A RE-APPRAISAL OF DESIGN CRITERIA AT THE LOW-ENERGY END OF PROTON LINAC INJECTORS

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C O N T E N T S

1. INTRODUCTION

Most operating proton linear accelerators have been designed following principles that were established some years ago, based on the experience and technological development of that time.

Some of these accelerators, in particular those in service as synchrotron injectors, now operate at intensities where space charge and beam-loading effects limit their performance. Furthermore, the injectors for future high-energy synchrotrons and for improvement programmes of existing machines will be required to provide even better performance, in intensity, reliability and beam quality.

In the present situation of more stringent requirements and more advanced knowledge it is appropriate to re-examine the basic design philosophy of injector linacs. Since the present performance limits appear to be determined mainly by conditions in the low-energy region, say up to 5 or 10 MeV, we shall concentrate on this aspect in what follows.

Beam loading effects do not appear to present a serious problem for future linacs and it is reasonable to suppose that compensation can be made effective up to the highest currents of interest.

2. SPACE CHARGE AND COUPLING EFFECTS

The influence of space charge forces on the longitudinal and radial motions is to increase the amplitudes, leading to a reduction of radial acceptance, and to reduce the frequencies of oscillation. In general, the intensity dependence of frequency is different for the betatron and phase motions, and the ratio q of their frequencies is a function of intensity and local charge density.

In the early part of a high-intensity linac, before bunch filamentation has fully developed, local charge density gradients can produce defocusing forces comparable in magnitude to the phase and radial focusing forces. It is quite possible for a large fraction of the particles to cross coupling resonances, due to the combination of space-charge forces and large phase oscillation amplitudes. This would lead to further increases in radial amplitude, as indicated by Gluckstern (1966), Ohnuma (1966) and Chasman (1966), and to apparent dilution of the central regions in the longitudinal and transverse phase planes. These hypotheses are consistent with observations on the CPS Linac (Taylor et al. 1966).

In addition to influencing the phase motion in the linac itself, the space charge forces affect quite seriously the action of a conventional buncher. With a single cavity buncher operating in a regime chosen for high trapping efficiency at low intensity, there is a region of the drift space between the bunching cavity and the linac where the local charge density could be much higher than would be required in the trapped bunches inside the linac. Since there is no compensating phase focusing force in this region, the effectiveness of the buncher is severly reduced at the high intensities now of interest. Furthermore, the radial defocusing forces in this region can cause beam loss.

Two general lines of approach seem possible in order to counteract these phenomena, to increase the focusing forces and to avoid unnecessarily high local charge densities at low energies. Possible ways of achieving these will be discussed in Section 3.

3. CHOICE OF SOME BASIC FEATURES

3.1 Frequency and Type of Structure

It has long been known that the linac beam dynamics at low energy are favoured by the choice of a low accelerating frequency. However, up to intensities of 60 - 80 mA there is no strong incentive to go below about 200 MHz in proton injectors for this reason alone, especially with the Alvarez structure which becomes somewhat cumbersome at low frequencies. For higher intensities, in the range above 100 mA or so, there appears to be a good case for using a lower frequency in the first few MeV, since the influence of space charge and coupling effects scales linearly with the accelerating frequency.

The frequency of the first part of the linac should clearly be a subharmonic of that of the higher energy part. If the latter operated at 200 MHz one could contemplate using a 100 MHz Alvarez up to 5 or 10 MeV, though for practical reasons this might be at the low-frequency limit. There is then some interest in considering more compact structures than the Alvarez and perhaps frequencies even lower than 100 MHz.

3.2 The Helix Structure

The helix is a structure, well adapted to low-frequency operation, which deserves more study than it has received in the past. (References to much of the previous work are given by Dänzer et al., 1966.) It can have, in theory, a higher shunt impedance than the Alvarez at low energies. Preliminary model measurements made recently at CERN suggest that in practice the shunt impedance can at least be made comparable to that of the Alvarez. More important advantages of the helix in the present context are its low dispersion, easy tolerances, physical compactness and favourable geometry for image-field compensation of longitudinal space-charge forces. This latter property has been examined by Neil and Briggs (1966) for the stabilization of non-relativistic beams and by Sessler and Vaccaro (1967) in connection with space-charge effects at transition energy in synchrotrons.

Two practical questions remain to be resolved before the helix can be accepted as a serious competitor to the Alvarez. Firstly, insufficient is known at present about its RF breakdown properties. Theory indicates that for standing wave operation, the ratio of peak field to axial accelerating field would be appreciably higher than in the Alvarez, but since the helix, because of its compactness, is easier to pump and to keep clean, we feel fairly hopeful about the RF breakdown question.

The second point concerns the method of supporting the helix without unduly reducing the shunt impedance or degrading the low-dispersion property. A method previously used, of supporting the helix by means of dielectric strips or combs, appears to have rather little effect on the losses and dispersion. However, it seems undesirable to have dielectric in the immediate vicinity of intense beams because of surface charge effects, and we are therefore investigating a type of support consisting of short metal stems attached at the nodes of a standing wave helix. Preliminary results on a model are very promising.

3.3 Varying Stable Phase Angle during Acceleration

It has been shown by Lapostolle (1966, 1967) that longitudinal space charge effects could be reduced substantially by arranging for the stable phase angle φ_s to change progressively during the early acceleration, starting from a large value (measured from the wave peak) at injection and reaching the conventional $20^\circ - 30^\circ$ at an energy where space charge effects are no longer troublesome.

The use of a progressive φ_s law, possibly with the adoption of a lower accelerating frequency, is an important step towards reducing longitudinal space-charge effects at low energies.

3.4 Radial Focusing

In most quadrupole-focussed proton linacs the radial focusing parameters are chosen so as to maintain radial stability even for particles with large phase oscillation amplitudes. This already leads to quadrupole strengths near to the practical limit at the low-energy end of existing 200 MHz Alvarez linacs. However, it would be desirable to strengthen the focusing further, both from the point of view of longitudinal-radial coupling, as the computations of Chasman (1966) have shown, and to compensate space-charge forces at high intensities as we have previously indicated.

In future Alvarez linacs operating at 200 MHz it may be possible to increase quadrupole strengths by various means, and at lower frequencies this certainly becomes easier. With a helix structure some new possibilities are opened up, since with external quadrupoles the focusing period no longer has to be related to the periodicity of the accelerating structure.

The focusing of a low-frequency helix linac has been re-examined recently (Montague 1967 b), leading to conclusions that may be summarized as follows. By removing the constraint of maintaining radial stability for particles with extreme phase oscillation amplitudes, it becomes possible to obtain unusually strong radial focusing at normal acceleration rates with modestly rated d.c. quadrupoles. This is arranged by choosing the initial operating point in the radial stability diagram further out than is customary, as shown in Fig. 1. The situation with respect to space charge and coupling resonances is favourable and the system has a large radial acceptance. With a correctly operating buncher, only a small proportion of the particles, those with phase oscillations approaching the unstable fixed point, move into the $\mu = \pi$ stopband.

3.5 Accelerating Buncher

In Section 2 we referred to the unfavourable space charge situation in a conventional single-cavity bunching system, which leads one to examine other bunching methods. Early in 1966 Maschke (private communication to W.E.K. Hardt) suggested the use of adiabatic trapping in a proton linac, but it turns out that such a scheme, at least in the sense normally understood for a synchrotron, would require a very long buncher indeed.

A method intermediate between adiabatic trapping and single-cavity bunching would be an accelerating buncher in which the parameters are chosen to make the bunching increase progressively with acceleration. Similar schemes have been in use for many years on electron linacs, and Lapostolle's proposal of a progressive φ_s law is a first step in this direction for a proton linac.

Of at least two possible ways in which accelerating bunching can be obtained, we briefly describe one which offers some important advantages. The buncher is in two sections, the first being a length of structure with a constant phase-velocity equal to the velocity of particles from the pre-injector. In this section the pre-injector beam of small energy-spread starts filamentation in the stationary RF buckets, as shown in the phase-plane diagram of Fig. 2(a). Such a section has been examined by Johnsen (1955) for proton linac debunching and by Dôme (1960) for electron linac bunching.

The second section is phased so that the incipient bunch is accelerated around the unstable fixed point of the separatrix (Fig. 2(b)). Bunching takes place in a similar but converse manner to the debunching scheme discussed by Teng (1961). This section has a progressive law of accelerating field and phase arranged so that the contours of charge in the phase plane match as well as possible the shape of the separatrix and adjacent trajectories during the process of acceleration and bunching. Towards the end of this section the situation is as in Fig. 2(c) and thereafter the bunches enter the normal linac at the stable phase.

This method has several advantages for low-energy bunching. Firstly the beam energy is increasing as the local charge density increases. Secondly, a high trapping efficiency should be possible without serious dilution of the central density caused by filamentation. Thirdly, acceleration around the unstable fixed point makes the radial RF forces focusing and thus reduces the quadrupole focusing requirements in the most difficult region.

It appears that the helix structure would be very suitable for such a bunching method, since it is relatively easy to prescribe the field and phase-velocity law.

3.6 Double Pre-Linac

The use of two or more low-energy linacs as a means of reaching high intensities and high phase-space densities has been discussed recently (Montague, 1967 a). Such a system with two pre-injectors is shown schematically in Fig. 3. The two pre-linacs operating at half the frequency of the main structure provide alternate bunches which are brought on to the same trajectory by the use of an RF deflector for subsequent acceleration in the main linac.

This arrangement combines the advantages of a low accelerating frequency at low energy with the full use of the RF buckets at higher energies, and would permit the efficient acceleration of very high intensity proton beams, probably in the 250 to 500 mA range. A further advantage of the proposal is the duplication of the low-energy end, providing a reserve facility in the event of a failure in one pre-injector channel.

4. CONCLUSIONS

We conclude that there are several ways of reaching higher intensities in linac injectors, or of improving the beam quality at present intensities. Some of the methods discussed are relatively simple and could be applied to existing linacs or to designs projected for the near future.

A more comprehensive application of these ideas could result in beams whose phase-space density is much too high for acceptance into the synchrotron, unless such linacs were also extended to considerably higher energies. It then becomes appropriate to examine seriously the possibilities for compensating the transverse incoherent space charge Q-shift in the synchrotron, by using programmed quadrupoles and RF quadrupoles.

Finally, improvements in the low-energy beam dynamics might call for a new optimisation of the higher-energy section of the linac and perhaps an increase in frequency for the Alvarez or other drift-tube structure.

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DISCUSSION (condensed and reworded)

R. Miller (SLAC): Have you looked at a counter-wound helix?

Montague: As far as proton linacs were concerned, it was always assumed that the helix would cease to be interesting anywhere above about 20 Mev, but I think this assumed a single-start helix. The high-power traveling-wave tube people have been making multistarts and contra-wound helices for quite a long time precisely for higher β's. We wonder whether perhaps the helix might not be interesting even up to higher energies than used to be thought possible.

Miller: Why stop at two injectors? You could have three at a third of the frequency.

Montague: There was only time to discuss 2 in this talk, but there are 2^n in the original report.

J.P. Blewett (BNL): Aren't there some mechanical problems with supporting even one helix?

Montague: I think if we solve the mechanical problems for one helix, we would be able to do it for several.

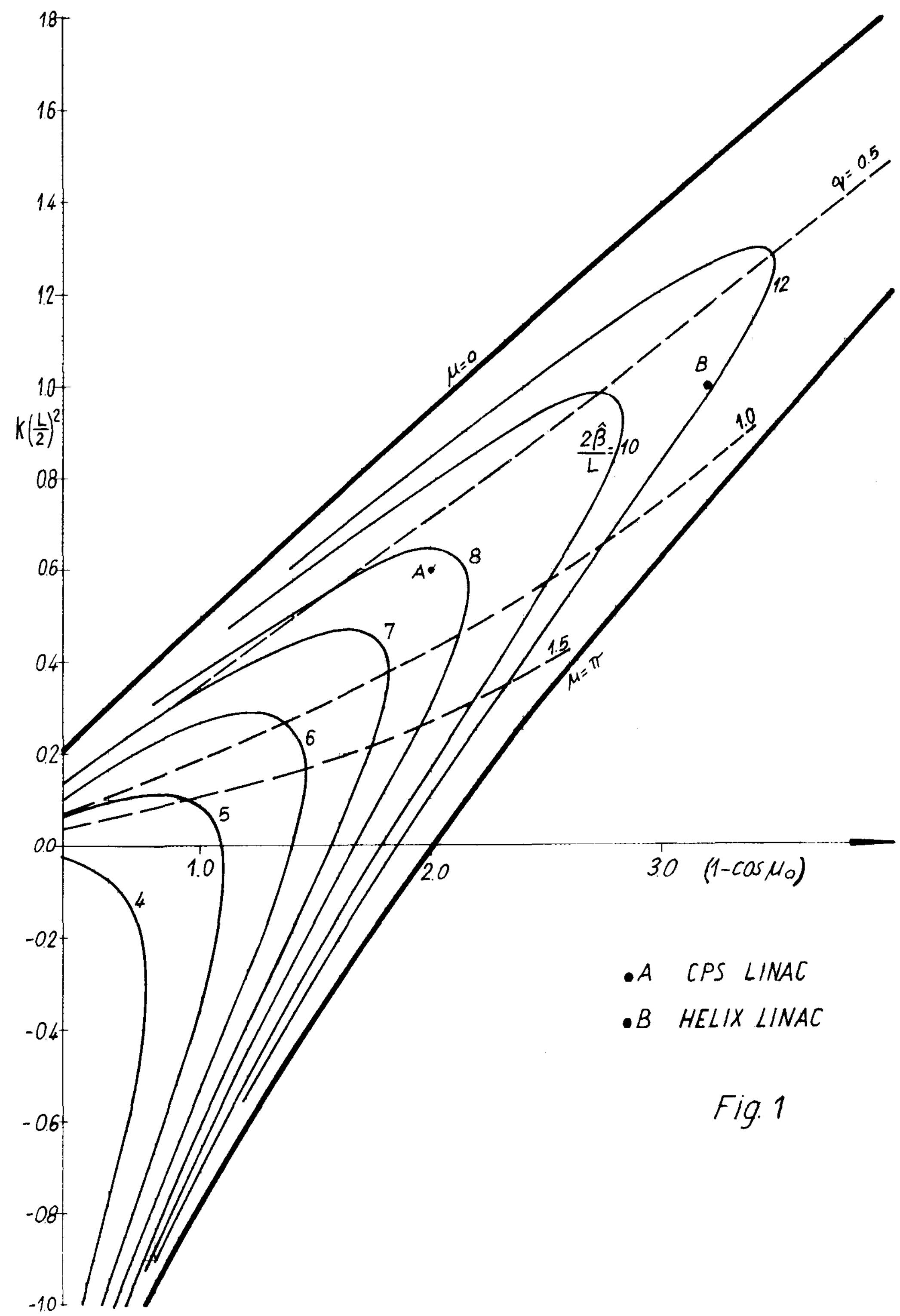


Fig. 1 Radial Stability Diagram, with betatron amplitude function and coupling resonance lines.

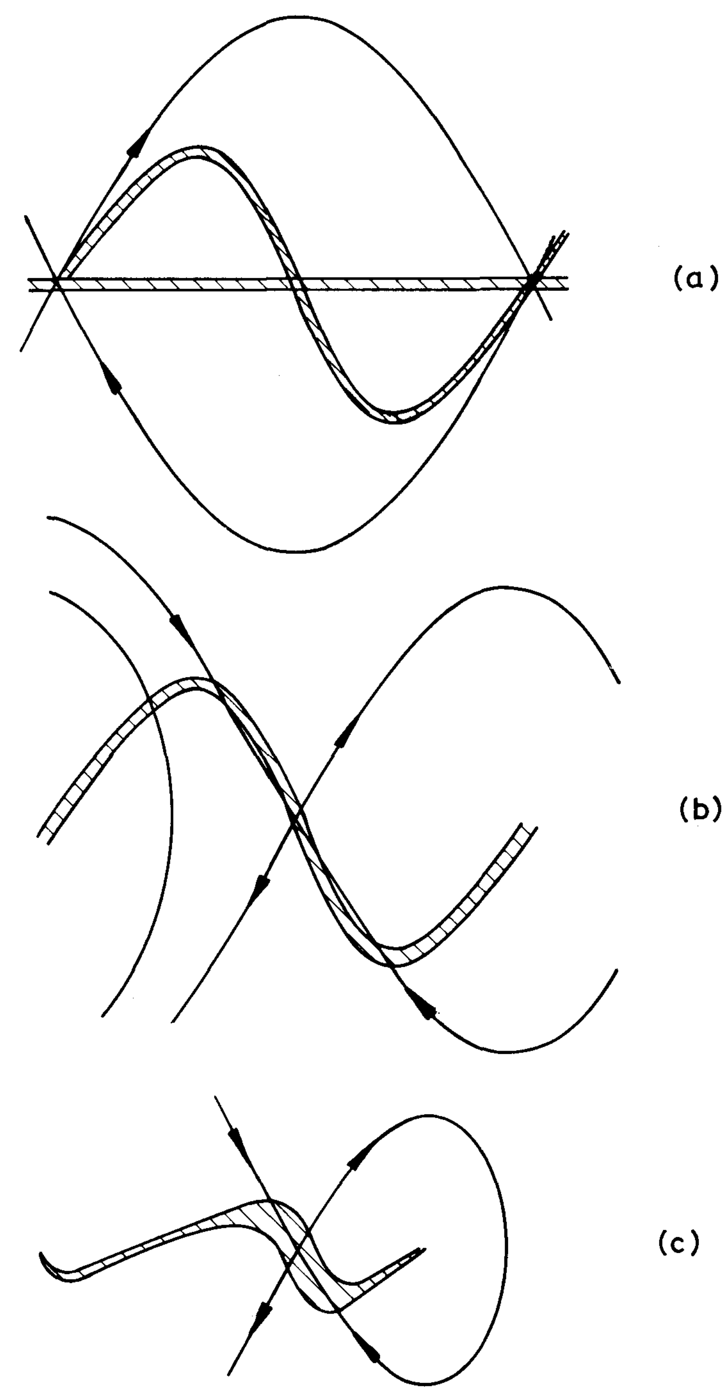


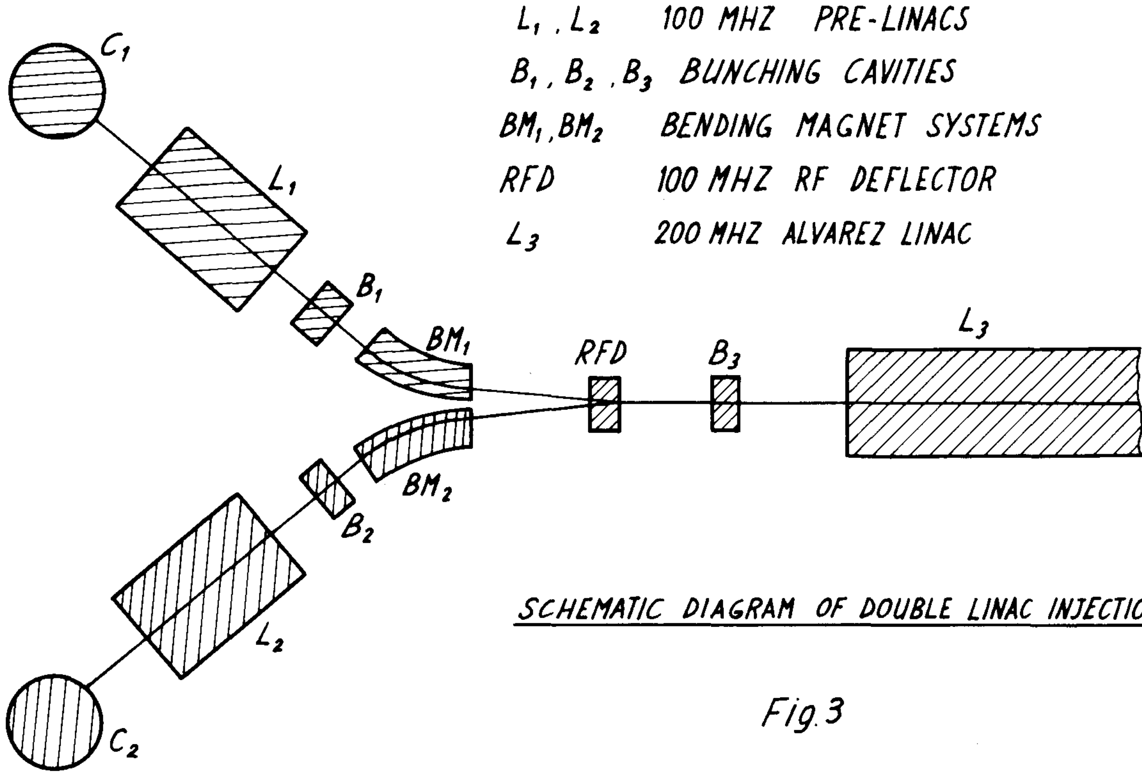
Fig. 2 Phase plane for Accelerating Bunching:

(a) Entry and exit of constant velocity section

(b) Entry of accelerating section

(c) End of accelerating section - bunching almost complete.

C_1 , C_2 PRE-INJECTOR COLUMNS AND ION SOURCES
L_1 , L_2 100 MHZ PRE-LINACS
B_1 , B_2 , B_3 BUNCHING CAVITIES
BM_1 , BM_2 BENDING MAGNET SYSTEMS
RFD 100 MHZ RF DEFLECTOR
L_3 200 MHZ ALVAREZ LINAC



SCHEMATIC DIAGRAM OF DOUBLE LINAC INJECTION SYSTEM

Fig.3