma_{11} & \sigma_{12}\\ \sigma_{12} & \sigma_{22}\end{bmatrix} = \begin{bmatrix}\ell_o^2 & r_o\ell_o\delta_o\\ r_o\ell_o\delta_o & \delta_o^2\end{bmatrix} \tag{21}$$

where ℓ_o and δ_o were defined by eq. 1 and r_o is the usual statistical correlation coefficient.

$$r = \frac{\langle \ell_o \delta_o \rangle^2}{\langle \ell_o^2 \rangle \langle \delta_o^2 \rangle} = \frac{\sigma_{12}}{\sqrt{\sigma_{21}\sigma_{22}}} \qquad (22)$$

The σ or phase space matrices transform as[7])

$$[\sigma_1] = [R][\sigma_o][\tilde{R}] \qquad (23)$$

where in this case R is the 2 x 2 longitudinal transfer matrix[4,7,5]).

The bunching solution given in eq. 15, 16, 17 can be represented as follows using the phase ellipse formalism.

$$[\sigma_1] = [L_o][K_o][\sigma_o][\tilde{K}_o][\tilde{L}_o] \qquad (24)$$

where

$$\sigma_o = \begin{bmatrix} \ell_n^2 & 0 \\ 0 & \delta_n^2 \end{bmatrix} \qquad (25)$$

and we assume an initially random noise distribution δ_n^2 which implies r=0; here $\ell_n^2 = \ell_o^2$ in analogy with eq. 12; i.e. ℓ_n is the variance of the uniform, rectangular spacial distribution of the particles in the chosen segment of the initial d.c. beam.

$$[K_o] = \begin{bmatrix} 1 & 0 \\ K_o = -1/L_o & 1 \end{bmatrix} \qquad (26)$$

and is a representation of the bunching phase of the triangular buncher wave. If we set $K_o = -1/L_o$ then we reproduce the results in section 3.

$$[L_o] = \begin{bmatrix} 1 & L_o \\ 1 & 0 \end{bmatrix} \qquad (27)$$

which is just the transformation matrix for a drift distance. Thus eq. 24 becomes

$$[\sigma_1] = \begin{bmatrix} \ell_n^2 + 2L_oK_o\ell_n^2 + L_o^2\delta_1^2 & K_o\ell_n^2 + L_o\delta_1^2 \\ K_o\ell_n^2 + L_o\delta_1^2 & \delta_1^2 = (K_o^2\ell_n^2 + \delta_n^2) \end{bmatrix}$$

which reduces to

$$[\sigma_1] = \begin{bmatrix} L_o^2\delta_n^2 & L_o\delta_n \\ L_o\delta_n & (\ell_o/L_o)^2 + \delta_n^2 \end{bmatrix} \qquad (28)$$

if we set $K_o = -1/L_o$ (see eq. 10,14,15). We see immediately that the σ_{11} matrix element is just Var(s) (eq.17) and the σ_{22} matrix element is δ_T^2 (eq.12). This matrix (eq.28) represents the minimum bunch length that can be achieved by varying the buncher amplitude, K, for a given drift length L_o and noise component δ_n. We note also that the "longitudinal phase space" of the beam is

$$\Omega = (\det|\sigma|)^{1/2} = \ell_n\delta_n \qquad (29)$$

for both σ_o (eq. 25) and for σ_1 (eq. 28). Thus a buncher does not increase the phase space of the beam because it adds only completely correlated momentum terms.

The correlation coefficient for σ_1 is

$$r_1 = \frac{L_o\delta_n}{(L_o^2\delta_n^2 + \ell_n^2)^{1/2}} \qquad (30)$$

and is usually <<1 at the time "focus".

If we were to produce a "time waist" instead, (that is $r_1 = 0$) we find that

$$K_o \approx -\frac{1}{L_o}\left(1 - L_o^2\delta_n^2/\ell_n^2\right) \qquad (31)$$

and the "bunch length" (σ_{11}) is

$$\sigma_{11} = L_o^2\delta_n^2\left(1 + L_o^2\delta_n^2/\ell_n^2\right) \qquad (32)$$

where we have assumed $L_o^2\delta_n^2 << \ell_n^2$.

Comparing this with the σ_{11} element of eq. 29 we see that for reasonable bunching factors, of the order of 1/5 to 1/10 there is little difference between minimizing the bunch length or producing a "time waist".

5. Addition of Secondary Noise Sources (Straggling).- We have seen in the previous sections how a noise source limits the ultimately achievable bunch length. In this section we shall investigate what happens when a second noise source is added some distance from the buncher. Such a situation is shown at the top of Fig. 2, which is a highly schematic representation of the beam bunching system for the Chalk River MP Tandem-Superconducting Cyclotron facility. Here all quantities have been normalized to the 250 keV low energy injector. That is, the effective distance from the low energy buncher to the stripper in the tandem terminal has been reduced to take into account the acceleration of the beam. Also, the equivalent bunch length required at the center of the cyclotron is about a factor of 10 smaller when scaled to the low energy buncher energy. The advantage of using scaled effective distances is that we need not discuss explicitly what happens as the beam passes through the tandem[2]).

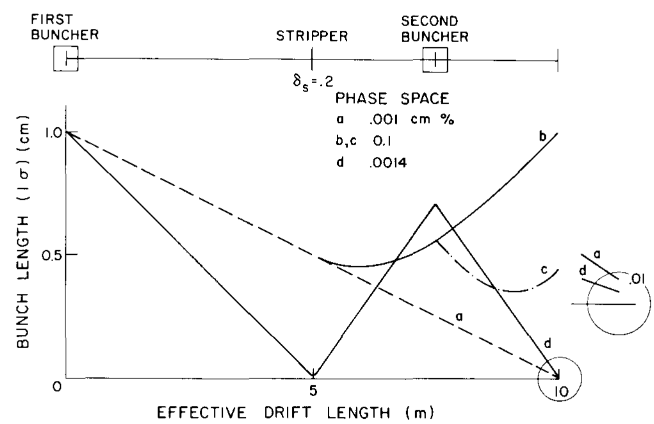

Fig. 2: (a) Propagation of a beam bunch of initial length 1 cm (1σ:34% contour), initial noise δ_n = .001% and energy 250 keV to a "time focus" an effective distance of 10 m from the first buncher. (b) Same as (a) but with stripper noise δ_n = .2% added. (c) Same as (a) and (b) with with a second buncher adjusted to minimize the bunch length at the focus. (d) Same as (c) but with first buncher adjusted to minimize bunch length at the stripper ($\delta_{\beta 1}$ = .2%) and second buncher adjusted to minimize bunch length at the focus.

Curve (a) in Fig. 2 shows the propagation of a bunch with initial parameters shown in Table 1; as is indicated an initial noise δ_n = .001% is assumed. (This is somewhat lower than is typical of many ion sources, but was used here for convenience. With no stripper

Table 1

Parameters used in calculation for Fig. 2

Curve	ℓ_n(cm)	δ_n(%)	$\delta\beta_1$(%)	δ_s(%)	$\delta\beta_2$(%)	r_2	ℓ_T(cm)	δ_T(%)	r_T	$\Omega_T$cm-%
a	1.0†	.001	0.1	0	0		.010	.1	.01	.001
b	1.0	.001	0.1	.2	0	.6000	1.0	.223	.894	.10
c	1.0	.001	0.1	.2	.358	.6000	.447	.286	.625	.10
d	1.0	.001	0.2	.2	.566	.9999	.005	.283	.007	.0014

†All parameters are for the 1σ (34% of beam intensity) phase space contour.

noise present, we obtain an ion source noise limited bunch of width (1σ) .01 cm, which is typical of the bunch length required (normalized to 250 keV) at the cyclotron center. Here eq. 28 has been used. As is seen from eq. 28 and 17, $\ell_T = L_o\delta_n$ and is directly proportional to the ion source noise. We see also from Table 1 that the r_T is very small and thus the "time focus" is also approximately a time waist.

Curve (b) in Fig. 2 shows what happens when noise is added by the "Stripper". From the discussion in section 3 and eq. 12, we see that the stripper noise δ_s is added in quadrature with the momentum spread σ_{22} in eq. 21 or 28. (This is true because the stripper noise is not correlated with σ_{22}.) The σ_{22} matrix element of eq. 28 becomes

$$[\sigma_{22}]_1' = (K_o\ell_n)^2 + \delta_n^{\ 2} + \delta_s^{\ 2} \qquad (33)$$

The properties of the bunch at the cyclotron are found by transforming eq. 28 evaluated at $L_o = 5$ m with $K_o = K_1$ in Table 1 and using the transformation

$$\sigma_T = [L][\sigma_1'][\tilde{L}]. \qquad (34)$$

where in this case L is 500 cm. We see from Table 1 that the bunch length ℓ_T increases 100 fold as does the phase space. The correlation coefficient r_T becomes ∿ .9 which implies a stretched and relatively highly correlated bunch. The choice of $\delta_s = .2\%$ (normalized) is typical of the stripper straggling encountered for medium mass heavy ions passing through a N_2 gas stripper. We see, that for this example, the stripper straggling completely debunches the beam!

A partial solution to this problem is to add a second buncher. If we leave the first buncher unchanged and add a second buncher as illustrated in the figure, we obtain the results shown in Fig. 2(c). The second buncher has been set to minimize ℓ_T. The bunch length is reduced from 1 cm to .45 cm and, of course, the phase space remains unchanged. That the bunch length is not further reduced is a result of the correlation coefficient r_2 being much less than 1. If r_2 was ∿ 1 then the second buncher could in fact rebunch the beam, as will be seen shortly.

Here eq. 34 was used to transform from the stripper to the second buncher and the following transformation is used to compute the bunch length at the cyclotron:

$$\sigma_T = [L][K][\sigma][\tilde{K}][\tilde{L}] \qquad (35)$$

$$= \begin{bmatrix} \sigma_{11} + 2L(K\sigma_{11} + \sigma_{12}) + L^2\delta_T^{\ 2} & K\sigma_{11} + \sigma_{12} + L\delta_T^{\ 2} \\ K\sigma_{11} + \sigma_{12} + L\delta_T^{\ 2} & \delta_T^{\ 2} = (K^2\sigma_{11} + 2K\sigma_{12} + \sigma_{22}) \end{bmatrix}$$

where the matrices have been defined by eq. 21,26,27. (Note that [σ] now has its general form; not as in eq. 25.)

If we minimize $(\sigma_{11})_T$ with respect to K we find that

$$K = -\frac{1}{L}(1 + L\sigma_{12}/\sigma_{11}) = -\frac{1}{L}(1 + rL\delta/\ell) \qquad (36)$$

K varies from $-1/L$ for an uncorrelated beam to $-1/L(1 + L\delta/\ell)$ for a perfectly correlated beam.

It is easily shown, by substituting eq. 36 into the (11) matrix element of eq. 35 that

$$(\sigma_{11})_T = \ell_T^{\ 2} = L^2\delta^2 \qquad (37)$$

for an uncorrelated beam $(r = 0)$; δ^2 is given by eq. 33. Similarly it can be shown that

$$\lim_{r_2 \to 1} \ell_T^{\ 2} \to 0. \qquad (38)$$

Thus if a noisy beam bunch is allowed to drift a sufficient distance so that $r_2 \to 1$ then it can be rebunched to an arbitrarily small bunch (neglecting space charge, nonlinearities and other high order aberrations). Thus, a second buncher can be used, under appropriate conditions to overcome both the problem of a second noise source and excessive ion source noise.

The recorrelation distance is related to the growth in the phase space, as is the buncher voltage V_β, (δ_β) required to rebunch the beam. In general, therefore, it is useful to operate such that the phase space growth is minimized. This situation is shown in Fig. 2(d). Here the first buncher is adjusted to produce a "time focus" at the stripper. It will be shown later that this minimizes the phase space growth. We see that now the second buncher is very effective, producing a final bunch length (1σ) of .005 cm with the final phase space .0014 cm%, just 40% larger than the initial phase space instead of the factor of 100 greater found in cases b,c.

The phase space, after adding stripper noise, can be written in general form as:

$$\Omega^2 = \ell^2(\delta^2 + \delta_s^{\ 2}) - r^2\ell^2\delta^2 \qquad (39)$$

where eq. 21 and 29 have been used. The initial phase space at the stripper is

$$k^2 = \ell^2\delta^2(1 - r^2) \qquad (40)$$

and is assumed to be an invariant. On substituting eq. 40 into eq. 39 we have that

$$\Omega^2 = k^2 + \ell^2\delta_s^{\ 2}. \qquad (41)$$

It is seen immediately that Ω is minimized by minimizing ℓ, the bunch length at the stripper.

If we minimize eq. 39 subject to the condition that eq. 40 is a constant, we find that ℓ is a minimum when $r = 0$, that is when a longitudinal waist exists at the point where the noise is added. We see also from eq. 40 that if δ can be increased without increasing k one can make ℓ arbitrarily small.

However, for the situation in Fig. 2(d) where one has the buncher a fixed distance L_o from the stripper, a waist does not lead to the minimum phase space growth, although the difference is small.

If we add the stripper noise to (σ_{22}), (eq. 28) and minimize Ω^2 with respect to K_o, we find that the minimum in Ω^2 occurs for $K_o = -1/L_o$ as in eq. 28 and that

$$\Omega^2 = k^2 + L_o^{\ 2}\delta_n^{\ 2}\delta_s^{\ 2} \qquad (42)$$

where we note that $\ell^2 = L_o^{\ 2}\delta_n^{\ 2}$ from eq. 28. Eq. 42 has the same form as eq. 41, with, as expected, the minimum value for ℓ^2. The correlation at the stripper is given by eq. 30. It is .005 which is in practice indistinguishable from 0.

6. Nonlinear Effects.-The buncher wave form assumed in the previous sections was perfectly linear. Here we will investigate the effects of the nonlinearities produced by approximating the triangular wave with a first and second harmonic buncher waveform. That is

$$V_\beta = V_o(\sin(\omega t) - .207 \sin(2\ \omega t)). \qquad (43)$$

V_β is shown in Fig. 3a and deviates by only a few percent from a triangular wave.

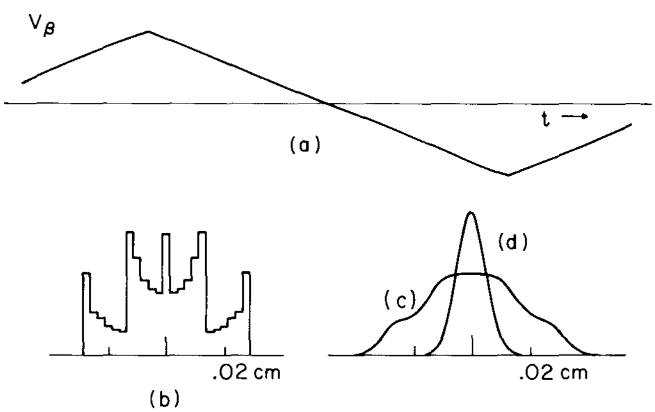

Fig. 3: (a) Buncher voltage V_β given by eq. 43. (b) Effects of nonlinearities, 5 m drift. (c) Effect of adding noise, δ_n = .001%; (d) Linear buncher with noise (see eq. 16).

In analogy with eq. 14, the position of any particle after a drift distance $\bar{s}$ becomes

$$\ell(\bar{s}) = \ell_o\left\{\frac{s}{\ell_o} - \frac{\bar{s}}{L_o}\left[\sin\left(\frac{\pi s}{2\ell_o}\right) - .207\ \sin\left(\frac{\pi s}{\ell_o}\right)\right]\right\} \qquad (44)$$

Unlike eq. 14, this is a multi valued nonlinear function, and although at $\bar{s} = 0$ the distribution function is uniform, it rapidly deviates from uniformity so the convolution integrals (see eq. (15)) must be done numerically. The results are shown in Fig. 3b for the case where no noise is added at the source, and in Fig. 3c where an initial noise δ_n = .001% has been added; the bunch has drifted 5m as in Fig. 2. It is seen that the noise rapidly smoothes the spacial distribution. At the stripper, the bunch is 3.2 times wider than before. If we add the stripper noise δ_s = .2%, we find that at the target the phase space growth is 3.2 times larger as expected, becoming .0045 cm%. The final bunch parameters are ℓ_T = .016 cm δ_T = .283% and r_T = .023. The bunch length ℓ_T is also 3.2 times larger than in Fig. 2(d) (the second buncher acts as a lense in longitudinal space with unity magnification).

Thus we find that the same techniques used to alleviate the problems of ion source and stripper noise will also reduce in principle the effects of buncher nonlinearities. Nonlinearities in the second buncher are not usually a problem because one makes use of only a few degrees of RF phase in most situations.

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" DISCUSSION "

M. REISER : Are space charge effects negligible in your bunching case ?

W.G. DAVIES : For the beam currents we envisage in our situation, we believe that space charge effects should not be a limitation.

K. ZIEGLER : Why do you need these extremely short beam pulses ? Do you need them always or only for special beam experiments ? What phase width is acceptable for obtaining separated turns at extraction ?

W. DAVIES : The short beam pulses are required to meet the energy resolution specifications at the extracted beam. The desired phase width is ± 1.5° RF and we loose separated orbits at about ± 4.5° RF phase.

H.G. BLOSSER : Do your calculations include the effect of voltage fluctuations in the ion source platform and on the tandem terminal ? The beam analysis system only senses total energy whereas a voltage change on the source platform has a much greater effect on the time spectrum.

W. DAVIES : The calculations do not include the effect of voltage fluctuation on the ion source platform. We have a high resolution energy analysis system followed by a high resolution phase analysis system but these correct only long term changes in the time scale of a few Hertz. We cannot detect or correct very short term fluctuations.
I agree with your comment. One must have very stable high voltage power supplies for beam extraction if the first buncher is to give very sharply focussed bunches.

G. DUTTO : Did you use a special computer program for your work or was this mainly analytical ?
W. DAVIES : As you will see from the written text, most of the work is analytical. The only numerical part is the analysis of the non linear effects.