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AUTHOR: C. G. Yao	DATE: July 2, 1985

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TITLE: INCREASING THE ENERGY OF SLC BY TRANSIENT WAKE FIELD***1. Introduction**

Here we present a possible way to further increase the energy of SLAC single bunch from 50 GeV to 65 GeV or even more, without increasing the RF peak power and accelerator length. The field distribution along the structure with variable dimension in the steady state induced by the beam is as follows:

$$E_b = I \sqrt{\alpha R_m} e^{-\int_0^z \alpha dz'} \int_0^z \sqrt{\alpha R_m} e^{\int_0^{z'} \alpha dz''} dz' . \quad (1)$$

For constant impedance structure, it has the following form:

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

and for constant gradient structure it becomes:

$$E_b = \frac{IR_m}{2} \ln(1 - 2\alpha_0 z) . \quad (3)$$

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:^{1,2}

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$$\Delta(t) = \int_0^L E_b(z,t) dz \approx \frac{\pi c R_m L}{\lambda Q} I t = \frac{\pi c R_m L}{\lambda Q} q(t) . \quad (4)$$

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:

$$\begin{aligned} R_m &= 53 \text{ M}\Omega/\text{m} , & L &= 10000 \text{ ft (94.8\% effective)} , \\ \lambda &= 0.1 \text{ m} , & Q &= 13000 . \end{aligned}$$

Formula (4) becomes:

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

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

2. How to Use Transient Wake Field to Increase SLC Energy

The bunches in the beam are usually located in the maximum accelerating phase of the RF field from the klystrons and in the maximum decreasing phase of wake field induced by the beam itself. The two fields have 180° difference in the phase and they cancel each other partly (the resulting field distribution is shown by curve 2 in Fig. 1). But if the driving bunches are located in the maximum decelerating phase of RF field from klystrons, the two fields are in phase and add to each other (the resulting field is shown by curve 3 in Fig. 1). In this case the single bunch will be accelerated by both RF and wake fields, if it is located in the maximum accelerating phase near the end of the driving beam (the single bunch is 180° apart from the driving bunch). The single bunch will obtain extra energy gain from driving bunches and driving bunches will lose nearly their whole energy.

3. 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

$$W = W_0 - \delta W \quad , \quad (6)$$

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

$$W_L = W_0 + \delta W \quad . \quad (7)$$

Obviously, W_L is always larger than W which means the tail of the driving beam will lose its whole energy by reaching the end of the section, so we need to get at least two driving beams from a certain length of section and use each of them to drive the single bunch within each half of the section. The scheme is shown in Fig. 2. The maximum possible extra energy gain of the single bunch is

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

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 $n = 4$,

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

In general,

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

There is a subinjector in every subsection. The first two driving beams pass through the whole subsection, where both obtain an energy gain of $W_0 - \delta W$

(last bunch) from two RF pulses with the SLED and then are stored in ring 1 and ring 2, respectively. When the third RF pulse turns on, the driving beams enter the subsection from the head and the middle of the subsection and are taken out from the middle and the end of it, respectively. The bunches in both of them are located on the maximum decelerating phase of the RF field. The single bunch and the last bunch of the driving beam are placed on the SLED peak energy gain point. Both of the driving beams lose energy $(W_0 + \delta W)/2$, and the single bunch gains energy $(W_0 + \delta W)$ with the W_0 coming from the RF pulse with SLED and the δW coming from two driving beams.

We would face more difficulties if we deal with two driving beams with very high energy, setting $W_0 = 50$ GeV, and $\delta W = 15$ GeV, so the energy of the driving beam varies from 42.5 to 50 GeV. Very big magnets with high magnetic field are needed to deflect them. Secondly, setting $pps = 180$, the time interval between RF pulses is about 5.5ms and the bunch with velocity c takes about $10\mu s$ to make a rotation. The beams would rotate about 1100 and 550 times before they reenter the structure to drive the single bunch. The energy loss per rotation is proportional to W^4 and $1/R$, so the driving beams would rapidly lose their energy and large changes in the energy of driving beams also makes it very difficult to keep them within the rings.

Fortunately, the wake field induced by the driving beams is independent of the beam energy. The whole accelerator can be divided into M subsections. We will deal with driving beams with energy about W_0/M . The number of rotations is proportional to M . We can find a reasonable M with acceptable energy loss during storage of the driving beams and acceptable structural complexity.

In addition, the RF pulses can be arranged as shown in Fig. 3 to reduce the number of rotations during storage of the driving beams.

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%. The energy gain property of SLED provides a very good means³ for reducing the energy spread. 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. 4. We are mainly concerned with the energy of the last bunch 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 $I \sim 280$ 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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References:

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FIGURE CAPTIONS

- 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:
- Fig. 2. One subsection scheme ($n = 3$). The whole accelerator consists of M subsections.
- Fig. 3. Rearrangement of RF pulses to reduce energy loss by radiation during period of storage.
- Fig. 4. Improving the energy spectrum of driving beams with SLED.

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Fig. 4. Improving the energy spectrum of driving beams with SLED.

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