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A STUDY FOR EMITTANCE GROWTH COMPENSATION BY SPACE CHARGE EFFECTS AT THE INJECTOR OF KEK-STF AFTER DRY ICE CLEANING OF THE RF GUN

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Abstract

The Round to Flat Beam Transformation (RFBT) is one of the emittance exchange techniques that can improve the Luminosity for the future accelerator project International Linear collider (ILC). RFBT experiment can be conducted in the KEK-STF, and the expected performance is 334 in emittance ratio. In December 2023, we performed a pilot experiment at STF to optimize the injector conditions. To improve the RF Gun of STF, we applied dry ice cleaning to reduce the field emission. The field enhancement factor was improved from 233 to 100.

INTRODUCTION

The International Linear Collider (ILC) is a future accelerator project in Japan that will enable the collision of electrons and positrons at a center of mass energy of 250 GeV to 1 TeV [1] and the initial target is a detail study of Higgs boson. The Luminosity of linear collider is inversely proportional to the vertical beam size at the collision point, which can be increased with the emittance exchange techniques [2]. One of the emittance exchange technique, Round to Flat beam transformation (RFBT) was performed in KEK Superconducting Test Facility (STF) but we observed emittance growth due to the space charge effect. The purpose of RFBT is to generate an asymmetric flat beam that will increase the beam luminosity (L) and reduce the energy loss by Beamstralung (ΔE) simultaneously which are given by the equations:

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

$$\Delta E \propto (\sigma_x + \sigma_y)^{-2},$$

where σ_x and σ_y are the transverse beam sizes as described in Ref [2]. Thus, an asymmetric flat beam with the condition ($\sigma_x \gg \sigma_y$) is required for this purpose. In the RFBT transformation the beam with angular momentum is passed through three skew quadrupoles which remove the angular momentum components from the beam matrix and make it block diagonalized. The flat beam emittances can be obtained from the diagonalized matrix as:

$$\varepsilon_\pm = \sqrt{(\varepsilon_{th}^2 + l^2)} \pm l$$

where ε_{th} is the thermal emittance, and l is the angular momentum [3]. On December 2023 we couldn't perform the RFBT experiment at STF, but operated the beam till the first beam-dump and the capture-cryomodule was turned off due to budget issues. Our main purpose during this beamtime was to understand the injector characteristics and evaluate the expected RFBT results using simulation.

Before our beam operation we used the dry ice cleaning technique to remove the contaminations inside the RF cavity because it would reduce the dark current. The RF cavity was dismounted after 13 years, and we saw silver-colour coated trace on the cathode endplate, around the iris edge and at the bottom of the acceleration cell. Finally, a new cathode surface (Cs_2Te) was also fabricated by vapour deposition to increase the quantum efficiency. In this paper we report the results after dry ice cleaning of the RF gun, the simulation studies, the expected RFBT performance, and our future target.

DRY ICE CLEANING AT KEK-STF

The linear accelerator beamline at KEK-STF contains 1.3 GHz L-band normal conducting RF gun [4], two solenoid coils for adjusting the magnetic field, a chicane region with four dipole magnets, two cryomodules, and some quadrupoles and skew quadrupoles as shown in Fig. 1.

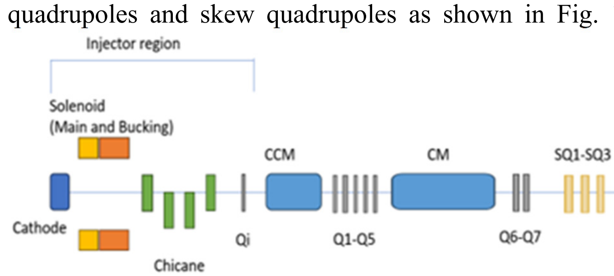

Figure 1: Block diagram of the STF beamline

The RF cavity was cleaned by dry ice and most of the contaminations were removed from the cathode endplate as shown in Fig. 2. During the dry ice cleaning, the RF gun was removed from the beamline and was placed on the frequency tuning machine (Fig. 3). There was a motor attached to the setup which allowed the cavity to rotate 360 deg/min. Dry ice was applied from the bottom with two types of nozzles, one is straight and the other has 45 degrees bend. The nozzles were inserted into the cavity alternatively for 10 min each and operated in up-down manner. The jet pressure for dry ice was kept constant at 0.3 MPa. However, during the cleaning process the cathode was taken out and thus the contaminations were only removed from the cavity surface.

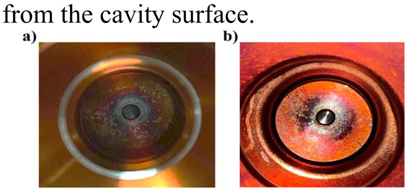

Figure 2: Pictures of RF gun cavity (a) before and (b) after dry ice cleaning.

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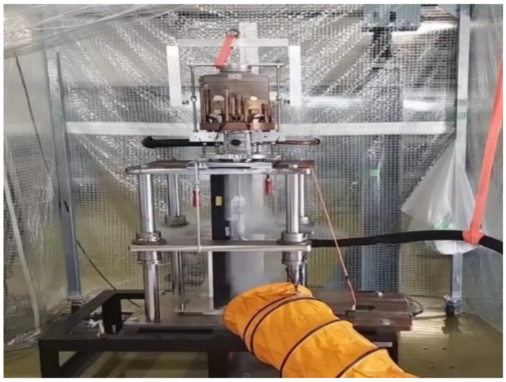

Figure 3: RF gun was placed at the frequency tuning machine and dry ice was applied from the bottom.

After the cleaning process, the RF gun was reassembled, and the Caesium Telluride cathode (Cs_2Te) was prepared by evaporation process. The dark current was measured, and the field enhancement factor (β) is determined from Fowler Nordheim plot (Fig. 4) which is based on the equation [5]:

$$I \propto (\beta E)^{2.5} \exp\left(-\frac{6.53\times10^3 \varphi^{1.5}}{\beta E}\right),$$

where I is the dark current in µA, E is the RF field in MV/m, and φ is the work function in eV. The enhancement factor reduced from 233 to 100 after the cleaning process. This shows the effectiveness of dry ice cleaning for reducing the field emission from the cavity surface.

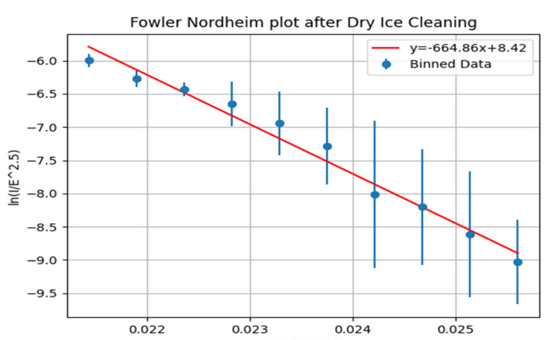

Figure 4: Fowler Nordheim plot after dry ice cleaning process.

EXPERIMENT AND SIMULATION

The STF experiment was performed by turning off the capture cryomodule (CCM), and thus the beam was accelerated only by the RF gun. The beam position was not on the magnetic centre of the solenoid. We measured the beam emittances by Qscan at PRM04, and used the Solenoid main and bucking coils to make the B field zero at the cathode surface because beam without angular momentum gives better understanding. Table 1 shows the emittance observed in experiment and reproduced by ASTRA simulation which are consistent to each other. The initial beam conditions are listed in Table 2.

Table 1: Transverse Emittances in Experiment and Simulation

Emittances measured at PRM04	**Experiment (π mrad mm)**	**Simulation (π mrad mm)**
X	11.3 +/- 2.1	11.5
Y	7.4 +/- 1.0	6.9

Table 2: Initial Parameters Taken in Simulation

Parameter	**Value**	**Unit**
Bunch charge	48	pC
Laser pulse duration	12	ps
Laser rms spot size in x	1.2	mm
Laser rms spot size in y	2.4	mm
Thermal emittance for beam in x	1.0	π mrad mm
Thermal emittance for beam in y	2.0	π mrad mm

The generated gaussian beam was asymmetric in x and y as listed in Table 2 observed as the laser spot. The initial beam position was found to be at x = 3.6 mm and y = 3.0 mm from the magnetic center of the solenoid field, respectively. The emittance growth in x and y took place due to several factors like the initial laser profile, Rf phase, Solenoid focusing, space charge forces, etc. We compared the beam performance with the symmetric and asymmetric beams having the same charge density. For the asymmetric beam, the emittance growth is much higher because the space charge force is asymmetric, but the compensation by Solenoid is common for x and y. We also studied the effect of initial beam position on the emittance growth. When the beam is not on the magnetic center, it experiences dispersion from solenoid. The dispersion effect is more significant in the y direction than x which is evident by looking at the slice shifts in YY' phase space (Fig. 5). After obtaining the initial beam conditions from our simulation we determined the expected the RFBT results in the STF.

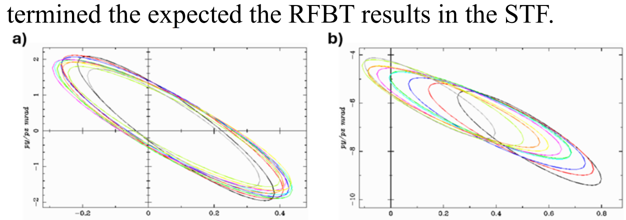

Figure 5: Slices in YY' phase space at Z=0.9 m when the initial beam position is (a) at magnetic center and (b) away from the magnetic center. The slices are shifted horizontally due to dispersion during off-centered condition.

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We studied the RFBT performance for the asymmetric gaussian beam. In this case we used the simplex optimization by ELEGANT and combined ASTRA simulation. For RFBT case the Solenoid field was optimized for minimum space charge effect and the chosen value of the theoretical flat beam ratio was 400. This optimization was done for a cylindrical beam of 1mm rms spot size symmetric in x and y and not optimized to this asymmetric beam parameter. For symmetric gaussian case, the spot size was 1.7 mm in x and y respectively, and the theoretical flat beam ratio is 1130. We satisfied the necessary conditions required for RFBT, i.e., 1) matching the Twiss parameters ($\alpha_x = \alpha_y$ and $\beta_x = \beta_y$) before skew quadrupoles by minimizing the optimization function to zero:

$$\left(\alpha_x - \alpha_y\right)^2 + \left(\beta_x - \beta_y\right)^2 = 0,$$

and 2) removing the angular momentum with the help of three skew quadrupoles by minimizing the off-diagonal elements of the beam matrix (which have angular momentum contributions) to zero:

$$|s_{13}|^2 = |s_{14}|^2 = |s_{23}|^2 = |s_{24}|^2 = 0.$$

The flat beam ratio is 334 for the symmetric gaussian beam whereas around 115 when the beam is asymmetric. These are the results when the initial beam position is at the magnetic centre. But when the initial beam is off-centred, the flat beam ratios are 118 and 6 for the symmetric and asymmetric beams, respectively. Table 3 compares the RFBT results for symmetric and asymmetric beams while Table 4 shows the effect of initial beam positions on the flat beams. The reasons for the deviation from the theoretical ratio are the space charge effects, and dispersion by solenoid. We found out that the y emittance has largely increased for asymmetric beam (Fig. 6) because the emittance growth by the space charge was significant.

Table 3: RFBT Results with Different Beam Shapes

Gaussian beam shapes	**X emit after RFBT (π mrad mm)**	**Y emit after RFBT (π mrad mm)**	**Flat beam ratio**
Symmetric	48.6	0.15	334
Asymmetric	48.7	0.42	115

Table 4: Flat Beams that are Obtained with Different Initial Beam Positions in Case of Asymmetric Gaussian Beam

Initial beam position at cathode	**X emit after RFBT (π mrad mm)**	**Y emit after RFBT (π mrad mm)**	**Flat beam ratio**
Center	48.7	0.42	115
Off-centered	48.4	7.80	6

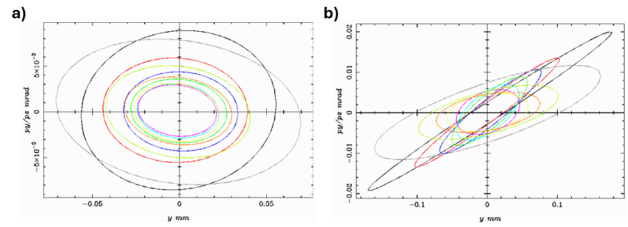

Figure 6: Slices in YY' phase space at Z=55m after RFBT when the beam is at magnetic center. (a) For symmetric beam, the y emittance is 0.15 π mrad mm and (b) for asymmetric beam it is 0.42 π mrad mm which shows higher emittance growth in asymmetric beam due to space charge effects.

CONCLUSION AND FUTURE TARGET

The dry ice cleaning improved the RF gun performance, the field enhancement factor becomes by 2.3 times less. Due to this reason the dark current has reduced by 1/4 of its previous value. The expected RFBT performance at KEK-STF is 334 in the emittance ratio. The emittance ratio is sensitive to the laser beam profile and the beam position at the cathode. The beam position must be aligned at the magnetic center of the solenoid field.

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