A STUDY FOR ENVELOPE MATCHING OF ELECTRON BUNCH FOR EMITTANCE REPARTITIONING EXPERIMENT IN KEK-STF

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Abstract

The International Linear collider (ILC) is a e^+ e^- linear collider at centre of mass energy up to 1 TeV. At the interaction point, the beam shape must be flat in the transverse space to maximize the luminosity, compensating the energy spread by beamstrahlung. The flat beam is obtained by asymmetric emittance in *x* and *y* made up by radiation damping with a 3 km damping ring. We propose a new method to make the asymmetric emittance based on emittance exchange techniques using the two beamlines called as Round to Flat beam transformation (RFBT) and Transverse to Longitudinal Emittance exchange (TLEX). In KEK Superconducting Test facility (STF) the RFBT experiment has been performed but the results are not as expected due to a significant emittance growth due to the space charge effect. We studied the emittance growth compensation by space charge effect by the envelope matching in the STF injector. We report the results of our study here.

INTRODUCTION

The purpose of flat beam generation is to increase the luminosity of the linear collider and to reduce the beamstrahlung effect. The beam luminosity is inversely proportional to beam sizes, i.e., $L = \frac{f n_b N^2}{4\pi\sigma_x\sigma_y}$, whereas the beamstrahlung is proportional to $(\sigma_x + \sigma_y)^{-2}$. Thus, to simultaneously increase luminosity and reduce beamstrahlung we should have an asymmetric flat beam ($\sigma_x \gg \sigma_y$) [1]. Generation of such flat beams is usually carried out by damping rings. However, the emittance exchange techniques RFBT and TLEX have a much simpler beamline design which could reduce the maintenance cost as well. In this paper the description of RFBT experiment and its implementation at the STF beamline of KEK is given. The concept of RFBT [2] was previously studied by several groups. The flat beam generation for KEK-STF had been studied and experiments were performed by M. Kuriki and S. Aramoto et al. [1], but the flat beam generation was not confirmed due to the emittance growth of the beam. In this article, we report the results of studies of the emittance growth and its compensation due to the space charge effect in the STF injector part. Simulations were performed with ASTRA.

ROUND TO FLAT BEAM TRANSFORMATION

The RFBT involves transformation of an angular momentum dominated beam into a flat beam after passing through three skew quadrupoles. The solenoid provides the necessary magnetic field for generating an angular momentum dominated beam according to the equation:

$$\mathcal{L} = \gamma m r^2 \dot{\varphi} + \frac{e}{2\pi}\Phi = const.,$$

where $\mathcal{L}$ is the angular momentum and Φ is the magnetic flux. After passing through the solenoid field, the electron trace space coordinate transforms as:

$$X = \begin{pmatrix} x \\ x' - ky \end{pmatrix}, Y = \begin{pmatrix} y \\ y' + kx \end{pmatrix} \text{ where } k = \frac{eB}{2P_z}.$$

As a result, the beam matrix becomes: [3]

$$\Sigma = \begin{bmatrix} \sigma^2 & 0 & 0 & k\sigma^2 \\ 0 & k^2\sigma^2 + \sigma'^2 & -k\sigma^2 & 0 \\ 0 & -k\sigma^2 & \sigma^2 & 0 \\ k\sigma^2 & 0 & 0 & k^2\sigma^2 + \sigma'^2 \end{bmatrix}$$

where $\sigma^2 =< x^2 >=< y^2 >$, $\sigma'^2 =< x'^2 >=< y'^2 >$ and $\mathcal{L} = k\sigma^2$ is the angular momentum. If the Twiss parameters are matched, i.e., $\alpha_x = \alpha_y$ and $\beta_x = \beta_y$ just before the skew quadrupoles then the *x-y* correlation can be removed and the flat beam can be obtained which has asymmetric emittances $\varepsilon_x = \sqrt{\varepsilon_u^2 + \mathcal{L}^2} + \mathcal{L}$ and $\varepsilon_y = \sqrt{\varepsilon_u^2 + \mathcal{L}^2} - \mathcal{L}$, giving its ratio as $\varepsilon_x/\varepsilon_y \sim 4\mathcal{L}^2/\varepsilon_u^2$.

KEK-STF

KEK-STF is a linear accelerator based on the superconducting accelerator model. The beamline consists of a 1.3 GHz L-band normal conducting RF gun [4] with Cs_2Te photocathode and two cryomodules as shown in Fig. 1. The first module is referred to as CCM (Capture Cryomodule)

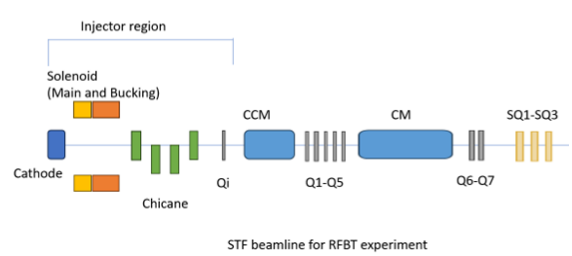

Figure 1: Block diagram for the STF beamline at KEK

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which accommodates two super-conducting cavities. The second is referred to as CM (Cryomodule) which accommodates 12 superconducting cavities. The CM section consists of CM-1a and CM-2a which are also cryomodules. In CM-1a and CM-2a, there are 9 TESLA cavities with 40 MV/m gradient.

The RF gun has a peak field of 44 MV/m with 3.5 MW RF input [5]. The cathode is Cs_2Te semiconductor formed on a molybdenum block by evaporation in vacuum. The laser spot size is 2 mm in radius and the thermal emittance is 0.80 π mrad mm. A solenoid magnet is placed for focusing. There is a bucking coil whose purpose is to cancel the magnetic field on the cathode generating angular momentum. The angular momentum spoils the 2D emittance in *x-x'* and *y-y'* plane. For performing the RFBT experiment only we need angular momentum. A B-field on cathode can be obtained by switching the bucking coil polarity.

The chicane is placed at downstream of the RF gun, followed by CCM. The chicane, shown in Fig. 2 consists of four dipole magnets of length 0.114 m each. The bending angle and strength of the dipole magnets are 16.2^o and 0.048 T respectively. The bending magnets bend the beam in a horizontal direction whereas the beam is focused on the vertical direction due to the edge-focusing effect. The focal length is estimated as 1.04 m based on linear dynamics. Between CCM and CM, a beam diagnostic section is placed where emittance can be measured by Q-scan method. There is a momentum analyser with a bending magnet in the middle which is not shown in the figure.

Downstream of CM-2a is the RFBT section composed of two Q-magnets, three skew Q-magnets, two Q-magnets, and RPM06 (screen). The two Q-magnets match the Twiss parameters before the skew Q-magnets for generating flat beam.

Table 1: Simulation Parameters

Parameter	value	Unit
Charge	0.06	nC
Laser pulse duration	12	Ps
Laser rms spot size	1.0	mm
Thermal emittance	0.80	π mrad mm
Bunch size (RMS)	0.77	mm
RF gun gradient on cathode	-43.5	MV/m
RF gun frequency	1.3	GHz
Beam energy before CCM	5.474	MeV

SIMULATION STUDY

Figure 3 shows the initial beam distribution in the *x-z* and *y-z* planes. 10,000 macro particles are generated in Gaussian distribution. The initial beam parameters are summarized in Table 1 together with other simulation parameters. To investigate the space charge in emittance growth, we used a non-magnetized beam. Therefore, the main and bucking solenoid coils are adjusted to provide zero magnetic field at the cathode.

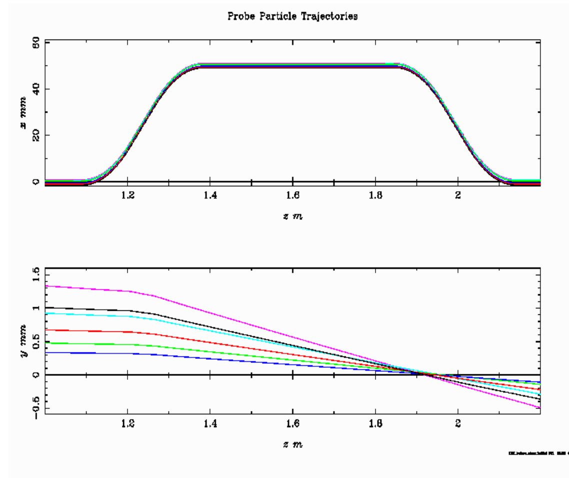

Figure 2: Beam trajectory in horizontal and vertical plane after passing through the chicane.

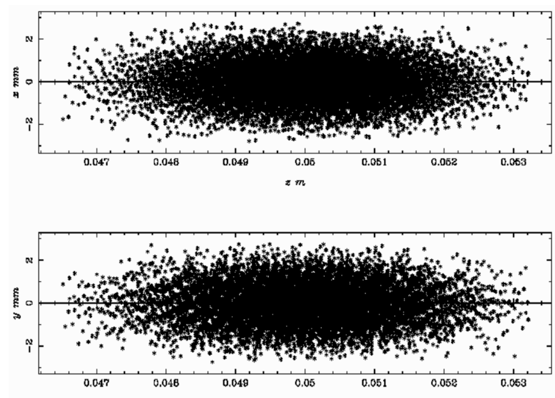

Figure 3: Gaussian beam generated in ASTRA with rms laser spot size 1.0 m.

Space charge effect

Our goal at the injector region of STF beamline is to compensate the emittance growth by space charge to obtain sufficiently good emittance to perform the RFBT experiment. Because the space charge effect is highly suppressed by acceleration, the emittance is conserved after acceleration. We expected the emittance growth in the injector region due to 1) Slice deformation and mismatch in transverse space by the transverse space charge effect, 2) Slice mismatch in transverse space by combination of longitudinal space charge effect and the transverse dispersion in chicane. 1) and 2) are occurred in *x*, but only 1) in *y* because of no dispersion in *y*.

The space charge force is non-linear effect because of the Gaussian distribution, and it rotates at different angles on the beam due to which we get slice mismatches. As a result, both the area of each slice and the area of the projected slice are increased.

The solenoid gives focusing in both x and y direction and can reduce the space charge effect in the transverse directions by envelope matching. In our case, the chicane provides additional focusing in y as the edge focusing which causes the beam size to shrink and thus increase the space charge effect in the y direction. For this reason, we have the Qi magnet at the downstream of chicane to compensate by focusing in the x direction and de-focusing in y to achieve quasi-symmetric focusing.

The chicane gives another emittance growth effect. The longitudinal space charge effect gives energy spread between the bunch head and tail. If the effect exists wherever there is dispersion, the emittance is increased due to the horizontal slice shift according to the slice energy. This emittance growth by the longitudinal space charge cannot be compensated by solenoid focusing in x. We varied the solenoid strength and observed asymmetric emittances in x and y at s=4.5 m and the results are shown in Fig. 4. The x emittance is minimized with 0.18 T solenoid field, but the evolution of y emittance is quite different. The chicane gives edge focus in y direction which disturbs the emittance compensation by the solenoid. The minimum emittance in x is, however, 2.2 π mrad mm which is larger than the thermal emittance at the cathode. Because the emittance growth by the longitudinal space charge effect with dispersion in chicane could not be compensated by solenoid focusing, it remains even if the emittance growth by the slice mismatch is compensated.

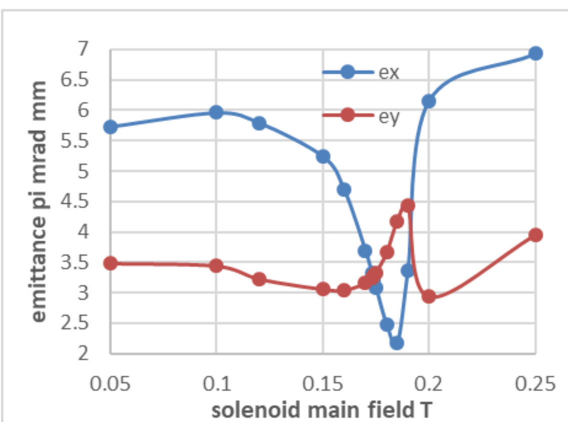

Figure 4: Transverse emittance as a function of solenoid field. Due to the chicane, we have asymmetric focusing on x and y and thus the emittances could not be simultaneously optimized.

To confirm this speculation, the slice motion was observed in the STF injector with and without chicane. The solenoid field is applied in both cases. The longitudinal phase ellipse is observed at s=2.15.

Figure 5 and 6 show the longitudinal slice ellipse in transverse phase space x and y, respectively without the chicane. The slice deformation and angle mismatch are observed as an imperfection of the emittance compensation by solenoid, but Fig. 5 in x and 6 in y are symmetric because the system is symmetric in x and y.

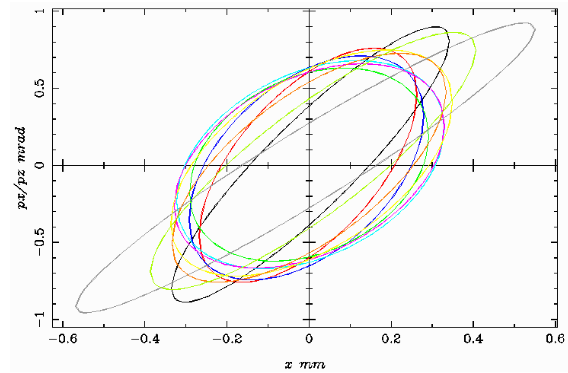

Figure 5: Ellipse of longitudinal bunch slice in x phase space giving 2.0 π mrad mm emittance at s=2.15 m.

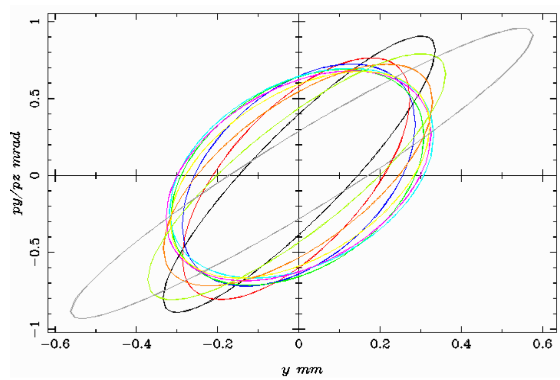

Figure 6: Ellipse of longitudinal bunch slice in y phase space giving 2.0 π mrad mm emittance at s=2.15 m.

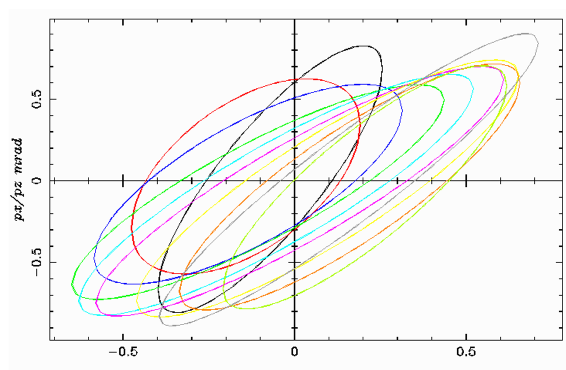

Figure 7: Ellipse of longitudinal bunch slice in x at s=2.15 m with chicane giving 2.2 π mrad mm.

Figure 7 and 8 show the same plot, but with the chicane. Figure 7 shows that slices are shifted in x direction which is consistent with the speculation that the emittance is increased by slice shift due to dispersion with the longitudinal space charge effect. Figure 8 shows slice rotation mismatch which is also consistent to the envelope matching with solenoid is disturbed by the edge focus effect of chicane.

The phase space distribution of particles in x without chicane is shown in Fig. 9. In this condition, the solenoid field is adjusted to compensate the emittance growth, but the non-linear deformation is observed which is evidence of non-linear contribution in the emittance growth.

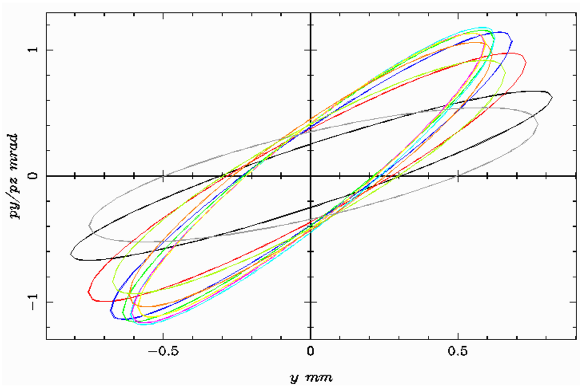

Figure 8: Slice ellipse at 2.15 m with chicane. The y emittance is 3.4 π mrad mm.

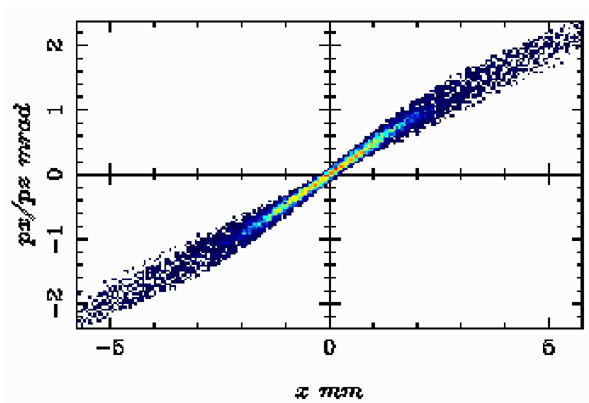

Figure 9: Nonlinear space charge effect in x phase space. At 4.5 m, the emittance has increased to 3.1 π mrad mm without chicane.

CONCLUSION

We attempted to optimize the STF injector to perform RFBT experiment. A simulation study with ASTRA was carried out and we found that the chicane causes asymmetric emittance growth in x and y. In the horizontal direction, the emittance is increased by a combination of the longitudinal space charge effect in chicane where dispersion exists. In the vertical direction, the emittance is increased because the edge focus of the chicane disturbs the emittance compensation by the solenoid. We could not find the best condition of the injector because the horizontal and vertical emittances are not able to be optimized simultaneously. We will evaluate the expected RFBT experiment performance with this condition.

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