ON THE DESIGN OF A HIGH INTENSITY PROTON LINEAR ACCELERATOR

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Summary

In the CERN linear accelerator, intensities above 125 mA have been accelerated. For very big, present and future AG synchrotrons, however, there is a need for injectors giving 200 mA or more. At this intensity level, very strong longitudinal space charge effects occur which limit the phase stability in linacs and which also have been shown to prevent efficient bunching with conventional bunchers.

Proposals are given to raise the limit of these effects to about half an ampere where beam loading compensation may become difficult. For a better prediction of the performances, several studies are still to be made and various methods are outlined; a few difficult points may, however, require further effort, especially if still higher intensities and extreme performances are needed.

Bunching

Conventional Buncher. As pointed out by Taylor at the Los Alamos Conference[1], the trapping efficiency into the CERN "linac" is reduced with high intensity to about 30%, and the "bunching factor" (improvement in trapping efficiency from buncher off to buncher on) goes down from 2.5 to 1.4.

This effect is mostly due to space charge phenomena. Experimentally, it appears to occur for a gridded as well as for a gridless buncher cavity.

Chodorow and Zitelli[2] have shown that for a gridless buncher and a Brillouin flow, because of the zero divergence properties of the modulating field, the modulation produced is only superficial.

For the case of stronger focusing but still laminar flow, the approach of Ramo[3] can be used. This method introduces an infinite set of space charge waves to represent the fields and beam modulation (in a linear approximation), the successive pairs of waves having more and more complicated radial distributions (more and more zeros of a Bessel function). It is usual practice to consider only the first pair of waves; this one shows an alternation of velocity and density modulation in the beam. But it is of some interest to look at the effect of the higher order waves[4].

Including them one finds that the modulation produced by the buncher is progressively distorted by space charge. If the longitudinal velocity modulation is not affected on the boundary of the beam (since space charge is there purely transverse), it becomes zero on the axis after a distance

$$L_o \# \sqrt{\frac{8\pi\,\epsilon_o v_o^5}{\omega^2}\;\frac{m}{e\,I}\,(1 + 0.06\,k_o^2 a^2)} \qquad (1)$$

where v_o is the velocity of the particles of charge e and mass m, ω is the angular frequency, $k_o = \omega/v$, a is the beam radius (assumed constant along the drift length), and I the beam intensity.

For longer drift lengths the velocity modulation is reversed and hence density modulation goes down on the axis while it still increases on the boundary. As soon as saturation occurs at any place (and primarily on the boundary) further distortions take place and no good bunching can be reached.

For a voltage of 500 kV and 200 MHz,

$$L_{o\ \mathrm{meter}} \# \frac{0.4}{\sqrt{I_{\mathrm{amp}}}} \qquad (2)$$

is the maximum length over which higher order space charge waves, or saturation will irremediably distort any bunching phenomena.

This limit is very similar to what one might deduce from the Chodorow approach. The difficulty mentioned by Taylor is then easily explained.

Adiabatic Buncher. In order to force bunching to take place even in the presence of high space charge, one may try to produce it progressively in an adiabatic manner. The drift length would have to be replaced by a sort of linac cavity at constant velocity with a field increasing linearly up to the linac input. This had been mentioned at the Los Alamos Conference (see Proceedings, page 244).

A space charge wave treatment, as mentioned above or as used to study travelling wave amplifiers[5], in which the line or cavity where the beam travels is characterized by its shunt impedance and its dispersion curve, can be extended to cover that case even for a zero mode structure[4].

The consideration of the fundamental waves alone indicates interesting possibilities. But higher order waves still risk distorting the bunching and preventing high efficiency. The limit given by (1) and (2) still roughly applies in this case.

Proposed Double Buncher. The preceding remark leads one to look for shorter bunching devices.

A possibility is the double buncher. In this system a first cavity produces a strong velocity modulation of the beam. This modulation can be too high to be accepted by the linear accelerator, but would produce full bunching over a very short distance (much smaller than L_o).

A little before full bunching takes place, a second cavity removes the excess of velocity modulation and another drift achieves the full bunching. The total drift length can be made shorter than L_o, avoiding any important space charge distortion. The process is indicated schematically on Fig. 1.

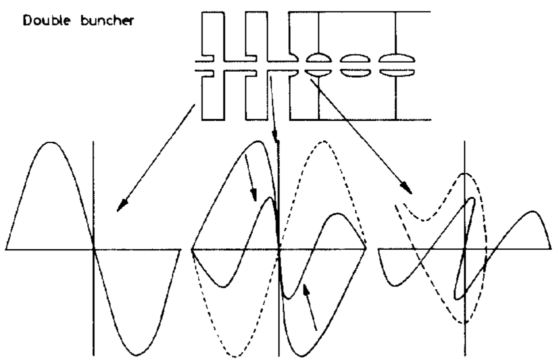

Fig. 1 Double buncher. Schematic phase space distributions are shown at each buncher cavity gap and at linac input.

In this scheme the two bunchers can be on the same frequency; but the second one could also be on a harmonic frequency, as suggested by Emigh. Better bunch shapes and density distributions might then be obtained, at least theoretically.

In any case, it should be possible to achieve efficient bunching for beam intensities, even at 500 kV, of at least 500 mA at 200 MHz(a).

Of course, relation (1) shows the improvement one might get by increasing the injection voltage; in order to reach still higher intensities it would be necessary to go from 500 kV to, say, 1 or 2 MV.

Studies to be Made. The previous proposal is based on two space charge theories, both of which assume a laminar flow and a continuous focusing device. These two conditions are never met, in practice. They are also both limited to a linear approximation which cannot treat full bunching. A more realistic treatment would then be needed.

Crandall has studied the motion of a high-intensity unmodulated beam inside an arbitrary focusing system[6] and his computation is now extended to include modulation; but it is limited to the case of circular symmetry, while practical focusing devices now always use quadrupolar lenses. Though it might make little difference, one would like to remove that restriction also.

It would furthermore be extremely useful to check all the theoretical predictions by an experimental analysis in a way similar to the work done for electrons by Chodorow et al.[7]; if possible, this should include a measure of the velocity distribution of the particles inside the bunches.

Acceleration

The operation of the linear accelerator itself is also affected by the presence of a high intensity beam.

At the Los Alamos Conference, Taylor[1] emphasized two aspects: beam loading effect and its compensation; modification of beam emittances under high space charge conditions.

Both of them are different aspects of the same phenomenon: the perturbation of the RF fields in the cavities by the charge of the particles to be accelerated.

From the theoretical point of view, this effect may be divided into two parts: distant effect and local effect.

Distant Effect: Beam Loading - Frequency Shift. The charges travelling along the cavities may excite electromagnetic oscillations or change resonance properties.

A bunched beam can be represented in a Fourier analysis by a d.c. current and by RF fundamental and harmonic components.

The harmonic terms are usually of no importance if there is no resonance on their frequency.

The fundamental current, on the contrary, strongly excites the cavities; this effect is usually described as beam loading. In order to maintain the electromagnetic fields at the level required for acceleration, extra power has to be fed into the cavities.

The system described by Taylor[1], where this extra power is driven from a chain independent of the one which feeds the Joule losses, is extremely satisfactory: it allows an adjustment in phase and amplitude; it also seems quite practicable.

It is limited, however, in its performance by transient phenomena because in pulse operation transients are not the same for the beam loading excitation and for a compensating signal[8]. Nevertheless, with short enough Alvarez cavities, as in the CERN Linac, compensation could be made for intensities up to 300 or 400 mA.

Other ideas have been developed recently to reduce further these effects and they will be discussed later.

The d.c. component of the beam has never been of any great concern so far. It could, however, be responsible for several effects.

A slight shift of the resonance frequency of the cavities is produced by the presence of charges on the axis. The theory of space charge waves already mentioned[4] can be used to estimate this shift. But this computation can only be done for a constant velocity beam and only in the presence of a small bunching. Since the effect is extremely sensitive to the velocity and since the beam is in practice always fully bunched, only very rough figures can be obtained. For a cavity starting at 500 keV, this shift could be of several kHz for a few hundred mA beam. But it might be less if the approximations made in the rough computation tend to exaggerate it.

An interesting point of view, however, that one can get from this computation, is that such an effect is closely related to the longitudinal stability of the beam.

(a) If sharp bunching is desired, where intense harmonics with much higher frequencies should be present, the length L_0 according to (1) should probably be reduced; but this cannot be specified in this linear treatment.

This problem of stability, longitudinal as well as transverse, could be a further limitation for high intensity linear accelerators but probably it is still far away.

Local Effect: Transverse and Longitudinal Space Charge Effects. The fields induced by the charges are particularly strong inside the beam itself. There they tend to expand the beam and to prevent the bunching of the particles (as in the buncher itself) or destroy phase stability.

These local fields are, of course, affected by the presence of the cavity and, in particular, by the drift tube walls which introduce some image effects. But this is only a distortion, which forces the fields to be more or less longitudinal or radial at the expense of the other component. The total strength remains the same.

The radial repulsion then adds to the defocusing effect of the RF accelerating field. Even if it may not be negligible and may require an appreciable increase in focusing strength (by up to 50%, for instance), there is however no difficulty in compensating it.

This is not true on the contrary for the longitudinal effect. Very simple and rough computations can be made to estimate these longitudinal space charge effects, assuming the bunches of ellipsoidal shape and replacing space charge fields by approximate expressions[9].

A relevant parameter to express these effects is given by

$$\alpha = \frac{I}{2a\,\epsilon_o\,v_s\,ET} \qquad (3)$$

where I is the intensity of the beam of diameter 2a and mean velocity v_s, and ET is the transit time corrected peak accelerating field. The maximum α which can be accepted under stable conditions in an accelerating wave is related to the φ_s, synchronous phase angle, as indicated on Figs. 2 or, for small angles by

$$\alpha_{max} = \frac{4}{9}\left|\varphi_s\right|^3 . \qquad (4)$$

According to equation (3) for increasing I, one should increase a, v_s or ET. The electric field is limited by breakdown problems, and even if improvements may be expected in new structures or on the maximum field acceptable, the gain cannot be very large. The velocity v_s is minimum at injection; there would be a clear advantage in increasing the injection energy to 1 or 2 MeV, but it may become technologically difficult to go much higher with very high intensities. The diameter of the beam is limited by coupling problems and depends on RF frequency; this question will be discussed later.

If the form of the parameter α does not, however, seem to leave very much possibility for a large increase in intensity, the relation (4) or the curve of Fig. 2 opens a wide range of improvements. A change of the phase φ_s from the present 30° (or even less) to 45° would lead to a possible increase of almost 3.5 and to 60° of about 7.5.

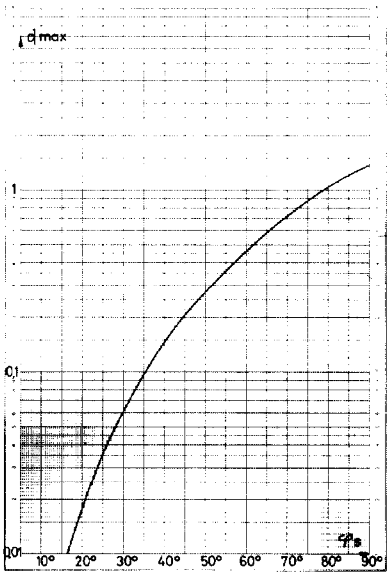

Fig. 2 Maximum permissible space charge parameter for keeping phase stability.

Phase Law Proposed for a High-Intensity Linear Accelerator. An increase in φ_s over the complete length of a linac would be costly in RF power. But according to our discussion, a large φ_s is important only at injection. It can be reduced when energy goes up.

The present proposal is to use a φ_s at injection between 45° and 60° and to reduce it progressively along the accelerator down to 20° or 25° (not more, in order not to make amplitude tolerances too critical). The law of reduction of φ_s versus v_s may, however, be subject to discussion[9].

In order to operate the linac all the way along at the limit of intensity, one can keep between α and φ_s, the relation indicated on Fig. 2.

If the diameter 2a of the beam was constant, one should then have, for not too large φ_s:

$$\varphi_s/\varphi_{s,o} = (v_{s,o}/v_s)^{1/3} \qquad (5)$$

In practice, the beam size very often increases along a linac. This size can be chosen somewhat arbitrarily as far as beam dynamics is concerned, and this choice then dictates the focusing strength to install. The growth in beam diameter should, however, not be faster than the increase in velocity, so as not to produce unnecessary coupling between radial and longitudinal motions.

To keep within this limit would correspond to a new phase law of the type

$$\varphi_s/\varphi_{s,o} = (v_{s,o}/v_s)^{2/3} \qquad (6)$$

for not too large φ_s.

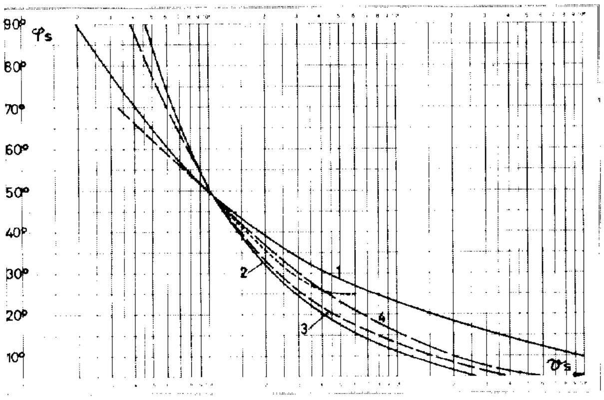

Fig. 3 Various synchronous phase laws versus velocity.

However, the linear accelerator may also not be run at its full intensity limit. In this case it would still be interesting to use a decreasing φ_s. The stable phase could then be chosen in order to keep constant the bucket area, or in order to minimize the non-linear terms in the equations of longitudinal motion; this would give:

$$\varphi_s/\varphi_{s,o} = (v_{s,o}/v_s)^{3/5} \qquad (7)$$

for small φ_s.

Figure 3 shows, labelled 1 to 4, the exact laws corresponding to approximate expressions (5), (6), and the two cases of (7). The dotted curve gives, as a typical example, the law adopted in the project of a 20 MeV linear accelerator, new injector for the synchrotron Saturne[10].

Studies to be Made. Many approximations are introduced in the computations of space charge which have been mentioned here[9]. For instance, an adiabatic treatment is made which is not necessarily valid at low energy with a fast acceleration; space charge effects also may change fast.

Computer studies have been started by Gluckstern and Benton[11] on the motion of bunches in a linear accelerator under heavy space charge conditions. These computations are based on an ellipsoidal model with uniform density; such a model is satisfactory for a first approach, but should be progressively improved and made closer to the actual distributions. A steady state distribution has been studied by various authors[12,13] and could serve as a guide.

Such computations should, in principle, help in the optimization of phase and focusing laws for a high intensity linear accelerator.

Another class of problems where studies should be made, however, refers to coupling phenomena. Studies have also been started on this subject by Gluckstern and Chasmann[14,15]. These studies have shown the importance of the focusing on the apparent phase space growth which is observed in linear accelerators. Other computations by Regenstreif[16] take into account the fringing fields of magnetic quadrupoles.

It seems, nevertheless, that experimentally space charge may have the main responsibility for large coupling phenomena between transverse directions[17], but also probably with longitudinal motion. A prediction of longitudinal and transverse emittances from a high-intensity linac is a little hazardous. It is certain that in practice the density distribution of the charges in the bunches is never uniform; but it is not possible at present to say what it is exactly.

Probably the low-energy part is the most critical and it should be studied in detail; the various models of bunches mentioned above could be used, but computations should include radial as well as longitudinal motion. Accurate equations now exist[18] to describe the motion of particles in accelerating gaps. They should be completed with space charge effects to obtain a more complete picture of the beam dynamics.

Apart from theoretical studies, experimental work[1] should be done to check the computations and maybe also to guide them.

Choice of Structures - Transients. In discussing the proposal of phase law, we have omitted to speak about the accelerating structure.

The Alvarez cavities in common use today at the frequency of 200 MHz have reasonably good qualities for shunt impedance, peak accelerating field, and transit time factor; their transient properties, even on the zero mode, are not bad if not too-long cavities are used. The proposal of Giordano[19] to use multi-stem structures, or the possibility of producing a resonance with a cross-bar mode[20], as suggested by Dôme, would increase the velocity of energy propagation along the Alvarez structure and remove the necessity of using short cavities for high intensities.

In order to push up the space charge limit, however, it might be interesting to use thicker beams with much lower frequencies; in this case coupling phenomena and emittance growths could also perhaps be reduced. Structures other than Alvarez cavities might then have to be considered. The helix could be interesting if good focusing was possible with it, but more has to be done to confirm a new choice.

Lower frequencies and thick beam at injection may also be used, as suggested by Montague[21], by having several low-energy linacs on a sub-harmonic frequency filling alternately all the buckets of a subsequent conventional accelerator. This idea could lead to many attractive possibilities.

Conclusion

The present proposals of double buncher and variable phase linac (Alvarez or new structure) would reach intensities of 300 or 400 mA and even 500 mA, if necessary. The expected emittances are nevertheless still difficult to predict exactly. Even if most of the problems are now under control, an apparent space charge induced coupling effect may still require some effort before being completely understood.

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