Phase Gradients in Acceleration Structures

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Abstract

In linear accelerators with two or more bunches the beam loading of one bunch will influence the energy and energy spread the following bunches. This can be corrected by quickly changing the phase of a travelling wave structure, so that each bunch recieves a slightly different net phase. At the SLAC Linear Collider (SLC) three bunches, two (e^+, e^-) for the high energy collisions and one (e^--scavenger) for producing positrons should sit at different phases, due to their different tasks. The two e^--bunches are extracted from the damping ring at the same cycle time about 60 ns apart. Fast phase switching of the RF to the bunch length compressor in the Ring-To-Linac (RTL) section can produce the necessary advance of the scavenger bunch (about 6° in phase). This allows a low energy spread of this third bunch at the e^+-production region at 2/3 of the linac length, while the other bunches are not influenced. The principles and possible other applications of this fast phase switching as using it for multi-bunches, as well as the experimental layout for the actual RTL compressor are presented.

1 Introduction

In current designs for future linear colliders each RF cycle accelerates several bunches in one pulse train to drop energy costs and to increase the luminosity. This multi-bunch scheme can be disturbed by longitudinal and transverse wakefields of the high intensity bunches or by different purposes of the bunches, as in the SLC. Here the two interaction bunches, e^+ and e^-, are followed by a scavenger bunch which produces the positrons for the next cycle at about 2/3 of the linac (Sector 19). At this point the scavenger beam should have a minimum energy spread, while the other two bunches are still decreasing their energy spread.

For the transverse stability of the beams an energy spread is introduced in the beginning of the linac, called BNS-damping or autophasing [1, 2, 3]. At the later part it is decreased so that the energy spread of the bunches is a minimum at the end of the linac. At Sector 19 the beams have about three times the final energy spread. By changing the longitudinal position of only the scavenger bunch by about 6° in phase (1.75 mm) the energy spread can be compensated there. This relative position shift can be either done at the beginning of the linac with a compressor phasing or by a fast phase switching of the RF drive to the linac after the first two bunches have passed through.

The principle and some details of this fast phase switching are presented first. Then the current set up for the scavenger beam with some experimental data are shown. At the end a possible scenario for a multibunch scheme even at the SLC demonstrates how powerful this fast phase switching can be.

2 Fast Phase Switching

A fast phase change introduces a phase gradient in an acceleration structure. The spatially separated bunches can be influenced differently in integrated phase and amplitude.

2.1 Principle

A travelling wave accelerator structure is fed by an RF source which produces a sudden phase change from 0° to 90° (Fig. 1). A bunch of particles just prior to this change will see no difference. It will

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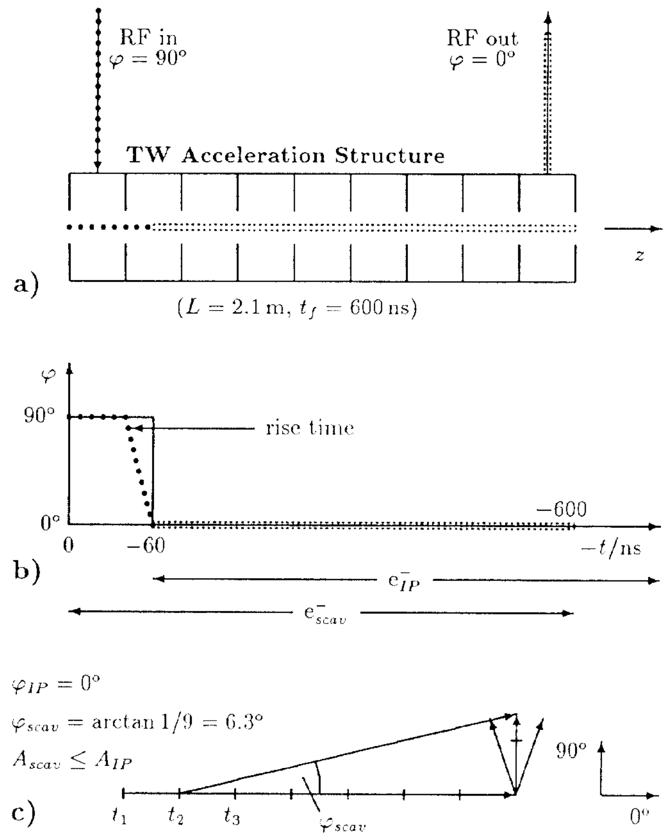

Figure 1: Principle of fast phase switching.

The phase of the RF to the input of a travelling wave structure is changed quickly (a), so a second bunch 60 ns later (b) will see a different net phase of about 6° (c).

experience a phase of 0° and amplitude A_1. A second bunch, say the scavenger, arives a time t_b later, which corresponds to the bunch separation. When t_f is the filling time of the whole structure, t_b/t_f of its length is filled with the new phase. (No losses in a constant impedance structure are assumed.) For a 90° phase change the second bunch will see a net phase and amplitude of

$$\varphi_2 = \arctan\left(\frac{t_b}{t_f - t_b}\right), \quad A_2 = A_1 \frac{\sqrt{(t_f - t_b)^2 + t_b^2}}{t_f}.$$

For $t_f = 600$ ns and $t_b = 60$ ns this gives $\varphi_2 = 6.3°$ and $A_2 \approx 0.9A_1$. Figure 1 c) shows the phasors of that change. Zero phase is horizontal, 90° is vertical and the length between the time steps corresponds to the amplitude of the averaged seen RF field. By changing the input phase a little bit around 90° the amplitude A_2 can be varied while the phase keeps mainly constant.

In general it is possible to change the phase φ_i and amplitude A_i for a bunch number i by a certain amount by changing the timing and the amount of the phase change.

2.2 More Detailed Aspects

Double Amount. Instead of only one phase change two can be introduced. For instance a phase of 90° flowing in and −90° flowing out with something like 0° in between provides twice the amount of the simple scheme: $2 \times 6.3° = 12.6°$. A slowly varying change would cause the same amount, but would consume more RF power (compare length of the circle line in Fig. 2.)

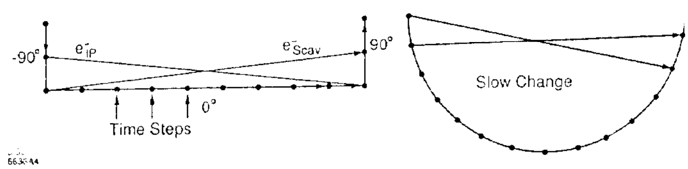

Figure 2: Two phase switches and one slow one.
Two phase changes produce twice the normal amount (left). A slow varying (right) does the same, but needs more energy (length of circle)

Real Structure, Real RF Pulse. In the constant gradient structure of the SLC compressor the higher group velocity at the input rather than at the output changes the possible phase change in 60 ns to about 8.5° (in) and 4.0° (out). A constant impedance structure has a similar behavior since the amplitude is damped at the output and therefore the influence is less there.

Like a short RF pulse (short compared to the the filling time) decreases its influence to about 30 – 40 % during the passage time in the structure, a short phase pulse (e.g.: 0°, 90° (short), 0°) will also decrease its influence. So the influence of a change can be even located in the middle of the structure.

Risetime and Dispersion. In practice, the fast phase switch pulse has a finite risetime. Behind the actual phase shifter there is an amplifier and a klystron. acceleration structure has shown a risetime (10 % to 90 %) of 30 ns, which corresponds to the combined risetimes of all preceding components. At the output coupler a risetime of about 120 ns has been observed, with an under- and over-shooting of the signal corresponding to the dispersion of the generated frequencies during the switch time. As long as these risetimes are less than the filling time of the structure, a controlled influence is possible.

Additional Flight Time. Till now it was assumed that the flight time of the bunch through the structure is short compared to the bunch separation, or in another picture that the bunch experiences the RF distribution of its arrival time. When the bunch travels through the structure the fields also do. In the case of the SLAC 3 GHz structure the group velocity is about $0.02\,c$ (input) and $0.007\,c$ (output), where c is the velocity of light. Therefore only a neglectable 0.7 – 2 % effect can occur during the flight time. The effect gets bigger with a higher group velocity of about $0.1\,c$ like in the design of the NLC [4].

Nonflat RF Pulse. In the case of a nonflat RF pulse, e.g. like the SLED pulse of the SLAC Energy Doubler [5] a similar behavior at the input and output occures like the case of real structure with attenuation. The difference to that type is that the amount of net phase change depends on the local pulse height of the RF in the structure.

Partial Influence. If only a part of the incoming RF can be changed, the influence is partial. For instance the amplitude of the SLED pulse consists of two parts: About 2/3 are coming from a storage cavity and 1/3 from a klystron at the beginning and about 1/2 and 1/2 for each at the end of the pulse. So the influnce by changing the klystron phase is reduced to about 1/3 (or 1/2) of the amplitude. Delay lines or travelling wave structures for storaging the energy for the pulse compression can provide the full range of phase change influence, but then there are several changes necessary to provide one big change in the acceleration structure.

3 Phasing of the Scavenger Bunch

The different task of the scavenger beam needs another phase setting. The amount of this and some experimental result are shown.

3.1 Necessary Amount of Phase Shift

As mentioned in the introduction a phase shift of about 6° is necessary. A rough linearized picture for this amount can be obtained in the following way. Say at a certain beam current and bunch length we would need an overall phase of $\varphi = -10°$ off crest. The tail sits on a higher energy than the head compensating the longitudinal wakefield to get the lowest energy spread. This can be achieved by putting the beam to $\varphi_a = 10°$ in the first third and $\varphi_b = -20°$ in the left 2/3 of the linac:

$$\varphi = 1/3 \cdot \varphi_a + 2/3 \cdot \varphi_b = -10°.$$

The positive phase φ_a at the beginning provides that the tail has a lower energy than the head and therefore is stronger focussed and damped (BNS-damping) [2].

For the scavenger beam, which is extracted at about 2/3 of the linac the average phase would be

$$\varphi_{2/3} = 1/2 \cdot \varphi_a + 1/2 \cdot \varphi_b = -5°.$$

By putting the scavenger beam about 5° earlier in the linac this can be compensated.

It should be mentioned here that the lower RF amplitude (compare Fig. 1 c) gives a lower compression and therefore a longer bunch, which doesn't need to sit so far away from the crest. So the lower amplitude helps to get to the right setting. Another helpful effect is the beam loading of the first beam. At $5 \cdot 10^{10}$ particles the beamloading in the compressor corresponds to a phase difference of about 1.2°.

3.2 Experimental Results

The long bunches of the damping ring ($\sigma_z = 6 - 10$ mm) are compressed to about $\sigma_z = 1$ mm in the Ring-To-Linac section (RTL). A compressor at the beginning introduces an energy spread $\pm E_0 \sin\varphi$ ($E_{head} > E_{tail}$) so the earlier head particles have to go a longer path in the high dispersion region of the RTL. A certain phase φ_2 and amplitude change ($A_1 \longrightarrow A_2$) corresponds to an energy variation of the center of

$$\Delta E = E_0 \sin\varphi_2 \cdot \frac{A_2}{A_1}.$$

For small changes and 90° phase switch (A_2 and φ_2 are correlated) ΔE is about:

$$\Delta E \approx E_0 \varphi_2 (1 - \varphi_2).$$

For a given beam energy E this energy variation causes an offset in the horizontal plane x at a certain dispersion point η:

$$\Delta x = \eta \frac{\Delta E}{E} \approx \eta \frac{E_0}{E} \varphi_2 (1 - \varphi_2).$$

The offset Δx was measured with a beam position monitor (BPM) versus the negative time of the phase change pulse corresponding to the time of the beams. Figure 3 shows the result. A bunch separation of about 60 ns produces an offset $\Delta x = 2.2$ mm. With $\eta = 85$ m, $E_0 = 28$ MeV, $E = 1.15$ GeV the measured phase φ_2 is about 6.8°. The expected value for this 2.1 m long section is 8.5° for a step change (see real structure in Section 2.2). The risetime of about 30 ns would expect about $3/4 \cdot 8.5° = 6.4°$, which is in a quite good agreement with the measured value.

Together with the phasing of the output, the amplitude and beam loading effect it is guaranteed that, even at a stronger BNS-phasing (necessary for higher currents), the energy spread of the scavenger bunch can be minimized. It should be noted that the absolut energy also changes a little bit to a smaller value. This can be used for feedback or feedforward aspects.

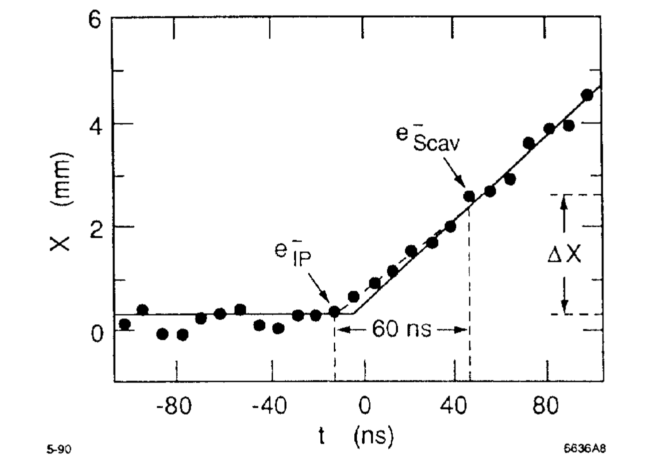

Figure 3: Beam respond to the phase switch.
Two bunches 60 ns apart are separated up to 2.2 mm, which corresponds to a phase variation of 6.8°.

Controlling time and amplitude of the phase change, φ_2 and A_2 changes for the second bunch in the compressor, which determinds the phase and bunch length in the linac resulting to a certain energy and energy spread at the end.

The possibilities of this fast phase switching has urged us to study the advantages of this scheme for controlling multibunches.

4 Multi-Bunches in the SLC

To propose multi-bunches it is necessary to consider a lot of effects like the peak beam power for machine protection, flat kicker pulses for extraction out of the damping ring, timing slots for measuring induvidual bunches, and so on. Here a result is presented, that the beam loading of bunches, with $5 \cdot 10^{10}$ particles each, can be controlled so that each bunch has the same energy and energy spread.

4.1 Beam Loading

A bunch of $5 \cdot 10^{10}$ particles produces a beam loading of 800 MeV [6], this is about 1.7 % of 47 GeV, half the Z^0-mass. But addionally to this amplitude effect the beam loading can have an influence to the phase of the RF. For compensating the longitudinal wakefield, a very short bunch has to sit about 25° off crest. The phase will change by 0.4° to about 25.4° for the following bunch. In the compressor this effect is much stronger and has a value of about 1.2°. Effects of the damping ring are not taken into account.

When the bunch sits at a certain phase, e.g. 25°, the influence of the amplitude effect and the phase effect can be compared to each other. A phase change of about 2.2° (from 25° to 22.8°) can compensate the 1.7 % amplitude effect. So an overall phase change of about 3.8° or an amplitude change of 3 % (or a mixture 1.6° + 1.7 %) is necessary to compensate the beam loading of a bunch with $5 \cdot 10^{10}$ particles.

4.2 Compensation Mechanisms

Different possibilities exist to compensate the beam loading. To get a numerical value we assume a bunch separation of 5.6 ns which correponds to the wavelength of the subharmonic buncher.

Partial Filling of the Structure. In the present SLC scheme three bunches 58.8 ns apart are located on the rising part of the SLED pulse. So each bunch has about the same energy. If they would be 5.6 ns apart, only about 10 % of the beam loading is compensated. To increase this value without lowering the current the bunch has to be placed on a part with a steeper slope, but then the peak energy will drop significantly. Allowing an energy drop of 10 % will control only about a quarter of the current [7]. Other investigations using an amplitude variation should include the possibility of changing the incoming RF pulse, which already has a special kind of phase switch from 180° to 0°.

Sitting on Different RF Phases. The following scheme is assumed: The first bunch is very short ($\sigma_z \approx 0.5$ mm) and sits far off crest (25°) in the linac. The next bunch sits nearer to the crest to cancel the beam loading of the first one. It has to be a little bit longer to minimize the energy spread, and so on for the next bunches.

About 1/4 of the necessary amount can be controlled by the rising slope of the amplitude within 5.6 ns. The rest of about 2.8° (compare Section 4.1) should be handled by phasing the linac and the compressor. The linac phase has only a small influence of about a half (SLED) of $5.6/800 = 0.7\,\%$, resulting in 0.3°. The main amount of about 2.5° should come from the compressor, but with the current set up only about $12.6° \cdot 5.6/60 = 1.2°$ can be achieved. Shortening the compressor pulse by 50 % to 300 ns with twice the amplitude would provide the desired value. Then only a part of the compressor is actually used. Eliminating the unused part decreases the beam loading phase shift to about 0.6°, providing an even more relaxed overhead.

This scheme helps to adjust energy and energy spread of two consecutive bunches of $5 \cdot 10^{10}$ particles each, which are separated by only 5.6 ns. But 3×10 bunches with this charge would decrease the RF amplitude by about 50 %. Therefore 3×5 bunches with a more relaxed separation of 11.2 ns seems to be reasonable. This would increase the luminosity by a factor of 5, which is comparable with a current of $11 \cdot 10^{10}$ particles per bunch in the two bunch mode.

5 Conclusion

The fast phase switching works. By varying the time and phase amount of the phase change the energy and energy spread of a bunch is controlled. Even the beam loading of a bunch with $5 \cdot 10^{10}$ particles can be compensated within 5.6 ns which makes multi-bunches in the SLC possible.

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