High Aspect Ratio Electron Beam Generation in KEK-STF

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Abstract

Phase-space manipulation on the beam gives a way to optimize the beam phase space distribution for a specific purpose. It is realized by beam optics components which have couplings between degree of freedoms. In this article, a high aspect ratio beam generation with a photo-cathode in a solenoid field is described. In International Linear Collider (ILC) project, a high aspect ratio electron beam is employed for high luminosity up to several $10^{34} cm^{-2} s^{-1}$ by keeping “beam-beam effects” reasonably low. In the current design of ILC, a high aspect ratio beam which corresponds to 250 in transverse emittance ratio, is generated by radiation damping in a 3km storage ring prior to the main acceleration. If such high aspect ratio beam is directly generated from an injector linac, the 3km damping ring, a couple of long transport lines, and a part of the bunching section can be omitted and the system becomes much simpler and cost-effective. We give a result of a simulation study of the high aspect ratio beam generation. Here, we assume a test experiment in STF (Super conducting Test Facility) in KEK. At last, an ILC design based on this method is discussed.

INTRODUCTION

E+ and e- collider (lepton collider) is a powerfull tool for high energy particle physics. It reveals the hidden symmetry of the nature by discovering verious new partilces, resonance states, and weak-bosons, etc. Precise Z^0 studies[1] by SLC[2] and LEP[3] and CP violation measurements by B-factories[4] which had large impacts to establish the standard model of particle physics. These experiments were carried out at the lepton colliders. After the big discovery of Higgs particle by LHC[5], a precise study of Higgs particle property is strogly demanded and would open a new era of modern physics[6]. Unfortunately, LHC is a proton-proton collider which is suitable for discovering a heavy mass particle, but not suitalble for any precise measurement, because the initial state can not be determined well. In contrast, the initial state can be well defined in a lepton collider including the particle helicity.

Due to the complemental property of the hadron collider and the lepton collider, these two accelerators have been a inseparable drinving force on the high energy physics. Unfortunately, a lepton collider based on storage rings have a practical difficulty raising the beam energy beyond 100 GeV due to the huge synchrotron radiation energy loss . The synchrotron energy loss is proporotional to 4th order of the beam energy and rapidly increased as a function of the beam energy. For example, in LEP accelerator[3] which is the last e+ and e- collider based on storage rings at this moment, the energy loss per turn was 2.1 GeV at 100 GeV beam energy. If the energy is increased up to 250 GeV which is required to measure Higgs self-coupling, the energy loss becomes 72 GeV which can not be maintained at all.

Linear collider concept has been proposed to break this difficulty. There is no fundamental limit on the energy for linear colliders [7][8]. The acceleration is done by linear accelerators instead of Synchrotron. The energy is simply scaled with the total length of the linear accelerator and accelerator gradient. On the other hand, eanch bunches passs through the interaction point (IP) only once due to the open topology. In a storage ring collider, each bunches pass through IP many times and the luminosity can be naturally large.

The luminosity L of a collider is expressed as

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

in case of gaussian beam profile. Here, f is pulse repetition, n_b is number of bunches in a pulse, N is number of particles in a bunch. We assume the same numbers of e+ and e-, respectively. σ_x and σ_y are transverse beam size in horizontal and vertical direction. According to this formula, L can be enhanced by decreasing the beam size. L is also enhanced by increasing f, n_b and N, but increasing these numbers make also power consumption large.

For a lepton linear collider, the small beam size at IP is essential. On the other hand, the small spot size at IP makes the beam current density quite high and enhances beam-beam effect. The most serious effects among them is Beamstrahlung which is a synchrotron radition by magnetic field induced by the collison partner beam. By a simple consideration, the energy spread by this effect is

$$\frac{\Delta E}{E} \propto \frac{N^2 E}{(\sigma_x^2 + \sigma_y^2)\sigma_x}, \tag{2}$$

where ΔE is energy spread, E is beam energy , σ_z is longitudinal bunch length. An optimization to maximize L and minimize $\Delta E/E$ is a high aspect ratio beam, i.e. a flat beam. For example, if σ_x is kept at a reasonable value and σ_y is minimized, L can be enhanced inversely proportional to σ_y, but $\Delta E/E$ is increased only up to factor 2.

Table 1 shows the beam parameters of ILC at IP[8]. The aspect ratio in the transverse emittance is 250. In the current design, the high aspect ratio beam is generated by radiation damping in a 3km storage ring. During the damping,

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Table 1: Parameters of ILC IP

Parameter	Value
Horizontal beam size	640 nm
Vertical beam size	5.7 nm
Bunch length	300 μm
RMS energy spread by BS	2.4%
Horizontal n. emittance	10 mm.mrad
Vertial n. emittance	0.04 mm.mrad

there is a sub-effect that the bunch length becomes 9mm which is not suitable for further RF acceleration. The beam is then bunched down to 300 μm again after the damping.

If the high aspect ratio beam is generated directly from an injector, we can omit the 3km storage ring and a part of bunch compressor. It makes the accelerator simpler and more costeffective. In this article, we discuss about the high aspect ration beam generation from a photo-cathode in a solenoid field. The simulation assumes a test experiment at KEK-STF. At last, we discuss about a possible design of ILC employing this method.

HIGH ASPECT RATIO BEAM GENERATION BY MAGNETIZED BEAM

Phase-space distribution of particle beam is expressed with sigma matrix. Here, we consider two dimensional space, x and y, four dimensional in phase space. In case of no correlation between x and y, the sigma matrix is

$$\mathbf{\Sigma_0} = \begin{pmatrix} \sigma_{\mathbf{x0}} & 0 \\ 0 & \sigma_{\mathbf{y0}} \end{pmatrix}, \tag{3}$$

where $\sigma_{x0,y0}$ are nominal σ matrices for one dimensional case. From simpleticity, this Σ_0 can be convereted to Σ_1 with a simpletic transformation $\mathbf{M}$ as

$$\Sigma_1 = \begin{pmatrix} \sigma_{x1} & 0 \\ 0 & \sigma_{y1} \end{pmatrix} = \mathbf{M\Sigma_0 M}^T, \tag{4}$$

where $\sigma_{x1,y1}$ are sigma matrices after the transformation. From the simpleticity, matrix determinant should be constant as

$$det(\mathbf{\Sigma_0}) = det(\mathbf{\Sigma_1}), \tag{5}$$

that leads

$$det(\sigma_{\mathbf{x0}})det(\sigma_{\mathbf{y0}}) = det(\sigma_{\mathbf{x1}})det(\sigma_{\mathbf{y1}}), \tag{6}$$

and can be

$$\frac{det(\sigma_{\mathbf{x0}})}{det(\sigma_{\mathbf{y0}})} \ll \frac{det(\sigma_{\mathbf{x1}})}{det(\sigma_{\mathbf{y1}})}. \tag{7}$$

In short, high aspect ratio beam can be generated by simpletic transformation witout any dissipation interactions. To realize this transformation, correlation between two degrees of freedom should be made once and the correlation has to be removed asymmetrically.

One way to generate such correlation is using fringe field of solenoid[9]. The fringe field of a solenoid at both ends are symmetric and the correlation made at the entrance is cancelled at the exit, i.e. the beam passing through both ends does not have any correlation. To make the correlation, the beam should passes fringe field only at an end. If the beam is generated in the solenoid field, the beam feels only one fringe field.

The vecotor potential of a solenoid field is given as

$$A_x = -\frac{B}{2}y, \tag{8}$$

$$A_y = \frac{B}{2}x. \tag{9}$$

We assume here no transverse momentum at the cathode surface. Because the canonical momentum is conseved, transverse momentum at the solenoid exit is

$$\vec{P_c} = \frac{eB}{2}\begin{pmatrix} y \\ -x \end{pmatrix}, \tag{10}$$

which gives Σ matrix as

$$\mathbf{\Sigma_0} = r^2 \begin{pmatrix} 1 & 0 & 0 & -\kappa \\ 0 & \kappa^2 & \kappa & 0 \\ 0 & \kappa & 1 & 0 \\ -\kappa & 0 & 0 & \kappa^2 \end{pmatrix}, \tag{11}$$

where r is beam size in rms. The matrix has un-diagonal components. It means that the beam has x-y correlation.

The correlation made by the solenoid fringe field can be removed by series of skew-Q magnets. It consists from (at least) three skew-Q magnets represented by a matrix as

$$\mathbf{M} = \mathbf{R}^{-1}\mathbf{Q(q_3)O(d_2)Q(q_2)O(d_1)Q(q_1)R}, \tag{12}$$

where R is rotation matrix given as

$$\mathbf{R} = \frac{1}{\sqrt{2}}\begin{pmatrix} I & I \\ -I & I \end{pmatrix}, \tag{13}$$

where I is 2×2 unit matrix. $\mathbf{Q(q)}$ is a matrix of a nominal quadrupole with gradient q and $\mathbf{O(d)}$ represents drift space length d. Condition for removing the corelation is given by

$$q_1 = \pm\sqrt{\frac{2/eB + d_1(d_1+d_2)eB/2}{d_1(d_1+d_2)2/eB}}, \tag{14}$$

$$q_2 = \frac{-2/eB}{d_1 d_2(1+q_1 2/eB)}, \tag{15}$$

$$q_3 = \frac{-q_1 - q_2 - eB/2}{1 + d_2 d_3 q_2(q_1 + eB/2)}. \tag{16}$$

These conditions are extracted as follows. In case of full correlation, $\vec{x_0}$ and $\vec{y_0}$ vectors are in a relation of

$$\vec{y_0} = \mathbf{S}\vec{x_0} = \begin{pmatrix} 0 & \frac{2}{eB} \\ -\frac{eB}{2} & 0 \end{pmatrix}\vec{x_0}. \tag{17}$$

This correlation should be removed with matrix in eq.(12) that leads

$$\vec{y_1} = (\mathbf{M_{21}} + \mathbf{M_{22}S})\vec{x_0} = 0. \tag{18}$$

SIMULATION

The high aspect ratio beam generation is simulated with GPT(General Particle Tracer) beam tracking code. The beam is generated by an RF gun which is a normal conducting L-band RF gun[10]. It has been developed originally for TTF (Tesla Test Facility) at DESY and it is used as the injector of FLASH/XFEL at DESY. The same gun was placed for the beam acceleration test at STF with the ILC type super-conducting accelerator. A solenoid magnet is attached to the gun cavity for emittance compensation and magnetic field at the cathode surface is vanished by a bucking coil in the nominal operation because x-y correlation makes the x and y projected emittance larger. In our case, the beam should be generated in a solenoid magnetic field and it is realized that the bucking coil polarity is reveresed.

In the first simulation, we assume a simple beam line as shown in Figure 1. At the downstream of the RF gun, a skew-Q channel is placed to remove x-y correlation by rotating the beam in x-y phase space.

Figure 1: Layout of the first simulation.

Figure 2 shows particle distribution at the solenoid exit in $x - y'$ space. A clear correlation between x and y' is observed.

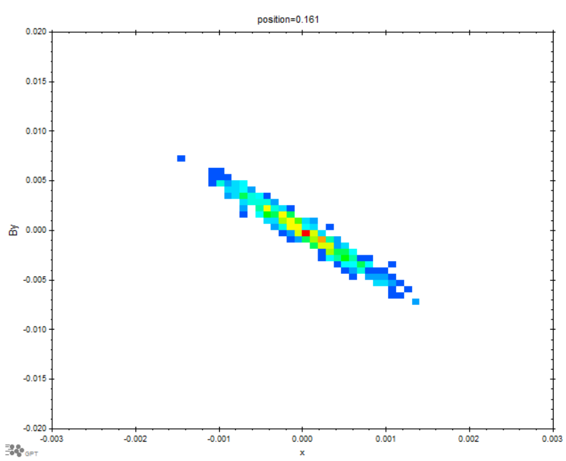

Figure 2: Particles distribution in x and y' space at the solenoid exit. A clear correlation was observed.

The high aspect ratio beam is generated by sending this highly correlated beam to the skew Q channel. The emittance evolution along the beamline is shown in figure 3. At the last skew-Q magnet (at 1.1 m from the cahode), the correlation between x and y is removed and the horizontal emittance is minimized. In this case, the initial emittance right after the cathode was 2.0 mm.mrad for x and y. After the skew-Q channel, the emittance for x and y were 0.096 mm.mrad and 55 mm.mrad, respectively. The aspect ration in emittance was 63.

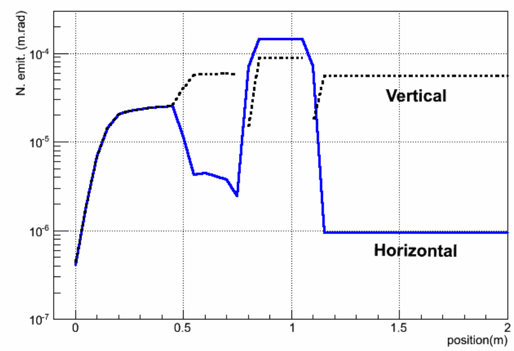

Figure 3: Emittance evolution along the beam line. Cathode is at zero position and Skew Q magnets are placed at 0.5, 0.8, and 1.1 m from the cathode. In this case, horizontal emittance is minimized by the emittance exchange technique.

To evaluate expected performance in a real experiment at STF, another simulation was performed. In this simulation, the beam line layout was modified as shown in fig. 4. In STF injector, a chicane section was implemented to

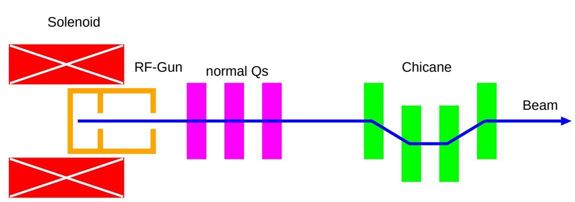

Figure 4: Layout of the second simulation.

introduce laser pulse for elelctron beam generation in right angle to the cathode. In this simulation, the chicane is included. The result is shown in fig. 5. In this case, the vertical emittance is minimized as same as in ILC case. Unfortunately, a significant emittance growth was observed by the chicane section. The reason of this emittance growth by the chicane is not studied yet. Edge focus effect of the chicane magnet might cause this problem. The emittance growth should be observed as a function of the bending angle by the chicane magnet, beam spot size, etc.

ILC DESIGN BASED ON THE EEX TECHNIQUE

Although the design of the injector producing the high aspect ratio beam is not completed yet, let us consdier an impact on ILC design if the injetor was possible. Employing this method, an alternative ILC design is possible as

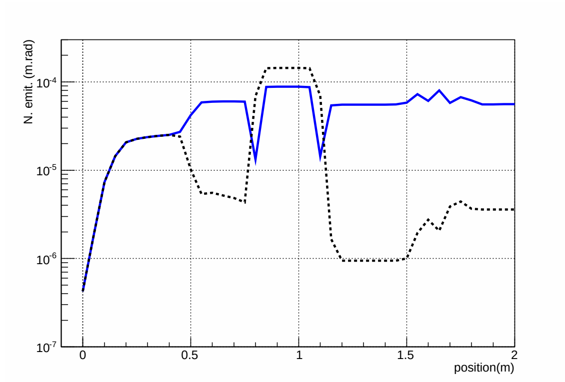

Figure 5: Emittance evolution along the beam line. In this case, vertical emittance is minimized by the emittance exchange technique. A significant emittance growth by the chicane was observed.

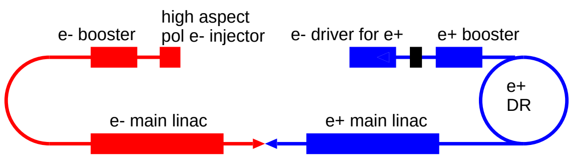

Figure 6: An alternative design of ILC based on the high aspect ratio beam generation with the emittance exchange technique.

shown in fig. 6. In this configuration, a 3km ring for e- beam damping was omitted. In addition, a couple of long transport lines to the linac entrance are also omitted, because two storage rings for e- and e+ are located at the center to share one tunnel in the current design. The e- injector and the storage ring for e+ are are able to be located at near of the main linac entrances, respectively.

There are many issue to realize this proposal. One is to extrac enough amount of bunch charge from the gun and perform the emittance exchange to realize high bunch charge and high aspect ratio elelctron beam simultaneously. Another issue is transporting the high aspect ratio beam without any emittance growth as we faced in this research.

In this study, electron beam generation from a photo-cathode RF gun is assumed. However, polarized electron generation with NEA GaAs cathode in an RF gun is never been demonstrated yet, because of the cathode surface is sensitive to ion impact. Thererfore, it is difficult to operate NEA GaAs cathode in an RF gun with the conventional activation methode. We need a new technique to activate the NEA GaAs cathode with a robust surface.

SUMMARY

We have studied a high aspect ratio electron beam geneation with the emittance exchange technique. In a simulation, more than 60 aspect ratio is expected from STF RF gun, but the ratio is decreased 5 times less because of the emittance growth by the chicane section. Controling the beam transport without any emittance growth is important. A possible ILC design employing this technique is disscussed. In addition to one 3km storage ring, a couple of long transport lines can be omitted, but many issue should be solved to realized this design.

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