HIGH EFFICIENCY BUNCHER FOR LINAC

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Introduction

Since the output current of proton sources has increased by several orders of magnitude during the past twenty years, the striving toward higher efficiency buncher systems for linacs has waned considerably. Recently, however, the desire to accelerate exotic particles such as polarized particles and antiparticles, negative and heavy ions, etc. for which the source currents are still rather low, revived interest in pushing for higher efficiency buncher systems. In addition, for extremely high current applications, the radiation and radioactivity problems caused by the uncaptured beam is becoming more acute. This also calls for higher capture efficiencies to be attained by improved buncher systems.

The ideal beam buncher for injection into a linac should have a single-slope sawtooth voltage waveform. Such a buncher, in principle, bunches a d.c. beam into δ-function bunches, thus leading to 100% rf capture efficiency; but sawtooth waveforms are difficult to produce at high powers. A sinusoidal waveform buncher gives a capture efficiency of only about 2/3. Higher efficiencies can be obtained by adding second and higher harmonics to approximate the sawtooth waveform, but with the addition of each higher harmonic the complexity and cost of the buncher system get progressively higher and the gain in efficiency gets progressively lower. The proposed buncher system is based on an idea introduced many years ago by Beringer and Gluckstern.[1] To make it realistic and practicable their original idea is augmented and modified.

A single harmonic buncher bunches a 360° section of beam so that about 240° of it is contained in a linac rf bucket 90° wide. In fact, 180° of it can be contained in a bucket approximately 22° wide (Fig. 1). The basic idea for the proposed buncher system is to cut the beam into 360° sections and send alternate sections through two separate but identical buncher cavities operating at half the linac frequency. Each beam section is, then, 180° in buncher phase. When bunched it should fit inside a bucket 22° wide in buncher phase or 44° wide in linac phase. The efficiency of capture into a 90° wide bucket is, therefore, easily 100%. In fact, for buckets 90° wide in linac phase or 45° wide in buncher phase, the beam sections can be considerably longer than 180° buncher phase. This latitude is useful for accommodating imperfections in the beam sectioning, bunching, and recombining operations. In any case, some small amount of beam loss unrelated to capture is expected during these operations.

Beam Sectioning and Branching

As shown in Fig. 2, this is accomplished by a sinusoidal transverse deflector (wobbler W), an electrostatic septum S, and two dewobblers $\overline{W}_1$ and $\overline{W}_2$. The beam is wobbled laterally (not visible in the scale of Fig. 2) back and forth across the septum at half the linac frequency by the wobbler field. Sections of the beam on opposite sides of the septum are deflected in opposite directions to form two separate branches each containing every other section. The half-wobble of the sections of beam in each branch is, then, annulled by a properly phased dewobbler identical in construction to the wobbler. Lens L (e.g. a magnetic quadrupole triplet) images point-to-point with unit magnification between W and $\overline{W}$ ($\overline{W}_1$ or $\overline{W}_2$) so that the cancellation between the effects of the wobbler and the dewobbler is straightforward. If the wobbler can produce a square waveform which may well be possible at the very low power level required for transverse deflection, there will be no need for the dewobblers. To obtain clean beam sectioning with minimum loss the septum should be as thin as possible and the beam should be focused at the septum by lenses upstream (including L).

Hardware feasibility depends, of course, on the beam energy and emittance, and the linac frequency. In discussion of parameters we will take as an example a 750 keV proton beam with an emittance of 50π mm-mrad entering a 200 MHz linac. The parameters given are by no means optimal and serve only to demonstrate feasibility.

For a 750 keV proton beam, lenses of focal length 30 cm are reasonable. In discussion of beam optics and as shown in Fig. 2 only thin lenses with 30 cm focal length are used. Thus, the wobbler and dewobblers are located 60 cm up- and downstream of lens L.

The electrostatic septum could be made of an array of 0.1 mm tungsten wires having an effective field length of 10 cm and

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producing a transverse field of ±45 kV/cm. This septum will deflect the branch beams ±0.3 rad. Thus, at the location of the dewobblers the two branches are already separated by some 30 cm.

We assume a beam width at the wobbler of ±10 mm, hence a divergence of ±5 mrad. For sectioning the beam the peak deflection produced by the wobbler should be larger than the divergence. We will take the peak deflection to be ±10 mrad. The wobbler is conceived as a pair of parallel plates with an effective field length (taking into account fringe field and transit time) of 1 cm and a peak field of 15 kV/cm. When focused down to a waist at the septum the beam width will be approximately ±3 mm, and the ±10 mrad deflection at the wobbler will wobble the beam ±6 mm at the septum. This gives a beam loss on the 0.1 mm thick septum of about 0.5%. For pulsed linac operation this amount of beam heating of the septum is tolerable.

Associated with the transverse deflection the wobbler will also wobble the energy of the beam.[2] With the parameters given above, the peak energy swing is only about ±8 keV which is small. Furthermore, this energy wobble will be annulled by the dewobblers to the extent that the bunching effect between the wobbler and the dewobblers due to this energy swing is negligible. Thus, to first order, exiting from the dewobblers the two branch beams are identical and uniform in energy, each consisting of a train of beam sections 360° linac phase long, spaced by gaps of the same length.

Beam Recombining

After the dewobblers the branch beams are refocused at the buncher cavities B_1 and B_2 by lenses L_1 and L_2 which are identical to lens L. The distances between S and L_1 (or L_2) and between L_1 (or L_2) and B_1 (or B_2) are, thus, all 60 cm. In the perpendicular plane the beams should also be focused at B_1 and B_2 to reduce the required aperture of the buncher cavities to a minimum. Since there is no other focal requirement elsewhere in this plane, this should not be difficult to accomplish.

In addition, two electrostatic dipoles D_1 and D_2 are placed 30 cm upstream of the buncher cavities. These dipoles have twice the strength of the septum and deflect the branch beams toward each other for eventual recombination. The beams are refocused at the recombining septum $\bar{S}$ by lenses L_3 and L_4 which are again identical to lens L. Septum $\bar{S}$ is identical to S but used in reverse.

After the bunchers the beams have sizeable energy variations, hence the beam transports must be achromatic from the bunchers through the recombining septum $\bar{S}$. One simple achromatic arrangement is shown in Fig. 2. Electrostatic dipoles D_3, D_4, D_5 and D_6 have the same strength as septum $\bar{S}$, and are located at the foci of lenses L_3 and L_4. The strengths of $\bar{S}$ and the dipoles are fine-adjusted so that at the exit of $\bar{S}$ the beams are separated just by their width (touching), 6 mm, and are directed toward each other by the small angles ±10 mrad. They cross each other 30 cm downstream of $\bar{S}$ where the beams are also optimally bunched. At this location a combiner C identical in construction to the wobbler W will kick the bunched beams laterally ±10 mrad on the peaks of the field to remove the remaining 20 mrad angle between the branches and achieve total recombination.

The entrance to the linac is located immediately downstream of C. The first 3 or 4 quadrupoles in the linac are used to match the transverse optics of the beam.

Beam Bunching

At the buncher cavities the beams are focused in both planes so that the apertures of the cavities can be made small (~8 mm diameter) to reduce the energy spread caused by the transit-time factor. For a 180° section of beam, straightforward geometry (see Fig. 1) gives a minimum bunch length of about 22° after the particle receiving the peak energy from the buncher cavity has gained $\Delta\phi = -1.38$ in phase. At a drift distance ℓ after the buncher cavity the phase gain is

$$\frac{\Delta\phi}{2\pi\frac{\ell}{\beta\lambda}} = \frac{\Delta\ell}{\ell} - \frac{\Delta v}{v} = \frac{\Delta\ell}{\ell} - \frac{1}{2}\frac{\Delta E}{E}$$

where $\frac{\Delta v}{v} = \frac{1}{2}\frac{\Delta E}{E}$ relates the relative gain in velocity to that in kinetic energy (non-relativistic), and $\frac{\Delta\ell}{\ell}$ is the relative orbit length increment which, because of dispersion in the beam transport, is not vanishing in our case. Instead we have

$$\frac{\Delta\ell}{\ell} = -\,\theta^2\,\frac{d}{\ell}\,\frac{\Delta E}{E}$$

where d is the distance between D_5 (or D_6) and $\bar{S}$, and θ is the bending angle of the dipoles. Altogether we have

$$\frac{\Delta E}{E} = -\,\frac{\beta\lambda\,\Delta\phi}{\pi(\ell+2\theta^2 d)}\ .$$

With d = 30 cm, θ = 0.3 rad, E = 750 kV, ℓ = 150 cm = distance from B(B_1 or B_2) to C, $\beta\lambda$ = 12 cm (750 keV protons and 100 MHz), and $\Delta\phi$ = −1.38 rad we get the required peak voltage

$$\Delta E = 25.4\ \text{kV},$$

a rather modest value.

Discussion

The example shows that at least for the application specified the hardware requirements of this buncher system are realistic. A few special remarks should be made.

1. In principle, except for the 0.5% loss on the upstream septum there should be no other beam loss through this buncher system and through capture into the linac rf buckets. The number of components involved in this system is more than double that of a simple first harmonic buncher system, and the tuning is considerably more complicated. But for special application where the source current is low or where the radiation from lost beam must be minimized, the near 100% efficiency may well be worth the cost and complexity.

2. In deriving the parameters we used many simplifying approximations such as: thin lenses, first order optics (no aberration), etc. More exact calculations are needed for a real design. In particular, the effect of the energy swing between the wobbler and the dewobblers caused by the wobbler field, although small, should be investigated more thoroughly.

3. More effort should be made to optimize the parameters. For example, if the lateral dimensions of the components in the branch beams do not require such large separations between the branches, the septa field can be reduced, thereby making their operation easier and more reliable. The total length from W to C is about 3.3 m and scales almost linearly with the focal length of the lenses. We can shorten the system by increasing the strength of the lenses. For beam bending we used electric dipoles. Clearly, they can equally well be magnetic dipoles. The transports downstream of the buncher cavities are achromatic as long as all bending elements have the same dispersive properties (all electric or all magnetic).

4. The basic idea of sectioning the beam into two branches each using only 180° of the rf field in a buncher cavity is simple and attractive. The complexity of the system lies mostly in the manner in which beam sectioning, branching, and recombining are performed. Perhaps simpler and more clever schemes can be devised to accomplish these operations.

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References

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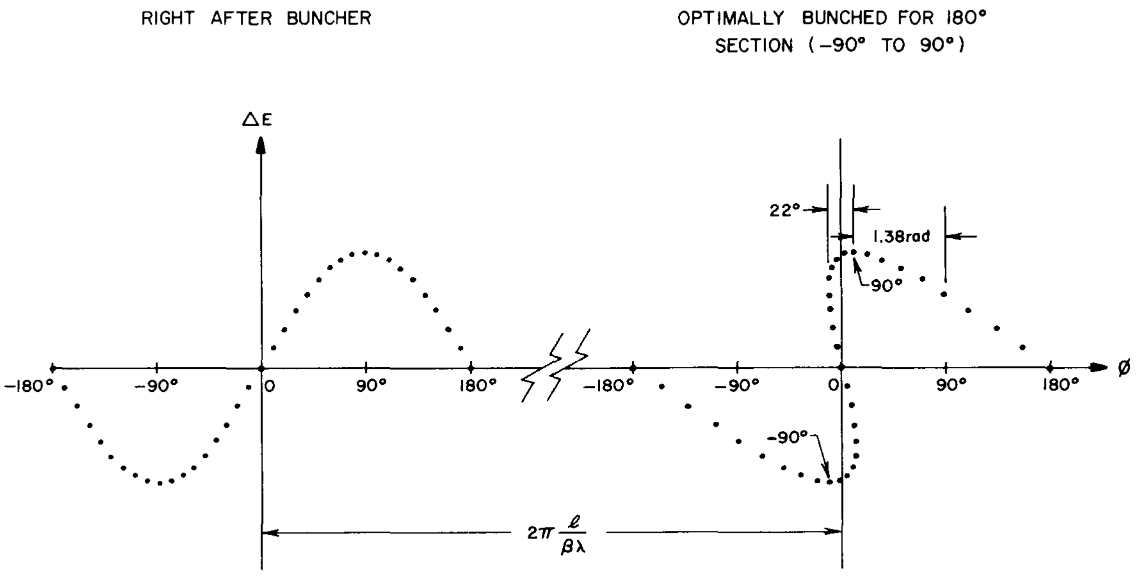
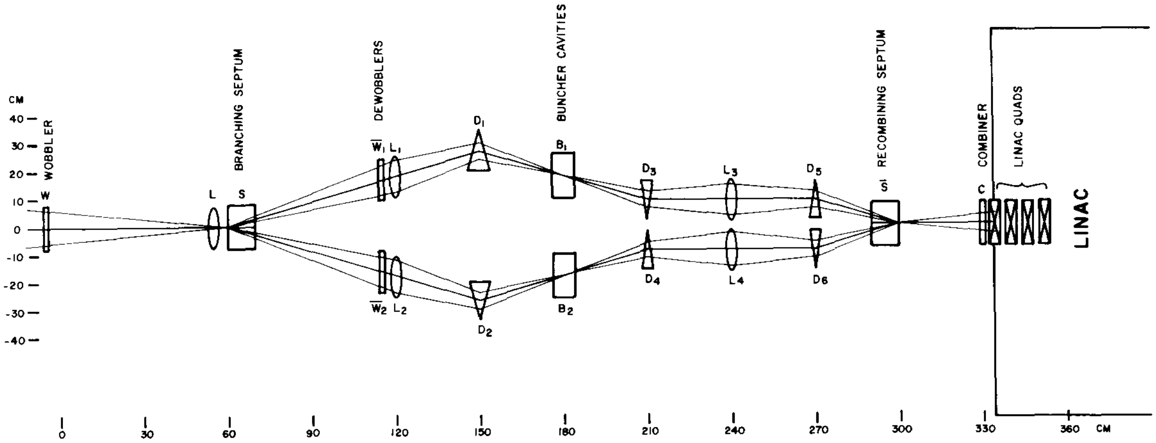
2. T.K. Fowler and W.M. Good, Nucl. Instr. and Methods 7, 245-252 (1960). See also L.J. Laslet "On the Passage of a Beam Through a Cavity", LBL Report ERAN-72 (1970)


RIGHT AFTER BUNCHER

OPTIMALLY BUNCHED FOR 180° SECTION (−90° TO 90°)

PHASE DIAGRAM OF BEAM AFTER BUNCHER CAVITY
(10° INITIAL PHASE BETWEEN DOTS)

FIGURE 1



LAYOUT AND OPTICS OF THE BUNCHER SYSTEM

FIGURE 2

DISCUSSION

D. Warner, CERN: I think in the paper by Beringer and Gluckstern they made it quite clear that they weren't happy with the longitudinal modulation aspects of the wobbler and in fact I put a paper in for Frascati (1963) which put this same point of view. I don't believe that your dewobbler does reverse what your wobbler does. I don't think bunchers act like that.

Teng: It has to. Aside from the fact that the beam is broadened by the bunching effect, if you look at the whole thing as a black box, you are coming in with no transverse deflection and you are going out with no transverse deflection.

Warner: I don't believe you are going out with no transverse deflection because your phases are wrong now.

Teng: Yes, you have some remaining transverse deflection of course. The energy wobbling in between the wobbler and the dewobbler broadens the beam so that the phase of the dewobbler is slightly wrong. It is off by say ± 15° but it is wrong only to that extent.

Warner: I look at it as if the wobbler were acting as a buncher. With a buncher can you put another buncher at a certain distance and exactly cancel it?

Teng: No, I didn't say exactly, but ± 15°. It's largely but not exactly cancelled. I have to invoke the fact that the linac bucket is ninety degrees instead of 44° so that you have some slop there and I think you need all that. You probably fill up the whole bucket.