ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEOGC2

AN EXPERIMENTAL STUDY OF X-Y EMITTANCE REPARTITIONING IN KEK-STF

M. Kuriki*, Z. J. Liptak, Hiroshima University, S. Mukherjee, Higashihiroshima, Japan
J. Power, Argonne National Laboratory, Lemont, United States
K. Sakaue, University of Tokyo, Tokyo, Japan
L. Guo, Nagoya University, Nagoya, Japan
H. Hayano, X. Jin, S. Kashiwagi, N. Yamamoto, Y. Yamamoto, KEK, Tsukuba, Japan
S. Kim, European Organization for Nuclear Research, Meyrin, Switzerland
P. Piot, Northern Illinois University, DeKalb, United States

Abstract

In a linear collider, the colliding beam has to be flat in the transverse plane to suppress energy spread by Beamstrahlung and to maximize the luminosity, simultaneously. In the current design of ILC, the flat beam is realized by the asymmetric emittance generated by the radiation-damping effect. We propose to generate the equivalent beam directly in the injector linac employing the emittance repartitioning technique. As an experimental demonstration, a beam experiment was carried out at KEK-STF. We present the experimental results.

INTRODUCTION

Following the discovery of the Higgs Boson in 2012, searches for new physics beyond the Standard Model are increasingly considering detailed, high-statistics studies of Higgs particles. Particularly in light of the lack of evidence for supersymmetry theories, searches for small deviations from theory in Higgs decays are taking on a growing importance as one of the last sectors to potentially contain hints of new physics. To realize such studies, a high-luminosity collider with a clean background environment at the Higgs resonance is called for. The International Linear Collider (ILC) [1], a proposed linear e^+e^- collider to be constructed in Iwate, Japan, is a candidate machine designed to satisfy these criteria. The ILC is planned as a superconducting accelerator with a center-of-mass energy from 250 to 1000 GeV.

Luminosity in colliders, representing the number of collisions produced as a metric of performance, can be represented as

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

where f represents the frequency of collisions, n_b the number of bunches per pulse, N the number of particles per bunch and $\sigma_{x,y}$ the transverse beam sizes.

At the energies needed to produce Higgs Bosons, the loss of energy to synchrotron radiation in a circular collider would render an e^+e^- collider impractical; to avoid this issue, we consider a linear collider to produce beams at the requisite energy. In contrast to circular colliders, however, the beam must be dumped after a single crossing and thus maximizing the number of collisons per bunch crossing is of paramount importance. Operating beams at a high current similar to the modus operandi of circular colliders would require an impractical amount of energy, therefore increasing the luminosity by reducing the transverse beam sizes $\sigma_{x,y}$ is a more attractive option.

Squeezing the beam size, however, induces an energy spread via Beamsstrahlung:

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

One possible practical way of suppressing this energy spread while increasing luminosity is to squeeze the beam in only one transverse direction, e.g., $\sigma_x \gg \sigma_y$, such that the beam is effectively flat. In the ILC, for example, the beam size at the interaction point is planned to be 640 nm (5.7 nm) in the horizontal (vertical) direction, with corresponding emittances of 10 and 0.04 mm·mrad. The current design calls for this asymmetric-emittance beam to be created by radiation damping in dedicated damping rings, as shown in Fig. 1.

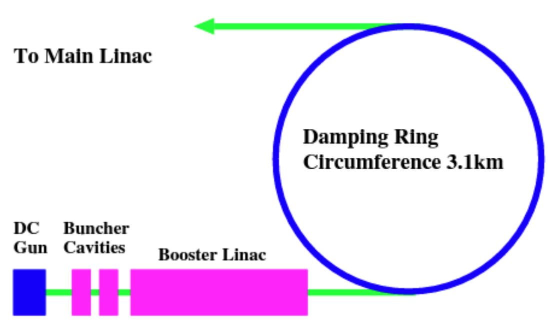

Figure 1: Conventional design of an injector for a linear collider, utilizing a damping ring to produce asymmetric beam emittance utilizing radiation damping effects.

Using X-Y emittance repartitioning with the Round to Flat Beam Transformation (RFBT) [2] and Transverse to Longitudinal Emittance eXchange (TLEX) [3] schemes, we consider the possibility of creating a flat beam for the ILC without the damping ring. A schematic representation of the combined setup is shown in Fig. 2. Here we discuss the results of flat beam generation at the KEK Superconducting

* mkuriki@hiroshima-u.ac.jp

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEOGC2

Test Facility (STF) from an angular momentum-dominated beam produced by emission in a solenoid field.

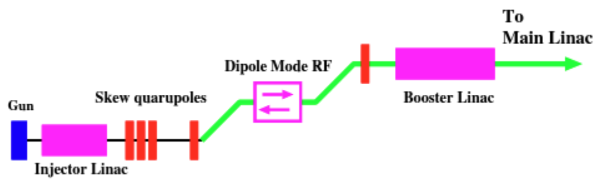

Figure 2: An injector design utilizing emittance repartitioning techniques to produce an asymmetric beam without the use of a damping ring.

THE KEK-STF BEAMLINE

The KEK-STF beamline is a test facility in place at KEK in Tsukuba, Japan, intended to demonstrate beam acceleration with a superconducting accelerator. It consists of a 1.3 GHz L-band RF gun compatible with XFEL/FLASH, a superconducting accelerator module consisting of 1 m TESLA-type cavities. A solenoid and bucking coil situated near the cathode can be used to induce a magnetic field on the beam at its generation, in contrast to the normally field-free cathode gun. After passing through the superconducting cavities, a series of skew-quadrupole magnets is used to perform rotation on the beam in flight. Screen and wire monitors distributed along the beamline are used to monitor beam position and emittance. The full beamline is shown in Fig. 3.

SIMULATION

Simulation of the STF beamline was carried out in ASTRA and ELEGANT for both regular, i.e., zero B_z field on cathode, and RFBT operation to determine optimum magnet parameters using the beam values as shown in Table 1. Based on the output of simulation optimization, parameters for the optimal realization of the RFBT technique were determined, and also their expected emittances and emittance ratios. These parameters are listed in Table 2 and the evolution of the transverse emittances along the beamline is shown graphically in Fig. 4.

Table 1: Beam parameters used in STF simulations

Parameter	Value	Unit
Laser spot size (RMS)	1.0	mm
Main coil peak B_z	0.07	T
Bucking coil peak B_z	0.09	T
Thermal emittance ε_u	0.85	mm·µrad
Angular momentum $\mathscr{L}$	10.14	mm·µrad
E_{kin} after CCM	40	MeV
E_{kin} after CM	360	MeV
Skew 1 Gradient	2.603	m^{-1}
Skew 2 Gradient	-3.876	m^{-1}
Skew 3 Gradient	-4.972	m^{-1}

Table 2: Summary of theoretical and simulated transverse emittances for RFBT operation

Parameter	Simulation	Theory	Unit
ε_x	20.36	20.32	µm · mrad
ε_y	0.05	0.04	µm · mrad
$\varepsilon_x/\varepsilon_y$	407	508	

EXPERIMENTAL PROCEDURE

During the KEK-STF experimental run period carried out in December 2022, we performed measurements according to the following procedure:

1. Beam operation with zero B_z field on the cathode.
2. Adjusting the symmetric (x,y) beam optics and confirming the measurements of the beam Twiss parameters by Q-scans with downstream focusing quadrupole magnets.
3. Set the solenoid and bucking coil fields to apply a non-zero B_z field on the cathode for the RFBT test.
4. Set the skew quadrupole magnet currents based on results from simulation.
5. Optimize the skew quadrupole magnets to find the minimum possible ε_y.

EXPERIMENTAL RESULTS

Following the procured outlined in the previous section, we first operated the STF beam with no magnetic field on the cathode. During this mode of operation, with no angular momentum imparted to the beam from the solenoid, we observe roughly symmetrical emittance in the transverse directions following Q-scans downstream of the superconducting RF cavities. An example of such a Q-scan showing an emittance of the order of 2 mm·mrad is shown in Fig. 5.

After applying a magnetic field to the cathode, we observed transverse emittances much larger than expected and incompatible with simulation. We found that the emittance grew unexpectedly upstream of the skew-quadrupole magnets, and the traversing of the cryomodules exacerbated the excess growth.

CONCLUSIONS AND FUTURE PLANS

We performed an experimental test of production of a flat beam using the RFBT technique at the KEK-STF accelerator. Due to an unexpected emittance increase in the beam upstream of the skew-quadrupole magnets used to rotate the beam, we were unable to observe RFBT.

Current investigations of the cause of the magnetic field point to undesirable space charge effects due to focusing in the chicane. An example of this effect is shown in Fig. 6, showing the simulated trajectories of a set of test particles from the cathode to the entrance of the capture cryomodule.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEOGC2

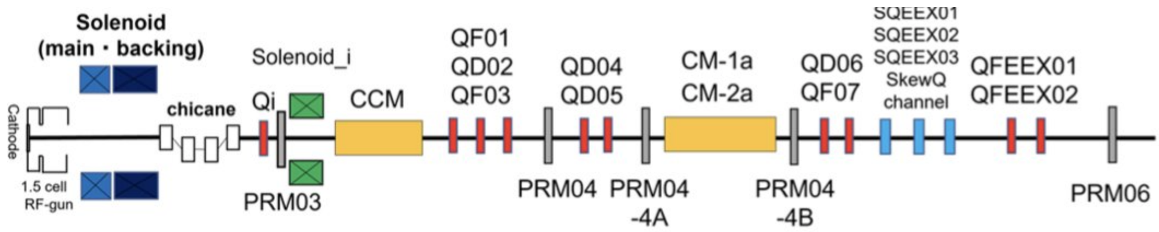

Figure 3: Layout of the KEK-STF accelerator (not to scale). The solenoid field imparting angular momentum to the generated beam is positioned immediately downstream of the cathode, and the skew-quadrupole magnets used for rotation are indicated in blue. Superconducting RF cavities are indicated in yellow.

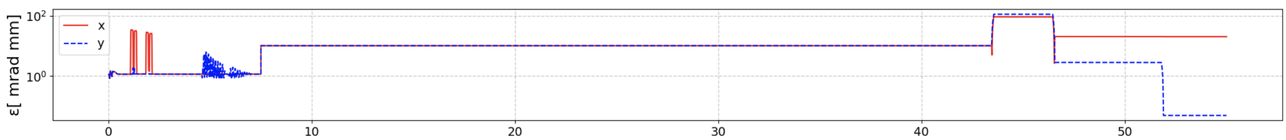

Figure 4: Simulated evolution of transverse (x and y) emittances along the STF beamline during RFBT operation.

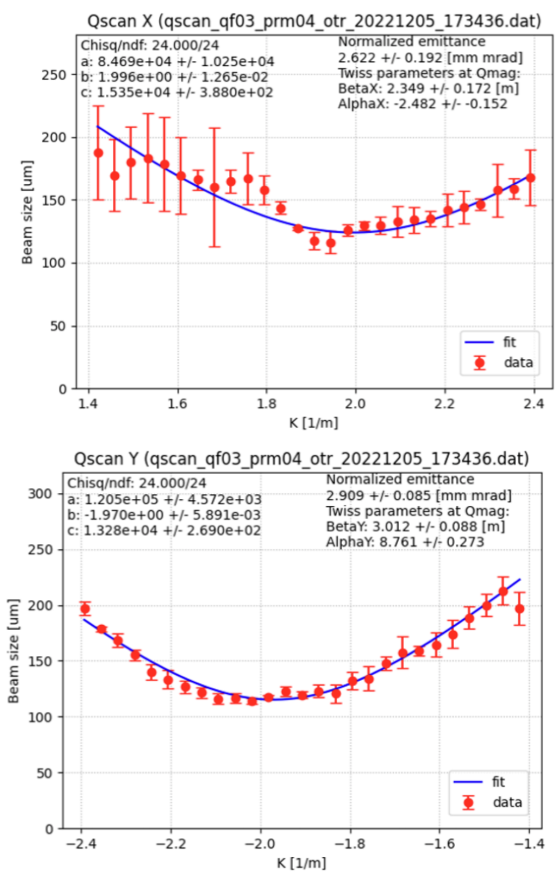

Figure 5: Q-scan plots measured with the QF03 quadrupole magnet in the horizontal (top) and vertical (bottom) directions.

The resulting simulated space charge effects due to the excess focusing are shown in Fig. 7. We plan to test updated simulations aimed at resolving this issue in the coming year, ensuring that the beamline upstream of the superconducting RF cavities is well-represented by simulation and does not exhibit unwanted focusing or space charge effects detrimental to the overall emittance growth in the beamline.

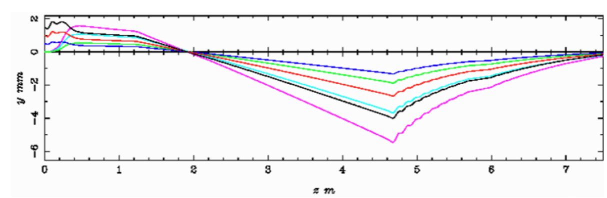

Figure 6: Simulated trajectories of a set of test particles along the STF beamline from the cathode (situated at 0) and the exit of the capture cryomodule (at 7.5 m).

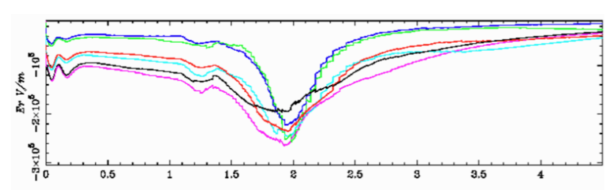

Figure 7: Simulated space charge forces acting on a set of test particles along the STF beamline from the cathode (situated at 0) and the entrance to the capture cryomodule (at 4.5 m).

ACKNOWLEDGEMENTS

This work is partly supported by the Grant-in-Aid for Scientific Research (B).

REFERENCES

[1] ILC Technical Design Report, KEK Report 2013, https://linearcollider.org/ILC/Publications/Technical-Design-Report

[2] R. Brinkmann, Y. Derbenev, and K. Flöttmann, "A low emittance, flat-beam electron source for linear colliders", *Phys.*

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEOGC2

Rev. ST Accel. Beams, vol. 4, p. 0535501, 2001. doi:10.1103/PhysRevSTAB.4.053501

[3] M. Cornacchia and P. Emma, "Transverse to longitudinal emittance exchange", *Phys. Rev. ST Accel. Beams*, vol. 5, p. 084001, 2002. doi:10.1103/PhysRevSTAB.5.084001