- IMPROVEMENT OF THE BUNCHING IN INJECTORS FOR ELECTRON LINACS -

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Summary

Computation results are presented showing an improvement in the final bunching characteristics when a long cavity is used at the beginning of a synchronous classical buncher. An analysis of several combinations has been done and suggests to adjoin at the entrance of such a buncher a long cavity leading to a phase-shift of about 4 Π/3 for the electron around which the bunching occurs. An improvement by a factor of two is obtained and variations of physical parameters are not critical. Comparison with a synchronous buncher is done, including eventually the use of a modulation cavity with drift space. Results including space-charge effects are given for a practical injector.

Introduction

We try to design injectors for electron linacs giving bunches of very small longitudinal extension (phase extension) so that all the electrons will gain the same amount of energy in the following accelerating structures. The energy dispersion at the output of the injector is less important when the following increase in energy is great.

Investigations in the bunching given by an accelerating structure with phase law synchronous with the center of the electron bunch shows the interesting possibility of injecting electrons bunched in phase even if there is a high energy dispersion. For a half-meter long synchronous structure with an electrical field of 5 MeV/m bunch phase extensions of the same order results from electrons injected with a phase extension of 90° around - 40° at the same energy of 60 keV or from electrons injected at the same phase of - 40° and energies between 40 and 80 keV.

The same study shows that for a synchronous accelerating structure the best value of the accelerating field must decrease with the energy of the electrons injected to avoid a too high convergence. Usually electrons crossing each others early in such a structure cannot be avoided as the phase of the bunch in the process of formation must be kept well behind the crest of the field. The convergence is enhanced by use of a prebunching system.

The use of a first long cavity[1] has the prebunching effect of a modulation cavity followed by a drift space together with a possibility of control of the convergence ; the cavity itself combines modulation and drift space and its length is much shorter ; this can be of great advantage when space-charge problems occurs with high currents. As this cavity can be the first cell of the structure there is no need for an independant RF feeding nor for a critical phase control.

Analysis and choice of parameters for the long cavity

The contribution to the beam dynamics of a long cavity cannot be computed easily by analytical methods even with a uniform field in space. With a sinusoïdal time variation of field the analytical expressions are of a transcendental type. A saw-tooth field leads to equations of the second or third order. Furthermore the relativistic effects are important on the bunching evaluation and lead to elliptical integrals.

Relativistic calculations done step by step with a computer[2] show that the initial phase of the electron around which bunching occurs at the cavity output is - Π (the maximum field occurs for zero phase) and depends little on the field strength and the cavity length. For this central electron initially at 40 keV and for a field of 4 MeV/m, the output phase is :

$\varphi_0 = \varphi_i + \alpha h$ for φ_i (input phase) = - 2.8 rad

α is slowly decreasing as the length h increase (α = 0.18 for h = 16 mm, α = 0.15 for h = 35 mm) and the output energy, 56 keV for h = 16 mm, reach a maximum of 80 keV for h = 26 mm and decreases to 64 keV for h = 35 mm.

A good bunching at the cavity output occurs at a phase of about + Π/6 for the electrons and corresponds to the maximum of the output energy for the central electron.

For a simple design the cavity must be the first cell of the structure. Is it possible in the case of a travelling-wave buncher in Π/2 or 2 Π/3 mode ? For the sake of generality we look for the available length of the two first cavities (one or two can have a great length) in the case of a Π/2 phase shift between cells. The electrons must enter into the following "synchronous" short-length cavities of the buncher at a phase chosen by compromise between further bunching and energy gain : $\varphi_0 = \varphi + \Pi/4$, where φ_0 is the mean output phase from the first cavities and φ is the phase in the center of the first "synchronous" cell of the structure. For the two first cells ℓ_1 and ℓ_2 and the mean speeds v_1 and v_2 of the electrons into these cells and the initial phase φ_i of the electron around which bunching occurs :

$$\varphi_0 - \varphi_i \simeq \frac{2\pi}{\lambda_0}\left(\frac{c}{v_1}\ell_1 + \frac{c}{v_2}\ell_2\right) - \frac{\pi}{2} + 2k\pi$$

- Π/2 corresponds to the dephasing between these two first cells.

For $\varphi = -\Pi/6$, $\varphi_i = -\Pi$, an accelerating field of 4 MeV/m and electrons initially at 40 keV, we can estimate the average speeds into the two first cells :

$$\frac{v_1}{c} \simeq \frac{v_2}{c} \simeq 0.355 \text{ for } k = 1$$

$$\frac{v_1}{c} \simeq 0.355 \text{ and } \frac{v_2}{c} \simeq 0.5 \text{ for } k = 0$$

All possible couples (ℓ_1 , ℓ_2) can then be obtained.

The exact calculation will give output mean phases of the bunched electrons distinct from couple to couple and slighly different from the preceding estimation. In figure 1 phase versus energy of electrons is plotted at the output of five representative couples. Good bunching with sizeable acceleration are obtained with k = 0. The couple (ℓ_1 = 29.2 mm, ℓ_2 = 8.8 mm) is selected as the structure will have only one first long cell ℓ_1 . In this case the output mean phase in the mid-plane of the first synchronous cavity (the third cavity of the buncher) would be slightly before the crest of the wave and it is necessary to reduce the lengths of several cells from the synchronous values to drive the bunch behind the crest into the convergent phase domain.

Computation of the dynamics of such an injector with a first long cell (A + B) and of an equivalent injector (B') has been done. Figure 2 and its table represent the two injectors with their field and phase law together with phase-energy plots at the output and values of compression, energy dispersion, "quality index" values. Improvement by a factor of two is obtained on the phase compression for a given initial phase extension or on the phase admittance at the input for a given compression

Dynamics for practical injector designs

We use a 2 Π/3 phase-shift between cavities to keep electrons inside the convergent phase domain for a best choice of the first long cell. The field is taken from measured values on laboratory structures at each point of the axis by a travelling-wave perturbation method(3) taking into account the z dependance inside the first cells to include harmonics(4) and to account for the bell shape of the field inside the long cavity which includes a part of the input coupler in THOMSON-CSF design. Electrons are injected at an energy of 40 keV.

Figure 3 compares the output phases at an energy of 2.9 MeV, versus input phase, with and without a first long cell. The mean field of this cell is 3 MeV/m for a peak field of 4 MeV/m, its length is 28 mm, corresponding to a shorter length for a long cell with uniform field. The mean field in the following cells is increasing from 3.2 to 5 MeV/m, together with their lengths. These values correspond to a power of 1.4 MW for c/v_g = 50 at v_φ = 1 and a frequency of 3 GHz. In the two cases the bunching is too high as the electrons cross each others : the two curves have a negative slope. $\Delta\varphi_o / \Delta\varphi_i$ = 0.25 without the long cell, $\Delta\varphi_o / \Delta\varphi_i$ = 0.13 with a long cell. The crossing occurs in the two cases early in the accelerating process (around the third cell) and the choice of a phase law along the structure nearer the crest of the accelerating wave is not very interesting as the decreasing of the convergence will be obtained at the expense of the number of accelerated electrons.

We decrease the level of the field to three-quarter of its preceding values and figure 4 compares the output phases at an energy of 2.5 MeV, as function of the input phase with and without a first long cell. The long cell has been lengthened by 4 mm and the lengths of the following cells increase more slowly. The bunching is now optimized. 60 % of the output electrons are inside a 4° bunch corresponding to an initial extension of 130° (figure 4.b). Without the long cell, crossing occurs again (figure 4.a).

Sensitivity to variation of parameters has been analysed for this design : in figure 4.c the long cavity is reduced by 3 mm, in figure 4.d the fields are increased by 22 %.

To these structures we add now a premodulation cavity with its drift space. The drift space was taken equal to 75 mm with the long cavity and 112 mm without it, for a modulation of ± 4 kV. Figure 5 gives the corresponding output phases at a 2.5 MeV level versus the input phase before the modulation cavity.

We see that we are able to reach the performances of the buncher with a long cavity when prebunching is added to a buncher without a long cavity (figure 5.a). However, this result is very sensitive to the drift space value (and to space-charge effects which correspond to a change of this value), to adjustement of dephasing between premodulation field and the structure field and to the level of premodulation. In particular if the drift space is 75 mm against 112 mm (or if the premodulation is decreased) the bunching is destroyed (figure 5.b).

With prebunching added to the buncher with a long cavity the number of accelerated electrons is increased. The drift space value (or level of premodulation) is not at all critical as shown in figures 5.c and d, this last figure corresponding to a drift space of 112mm.

The convergence has been increased but the crossing occurs far in the structure and the space-charge has a favorable effect. Space-charge effect was computed for a beam of 2.5 mm diameter(2) between 0 and 200 mA and results are given in table 1.

Conclusion

A buncher including a first long cell is equivalent to a classical synchronous buncher with a well optimized prebunching system. Advantage results from simplicity of design and from the absence of critical prebunching parameters modified by space-charge effects. If a prebunching is added to such a buncher acceptance in phase can be increased even more with a lower sensitivity to prebunching parameters and linked space-charge effects.

References

(1) Patent n° 70 30 261
(2) D. TRONC "Electron prebunching with space-charge effects", this conference 1971
(3) K.B. MALLORY, R.H. MILLER "On non-resonant perturbation measurements, IEEE-MIT February 1966
(4) J. HAIMSON "Electron bunching in travelling-wave linear accelerators", Nuclear Inst. and Methods 39 - 1966

Injected current (mA)	Accelerated current (mA)	Bunch extension		
		(1)	(2)	(3)
0	0	8.2°		
50	38	6.2	4.6	2.3
100	75	7.0	5.3	2.8
200	150	7.9	6.5	4.2

(1) 0.75 I_a, 2.5 MeV - (2) 0.75 I_a, 4 7 MeV -
(3) 0.5 I_a - 4 7 MeV Table 1

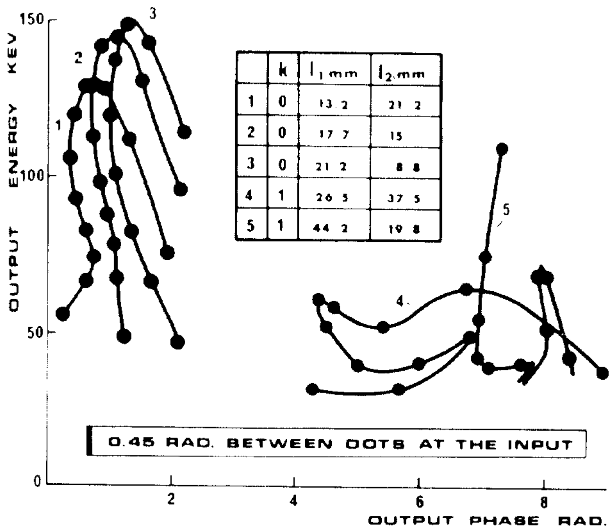
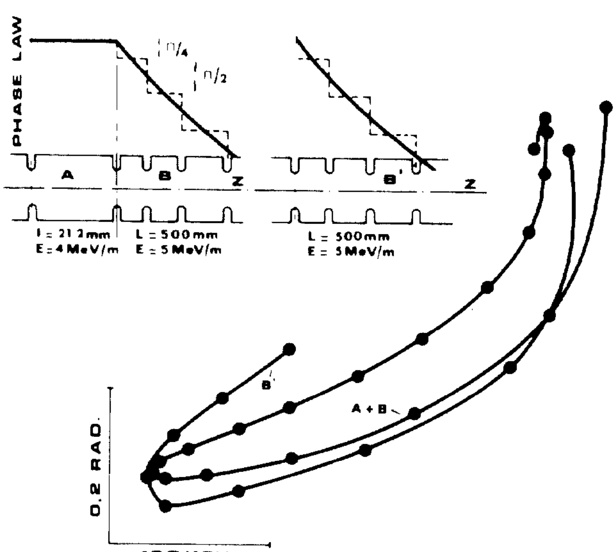


Fig. 1 - Electron bunching by two cavities



Injector	$\Delta\varphi_e$ rad.	$\Delta\varphi_s$ rad.	Compression $\Delta\varphi_e / \Delta\varphi_s$	$\frac{\Delta V_s}{V_s}$ (1)	Quality index $\left(k \frac{\Delta\varphi_e}{\Delta\varphi_s} \cdot \frac{V_s}{\Delta V_s}\right)$
A + B	1.4	0.1	14	0.038	1.75
B'	0.8	0.1	8	0.038	1.
A + B	0.8	0.04	20	0.021	5.
B'	0.8	0.1	8	0.042	1.

Fig. 2 - Comparison between injectors with and without a long cavity

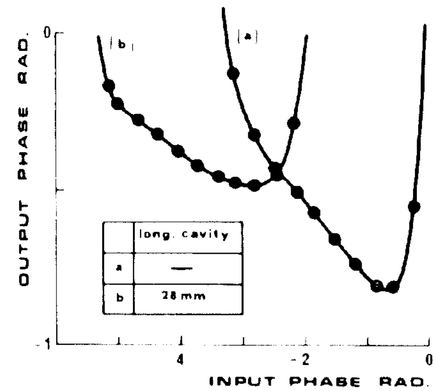


Fig. 3 - Practical injector designs without and with a long cavity:(a), (b)

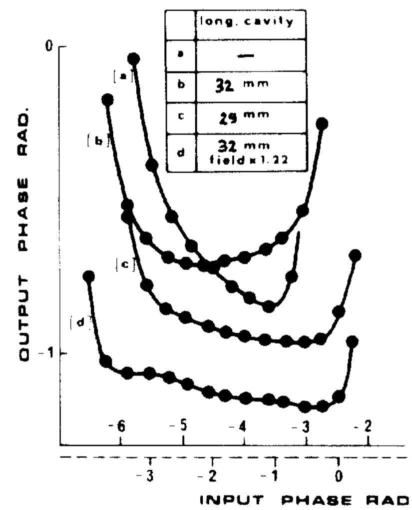


Fig. 4 - Practical injector designs with lower field : (a), (b) and with a variation of parameters : (c), (d)

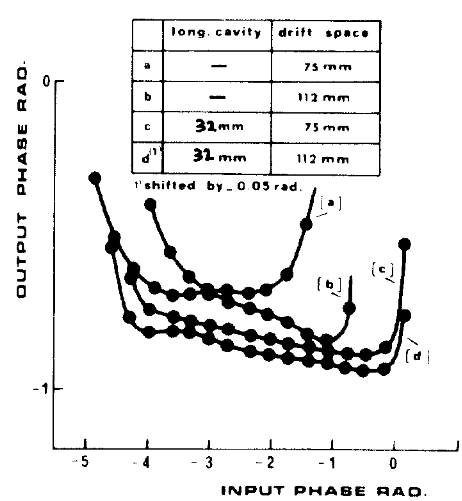


Fig. 5 - Practical injector designs of fig. 4 with prebunching