

COMPENSATION OF BEAM LOADING IN THE ALS INJECTOR LINAC\*

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**Abstract**

For the Advanced Light Source (ALS) 50 MeV injector linac, a modest level of beam loading is expected, which if uncompensated, will cause an energy spread greater than 4% in the beam intended for the booster synchrotron. Use is made of the fact that the linac consists of two equal, independently driven sections. Phase jumps of appropriate amount are introduced, which effectively, result in a power step to offset the beam loading.

**ALS Injector Requirements**

The ALS injector design has been described in previous papers.<sup>1,2</sup> The components that concern us here are the 50 MeV linac, and the subharmonic bunching system between the gun and linac. This is shown schematically in Fig. 1. The nominal requirement for multibunch beam intensity at the linac exit is  $8 \times 10^{10}$  electrons in a 100 ns pulse. To allow for possible losses in the linac, it is conservative to assume injected current will be higher, and assume  $1.2 \times 10^{10}$  electrons in a 100 ns pulse, or an average current of 0.2 A. Also, for beam loading compensation, we will assume that a pulse as long as 150 ns could be employed to inject the booster. The current can be regarded as a dc pulse, even though the electrons are in bunches 8 ns apart due to the 125 MHz buncher, because the response of the linac structure is determined by the filling time  $t_f$ , which is much longer. The induced voltage  $V_b$  due to the beam pulse opposes the accelerating voltage due to the power supply, and is given by<sup>3</sup>:

$$V_b = -irL[(1-\tau^{-1}) (1-e^{-x\tau}) + xe^{-x\tau}] \quad (1)$$

where  $x=t/t_f$ . This exponential function is nearly linear for small  $x$ . The constants, and their values for the ALS linac structure, are

$i = 0.2$ A,	average current
$r = 56$ M $\Omega$ /m,	shunt impedance
$L = 2 \times 2 = 4$ m,	structure length
$\tau = 0.138$ nepers,	attenuation constant
$t_f = 397$ ns,	filling time (for a 2m section).

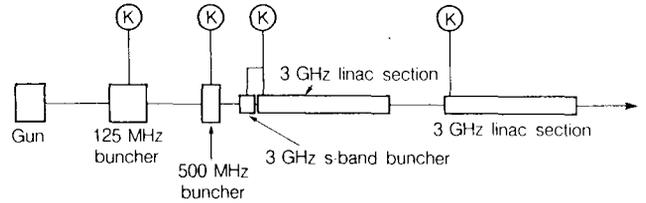


Fig. 1. Schematic of the gun, bunchers, and 50 MeV linac of the ALS injection system.

Beam loading will be zero for the front of the pulse, and will increase in an approximately linear fashion for  $x \ll 1$ . For a 150 ns pulse,  $x = 0.378$ , and  $V_b = 2.2$  MeV. This is a significant change, amounting to a 4.4% energy spread, and needs to be compensated. A relatively simple means for compensation would be to introduce a step increase in klystron power  $P_0$  coinciding with the start of the beam pulse, which will tend to offset the beam loading. The energy gain from such a step increase is<sup>3</sup>

$$V_g = \sqrt{2rLP_0/\tau} (1-e^{-x\tau}) \quad (2)$$

This is another exponential function, which is nearly linear for small  $x$ . If  $P_0$  is chosen properly,  $V_g + V_b$  will be near zero, for small  $x$ . For large values of  $x$ , as steady state beam loading is approached, the cancellation will not be so good. In the case of the ALS injector, 150 ns is the longest expected pulse. A plot of  $V_g + V_b$  as a function of  $x$ , for several values of  $P_0$ , shows the effect of the cancellation (Fig.2). It should be possible to reduce the energy spread due to beam loading to something less than  $\pm 0.1$  MeV.

**Compensation Method**

In practice, a step increase in klystron power is not desirable because it means running the klystrons in an unsaturated mode; we wish to run in a saturated mode, as this will make the klystrons less sensitive to input disturbances, such as power line fluctuations. Pulse-to-pulse reproducibility will thus be much better.

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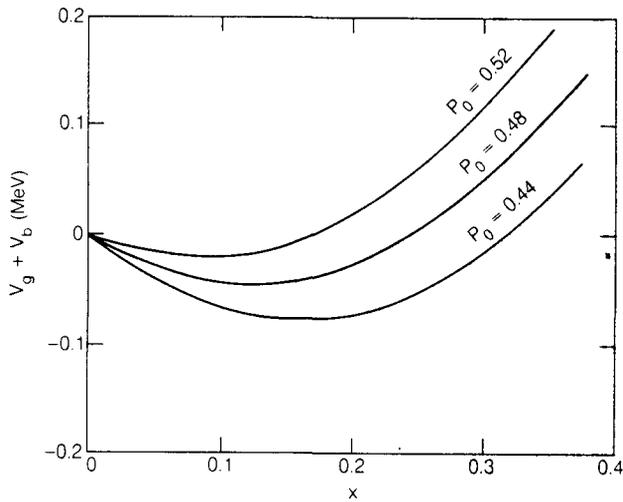


Fig. 2. Effect of using a step power input  $V_g$  to offset beam loading  $V_b$ , as a function of  $x = t/t_f$ , where  $t_f$  is the filling time for one linac section.

The step power increase can be achieved by appropriate phase-shifting of the klystrons, when, as in the present case, at least two accelerating structures are independently phased. This method will be adequate for the relatively modest step in power needed. This is accomplished as follows: first, a power level and phase setting is found for the klystrons which is adequate for the final energy, allowing for the beam loading (Fig.3a). This level, however, is needed only at the tail of the pulse. Next, a phase shift  $\theta$  is found, such that by shifting the first section by  $\theta$  and the second section by  $-\theta$  (so that the beam in one section sees a rising voltage, and in the other a falling voltage), the acceleration would be correct if there were no beam loading (Fig.3b). Before the arrival of the beam pulse, the klystron phases are offset by  $\pm \theta$ . Then, as the beam pulse moves through the accelerator sections, the offsets  $\theta$  are removed, and each accelerating section will experience a rising voltage pulse, analogous to a step in klystron power input.

**Calculation of phase step required**

We can write the energy gain, without the step, as

$$V_0 = V_1 \sin \varphi_1 + V_2 \sin \varphi_2. \quad (3)$$

The phases  $\varphi_1$  and  $\varphi_2$  are close to  $90^\circ$ , and are introduced because some small phase compensation may need to be introduced in order to minimize energy spread, apart from the beam loading effects. With the  $\pm \theta$  step, the energy gain is

$$V_s = V_1 \sin(\varphi_1 + \theta) + V_2 \sin(\varphi_2 - \theta), \text{ which,}$$

neglecting small terms, becomes

$$V_s = V_0 \cos \theta. \quad (4)$$

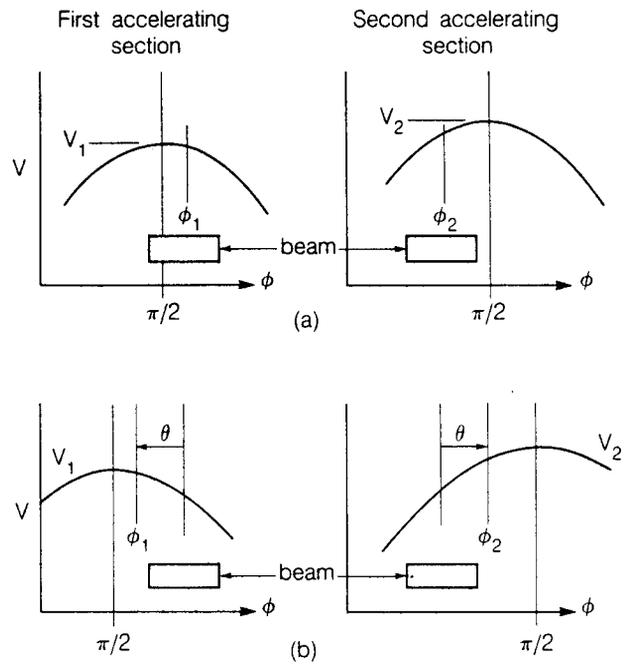


Fig. 3. Relation of electron beam to accelerator section phasing  
(a) after start of beam pulse,  
(b) before start of beam pulse, with  $\pm \theta$ .

Thus the accelerating voltage is just the original  $V_0$ , lowered by the factor  $\cos \theta$ . When  $\theta$  is set to zero, the voltage will rise, and after a time  $t_f$  has elapsed, will equal  $V_0$ . This is shown schematically in Fig.4. The depression  $V_0 - V_s$  must be such that the rising voltage  $V_x$  matches the expected beam loading, with  $t_x$  taken as the end of the beam pulse. Noting that  $V_0$  occurs when  $x = 1$ , we can write, using Eq.2,

$$\frac{V_x - V_s}{V_0 - V_s} = \frac{[1 - e^{-x\tau}]}{[1 - e^{-\tau}]} = x \quad (5)$$

and using Eq.4 to solve for  $\cos \theta$ ,

$$\cos \theta = 1 - (V_x - V_s) / (V_0 x). \quad (6)$$

Using  $t = 150 \text{ ns}$ ,  $x = 0.378$ , and with  $V_s = 50 \text{ MeV}$ ,  $V_0 = 55 \text{ MeV}$ , from Eq.5 we find  $V_x = 51.9 \text{ MeV}$ , and from Eq. 6,  $\theta = 24.6^\circ$ .

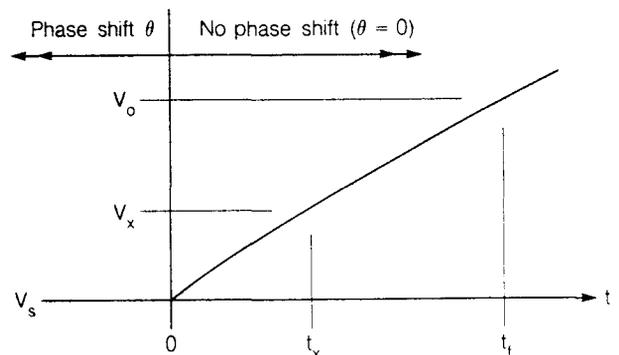


Fig. 4. Rise of effective accelerating voltage after phase shift  $\pm \theta$  is removed.

**Timing Considerations**

As indicated schematically in Fig.1, two independently driven subharmonic bunchers compress the beam in phase before it reaches the linac. The s-band buncher located immediately in front of the linac, receives power from the same klystron that drives the first accelerating section, by means of a splitter in the waveguide. If the phase compression of the beam is to work properly, the correct phase relation must be maintained between the subharmonic bunchers, the s-band buncher, and the first 0.5 m of the accelerating section, known as the capture section. This will not be the case if the phase shift  $\theta$  occurs while the beam is transiting this region.

The remedy is to remove the phase displacement sometime before the gun pulse. There is some leeway in the actual time, but for our parameters, it should be at least 120 ns before, but not more than 250 ns before, the start of the 150 ns gun pulse. To see why this works it is necessary to consider how a disturbance, such as a change in power level, propagates through the disk-loaded waveguide, both in space and time. Relevant numbers for this application are:

Filling time of 2 m section	400 ns
Time of beam pulse	150 ns
Length of beam pulse	45 m
Capture section transit time	100 ns
Power pulse risetime (a guess)	20 ns

Note that the term "power pulse" as used here, refers to the  $\theta$  shift, not to the turning on of the klystron, which has occurred much earlier. The power pulse starts at the front of the linac, and progresses, with a lower electric gradient  $E_1$  in front of the pulse, and a higher gradient  $E_2$  behind the pulse. This is shown schematically in Fig.5. The power pulse takes 400 ns to travel through the 2 m section. The beam pulse requires 150 ns to travel through the section, during which time the power pulse has traveled a distance  $s = 0.75$  m. The effective voltage gain is rising during this time; the net increase will be  $s(E_2 - E_1)$ , and this will be equal to the required gain  $V_x - V_s$  of Eq.6. Referring to Fig.5, we see that the same result will be achieved, regardless of start time, provided that the end of the beam pulse occurs before the power pulse reaches the end of the accelerating section. We want, however, for the power pulse to have progressed at least 120 ns into the section, before the beam pulse starts, in order to leave the capture section unaffected.

When the operation is carried out as described, there is also no problem with the s-band buncher, which is fed in parallel with the accelerating section, because it has a much shorter filling time than 120 ns. The timing of the power pulse (i.e., the  $\theta$  shift) in the second accelerating section is less critical, but in practice, will be most conveniently synchronized with the first.

**Acknowledgements**

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**References**

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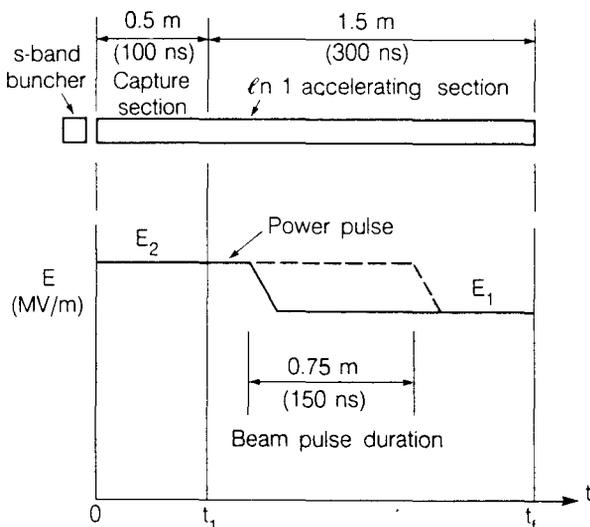


Fig. 5. Timing relation between the power pulse and the beam pulse in the first accelerating section. During the 150 ns beam pulse, the power pulse travels 0.75 m.