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LOW EMITTANCE ELECTRON BEAM TRANSPORTATION IN COMPACT ERL INJECTOR

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Abstract

For future light source based on Energy Recovery Linac (ERL), an injector, which consists of a photocathode DC gun and superconducting RF cavities, is a key part to generate a low emittance, short pulse and high bunch charge electron beam. In compact ERL (cERL), which is a test accelerator to develop key technologies for ERL, the generation of low emittance electron beam with 0.1 mm mrad normalized emittance and 390 keV beam energy from the photocathode DC gun, and the acceleration to 5.6 MeV by superconducting cavity, were demonstrated in the first beam commissioning. To keep the high quality in the beam transportation, understanding the beam optics, which is affected by not only the focusing effects due to the gun, solenoid magnets and RF cavities but also space charge effect, is required. In this paper, we show that how to measure and correct the gun focusing effect by experimental method. Using this method, we succeeded in correcting the numerical model to give the good agreement with the measured gun focusing effect for low charge beam. And, we show the space charge effect for high bunch charge beam.

INTRODUCTION

Photocathode DC gun was employed as an electron source for an Energy Recovery Linac (ERL) to generate high brightness and high average current beam. The required properties of electron beam from the photocathode DC gun for the ERL are low normalized emittance of 0.1 mm mrad, short pulse length of few ps, high bunch charge of 77 pC/bunch, and CW operation with 1.3 GHz repetition rate. In the compact ERL (cERL) [1], which is a test ERL accelerator, a 500 kV photocathode DC gun, which is developed by JAEA [2], is operated with the operating voltage of 390 kV. To keep the high quality in the transportation line, to understand the beam dynamics from the gun is important. Around the gun, not only space charge effect, but also gun focusing effect due to transverse electric field, initial condition of excitation laser, e.g. laser spot size, laser pulse width and laser power, and focusing optics due to a solenoid magnet affect the beam transportation. To verify the condition of the beam transportation, we measured the gun focusing effect and the solenoid focusing effect using the cERL injector. And, we modified our numerical model around the gun to reproduce the measurement results. In this paper, we show the measurement results of the gun and solenoid focusing effects, and a method to adjust the numerical model. After correcting the numerical model, we increased the bunch charge from 10 fC to 7.7 pC to study space charge effect.

FOCUSING EFFECT OF GUN

The cathode and anode shape of the photocathode DC gun for the cERL is shown in Fig. 1. The gap between the cathode and anode is 160 mm. The longitudinal electric field on the longitudinal axis, $E_{z0}(z)$, is shown in Fig. 2. Because the gun shape has axisymmetry, we can calculate the longitudinal and transverse electric fields with a radial offset, r, from $E_{z0}(z)$ as follows,

$$E_z(r,z) = E_{z0}(z) - \frac{1}{4}r^2\frac{\partial^2 E_{z0}(z)}{\partial z^2}, \quad (1)$$

$$E_r(r,z) = -\frac{1}{2}r\frac{\partial E_{z0}(z)}{\partial z}. \quad (2)$$

The transverse electric field depends on $\partial E_{z0}/\partial z$. Therefore, the electron beam is affected by focusing effect in $\partial E_{z0}/\partial z < 0$, and defocusing effect in $\partial E_{z0}/\partial z > 0$. Based on the electric field, single particle tracking simulations with different initial radial positions were carried out using General Particle Tracer (GPT), and the result is shown in Fig.3. The gun causes focusing effect on and around the cathode, and the total transverse force is defocusing, as shown in Fig.3. By the measurement of the relationship between the initial position on the cathode and the beam position on the screen, we can estimate the gun focusing effect.

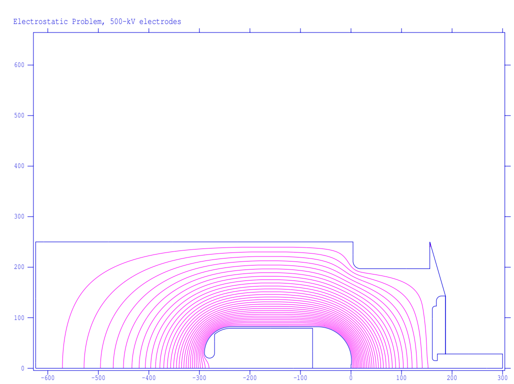

Figure 1: Cross section view of cathode and anode shape of 500 kV DC gun. The cathode and anode are located on $z = 0$, and 160 mm, respectively.

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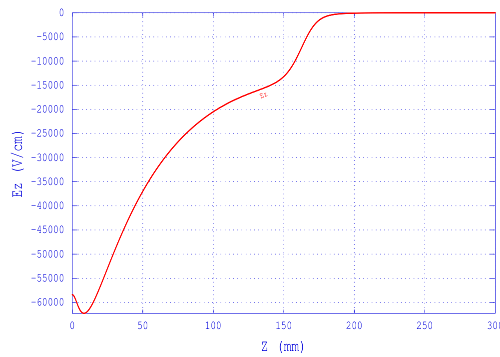

Figure 2: Longitudinal electric field, $E_{z0}(z)$, along longitudinal axis, z, from cathode to anode.

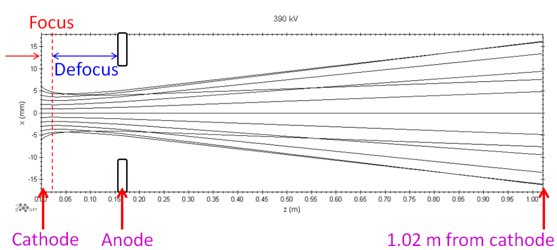

Figure 3: Calculated particle trajectories with different offsets from cathode center.

MEASUREMENT OF GUN FOCUSING

In order to measure the gun focusing effect, we used a screen monitor, MS1, as shown in Fig. 4. In the measurement, a solenoid magnet, SL1, and a bunching cavity were turned off to avoid the additional focusing effect due to them, and the beamline between the gun to MS1 was a drift space. The measurement method of the gun focusing effect is shown in Fig. 5. We shifted the laser position on the cathode, and measured the beam center position on MS1. To avoid space charge effect, the bunch charge is 10 fC. The measured and calculated beam positions on MS1 is shown in Fig. 6. The horizontal and vertical responses are almost the same. It shows that the electrode has axisymmetric shape. However, the measurement result did not agree with the particle tracking result. To reproduce the measurement result, we modified the cathode electrode shape for the particle tracking simulation, because the focusing effect is sensitive to it.

CORRECTION OF GUN MODEL

As shown in Fig. 7, the cathode electrode has a margin to connect the cathode pack, which hold GaAs material. The recess of the gun may be different from the design value of 0.5 mm. As shown in Fig. 6, the measurement result has weaker defocusing effect compared with the simulation result. It indicates that the actual recess is larger than the original value, because larger recess increases E_{z0} on the cathode, and decreases $\partial E_{z0}/\partial z$. Therefore, it causes stronger focusing effect around the cathode. In order to correct the gun

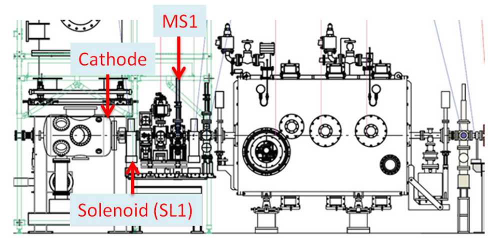

Figure 4: Layout of injector beamline, which consists of a gun, solenoids, a bunching cavity, and screen monitors (MS1 and MS2).

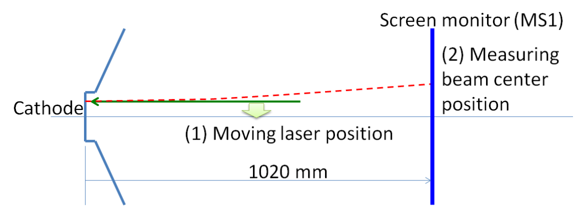

Figure 5: Procedure to measure gun focusing using screen monitor, MS1.

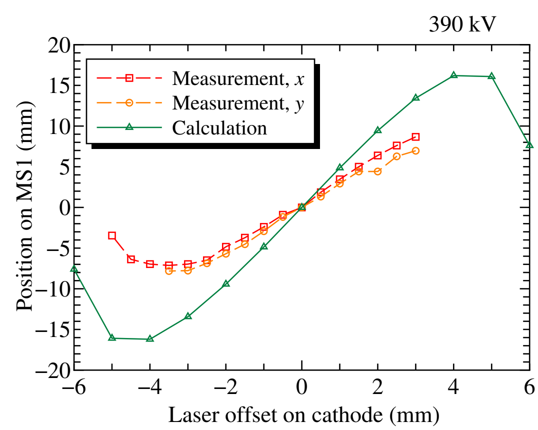

Figure 6: Measured and calculated results of gun focusing.

focusing effect, we calculated the field maps with different recess of 0.9, 1.0 and 1.2 mm, which cause stronger focusing effect, and carried out the particle tracking simulations. As shown in Fig. 8, the recess of 0.9 mm reproduced the measurement results. From this correction, we decided the cathode shape for the particle tracking simulation as the recess of 0.9 mm. So far, we treated the beam as a single particle. In the next step, we check the multi particle dynamics by solenoid scan method.

BEAM TRANSPORTATION

The emitted electron beam from the cathode strongly depends on initial laser condition, e.g. spot diameter, wave length, pulse width and power. In the beam operation, the laser wave length is 532 nm, and the initial thermal transverse energy, $k_B T$, is 120 meV for GaAs photocathode [3]. The laser temporal pulse width is 3 ps rms with gaussian profile. For the transverse beam dynamics, the initial laser spot

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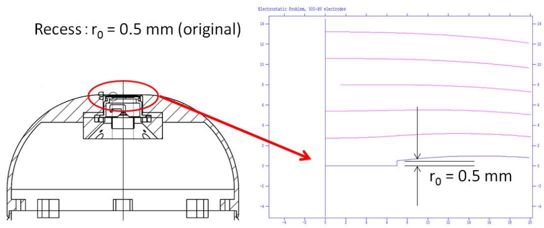

Figure 7: Cathode recess. The designed recess is 0.5 mm.

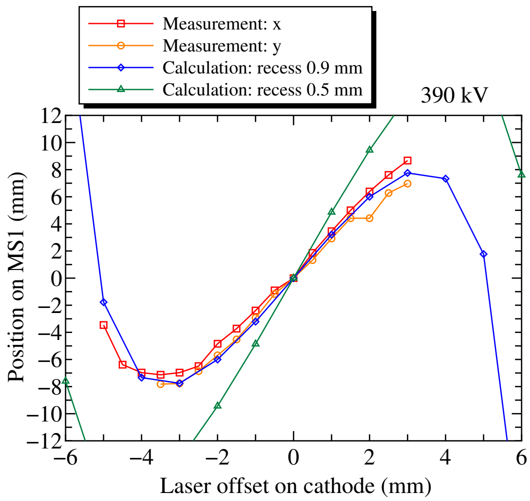

Figure 8: Measured and calculated results of gun focusing with corrected cathode shape.

diameter is important. We can estimate it by measurement of the beam size on the screen with 10 fC/bunch to avoid space charge effect. To increase measurement accuracy, we carried out solenoid scan using SL1 and MS1 in Fig. 4. The measured and calculated results with the design value of 1.2 mm diameter are shown in Fig. 9. The calculated result with the corrected gun shape almost agreed with the measurement. However, the slight difference remains. To improve the agreement, we carried out the fine tuning of the initial laser spot diameter in the numerical model. The calculation result with the diameter of 1.1 mm reproduced the measurement results as shown in Fig. 9. To confirm it, we also measured the laser spot diameter on the cathode. The measured horizontal, vertical and average diameters are 1.02 mm, 1.09 mm and 1.06 mm, respectively. The measured laser spot diameter agreed with the corrected diameter of 1.1 mm. Form the correction, we decided the initial laser spot diameter as 1.1 mm.

SPACE CHARGE EFFECT

In order to study space charge effect, we carried out solenoid scan with 7.7 pC/bunch. The solenoid response for 7.7 pC/bunch is different from no space charge case as shown in Fig. 10. To reproduce the measurement result, we carried out numerical simulations. The simulation results suggest that the charge density in the measurement may be lower. So far, slight difference between the numerical model and the measurement still remains.

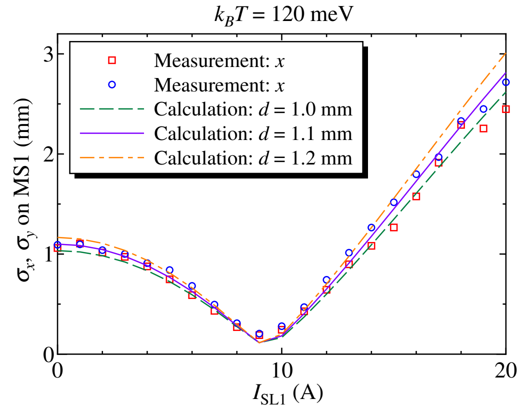

Figure 9: Measured and calculated results of solenoid scan with different initial laser spot diameters.

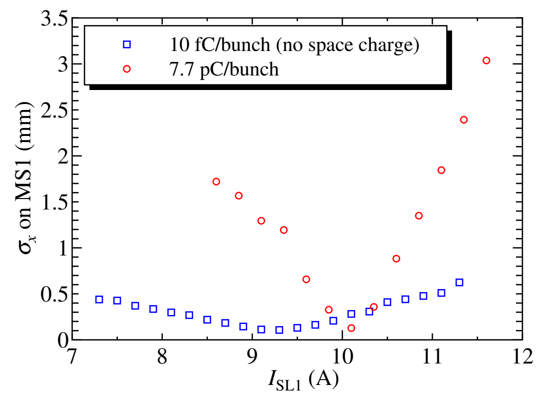

Figure 10: Measurement results of solenoid scan on MS1 with and without space charge effect.

SUMMARY

To reproduce the measured low emittance beam transportation from the photocathode DC gun by numerical model, we measured the gun focusing effect, and carried out solenoid scans with and without space charge effect. From the measurement results, we decided the cathode shape for the corrected numerical model as the recess of 0.9 mm. Form the solenoid scan result without space charge effect, we decided the initial laser spot size as 1.1 mm for the corrected numerical model.

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