BEAM LOADING COMPENSATION IN THE CAPTURE LINAC OF ILC E-DRIVEN POSITRON SOURCE

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Abstract

Linear colliders requires huge amount of positrons comparing to ring colliders, because the beam is dumped after the collision. Electron Driven ILC Positron source has been designed as a technical backup of the undulator position source including the beam loading effect, etc. To avoid any damage on target by thermionic and acoustic effects, the positrons are generated in multi-train and multi-bunch format with normal conducting accelerator resulting a high beam current more than 1 A in the initial part of positron linac, the positron capture linac composed from L-band standing wave linac. The beam loading compensation method for the positron capture linac is considered.

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].

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 configuration is schematically shown in Fig. 1. 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 (Energy Compressor System) is composed from 2.0 m L-band traveling wave accelerators with chicanes. ECS optimizes the phase-space distribution of the positron to DR acceptance to improve the positron capture efficiency. In E-Driven ILC positron source, the positrons for one pulse (1312 bunches) in main linac are generated in 64 ms. To spread the heat deposition on target on a wider area, the positron is generated in 20 pulses which contains 66 bunches

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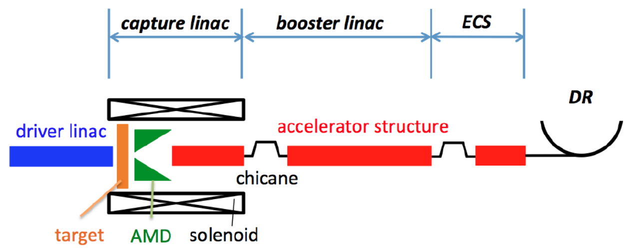

Figure 1: Configuration of E-Driven ILC positron source is schematically shown.

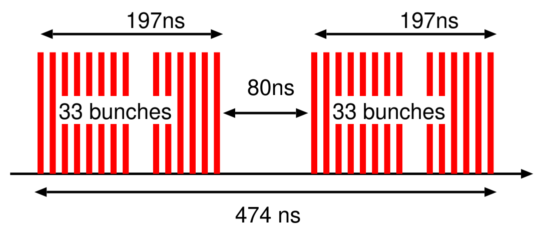

Figure 2: The beam structure in the positron source for the 39 mini-train case. Each mini-train contains 33 bunches. Each pulses contain 2 or 1 mini-trains.

as shown in Fig. 2 and the pulse is repeated by 300 Hz in 64 ms with normal conducting accelerator. The heat load on the target is much relaxed with this pulse structure, because only the heat of 66 bunches is accumulated, instead of 1312 bunches [3]. The pulse format shown in Fig. 2 is identical to a part of the DR fill pattern. Depending on the DR fill pattern [4], the beam structure is should be matched.

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] giving the peak energy deposition density less than the practical limit, 35 J/g [7].

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 an important issue. Historically, the acceleration capture has been pursued. The generated positrons are placed on acceleration phase of RF cavity to suppress the momentum spread adiabatically, but this method has some limitation because only positrons in a good phase space are captured and others are lost. 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. At the exit of the capture linac, the positron phase space distribution is large in longitudinal, it is suppress by the positron booster resulting a good capture efficiency. This deceleration capture cause a difficulty on the beam loading compensation. We discuss this issue in this article.

POSITRON CAPTURE LINAC

We explain the positron capture linac in this section. For other systems, please refer Ref. [9]. For the positron capture linac, we employ the standing wave L-band structure developed for the undulator positron source [10]. The advantage of this structure is 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.

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. In the capture linac, the beam loading current is dynamically varied by bunching and particle loss. It is up to 1.6 A [9]. In the simulation, the accelerator voltage is determined according to the beam loading current for each cavity [9]. The acceleration voltage per structure is between 12 - 20 MV.

According to the simulation, the configuration is determined as 9 units (18 klystrons and 36 accelerators). One unit length is 6.00 m giving the total length of the capture linac is 54 m.

In the simulation, both positrons and electrons were accounted. The accelerating field of the structure is determined by the input 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 beam loading current is small at the down stream of the target, because the electron and position cancel their contributions to each other. They are bunched at the opposite phase and the beam loading current is rapidly increased. Because the particle motion depends on the accelerating field, the beam loading current is determined by iterations of the simulation. The beam loading current extracted from the previous simulation was used as the input to the next iteration. Figure 3 shows the beam loading calculated from the simulation results for each iteration. The horizontal axis shows the order of the cavity in the capture linac. The 1st cavity is in the most upstream. The beam loading currents after the third iteration are almost same. Therefore, the beam loading current calculated from the simulation result is consistent to the beam loading current assumed in the simulation.

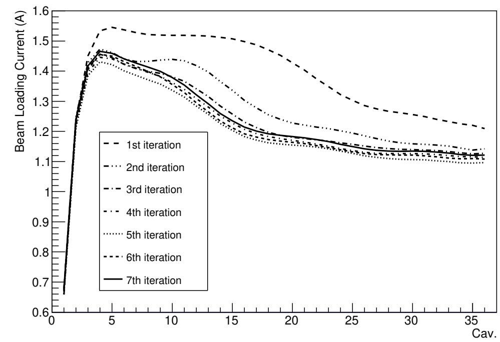

Figure 3: The beam loading current for cavities of the capture linac. Cavity 1 is the most upstream. The beam loading currents obtained from each iteration is plotted.

Beam Loading Compensation

The voltage evolution of a standing wave structure $V(t)$ is

$$V(t) = \frac{2\sqrt{\beta P_0 r L}}{1+\beta}\left(1 - e^{-\frac{t}{T_0}}\right) - \frac{rIL}{1+\beta}\left(1 - e^{-\frac{t-t_b}{T_0}}\right), \quad (1)$$

where β is a coupling, $P_0[W]$ is the peak input power, $r[\Omega/m]$ is shunt impedance, $L[m]$ is the structure length, $I[A]$ is beam current, t_b is timing when the beam pulse starts, and T_0 is a time constant given as

$$T_0 = \frac{2Q}{\omega(1+\beta)}, \quad (2)$$

determined with Q and ω. The first term of Eq. (1) is RF term and the second term is the voltage induced by the beam (Beam loading). These two terms have the same time constant, the accelerating voltage can be constant during the acceleration with a proper condition. If we differentiate Eq. (1) with t,

$$\frac{\partial V}{\partial t} = \frac{2\sqrt{\beta P_0 r L}}{1+\beta}\frac{1}{T_0}e^{-\frac{t}{T_0}} - \frac{rIL}{1+\beta}\frac{1}{T_0}e^{-\frac{t-t_b}{T_0}}, \quad (3)$$

is obtained. It becomes zero if

$$t_b = -T_0 \ln\left(\frac{I}{2}\sqrt{\frac{rL}{\beta P_0}}\right). \quad (4)$$

If this condition is satisfied, the acceleration voltage is flat during the acceleration. The voltage V is

$$V = \frac{2\sqrt{\beta P_0 r L}}{1+\beta}\left(1 - \frac{I}{2}\sqrt{\frac{rL}{\beta P_0}}\right). \quad (5)$$

This is a conventional way to compensate the beam loading effect in a standing wave. This is applicable as long as the beam is accelerated on the crest, i.e. zero phase. If the beam is in off crest, Eq. (1) becomes

$$\begin{aligned} V(t) &= \frac{2\sqrt{\beta P_0 r L}}{1+\beta}\left(1 - e^{-\frac{t}{T_0}}\right)\cos(\omega_0 t + \phi_0) \\ & \frac{rIL}{1+\beta}\left(1 - e^{-\frac{t-t_b}{T_0}}\right)\cos(\omega_0 t + \theta + \phi_0), \quad (6) \end{aligned}$$

where ω_0 is angular frequency of 1.3 GHz, ϕ_0 is initial phase, and θ is the beam phase with respect to the RF phase. In this case, a constant RF amplitude can't be made by adjusting the amplitude. RF amplitude and phase (sum of input RF and beam) are varied over the pulse. The capture efficiency is also varied resulting a large variation of positron intensity.

In the deceleration capture, the positron is placed on a deceleration phase and captured in an acceleration phase. The positron phase is then moving from the deceleration phase to the acceleration phase by phase slipping. Figure 4 shows the phase as $\cos\psi$ along the capture linac position from the target. $\cos\psi$ is defined as

$$\cos\phi = \frac{1}{N}\sum_i \frac{q_i}{e}\cos(\phi_i - \phi_0), \tag{7}$$

where N is number of particle, q_i is charge of the particle, e is elementary charge, $\phi_i - \phi_0$ is the phase of the particle with respect to the RF phase. The vertical axis shows the average position of the particle. The minus sign at the start (z<2 m) shows the particle is decelerated, but it is rapidly went to the positive phase after several meter. Because this

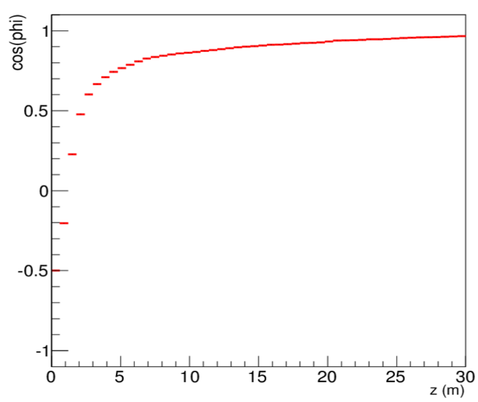

Figure 4: $\cos\psi$ is shown along the capture linac.

rapid change on the phase and the off-phase acceleration over the capture linac, the phase effect on the beam loading compensation should be accounted.

To revive the beam loading compensation, we introduce a detuning angle, ψ [11]. Detuning angle is defined as

$$\psi \equiv \tan^{-1}\left(Q\frac{2\Delta\omega}{\omega_0}\right), \tag{8}$$

where $\Delta\omega$ is the detuning angular frequency of the cavity.

In this case, the cavity induced voltage V_c has a phase shifted from the input RF power phase with ψ as shown in Fig. 5. If the beam is placed at the same phase to the input RF, the power by the beam loading is in opposite phase as shown in Fig. 5. The induced voltage by the beam loading V_{BL} has angle ψ from the beam loading power as shown in the figure with a dotted-dash line. As a result, the induced voltage by RF V_{RF} and beam loading V_{BL} are in opposite phase (π) and the beam loading compensation by Eq. (6) is revived [6].

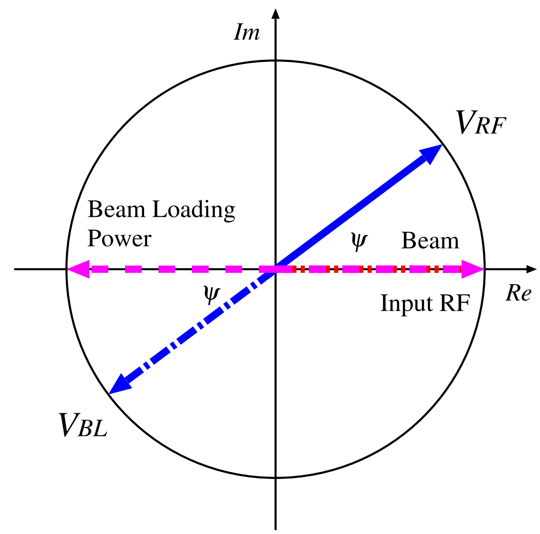

Figure 5: Phase diagram of cavity voltage with a detuning angle. Input RF is defined as zero phase shown with a dashed line arrow. The induced voltage by RF (V_{RF}) has an angle ψ from the input RF shown with a solid line. The beam loading input is opposite phase to the input RF. The induced voltage by Beam loading V_{BL} has an angle ψ from the beam loading input.

The effective acceleration phase to the beam is determined by the detuning angle, ψ in this case. Therefore, the acceleration phase should be adjusted by the detuning. Because setting a plunger for each cavity is not realistic for the standing wave cavity, the frequency should be adjusted by temperature variation. If we assume $\psi = \pi/4$, required detuning on the frequency is

$$\frac{\Delta\omega}{\omega_0} = \tan\psi\frac{1}{2Q}, \tag{9}$$

giving 1.7×10^{-5} with Q = 29700 [10]. By using thermal expansion coefficient of copper, 16.8×10^{-6} 1/K, the equivalent temperature of the detuning is 1.0 K. A typical accuracy of the temperature control of RF cavity is 0.1 K which corresponds to the phase resolution of 0.08 rad. The amplitude error by the phase fluctuation $\Delta\psi$ is

$$\cos(\psi + \Delta\psi) \sim \cos\psi - \sin\psi\sin\Delta\psi, \tag{10}$$

It is negligible for small ψ, but could be significant for large ψ. The effect should be evaluated with a simulation, but it could be a next issue.

One RF power unit is composed from two klystrons and four accelerators. The issue is the operation for the first four accelerators where there are a large variation of the phase. The detuning angle can be adjusted independently for each accelerator, if cooling water circuit is prepared for each accelerators. In this method, the beam phase and the input RF phase should be matched (same) as shown in Fig. 5. The operation (commissioning) is basically same as that for an usual standing wave linac. To adjust a small variation of the positron velocity from the velocity of light, a small phase-adjustment for each accelerator is desirable.

SUMMARY

We consider the beam loading compensation for the positron capture linac for ILC E-Driven positron source. Due to the heavy beam loading, the compensation is a key issue of the positron source. The conventional way by adjusting the amplitude does not work properly, because the beam loading phase is dynamically varied in the deceleration capture method and off-crest over the capture linac. We consider the beam loading compensation with the detuning angle. In this method, the beam is placed always on the same phase as the input RF phase. The RF induced voltage and beam induced voltage are exactly same phase (opposite phase). In this case, the beam loading compensation works well as expected. The phase of the cavity RF felt by the beam is controlled by the detuning angle. To vary the phase $\pm\pi/4$, the temperature should be consoled ± 1.0 K. The phase accuracy is 0.08 rad assuming 0.1 K temperature stability. The effect of the temperature stability should be confirmed by a simulation. The operation and commissioning is basically same as that for an usual standing wave linac, because the input RF and the positron beam should be always on phase. To control the detuning angle, independent temperature control for each accelerator is desirable, especially where the beam loading phase is rapidly changed in.

ACKNOWLEDGEMENTS

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