SIX-DIMENSIONAL PHASE-SPACE ROTATION AND ITS APPLICATIONS

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Abstract

Recent progress on the accelerator science requires optimized phase space distributions of the beam for each applications. A classical approach to satisfy the requirements is minimizing the beam emittance with a bunch charge as much as possible. This classical approach is not efficient and not compatible to the beam dynamics nature. 6D phase-space rotation, e.g. z-x and x-y, gives a way to optimize the phase space distribution for various applications. In this article, we discus possible applications of the 6D phase space rotation. The x-y rotation generates the high aspect ratio beam for linear colliders directly without DR (Damping Ring). Combination of bunch clipping with a mechanical slit and x-z rotation can generate micro-bunch structure which is applicable for FEL enhancement and drive beam for dielectric acceleration. We present our theoretical and simulation study on these applications.

INTRODUCTION

In recent years, a short bunch, high peak current, extremely small emittance electron beam is required by many applications, such as FEL, pump-probe experiment, Linear colliders, Laser-Compton Photon source, etc. Photo-cathode electron gun with a short pulse laser is a powerful tool to generate such beams, but it is not compatible to nature of beam dynamics because the repulsion force by space charge becomes larger and larger and the initial phase-space distribution is diluted. As a classical approach, we try to minimize the phase-space volume of the electron beam to satisfy these requirements, but all of the degree of freedom (DOF) is not equal for each applications. The phase-space manipulation [1] [2] [3] gives another way to obtain the required beam for many applications. By combining the electron beam with the photo-cathode and the phase-space rotation, the transverse and longitudinal emittance of the beam from the cathode can be moderate (not extremely small) and the phase-space rotation can optimize it to satisfy the requirements from applications. The 6D-volume of the phase-space is conserved according to the Louisville's theorem, phase-space are of some DOF is increased and other is decreased.

In this article, we discuss the applications of EEX (Emittance EXchange) by the phase-space rotation. As the applications, we assume Pre-bunched FEL and a high-aspect ration beam for Linear colliders. In the following sections, the detail is expressed.

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PRE-BUNCHED FEL WITH X-Z EEX

Several noble ideas of FEL with a Pre-bunching have been proposed as HGHG [4], EEHG [5], etc. In this section, we describe a Pre-bunched FEL with X-Z EEX. The beam line consists from a chicane orbit with a dipole mode cavity as shown in Fig. 1. The slotted beam in transverse direction by a mechanical slit is transformed to the micro-bunched beam with this beam line. The matrix of this beam line is expressed as [1]

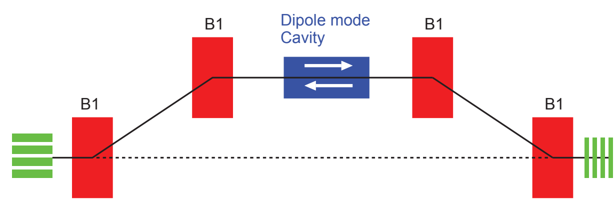

Figure 1: Schematic view of the Z-X EEX beam line composed from a chicane with a dipole mode cavity. X and z phase-space distributions are exchanged.

$$\mathrm{M}_{EX} = \begin{bmatrix} 0 & 0 & -L/\eta & \eta - L\xi/\eta \\ 0 & 0 & -1/\eta & -\xi/\eta \\ -\xi/\eta & \eta - L\xi/\eta & 0 & 0 \\ -1/\eta & -L/\eta & 0 & 0 \end{bmatrix}, \quad (1)$$

where L is the length of one dogleg section (the half of the chicane), η is dispersion, and ξ is momentum compaction. In the derivation of the matrix, we assume a matching condition as

$$1 + \eta k = 0, \quad (2)$$

where k is defined as

$$k = \frac{V_0(a)}{aE_0}, \quad (3)$$

where V_0 is accelerating voltage, a is distance from the cavity center, and E_0 is the beam energy. Please note that $V_0(a)$ is defined at the position a because the voltage is zero at the cavity center. The matrix (1) clearly shows that X and Z phase spaces are exchanged by this beam line. (3,1) and (3,2) component shows the transfer from x and x' to z, respectively. (3,1) is a conversion factor from x to z, but (3,2) is a dilution factor which blurs z micro-bunching structure. (4,1) component makes energy chirp (energy and z correlation) because both z and δ after EEX depends on x before EEX through (3,1) and (4,1) components. The energy chirp made by (3,1) and (4,1) components is not acceptable for FEL and has to be corrected. For the correction, the beam is placed at the zero-cross phase of an additional accelerating cavity operated in TM_{010}. The simulation parameters are summarized in Table 1.

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Table 1: Parameters of the Simulation

Parameter	Value	Unit
Bunch charge	1.0	nC
Transverse Emitttance	2.0	mm.mrad
Beam Energy	25	MeV
Beam radius	2.0	mm
Slit width	200	μm
Slit interval	330	μm
V_0/a	1.69	MV/m
η	62.7	mm

Fig. 2 shows the $z-\gamma$ phase-space distribution after EEX. The energy chirp is corrected with a C-band TM_{010} mode cavity. The micro-bunch structure whose interval is $26\mu m$ is observed. The relative energy spread is 4.6×10^{-4} which is enough for FEL. We examined FEL with this beam by

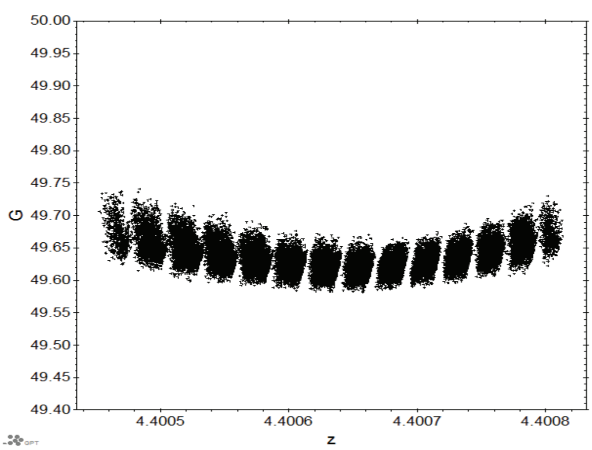

Figure 2: $z-\gamma$ phase space distribution after EEX. The energy chirp is corrected by a TM_{010} mode cavity.

using GENESIS code [12]. In a previous simulation [6], we have observed 50% enhancement of FEL power after 2 m undulator by comparing the beam with and without the slit. The number of micro-bunch was 6. The undulator period was 60 mm and $K = 1.08$, undulator radiation wave-length is same as the micro-bunch interval, 26μm. The power spectrum was sharpen with the micro-bunching, but that was a small enhancement with the super-radiance and not FEL saturation. This time, we have increased number of micro-bunch from 6 to 12 and decreased the dipole mode RF from 2856 MHz to 714 MHz to compensate the deformation by the non-linearity. With 30 mm undulator period, the emission power is shown as a function of Aw (K value) in Fig. 3. Comparing the power with (blue solid circle) and without (red solid circle) slits, the power was enhanced from 52.5 W to 70.0 W by the micro-bunching. The enhancement is 33 % which is lower than the previous result, 50%. The reason is not understood well, but the longer bunch length might make the enhancement small. To improve the micro-bunch FEL performance, the ideal microbunch shape should

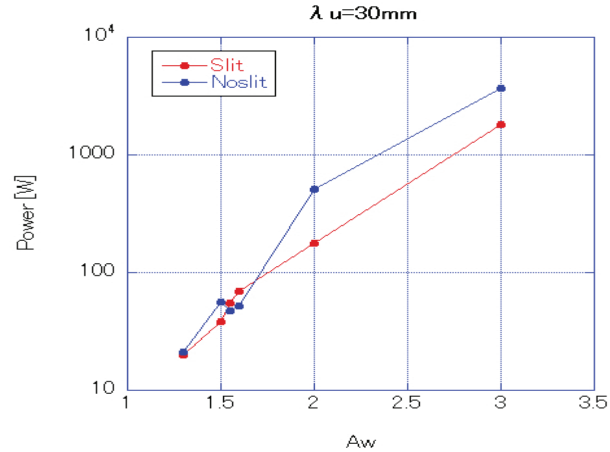

Figure 3: Output power from 30 mm period undulator with (blue solid cricle) and without (red solid circle) slits.

be well studied, and then how to make the ideal microbunch with EEX, should be considered.

A HIGH ASPECT RATIO BEAM GENERATION

In Linear Collider [7], e+ and e- beams are collided in a flat shape to compensate the beam-beam effects. For example, in ILC, the beam size at interaction point is 640 nm in horizontal direction and 5.7 nm in vertical direction. To make the high aspect ratio of the beam shape, the horizontal and vertical emittances are 10 mm.mrad and 0.04 mm.mrad, respectively. The emittance ratio is 250. In the current design [7], this asymmetric emittance is made with the radiation damping in a storage ring (DR; Damping Ring). The electron beam generated from a photo-cathode is boosted up to 5 GeV and it is stored in DR for the radiation damping. The beam is handled in a macro pulse format which contains up to 2600 bunches. These bunches are stored in a compressed format to shorten DR circumference, but it is still 3.0 km. If the asymmetric beam can be obtained directly from an injector, the electron DR can be omitted. The asymmetric beam generation from an injector has been proposed by K-J. Kim [3] and the experimentally demonstrated by Piot [8]. In this scheme, the beam is generated in a solenoid field as shown in Fig.4 and the beam has an angular momentum, i.e. strong $x-p_y$ and $y-P_x$ correlation. The asymmetric emittance beam in x and y can be obtained by removing these correlations by a skew-channel composed from three skew quadrupole magnets [3] [8]. If the technique can make the high emittance ratio required in ILC, we can omit the electron DR.

Linear Collider requires highly spin-polarized beam to define the initial state as precisely as possible. By employing a strain compensated super-lattice GaAs photo-cathode [9], more than 98% spin polarization is obtained. Thermal emittance (transverse energy) of the beam from the super-lattice GaAs photo-cathode was measured by N. Yamamoto to be 35 meV [10]. The expected emittance with a cathode radius

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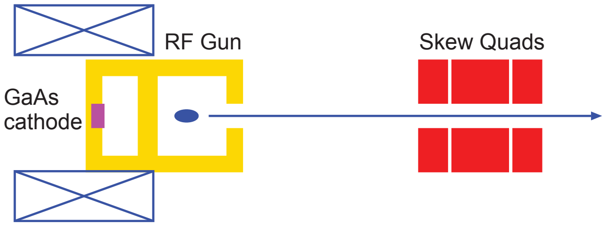

Figure 4: Schematic view of X-Y EEX beam line.

R is

$$\varepsilon_{x,y} = \frac{R}{2}\sqrt{\frac{35\times10^{-3}}{0.511\times10^{6}}} = 1.3\times10^{-4}R. \quad (4)$$

If the product of the emittances is conserved in X-Y EEX, the symmetric emittance to produce the asymmetric emittances required by ILC is

$$\varepsilon_{sym} = \sqrt{\varepsilon_{lcx}\varepsilon_{lcy}} = 5.9\times10^{-7}. \quad (5)$$

This value can be made with $R = 4.5mm$ with the GaAs cathode. ILC requires 3.2 nC bunch charge at IP and the bunch charge at the electron gun should have an additional 50% margin, i.e. the bunch charge has to be 4.8 nC. To obtain this beam from $R = 4.5mm$ area, the required electric field in the gun is

$$E = \frac{4.8\times10^{-9}}{\epsilon_0\pi R^2} = 8.5\times10^{6}, \quad (6)$$

i.e. 8.5 MV/m which is easily obtained an RF gun.

Obtained emittances after the X-Y EEX is give as [3]

$$\varepsilon_{\pm} = \sqrt{(\varepsilon_0)^2 + (L^*)^2} \pm L^*, \quad (7)$$

where $\varepsilon_{\pm}$ are the large and small emittances after EEX, ε_0 is the initial emittance before EEX, and L^* is the normalized angular momentum by the magnetic field given as

$$L^* \equiv \frac{eB_0R^2}{2mc}, \quad (8)$$

where B_0 is the magnetic field on the cathode surface. If $L^* \gg \varepsilon_0$, the emittance ratio after EEX is

$$\eta = \frac{\varepsilon_+}{\varepsilon_-} \sim \left(\frac{L^*}{\varepsilon_0}\right). \quad (9)$$

The emittance ratio of 250 will be obtained with 30 Gauss magnetic field.

To demonstrate the asymmetric beam generation with this technique, a tracking simulation was performed with GPT simulation code [11]. In the simulation, we assume an L-band RF gun [13] developed by DESY which is identical to that in STF facility at KEK [14]. The cathode of the STF RF gun is Cs_2Te and 2.0 mm.mrad is assumed as the initial emittance which is larger than that of GaAs. At the downstream of the gun, the skew channel (three skew quads)

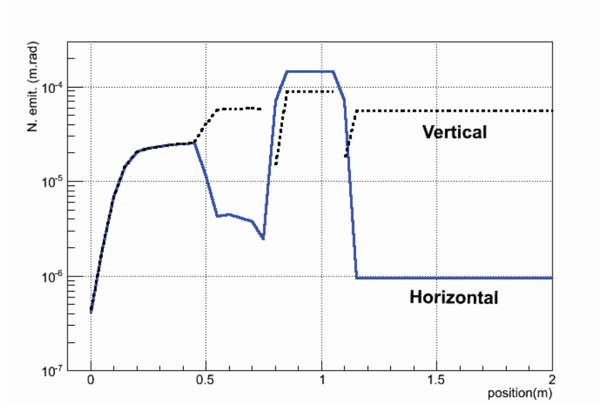

Figure 5: Transverse emittance along the beam line.

was placed. The result is shown in Fig. 5. The emittance ratio was 63. The ratio is still factor 4 lower than the ILC requirement. We have also tried another simulation by assuming a tiny emittance expected from GaAs cathode, but the simulation did not converge yet.

SUMMARY

Phase-space rotation gives a wide variety of operability on the beam and it is applicable for various application. In this article, the Pre-bunched FEL and the flat beam generation for Linear Colliders are studied. We have observed a gain enhancement and a sharper spectrum of FEL for the Pre-bunched FEL. 70 emittance ratio is demonstrated for the flat beam generation. The performance is not enough for the real applications and we continue the optimization.

ACKNOWLEDGMENT

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