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SINGLE- AND DOUBLE-DRIFT BUNCHERS
AS POSSIBLE INJECTION SCHEMES FOR THE CPS LINAC

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Summary

Two bunching schemes are considered in the frame of the CPS Linac, one with a single buncher, the other with a double-drift harmonic buncher. The matching of the beam to the Linac acceptance in six phase-space dimensions is achieved by computer programs in an iterative way: zero current solutions are found first, and then the intensity is progressively raised until 200 mA are trapped into the Linac.

Introduction

Over the past years, some computational methods and computer programs have been developed in order to analyse the operation of the whole complex of the linear accelerator under space charge conditions.¹ In particular, a certain effort has been devoted to the preinjector, where the bunching and matching have been checked and found to be not very satisfactory for beams of the present operating intensity.

This paper reports some analysis concerning the re-design of the 520 keV beam transport system in the frame of an eventual improvement or rebuilding of the Linac. The considerations are based on the present preinjector layout; some of the elements have to be shifted and others added in order that the beam at the Linac input satisfies the requirements.

Two schemes have been analysed, one containing a single, the other a double-drift harmonic buncher system. Both have been optimized so as to match preinjector currents in a range sufficient to give trapped beams of up to 200 mA. The schemes are to be looked at as the outcome of a feasibility study rather than as a definite design proposal.

The computing technique, especially the routines dealing with matching optimization, have been refined in the course of this study. It turned out, however, that in order to avoid "local" optima and converge to the "absolute" optimum, initial guesses put into the program had to be close enough to the true solutions. This was done by calculating first zero current solutions carefully, and then raising the beam intensity progressively, each time replacing the initial solutions. All the forces in the program are linearized; the evolution of r.m.s. beam emittances is determined by linearized forces, provided the density distribution is of the ellipsoidal type.²

Beam matching calculations

The methods underlying the beam matching calculations have been presented in another paper, submitted to this conference.³ Some definitions and procedures used in the matching optimization program are listed below.

Definition of the beam

The beam is defined at the input to the beam transport system, which in our case is just after the d.c. accelerating column: the density distribution in real space and the transverse emittances have to be given. With these, one calculates the second momenta $\overline{x^2}$, $\overline{x'^2}$, and $\overline{xx'}$ for both transverse planes, and defines an equivalent, uniform beam with marginal phase plane coordinates $\hat{x} = \frac{2\sqrt{\overline{x^2}}}{\sqrt{1+\overline{x'^2}}}$ and $\hat{x}' = \frac{2\sqrt{\overline{x'^2}}}{\sqrt{1+\overline{x^2}}}$ and a marginal emittance $E_x = 4\sqrt{\overline{x^2\overline{x'^2}} - (\overline{xx'})^2}$ (the factors before the square roots are valid for a cylindrical beam in real space). It is the uniform, equivalent beam which is transported to the Linac and matched to its acceptance. The justification for this procedure is given in Ref. 2.

The transverse emittances in all the calculations were:

$$E_x = E_y = 100\pi \times 10^{-6} \text{ m}\cdot\text{rad (at 520 keV)}.$$

The longitudinal beam emittance is formed in the beam transport system itself by the non-linear energy modulation imparted to the beam by the buncher(s); this emittance is defined in an analogous way to that above, but only after all the energy modulation has taken place, i.e. at the last buncher:

$$\hat{z} = \sqrt{5z^2}; \quad \hat{z}' = \sqrt{5z'^2}; \quad E_z = 5\sqrt{z^2z'^2 - (zz')^2}$$

(the factors in the formulae are valid for an ellipsoid in real space).

Linac acceptance and matching conditions

The Linac acceptance in the six phase-space dimensions is not a symmetric figure due to the asymmetry in the longitudinal plane. This is inconvenient for matching calculations based on linear analysis, and one is obliged to introduce some approximations: the longitudinal bucket is replaced by an ellipse, centred on the stable fixed point and extending, on one side, to the separatrix, but leaving out, on the other side, the region in the neighbourhood of the unstable fixed point, see Fig. 1:

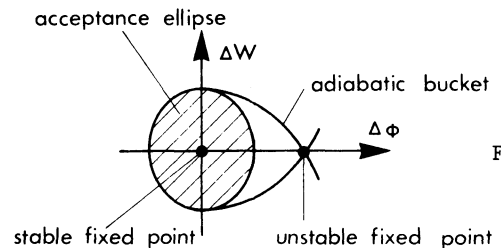


Fig. 1

With these approximations, one obtains a six-dimensional hyperellipsoid as acceptance, with ellipses as projections in each of the phase planes.

In each of the transverse phase planes, there are two matching conditions to be fulfilled in order that the emittance ellipse be homothetic to the acceptance. In the longitudinal plane, there is one more condition: the area of the emittance has to be equal to the acceptance. This additional condition is needed for our model and is essential for the determination of bunching parameters.³

The Linac acceptance is a function of beam intensity; the acceptance used in our study has been determined for a focusing structure $N = 1$, and a stable phase angle $\phi_s = -30^\circ$.¹

Matching optimization

The optimization of the matching follows essentially the following scheme:

1. find preliminary, zero space-charge matching solutions analytically, graphically or with ancillary computer programs;
2. introduce the above solutions into a computer program, which optimizes the matching with space charge (program PREINJ);¹ raise the current progressively, each time renewing the initial solutions. The position of the matching elements can be varied and enters into the optimization.

3. With all the elements in fixed positions, check the matching of the system for a given range of beam intensities.

Steps 2 and 3 are usually repeated several times. It has been found that the matching is satisfactory in the transverse phase planes, provided the number and the position of the lenses are adequately chosen. Longitudinally however, in fixing the buncher(s) position, one lacks a matching parameter. The energy modulation, imparted to the beam by the bunching system, is decreased by the space charge action during the beam transport; a correction is necessary to fulfil the matching requirements. This can be done by installing an additional buncher, close to the Linac: the particles supposed to be trapped have there already a limited phase extension, and are thus modulated only by the quasi-linear part of the sinusoidal RF voltage. Therefore the additional buncher does not practically increase the longitudinal emittance; it acts as a kind of a linear, longitudinal lens and is called "energy spread corrector" when used in our schemes of transport systems.

Transport system with a single buncher and energy spread corrector

The length of the 520 keV preinjector transport system is approximately 2 m; the optimized disposition of matching elements is shown in Fig. 2:

Two triplets match the beam to the buncher, leaving an empty space in between for beam measuring devices. From the buncher onwards, four quadrupoles ensure the transverse matching to the Linac acceptance, defined in this study at the dynamic midplane of the first gap. The fourth quadrupole is located in the half drift tube preceding the gap. The single buncher, with an energy spread corrector placed between the second and third quadrupoles, matches the beam longitudinally in a range up to 400 mA of preinjector current.

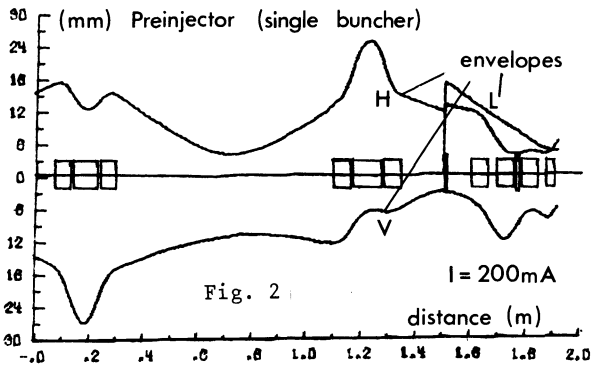


Fig. 2

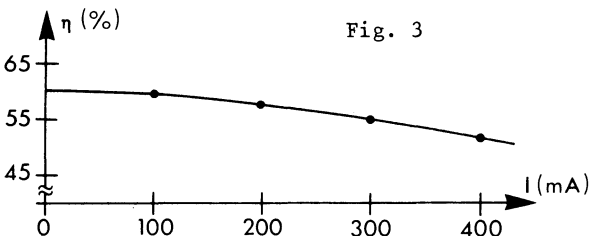


Fig. 3

The beam envelopes (for 200 mA) in all the three phase planes are shown in Fig. 2. The bunching efficiency as function of preinjector current is shown in Fig. 3; the drop is mainly due to the longitudinal acceptance decrease with beam intensity.

Transport system with a double-drift harmonic buncher and energy spread corrector

The drawback of a single buncher system lies not so much in its relatively low efficiency as in the rather

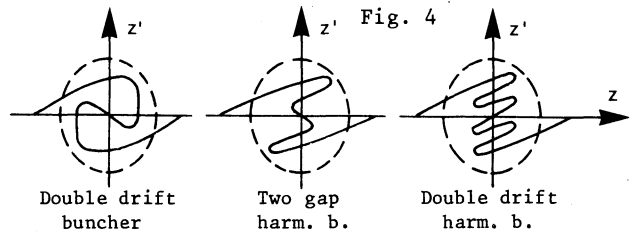


Fig. 4

non-uniform filling of the longitudinal acceptance. This is inconvenient for high-intensity beam acceleration in the Linac. Systems with two bunchers are superior⁴⁻⁸ and Fig. 4 shows some typical fillings of the longitudinal acceptance:

The most interesting and flexible system is the double-drift harmonic buncher (the second buncher operates on the first harmonic of the RF), which has been considered as an alternative solution in our preinjector study. The distance between the bunchers and the ratio of their respective voltages have been determined to give the best bunching efficiency;³ the distance from the Linac and the absolute value of the voltages have been fixed in connection with longitudinal matching requirements.

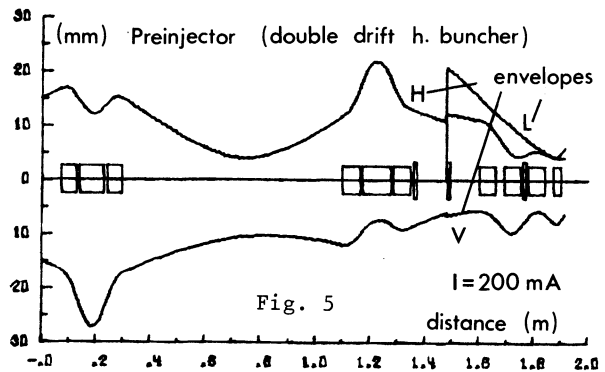


Fig. 5

Figure 5 shows the layout of the transport system containing a double-drift harmonic buncher with an energy spread corrector; the beam envelopes for 200 mA are drawn in. Figure 6 gives the bunching efficiency, which is much higher than with a single buncher.

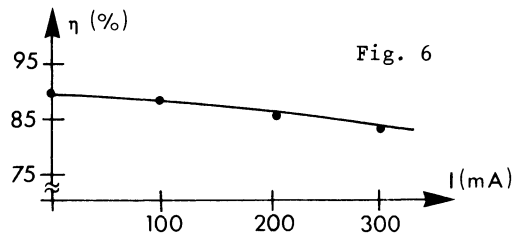


Fig. 6

Check of the validity of the matching optimization method

The six-dimensional matching problem of the preinjector has been solved by a method which has been developed for this purpose and introduced into computer programs; the method included several simplifications and assumptions, and it is not *a priori* certain that the results so obtained are accurate. It is therefore important to check the solutions with a different technique, e.g. the simulation of the beam by a number of macroparticles and their transfer through the optimized beam transport system.

A beam simulation program, BUNCH 73,⁹ which is still under improvement, has been applied in our analysis. It is possible to introduce an arbitrary number of

"measuring points" into BUNCH 73; at such points the beam emittances are compared with those computed by PREINJ. The initial filling of particles, adopted in BUNCH 73 for this study, is a Gaussian one in the transverse phase planes and a uniform one longitudinally. The phase-space coordinates are generated at the input plane of the beam transport system; their second transverse momenta equal those in PREINJ. The longitudinal extension of the continuous beam, as required by BUNCH 73, is obtained by shifting the particles upstream and downstream from the input plane, with linear drift matrices: the particles should uniformly fill a length $\beta\lambda$.

The agreement between PREINJ and BUNCH 73 has so far not been complete, but is nevertheless satisfactory in all the cases which were analysed. Refinements in both programs are under way.

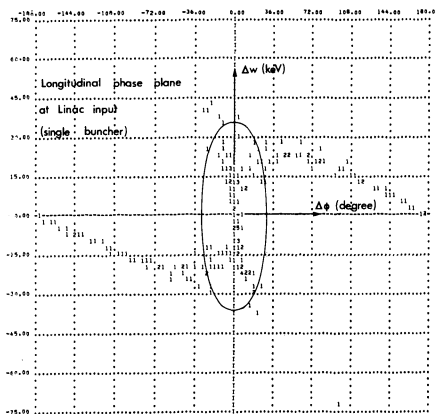


Fig. 7

Figure 7 shows the distribution of macroparticles in the longitudinal phase plane at Linac input, as obtained by BUNCH 73; the ellipse drawn in the same figure represents the longitudinal emittance, as obtained with PREINJ. The results apply for the transport system with a single buncher.

Figures 8 and 9 represent the situation when a double-drift harmonic buncher is applied. In order to follow the process of bunching more clearly, the radial variation of the transit time factor in a buncher gap, as well as the energy spread corrector, have not been considered in either program. Figure 8 shows the bunching at an intermediate stage: the energy modulation imparted by both bunchers is quite visible. Figure 9 shows the longitudinal matching at Linac input; the ellipse represents the result obtained with PREINJ. (It should be mentioned that with a variable transit time factor, the particles fill the emittance ellipse more uniformly).

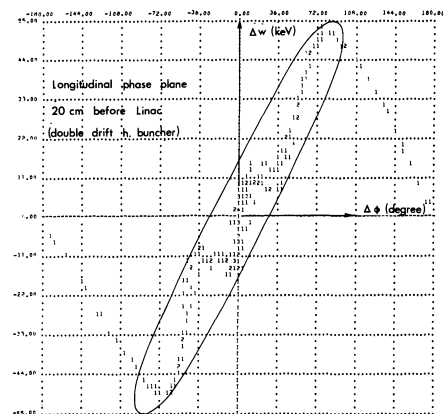


Fig. 8

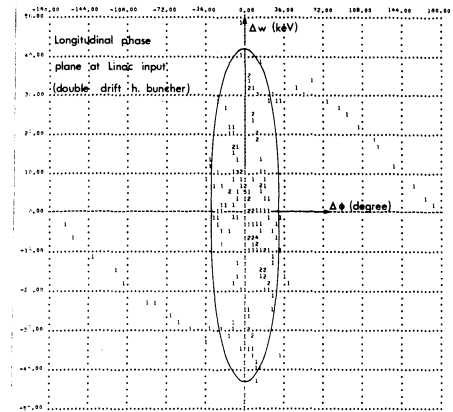


Fig. 9

Comparing Figs. 7 and 9, one sees that with a double-drift harmonic buncher the dense part of the beam sits in the centre of the emittance, whilst with a single buncher the dense parts are placed at the two extremes of the ellipse.

The bunching efficiencies for a single buncher obtained with PREINJ and BUNCH 73 are 58% and 53% respectively; for two bunchers the figures are 86% and 80%. The results apply for a preinjector current of 150 mA.

In general one can say that the agreement between PREINJ and BUNCH 73 is sufficient in order to justify the application of our method in problems dealing with beam matching optimization.

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