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BEAM LOADING COMPENSATION OF STANDING WAVE LINAC WITH OFF-CREST ACCELERATION

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Abstract

In E-Driven positron source of ILC, the generated positron is captured by a standing wave cavity. Because the deceleration capture method is employed, the positron is off-crest over the linac. Because the beam-loading is expected to be more than 1A in a multi-bunch format, the compensation is essential to obtain uniform intensity over the pulse. A conventional method for the compensation controlling the timing doesn't work because RF and Beam induced field are in different phase. In this manuscript, we discuss the compensation with the off-crest acceleration case. A simple phase modulation on the input RF is a solution.

ILC is an e+e- linear collider with CME 250 GeV - 1000 TeV [1]. It employs Super-conducting accelerator (SCA) to boost up the beam up to the designed energy. The beam is accelerated in a macro pulse with 1300 bunches by 5 Hz repetition. The bunch charge is 3.2 nC resulting the average beam current 21 A. This is a technical challenge, because the amount of positron per second is more than 40 times larger than that in SLC [2].

INTRODUCTION

In the ILC positron source, the generated positron is captured in a RF bucket by a linac based on a standing wave (SW) linac with APS (Alternate Periodic Structure) cavity. The capture linac is composed from 36 1.3 m L-band APS cavities with 0.5 Tesla solenoid field.

In E-Driven ILC positron source, positrons are generated in a multi-bunch format as shown in Fig. 1. It contains 66 bunches with 80 ns gap. To generate 1312 bunches for positrons in one RF pulse in the main linac, the positron generation is repeated 20 times in 64 ms. Because the positron is generated over 64 ms, the instantaneous heat load on the target is much suppressed [3, 4].

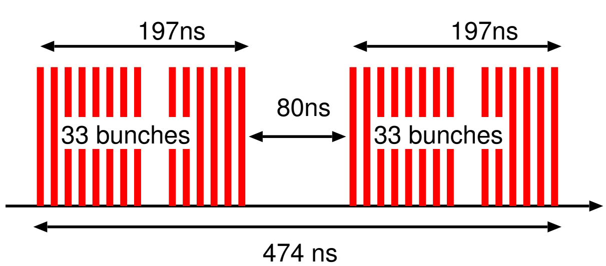

Figure 1: The beam structure in the positron source. Each mini-train contains 33 bunches. Each pulses contain 2 or 1 mini-trains.

The generated positron has a large spread in both longitudinal and transverse momentum space. Capturing the positron in an RF bucket for further acceleration is the role of the capture linac. Deceleration capture was proposed by M. James et al. [5] for better capture efficiency. In this method, the positrons are placed on a deceleration phase initially and move to the acceleration phase by phase slipping.

This deceleration capture cause a difficulty on the beam loading compensation, because the cavity field induced by the beam (beam loading field) and the cavity field by RF (acceleration field) has a finite angle. Because the conventional theory of the compensation assumes the crest acceleration, the conventional method doesn't work in this case.

BEAM LOADING COMPENSATION WITH A STANDING WAVE LINAC

The acceleration voltage by a standing wave RF accelerator with the beam loading is

$$V(t) = \frac{2\sqrt{\beta PrL}}{1+\beta}\left(1-e^{-\frac{t}{\tau}}\right) - \frac{IrL}{1+\beta}\left(1-e^{-\frac{t-t_b}{\tau}}\right)e^{\imath\theta} \quad (1)$$

where β is coupling beta, P is input RF power, r is shunt impedance, L is structure length, $\tau = 2Q/\omega/(1+\beta)$, I is beam loading current, t_b is timing to start the beam acceleration, and θ is relative phase of the beam center to the RF. Here, we omit the RF oscillation term, $e^{\imath\omega t}$. If $\theta = 0$ and t_b is adjusted properly as $t_b = -\ln\left(\frac{I}{2}\sqrt{\frac{rL}{\beta P}}\right)$, $V(t)$ can be a constant.

If θ is a finite value, there is no solution in this framework. To compensate the voltage variation by the beam term, RF term should contain imaginary part, i.e. phase modulation (PM) is introduced. Figure 2 shows the phase diagram of the beam loading compensation with PM. V_{RF} is the amplitude of the asymptotic value of the cavity field by the input RF, ϕ is PM angle on the input RF, V_B is the asymptotic value of the beam loading voltage, θ is the beam phase, V_C is the cavity voltage when the beam acceleration is started. If the sum of $V_{RF}e^{\imath\phi}$ and $V_B e^{\imath\theta}$ is equal to V_C, the cavity field is kept as a constant at V_C.

$$V_{RF}e^{\imath\phi} + V_B e^{\imath\theta} = V_C \quad (2)$$

From this condition, ϕ is determined as

$$\phi = \sin^{-1}\left(-\frac{V_B}{V_{RF}}\sin\theta\right) \quad (3)$$

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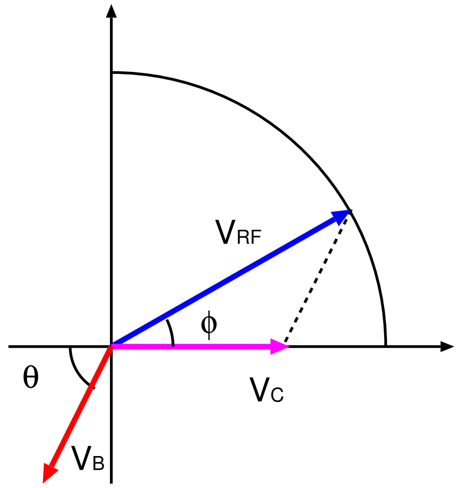

Figure 2: Phase diagram of V_{RF} (blue arrow), V_B (red arrow), and V_C. PM angle ϕ should determined as the $V_{RF}e^{\imath\phi} + V_B e^{\imath\theta} = V_C$

and V_C is

$$V_C = \sqrt{V_{RF}^2 + V_B^2 \sin^2\theta} + V_B \cos\theta \qquad (4)$$

t_b is obtained as

$$t_B = -\tau \ln\left(1 - \frac{V_C}{V_{RF}}\right) \qquad (5)$$

If $\theta > \pi/2$, the solution is different, because V_B gives acceleration. In this case, V_C is

$$V_C = V_{RF}e^{\imath\phi} + V_B e^{\imath\theta} \qquad (6)$$

and is larger than V_{RF}, but it is impossible. Instead, we change the RF input power as V_{RF1} after the acceleration is started. In this case

$$V_C = V_{RF1}e^{\imath\phi} + V_B e^{\imath\theta} \leq V_{RF} \qquad (7)$$

if we take the equal as the maximum acceleration,

$$V_C = V_{RF}, \qquad (8)$$

and

$$V_{RF1}^2 = V_{RF}^2 + V_B^2 - 2V_B V_{RF}\cos\theta. \qquad (9)$$

The PM angle ϕ is

$$\phi = \sin^{-1}\left(-\frac{V_B}{V_{RF1}}\sin\theta\right). \qquad (10)$$

BEAM LOADING COMPENSATION AT THE PULSE GAP

ILC pulse has a gap in a pulse and the duration is 80 ns as shown in Fig. 1. In the gap, the balance between the RF term and the beam term isn't maintained because the beam term amplitude becomes zero. We want keep V_C without V_B in the gap. The solution is very simple, the input RF power should be modulated as giving V_C as the asymptotic value. The input power P_1 should be

$$P_1 = \frac{(1+\beta)^2(\sqrt{V_{RF}^2 - V_B^2\cos^2\theta} + V_B\sin^2\theta)^2}{4\beta rL} \qquad (11)$$

At the gap end, amplitude and phase of the input RF should be back to values according to Eq. (2) and (3), respectively. The beam voltage and the counter part by the input RF are growing again, but they are cancelled to each other. This cancellation is maintained if the input RF is switched in a same manner.

INPUT RF MODULATION

The cavity voltage variation including the pulse gap is perfectly compensated by the input RF phase and amplitude modulation as demonstrated in the previous section. Here, we consider how the modulation is implemented.

A direct method to implement AM and PM on the input RF is AM and PM on the input RF signal to klystron. This method is not ideal because the response (amplification) is not linear and changing the input RF signal amplitude causes a beat-wave.

Instead of the direct modulation, we consider a combination of two input RF signals with a constant RF amplitude. The phase of each input RF signals are modulated. If the phase modulation for the two klystrons are same sign, the combined RF is

$$V_{RF}e^{\imath\phi} + V_{RF}e^{\imath\phi} = 2V_{RF}e^{\imath\phi}. \qquad (12)$$

This is a phase modulation with ϕ. If the sign are opposite,

$$V_{RF}e^{\imath\phi} + V_{RF}e^{-\imath\phi} = 2V_{RF}\cos\phi. \qquad (13)$$

This is an amplitude modulation with $\cos\phi$. If we want the phase and amplitude modulation simultaneously, the modulation should be

$$V_{RF}e^{\imath(\phi_1+\phi_2)} + V_{RF}e^{\imath(\phi_1-\phi_2)} = 2V_{RF}e^{\imath\phi_1}\cos\phi_2. \qquad (14)$$

resulting phase modulation with ϕ_1 and amplitude modulation with $\cos\phi_2$.

If the phase modulation to RF is instantaneous, the above conclusion is realized. In reality, however, the klystron is driven by a cavity, which has a finite time constant; even if the phase of the RF input is modulated, the modulation of the klystron output appears with a delay. To evaluate the effect of the delay of PM, we perform the numerical calculation. RF voltage (asymptotic value) $\tilde{V_{RF}}$ in the cavity by PM with no delay is expressed as

$$\tilde{V_{RF}} = V_{RF}\{u(t) - u(t-t_b)\} + V_{RF}u(t-t_b)e^{\imath\phi}, \qquad (15)$$

where $u(t)$ is the step function, t_b is time to start the beam acceleration.

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If there is a delay with τ as the time constant, it becomes as

$$\begin{aligned}\tilde{V_{RF}} &= V_{RF}\left\{u(t) - u(t-t_b)\right\} \\ &+V_{RF}e^{-\frac{t-t_b}{\tau}}u(t-t_b) \\ &+V_{RF}u(t-t_b)e^{\iota\phi}\left(1-e^{-\frac{t-t_b}{\tau}}\right). \qquad (16)\end{aligned}$$

It shows the RF input is gradually modulated.

We calculate the cavity response with this modulation. As the klystron Q value, we assume 2000. It can be compared with Q value of APS cavity, 25000. Klystron response is 12 times faster than that of APS cavity. The time constant τ is 0.24s in this case. This Q value of klystron is quite ordinal and further optimization for a faster response is possible, but we assume this value anyway. The cavity voltage is calculated using a coupled pendulum model developed by T. Shintake [6].

Figures 3 and 4 show the cavity voltage evolution with zero delay of the klystron output. Figures 3 and 4 show the real part and the imaginary part, respectively. We start the beam acceleration at the filling time (kink in Fig. 3), the real part is kept as a constant. The input RF power is 22.5 MW and the beam current is 1 A. The beam angle θ is $\pi/6$.

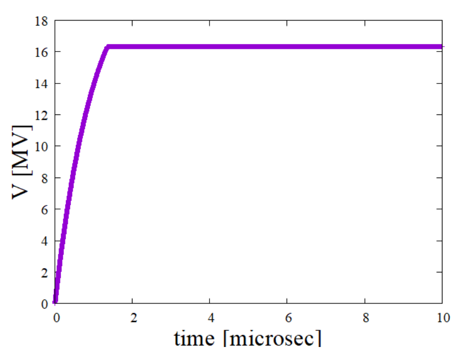

Figure 3: Real part of the cavity voltage evolution with 22.5 MW RF power with 1 A beam loading current starting at the filling time. PM with no delay is applied.

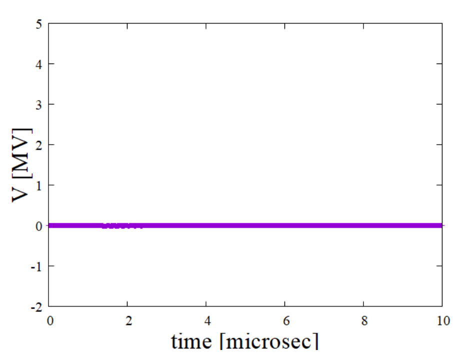

Figure 4: Imaginary part of the cavity voltage evolution with 22.5 MW RF power with 1 A beam loading current starting at the filling time. PM with no delay is applied.

Figures 5 and 6 show the cavity voltage evolution with delay of the klystron output according to Eq. (16). Figures 5 and 6 show the real part and the imaginary part, respectively. The conditions are same as those for Figs. 3 and 4 case. The real part is almost identical, but the imaginary part (Fig. 6) has a small dip. The amplitude is -0.15 MV. This value should be compared to the real part amplitude, 16 MV. The dip of the imaginary component cause the phase fluctuation of 9.4 mrad, whose impact on the acceleration is limited.

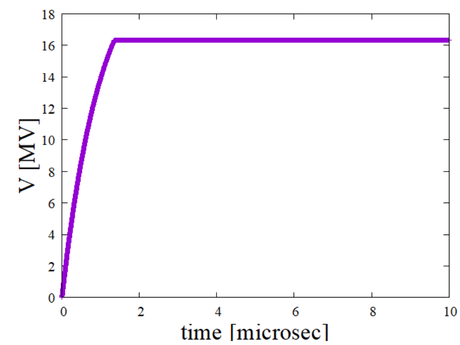

Figure 5: Real part of the cavity voltage evolution with 22.5 MW RF power with 1 A beam loading current starting at the filling time. PM with delay is applied.

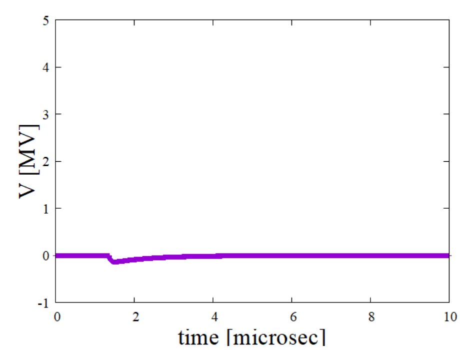

Figure 6: Imaginary part of the cavity voltage evolution with 22.5 MW RF power with 1 A beam loading current starting at the filling time. PM with delay is applied.

CONCLUSION

We consider the beam loading compensation of the positron capture linac for ILC E-Driven positron source. Due to the heavy beam loading, its compensation is essential to obtain an uniform intensity positron pulse. We consider PM and AM on the input RF to compensate the beam loading with a finite beam angle comparing to RF input. It works well including the gap in a pulse. AM and PM can be implemented by combining two RF with PM on the input signal. It was confirmed that the effect of the finite time response of the klystron output to the input low level RF PM was very limited.

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