TRANSVERSE EMITTANCE MEASUREMENT OF KAERI LINAC WITH THICK LENS QUADRUPOLE SCAN

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Abstract

The UED (Ultrafast Electron Diffraction) beamline of KAERI (Korea Atomic Energy Research Institute) WCI (World Class Institute) Center has been completed and successfully commissioned. Transverse emittance of the electron beam was measured at the entrance of the UED chamber with the quadrupole scan technique. In this technique, larger drift distance between the quad and screen is preferred because it gives better thin lens approximation. A space charge dominated beam however, will undergo emittance growth in the long drift caused by the space charge force. We suggest mitigating this growth by introducing quadrupole scan with short drift and without thin lens approximation. We shall discuss the measurement process and results.

INTRODUCTION

The RF photogun of KAERI WCI Center is designed to generate sub-picosecond electron bunches with energy around 3.2 MeV. The beam can be delivered to UED experiments or can be further accelerated up to 20-30 MeV by the main accelerating cavity for X-ray/THz pump and probe experiments as shown in the Fig. 1. The UED section of beamline is designed to supply electron bunches with 0.1 ps length, 1 pC charge, and nominal energy of 3 MeV a ninety degree using an achromatic bend by velocity bunching [1].The UED section has been successfully commissioned recently and electron beam parameters were measured.

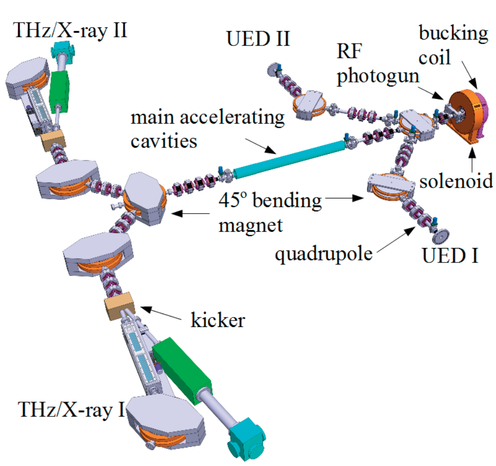

Figure 1: KAERI WCI center electron beamline layout.

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Transverse emittance and Twiss parameters are important parameters of an accelerator to quantify the beam quality and match optics. Most common methods to measure emittance are quadrupole scan [2–6], the slit and collector [7, 8], the pepper-pot [9]. In the quadrupole scan, the beamsize is measured as a function of the quadrupole magnetic field strength [2]. Imaging screens like OTR (Optical Transition Radiation), YAG (Yttrium aluminium garnet), or phosphor screens are used to observe beam profile along with a synchronized camera. Generally, thin lens approximation is applied and rms beamsizes obtained from the beam profile are used to extract the emittance and Twiss parameters by fitting a parabolic function.

The thin lens approximation is effective when $\sqrt{k_1}L << 1$, where k_1 is quad strength and L is its effective length. The quad here is viewed as a thin focusing/de-focusing lens. In quadrupole scanning method, for a better thin lens approximation k_1 is kept small while the drift distance between the quad and screen is set as large as possible (usually few meters). But a space charge dominated beam pass through a long drift will experience emittance growth due to the space charge force [10]. This growth can be mitigated by shortening drift length and extracting emittance without using thin lens approximation. In our case, drift length is 23 cm.

THICK LENS QUADRUPOLE SCAN

In quadrupole scan, a quadrupole magnet and a screen are used to measure the emittance ans Twiss parameters of the beam. The screen is separated from the quad by a drift distance. Transfer matrix of the scanning region **M** is given by the matrix product of the transfer matrices of drift **S** and quad **Q**

$$\mathbf{M} = \mathbf{SQ} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}. \quad (1)$$

Here **S** and **Q** are given by

$$\mathbf{Q} = \begin{pmatrix} cos\sqrt{k_1}L & \frac{1}{\sqrt{k_1}} sin\sqrt{k_1}L \\ -\sqrt{k_1} sin\sqrt{k_1}L & cos\sqrt{k_1}L \end{pmatrix}, \quad (2)$$

$$\mathbf{S} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}, \quad (3)$$

where l is the drift length. The beam matrix at the screen ($\sigma_\mathbf{s}$) is related to the beam matrix of the quadrupole ($\sigma_\mathbf{q}$) using the similarity transformation [11]

$$\sigma_\mathbf{s} = \mathbf{M}\sigma_\mathbf{q}\mathbf{M}^\mathrm{T}. \quad (4)$$

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where the $\sigma_\mathbf{s}$ and $\sigma_\mathbf{q}$ are defined as

$$\sigma_{\mathbf{s},x} = \begin{pmatrix} \sigma^2_{s,x} & \sigma_{s,xx'} \\ \sigma_{s,xx'} & \sigma^2_{s,x'} \end{pmatrix}, \ \sigma_{\mathbf{q},x} = \begin{pmatrix} \sigma^2_{q,x} & \sigma_{q,xx'} \\ \sigma_{q,xx'} & \sigma^2_{q,x'} \end{pmatrix}. \tag{5}$$

The matrix element $\sigma_{s,x}/\sigma_{q,x}$ is the horizontal rms beam size at the screen/quad. $\sigma_{s,x}$ can be expressed as the function of the matrix elements m_{11} and m_{12} as

$$\sigma^2_{s,x} = \sigma_{q,x}\beta_{q,x}\left(m_{11} + m_{12}\frac{-\alpha_{q,x}}{\beta_{q,x}}\right)^2 + m^2_{12}\frac{\sigma_{q,x}}{\beta_{q,x}}. \tag{6}$$

The transfer matrix elements m_{11} and m_{12} are given as

$$\begin{aligned} m_{11} &= cos\sqrt{k_1}L - l\sqrt{k_1}sin\sqrt{k_1}L, \\ m_{12} &= \tfrac{1}{\sqrt{k_1}}sin\sqrt{k_1}L + lcos\sqrt{k_1}L. \end{aligned} \tag{7}$$

When thin lens approximation is valid, Eq. (6) becomes a parabolic function. The emittance and Twiss parameters are extracted by measuring $\sigma_{s,x}$ and fitting the parabolic function. Since we used short drift distance to mitigate emittance growth, the thin lens condition $k_1L \ll 1$ is no longer satisfied. So, we obtained emittance and Twiss parameters by directly fitting Eq. (6) and by treating the quad as a thick lens.

EMITTANCE MEASUREMENT

Experiment Setup

The experimental setup of the emittance measurement with quad scan is shown in the Fig. 2. Electron beam from the RF photogun is delivered to the UED chamber using two 45° dipole magnets and 6 quads. Five retractable imaging screens s1-s5 as shown are used observe the beam. The current quad 6 (q6) shown in the Fig. 2 is varied to perform scanning. A P-22 type phosphor screen s5 with 12.7 mm diameter is located at 23.0 cm downstream of the q6. A synchronized camera (Basler scout scA 600-28fm) placed under the screen are used to observe beam profile.

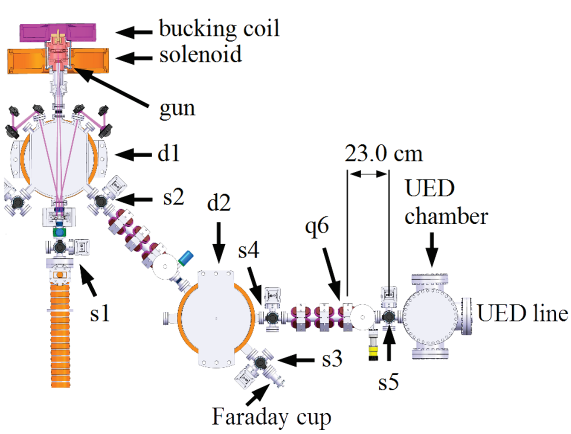

Figure 2: Quadruple scan experimental setup.

The beam energy and energy spread are measured using dipole d1 and screen s2. The magnetic field of the d1 is mapped to determine the energy of the beam when it bent by 45°. A Faraday cup is placed at the end of the 45° line to measure electron bunch charge. The effective length of the quad was measured to be 8.335 cm by mapping the quad magnetic field.

Experiment Procedure

As shown in the Fig. 2, the electrons in the gun is focused by a solenoid. The beam is first observed at screen s1 where it is tuned to round shape. Then it is bent 45° by d1 and observed on s2. By observing beam position on s2, the beam energy is maximized by adjusting laser delay. Then d1 is turned off and beam is observed on s1 and tuned to round shape again. Then beam is bent again by d1 and observed on s2. The coil current of the d1 is recorded to estimate energy and energy spread of the beam.

Then this beam is then delivered s3 using d1 and q1-q3. The beam is centered and tuned to round shape at s3. Then the screen s3 is retracted from the beamline and beam is delivered to FC. The electrical signals from FC created by electron bunches are amplified by a preamplifier and observed using a oscilloscope. The upstream magnets tuned to obtain maximize the oscilloscope which is used to calculate electron bunch charge.

Then d2 is turned on beam is delivered s4 first and s5 later. The horizontal beamsize at s5 usually is larger than vertical because of the beam dispersion. The dispersion is suppressed by adjusting q1-q3 while turning off q4 and q5. When dispersion is suppressed, q6 can focus the beam into a horizontally narrow shape on s5. Then q4 and q5 tuned to form a round beam on s5 while q6 is off. The scan is performed by changing q6 coil current and recording beam image.

DATA ANALYSIS AND RESULTS

Beam images from camera were calibrated using the screen target frame which has 12.7 mm diameter. The scaling factor can be obtained by dividing the diameter of the frame with the number of pixels in the diameter. The result is a horizontal scaling factor of 0.0158 ± 0.0006 mm/pixel. Beam images processed using a MATLAB based script. Beam profile observed on phosphor is shown in the Fig. 3. The yellow lines are beam projections and fitted with Gaussian distribution as shown by red curve.

The emittance measurement was performed by changing the quadrupole current, which changes quad strength k_1, and measuring the corresponding beam image on the view screen. The measured two-dimensional beam image was projected along the image's abscissa and ordinate axes. The rms value is extracted by fitting Gaussian distribution to the beam projection. Measurements of σ_s for several quadrupole currents/k_1 is then fit using the function in Eq. (6) to determine the emittance and the Twiss parameters. The Fig. 4 shows the square of the rms (σ_s^2) vs k_1 for x (horizontal)

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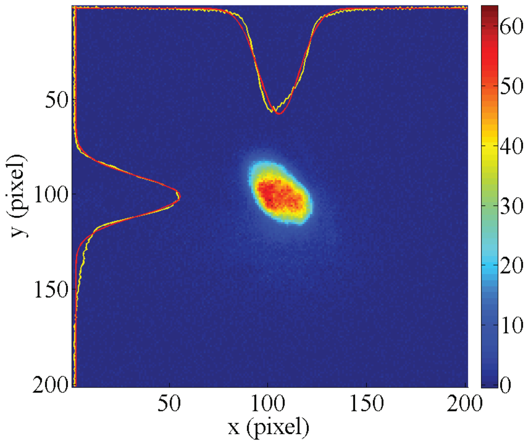

Figure 3: Electron beam profile observed on phosphor screen when q6 is off. The yellow/red line is projection/Gaussian fits.

and y (vertical) beam projections along with the fits using Eq. 6. The emittances and Twiss parameters from these fits are summarized in Table. 1.

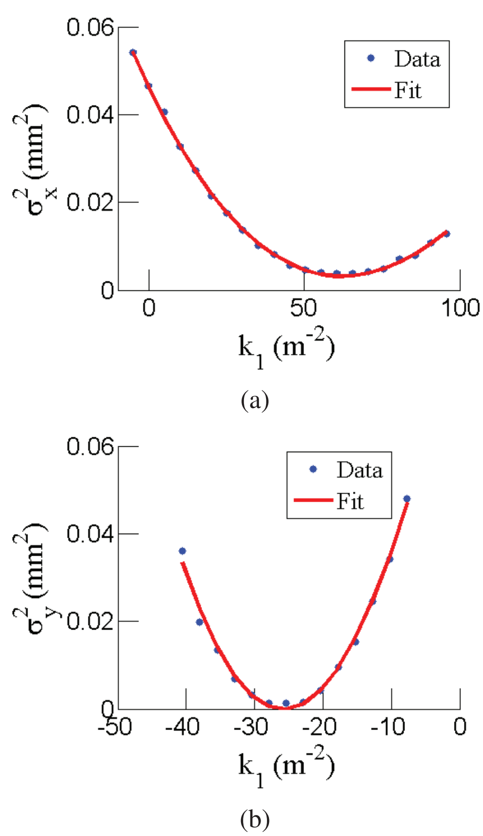

Figure 4: Squares of rms beamsize *vs* k_1 and fit using thick lens equation; (a) beam horizontal projection, (b) beam vertical projection.

The vertical emittance is significantly larger than horizontal one. One possible reason is vertical beam size reached its waist during the scanning and couldn't be focused further. However, the curve in Eq. (6) follows smaller vertically minimum beamsize as can be seen in the Fig. 4 (b). We plan to perform a test by beginning the quad scan with a with larger vertical size instead of round shape.

Table 1: Emittance Measurement Results

Parameter	Unit	Value
normalized emittance $\epsilon_{n,x}$	µm	0.23 ± 0.03
normalized emittance $\epsilon_{n,y}$	µm	0.42 ± 0.07
β_x-function	m	0.63 ± 0.10
β_y-function	m	5.5 ± 1.6
α_x-function	rad	0.9 ± 1.1
α_y-function	rad	0.23 ± 0.03
bunch charge	pC	1.12 ± 0.03
total energy E	MeV	3.26
relative energy spread $\Delta E/E$	%	0.32

CONCLUSIONS

We have used quadrupole scanning method with thick lens equation to measure the beam emittance of the WCI cetner UED Linac at the KAERI. The horizontal/vertical emittance was measured to be 0.23 ± 0.03/0.42 ± 0.07 µm for 1.12 ± 0.03 pC bunch charge. The vertical emittance is significantly larger than horizontal one. We plan to conduct further investigation on this matter. We also plan to measure emittance *vs* charge in the near future and compare emittances obtained with and without thin lens approximations as charge grow.

ACKNOWLEDGMENT

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REFERENCES

[1] N. Vinokurov *et al.*, in *Proc. FEL2013*, New York, USA (2013).

[2] S. Setiniyaz *et al.*, in *Proc. IPAC2012*, New Orleans, USA (2012).

[3] B. E. Carlsten *et al.*, "Nucl. Instrum. Methods. A", 1993.

[4] E. Chiadroni *et al.*, in *Proc. DIPAC2009*, Basel, Switzerland (2009).

[5] R. Spesyvtsev *et al.*, in*Proc. FEL2008*, Gyeongju, South Korea (2008).

[6] C. Thomas, *et al.*, JINST 6, P07004 (2011).

[7] A. V. Steenbergen, *Nucl. Instrum. Methods* 51, 245 (1967).

[8] M. Walter *et al.*, in *Proc. PAC2003*, Portland, USA (2003).

[9] K. Kubo, ATF internal report ATF-98-35 (1998).

[10] C. Sawyer and N. Norris, in *Proc. LINAC84*, Seeheim, Germany (1984).

[11] S.Y. Lee, *Accelerator Physics*, (Singapore: World Scientific, 2004), 61.

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