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INCREASING THE ENERGY OF SLC BY TRANSIENT WAKE FIELD*

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1. Introduction

Here we present a possible way to further increase the energy of SLAC bunch from 50 GeV to 65 GeV or even more, without at the same time increasing the RF peak power and accelerator length, at the expense of beam duty cycle. The basic idea is the following.[1]

The field distribution along the structure with variable dimension in the steady state induced by the beam is as follows:

$$E_b \;=\; I\sqrt{\alpha R_m}\;\, e^{-\int_0^z \alpha dz'} \int\limits_0^z \sqrt{\alpha R_m}\;\, e^{\int_0^{z'} \alpha dz''}\, dz' \;. \tag{1}$$

where α is the voltage attenuation coefficient, R_m is the shunt impedance and I is the beam current. For constant impedance structure, it has the following form:

$$E_b = IR_m \left(1 - e^{-\alpha z}\right) \quad , \tag{2}$$

and for constant gradient structure it becomes:

$$E_b \;=\; \frac{IR_m}{2}\, \ell n\, (1 - 2\alpha_0 z) \quad . \tag{3}$$

where α_0 is α at $z = 0$. We first consider the transient state which is more important for SLC. When the beam passes through the structure for both CG and CI, the energy loss at time t can be approximately expressed by the formula:[2,3]

$$\Delta(t) \;=\; \int\limits_0^L E_b(z,t)\, dz \;\approx\; \frac{\pi c R_m L}{\lambda Q}\, It \;=\; \frac{\pi c R_m L}{\lambda Q}\, q(t) \quad . \tag{4}$$

The bunch energies decrease linearly with time t. This only depends on the quantity of charge $q = I\tau$ in the pulse and the parameters of the structure, and is independent of the beam energy. For example, at the SLAC case the parameters are as follows:

$$R_m = 53\,\mathrm{M\Omega/m} \quad , \qquad L = 10000\,\mathrm{ft} \quad (94.8\%\ \text{effective}) \quad ,$$
$$\lambda = 0.1\,\mathrm{m} \quad , \qquad \mathrm{Q}{=}13000 \quad .$$

Formula (4) becomes:

$$\Delta W(t) \approx 0.1\, I(A)\, \tau\ (\mathrm{ns})\ \mathrm{GeV} \quad . \tag{5}$$

If we want the single bunch to obtain energy gain $\Delta W = 16$ GeV from the driving beam , the characteristics of the driving beam should be $I = 1\,\mathrm{A}$, $\tau = 160\,\mathrm{ns}$, or $I = 2\,\mathrm{A}$, $\tau = 80\,\mathrm{ns}$, or $I = 4\,\mathrm{A}$, $\tau = 40\,\mathrm{ns}$, and so on.

If a bunch of charged particles passes through a resonator it loses energy to the field (wake field). If the beam is accelerated in an RF-field, the wake field amplitude subtracts from the accelerating field (see curve 2 in Fig. 1). If, on the other hand, the bunch is decelerated in the RF-field, the wake field adds to the accelerating field (see curve 3 in Fig. 1). A "single bunch" following such a "driving bunch" and having the right phase for acceleration thus is accelerated by an extra field and gains extra energy.

2. How to Get Driving Beam Bunches

The driving beam bunches can be obtained from the existing SLAC accelerator. First we look at the energy relation. At the usual state the energy of the last bunch in the driving beam is

$$W = W_0 - \delta W \quad , \tag{6}$$

where W_0 is the energy by the RF power and δW by the wake field. In the single bunch acceleration case, δW is the extra energy gain and the energy loss of the last bunch in the driving beam is

$$W_L = W_0 + \delta W \quad . \tag{7}$$

Obviously, W_L is always larger than W which means the tail of the driving beam would lose all of its energy before reaching the end of the accelerator. Therefore at least two driving beams must be provided, each serving one half of the accelerator. In this way, the scheme shown in Fig. 2 results. The maximum possible extra energy gain of the single bunch is

$$\delta W_m = \frac{W_0}{3} \quad . \tag{8}$$

Assuming $W_0 = 50$ GeV, δW_m is about 16 GeV. In this kind of arrangement one RF pulse is used to accelerate a single bunch among three ($n = 3$) and the other two RF pulses are used to make driving beams. If $n = 4$,

$$\delta W_m = W_0/2 \simeq 25 \text{ GeV} \quad . \tag{9}$$

In general,

$$W_0 - \delta W_m = \frac{W_0 + \delta W_m}{n-1} \quad .$$

so

$$\delta W_m = \frac{n-2}{n} W_0 \quad . \tag{10}$$

In a first RF-pulse a beam is accelerated and then stored in a storage ring in order to serve as driving beam for the first part of the accelerator. In a second RF-pulse, the same is repeated for the benefit of the second part of the accelerator. Then, in a third RF-pulse, the two driving beams are sent down the accelerator in a decelerating phase and are followed immediately by a single bunch that takes up the energy, both of the RF and the wake fields.

In order to keep the storage rings at reasonable dimensions, and in order to avoid radiation losses, the accelerator has to be subdivided in a number of subsections with individual injectors of driving beams. To each subsection the scheme described is applied. This is possible, because the energy of the driving beam does not play a role.

Dividing the whole system into M subsections has other distinct advantages. It cuts off the coupling of deflecting waves between sections through the beam and makes it easy to get the required driving beam intensity as well as reduce the transverse emittance of the driving beams.

Another problem is transportation of driving beams with big energy spread. In the case above mentioned the energy spread is about 30%. Stanford Linac Energy Doubler (SLED) is a method used at SLAC accelerator for enhancing peak RF power at the expense of RF pulse width. The energy gain property of

SLED provides a very good means[4] for reducing the energy spread. The unloaded energy is seen to be increasing as a function of time as peak energy is approached. In fact, in order to reach the same extra energy gain δW for the single bunch only a certain pulse charge is needed, so it can be done to vary I (and τ) with SLED characteristics to obtain the best spectrum, as shown in Fig. 3. We are mainly concerned with the energy of the last bunch of driving beams because the wake fields cause the largest energy loss to the last bunch during both the making and using of the driving beam. In addition, during storage the energy spread of the driving beams will reduce.

The way to increase the energy of the single bunch is different from recirculating the single bunch again. In this case the single bunch still passes through the whole accelerator once, and the requirement on the driving beams is rather lower than that of the single bunch in either bunch phase width or the transverse emittance and other sides.

The method presented here still works for the short pulse operation or the long pulse steady state. The fields induced by the driving and accelerated beam all increase with the time t, but have 180° difference in phase. They partially cancel each other, so the energy spectrum of the accelerated beam will improve. Otherwise the energy or the charge per pulse with the same energy spread will increase.

For example, when SLAC operates at long pulse with RF power 50 MW from the klystrons, the energy is about 30 GeV at weak beam current. If $n = 3$, the energy will increase to 40 GeV. It is easy to estimate that a driving beam with $I \sim 280\,\mathrm{mA}$ is needed. In this case the energy spread is smaller for the driving beam than it is in the transient state and the problem of transportation of driving beams is simplified.

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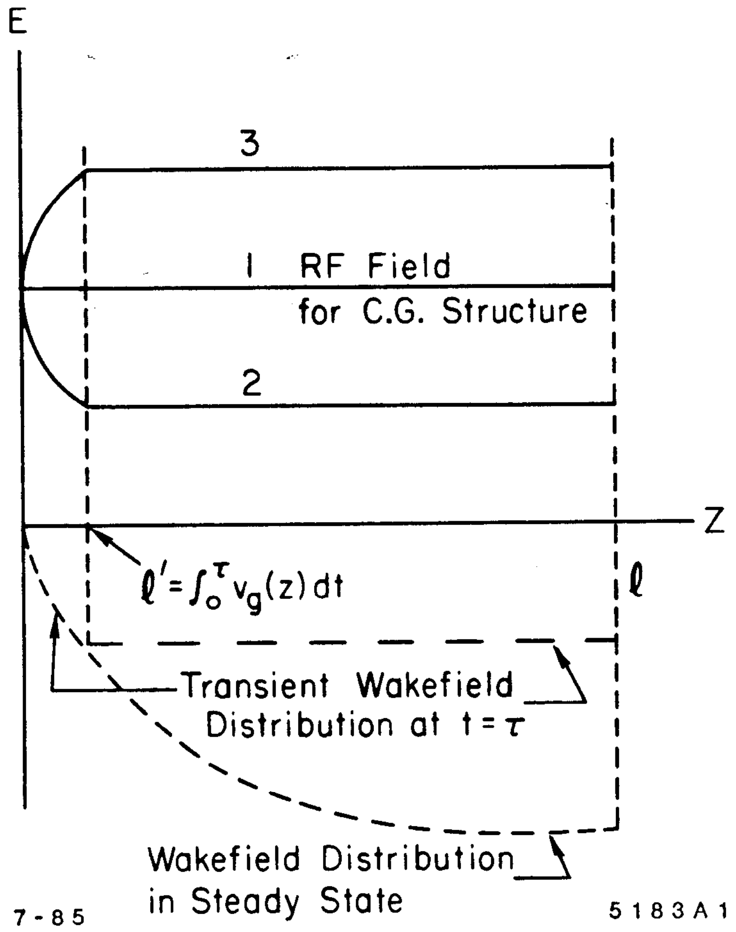
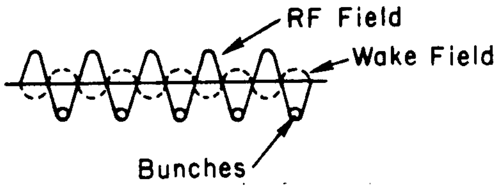
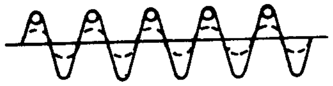


Fig. 1. (1) Field distribution with $I = 0$.

(2) Bunches in maximum accelerating phase of RF field:



(3) Bunches in maximum decelerating phase of RF field:



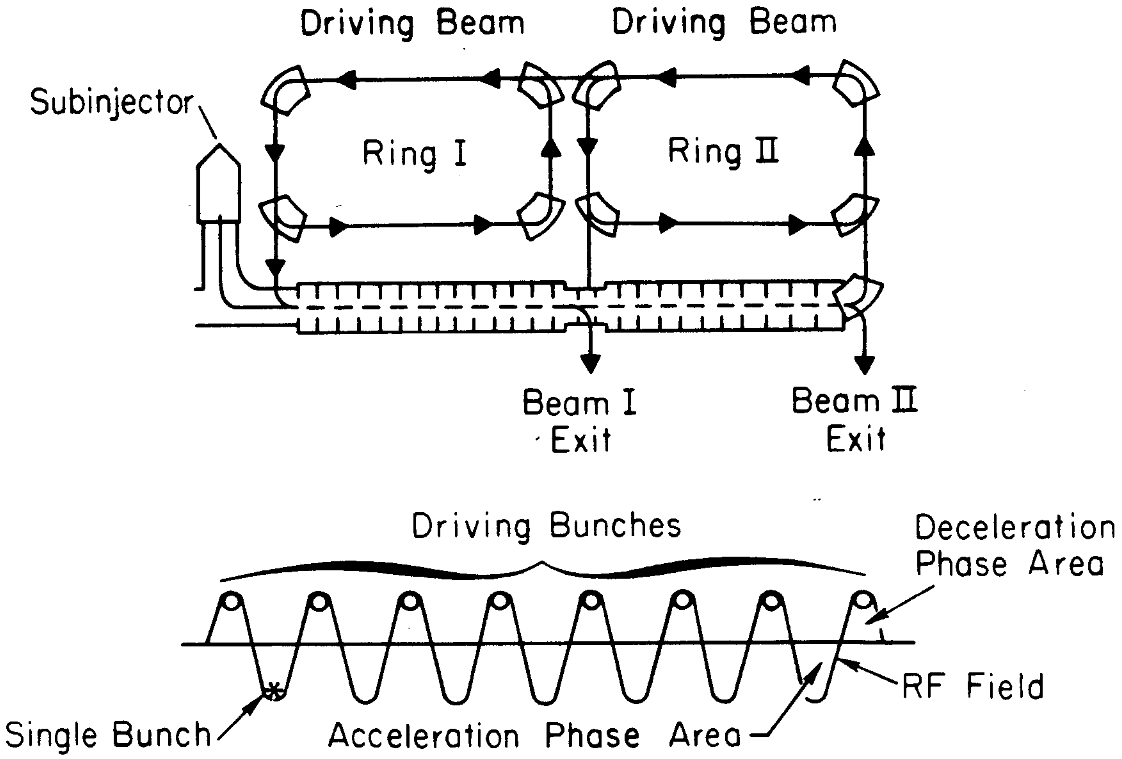


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Fig. 2. One subsection scheme ($n = 3$). The whole accelerator consists of M subsections.

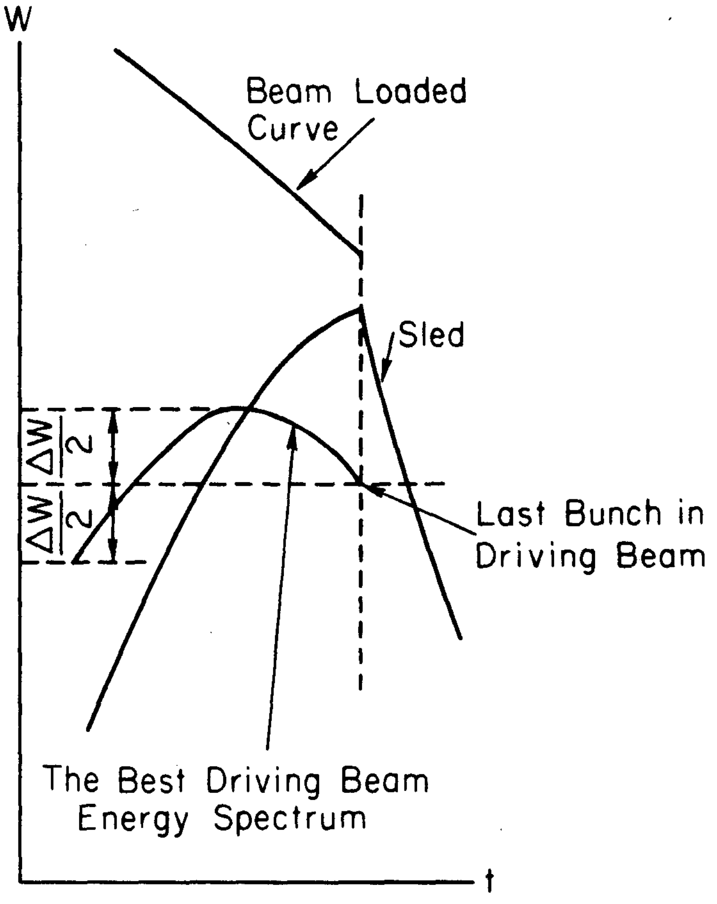

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Fig. 3. Improving the energy spectrum of driving beams with SLED.