SLED SYSTEM FOR LONG PULSE MULTI-BUNCH LINAC

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Abstract

The compensation for transient beam loading effect requires that a modulated RF pulse be fed to the accelerator. A new SLED system to be able to generate the modulated RF pulse in long pulse multi-bunch linac is studied. The required waveforms of SLED input pulses are computed to generate RAMP and Flat-top RF pulses. The optimisation method of SLED parameters is formulated. The results of cold test coincide with the theoretical one. RAMP and Flat-top RF pulses are generated using SLED for the first time.

1 PREFACE

Operation in multi-bunch mode can greatly increase the RF conversion efficiency. And it is the main measure to achieve the high luminosity of the next generation linear colliders. When operated in multi-bunch mode, transverse wake field will increase the beam transverse emittance, while longitudinal wake field will dilute beam energy spread. The design of new type accelerating structures concerns mainly about the suppression of the transverse wake field, such as damped structure, detuned structure, damped-detuned structure, rounded damped –detuned structure. The beam's wake field can also excite the elementary mode, which is used to accelerating the beam and can't be suppressed by the design of accelerating structures. Multi-bunch beam loading will introduce additional energy spread between beam bunches. It must be compensated. There are three methods to compensate the Multi-bunch beam loading, namely: ΔT method、ΔF method、precise compensation[2]. The ΔT method is also called early injection method. This method can be applied when beam length is much shorter than the filling time of the structure. ΔF method uses special compensation structures, which is the same as the standard structure but operates at a frequency about 1to 2MHz from the frequency of the standard structure. The phase of special compensation structures is 90^0 from the phase of the standard structure. It can be applied when $t_b \le (1/6\Delta F)$. Precise compensation method can be applied to any kind of beam no matter how long it is. When beam width is longer than filling time, the precise compensation method must be used. RF pulse compressor is a device to convert long RF pulse into short one with much higher peak RF magnitude. SLED is the earliest RF pulse compressor used in accelerators. It was one of the key technologies for SLAC to achieve the energy of 50GeV.We also use SLED in our BEPC Linac. Many new types of RF pulse compressors have been designed for the next generation colliders, namely BPC[5]、SLED-II[6]、DLDS[7] etc. In this paper, we will discuss how to apply SLED system to constant gradient structure with long pulse beams. For intensive beam, SLED must provide RAMP pulse. For weak beam, rectangle RF pulse is required. The results of low power test coincide with the theoretical predictions.

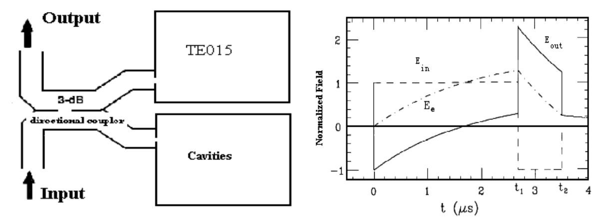

Fig. 1 SLED and its typical input and output waveform

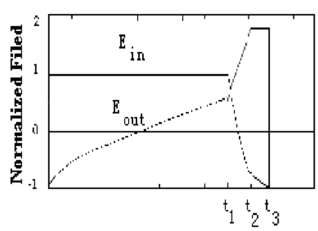

Fig. 2 Generate RAMP pulse

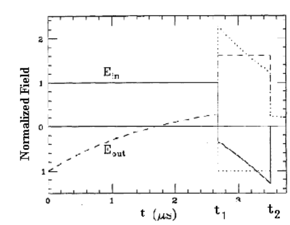

Fig. 3 Generate Flat-top pulse

2 THE INPUT RF PULSE REQUIRED BY LONG MULTI-BUNCH BEAM

For intense beam, the precise compensation method requires that the structure be filled with the field type of $G_L(z) = G_0(z) - G_b(z)$ when $0 < t < t_f$, where t_f is the filling time of the structure, $G_0(z)$ is the accelerating field excited by a rectangle RF pulse, $G_b(z)$ is the steady state beam loading field. When $t_f < t < (t_b + t_f)$, the input RF pulse keeps in the peak power. If the charge of every bunch is the same, every bunch will see the same steady state field profile and the energy of every bunch is the same. The input RF pulse at the input of the structure when $0 < t < t_f$ is shown as equation (1). This kind of RF pulse is called RAMP pulse.

$$\left[\frac{P(t)}{P_0}\right]^{1/2} = 1 - \frac{I_0 s_0 T_F}{2G_0}(1 - \frac{t}{T_F}) \qquad (1)$$

For weak long beam, a square RF pulse of the length $t_f + t_b$ is required.

3 THE INPUT RF PULSE OF SLED TO GENERATE RAMP AND SQUARE RF PULSE AND PARAMETER OPTIMIZATION METHOD

The structure of SLED is shown in Figure 1. The parameters of the two cavities are the same. The 3 dB hybrid will guide the reflected wave of the two cavities to the output port. There is no any reflection back to the klystron. When $0 < t < t_1$, the field in the two cavities builds up. The reflection from the cavities can be viewed as the superposition of the emission of the cavity E_e and the reflection $-E_{in}$ at the cavity entrance. That means at any instant: $E_{out} = E_e - E_{in}$. At t_1, the phase of the input RF pulse changes 180 ^{0}. The phase of the emitted wave doesn't change and it is the same as the reflected wave. The output power increases magnificantly. The peak power can be increased to theoretical limit of 9. The basic function for the SLED is shown as equation (2).

$$T_c \frac{dE_e}{dt} + E_e = \alpha E_{in} \tag{2}$$

where $T_c = 2Q_l / \omega$, $\alpha = 2\beta /(1+\beta)$, $Q_l = Q_0 /(1+\beta)$, β coupling coefficient of the cavity. It is also a basic function describing the transient behavior of a resonant cavity. This is a first order differential funtion.The typical waveforms of the input and output are shown in Figure 1b. It can be seen that the output power of SLED decays exponentialy. The reason is that the cavities are being charged to the opposite phase while they are quickly emmiting after the phase reverse. To obtain the waveform required by multi-bunch long beam Linac, the input of SLED must be modulated. We will deduce the required input waveform of SLED.

3.1 Intense long beam

As discussed in section 2, the input of the structure should increase linearly first and then remains in the peak power. The input and output waveforms of SLED are shown in Figure 2.

3.11 Input waveform during $t_1 \leqslant t < t_2$

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The output waveform during $t_1 \leqslant t < t_2$ is

$$E_{out} = a + b(t - t_1). \tag{3}$$

$$a = \sqrt{\frac{P(t = t_1)}{P_0}} \qquad b = \frac{c - a}{t_2 - t_1}$$

The initial power is determined by the beam loading, c is the peak field multiplication. At any instant, we have

$$E_{out} = E_e - E_{in} \tag{4}$$

From equation (3) and equation (4), we can get

$$E_e = E_{in} + a + b(t - t_1)$$

Replace it into equation (2), we can get a differential equation for the input waveform

$$\frac{dE_{in}}{dt} + \frac{1-\alpha}{T_c} E_{in} = -\frac{b(t-t_1)}{T_c} - \frac{a + bT_c}{T_c} \tag{5}$$

The initial condition is that $E_e(t = t_1) = \alpha(1 - e^{-\frac{t_1}{T_c}})$ at $t=t_1$.

From equation (5), we can get the required input waveform

$$E_{in}(t_1 \le t < t_2) = [\frac{bT_c}{(1-\alpha)^2} - \frac{\alpha + bT_c}{1-\alpha}] + \frac{b(t-t_1)}{\alpha - 1} + e^{\frac{(\alpha-1)(t-t_1)}{T_c}} [\frac{\alpha + bT_c}{1-\alpha} - \frac{bT_c}{(1-\alpha)^2} + \alpha(1 - e^{-\frac{t_1}{T_c}}) - \alpha] \tag{6}$$

3.12 Input waveform during $t_2 \leqslant t < t_3$

The output waveform during $t_2 \leqslant t < t_3$ is

$$E_{out} = c \tag{7}$$

From equation (7) and (4), we can get $E_e = E_{in} + c$

Replace it into equation (2), we can get a differential function for the input waveform

$$\frac{dE_{in}}{dt} + \frac{1-\alpha}{T_c} E_{in} = -\frac{c}{T_c} \tag{8}$$

E_{in} is continuous at $t=t_2$, so we can get

$$E_{in}(t_2 \le t < t_3) = \frac{c}{\alpha - 1} + e^{\frac{(\alpha-1)(t-t_2)}{T_c}} \{[\frac{bT_c}{(1-\alpha)^2} - \frac{a + bT_c}{1-\alpha}] + \frac{b(t_2 - t_1)}{\alpha - 1} + e^{\frac{(\alpha-1)(t_2-t_1)}{T_c}} [\frac{a + bT_c}{1-\alpha} - \frac{bT_c}{(1-\alpha)^2} + \alpha(1 - e^{-\frac{t_1}{T_c}}) - a)] - \frac{c}{\alpha - 1}\} \tag{9}$$

3.13 Parameter optimization of SLED with RAMP output waveform

The output waveform will be kept at the peak during $t_2 \leqslant t < t_3$. To compensate the decrease of the field emitted from cavities, the input field should be increased. When E_{in} reaches –1 at the time $t=t_3$, the power multiplication factor will be the maximum.

The relation between a and c is $a = c(1 - \frac{I_0 s_0 T_F}{2G_0})$.

Use equation (9), let $E_{in}(t = t_3) = -1$, we can get

$$c = \frac{f_2}{f_1} \tag{10}$$

$$f_1 = \frac{1-e^{\frac{(\alpha-1)(t_3-t_2)}{T_c}}}{\alpha-1} +$$
$$e^{\frac{(\alpha-1)(t_3-t_2)}{T_c}}\left[\frac{1}{\alpha-1}+\frac{T_c}{(t_2-t_1)(\alpha-1)}(1+\frac{1}{\alpha-1})(1-e^{\frac{(\alpha-1)(t_2-t_1)}{T_c}})\right]$$
$$+(1-\frac{I_0 s_0 T_f}{2G_0})e^{\frac{(\alpha-1)(t_3-t_2)}{T_c}}\{e^{\frac{(\alpha-1)(t_2-t_1)}{T_c}}\left[\frac{\alpha}{1-\alpha}+\frac{T_c}{(t_2-t_1)(\alpha-1)}(1+\frac{1}{\alpha-1})\right]$$
$$-\frac{T_c}{(t_2-t_1)(\alpha-1)}(1+\frac{1}{\alpha-1})\}$$

$$f_2 = -1-e^{\frac{(\alpha-1)(t_3-t_2)}{T_c}} e^{\frac{(\alpha-1)(t_2-t_1)}{T_c}} \alpha(1-e^{-\frac{t_1}{T_c}})$$

This is the equation to optimise the parameters of SLED. Using this equation, we can optimise β for given Q_0 and given input pulse length to get a maximum c. We can also get the shortest input pulse length for a given c.

3.2 Weak long beam

As shown in Figure 3, the output waveform during $t_1 \leqslant t < t_2$ is

$$E_{out} = c$$

We can get a differential function

$$\frac{dE_{in}}{dt} + \frac{1-\alpha}{T_c}E_{in} = -\frac{c}{T_c}$$

The initial condition is at time $t = t_1$

$$E_e(t = t_1) = \alpha(1-e^{-\frac{t_1}{T_c}})$$

E_e is continuous at time $t = t_1$. We can get

$$E_{in}(t_1 < t < t_2) = \frac{c}{\alpha-1} + (1-e^{-t_1/T_c} - \frac{c}{\alpha-1})\alpha e^{(\alpha-1)(t-t_1)/T_c} \tag{11}$$

When E_{in} reach –1 at time $t = t_2$, the multiplication factor reach a maximum. From this we can get

$$c = -\frac{[1+(1-e^{-t_1/T_c})\alpha e^{(\alpha-1)(t_2-t_1)/T_c}](\alpha-1)}{1-\alpha e^{(\alpha-1)(t_2-t_1)/T_c}} \tag{12}$$

We can use this equation to optimise the SLED parameters when square output waveform is required.

4 LOW POWER TEST

Because the klystron is a non-linear device and must work in saturation state, the modulated input waveform required by SLED can't be generated by klystron directly. We must combine the output of the klystron to get the desired waveform. We can use PM-AM technique to combine the output of two klystrons and get arbitrary waveform RF pulse. The RF system is shown in Figure 4.

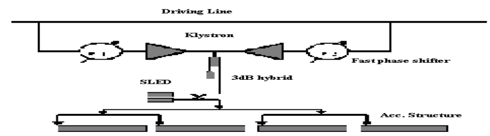
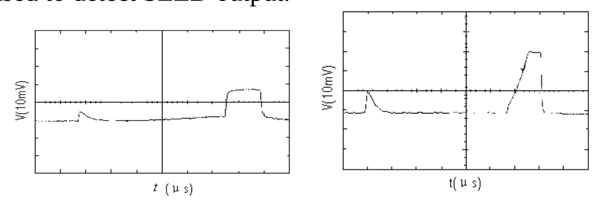


Fig. 4 RF system archethighture

In the low power test, the input of SLED is modulated according to theoretical calculation. The input waveform is calculated first and then generated by LeCroy9100 arbitrary waveform generator. A double-balanced mixer is used to modulate the continuous RF signal. A detector is used to detect SLED output.



a) flat-top waveform b) RAMP waveform

Fig. 5 output waveform of SLED

Figure 5(a) is the flat-top waveform generated by SLED. Figure 5(b) is a RAMP waveform generated by SLED. the shortest input pulse length need to get a RAMP waveform with power multiplication factor of 2.25 is 7.16 μs. The low power test coincides very well with the theory.

5 CONCLUSION

In this article, the author gives the input waveform of SLED needed to generate RAMP and Flat-top RF pulse. The parameter optimization methods for these two situations are given. The low power test coincides very well with the theory. RAMP and Flat-top RF pulse are observed at the SLED output for the first time.

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