# DESIGN OF A BUNCHER AND THE TRANSPORT SYSTEM IN ITS DRIFT SPACE FOR THE 200 MeV BNL INJECTOR LINAC*

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## Introduction

The purpose of this paper is to examine the effect of space charge on the bunching process and to find a buncher design that will fulfill the following requirements:

(1) Optimal performance with regard to bunching efficiency and transverse beam matching throughout a beam current range of 50-400 mA.

(2) Ability to produce a tight beam bunch at low current to facilitate the calibration procedure of the linac.

Because the problem of bunching a continuous beam appears to have numerous solutions and approaches (this is especially true when a double buncher is used), we will limit ourselves to some satisfactory solutions rather than explore the full range of possibilities.

Two-dimensional numerical calculations in longitudinal phase space were performed in order to explore operation characteristics of different bunchers. For one particular set of buncher parameters these calculations were repeated in six dimensions and the parameters of the transverse focusing system in the buncher linac drift space were added as input numbers.

In all calculations it was assumed that the buncher voltage is applied over an infinitesimally small interval. The radial field in the buncher gap was neglected. No beam loading effects in the buncher were considered. All fixed parameters used in the calculations are those of the new 200 MeV injector linac: injection energy 750 keV, rf frequency 200 Mc, and synchronous phase -32°.

## I. Two-Dimensional Calculations

### 1. Computer Program

In order to investigate the effect of space charge on the longitudinal motion during the bunching process a very simple non-time-consuming longitudinal particle motion code was written. Space-charge forces are calculated in a subroutine employing the point-disc model, i.e. assuming that the beam is a collection of uniformly charged discs whose radii equal the beam radius.[1] The program allows for linear variation of this radius along the axis of the buncher-drift space system. Sixty-three particles, all having an energy of 750 keV, depict the continuous beam which enters the buncher in one period. The space-charge force acting on a point in the simulated beam bunch is the sum of forces from all the discs in this bunch and also from discs in six identical neighboring bunches, three on each side of the central, simulated bunch. Space-charge forces are calculated in steps of $\beta\lambda$. An output routine calculates the bunching efficiency which is defined as the ratio of number of particles within $\pm$ 32° phase spread and $\pm$ 25 keV energy spread around the synchronous phase and energy at the input of the linac over the total number of particles which enter the buncher in one rf period. This definition is consistent with the longitudinal acceptance of the linac assuming corresponding transverse beam dimensions which lead to a longitudinally and transversely matched beam.

### 2. Results for Single Buncher

The single buncher efficiency has been examined as a function of buncher voltage for five beam currents of 50, 100, 200, 300 and 400 mA, and for various buncher-linac drift distances. The transverse radius of the beam varied linearly from 1.5 cm at the buncher to a "matched" 0.2, 0.275, 0.35, 0.44, and 0.48 cm for the five currents mentioned above.

Figures 1 to 2 show the bunching efficiency, varying the buncher voltage, for drift distances of 71, 83, 101, and 154 cm respectively; 154 cm is very close to the drift space distance of the existing Brookhaven buncher. The operating voltage of that buncher is 18 kV. It is clear from Fig. 2b that for currents higher than 100 mA the bunching efficiency decreases sharply and is independent of the buncher voltage. As can also be seen in Fig. 2b, for 50 and 100 mA, increasing the voltage beyond 18 kV results in a drop in the bunching efficiency. The reason for this is that the majority of the particles cross the synchronous phase well before the input of the linac. From the moment that a particle crosses the synchronous phase, it starts diverting from the synchronous energy due to space-charge forces and at the input of the linac the particle is already outside the energy spread of $\pm$ 25 keV. The number of particles which are lost with regard to energy spread exceeds the number of new particles which are gained with regard to phase spread and the bunching efficiency decreases.

For currents of 200, 300 and 400 mA and a buncher voltage of 18 kV fewer particles are able to approach the synchronous phase than in the case of the low currents, because stronger space-charge forces are present. Therefore, the bunching efficiency decreases. When the voltage is increased beyond 18 kV the bunching efficiency re-

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mains at the same level because the number of new particles which are able to enter the region of phase spread of ± 32° is of the same order as the number of particles that are lost due to excessive energy spread.

Better bunching results can be achieved for smaller buncher drift distances. As can be seen in Figs. 1a, 1b and 2a, the bunching efficiency for high currents increases as the buncher-linac distance decreases. For a buncher drift distance of 71 cm good bunching efficiency can be achieved for currents of 50 up to 400 mA varying the buncher voltage.

Table I shows the fraction of particles lying within a phase space spread ± 10°, ± 20° and ± 32°, respectively, and an energy spread of 25 keV for a single 71 cm buncher. As can be seen from this table a tight beam bunch can be obtained for the lower beam currents.

Figures 3 and 4 illustrate the bunching process occurs as the bunch approaches the linac through an 83 cm buncher-linac drift space. The two bunches correspond to 50 and 300 mA. The buncher voltage is 27.5 kV for both currents.

### 3. Results for Double Buncher

In an effort to increase the bunching efficiency, numerical calculations have been performed for a double buncher varying parameters such as distance, voltage and frequency of each buncher for the same set of beam currents.

Figure 5 shows the bunching efficiency of a double buncher as a function of the first buncher voltage $V_1$ and for an optimum voltage $V_2$ for each beam current. The first buncher-second buncher drift distance is 83 cm and the distance of the second buncher from the linac is 71 cm. This double buncher has the over-all length of the existing Brookhaven single buncher with an additional buncher inserted at a distance of 71 cm from the linac. The combination of the two bunchers gives somewhat higher bunching efficiencies.

Table II shows the efficiency of a double buncher with a first buncher-second buncher distance of 24 cm and a second buncher-linac distance of 71 cm. The second buncher operates at a frequency of 600 Mc while the first buncher is a 200-Mc cavity. This double buncher is chosen from a set of double bunchers whose second buncher operates at a higher harmonic because of its good bunching efficiency. As can be seen in Table II for high beam currents, the bunching one gets with this double buncher is not as good as that obtained with a single buncher (see Table I). Generally, bunching for high beam currents decreases as the drift distance of the bunching process increases. For a 400-Mc second buncher less satisfactory bunching effects were obtained.

## II. Six-Dimensional Calculations

### 1. Computer Program

A six-dimensional particle motion code, taking into account space-charge forces, has earlier been written for the linac.[2] This program was slightly modified in order to be applicable to the buncher system. Space-charge forces were achieved by assuming that the beam is a collection of small spheres. Two adjacent bunches (one on each side of the central bunch, whose motion is being simulated) were considered in the space-charge calculations. The central bunch was represented by approximately 400 small spheres.

### 2. Input Conditions at Buncher Gap

In longitudinal phase space, particles were evenly distributed in phase and had no energy spread. The initial distribution in $x$-$p_x$-$y$-$p_y$ space was that of a randomly populated four-dimensional hyperellipsoid. Transverse initial emittances were chosen in the following way: As will be pointed out in another paper at this conference[3] it is important to match the beam both longitudinally and transversely at the input of the linac. Results from the two-dimensional longitudinal calculations described above were used to determine the matched transverse beam emittances at this point employing the ellipsoidal model for the beam bunch. (The size of the transverse emittances was taken in accordance with measured characteristics of the new Brookhaven preinjector system.[4]) A four-dimensional transverse motion code, in which space-charge forces are calculated from interactions between infinitely long, very thin cylinders, was used to trace back the required matched transverse emittances through a quadrupole triplet in the buncher-linac drift space to the buncher gap. A slowly varying bunching factor derived from the results of the two-dimensional longitudinal calculations, was introduced to account for beam bunching (or rather debunching, going from the linac to the buncher). The output of this calculation gives the transverse initial conditions for the six-dimensional calculation at the buncher gap.

The strength of the quadrupole triplet was adjusted to give an average beam radius of 1-1.5 cm at the buncher gap.

### 3. Results

Runs were made for a single buncher with a drift space distance of 71 cm and a buncher voltage of 30 kV. Table III gives the bunching efficiency, defined as the fraction of particles within ± 32° phase spread at the input of the linac and also the energy spread at this point for different values of beam current. Comparison of these results with those obtained from the two-dimensional longitudinal calculations (see Fig. 1) shows good agreement.

Figures 6 to 9 show the x and y beam profiles in the buncher-linac drift space for 50, 100, 200 and 400 mA, respectively, and also the position and the gradients of the quadrupole triplet which will match the beam at the input point of the linac. Because this point constitutes a symmetry center in the linac quadrupole focusing system the beam has to come to a waist in both the $x$-$p_x$ and $y$-$p_y$ planes.

## III. Summary

Numerical buncher calculations taking into account the effects of space charge suggest the following conclusions regarding beam bunching for injection into the new 200 MeV Brookhaven linac.

1) Beams of currents up to 400 mA can be bunched into the longitudinal acceptance of the linac with an efficiency of 50-60% by the use of a single buncher whose drift space is 70-80 cm. Maximum bunching efficiency can be obtained for a particular current by slight adjustment of the buncher voltage.

2) For 50 mA several double buncher designs were found which can bunch the beam into a phase spread of $\pm$ 20° with an efficiency of 60%.

3) It is possible to match the beam transversely at the input of the linac by the use of a quadrupole triplet in the buncher-linac drift space. For a particular buncher design considered in this paper the required magnetic field gradients in the quadrupoles were found to vary from 0.6 to 1.8 kG/cm for corresponding beam currents between 50 and 400 mA.

## DISCUSSION

(C. Agritellis)

MILLER, SLAC: Do your calculations include the image charge effects in the conducting tube around the drifting beam?

AGRITELLIS, BNL: No, they don't.

MILLER, SLAC: At least in electron accelerators this can have quite a significant effect on the optimization of the drift space.

CHASMAN, BNL: I would like to answer this question. The drift tube around the beam is probably going to be much larger than the beam dimensions so I don't think the image effect will be very serious.

TABLE I

Bunching efficiency for a single buncher of 71 cm drift distance for different currents and different buncher voltages using 2-dimensional calculation.

| I (mA) | V (kV) | Energy Spread $\pm$25 keV $\pm$ 10° | $\pm$ 20° | $\pm$ 32° |
|---|---|---|---|---|
| | 20 | .25 | .37 | .46 |
| 50 | 25 | .28 | .46 | .52 |
| | 30 | .43 | .50 | .56 |
| | 20 | .22 | .35 | .44 |
| 100 | 25 | .35 | .44 | .51 |
| | 30 | .44 | .51 | .54 |
| | 20 | .17 | .30 | .41 |
| 200 | 25 | .29 | .40 | .49 |
| | 30 | .38 | .48 | .56 |
| | 20 | .16 | .29 | .40 |
| 300 | 25 | .22 | .37 | .46 |
| | 30 | .32 | .44 | .52 |
| | 20 | .14 | .27 | .37 |
| 400 | 25 | .19 | .33 | .43 |
| | 30 | .26 | .40 | .49 |

TABLE II

Bunching efficiency for a double buncher for different beam currents and different buncher voltages using 2-dimensional calculation.

First-Second Buncher Distance 24 cm
Second Buncher-Linac Distance 71 cm
First Buncher Frequency 200 Mc
Second Buncher Frequency 600 Mc

| $V_1$ (kV) | $V_2$ (kV) | I (mA) | ± 25 keV Spread ± 10° | ± 20° | ± 32° |
|---|---|---|---|---|---|
| 25 | -10 | 50 | .36 | .60 | .63 |
| | | 100 | .29 | .63 | .66 |
| | | 200 | .14 | .36 | .60 |
| | | 300 | .13 | .25 | .48 |
| | | 400 | .09 | .20 | .36 |
| | -5 | 50 | .53 | .60 | .65 |
| | | 100 | .40 | .57 | .63 |
| | | 200 | .19 | .41 | .57 |
| | | 300 | .16 | .30 | .49 |
| | | 400 | .12 | .24 | .40 |

TABLE III

Bunching efficiency for a single buncher of 71 cm drift distance for different currents using 6-dimensional calculations.

| V (kV) | I (mA) | Bunching Efficiency | Energy Spread (keV) |
|---|---|---|---|
| 30 | 50 | .584 | 29 |
| | 100 | .579 | 25 |
| | 200 | .567 | 22 |
| | 400 | .541 | 21 |

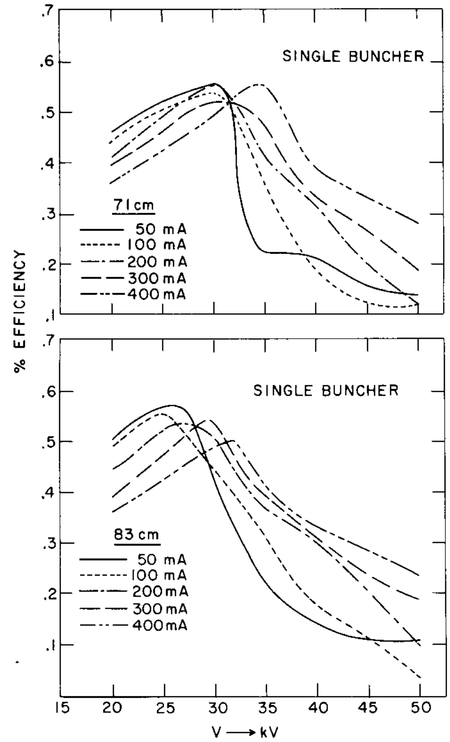



Figure 1 - Single buncher bunching efficiency versus buncher voltage for different currents with drift distances of 71 and 83 cm.

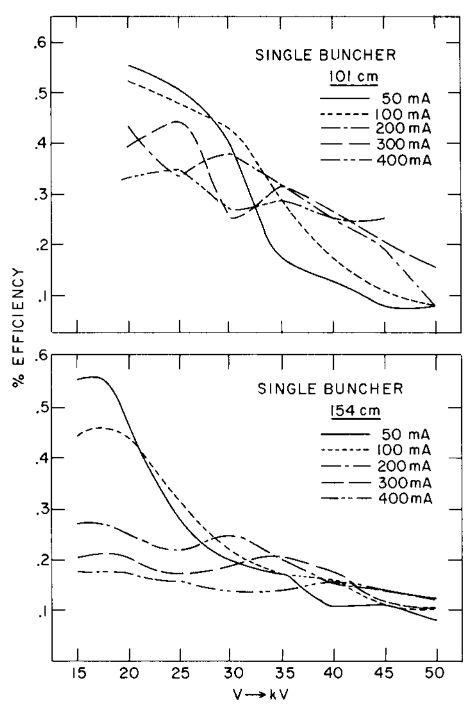
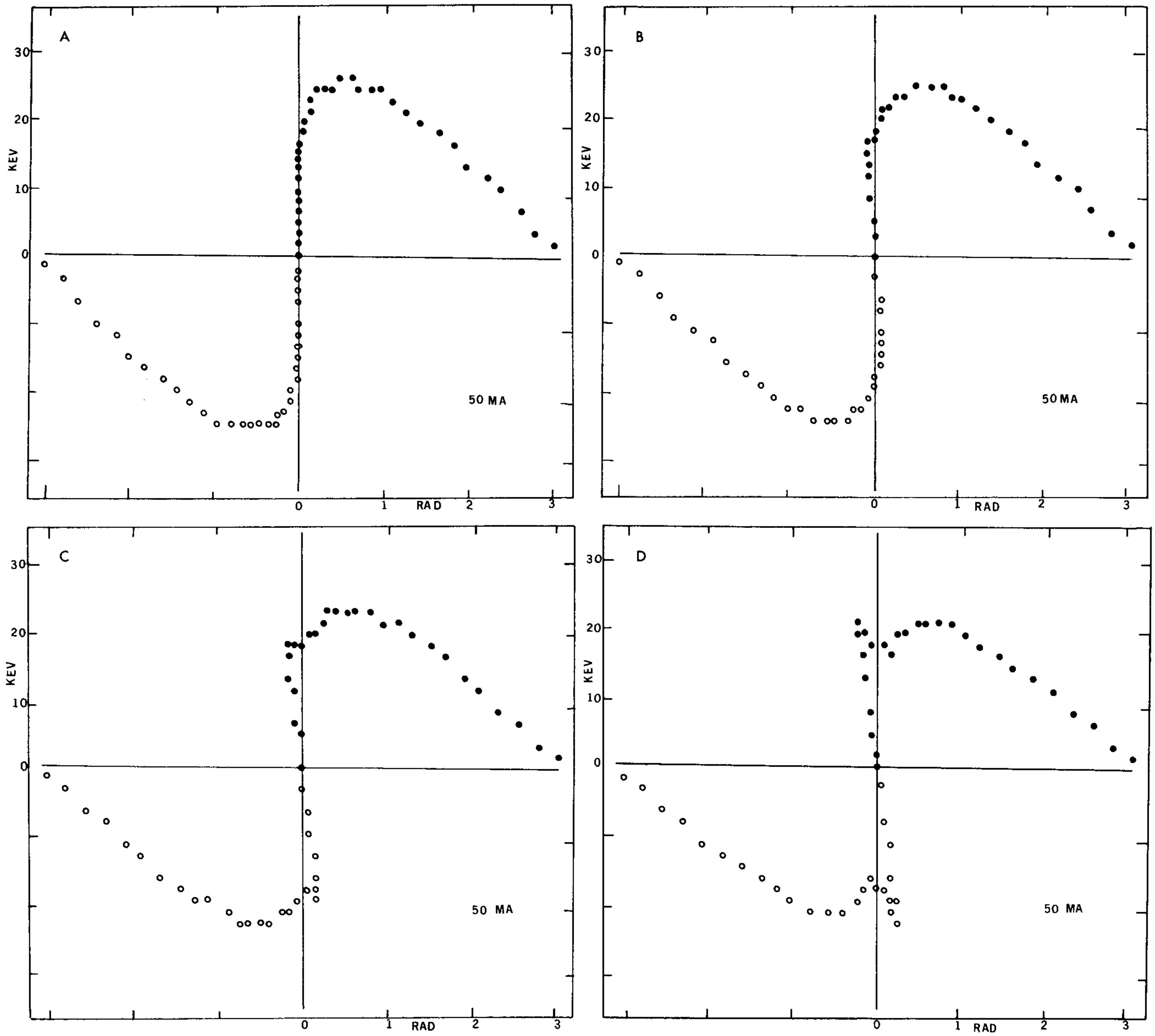



Figure 2 - Single buncher bunching efficiency versus buncher voltage for different currents with drift distances of 101 and 154 cm.



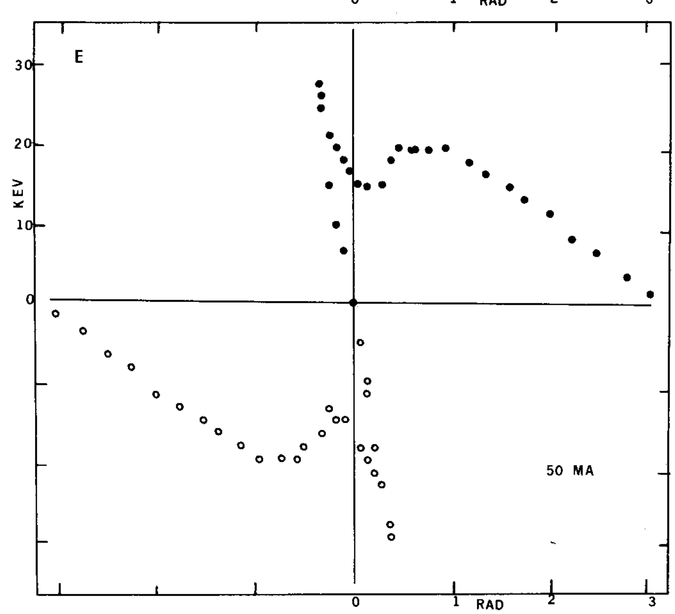




Figure 3 - Five plots of energy versus phase at axial positions of: A, 59 cm; B, 65 cm; C, 71 cm; D, 77 cm; E, 83 cm; for a beam matched at 83 cm. Beam current 50 ma.

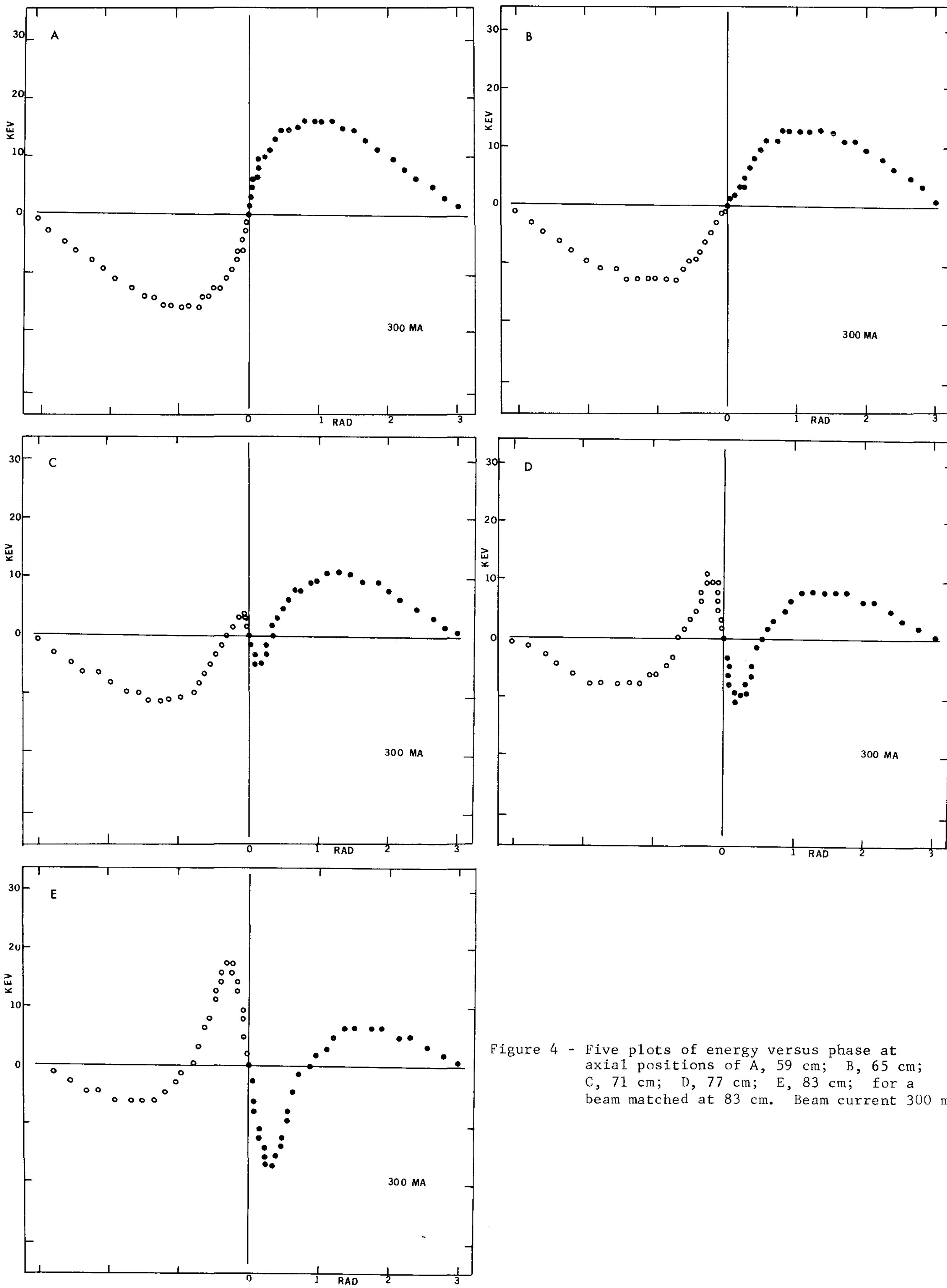



Figure 4 - Five plots of energy versus phase at axial positions of A, 59 cm; B, 65 cm; C, 71 cm; D, 77 cm; E, 83 cm; for a beam matched at 83 cm. Beam current 300 ma.

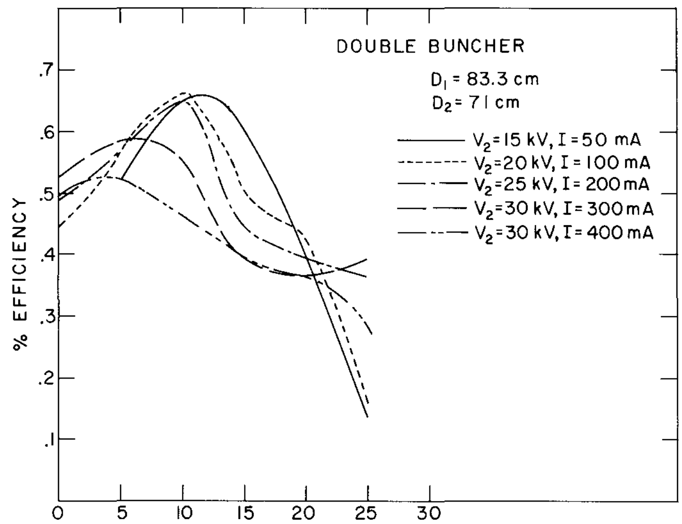



Figure 5 - Double buncher bunching efficiency versus first buncher voltage $V_1$ for an optimum voltage $V_2$ on the second buncher for each beam current.

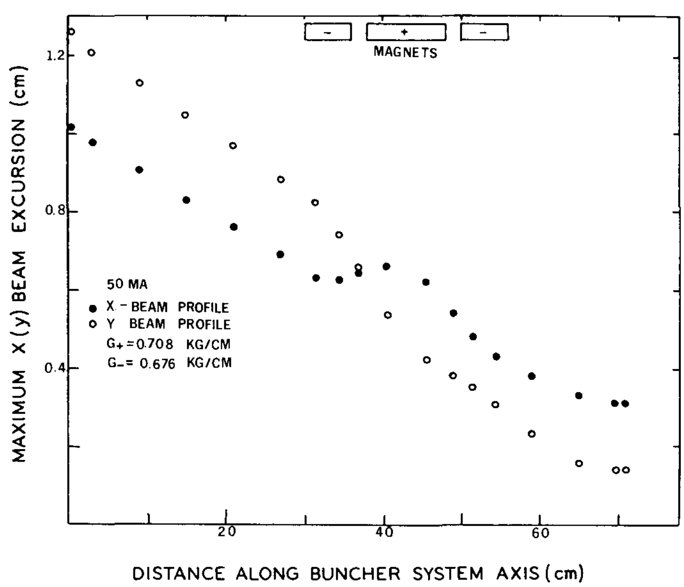



Figure 6 - X and Y beam profile as a function of drift distance for a matched beam at 71 cm. Beam current 50 mA

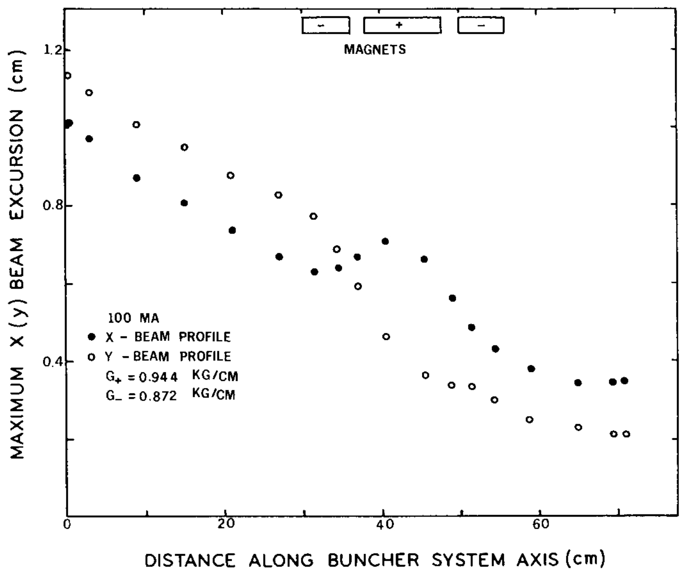



Figure 7 - X and Y beam profile as a function of drift distance for a matched beam at 71 cm. Beam current 100 mA.

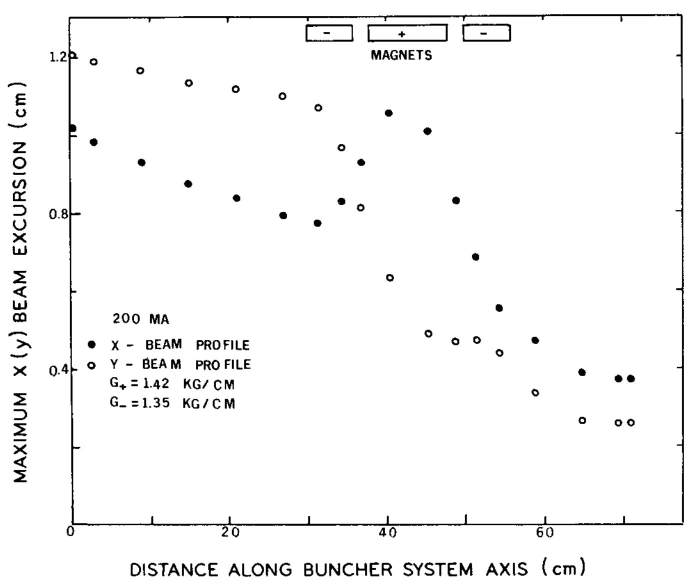



Figure 8 - X and Y beam profile as a function of drift distance for a matched beam at 71 cm. Beam current 200 mA.

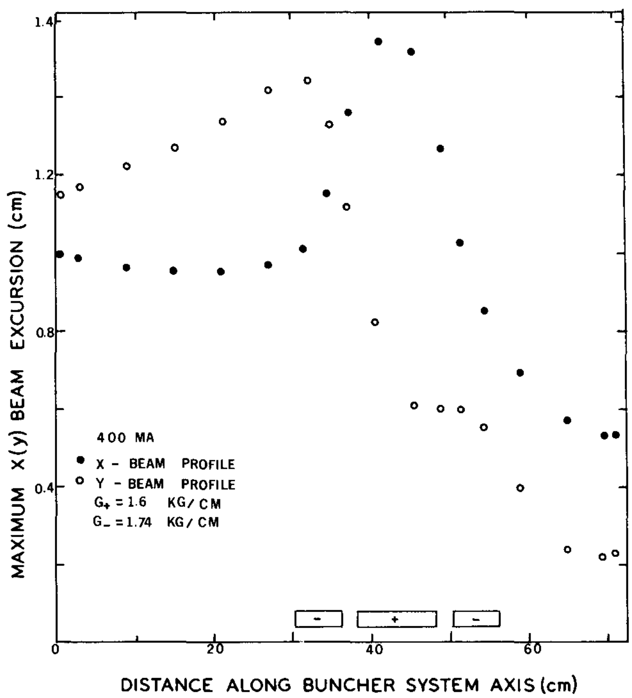



Figure 9 - X and Y beam profile as a function of drift distance for a matched beam at 71 cm. Beam current 400 mA.