BEAM LOADING COMPENSATION OF APS CAVITY WITH OFF-CREST ACCELERATION IN ILC E-DRIVEN POSITRON SOURCE

M. Kuriki*, S. Konno, H. Nagoshi, T. Takahashi, Hiroshima University, Hiroshima, Japan
T. Omori, J. Urakawa, K. Yokoya, KEK, Ibaraki, Japan

Abstract

In E-Driven positron source of ILC, the generated positron is captured by RF accelerator by APS cavity. The positron is initially placed at the deceleration phase and gradually slipped down to acceleration phase. Because the beam-loading is expected to be more than 1 A with a multi-bunch format, the compensation is essential to obtaine uniform intensity over the pulse. A conventional method for the compensation is controlling the timing, but it doesn't work in off-crest case. In this manuscript, we discuss the compensation with the phase and amplitude modulation on the input RF.

INTRODUCTION

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 μA. This is a technical challenge, because the amount of positron per second is more than 40 times larger than that in SLC [2].

The configuration is schematically shown in Fig. 1. The generated positron is captured and boosted up to 5 GeV by the capture linac and positron booster. In the E-Driven ILC positron source, 3.0 GeV electron beam is the driver for positron generation with 16 mm W-Re alloy target. The 16 mm W-Re target is rotating with 5.0 m/s tangential speed to prevent a potential target damage. FC (Flux Concentrator) generates a strong magnetic field along z direction to compensate the transverse momentum of the positron. 36 1.3 m L-band standing wave accelerators with 0.5 Tesla solenoid field are placed for positron capture. This section is called as Positron Capture Linac. At the downstream of Positron Capture Linac, a chicane is placed to removes electrons. The positron booster is composed from 2.0 m L-and and 2.0 m S-band traveling wave accelerators. ECS is composed from 2.0 m L-band traveling wave accelerators with chicanes.

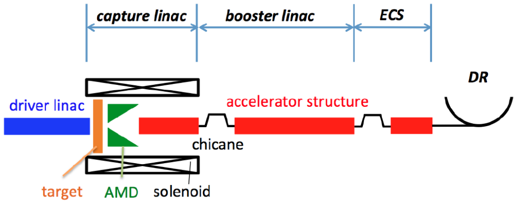

Figure 1: Configuration of E-Driven ILC positron source is schematically shown.

In E-Driven ILC positron source, positrons are generated in a multi-bunch format as shown in Fig. 2. 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. The positron is stored in DR for 135 ms before the acceleration at the main linac for collision. Because the positron is generated over 64 ms, the instantious heat load on the target is much suppressed [3]. The pulse format shown in Fig. 2 is identical to a part of the DR fill pattern [4].

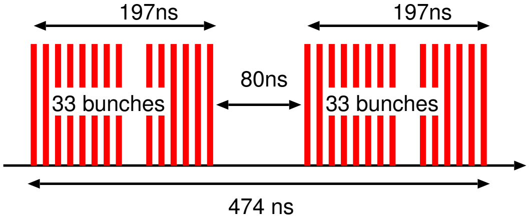

Figure 2: The beam structure in the positron source. Each mini-train contains 33 bunches. Each pulses contain 2 or 1 mini-trains.

A first simulation for the injector part is made by T. Omori [3]. A simulation with the tracking down to DR was made by Y. Seimiya [5] , but no beam loading effect was accounted. A new simulation with the beam-loading effect was done by Kuriki and Nagoshi [6]. For those simulation, the peak energy deposition density on the target is kept less than 35 J/g [7], which is considered to be a practical limit of the target destruction.

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. [8] for better capture efficiency. In this method, the positrons are placed on a deceleration phase and move to the acceleration phase by phase-slipping. As the result, the positron phase space distribution is large in longitudinal momentum, but small in longitudinal space (z). By boosting the positrons further, the longitudinal momentum spread is suppressed resulting a good capture efficiency.

This deceleration capture cause a difficulty on the beam loading compensation, because the beam phase (RF phase where the beams is) is moving from $-\pi$ to 0. It causes a problem on the beam loading compensation, because the conventional theory assumes the beam phase is constant.

POSITRON CAPTURE LINAC AND BEAM LOADING COMPENSATION

The positron capture linac is composed from L-band APS (Alternate Periodic Structure) cavity. APS cavity is a standing wave structure with $\pi/2$ mode. In $\pi/2$ mode cavity,

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* mkuriki@hiroshima-u.ac.jp

electric field in induced only in every other cavity. APS cavity is composed from 11 long cells (accelerator cell) and 10 short cells (coupling cavity) to improved the shunt impedance. The designed APS cavity has a wide aperture, 60 mm in $2a$ resulting a better positron capture. The accelerator is surrounded by solenoid magnet to provide 0.5 Tesla magnetic field along the accelerator for focusing. The shunt impedance is 52.7 M/m.

One RF unit is composed from two L-band klystrons and four accelerators. The power of the klystron is 50 MW. Accounting 10% WG loss, the effective input power for one accelerator is 22.5 MW. The capture linac composed from 11 units (11 klystrons and 44 accelerators). One unit length is 6.00 m giving the total length of the capture linac is 66 m. AM (Ampltude modulation) and PM (Phase modulation) are done by modulating the phase of input RF from the two klystron independently.

The accelerating field of the structure is determined by the input RF power (22.5 MW per structure) and the beam loading current. The beam loading current is a vector sum of each particle accounting the charge and RF phase.

The acceleration voltage by an RF accelerator with the beam loading is

$$\begin{aligned} V(t) &= \frac{2\sqrt{\beta PrL}}{1+\beta}\left(1-e^{-\frac{t}{T_0}}\right)\cos(\omega t) \\ &\quad -\frac{IrL}{1+\beta}\left(1-e^{-\frac{t-t_b}{T_0}}\right)\cos(\omega t+\theta), \end{aligned} \tag{1}$$

where β is coupling beta, P is input RF power, r is shunt impedance, L is structure length, $T = 2Q/\omega/(1+\beta)$, 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. If $\theta \neq 0 or \pi$, $V(t)$ can't be constant. To solve this problem, we introduce PM on the input RF.

The input RF voltage should be

$$V_{RF}(t) = V_{10}\cos\omega t + V_{b0}\left(1-e^{-t-t_bT_0}\right)\cos(\omega t+\theta), \tag{2}$$

to compensate the voltage variation by the beam loading, where $V_{b0} = \frac{IrL}{1+\beta}$. It can be transformed as

$$V_{RF}(t) = \sqrt{A^2+B^2}\cos(\omega t+\zeta), \tag{3}$$

where $A = V_{10} + V_2\cos\theta$, $B = V_2\sin\theta$, $V_2 = V_{b0}\left(1-e^{-(t-t_b)/T_0}\right)$, and $\zeta = \tan^{-1}B/A$. The asymtoptic voltage shuld be equal to that by the input RF, then

$$\sqrt{A^2+B^2} = V_0 = \frac{2\sqrt{\beta PrL}}{1+\beta}. \tag{4}$$

From this equatin, V_{10} (RF voltage when the beam starts) can be obtained as

$$V_{10} = -V_{b0}\cos\theta + \sqrt{V_0^2 + V_{b0}^2(\cos^2\theta - 1)}, \tag{5}$$

and t_b (time to start the beam) is

$$t_b = -T_0\ln\left(1-\frac{V_{10}}{V_0}\right). \tag{6}$$

Figure 3 shows the voltage variation with 2.0 A beam loading with different phase, from 0.0 to 0.8 rad. According to Eq. (5) and (6), the voltage and the timing depend on the phase. The voltage is kept as a constant over the beam pulse. Figure 4 shows phase modulation on the input RF.

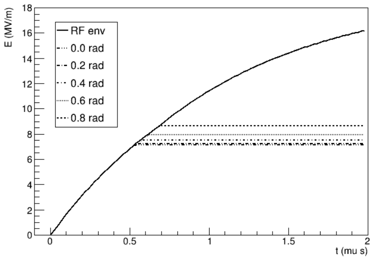

Figure 3: Accelerating voltage evolution with 2.0 A beam loading. The conditions are adjusted to compensate the variation according to the beam loading phase as shown with the legend.

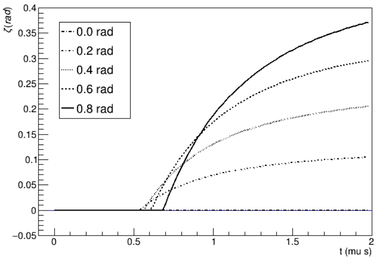

Figure 4: Phase modulation ζ as a funtion of time for different phase.

LINAC COMMISSIONING

As explained in Introduction, the positrion is initially placed at the deceleration phase and the beam phase is dynamically changed over the linac. Not only positrons, but also electrons contribute to the beam loading. The beam loading current is evaluated as

$$I_B = \sum \frac{q_i}{\Delta t}\cos\left[k(\bar{z}-z_i)\right], \tag{7}$$

where q_i is charge of the particle, Δt is bunch separation, k is the wave number of RF, $\bar{z}$ is the position of bunch center, z_i is particle z position. Electron gives negative sign current, but the contribution is addetive because electrons and positrons are bunched at oppsite phase to each other. Figure 5 shows the beam loading current, positron (red line), electron (green line), and the total (black). For each component, the current is obtained at the average position. Therefore, the total current is not a simple sum of the position and electron currents.

Accoridig to Eq. (5) and (6), t_b (timign to start the beam acceleration) and $\zeta(t)$ (PM on the input RF) depends on the beam loading current. The beam loading current is varied over the linac as shown in Fig. 5 and it is hard to know the exact the beam loading current at each accelerator tube. Here

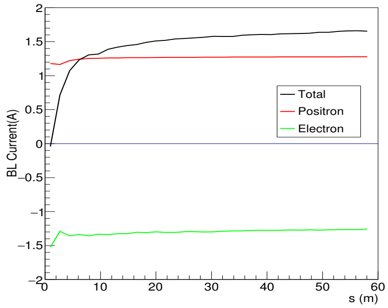

Figure 5: The beam loading current over the capture linac. s is distance from the target. The red, green, and black lines are the current by positron, electron, and the total.

we consider a commisioning of the lianc to compensate the beam loading.

Instead of a fine tuning on each accelerating tube indenpendenlty, we consider a global tuning of the linac. We assume a common t_b and commong $\zeta(t)$ over the linac. The simulation was done with GEANT4 [9] to produce the initial particle distribution from the target [10]. Trakcing simulation was done with GPT [11]. The effect of the beam loading was simulated as the energy modulation on the particle distribution obtained by the tracking simulation.

After the catpture linac, positrons are sent to positron booster through a chicane to remove electrons. The energy becomes 5 GeV after the booster. The particle distribution is transformed by ECS (Energy Compressor Section) composed from chicanes and RF accelerators [10]. These section was simulated by a simple transformation with transfer matrixes. Finally, the positron after ECS is examined with DR acceptance (dynamic aperture) as [1]

$$\gamma A_x + \gamma A_y < 0.09 \tag{8}$$

$$\frac{z^2}{0.035^2} + \frac{\delta^2}{0.0075^2} < 1, \tag{9}$$

where γ is Lorentz gamma, A_x and A_y are action in x and y phase space, z and δ are cordinate in longitudinal phase space, $\delta \equiv (\gamma - \bar{\gamma})/\bar{\gamma}$ with $\bar{\gamma}$ is average of γ. Figure 6 shows the longitudinal phase space distribution after ECS. The DR acceptance in the space is drawn as a circle with dotted line. Positrons in the acceptance is defined as the captured positron. The ratio of the number of the captured positron to the number of the incident electron on the target is defined as the positron yied.

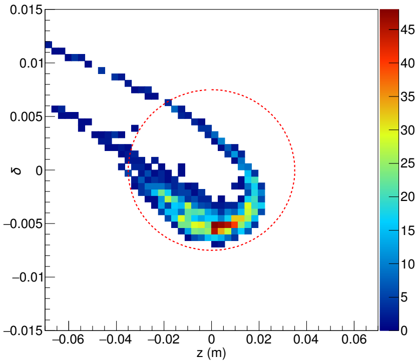

Figure 6: Longitudinal phase space distribution of the positron at ECS exit is shown. DR acceptance is shown with a circle.

Figure 7 shows the positron yield as a function of bunch index. Bunch index 1 and 66 correpond to the first and last bunches in a pulse. In this simulation, we ignore the 80 ns train gap as shown in Fig. 2. We assumed that the beam loading current can be measured for each accelerator, but we assumed a global beam phase, θ. In the figure, many data sets with different θ are drawn. Among them, a data set with $\theta = -0.3$ rad gives a uniform yield over the pulse. The positron yield is not sensitive to θ, because the yield with $\theta = -0.4$ and $\theta = -0.2$ are almost identical. From this study, a global PM on the input RF is sufficient to compensate the beam loading effect in the ILC E-Driven positron source.

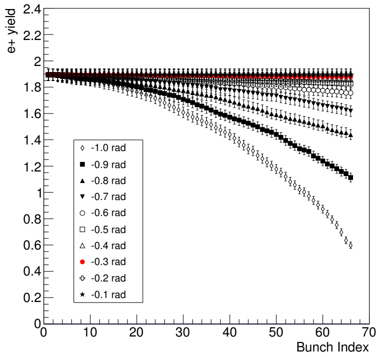

Figure 7: Positron yield as a function of bunch index, 1 is the first and 66 is the last. The global phase on the compensation is varied.

CONCLUSION

We consider the beam loading compensation for the positron capture linac for ILC E-Driven positron source. Due to the heavy beam loading, its compensation is essential to obaine a uniform intensity positron pulse. We consider PM on the input RF to compensate the off crest beam loading. It works well, but we have to know the beam loading current and the relative phase of the beam to RF for the compensation and it is not realistic. As a commisioning simulation, we apply a global compensation, i.e. the whole linac is controlled with a single phase value. As a result of the simulation, the global correction worked well and the obtained positron intensity was uniform over a pulse. According to this result, we don't have to know the exact beam phase for each accelerator tube and PM with a global parameter is sufficient.

ACKNOWLEDGEMENTS

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