HIGH LUMINOSITY FLAT BEAM GENERATION WITH PHASE-SPACE ROTATION FOR LINEAR COLLIDERS

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Abstract

Electron Positron Linear Collider is the only way to realize annihilation of elementary particles with more than 350 GeV center of mass energy in the current technology. In Linear Collider, the beam spot should be flat, i.e. tiny in one axis and moderate in another axis to maximize luminosity suppressing beam-beam effect. Instead of radiation damping with a storage ring, we propose to generate the flat beam with phase-space rotation technique in the injector. We plan to carry out beam tests at STF(Superconducting Test Facility)-KEK and WFA (Wake Field Accelerator)-ANL(Argonne National Laboratory). According to our simulation, the flat beam required at IP in ILC can be made with this technique.

INTRODUCTION

Electron Positron Collider is the only way to realize annihilation of elementary particles with controlled conditions with the current technology. Because there has been no any significant evidence of Super-symmetry in LHC experiments, the significance of detail studies of Higgs boson and searching inconsistency in the standard model with electron positron collider is maximized. ILC (International Linear Collider) [1] is an e+e- linear collider based on superconducting accelerator with CME from 250 to 1000 GeV. It would be constructed in Iwate, Japan, as the main project of High energy physics.

Luminosity L is the index showing the performance of colliders. It can be expressed as

$$L = \frac{f n_b N^2}{4\pi\sigma_x\sigma_y}, \tag{1}$$

where f is repetition of pulse, n_b is number of bunches in a pulse, N is number of particles in a bunch, $\sigma_{x,y}$ is transverse beam size. The numerator can't be too large, because it increases the wall plug power as

$$P_{wall} = \eta e E f n_b N, \tag{2}$$

where η is power efficiency and eE is beam energy. One way to enhance the luminosity is minimize $\sigma_{x,y}$, but it causes a large energy spread by Beamstrahlung as

$$\Delta E \propto \frac{1}{\sigma_z}\left(\frac{2}{\sigma_x+\sigma_y}\right)^2. \tag{3}$$

A practical way to enhance the luminosity and suppress Beamstrahlung simultaneously is squeezing the beam in one of the transverse direction, e.g. $\sigma_x \gg \sigma_y$. For ILC, The beam size at IP is 640 nm in horizontal direction and 5.7 nm in vertical direction. Emittances are 10 and 0.04 mm mrad in horizontal and vertical directions, respectively. This asymmetric emittance beam is made by radiation damping in a storage ring in the current design. We propose to generate the flat beam for ILC only with the injector by employing the emittance exchange technique.

As the phase-space rotation technique, there are two methods. One is RFBT (Round to Flat Beam Transformation) [2] generating the flat beam from an angular-momentum dominated beam produced by beam emission in a solenoid field. Another is TLEX (Transverse to Longitudinal Emittance eXchange) exchanging the phase-spaces between longitudinal and transverse directions by dipole mode cavity in a dispersive beam line [3].

EMITTANCE EXCHANGE TECHNIQUES

In this section, RFBT and TLEX are briefly explained.

RFBT

RFBT generates the asymmetric emittance beam between two transverse directions from an angular momentum dominated beam. A proof of principle experiment of RFBT was performed demonstrating 100 emittance ratio [4]. The angular momentum dominated beam is made by the beam emission in a solenoid field. Vector potential of the solenoid field $\boldsymbol{A}$ makes a canonical angular momentum $\boldsymbol{P_c}$ as

$$\boldsymbol{P_c} = \boldsymbol{P} - e\boldsymbol{A}, \tag{4}$$

where $\boldsymbol{P}$ is kinematic momentum, because

$$\boldsymbol{A} = \frac{eB_0}{2}\begin{pmatrix} y \\ -x \end{pmatrix}, \tag{5}$$

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where e is elementary charge and B_0 is the solenoid magnetic field. The correlation between x, y and P_y, P_x makes non-diagonal components of sigma matrix $\boldsymbol{\Sigma_0}$ as

$$\boldsymbol{\Sigma_0} = \begin{pmatrix} \varepsilon \boldsymbol{T_0} & L\boldsymbol{J} \\ -L\boldsymbol{J} & \varepsilon \boldsymbol{T_0} \end{pmatrix}, \quad (6)$$

where ε is the intrinsic emittance, $\boldsymbol{T_0}$ is sigma matrix components for the intrinsic emittance by Twiss parameters as

$$\boldsymbol{T_0} = \begin{pmatrix} \beta & -\alpha \\ -\alpha & \frac{1+\alpha^2}{\beta} \end{pmatrix}, \quad (7)$$

L is dimension less angular momentum

$$L = \frac{eB_0\sigma}{p_z}, \quad (8)$$

where σ is the beam size, p_z is longitudinal momentum, and

$$\boldsymbol{J} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad (9)$$

RFBT can be made with a linear beam transformation with three skew quadrupoles. The channel of the three skew quadrupoles can be expressed as

$$\boldsymbol{M} = \boldsymbol{R}^{-1}\boldsymbol{N_Q}\boldsymbol{R} = \frac{1}{2}\begin{pmatrix} \boldsymbol{A_+} & \boldsymbol{A_-} \\ \boldsymbol{A_-} & \boldsymbol{A_+} \end{pmatrix}, \quad (10)$$

where $\boldsymbol{R}$ is $\pi/4$ rotation matrix, $\boldsymbol{N_Q}$ is transfer matrix of three quadrupoles in normal coordinate as

$$\boldsymbol{N_Q} = \begin{pmatrix} \boldsymbol{A} & 0 \\ 0 & \boldsymbol{B} \end{pmatrix}, \quad (11)$$

and $\boldsymbol{A_\pm}$ is $\boldsymbol{A} \pm \boldsymbol{B}$. The sigma matrix transformed with $\boldsymbol{M}$ can be

$$\boldsymbol{\Sigma} = \boldsymbol{M}\boldsymbol{\Sigma_0}\tilde{\boldsymbol{M}} = \begin{pmatrix} \varepsilon_- \boldsymbol{T_-} & 0 \\ 0 & \varepsilon_+ \boldsymbol{T_+} \end{pmatrix}, \quad (12)$$

if

$$\boldsymbol{A_-} = \boldsymbol{A_+}\boldsymbol{S}, \quad (13)$$

where

$$\boldsymbol{S} = \pm \boldsymbol{J}\boldsymbol{T_0}^{-1}. \quad (14)$$

Analytic solution for $\boldsymbol{M}$ is expressed as [5]

$$q_1 = \pm\sqrt{\frac{-D_1 s_{11} + s_{12} + D_1 D_t s_{21} + D_t s_{22}}{D_1 D_t s_{12}}} \quad (15)$$

$$q_2 = -\frac{s_{12} + D_t s_{22}}{D_1 D_2 (1 + q_1 s_{12}} \quad (16)$$

$$q_3 = \frac{-q_1 - q_2 - D_1 q_1 q_2 s_{11} - s_{21}}{1 + (D_t q_1 + D_2 q_2) s_{11} + D_1 D_2 q_2 (q_1 + s_{21})}. \quad (17)$$

where D_1 and D_2 are drift space between the first and second, and the second and third skew quadrupoles, respectively. D_t is sum of D_1 and D_2. After the skew channel, the normalized emittance in transverse coordinate is

$$\varepsilon_{n\pm} = \sqrt{\varepsilon_{n0}^2 + (\gamma\beta L)^2} \pm \gamma\beta L, \quad (18)$$

giving the emittance ratio as

$$\frac{\varepsilon_{n+}}{\varepsilon_{n-}} \sim \left(\frac{\varepsilon_{n0}}{2\gamma\beta L}\right)^2. \quad (19)$$

TLEX

TLEX is implemented with a couple of doglegs and a dipole mode cavity. TLEX was experimentally demonstrated by showing transformation of the transverse intensity modulation to the longitudinal modulation [6]. The transfer matrix of a dogleg section $\boldsymbol{M_d}$ and dipole mode cavity $\boldsymbol{M_c}$ are expressed as

$$\boldsymbol{M_d} = \begin{pmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (20)$$

and

$$\boldsymbol{M_c} = \begin{pmatrix} 1 & 0 & 0 & \eta \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix}, \quad (21)$$

where $k = eV_0/(aE_0)$ with V_0 (cavity voltage at iris), a(cavity iris size), and E_0 (beam energy).

The dipole mode cavity is placed between the dogleg sections giving the transfer matrix of TLEX section $\boldsymbol{M_T}$ as

$$\boldsymbol{M_T} = \boldsymbol{M}_d \boldsymbol{M}_c \boldsymbol{M}_d = \begin{pmatrix} 0 & 0 & -\frac{L}{\eta} & \eta - \frac{L\xi}{\eta} \\ 0 & 0 & -frac1\eta & -\frac{\xi}{\eta} \\ -\frac{\xi}{\eta} & \eta - \frac{L\xi}{\eta} & 0 & 0 \\ -\frac{1}{\eta} & -\frac{L}{\eta} & 0 & 0 \end{pmatrix}, \quad (22)$$

where a matching condition of $1 + \eta k = 0$ is assumed. As easily recognized in this equation, the phase-space of x and z are exchanged with TLEX section.

FLAT BEAM GENERATION FOR LINEAR COLLIDERS

As explained in the introduction, the flat beam is essential to enhance the beam luminosity for linear colliders. In the ILC current design, the emittance at IP are 10 mm mrad for horizontal direction, 0.04 mm mrad for vertical direction, and 8.4×10^5 mm mrad for longitudinal direction. This beam is made up with radiation damping in 3 km DR. Figure 1 shows the schematic drawing of the injector with DR.

By employing the emittance exchange techniques (RFBT and TLEX), the ILC compatible beam can be generated only with an injector lilac as shown in Fig. 2. 3.1 km DR can be omitted. The emittance budget is summarized in Table 1. The first row is required emittance at IP for ILC. The second row is emittance at Gun when we employ only RFBT. In RFBT, the product of ε_x and ε_y is conserved. To make 10 mm mrad and 0.04 mm mrad with RFBT, the emittance from Gun should be 0.6 mm mrad. This small emittance cause several problems. One is emission density. To make this small emittance from the gun, the beam spot should be also small, cause a high density beam emission from the cathode surface. Including 50% margin of the bunch charge, 4.8 nC bunch charge should be extracted from the small spot. The bunch length can be large and a careful design for bunching

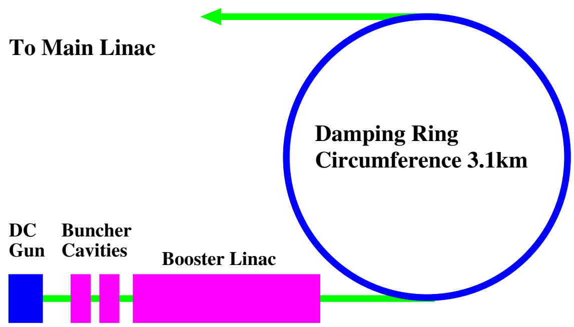

Figure 1: The conventional design of the injector for Linear colliders. The beam is stored in DR to make asymmetric beam emittance in horizontal and vertical directions by radiation damping.

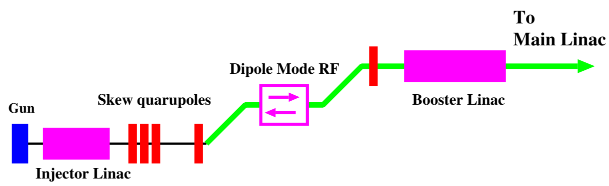

Figure 2: The injector design employing the emittance exchange techniques. The asymmetric emittance beam in horizontal and vertical directions are made by RFBT and TLEX.

section is required. Another problem is emittance growth by space charge effect. The small beam size cause a strong non-linear space charge increase the beam emittance. If the emittance growth of the space charge is significant, the ILC compatible beam can't be generated with RFBT because the product is not conserved anymore.

The third row shows the emittance at gun when we employ RFBT and TLEX. If we employ RFBT and TLEX, the product of three emittance (x, y, and z) can be conserved and therefore, ε_x and ε_y can be large to avoid the problem at the gun emission and the space charge emittance growth. The fourth row shows the expected emittance with the same parameter at IP. ε_x and ε_y are compatible to the ILC requirement at IP. ε_z is still less than the requirement.

SIMULATION

A simulation is performed by assuming a beam test at KEK-STF. KEK-STF is a test facility to demonstrate the

Table 1: Emittance budget for ILC at IP (TDR), case 1 (only RFBT, gun), case 2 (RFBT and TLEX, gun), and case 2 (RFBT and TLEX, IP). Emittance is in mm mrad.

Design	ε_x	ε_y	ε_z
ILC at IP (TDR)	10	0.04	2.5×10^5
Case 1 (RFBT, gun)	0.6	0.6	2.5×10^5
Case 2 (RFBT+TLEX, gun)	45	45	10
Case 2 (RFBT+TLEX, IP)	10	0.04	5.1×10^4

Table 2: Parameters of the simulation. $G_{1,2,3}$ are field gradient of skew quadrupoles, α is bending angle of dogleg,η and ξ are dispersion and momentum compaction of dogleg. RF voltage of dipole mode cavity is defined at λ from the cavity center.

Parameters	Value	unit
Solenoid field	0.1	T
Initial emittance (x,y)	1.5	mm mrad
Bunch length	12	ps (full width)
Beam size	1.6	mm (rms)
Lorentz γ after acceleration	49	
G_1	-0.503	T/m
G_2	0.926	T/m
G_3	2.058	T/m
α	0.3	rad
η	0.355	m
ξ	0.106	m
RF voltage	1.29	MV at λ

Table 3: Emittance evolution in the simulation. Emittance is in mm mrad.

Position	ε_x	ε_y	ε_z
Cathode	1.5	1.5	8.5
After RFBT	160	0.045	8.5
After TLEX	8.5	0.045	160

beam acceleration with super-conducting accelerator. It consists from 1.3 GHz L-band RF Gun which is compatible to XFEL/FLASH, a super-conducting accelerator module with two 1 m TESLA type cavities. The STF is now upgrading to increase number of accelerator module from one to two. The second accelerator module has 12 1 m cavities.

To implement RFBT, solenoid field should be on the cathode surface. Usually, the gun is designed to vanish solenoid field to avoid emittance growth by the angular momentum. The solenoid field can be induced on the cathode by changing the polarity of bucking coil. According to the solenoid design, up to 0.15 T field can be made. In the simulation, 0.1 T field is assumed. The parameters are summarized in Table 2. $G_{1,2,3}$ are field gradient of skew quadrupoles, α is bending angle of dogleg,η and ξ are dispersion and momentum compaction of dogleg. RF voltage of dipole mode cavity is defined at λ from the cavity center.

The simulation was performed with GPT. The optimization of skew Q setting was made to minimize the sum of non-diagonal components of Σ matrix, i.e. $< xy >$, $< xy' >$, $< x'y >$, and $< x'y' >$ by steepest descent method. The result of the simulation is shown in Fig. 3. The horizontal axis show the distance from the cathode surface. ε_x, ε_y, and ε_z are drawn with solid line, dashed line, and dotted line, respectively. The emittance evolution is summarized in Table 3. By comparing these numbers with them in Table 1, ILC requirements are almost satisfied.

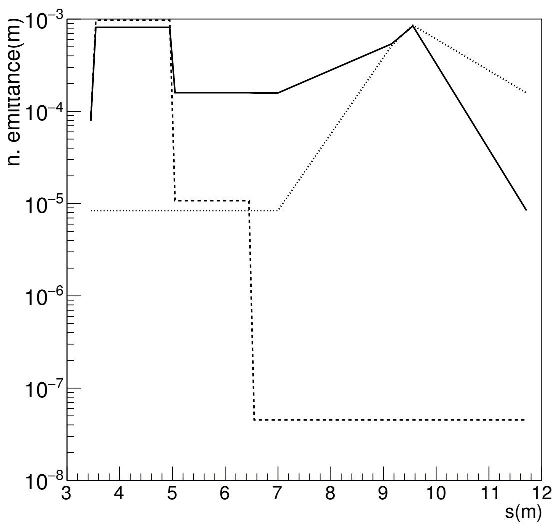

Figure 3: Emittance evolution of the simulation. The horizontal axis shows the distance from the cathode, and the vertical axis shows the normalized emittance in m. ε_x, ε_y, and ε_z are drawn with solid line, dashed line, and dotted line, respectively.

Please note that the simulation does not include space-charge effect, yet. Next, we perform a simulation with a larger beam emittance at the cathode with space-charge effect to confirm the feasibility of the method.

FUTURE PLAN

We schedule beam test at KEK-STF and ANL(Argonne National Laboratory) WFA(Wake Field Accelerator). In STF, an experiment for RFBT will be performed. In ANL-WFA, RFBT and TLEX will be performed. We will examine the feasibility of the method with these beam tests. If the experiment showed a good performance, a full demonstration should be made by introducing a dipole mode RF cavity in STF as a future plan.

SUMMARY

We propose the flat beam generation for linear colliders by employing the emittance exchange techniques. By using RFBT and TLEX, the flat beam compatible to ILC parameter can be made with a large initial x and y emittance from the cathode. The large emittance from the gun relaxes the condition for the beam emission density and space charge emittance growth. Beam tests will be carried out at KEK-STF and ANL-WFA for further investigations.

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