EFFECTS ON EMITTANCE ASYMMETRY CAUSED BY ASYMMETRY FIELDS OF TRAVELING WAVE ACCELERATOR STRUCTURE

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Abstract

Improving transverse emittance asymmetry is one of the most important issues for high-brightness photoinjectors. Especially, in the SPring-8 photocathode RF gun, we have observed that the vertical emittance is always larger than the other. We have tried to get rid of some possible causes of the asymmetry for last decade. However, the asymmetry of transverse emittance has not been improved yet. In this paper, we investigate the transverse emittance asymmetry caused by the geometrical asymmetry of a conventional single-feed coupler cell of the traveling wave accelerator structure. Emittance behaviors were simulated by fully 3D tracking code with 3D field data of the accelerator structure. According to the simulation results, off-centered magnetic field in the coupler cell is turned out the most probable cause of emittance asymmetry discussed here. A slice emittance in the bunch is kept constant, however projected emittance of the whole bunch becomes larger in the coupler cell, since the off-centering varies with the RF phase. From our simulation results, the asymmetry is drastically reduced in the case of a double-feed coupler.

INTRODUCTION

The asymmetry between horizontal (X) and vertical (Y) emittance of the photocathode RF gun is well-known and widely observed. These asymmetries in transverse emittance should be minimized as a high brightness injector for the Linac-based futures light sources. In our experiments of the SPring-8 photocathode RF gun until 2003, the apparatus consists of single cell S-band (2856 MHz) RF gun cavity which beam energy of 3.6 MeV, two solenoid coils and double slits for emittance measurements located downstream. In this case, large emittance asymmetry was observed as shown in Fig. 1. Since the laser incident angle to the cathode surface was 66 degrees to the beam axis, entire wave front of the laser pulse dose not reach the cathode surface simultaneously. Therefore, a large emittance asymmetry was appeared. The tendency of asymmetry effects is explained by our self-made 3D tracking simulation code. The both experimental and simulation results are simultaneously shown in Fig. 1 [1].

In the upgrade of our photocathode RF gun system in 2004, one S-band traveling wave accelerator structure was installed downstream as shown in Fig. 3. The beam energy was upgraded to 26 MeV and a quadrupole scanning was applied as an emittance measurement method instead of the former double slits, since accuracy of measurements becomes worse in double slits with higher energy. In order to get rid of the emittance asymmetry, the laser incidence method was changed to quasi-normal incidence. Contrary to expectation, the Y emittances were still lager than X emittances as shown in Fig. 2.

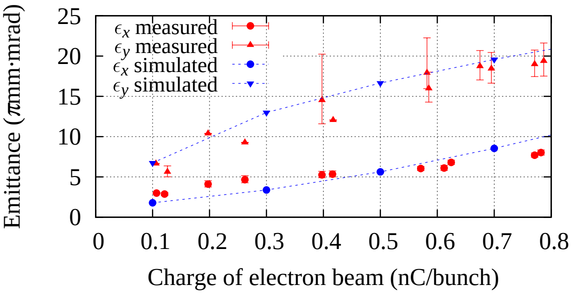

Figure 1: Emittance asymmetry due to the oblique laser incidence.

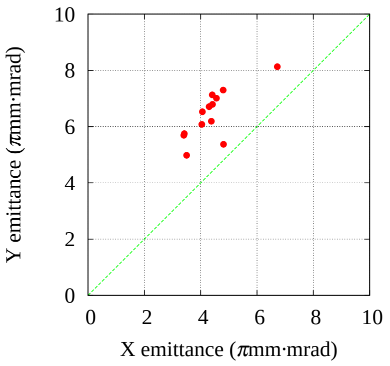

Figure 2: Measured emittance asymmetry.

POSSIBLE CAUSES OF EMITTANCE ASYMMETRY

Possible causes for the asymmetry are listed as follows;

- Imperfect laser spatial profile shaping
- Accuracy on emittance measurement system and data evaluation
- Field's asymmetry of the gun cavity, or solenoid coils
- Miss alignment of laser spot position on the cathode, field of cavity and solenoid coils
- Affects of the laser incident mirror

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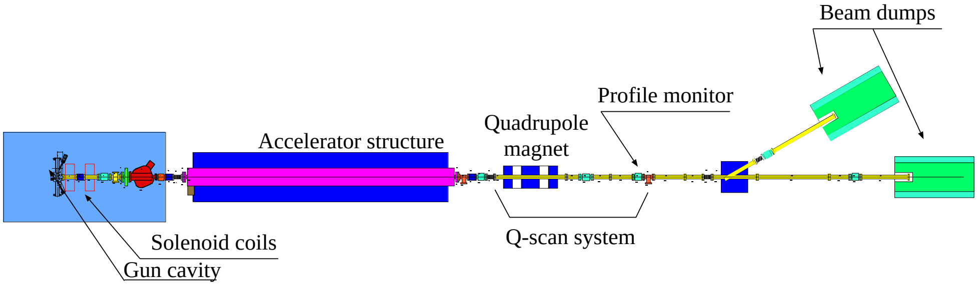

Figure 3: The SPring-8 RF gun system setup.

- Field's asymmetry of the RF coupler cell of the accelerator structure

Using laser profiles even with elliptically shapes elongated in X- or Y-axis, the Y emittance has been always measured larger than the X emittance. Therefore, the asymmetry of the laser spatial profile is not dominant as a cause of emittance asymmetry.

In the quadrupole scanning system [2], beam size variations are measured by CCD camera with an alumina fluorescence screen. The depths of focus of the camera between X and Y are sightly different. However, this effect cannot be significant to explain the large emittance asymmetry. We rotated the CCD camera 90 degrees to check the measurement system asymmetry, though the Y emittance was still larger.

Though our gun cavity, shown in Fig. 4, has two RF ports in the X direction to reduce field's asymmetry in the cavity, it is still remain slightly. Ensured by the 3D-simulation that emittance asymmetry caused by field's distortion in the cavity is negligible.

Alignment tolerance of laser position at the cathode and solenoid coils is estimated to be large enough from the numerical results using 3D tracking code.

The laser incident mirror is conventionally mounted with a metal holder in vacuum. If this mirror edge is not away enough from a beam axis, an asymmetric emittance growth occurs due to a wake field. Also, the mirror is coated with dielectric multilayer on an optical glass substrate, which may cause charging-up. So, we designed that the incident mirror is mounted outside of the vacuum chamber as shown in Fig. 4, incident angle was designed to be 3.6 degrees. From simulation results, emittance asymmetry caused by oblique incidence of 3.6 degrees is negligible.

Therefore, the most probable cause of emittance asymmetry is field's asymmetry of the RF coupler cell of the accelerator structure.

NUMERICAL APPROACH ON EMITTANCE ASYMMETRY

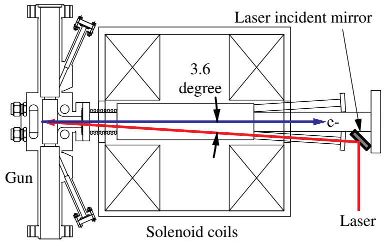

Figure 4: A cavity and a chamber for quasi-normal laser incident system. A laser mirror is located outside of the vacuum chamber.

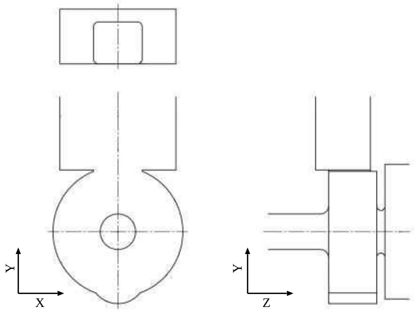

Figure 5: RF coupler cell of the accelerator structure.

Our accelerator structure has single-feed couplers whose RF ports are in the Y direction. In order to reduce asymmetry of longitudinal electric field in the coupler cell, crescentic shape cut is positioned at the opposite side of the RF feed port as shown in Fig. 5, though magnetic field is slightly off-centered.

Theoretical estimations of an emittance growth in the RF coupler cell was reported [3]. They pointed out that time dependent difference of head-tail deflection angle in the bunch results a emittance growth. We investigate these effects numerically, using self-made 3D beam tracking code and 3D field data of accelerator structure.

The field of whole 3 m long accelerator structure is hard for calculation. So we divide the structure into 3 parts, which are from the coupler cell to the third cell, last 3 cells, and the other normal cell section. The first and the last section data are calculated three-dimensionally using MW-STUDIO [4]. The normal cell section is calculated two-dimensionally using POISSON-SUPERFISH. Then, three data are connected smoothly. For each section, two kinds of data are calculated which boundary conditions for both longitudinal ends are the Neumann and the Dirichlet boundary. Fields at the given time is described as composition of these two data;

$$\begin{cases} E_z = N_E\left(z\right)\cos\left(\omega t\right) - D_E\left(z\right)\sin\left(\omega t\right) \\ B_\theta = N_B\left(z\right)\sin\left(\omega t\right) + D_B\left(z\right)\cos\left(\omega t\right) \end{cases} \qquad (1)$$

where, $N_E(z)$ and $N_B(z)$ are the Neumann condition data, $D_E(z)$ and $D_B(z)$ are the Dirichlet condition data.

Simulation was applied on our RF gun setup as shown in Fig. 3. Initial laser temporal shape is square with full width of 20 ps and beam bunch width at the entrance of the accelerator structure is 10 ps FWHM. Charge is 0.3 nC/bunch. Beam energy is 3.6 MeV at the entrance and 26.0 MeV at the exit of the accelerator structure. Beam size at the accelerator structure can be varied with the field strength of the solenoid coils.

The upper graph of Fig. 6 shows a result using single-feed coupler structure, and the lower is a result of double-feed coupler structure. In each figure, simulated emittance at the exit of the accelerator structure are plotted as a function of beam size at the entrance of the accelerator structure.

With the single-feed coupler structure, asymmetry is large and this effect is one of the causes of our experimental emittance asymmetry. Using the double-feed coupler cell, this asymmetry is able to be reduced.

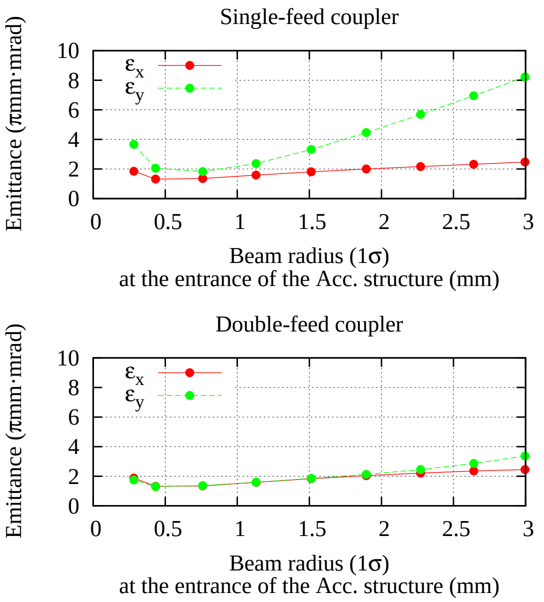

Figure 6: Simulated emittance asymmetry.

DISCUSSION

The Case of the Single-Feed Coupler

Understanding emittance growth mechanism, we discuss just about the data of the largest beam size in Fig. 6, which produces large emittance asymmetry at the single-feed coupler.

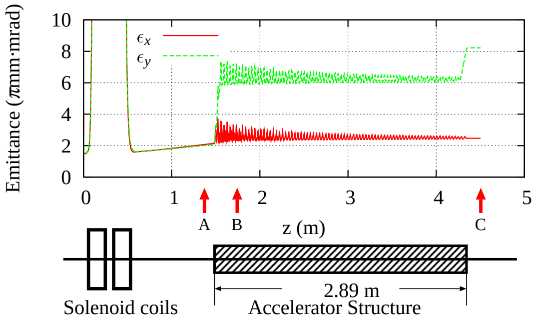

Figure 7: Time evolution of emittance with the single-feed coupler structure.

Figure 7 shows time evolution of transverse normalized emittance from the cathode to the exit of the accelerator structure. The emittance grows in the solenoid coils, since there is coupling between X and Y. After the solenoid coil section, the emittance is kept at low level, however Y emittance growth is enhanced at the entrance (z = 1.467 m) and the exit (z = 4.357 m) of the accelerator structure.

In Fig. 8, Y-Y' phase-space plots at the position of A, B and C in the Fig. 7 are shown. In each plot, slice emittance at head (red dots), middle (green dots) and tail (blue dots) of the bunch are plotted simultaneously. At point A before the accelerator structure, all of slice plots are overlapped each other. Though at the point B just downstream of the input coupler cell, each slice plot shifted in Y' direction and also rotated. Even if the slice emittance itself is kept almost constant, these shifts and rotations make projected emittance larger.

The cause of the shifts in Y' direction is an off-centering of magnetic fields in Y direction. That is, the field center is displaced in the coupler. This displacements are different for each slice plot because the off-centering varies with RF time evolution.

From Fig. 8, beam is defocused at A and focused at B. This is due to a focusing effect of the accelerator structure. Figure 9 shows time evolution of the beam size. Integration of $dv_y/dt = e/\gamma m_0 \left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}\right)_y$ from the entrance of the accelerator structure, which is acted on certain electron in the bunch is also plotted. The electron is basically defocused at the exit of a cell and focused at the entrance of the next cell by B_θ and E_r. These focusing and defocusing forces are canceled each other, and result an oscillation of integration of dv_y/dt in Fig. 9. So there are no focusing effects in the normal cell section. Though at the entrance of the input coupler, strong focusing force is remained, because the forces at the entrance are not canceled. In the same manner, defocusing force remained at the output coupler cell, however the defocusing effect on the beam is small because of higher beam energy. These focusing effects vary with RF time evolution in the bunch. So that the slice plot's rotation in Fig. 8 is occurred.

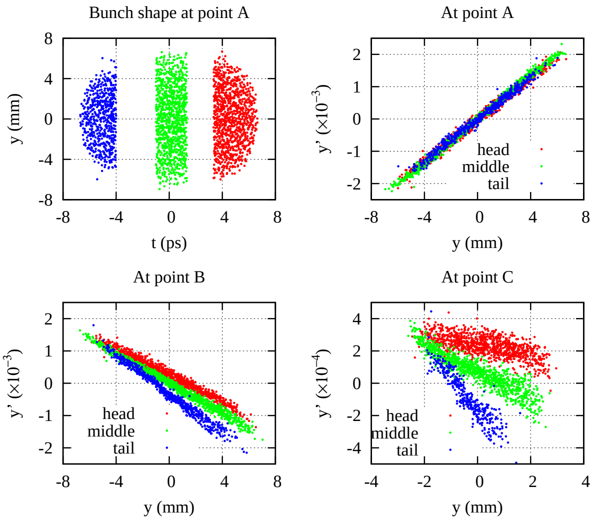

Figure 8: Slice emittance at before and after the accelerator structure with single-feed coupler. In real electron bunches, blank areas of the bunch at the upper left graph are filled with electron particles.

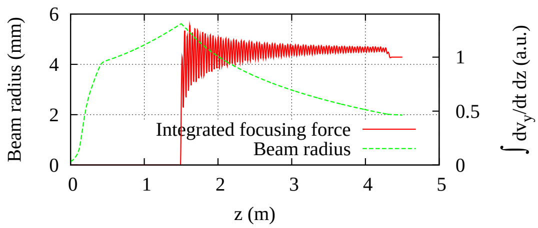

Figure 9: Focusing effect of the accelerator structure.

As shown in Fig. 6, emittance asymmetry becomes lower as the beam size is smaller, because of the growing process of projected emittance mentioned above. The emittance of the smallest beam size in Fig. 6 grows larger. In this case, beam size at the entrance is small enough that waist point of the beam exists in the accelerator structure, then the beam size at the output coupler becomes large, and the emittance grows.

The Case of the Double-Feed Coupler

The emittance asymmetry appears slightly when the beam size is large as shown in Fig. 6.

Figure 10 shows time evolution of emittance with the double feed coupler structure. Slice emittances at point A, B, and C is also plotted simultaneously in Fig. 11. The beam size at the entrance is equivalent to the single feed coupler case.

As for the double-feed coupler, the shift of each slice plot in the phase space disappears because of no geometrical asymmetry exists. However, the rotations are remained because it is not related to the fields' asymmetry. If we use a quadru-feed coupler, emittance asymmetry can be removed, though emittance growth due to the rotations of the slice plots will remain.

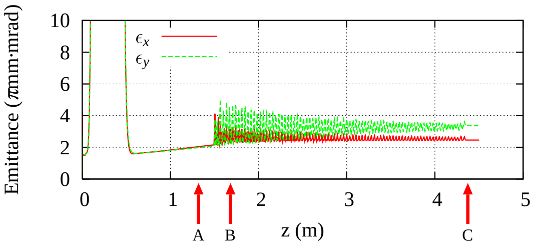

Figure 10: Time evolution of emittance with the double-feed coupler structure.

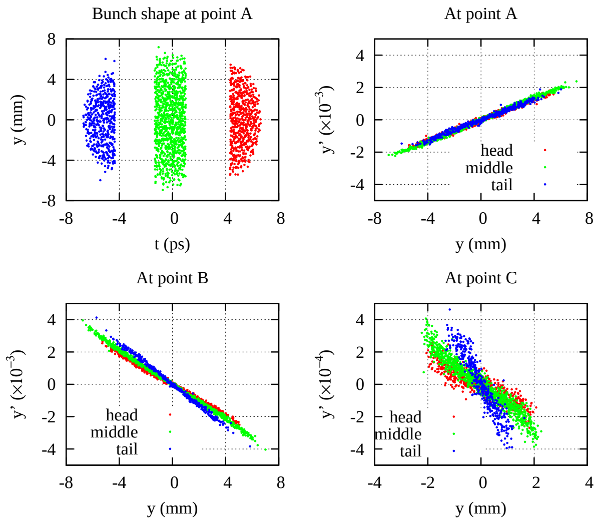

Figure 11: Slice emittance plots of the double-feed coupler structure.

SUMMARY

The causes of the emittance asymmetry and emittance growth mechanism are investigated. The emittance asymmetry due to the coupler cell of the accelerator structure is considered as one of the most dominant effects on this issue. The X and Y emittance differences of $1 \sim 2$ πmm·mrad in our experimental results are able to be explained by the off-centering field in the coupler at the both ends of accelerator structure. Even if we use the double-feed coupler cell, the asymmetry is not perfectly removed, however it will be negligible if the beam size is not large.

In the next step, we are planning to introduce an accelerator structure with double-feed couplers. We expected that this is the final solution for the imperfect emittance symmetry.

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