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# Low Energy Electron Beam Emittance Measurement at AREAL Accelerator

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**Abstract:** Advanced Research Electron Accelerator Laboratory (AREAL) is a 50 MeV RF gun-based electron linear accelerator project which has been developed at CANDLE Synchrotron Research Institute. In addition to its applications in life and materials sciences, the project intents as a test facility for advanced accelerator concepts and radiation sources. The beam emittance measurements at low energies are an important issue to optimize the facility performance and compensate the space charge effects. In this paper the results of electron beam emittance measurement for AREAL beam energy of 2.5 MeV are presented using the quadrupole scan technique. The least squared approximation is applied to evaluate the experimental results.

**Keywords:** Linear accelerator, electron beam, emittance.

## 1. Introduction

AREAL is a $50MeV$ electron linear accelerator project based on laser driven RF gun, developed at CANDLE Synchrotron Research Institute [1]. The main design parameters of AREAL linear accelerator are presented in Table 1.

**Table 1:** Beam parameters.

| | |
|---|---|
| Energy | $< 50MeV$ |
| Bunch charge | $10-250\,pC$ |
| Trans. norm. emit. | $0.5\ mm.mrad$ |
| Bunch length (rms) | $0.4-9\,ps$ |
| RMS energy spread | $< 0.15\%$ |
| Number of bunches per pulse | $1-16$ |
| Repetition rate | $1-50\ Hz$ |

The AREAL electron accelerator project was developed with the aim of generating ultra-fast and ultra-small electron beams which give a possibility to carry out a great number of experiments and research in a wide spectrum of scientific directions, starting from accelerator technologies to the study of dynamics of ultrafast processes.

The construction of AREAL accelerator project intends two stages. The first stage of AREAL linac design (gun section, diagnostic devices and $5 MeV$ 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 increase up to $50 MeV$.

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, 2]. The schematic layout of AREAL linac after the upgrade is shown in Figure 1.

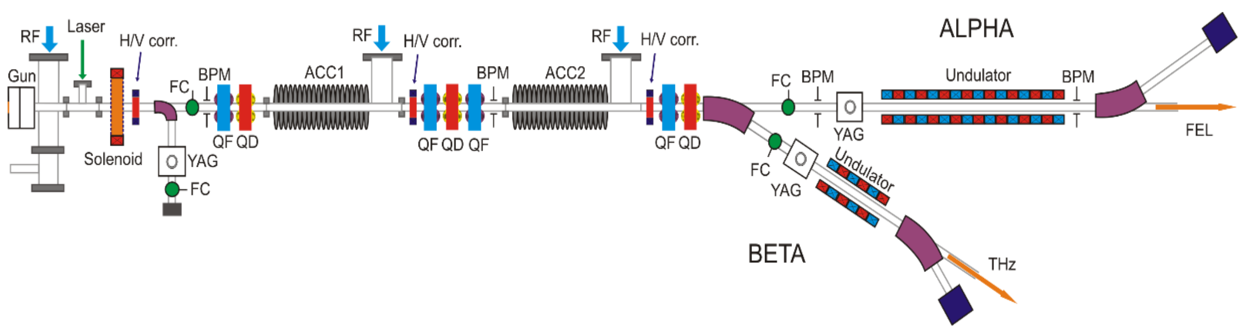



**Fig. 1:** Schematic layout of AREAL linear accelerator.

For the stable operation and machine design parameter achievement, it is required to have an appropriate beam diagnostic system. AREAL linac diagnostic tasks include the measurement of the transverse beam size, charge, emittance, beam energy and energy spread.

For the realization of these measurements a magnetic spectrometer for energy and energy spread, YAG stations for beam profile and Faraday Cup stations for beam charge measurements are used. The overall picture of the diagnostic system of AREAL linac is given in Ref. [3] and [4]. In addition to these parameters, beam transverse emittance can be measured at the gun section using solenoid or quadrupole magnet via solenoid/quadrupole scan method.

In this paper the electron beam transverse emittance measurement results at AREAL gun section and the description of the applied technique are presented.

## 2. Method description

Emittance is an important property of charged particle beams, allowing for a description of beam quality and the comparison of beams characteristics, it also allows to normalize accelerators parameters for comparison [5].

Particles in a beam occupy a certain region in phase space which is called the beam emittance. In general beam emittance is described in six-dimensional phase space $\left((x,y,z)/(x',y',z')\right)$, since transverse (horizontal/vertical) emittance is particularly interesting, it is defined in terms of the area occupied by the beam in two-dimensional phase space $\left((x,x')/(y,y')\right)$, where particle distribution is of elliptical shape.

The transverse (horizontal) emittance for a well-centered and aligned beam $\left(\langle x\rangle,\langle x'\rangle=0\right)$ can be determined as:

$$\varepsilon_x=\sqrt{\det\sigma}=\sqrt{\sigma_{11}\sigma_{22}-\sigma_{12}^2}. \tag{2}$$

where

$$\sigma=\begin{bmatrix}\sigma_{11} & \sigma_{12}\\ \sigma_{12} & \sigma_{22}\end{bmatrix} \tag{3}$$

is the beam matrix with elements $\sigma_{11}=\langle x^2\rangle, \sigma_{22}=\langle x'^2\rangle, \sigma_{12}=\langle xx'\rangle$.

There are different techniques and devices for measuring the transverse beam emittance [6]. For the transverse emittance measurements quadrupole scan method have been used at AREAL linac gun section. This method has been used because of its easy and fast implementation. In addition, this method does not require additional devices or machine setup modifications like in case of Pepper-pot or Slit and grid techniques.

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 (e.g. YAG screen). With the help of transfer matrix of the whole path, the beam matrix components can be found by doing the least square approximationafter which the emittance can be calculated.

Let $R$ be the total transfer matrix for the quadrupole and drift spaces from point $z_0$ to $z$:

$$R=\begin{bmatrix}R_{11} & R_{12}\\ R_{12} & R_{22}\end{bmatrix} \tag{4}$$

The beam matrix at position $z$ is related to beam matrix at point $z_0$ by

$$\sigma(z)=R(z)\sigma(z_0)R^T(z) \tag{5}$$

The first term in resultant matrix is

$$\sigma_{11}(z)=\sigma_{11}(z_0)R_{11}^2+2\sigma_{12}(z_0)R_{11}R_{12}+\sigma_{22}(z_0)R_{12}^2. \tag{6}$$

If $Q$ represents the transfer matrix of the quadrupole and $S$ represents the transfer matrix between the quadrupole and the imaging screen (Figure2), then in thin lens approximation the transfer matrices may be written as(without considering dispersion and momentum compaction factors, because beam passes through solenoid and quadrupole magnets and these magnets don't engender dispersion factor):

$$R=\begin{bmatrix} S_{11}+KS_{12} & S_{12} \\ S_{21}+KS_{22} & S_{22} \end{bmatrix}, \tag{7}$$

where

$$Q=\begin{bmatrix} 1 & 0 \\ K & 1 \end{bmatrix}, \qquad S=\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}, \tag{8}$$

($K$ is the integrated field strength of solenoid/quadrupole magnet).

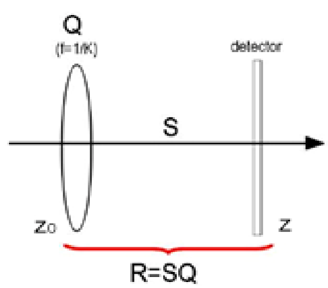



**Fig. 2:** The schematic layout of the setup.

Thus, eq. (6) takes the form

$$\sigma_{11}(z)=(S_{11}+KS_{12})^2\sigma_{11}(z_0)+2S_{12}(S_{11}+KS_{12})\sigma_{12}(z_0)+S_{12}^2\sigma_{22}(z_0), \tag{9}$$

or

$$\sigma_{11}(z)=AK^2+BK+C \tag{10}$$

Acquiring a set of beam size measurements at detector location $z$ as the solenoid/quadrupole field strength is scanned over a range of values (around the value providing maximal focused beam), and using least squares for parabolic fitting of beam horizonal size depending on solenoid/quadrupole strength, $A, B, C$ parameters can be determined. After which, with the help of Equation (9) and (10) we obtain:

$$\begin{aligned}
\sigma_{11}(z_0) &= \frac{S_{12}^2}{A}, \\
\sigma_{12}(z_0) &= \frac{B - 2S_{11}S_{12}\sigma_{11}(z_0)}{2S_{12}^2}, \\
\sigma_{22}(z_0) &= \frac{C - S_{11}^2\sigma_{11}(z_0) - 2S_{11}S_{12}\sigma_{12}(z_0)}{S_{12}^2}.
\end{aligned} \tag{11}$$

Which are the required parameters to calculate emittance with Equation (2).

## 3. Measurements Results

At AREAL linac Gun section (Fig. 3) transverse emittance measurement has been done with quadrupole scan method. Beam profile was measured at YAG 1 station, located $73\,cm$ away from the quadrupole magnet. Themaximum field gradient of thequadrupole magnet with a length of $75\,mm$ is $10.43\,T/m^2$. The relationship of the quadrupole magnet field gradient and the magnetic field strength is represented as follows:

$$K = 29.98\frac{g\left[\frac{T}{m}\right]}{p\left[\frac{Gev}{c}\right]}, \tag{12}$$

where $g$ is the magnetic field gradient and $p$ is the momentum of the beam. In the beginning of measurements, the beam was focused only by the solenoid magnetic field $(0.13T)$, which was constant throughout the measurement process. The measurements have been done for a beam with $2.5MeV$ energy, $110\,pC$ charge and $0.63\,mm$ initial horizonal size at YAG 1 station.

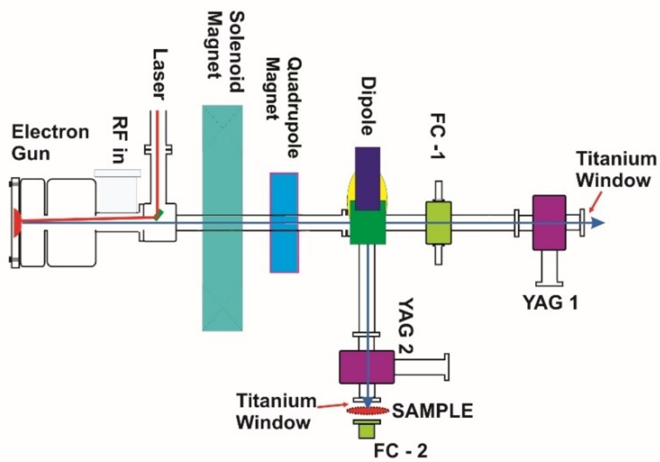
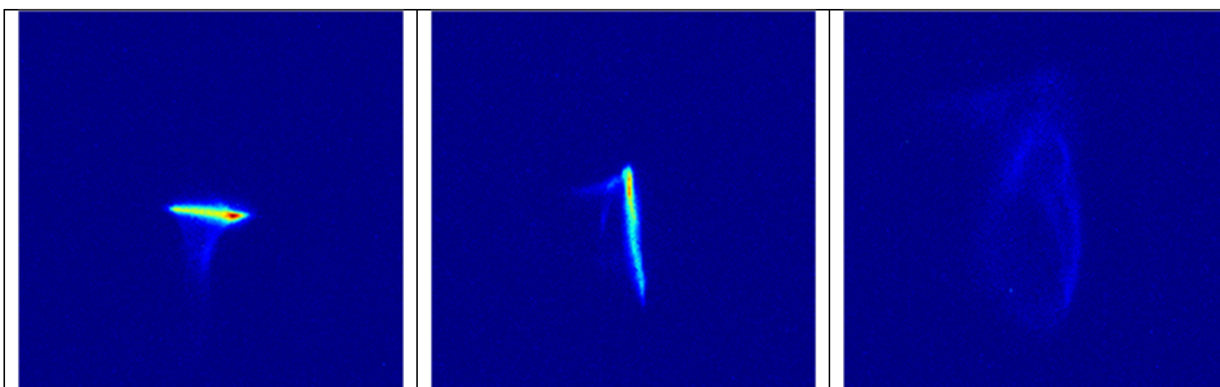



**Fig. 3:** Schematic layout of AREAL linac gun section.

For the first approach, the value of quadrupole magnet field strength $(7.499m^{-2})$ was found which provides beam maximal focusing. Around this point 13 measurements have been done,with magnetic field change of $0.9343m^{-2}$, from minimum to $13.166m^{-2}$ field strength (Fig.4). During the beforementioned measurements the horizontal beam size focuses up to minimum spot and after beam defocusing isobserved.

The further data analyses showed that beam horizontal size change is related to field strength by the quadratic rule with precise fitting of $R^2 = 0.99$ coefficient (Fig. 5).



$K = 1.954m^{-2}$

$K = 7.499m^{-2}$
Maximum focusing

$K = 13.166m^{-2}$

**Fig. 4:** Beam transverse size at different values of quadrupole strength.

As it has already been mentioned in Section 2, the fitting parameters A, B and C are used to calculate the beam matrix elements by Equation (11) after which the beam emittance is found $(1.18\ mm - mrad)$ by Equation (2).

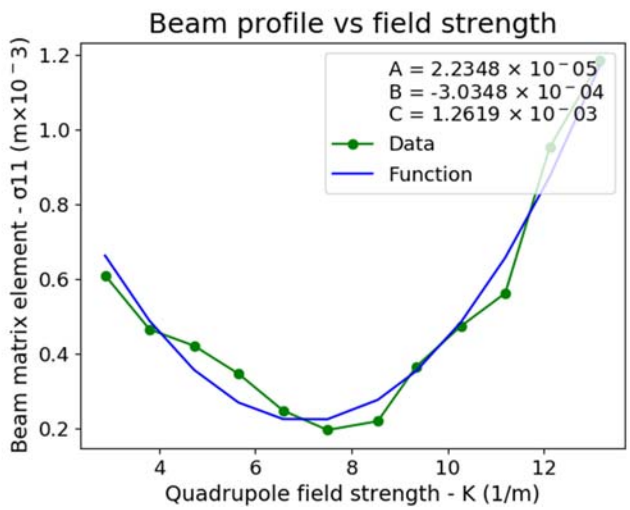



**Fig. 5:** Beam transverse size versus quadrupole strength.

All these measurements, data analyses and calculations are done with a script developed at CANDLE Institute (Fig.6).

On the left side of the GUI the beam live image and its profiles(horizontal and vertical) are represented, inthe middle section of the GUI the user hasanopportunity to observe the beam profile parameters, as well as to choose in which screen and quadrupole magnet to do the measurements, after this it can be chosen whether to calculatethe horizonal $(\varepsilon_x)$ or vertical $(\varepsilon_y)$ emittance. After setting up scan parameters (initial value, step size, step count and time to wait),by clicking on the "Start" button,on the rightsideof the interface the measured data and fitted function will appear.The obtained results will show up at the bottom of the middle section.

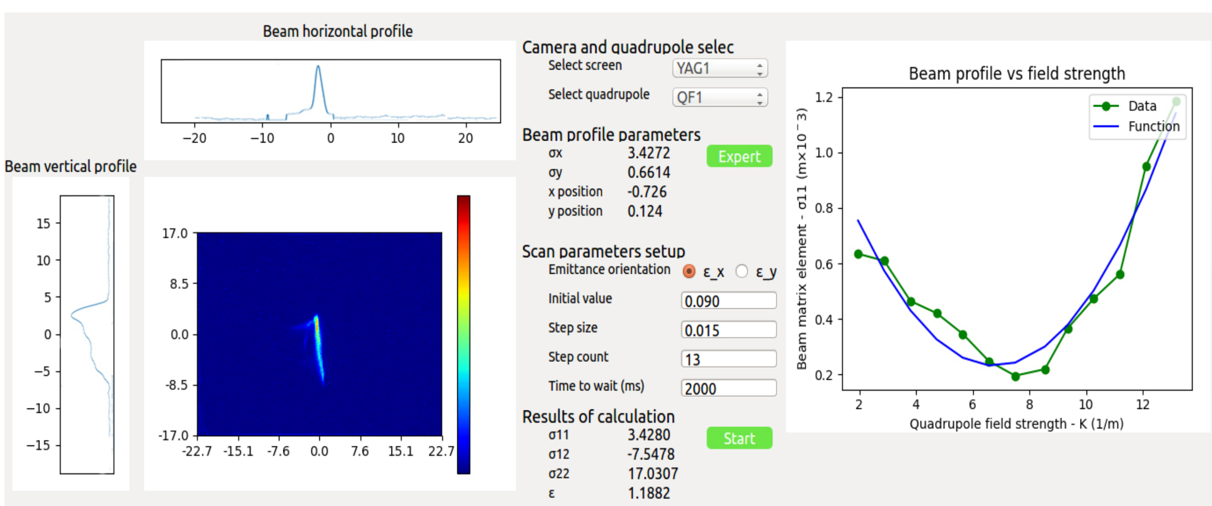



**Fig. 6:** Electron beam transverse emittance measurement tool.

## 4. Summary

Thus, the quadrupole scan method was implemented for the electron beam transverse emittance measurement for AREAL linear accelerator. The transverse emittance has been measured at the gun section for the electron beam energy of $2.5 MeV$. A dedicated control system tool was developed for transverse emittance measurements. These measurements are important for AREAL beam quality evaluation, as well as for future improvements. The measured emittance is 3.5 times bigger than the designed one $(0.35\, mm - mrad)$, which was expected, because some components of AREAL linac need to be adjusted for the obtainment of the design parameters [7].

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