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REDUCTION OF LOSSES IN LINACS FOR PROTONS OR HEAVY IONS*

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Summary

It is necessary to minimize the beam losses in linacs for high average currents in order to avoid serious problems due to radiation damage, dissipation and radio activation of the accelerator's structure. A large part of the losses in existing linacs is due to incomplete bunching of the injected beam. Proposed improvements generally appear to be deficient in one or more respects if applied to linacs with conventional frequencies, injection energies and current densities. By preceding the linac proper with an accelerating structure and an energy analyzer, it becomes possible to separate the particles that remained outside the buckets from those that are inside so that they can be dumped in a controlled manner.

Introduction

In order that an ion-linac may accelerate the beam current it is capable of, it is necessary that the injected beam populate all of its acceptance in six-dimensional phase space. It is also desirable that the space outside that acceptance stay empty, particularly so in linacs for high average current, to avoid particle loss and the problems due to the dissipation, radiation and radio-activation associated with such loss.[1] The beam that arrives from the preinjector usually cannot meet these requirements without modifications, since it is continuous in time and has only a small energy spread, while a bunched beam with an incoherent energy spread of several percent is what is wanted. Nearly always a matching section that consists of several quadrupoles and one or more bunchers is incorporated in the beam transport system between preinjector and linac; it is used to improve the match of the preinjector beam to the linac.

A prime task for the bunching system is to longitudinally modulate the charge density in the preinjector beam to form bunches that fit inside the rf buckets of the linac; it should also increase the incoherent energy spread. Conventional bunchers perform only moderately well in the first task and poorly in the second one. Although they put a good fraction of the beam inside the buckets the part that remains outside is sufficiently large to cause significant problems in existing and very severe ones in proposed high current installations. In magnitude the loss is directly related to the steepness of the net waveform produced by the bunchers, the ideal waveform showing at least one discontinuity per period. That steepness is determined by the number of harmonics (of the linac rf frequency) that are present in the waveform. The decrease in transit time factor with increasing frequency in cavities with fixed bore hole diameter limits the effectiveness of high order harmonics.

It is easier to generate a transverse discontinuity (aperture stop or septum) than a longitudinal one; the so-called deflecting bunchers, of which a number have been proposed,[2-5] take advantage of this fact. They have in common that the beam is chopped in synchronism with the linac rf by sweeping it transversally across the aperture of a collimator or across a septum. We discuss this seemingly attractive possibility in more detail and arrive at the conclusion that it raises more problems than it solves for high current linacs.

One solution for the problem is to redesign the transverse focusing system of the linac itself in such a way that it constrains the particles to stay inside the available aperture irrespective of their energy. With such a system particles outside the buckets would drift through the linac without much change in energy and emerge from it together with the high energy beam from which they would be separated afterwards by a momentum separator. Such focusing is obtained if the conventional quadrupoles are replaced by solenoids.[6] Solenoids have been used[7] but are generally considered impractical because of their power consumption; superconductivity may have changed this and perhaps their application should be re-evaluated.

Another solution is to preceed the main linac with an injection linac, complete with a conventional, or inconventional, buncher. This split would make it possible to introduce an energy selector between the two accelerators that would transmit the bunches from injector to the main linac but direct all particles outside the separatrices to a dump. The injector would be designed either to not intercept any particles, irrespective of energy, or with internal beam dumps that are easily interchangeable.[8] In this way the main accelerator could receive a perfectly matched beam that it could accelerate without any loss. We discuss this possibility and some of its implications in some more detail.

Deflecting Bunchers

Deflecting bunchers are basically beam choppers that operate synchronously with the linac rf. They form the bunches to be by displacing the particles between them to another region in transverse phase space, while leaving the particles inside the bunches undisturbed. For that reason they are inefficient if used by themselves; since the phase acceptance of a linac is no more than 90-120^o, 3/4-2/3 of the preinjector beam is lost. This becomes much better if they are combined with a conventional, longitudinal, bunching system because then they have to match the much larger phase acceptance of that; using special tricks it should be possible to approach an overall efficiency of close to 100%. In that configuration the deflection serves to hide the deficiencies of conventional bunchers.

Deflecting bunchers chop the incoming beam by sweeping it across the aperture of a collimator or across a septum. The amplitude of the motion must be large enough to carry the beam outside the acceptance of the collimator or to switch it between two channels, one on each side of the septum. If a collimator is used any beam intercepted by its jaws is lost; a septum acts as a collimator if one of its channels leads eventually to a beam dump. Both systems are lossy and flexible in terms of bunch lengths; their deflectors may be run at half the linac frequency because they may be set up to yield two bunches per deflection period. In L.C. Teng's[5] recently proposed system the beam is moved across a septum at half the linac frequency, each of the two resulting beams passes through its own longitudinal buncher, operated at half the linac frequency and is sent to the linac via another dynamic deflector. It is also possible, though not necessarily advantageous, to have the sweep frequency equal to the rf frequency.

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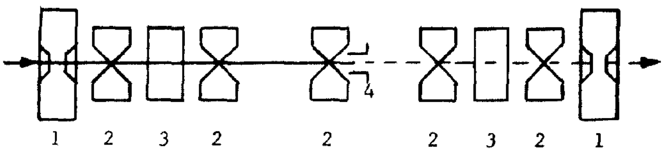
Then one bunch, slightly longer than π rad, is formed each period in each channel. Both channels feed into the linac, but with a difference in pathlength of π rad (or $1/2\ \beta\lambda$ m) between them, the bunches will arrive simultaneously at the merging point. An additional longitudinal buncher, downstream of the merging point is needed to compress the large phase spread in the bunches by a factor 2-3 to fit them inside the linac buckets.

A possible deflecting system might be arranged as indicated in Fig. 1, an elaboration of a method proposed by K.W. Zieher.[4] The incident beam passes successively through an accelerating gap, an achromatic bend or dog leg and a decelerating gap. The first gap modulates the beam energy, which causes a modulation



1 Accelerating Gap

2 Quadrupole

3 Bending Magnet

4 Collimator

Fig. 1

of transverse position in the dispersive part of the system. The second gap removes the energy modulation and the achromaticity ensures that any beam that enters the system coaxially with the system axis emerges from it in that manner. The exact removal of the energy modulation demands that the time-of-flight between the accelerating gaps be independent of energy.

We will show that the amplitude of the energy modulation must be relatively large; this implies that the accelerating gaps act as lenses of periodically varying non-negligible strength in transverse phase space that modulate the instantaneous transverse emittances and possibly cause blow-up of the apparent emittances. Without this consideration the time-of-flight between the gaps can be arbitrary because the phase difference between the gap voltages can always be set to match it. This is no longer so if emittance modulation is to be prevented. Then it becomes necessary to have the gaps an integer number of half betatron wavelengths apart and to run the gap voltages with a phase difference of 0 rad if the integer is odd or of π rad if it is even. If the gaps run in phase the time-of-flight between them must be an odd number of rf half periods, if they run in antiphase it must be an integer number of rf periods, in order to achieve zero energy modulation at the output.

The indirect deflection via energy modulation was preferred above the also possible dynamic direct deflection by means of a transverse magnetic or electric field.[9] The latter method unavoidably causes energy modulation as well as deflection on account of its dynamism. Both the deflection and the energy modulation are functions of the transverse coordinates and phase of the individual particle when it enters the deflector. We have not succeeded in removing, compensating or balancing out this coupling between transverse and longitudinal motion.

This system is transformed into a deflecting buncher by placing a collimator or a septum near the point of largest position dispersion. Only if the incident beam enters into the aperture of the collimator it is allowed to pass on to the second gap and beyond. If the deflection amplitude is larger than half the sum of aperture width and local beam width the beam is periodically intercepted completely. This is the bunching process proper. If a septum is used the beam will pass alternatingly on either side of it if the deflection amplitude is larger than half the sum of local beam width and septum thickness. If the septum separates to equally large but oppositely directed stationary deflecting fields, beams from a common source that pass on the two sides of the septum will be deflected with respect to each other, being kicked in opposite directions along the momentum axis in transverse phase space. If the fields are large enough the beams will be separated in the second bending magnet, coincide in the second gap and be physically separate again beyond some point downstream of the second gap. At this point each has regained all the characteristics of the incident beam except its continuity, and may be subjected to individual treatment e.g. in longitudinal bunchers.

All the system requirements can be met simultaneously for beams of low intensity although the design options are severely restricted. This is no longer so when space-charge defocusing becomes comparable to quadrupole focusing; though the beam axis behavior is independent of intensity, the betatron wavelengths for the off-axis particles increase as do their amplitude functions. These changes become functions of the longitudinal position in the bunch as soon as the bunches become distinct and the space charge field three dimensional. This is particularly so if the bunches are not much longer than wide. In causing additional acceleration or deceleration the longitudinal components of the space charge field modify the energies and times of arrival at the second gap for individual particles. Those near the front of the bunch will arrive early with too high an energy, those near its tail will be late with too little energy. Being too early or too late implies that the second gap does not have the expected and necessary transverse focusing characteristics (it will be too strong) and that a coherent energy error (with respect to the nominal energy) is left. Thus space charge causes an increase of the effective emittances (transverse as well as longitudinal) of the bunched beam.

By increasing the transverse focusing strength the transverse blow-up can be reduced. Such an increase implies a decrease in longitudinal scale (though not of bunch length) which in turn reduces the longitudinal blow-up. Since for a given emittance the beam diameter decreases only with the square root of the focusing strength the deflection angle has to increase in that manner.

This study was motivated by the need of a buncher system for a deuteron linac, for 200-300 mA, running at 50 MHz and injected at 500 keV[10] and a trial design, based on the considerations above, was attempted for that facility. The transverse space charge effects were estimated assuming that a uniformly populated beam of constant diameter passes through a sequence of thin quadrupoles with inverse focal lengths of Q and alternating polarities and center to center distances ℓ. The betatron phase advance per cell $\Delta\psi$ in such a structure follows from

$$\sin(\Delta\psi/2) = \frac{\sinh(\alpha\ \ell)}{\alpha}\ Q\sqrt{1-\left(\frac{\alpha}{Q}\right)^2} \qquad (1)$$

where

$$\alpha = \sqrt{1/2 \frac{\mu_o c}{E_o} \frac{j}{(\beta\gamma)^3}}$$

with μ_o the permeability of free space, c the velocity of light, E_o the rest energy of the ion, β and γ the usual relativistic parameters and j the current density. This expression does not contain any contributions from image fields. Choosing $Q\ell = 1/2\sqrt{2}$ (i.e. $\Delta\psi = \pi/2$ rad/cell) in the low energy part of the linac we have in this particular case $\ell = \beta\lambda \approx 0.138$ m, thus $Q \approx 4.66$ m^{-1}. Taking the average beam diameter to be 1/3 of the diameter of the bore hole diameter in the drift tubes, which is 4 cm in this design, one calculates from the total average current of 200 mA an average current density of $j = 143$ mA/cm^2 and finds $\alpha = 3.42$ m^{-1}. This corresponds with a space charge induced drop in phase advance per cell from $0.5\,\pi$ to $0.3\,\pi$ (90^o to 54^o). We note that the motion becomes unstable if $Q < \alpha$ and if $\alpha\ell > 1$, so that certainly $\ell < 1/\alpha$ or $0 < \ell < 0.29$ m under any circumstances. Since our bunching system represents an exercise in geometrical optics rather than a beam transport system (as is the linac) its design is more critical and one would like to choose even stronger focusing and consequently even smaller distances between the quadrupoles than $\ell \approx 14$ cm: a decrease in phase advance per cell of 36^o is large enough to prevent the second gap from properly compensating for the perturbations caused by the first one. Notwithstanding that we retain $\ell = 14$ and calculate the lower limit of the amplitude of the deflection angle modulation. We inserted two bending magnets into the lattice and adjusted the strengths of the three quads between them to obtain a non-dispersive bend and calculated the elements of transfer matrices from the first center of bending to the center of the central quadrupole as well as the amplitude function at that point neglecting space charge effects. Demanding that a beam that just scrapes the drift tube bores in the linac (i.e. that has a maximum width of 4 cm there) can be switched we find that the amplitude of the variation in deflection angle must be at least 46 mrad. With this value a beam, with a width of some 1.45 cm at this point, would just clear a septum of zero thickness and would be bunched to bunches with a phase spread of nearly 2π rad and a ($1-\cos\varphi$) linear density distribution. If we consider an amplitude for the relative energy modulation of 0.1 (i.e. 50 keV) as still acceptable it follows that the static deflection angle must be greater than $46/0.05 = 920$ mrad or 52^o. Since the effective length of each bending magnet can hardly be more than some 6 cm if it is not to interfere with the neighboring quadrupoles they should have flux densities of at least 1.915 T (= 19.15 kG).

With these results in mind we judged this design too marginal to merit further consideration. No improvement can be expected from variations in the injection energy and rf frequency of the linac, since the dimensions of the buncher system scale as those of the linac. This means that this approach to conditioning of high current beams for lossless transmission through Alvarez type linacs should be abandoned.

Injector Linac

Several advantages are gained by the use of one or more injector linacs. As mentioned before an injector linac offers the possibility to distinguish between the particles inside the buckets and those outside via energy selection at its exit. All particles with energies above a predetermined level are assumed to be part of the bunched beam and are injected into the main linac, all others are discarded. A simple computer simulation of the capturing process showed that in a 200 MHz proton linac with a stable phase angle of -30^o, an energy gain per meter of 1 MeV and an injection energy of 750 keV the particles outside the buckets can have nearly any energy up to 3.6 MeV, with the interval between 0.5-2 MeV dominating, at the point where the synchronous particles have reached 4 MeV, while the lowest energy in the bucket is about 3.87 MeV. The difference, 0.27 MeV (= 6.75 %), is enough to make energy selection effective. The large energy spread of the particles outside the buckets precludes their being drifted through a quadrupole focused structure without losses. However, there is no need to choose for the injector linac a conventional Alvarez. Since it is a relatively small part of a large system its capital cost nor its operating cost are matters of overriding importance. Therefore if features as a gradual increase in gradient, solenoid focusing, independent single gap accelerating cavities or any others seem advantageous in terms of flexibility, ease of realization or reliability, they can certainly be adopted. The same is true for the buncher system, if that can be distinguished from the injector linac. The structure could contain quick change internal aperture stops that would stop the particles that cannot be drifted through. Such stops would be removed and discarded when too radioactive as a standard maintenance routine.

A single injector linac is subject to the same objection raised against the buncher. Since the current limit of a linac is primarily determined by the ion species and the injection energy it is determined by the injection energy into the injector linac. This objection is removed if one provides the main linac with n injectors, each operating on $1/n^{th}$ of the frequency.[11] The injectors would be connected to the main accelerator via a dynamic switch in such a manner that together they would fill all its buckets in succession.

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