EXPERIMENTAL APPROACHES OF EMITTANCE DILUTION INDUCED BY MISALIGNMENTS IN A PHOTOINJECTOR*

J. Park#, M. Babzien, K. Kusche, and V. Yakimenko
BNL, Upton, NY 11973, U.S.A.

Abstract

One of the main issues in the generation of a high-brightness electron beam is the preservation of beam emittance. Here we discuss one of possible source of the emittance dilution by the rf kick due to misalignment. The emittance of a high-brightness electron beam from a photoinjector is affected by the status of alignments due to deflection force by the accelerating field. The misaligned beam with the accelerating field axis experiences emittance growth by an electron-beam defection that is proportional to the electric field strength in the cavity. Misalignments of beam axis induce different deflections on beam particles with energy spread, causing emittance dilution of the beam. In order to reduce the emittance dilution the photoinjector is required well alignments of all components. We show significant emittance growth as misalignments function against the electron beam-axis to accelerating column.

INTRODUCTION

High-brightness electron beams are essential for the accelerator-driven facilities such as light sources, free-electron lasers, laser accelerators, and linear colliders. In order to obtain a high-brightness electron beam requires devices such as a laser driven photocathode rf gun with advanced electron-beam diagnostics to analyze and understand the beam dynamics. The basic principle of the photoinjector is that short electron beams are generated by laser pulses illumination on a photocathode when an rf accelerating structure is located inside the cavity. The rf structure with a high accelerating field is essential to make the electron beam relativistic in a short distance for avoiding the emittance dilution due to space charge effect in the beam. The brightness of the beam is inverse proportional to square of beam emittance and is proportional to the beam peak currents. In order to improve the brightness of electron beam, various methods are attempted for emittance compensation [1-2].

The normalized rms emittance of the electron beam is mostly contributed the three emittance terms, such as the emittance due to the space charge, ε_{sc}, the emittance due to the rf transverse kicks, ε_{rf}, and thermal emittance, ε_{th} [1]. The normalized rms emittance is expressed in Eq. (1).

$$\varepsilon_{n,rms} \cong \sqrt{\varepsilon_{sc}^2 + \varepsilon_{rf}^2 + \varepsilon_{th}^2} \,. \tag{1}$$

The space charge effects, comprising linear and nonlinear forces, usually dominate the total beam emittance. The linear and the nonlinear space charge forces can be compensated by the solenoid focusing [2-3] and by the uniform transverse laser distribution illumination [4], respectively. The thermal emittance is related to the thermal energy of the photo-emitted electrons by expression, $\varepsilon_{th} = r_b/2\sqrt{E_{th}/mc^2}$, where r_b is the transverse beam size on the cathode, mc^2 is the rest energy of the electrons, and $E_{th} = E_{ph} - W$ is the thermal energy as difference between the photon energy (E_{ph}) and the work function (W) of cathode material. The thermal emittance is determined by the laser beam size on the cathode and the laser wavelength.

The emittance is affected by the rf deflections. If the accelerating structures are misaligned, the beam can deflect by the asymmetry field distribution at the entrance of the accelerating sections. The deflection force should be diluted the beam emittance. Emittance dilution due to the rf deflections is [5],

$$\Delta\varepsilon \approx \left(\Theta_{acc}\sigma_z k_{rf}\right)^2 \frac{\langle\beta\rangle L_{acc} G}{\alpha}\left[\left(\frac{\gamma_f}{\gamma_i}\right)^{\alpha} - 1\right], \tag{2}$$

where Θ_{acc} is the structure misalignment, σ_z and k_{rf} are the longitudinal length of the beam and the wave number of the rf, L_{acc} and $\langle\beta\rangle$ are the length of the accelerating structure and the initial average beta function, $\alpha = 0.5$ for the linac, γ_i and γ_f are the initial and final relativistic factor, and $G = e\,E_{rf}/m_0c^2$. In this paper we present experimental approaches of the dependence of the emittance dilution on structural misalignments and comparisons with analytical estimations.

EXPERIMENTAL SETUP

The experimental work is performed at Brookhaven Accelerator Test Facility (ATF). The Nd:YAG laser with a frequency-quadrupled illuminate on the cathode in order to produce electron beams from the photocathode rf gun. A photoinjector is consisted by the photocathode rf gun with emittance compensate solenoid to generate the beam with low emittance, two S-band (2856 MHz) linac sections to accelerate the beam, various magnets to transport the beam to the end of beam line, and auxiliary instruments to measure the beam parameters such as charge, beam size, shape, length, and etc. The electron beam, with a charge of 0.4 nC, is rapidly accelerated in

*This work was supported by the US Department of Energy.
#jpark@bnl.gov

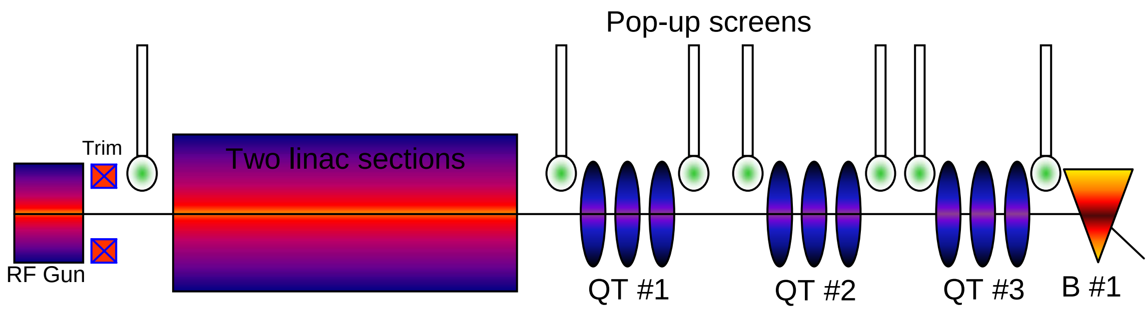


Figure 1. Schematic layout of the ATF for the experiments (not to scale).

the one and half cells of the rf cavity by a 110 MV/m peak electrical field to get an beam energy of 5.1 MeV. The beam from the gun is focused by a solenoid and injected into the two linac sections. A schematic diagram of the ATF photoinjector is shown Fig. 1.

The gun cavity is attached upstream the solenoid with four keys and attaching plates that is aligned mechanically. The cavity is well aligned with solenoid field because field axis of the solenoid is well aligned with the solenoid mechanical axis.

Laser Centering on the Cathode and the Solenoid Scan

If the laser is misaligned along to the electro-magnetic field in the gun cavity, the emittance is diluted due to the beam deflections interaction with the misaligned field. The misalignment of the laser position is significantly affected to emittance dilution. In order to laser position alignment on the cathode, we tried two methods. In the first method, the laser position on the cathode can adjust to align using a laser position mover of horizontal and vertical direction with step motor. In order to align the laser position, a good shape of the beam is searched by a laser mask before the cathode, the laser position mover, the solenoid, and a pop-up screen downstream solenoid. If the laser is well aligned with the field in the cavity, we can see an image of clear and same intensity laser mask on the pop-up screen at specific solenoid current. If the laser is misaligned, we can see a distorted image due to receiving deflection force in the cavity. This method can quickly align the laser position, but this is not enough to accurate alignment. One of contemporary method is solenoid scan of the beam center on the downstream solenoid. The laser alignment is a basic requirement for the linac alignment. The photocathode gun cavity has a single rf power coupler with tilted angle of 45 degrees on normal plane of the beam axis. The misalignment between the laser position on the cathode and fields axis in the cavity may affect the emittance growth and the orbit distortions by the coupler and the field as non-symmetric affection to the beam in the cavity.

The laser and the solenoid are well aligned along to electric field in the gun cavity. But the linac sections are not aligned with gun cavity because the trim coil should be used in order to transport the beam properly from upstream to downstream the linac sections. If the gun and the linac are well aligned, trim coils of the between the gun and the linac are not needed to transport the beam. At constant solenoid current and gun cavity power, we measured the beam position at just after linac sections on beam profile monitor without trim coil along to the rf power and the phase of the linac section. Both positions of vertical and horizontal are changed that comes from effect of misalignment between the gun and the linac section. If that is well aligned, at different power and phase the position should be pointed as the same before. In order to investigate a quantity of misalignments, after applied the trim coil current the positions are also measured at the same condition. Without position changing trim coils current are 0.77 A and -0.66 A in horizontal and vertical, respectively. The position of the beam profile downstream trim coils is changed along to trim currents. The changing rate of trim coil is measured 0.47 mm/A for each direction on the first pop-up screen. From these measurements we can convert the misalignment quantity at the entrance of the linac section of 0.80 mm in horizontal and -0.69 mm in vertical at the entrance of the accelerating section. The structure misalignment angles are 0.95 mrad in horizontal and 0.82 mrad in vertical.

In order for vertical alignment, the mover can adjust the structural misaligned angle between the gun and the linac. The mover is installed to adjust the angle by a hydraulic piston with a bolt from out of the gun hutch to bottom of the solenoid edge. If the piston is pushed with the bolt, the solenoid edge is pushed and simultaneously changed the gun with small angle counterclockwise. If the piston is pulled with the bolt at out of the gun hutch, the gun is rotated the contrary.

The vertical adjusting to align is necessary changing the adjusting screw. After the adjustments, the measurement is performed by the solenoid scan that can use for the measurement the misalignment quantity between the gun and the linac.

Emittance Measurements

The transverse emittance is measured at a first pop-up screen downstream two linac sections by a quadrupole scanning with multi-screen as shown in Fig. 1. The beam transport line for the emittance measurements by multi-screen method is consisted the photocathode rf gun, two accelerating sections, quadrupole magnets, beam profile monitors, several trim coils, and a spectrometer. The monitor comprises a phosphorescent to image of the beam intensity profile, measures with a charge coupled device (CCD) camera, and records data with a frame grabber. Each screen is scanned to obtain the distribution of beam and is fitted to obtain beam size by frame grabber. The beam matrix is reconstructed using transfer matrix elements from the beam transport line and the beam size from the measurements. The emittance is calculated the square root of the determinant of the beam matrix. The emittance ellipse parameters are also calculated from the beam matrix and the calculated emittance [6]. The beam energy is measured of 60 MeV using by a spectrometer magnet downstream the two linac sections as shown in Fig. 1. In order to measure the emittance, the quadrupole currents and the beam sizes on the screen are measured as shown Table 1 and Fig. 2, respectively.

Table1. The quadrupole current are measured for the emittance calculation.

Quad Name	Current (A)
HQ1	-8
HQ2	-7.3
HQ3	-5.6
HQ4	-10.4
HQ5	11.6
HQ6	-17.6
HQ7	-13.5
HQ8	-8.42
HQ9	16.5

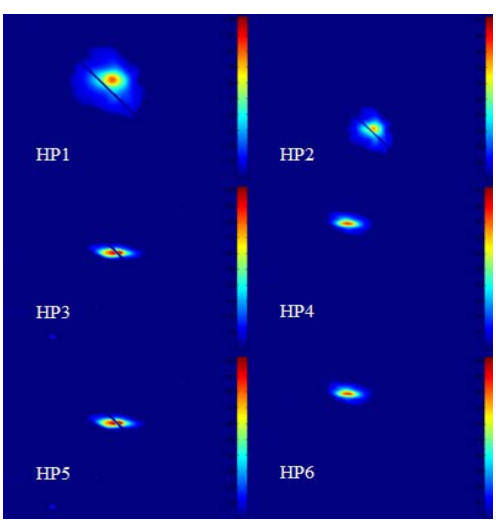
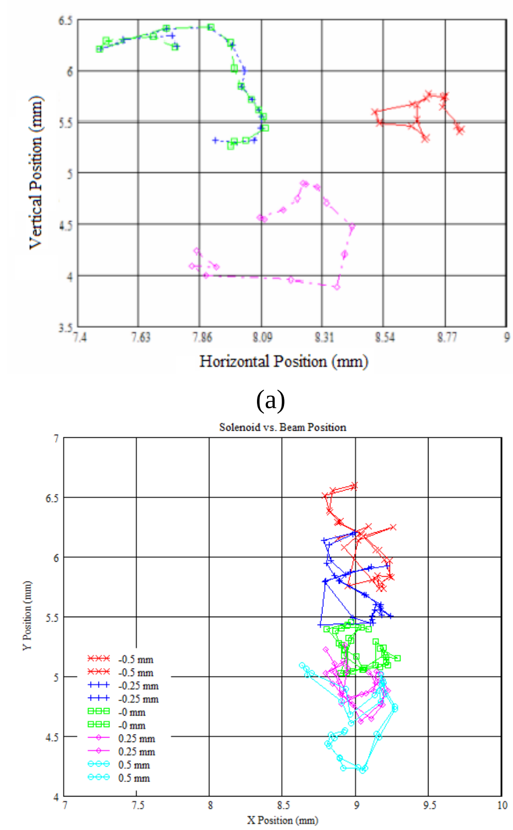


Figure2. The beam shapes for the beam size measurement are measured by the screen that is for the emittance calculation.

EXPERIMENTAL RESULTS

Solenoid Scan for the Alignments

In order to laser centering, we have two checking methods. The first method is measured by the beam shape insert mask for laser alignment on the screen just after the solenoid. The second method is the solenoid scan that measures the beam center position via solenoid current on the same screen as before. The second method is more accurate than the first. If the laser is well aligned, the beam position on the screen should not change along to change of the solenoid current. The electron beam is rotated and focused by the symmetric axial field of the solenoid. If the beam is tilted with the solenoid field, the beam is affected by the field such as the beam is pointed other position on the screen via other solenoid fields.



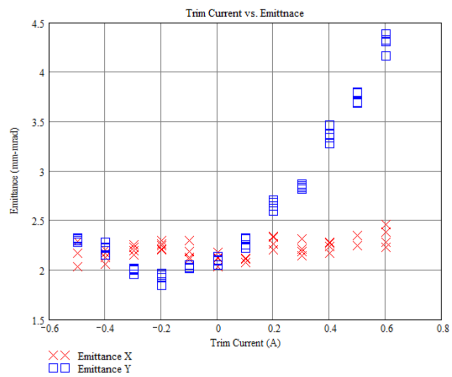
(a)

(b)

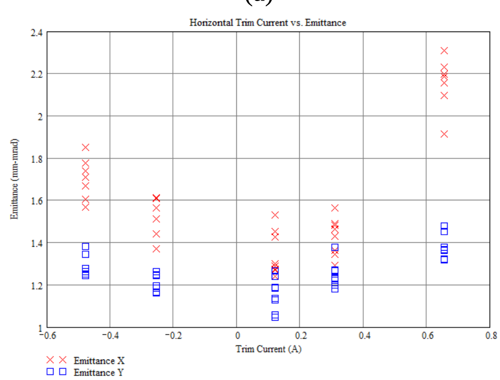
Figure3. The solenoid scan for gun alignment: (a) before (green line), 1st (purple line), and 2nd (red) gun moving in vertical direction for alignment, (b) the measured solenoid scan along to vertical mover position after horizontal alignment.

The alignments are tried by moving the angle of the gun from the linac in the horizontal and the vertical direction with adjustment bolts for fine adjusting. The solenoid scans are measured after and before gun moving as shown Fig. 3. When the gun is misaligned with the linac, the solenoid scans are such as green and purple line in Fig. 3(a). The green line in the Fig. 3(a) is before the gun moving for the alignment. The red line in the Fig. 3(a) is the solenoid scan after gun moving that has much small difference between the positions along to solenoid fields.

In order for the improvement of the vertical adjustment, a hydraulic mover is installed outside of the gun hutch that can remotely adjust the vertical angle without opening the heavy shielding for the gun. After the gun adjustment in the horizontal and the vertical, the solenoid scan is performed along to vertical angle as shown Fig. 3(b). The green line in the Fig. 3(b) is the smallest difference of the solenoid scan when the alignments are optimized.



(a)



(b)

Figure4. The measured beam emittance as function of the trim coil currents: (a) the vertical trim current vs. the beam emittance in the vertical (blue color) and the horizontal (red color), (b) the horizontal trim coil current vs. the beam emittance.

The misalignments vs. emittance

After the gun alignments by the gun moving using adjustment screw and the solenoid scan to find the alignments condition, the beam emittance is measured by quadrupole scan with six screens. The misalignment affects the beam emittance growth and also produces orbit distortions. In order to correct the orbit distortions due to the misalignments that should be applied the trim coil. We try to change the trim coil current between the gun and the linac in order to make misalignment condition in the vertical and the horizontal. The measured beam emittance as function of the trim coil current is shown as Fig. 4. In the vertical coil currents changing to get the results of Fig 4(a), the horizontal alignment offset is minimized by the solenoid scan in advance. In the horizontal coil changing, we tried in the same way as the vertical.

When the trim coil current is increased in the vertical and the horizontal, the beam emittance is significantly increased in comparison with the before an after the alignment. In particularly, when changing of the vertical trim current affect more the vertical emittance than the horizontal because the vertical emittance is affected by the vertical deflection force. The changing of the horizontal trim current is the same result of the vertical.

CONCLUSIONS

The emittance dilution due to the photoinjector misalignment is measured. The solenoid and the gun are well aligned because the magnetic field axis and mechanical axis of the solenoid are well aligned. The laser position centering on the cathode in order to reduce the emittance dilution induced by deflection force in the cavity is improved by the solenoid scan and the laser mask measurement method with the laser adjusting motor. The misalignment of the gun and the linac is improved by the horizontal and the vertical adjustment using by adjusting screws on the gun system. Moreover the vertical adjustment screw with hydraulic system is installed for the remote adjusting without opening the gun hutch with heavy shielding. From out of these improvements, the emittance dilution is reduced due to the rf deflection force by the photoinjector misalignments.

This work was supported by US Department of Energy. The authors are so appreciate to the ATF staff for their assistance and supporting to experiments.

REFERENCES

[1] K.-J. Kim, , Nucl. Instrum. Methods Phys. Res., Sect. A275, 201, 1989.
[2] B. E. Carlsten, Nucl. Instrum. Methods Phys. Res., Sect. A 285, 313 (1989).
[3] X. Qui, K. Batchelor, I. Ben-Ziv, and X-J. Wang, Phys. Rev. Lett. 76, 3723 (1996).
[4] F. Zhou, I. Ben-Zvi, M. Babzien, X. Y. Chang, R. Malone, X. J. Wang, and V. Yakimenko, Phys. Rev. ST Acel. Beams 5, 094203 (2002).
[5] M. G. Minty and F. Zimmermann, “Measurement and control of charged particle beams,” Springer (2003)
[6] A. Chao and M. Tigner, Handbook of Accelerator Physics and Engineering, p.252.