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STUDY OF A BUNCH TRAIN TOTAL ENERGY SPREAD IN A LINAC USING SLED

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Abstract

A SLED (SLac Energy Doubler) RF pulse compressor is a passive RF component which increases the peak RF power level at the cost of reducing the pulse length. The Canadian Light Source (CLS) plans to replace the current 250 MeV Linac with a new one in mid-2024 by RI Research Instruments GmbH. The new Linac has a similar energy and two of its three 5.3 m TW constant-gradient accelerating structures are connecting to a SLED. Since a SLED output is not flat, this introduces additional energy variation along a bunch train, increasing the total energy spread. In addition, the energy spread acceptance of the CLS booster ring is below 0.5% FWHM, and it is critical to minimize the SLED non-flatness output effect by different methods. This paper will study the SLED effect on a multi-bunch train energy variation and consider the transient beam loading effect. Finally, we will show that by selecting proper RF phase switching and beam injection timing, and by alternating energy gain slope between the SLED-ed and non-SLED-ed Linac cavities can achieve the required energy spread.

INTRODUCTION

A new Linac will be installed for the Canadian Light Source facility by RI Research Instruments GmbH, which consists of three 5.26 m (electrical length) constant gradient 3 GHz accelerating sections driven by two 40 MW Canon Klystrons. The first Klystron feeds the first accelerating section (23.8 MW input power), the TW buncher, and the ECS cavity, see Fig. 1. The second Klystron feeds the second and third accelerating structures through a SLED. The nominal bunch train length is 140 ns with 2 ns microbunch spacing, and the microbunch charge is 80 pC. The final energy is 250 MeV [1, 2]. The CLS booster energy spread acceptance is very tight (below 0.5% FWHM), and both SLED's non-flat output and transient beam-loading can affect the energy variation along a bunch train. We will show that they can cancel each other by proper timing to minimize the energy variation along the bunch train.

MODELLING THE SLED

A pulse compressor is located between the Klystron and the Linac cavity. SLED (SLAC Energy Doubler) [3] is the most common pulse compressor, which consists of two identical cylindrical cavities connected to the klystron output and

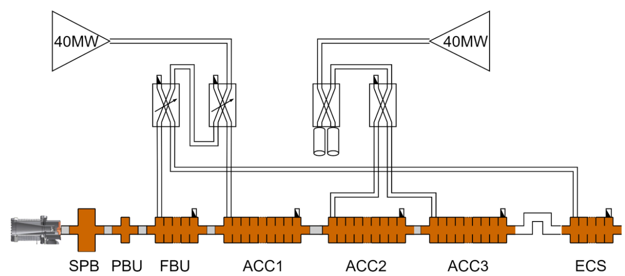

Figure 1: The new Linac layout.

the Linac cavity input through a 3 dB 90° hybrid coupler. The SLED output is controlled by the phase modulator of the RF input to the Klystron,see Fig. 2. In the beginning, when the SLED cavities are empty, the whole Klystron's RF output will be reflected and go toward the Linac cavity. The SLED cavities fill with energy as time passes, and the reflected field partially cancels the field from the Klystron. At a specific time(t_0), by a fast 180° RF phase change (Fig. 3), the field from the Klsytron and the field reflected from the SLED cavities add together instead of cancelling, and we will observe a sharp jump (two units of normalized voltage) in the total reflected field toward the Linac cavity, see Fig. 4. After a sharp jump, the total reflected field decays exponentially. Different methods, including the RF phase modulation, can flatten the SLED's output [3–5]. In this case, the fast RF phase switching would be less than 180°, and then the phase will be increased smoothly to 180°. Although phase and amplitude modulation is available with the RI Linac, this paper aims to show that the energy spread requirement can be achieved without using them.

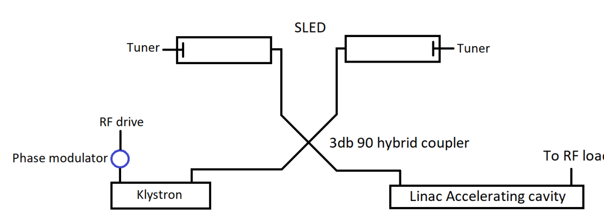

Figure 2: SLED layout and its related location to the klystron and the Linac cavity.

For a pulse compressor, based on the Ref. [3], the SLED output's voltage can be calculated using Eq.(1) which is normalized by the klytsron RF output voltage. Figure 4 shows V(t) using the RI SLED parameters.

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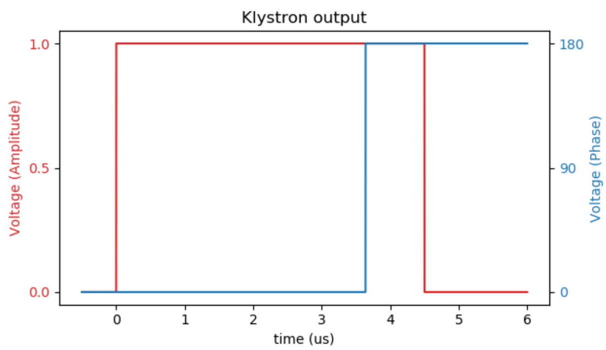

Figure 3: Klystron RF output and the 180° phase switching.

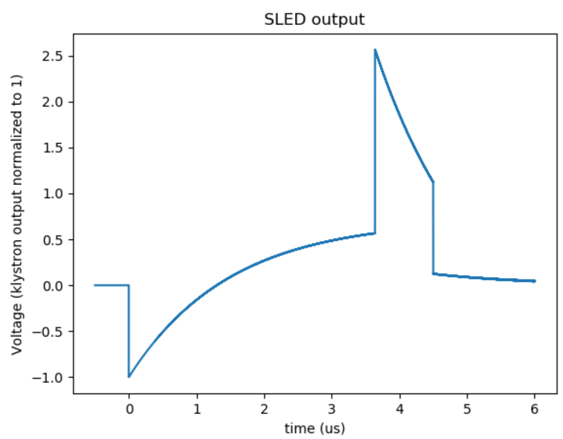

Figure 4: SLED output field amplitude.

$$\begin{cases} \omega_0 = 2\pi f_0 \\ \Gamma = \frac{\beta-1}{\beta+1} \\ \tau = \frac{2Q_0}{(1+\beta)\omega_0} \\ V(t) = \Gamma - (1+\Gamma)e^{\frac{-t}{\tau}} \;\; for\, t < t_0 \\ V_0^- = \Gamma - (1+\Gamma)e^{\frac{-t_0}{\tau}} \\ V_0^+ = V_0^- + 2 \\ V(t) = -\Gamma + (V_0^+ + \Gamma)e^{\frac{-(t-t_0)}{\tau}} \;\; for\, t_0 < t < t_p \\ V_{tp}^- = -\Gamma + (V_0^+ + \Gamma)e^{\frac{-(t_p-t_0)}{\tau}} \\ V(t) = (V_{tp}^- - 1)e^{\frac{-(t-t_p)}{\tau}} \;\; for\, t > t_p \end{cases} \tag{1}$$

As you notice in Eq.(1), it is more convenient to work with the output voltage instead of power because of the superposition of electromagnetic waves. The gradient inside the Linac cavity is proportional linearly to V(t). t_0 is the RF modulator switching time and t_p is the end of the klystron RF pulse.

ENERGY GAIN MODELLING

From Ref. [6], Eq. (4.20) is the general form of a constant-gradient structure in the Laplace space. Equation (4.26-27) are the case for the constant RF input power. For the case

Table 1: RI SLED cavities parameters

Parameter	Value	Unit
f_0	3000.24	MHz
Q_0	98000	
β (coupling coefficient)	6.0	

Table 2: RI accelerating cavity parameters

Parameter	Value	Unit
Length (Electrical)	5.26	m
Group velocity variation	3.19 to 1.19	%c
Filling time	855	ns
Average shunt impedance	55.7	MΩ/m
Axial gradient at $P_{in} = 23MW$	13	MV/m
Quality factor	13400	
Attenuation constant (τ)	0.6	

of variable RF input, the first term of them will change as follows:

$$E(z,t) = E(0,t-t_z)U(t-t_z) - \frac{\omega r i_0}{2Q}\left[(t-t_i)U(t-t_i) + (t-t_i-t_z)U(t-t_i)\right] \tag{2}$$

$$\begin{aligned} V(t) = &\int_0^z E(0,t-t_z)\,dz + \\ &\frac{ri_0}{2}\left\{\frac{\omega l e^{-2\tau}}{Q(1-e^{-2\tau})}(t-t_i) - \right. \\ &\left.\frac{l}{1-e^{-2\tau}}\left[1-e^{-\omega/Q(t-t_i)}\right]\right\}U(t-t_i) - \\ &\frac{ri_0}{2}\left\{\frac{\omega l e^{-2\tau}}{Q(1-e^{-2\tau})}(t-t_i-t_f) - \right. \\ &\left.\frac{le^{-2\tau}}{1-e^{-2\tau}}\left[1-e^{-\omega/Q(t-t_i-t_f)}\right]\right\}U(t-t_i-t_f) \end{aligned} \tag{3}$$

$t_z = -\frac{Q}{\omega} ln\left[1-(1-e^{-2\tau})z/l\right]$ is the time it takes the RF power to propagate from 0 to z and U(t) is the step function. In Eq.(3), the first term is the total energy gain without considering the beam loading. The second and third term represent the beam loading effect. For a bunch train length less than the filling time, only the second term, transient beam loading, plays a role. The second term can be reshaped as below:

$$\begin{cases} V_{b,t} = -\frac{rli_0}{2(1-e^{-2\tau})}\left[-2\tau t' e^{-2\tau} + 1 - e^{-2\tau t'}\right] \\ \Rightarrow V_{b,t} \approx -\frac{rli_0\tau e^{-2\tau}}{1-e^{-2\tau}} t' \;\; for\; t' = \frac{t-t_i}{t_f} << 1 \end{cases} \tag{4}$$

We wrote a Python code which calculates the energy gain for a bunch travelling the cavity at time t using the first term (no beam loading), see Fig. 5. We found that if the RF

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switching time is equal to one filling time before the end of the pulse,$t_0 = t_p - t_f$, a flat-top will be achieved, as can be seen in Fig. 6. And, the energy variation over a 140 ns bunch train would be 0.11 % RMS over the flat-top. The second term of Eq.(3), the transient beam loading, is independent of the cavity's RF input level and equal for all three cavities. Figure 7 shows the beam loading for different bunch charges. So for a relatively short bunch train, it is linear with a good approximation.

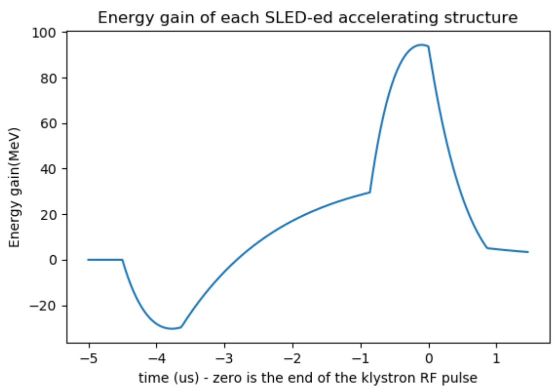

Figure 5: Energy gain evolution of the SLED-ed cavities.

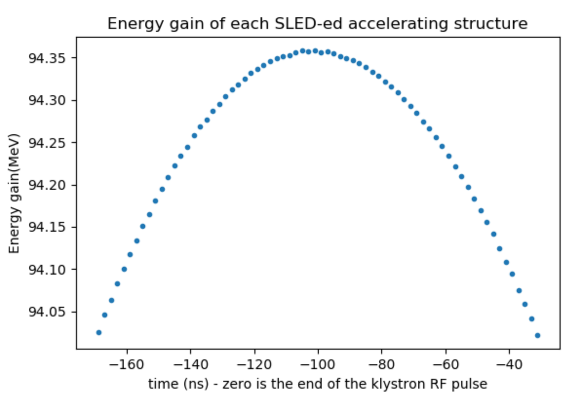

Figure 6: Energy gain evolution of the SLED-ed cavities over flat-top.

OPTIMIZED TIMING AND BEAM-LOADING COMPENSATION

For the first accelerating structure, which is not SLED-ed, the standard method of early injection can reduce the energy variation along a bunch train. However, in our case, the beam loading must be higher to cancel the linear part of the early injection energy gain. So to cancel this linear part, instead of early injection, we will use a different slope in the second and third SLED-ed accelerating cavities. As we mentioned previously, the beam loading amount is the same for all accelerating cavities; then, we need to find a beam injecting time in the second and third cavities that the slope is 1.5 times the beam loading slope to cancel the total beam loading. The remaining second-order energy variation would be similar to Fig. 6. In the Fig. 6, the bunch train was sent 170 ns before the end of the klystron pulse,t_p. Considering the beam loading, the bunch train should be sent 242 ns before the end of the klystron pulse to achieve the same energy gain varaiation along a bunch train. If we combine the energy distribution of any bunches inside a 140 ns bunch train, we can find the total energy spread, Fig. 8, which would be less than 0.5% FWHM.

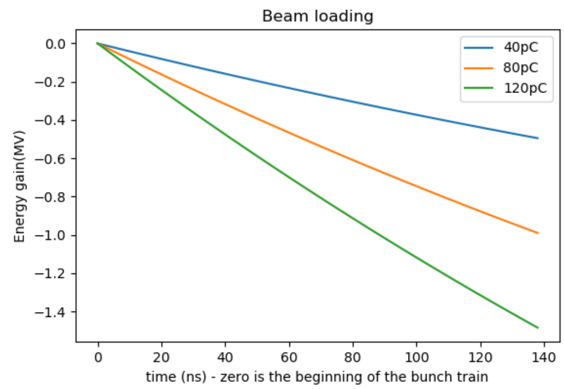

Figure 7: Beam loading for different bunch charges.

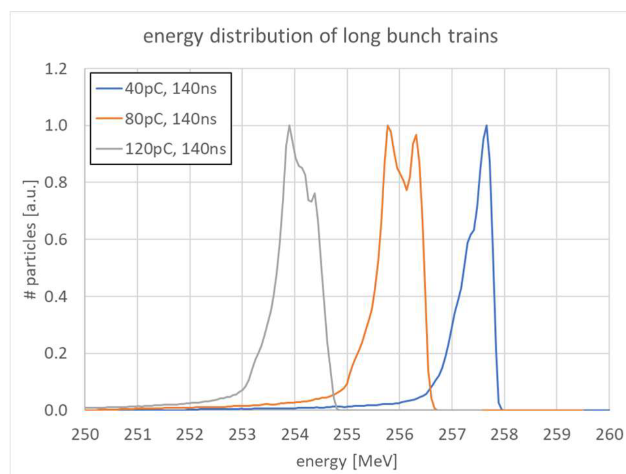

Figure 8: Total bunch train energy distribution for different charges.

CONCLUSION

Although a SLED produces a non-flat output, a flat-top energy gain over a relatively short bunch train can be achieved if we switch the klystron RF phase by a filling time before the end of the pulse. By purpose, we can choose a slope in the second and third accelerating cavities to cancel the linear part of total beam loading, and we kept the energy variation below 0.11% RMS for a 140 ns bunch train independent of the bunch charge. The total energy spread remains below 0.5% FWHM.

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