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MEASUREMENTS OF THE TRANSVERSE BEAM EMITTANCE AT THE AREAL LINAC

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Abstract

One of the main tasks for advanced experiments in modern accelerators is the generation of low-energy and high-brightness beams. The Advanced Research Electron Accelerator Laboratory (AREAL) is a linear electron accelerator based on a photocathode RF gun. The basic aim of this facility is to generate electron bunches of sub-picosecond duration with an extremely small beam emittance for ultrafast processes in advanced experimental studies in the fields of accelerator technology and dynamics, material, and life sciences. In this paper, the current status and plans for further upgrades of the diagnostic system, along with the techniques used for transverse beam emittance measurements, are presented.

INTRODUCTION

The pursuit of advanced particle accelerator technologies has led to the development of laser driven linear electron accelerators, which offer promising opportunities for compact and cost-effective particle acceleration. However, effective beam quality characterization remains a major challenge in these systems. One of the most important aspects of beam quality assessment is the measurement of transverse emittance. Transverse emittance refers to the extent to which particle trajectories spread in the transverse plane (perpendicular to the beam direction) within the particle beam. It characterizes the size and divergence of the beam, affecting its focusing ability and overall quality Accurate emittance measurement is essential to optimize beam performance for advancing applications in various fields and ensure compatibility with downstream applications such as free electron lasers (FELs) and medical accelerators. There are traditional methods for emittance measurements such as wire scanners, pepper-pot devices and quadrupole scan. In this article, we take a closer look at the approach to using quadrupole scanning techniques to measure transverse emittance in the AREAL linear accelerator.

AREAL LINAC

The main goal of the AREAL linear accelerator [1] is generation of 5-20 MeV energy, small emittance and ultrashort duration electron bunches for advanced research in the fields of accelerator and beam physics. The main design parameters of the electron beam for first two stages are given in the Tab 1:

Table 1: Main Parameters of AREAL Beam

		Single Bunch	Multi Bunch	Single Bunch	Multi Bunch
Bunch Charge	(pC)	10-100	30	10-100	30
Bunch length rms	(ps)	0.5-4	0.5-4	0.5-4	0.5-4
Number of Bunches Per Pulse		1	16	1	16
Norm. transv. Emittance	(mm-mrad)	<0.3	<0.3	<0.3	<0.3
Beam Energy	(MeV)	5	5	20	20

The construction of AREAL accelerator project intends three stages. The first stage of AREAL Linac design (gun section, diagnostic devices and 5MeV energy) was completed in 2014, which also included the opening of DELTA laboratory with two experimental stations of Microscope and Microfabrication. The second stage includes an upgrade program – electron beam energy increases up to 20MeV and the third stage - electron beam energy increases up to 50MeV.

Besides the experiments carried out in the fields of physics, chemistry, biology, nanotechnologies, environmental studies, the future upgrade program includes the design and development of two new experimental stations: the ALPHA station (Amplified Light Pulse for High-end Applications) which is designated for THz Free Electron Laser and BETA station (Booster for Emerging Technology Accelerators) designed for advanced accelerator and radiation concepts [1-3]. The schematic layout of AREAL Linac is shown in Fig. 1.

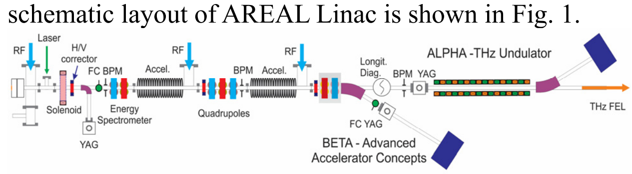

Figure 1: Schematic layout of AREAL linear accelerator.

For stable operation and achieving the design parameters of the machine, it is necessary to have an appropriate beam diagnostic system. AREAL Linac diagnostic tasks include measuring beam transverse size, charge, emittance, beam energy and energy spread. To implement these measurements, a magnetic spectrometer is used to measure the energy and energy spread, a YAG station to measure the beam profile, and a Faraday cup station to measure the beam charge [4], [5]. In addition to these parameters, the beam transverse emittance can be measured in the gun section using a quadrupole magnet using the quadrupole scanning method.

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Unlike some traditional emittance measurement methods that involve intercepting the beam, the quadrupole scan technique is non-destructive, allowing for continuous beam monitoring without perturbing its properties. Quadrupole scans offer high sensitivity to changes in beam parameters, making them suitable for characterizing beams with low emittance and high brightness, typical of laser-driven accelerators. The quadrupole scan technique is versatile and can be adapted to different beam energies and pulse durations, making it suitable for a wide range of AREAL Linac configurations.

QUADRUPOLE SCAN METHOD

The transverse (horizontal) emittance for a well centered and aligned beam (x, x′ = 0) can be determined as:

$$\varepsilon_x = \sqrt{det\sigma} = \sqrt{(\sigma_{11}\sigma_{22}) - \sigma_{12}^2}, \quad (1)$$

where

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} \quad (2)$$

$$\sigma_{11} = \langle x^2 \rangle, \sigma_{12} = \langle xx' \rangle, \sigma_{22} = \langle x'^2 \rangle \quad (3)$$

The Fig. 2 shows the beam ellipse and the physical interpretation of its physical components. In the Fig. 2 x and x' are the position and angle of the particles, respectively.

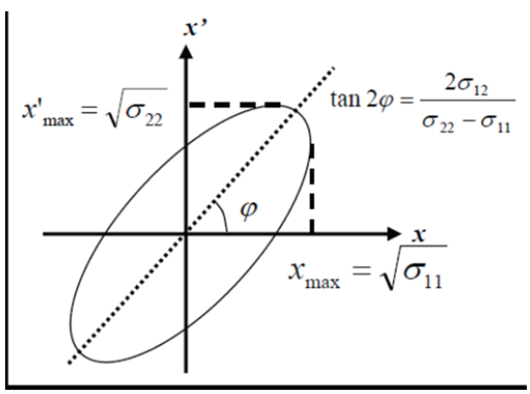

Figure 2: Beam ellipse with physical interpretation of the physical components.

Using the quadrupole-scan technique, there are two methods for estimating the transverse beam emittance: the "thick lens" model and the "thin lens" approximation. The "thin lens" approximation is valid only when the length of the quadrupole magnet is small compared to its focal length. Otherwise, the “thick lens” model is used.

The principle of quadrupole scan method is to get a beam size as a function of the magnet field strength of a quadrupole magnet at the beam size detector (YAG screen). With the help of transfer matrix of the whole path, the beam matrix components can be found by doing the least square approximation for the “thick lens” model and 2nd order polynomial fit for “thin lens” approximation. After which the emittance can be calculated [6].

If the quadrupole magnet is being considered to be thin focusing/defocusing lens, then the following transfer matrices: Q representing the transfer matrix of the quadrupole magnet, S - transfer matrix for the drift space, R - total transfer matrix for the quadrupole and drift space from point z_0 to z (Fig. 3) can be written as:

$$Q = \begin{bmatrix} 1 & 0 \\ Kl_q & 1 \end{bmatrix}, \quad S = \begin{bmatrix} 1 & L_d \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}, \quad (4)$$

$$R = \begin{bmatrix} S_{11} + Kl_qS_{12} & S_{12} \\ S_{21} + Kl_qS_{22} & S_{22} \end{bmatrix} \quad (5)$$

where L_d is the drift length, K is the quadrupole magnet field strength, l_q is a length of the quadrupole magnet. The beam matrix at position z is related to beam matrix at point Z_0 by

$$\sigma_z = R(z)\sigma(z_0)R^T(z) \quad (6)$$

The first term in resultant matrix is:

$$\sigma_{11}(z) = \sigma_{11}(z_0)R_{11}^2 + 2\,\sigma_{12}(z_0)R_{11}R_{12} + \sigma_{22}(z_0)R_{12}^2 \quad (7)$$

This equation can be written as:

$$\sigma_{11}(z) = \left(S_{11} + Kl_qS_{12}\right)^2\sigma_{11}(z_0) + 2S_{12}\left(S_{11} + Kl_qS_{12}\right)\sigma_{12}(z_0) + S_{12}^2\sigma_{22}(z_0), \quad (8)$$

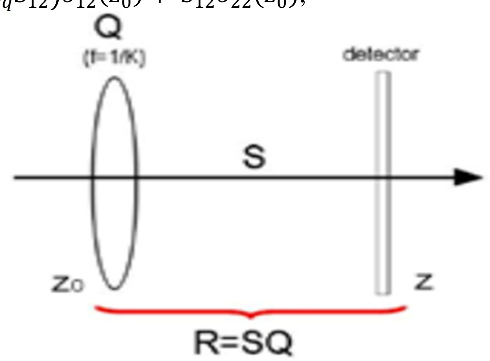

Figure 3: Schematic layout.

$$\sigma_{11} = \frac{A}{l_qS_{12}^2} \quad (9)$$

$$\sigma_{12} = \sigma_{21} = \frac{B - 2\sigma_{11}l_qS_{11}S_{12}}{2l_qS_{12}^2} \quad (10)$$

$$\sigma_{22} = \frac{C - \sigma_{11}S_{11}^2 - 2\sigma_{12}S_{11}S_{12}}{S_{12}^2} \quad (11)$$

$$\varepsilon_g = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2} \quad (12)$$

If the effective length of the magnet is not negligible when compared to the focal length, then the thin lens approximation cannot be used and the "thick lens" model is used, which is an exact linear model for the quadrupole matrix. For this model the total transfer matrix R for the quadrupole and drift space from point z_0 to z can be written as:

$$R = SQ = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} cos\varphi & \frac{1}{\sqrt{|K|}}\,sin\varphi \\ -\sqrt{|K|}\,sin\varphi & cos\varphi \end{bmatrix} \quad (13)$$

where $\varphi = \sqrt{|K|}l_q$

$$R_{11} = S_{11}cos\varphi - S_{12}\sqrt{|K|}\,sin\varphi \quad (14)$$

$$R_{12} = S_{11}\frac{1}{\sqrt{|K|}}\,sin\varphi + S_{12}cos\varphi \quad (15)$$

Also, as with the thin lens approximation, the reduced equation for the first element of the beam matrix is:

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$$\sigma_{11_s} = R_{11}^2\sigma_{11_q} + 2R_{11}R_{12}\sigma_{12_q} + R_{12}^2\sigma_{22_q} \tag{16}$$

For many measurements of the σ_{11} for different quadrupole settings, the full transfer matrix is:

$$\begin{bmatrix}\sigma_{11_s}^{(a)}\\ \sigma_{11_s}^{(b)}\\ \vdots\\ \sigma_{11_s}^{(n)}\end{bmatrix} = \begin{bmatrix}R_{11}^{2(a)} & 2R_{11}^{(a)}R_{12}^{(a)} & R_{12}^{2(a)}\\ R_{11}^{2(b)} & 2R_{11}^{(b)}R_{12}^{(b)} & R_{12}^{2(b)}\\ & \vdots & \\ R_{11}^{2(n)} & 2R_{11}^{(n)}R_{12}^{(n)} & R_{12}^{2(n)}\end{bmatrix}\begin{bmatrix}\sigma_{11_q}\\ \sigma_{12_q}\\ \sigma_{22_q}\end{bmatrix} = A\begin{bmatrix}\sigma_{11_q}\\ \sigma_{12_q}\\ \sigma_{22_q}\end{bmatrix} \tag{17}$$

The equation (17) is of the form $Ax = b$. There are more equations than unknowns and so an exact solution cannot be found [7]. The goal is then to minimize the error by employing a least-squares fit, which is performed by inverting the matrix A.

MEASUREMENTS

After the recent upgrade of the AREAL Linac Gun section (Fig. 4) the diagnostic and control system scripts are also upgraded.

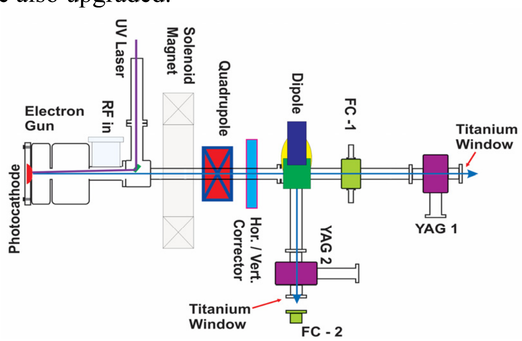

Figure 4: AREAL Linac Gun Section Layout.

Quadrupole magnet length is 0.0815m, the drift between the magnet and YAG1 screen is 0.73m. Magnetic field strength of the quadrupole magnet is calculated by the equation

$$K = \frac{0.2998g}{p}, \tag{18}$$

where g = 0.6 I and p - is the momentum.

For quadrupole scan procedure and emittance calculation several scripts are used (see Fig. 5, Fig. 6, Fig. 7).

Beam profile monitor script that allows you to select the YAG screen of interest, with closed laser shutter get the background image, after opening the laser shutter, preview and save the beam image, as well as the calculated beam parameters, such as x,y position, rms beam size.

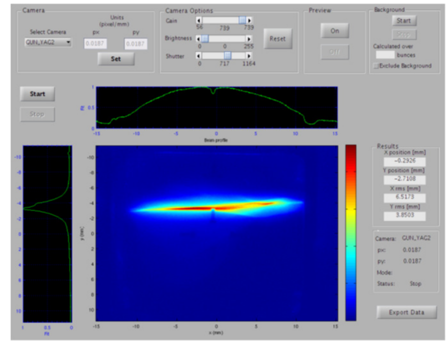

Figure 5: GUI for beam profile monitor.

Quadrupole power supply control script, which allows to control the current of the quadrupole magnet.

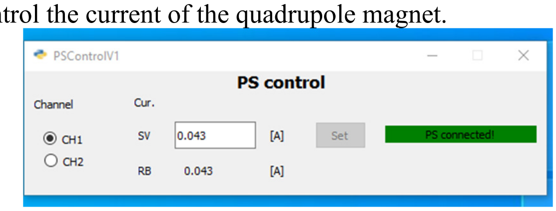

Figure 6: GUI for power supply control.

The Quadrupole Scan/Emittance calculation script, which allows to choose the model for quadrupole scan (thin or thick lens); loads the saved beam images and appropriate currents of the quadrupole magnets; converts the currents to magnetic field values, calculates the rms beam size for each loaded beam image; using the transfer matrixes and the chosen model calculates the $\sigma_{11} = \langle x^2\rangle, \sigma_{12} = \langle xx'\rangle$, $\sigma_{22} = \langle x'^2\rangle$ and the emittance.

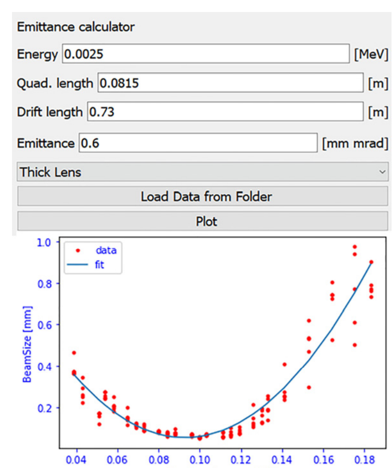

Figure 7: GUI and output plot for emittance calculation.

CONCLUSION

The upgraded quadrupole scan method was implemented to measure the transverse emittance of the electron beam in the AREAL linear accelerator. The transverse emittance was measured in the gun section at an electron beam energy of 2.5 MeV. The obtained results indicate that the hardware and diagnostic tools are not final yet, they will be upgraded for achieving better AREAL linac parameters.

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