BUNCHING

P. M. Lapostolle
European Organization for Nuclear Research
Geneva, Switzerland

Abstract

After having reviewed the various performances which can be attributed to a buncher and some of the devices which have been used so far or studied in the absence of space charge, the problem of bunching at high intensity is considered and various types of attempts are described with some numerical results given.

1. Introduction

The use of a buncher to increase the trapping efficiency of proton linear accelerators has been considered and tested since the early times of these machines : the first Berkeley 31 MeV linac had its current increased by a factor of three with the help of a buncher as reported by L. Alvarez et al (1955)[1].

This concept of bunching was in fact nothing else than the production of density modulation used in the microwave amplifiers called "klystrons" for an electron beam.

Klystrons or velocity modulated tubes have been the object of many studies two decades ago and during the 1950's; many approaches have been used to evaluate their efficiency and improve it by various devices as well for high as for low power operation. Bunching in a linac is, however, not exactly analogous to what is required in klystrons and only recently have the two problems been compared, in particular to study bunching limitations which occur in high intensity accelerators.

We shall here review the various problems which have been considered for linac bunching and shall do it in an historical order. That will lead us to examine first the various properties which can be aimed at by a proper bunching in a zero space charge approximation and with no coupling between longitudinal and transverse motions. We shall then arrive at the high intensity case where with present day approaches space charge and couplings are introduced in computer programmes ; these ones now give a better understanding of the phenomena and should permit to find a proper design of high intensity linac bunchers.

2. Longitudinal linac capture efficiency

The first aim of bunching has been to increase the percentage of injected particles which can be trapped around the stable phases of the linac accelerating wave and then brought to high energy.

In other words, the bunching is made to increase the longitudinal capture efficiency. This in fact has been and is still the main goal of bunching.

The way it is done is shown schematically on Fig.1.

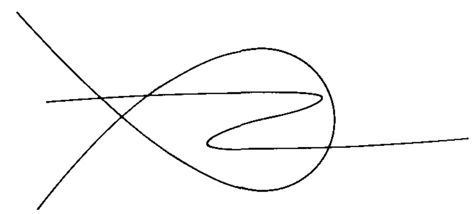


Fig. 1. Single gap bunching

There in the longitudinal phase space (φ, ΔW) the injected beam appears as an S or Z shaped line which represents the transformation of a purely sinusoidal velocity modulation into density modulation through a drift space ; a part of this Z falls inside the fish like stability bucket, that is to say, the curve which at that time of the linac theory was considered as the separatrix of the motion.

The buncher adjustment is then assumed to be made such as to increase the fraction of the injected particles which can be accelerated, i.e. to maximize the fraction of each RF period during which the particles which are crossing the buncher fall inside the stability bucket.

3. Double buncher

It was early recognised that a sinusoidal velocity modulation was not adequate to produce a very high trapping efficiency : the maximum theoretical efficiency in the case of a sinusoidal buncher always remains below 70%.

An ideal bunching would be obtained from a saw tooth modulation as in Fig.2 ; 2a shows the velocity modulation produced at the buncher and 2b the density modulation obtained at linac entrance.

Such a saw tooth modulation is of course very difficult to produce at an RF frequency of 200 MHz as commonly used in linacs. One may, however, try to approximate this ideal shape.

A saw tooth is a periodic function which can be decomposed by Fourier analysis into a complete spectrum of harmonics going up to infinity. If one limits the expansion to the first few terms, however, the waveform obtained is already approximately a saw tooth (see Fig.3) and should lead to a better bunching efficiency.

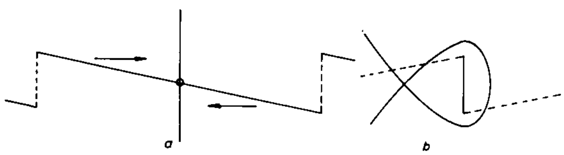


Fig. 2. Saw tooth bunching
a) at the buncher
b) at linac entrance

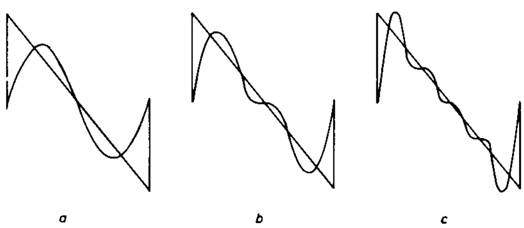


Fig. 3. Multicavity bunching
a) single
b) double
c) triple

This possibility was described in some detail by R. Perry in 1963[2]. The use of fundamental and double frequency buncher (see Fig.4) would lead to about 80% theoretical capture efficiency and the use of a triple buncher to almost 90%.

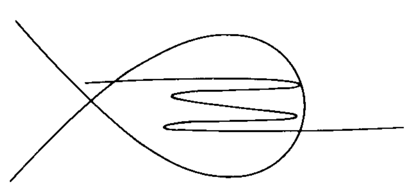


Fig. 4. Two cavity buncher

It is, however, surprising that none of the multiple (in practice double) buncher devices which have been constructed have ever been used operationally : hardly any improvement in capture efficiency could ever be obtained with them.

4. Reduction of beam loss in the linac
New family of bunchers

Approaching the era of high intensity (and high energy) linacs a new concern was submitted to accelerator physicists.

The untrapped protons are not only bad as a lack of accelerated particles ; they may also be prejudicial by producing radiation and radioactivity where they are lost.

This problem was stated by S. Ohnuma (1963)[3] and gave rise to a full new family of linac bunchers described by R. Gluckstern and R. Beringer (1964)[4]. There radial displacement is substituted or added to the velocity modulation in order to chop a fraction of the particles during each RF period. Various types of deflectors and several optical systems have been considered and their efficiency evaluated. To my knowledge, however, none of these were used in practice.

5. Energy spectrum. Density distribution in longitudinal phase space

For the design of a new linac injector for the synchrotron SATURNE, it had been specified that the energy spectrum from the linac had to lie within a certain width and that the distribution inside this spectrum had to be as uniform as possible : according to previous experience a line distribution could lead to a bad space charge situation after injection in the synchrotron.

As a result of coupling between longitudinal and transverse motion in a linac, a line distribution in longitudinal phase space at input gives for a non-infinitely thin beam a kind of ribbon distribution in longitudinal phase space at output. If now instead of a single Z at injection (corresponding to a single buncher) a multi Z is injected (see Fig. 4), the thickness of the ribbon may become large enough to produce overlapping of the successive branches, looking thus like a uniform distribution (M. Promé, 1966[5], see Fig. 5).

6. Small energy spread

The way double harmonic bunching is supposed to be adjusted for this SATURNE injector is, however, slightly different from what appears in Fig. 4 ; there were in fact two complementary requirements specified : in addition to a uniform distribution in the energy spectrum, the energy spread had to be minimized.

This was obtained by adjusting the bunchers in order to produce at injection a longitudinal phase space situation as shown in Fig. 6.

There two things are done :

particles are distributed as well as possible inside an elliptical contour, invariant during longitudinal oscillations

this contour is chosen as small as possible, i.e. as far as possible from the separatrix.

The first condition insures optimum matching, which means minimum phase and energy spread oscillations. The second condition entails a reduction of coupling between longitudinal and transverse motions. This last effect is somewhat contradictory with the uniform distribution requirement which might have been otherwise already satisfied with a single buncher and large phase width ; but it turns out to produce with a double buncher both a low energy spread and a good distribution. We shall, in fact, see later that other effects among which space charge may also play a role in producing a more uniform energy distribution.

bunchers should be made gridless.

The reason for using grids in the early linacs had been to avoid the transverse momentum imparted by the RF gap of the buncher and avoid the corresponding radial variation of the longitudinal velocity modulation. Grids are, however, never perfect and even often produce bad high order aberrations ; that may explain why their suppression was not bad.

This situation did anyway raise the need of taking into account radial effects for the high intensity bunchers.

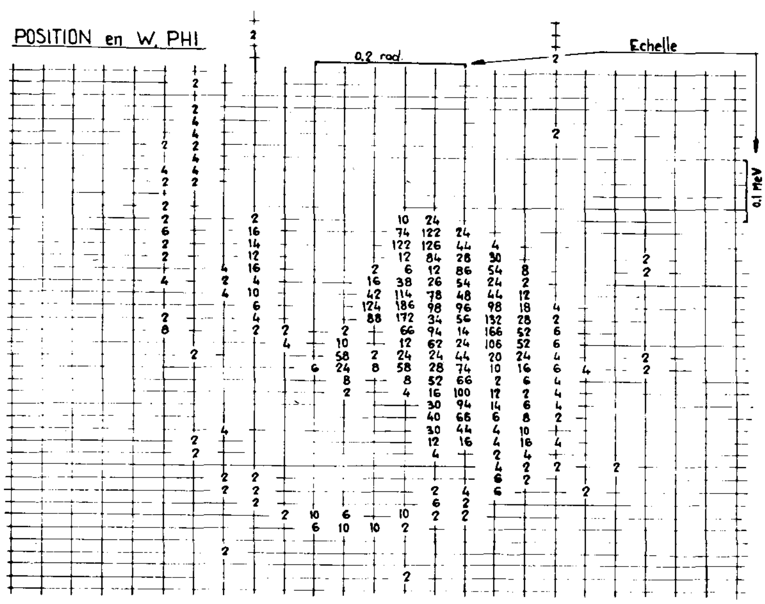


Fig. 5. Output longitudinal phase space from a 20 MeV linac

7. High intensity. Gridded or gridless bunchers. Transverse effects.

The first report about a high intensity operation was given in 1966 by C. Taylor et al.[6]

One of the effects observed was an anomalous beam loading of the buncher. This one was due to an inadequate vacuum, produced by outgassing and even melting or evaporation under severe beam bombardment of the grids which had been used so far.

In order to remedy this situation a modification has then been to remove the grids and replace them only by a circular hole with a 18mm aperture titanium diaphragm. No appreciable change was observed on the linac operation.

As a conclusion it was accepted that for a high intensity (several hundred mA) operation

8. Space charge effects. Comparison with klystrons

Another effect observed with high intensity was an appreciable reduction of the buncher efficiency (Taylor et al[6]).

In order to try to understand that it became necessary to introduce space charge effects in the buncher computations . Many space charge studies had been made in klystron theory and they were applied to the case of proton bunching.

Most of the klystron treatments make use of the space charge wave concept as opposed to the ballistic theory so far used for buncher computations(Lapostolle 1967, Srinivasan 1967[7]). These space charge approaches show that space charge acts in two ways :

one of them is to prevent bunching to take place by virtue of space charge repulsion;

another one is to introduce a radial dependence for this modulation since space charge repulsion is purely longitudinal on the axis but partly transversal on the beam edge where bunching may then proceed to higher values.

A particularly interesting treatment has been made by M. Chodorow et al in 1959[8]. Under some assumption they show that due to the divergence free property of the electric field, any action of a gridless buncher upon a beam of charged particles is restricted to types corresponding to the action on an incompressible fluid, that is to say, with a constant density. This means that the only way to produce a longitudinal bunching is to modulate the beam cross-section.

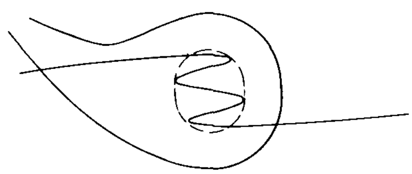


Fig. 6. Double buncher adjustment

In our case this is only true for small cross section modulation and so long as the space charge forces do not play an important role. This property, even if only qualitative, is nevertheless of a fundamental importance. In particular it shows that one cannot neglect transverse effects ; one reason for the loss of efficiency of bunching at high current is already the insufficient size of the linac input aperture which cuts out the outer part of the beam, i.e. the modulation itself ; that does not mean, however, that longitudinal space charge repulsion can be disregarded, but that it does not give a complete picture of the situation.

9. Computer programmes

This complicated situation encouraged a recourse to computers.

Detailed programmes were written where the beam was represented by several thousand particles acting one over the others according to the space charge laws.

An extremely good programme assuming a rotational symmetry problem has been written in Los Alamos in 1966 by C. Emigh and K. Crandall. The first part of it (K. Crandall, 1966[9]), with no longitudinal modulation yet, was presented at the 1966 Linac Conference, and the rest of it (C.R. Emigh, 1968[10]) will appear in the proceedings of this Conference.

With the kind permission of the author and of the Los Alamos Scientific Laboratory, this programme called MRA (many rings averaged) was communicated to CERN and Saclay. There, experiments on a 300 KV beam were performed in 1967 to check the computed results. This work has been presented at the Cambridge Conference last year by Bernard, Promé et al[11]. It showed a very fair agreement between computation and experiments but more qualitative than quantitative, and it was suspected that the differences could be due to the fact that neither the lens used in the experiments (a quadrupole triplet) nor the probe were of rotational symmetry.

Another elaborate programme has been written in CERN by F. Vermeulen* (1967)[12] where no symmetry is assumed and the beam is represented by a few thousand particles with three independent coordinates in the geometric space. With the help of this programme most of the differences observed in the experiments quoted above can be understood.

A difference between the circular symmetry and the general case programmes seems to be a larger blow up of the beam, especially of its outer part, in the three dimensional computation (triplet instead of symmetric lens). A quantitative estimate of this blow up is, however, difficult to give because of the quantized character of the computations where the beam is represented by a relatively small number of points (2000 is not very large).

10. Discussion of the computer results

Figures 7 and 8 show typical outputs from this last programme. Figures 7a to c represent phase space distribution (two transverse and one longitudinal) and figures 8a to c, two transverse and one longitudinal projections of the particles which cross the buncher during one RF period.

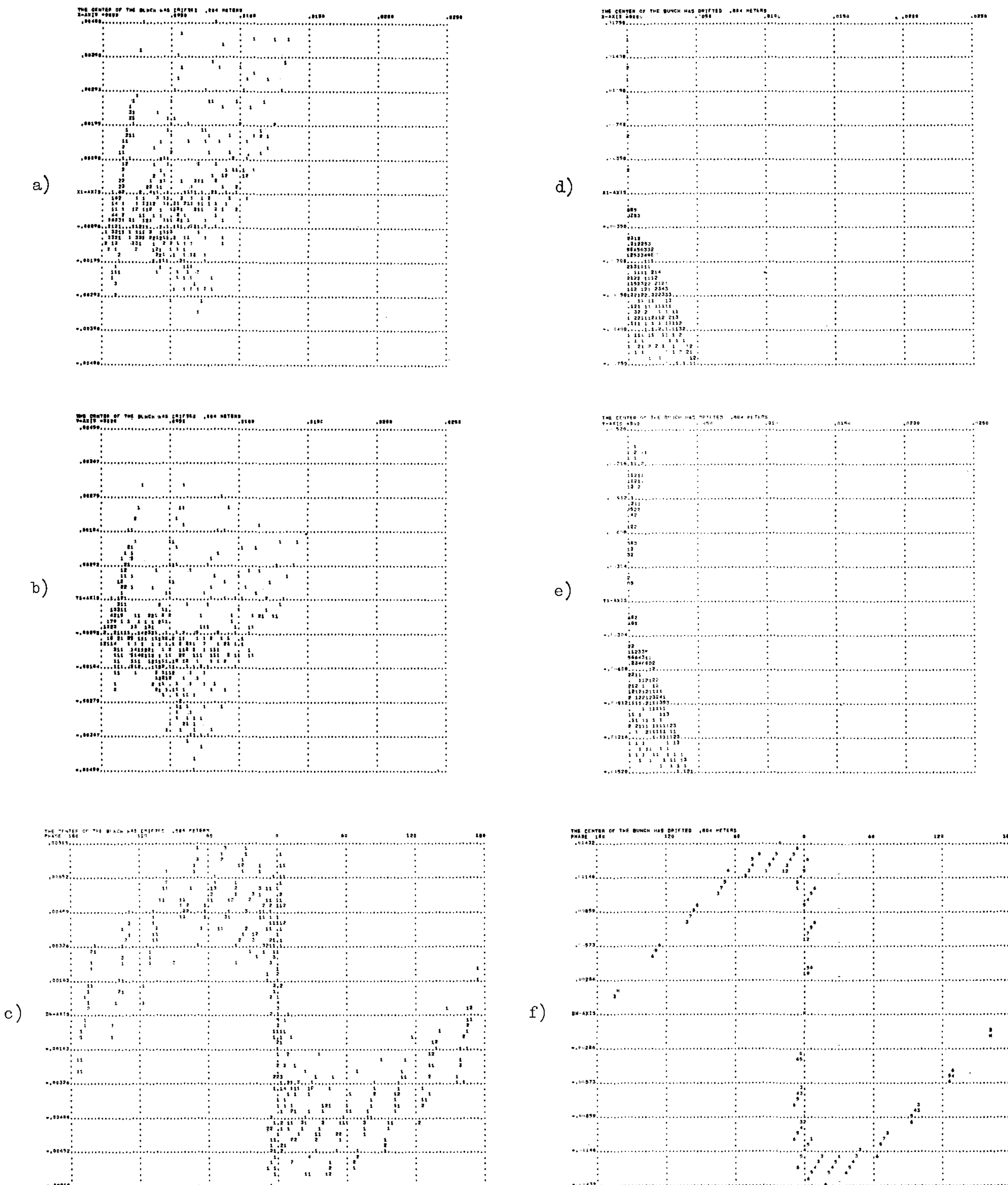
These correspond to CERN linac buncher optics with an intensity of 200 mA and a buncher voltage of 14 kV (12 on the axis).

Figures 7d to f and 8d to f show the corresponding outputs for no space charge.

A look at these results shows some distortion in the longitudinal phase space ; a detailed analysis would indicate that the energy is a function of the radial position : on the axis the energy modulation has been almost completely suppressed by space charge.

---

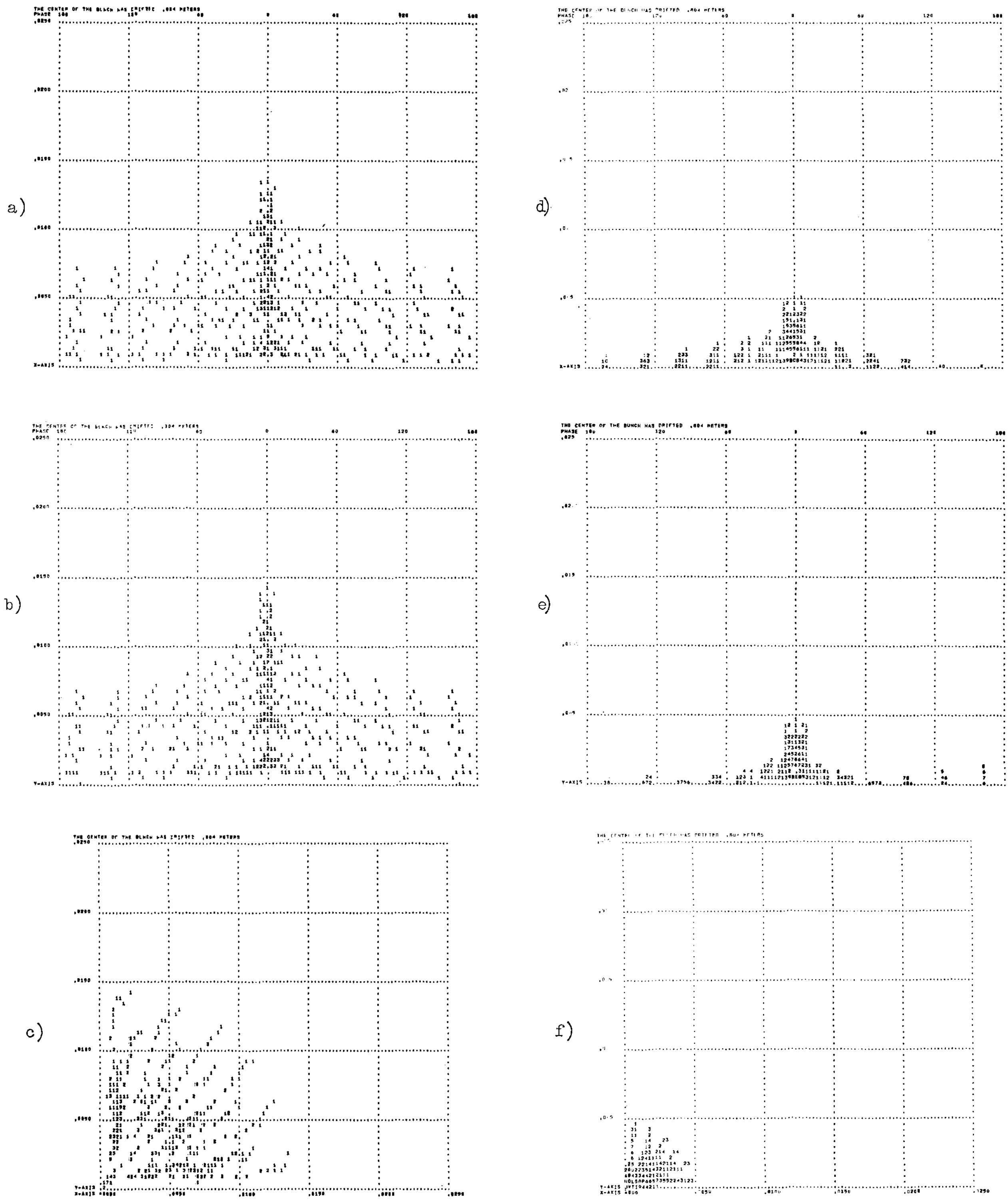
* Now at the university of Alberta, Edmonton, Canada.



200 mA

0 mA

Fig. 7
Phase space distributions at CERN linac input-14 kV modulation 0.8 metre drift



200 mA

0 mA

Fig. 8

Projections of particle distributions at CERN linac input-14 kV modulation 0.8 metre drift

Other sorts of distortion more of the saturation type can be seen with a higher voltage and longer distances. Figure 9a gives the longitudinal phase space for 20 kV (17 on the axis) modulation and a distance of 1 metre. Figure 9b gives one of the corresponding transverse projections. Such a distribution would not be particularly good for capture into a linac.

This curious situation entails the following surprising property : the suppression at the linac input of the central part of a beam coming out from a buncher does not affect very much the accelerated current while it reduces the injected one. In other words, the trapping efficiency is larger near the beam boundary than it is near the axis. Such a strange effect had been in fact measured already two

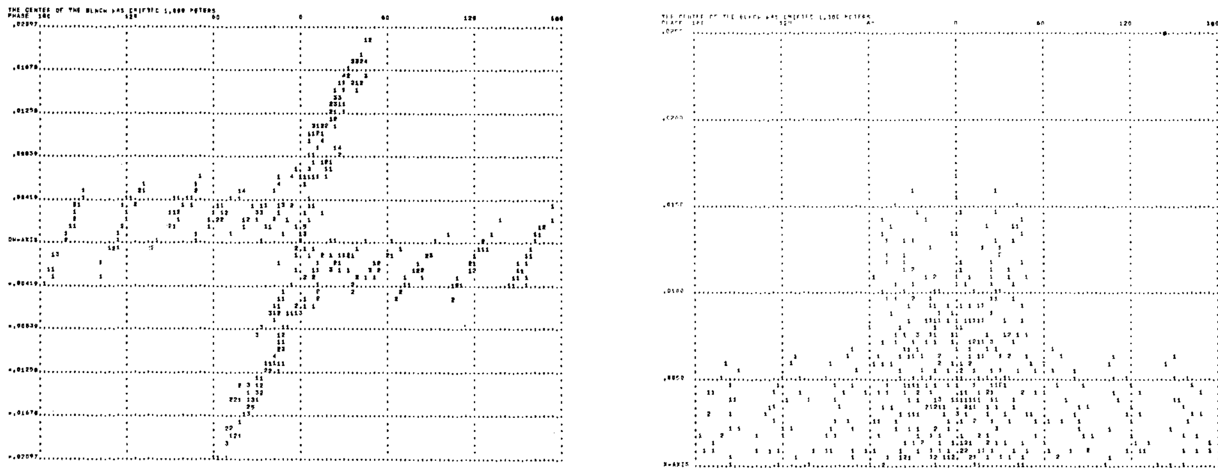


Fig. 9. Bunching with saturation
20 kV modulation
1 metre drift
200 mA

years ago on the CERN linac* but suspected at that time as possibly affected by some mysterious errors.

The transverse projections show the strong cross section modulation produced by the buncher ; with an intensity of 200 mA space charge forces are also such as to increase the beam size to a diameter where most of the buncher modulation is scraped out by the input aperture ; the bunching efficiency is then cut down as observed experimentally.

Figure 10 gives for similar cases the locus along the axis of the maximum and minimum radii of the modulated beam : continuous and dashed curves relate to the two transverse planes of the triplet. As one can see several cases are shown with different buncher voltages and different intensities.

It appears that with a proper choice of buncher voltage and optical system the ratio of beam cross sections at maximum and minimum modulation phases can be made rather large.

Concerning the volume density modulation inside the beam the results of the previous figures are not very well fitted for a detailed analysis. The results from the MRA computer give more information and show a surprisingly small modulation on and near the axis at least as far as the beam does not present any cross-over or waist : the modulation really lies in the outer part of the beam.

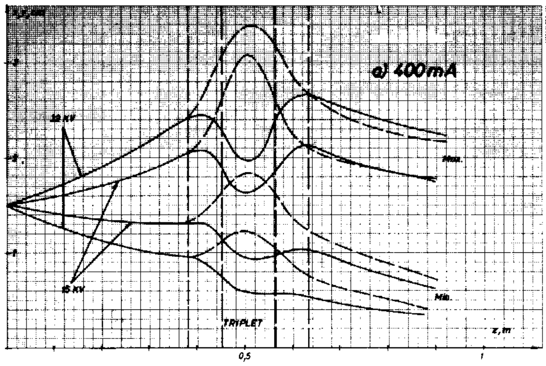
Another conclusion would be that there is an easy way to cut out the unaccelerated part of a linac beam : with proper optics of a bunched beam the trajectories corresponding to unwanted phases can all be put inside a certain diameter : with a correspondingly adjusted central diaphragm (circular or elliptical) only acceptable particles can be injected into the linac and all of them are trapped.

11. Bunching devices recently proposed

In 1966, C.Emigh, with the help of the MRA programme extended the double buncher system to what has been called the "double drift buncher."

In this system the two cavities are not put close together (ideally at the same place in the old proposal) but the beam is left to drift between them and after the second buncher. The second cavity is operated at double frequency (Fig. 11).

* Private communication from P. Tetu



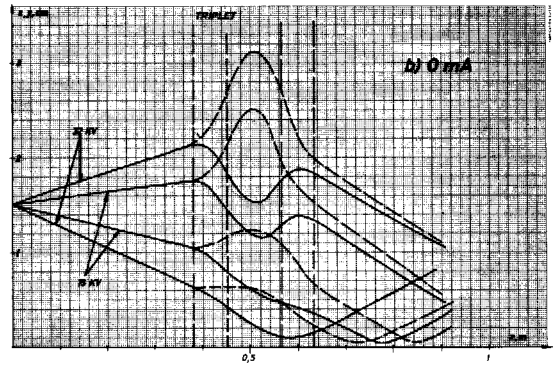


Fig. 10. Max. and Min. beam cross sections
a) 400 mA b) 0 mA

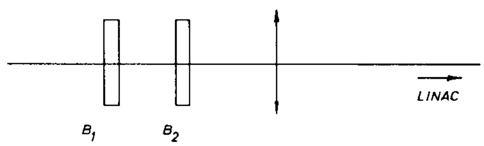


Fig. 11. Double drift buncher

This device is presented at this conference (C. Emigh) and will appear in the proceedings[10].

A similar suggestion was made last year at the Washington Conference (Lapostolle[13]) with the two separate bunchers, but operated at the same frequency. This proposal was made on the account of the success of multicavity high power klystrons.

Such a device, double drift, single frequency buncher, has been checked with the MRA programme and successfully tested on the proton linac of the Rutherford HEL (Carne et al 1967[14]). The intensity remains, however, not very high (10 mA) since this linac is a very long pulse grid focussed machine.

For the high intensity case the proposal made in Washington[13] also suggested to raise the injection energy as high as possible, up to 2 MV for instance.

Another interesting proposal was made last year at the Cambridge Conference by B. Montague (1967)[15] under the name of "accelerating buncher".

There the beam coming out of a conventional buncher is accelerated on the unstable phase of a linac (see Fig. 12). Two requirements are then fulfilled at a time :

immediate acceleration leaving the beam as little time as possible at low energy where space charge forces are dangerous -

shaping phase space distribution in the longitudinal direction and procuring transverse RF focussing (extra focussing can also be added) in order to minimize emittances and energy spread.

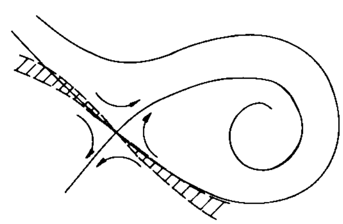


Fig. 12. Accelerating buncher

The principle there used is very similar to the device suggested in[13] but the two effects are made simultaneously in a very interesting way.

12. Conclusions

At the time of this Conference it seems still too early to draw any final conclusion from all the work reported hereupon.

It nevertheless appears already that tools exist to carry out systematic studies and to optimize a design with the help of one of the existing space charge programmes.

This has only been done, to my knowledge for LAMPF, the Los Alamos project, as will appear in the Proceedings[10].

The proposal of B. Montague should be studied in more detail to evaluate what performances could be obtained ; estimates should also be made of the tolerances required.

The single frequency double drift buncher has probably not been fully investigated for high space charge though C. Emigh made several computations on it.

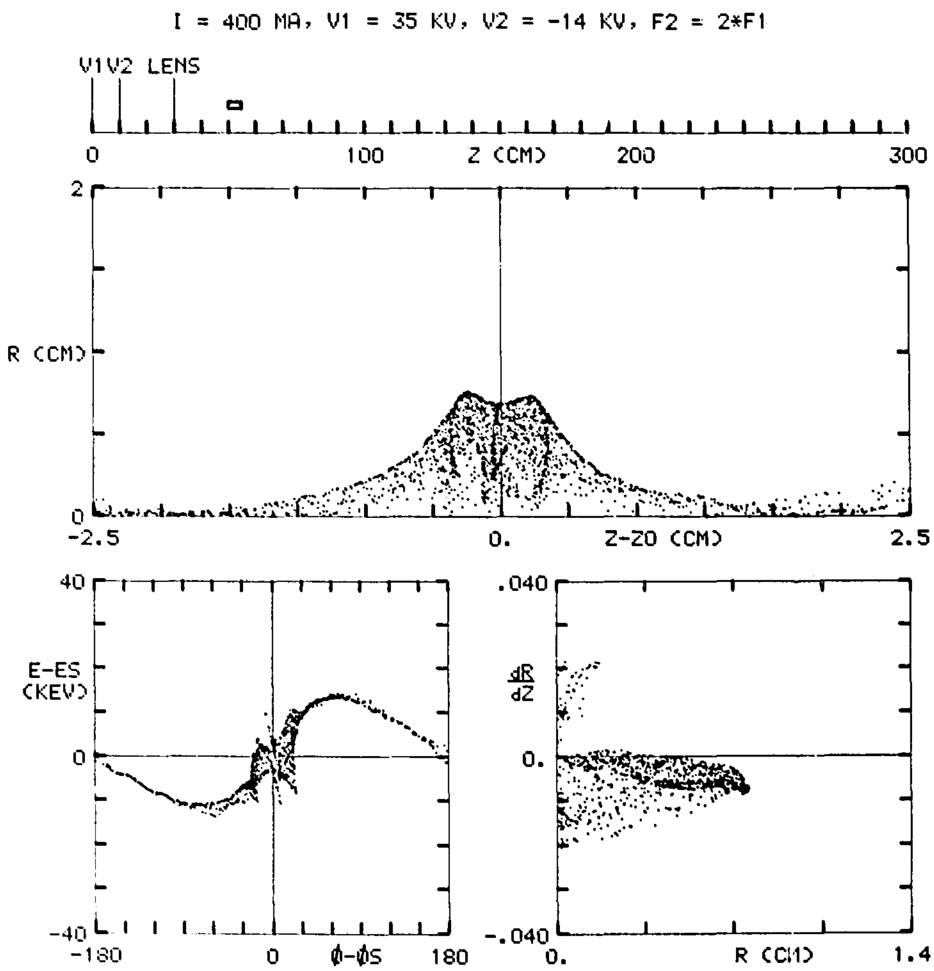


Fig. 13. Double drift, double frequency buncher according to Los Alamos MRA programme

The double frequency double drift buncher is itself certainly a very powerful device. Figure 13 gives the result of a run of the MRA programme for a case similar to the CERN linac injection already shown in Figures 7 and 8, with a 400 mA beam * .

There at 55 cm from the first buncher, all the beam is focussed inside a linac aperture of 1.5 cm diameter, where

21% of the beam is within 5° of phase
32% of the beam is within 10° of phase
43% of the beam is within 15° of phase
57% of the beam is within 20° of phase
67% of the beam is within 25° of phase
72% of the beam is within 30° of phase

The replacement of a rotational symmetry lens by a triplet would probably reduce slightly these performances but it is not sure that another scheme would yield better results.

In all cases, however, the only general conclusion which can be made is to stress the advantages, especially in terms of space charge of a high injection energy. Work is already going on for the study of pre-injector assembly at 2 or 3 MV. This must not be discontinued because whatever good a bunching device could ever be, its performances will always be reduced at high intensity and the only way to get round this limitation will be an increase in injection energy.

References

1. L. Alvarez et al. Berkeley Proton Linear Accelerator - R.S.I, Vol. 26, Feb. 1955, p. 132.

2. R. Perry. Multiple Harmonic Buncher for a Linear Accelerator - ANLAD 74, Feb.1963 and Yale Conference on Linear Accelerators. Oct. 1963, p. 279 - 287.

3. S. Ohnuma. Bunching for High Intensity Linacs - Yale loc. cit. p. 273 - 278.

4. R. Beringer and R. Gluckstern. A family of improved Linac Bunchers. MURA Conference on Linear Accelerators Jul. 1964, MURA 714, p. 564 - 601.

5. M. Promé. Design of a 20 MeV Proton Linear Accelerator, New injector for SATURNE, 1966 Linear Accelerator Conference, Los Alamos LA 3609, p. 403 - 409.

6. C. S. Taylor et al. Progress report on the CERN PS Linac - Los Alamos Conference on Linear Accelerators, Oct. 1966, LASL 3609, p. 48.

7. P. Lapostolle. Ondes de charge d'espace dans un faisceau de protons. Groupeurs et Linacs à haute intensité. CERN report ISR 300/LI 67-36, Sept. 1967.
T. Srinivasan - Measurements on non linear space charge waves IEEE Trans ED 14 no. 2, p. 89 - 97, (Feb. 1967).

8. M. Chodorow et al. The radio-frequency current distribution in Brillouin flow - IRE Transactions ED 6 No. 3, Jul. 1959, p. 352 - 357.

9. K. Crandall. A numerical experiment on space charge effects. Los Alamos Conference on Linear Accelerators, Oct. 1966, LASL 3609, p. 233 - 236.

10. C.R. Emigh. The double-drift buncher - Brookhaven Conference on Linear Accelerators, p. 338 this volume.

11. P. Bernard et al. New 20 MeV Saturne injector studies on ion sources and particle bunching - VI Int. Conference on High Energy Accelerators 1967, Cambridge CEAL 2000, p. A9-16.

12. F. Vermeulen. Computer simulation of beam bunching with the inclusion of space charge forces and quadrupole lenses. CERN Int. Report MPS/Int. LIN 67.5. Aug. 1967.

13. P. Lapostolle. On the design of a high intensity proton linear accelerator - Particle Accelerator Conference, Washington 1967. IEEE Transactions on Nuclear Science NS 14 No. 3, p. 573.

14. A. Carne, S. Norcliffe. Double buncher design study - PLA Progress Report 1967. RHEL/R 156 p. 33-35.

A. Carne, J. Dickson, S. Norcliffe, J. Webb, K. Batchelor. Reduction of energy spread on the Rutherford Laboratory PLA - p. 416 this vol.

15. B. Montague. A reappraisal of design criteria at the low energy end of proton linac injectors. VI Conference on High Energy Accelerators, Cambridge, 1967, CEAL 2000, p. 175.

DISCUSSION

(P. Lapostolle)

WARNER, CERN: Could you make some comment on the energy spread caused by deflection in the method of Beringer and Gluckstern? I was under the impression, (and indeed) there is a paper on this subject

* Given by C. Emigh, who is here gratefully acknowledged.

in the International High Energy Accelerator Conference at Frascati, 1965, that shows that the deflection of a beam of practical emittance introduces so much energy spread, that the production of a small area in longitudinal phase space by this method is impossible.

LAPOSTOLLE, CERN: I do not think this effect has been considered and I cannot answer. That reminds me, however, of something that is a curiosity. I have shown that in the radial distribution one gets after bunching, most of the density modulation takes place in the outer part of the beam. By placing a diaphragm in the central part of the beam, it is easy to cut out the unwanted particles. The out-of-phase particles are then removed while the remaining outer part of the beam is accelerated. That, in fact, has been observed in the CERN linac several years ago, where the trapping efficiency was found higher off axis than on axis. We thought something was wrong with the measurements but I think it was just this effect.

MILLER, SLAC: You mentioned getting difference results with the 3-dimensional program as opposed to the one that assumes cylindrical symmetry. I was wondering where the asymmetry comes in. Do you put in an asymmetrical beam or does the buncher not have cylindrical symmetry?

LAPOSTOLLE, CERN: The beam is assumed to be circular in cross section and the buncher also has circular symmetry. But the focusing is done with quadrupole triplets so that the beam takes different shapes in each transverse plane and, hence, becomes nonsymmetrical.

FEATHERSTONE, CERN: You mentioned that in "klystron practice" a prebuncher, corresponding to the type with which we are familiar, is used in conjunction with a following structural section which performs additional bunching. This would correspond to designing the first part of the first cavity to catch as many particles as possible. We know that some studies of this type have been done at such places as BNL, but I don't think anything has been published. Do you know of any effort to modify the structure of cavities in this way?

LAPOSTOLLE, CERN: I know this has been suggested many times and there is a program at CERN to build a short tank just to study the beginning of the acceleration, as will be described by D. Warner, but I don't know of any result yet.