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# BEAM-BASED ALIGNMENT OF MAGNETIC SYSTEM IN AREAL LINEAR ACCELERATOR

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*Abstract*

In this paper the beam-based alignment for solenoid and quadrupole magnets in the AREAL linear accelerator is presented. The AREAL accelerator, at this stage, operates with one solenoid, one quadrupole, corrector, and dipole magnets. The adjustment of solenoid and quadrupole magnets is crucial for the stable operation of the accelerator and for forming the desired beam required for the AREAL upgrade program. This work also takes into account the influence of the RF field radial component on the off-axis beam parameters and trajectory due to laser spot misalignment on the cathode. The study involves theoretical, simulation, and experimental comparisons.

## INTRODUCTION

Modern linear accelerators require precise combinations of various systems to generate beams with specific characteristics. As scientific advancements progress, the requirement for irradiated beam characteristics become stricter to facilitate highly accurate research [1, 2]. Ultrashort beams with small emittance, common in modern accelerators, are particularly sensitive to deviations in system settings. Therefore, tuning systems with high precision is crucial for achieving optimal performance and conducting accurate research in modern accelerator facilities.

Adjustment in modern accelerators involves aligning the axis and centres of systems with the accelerator axis and correcting angular deviations relative to the vertical. This adjustment process is crucial, and it is divided into three main groups based on different calculation systems. Specifically, in particle accelerators, tuning systems are categorized into angular, axial, and transverse groups to address various adjustment needs effectively. When focusing on angular adjustment, it is possible to consider the problem as a combination of one-dimensional transverse and one-dimensional axial adjustments.

The accuracy of adjustments is important to ensure that deviations do not significantly impact beam brightness. Mechanically, adjustments in accelerators are made using techniques such as laser tracking, stretched wire, among others [3]. Additionally, beam-based adjustment methods involve tuning systems based on beam characteristics, offering a comprehensive approach to fine-tuning accelerator systems for optimal performance.

The characteristics of the beam formed after the emission of electrons in the AREAL linear accelerator depend on the passage of the beam through the RF gun, solenoid, and quadrupole magnets [4]. The deviation of each system leads to changes in the parameters of the beam.

For precise tuning of the magnetic system, the beam must first be in co-axis with the accelerating field. In this paper, first the effect of the RF radial field of the AREAL electron gun on off-axis electron beams was investigated theoretically and experimentally. An analysis of the effects of solenoid magnet misalignments using ASTRA simulations are presented. Additionally, a beam-based alignment algorithm to adjust the magnets in the AREAL accelerator was outlined.

## RF RADIAL FIELDS EFFECTS ON OFF AXIS BEAM

The change in momentum of a particle under the influence of the RF field can be represented by two components: the kick by the RF radial fields and the effect of the ponderomotive forces [5].

$$p_r^I = \alpha(kr)\mu sin\varphi \qquad (1)$$

where $k \equiv \frac{2\pi}{\lambda} = \frac{\omega}{c}$ is the wavenumber, r- distance from axis, $\mu$ is defined as the RF harmonics amplitude sum, $\varphi$ is the initial phases of RF, and $\alpha = \frac{eE_0}{2kmc^2}$ is the dimensionless amplitude of the vector potential associated with the accelerating field, where $E_0$ is the accelerating gradient, $e$ and $m$ charge and mass of electron respectively, $c$ is the speed of light.

The ponderomotive force effect can be calculated by the formula:

$$\Delta\overline{p_r} = -\frac{\alpha^2k^2\eta}{16}(r_1 + r_2)\int_0^{zsc}\frac{dz}{\bar{\gamma}} \qquad (2)$$

Where $\bar{\gamma} = 1 + \alpha(kz)sin\varphi$ is an average linear growth of relative energy, $r_1$ and $r_2$ are the beam radius at the exit of the first and second cells, and limits of integration from cathode to the end of second cell.

The total momentum changes because of off axis particle is the sum of both effect:

$$p_r = \alpha ksin\varphi\left[\mu\overline{r_1} - \delta\frac{\eta log\overline{\gamma_2}}{16sin^2\varphi}(r_1 + r_2)\right] \qquad (3)$$

To calculate the RF field effect on beam emittance the variance of position $\langle\boldsymbol{x}\rangle$, momentum $\langle\boldsymbol{p}\rangle$, position-momentum correlation $\langle\boldsymbol{x}\cdot\boldsymbol{p}\rangle$ should be calculated. From (3):

$$< \Delta p_x^2 >= \left(\frac{\partial p_r}{\partial r}\right)^2\sigma_x^2 + \left(\frac{\partial^2 p_r}{\partial r\partial z}\right)^2(x_0^2 + \sigma_x^2)\sigma_z^2$$

$$< \Delta p_y^2 >= \left(\frac{\partial p_r}{\partial r}\right)^2\sigma_y^2 + \left(\frac{\partial^2 p_r}{\partial r\partial z}\right)^2(y_0^2 + \sigma_y^2)\sigma_z^2 \qquad (4)$$

$$\frac{<\Delta p_w\Delta z>}{\sigma_z^2} = w_0\left(\frac{\partial^2 p_r}{\partial r\partial z}\right) \text{ where } w = x, y$$

$$\frac{< \Delta p_x\Delta x >}{\sigma_x^2} = \frac{< \Delta p_y\Delta y >}{\sigma_y^2} = \left(\frac{\partial p_r}{\partial r}\right)$$

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The RF radial fields effect on off axis transvers beam emittance in approximation of $<\Delta x \Delta z>=<\Delta y \Delta z>=0$ is given by:

$$\varepsilon_{x,n} = \left|\frac{\partial^2 p_r}{\partial r \partial z}\right| \sigma_z \sigma_x \sqrt{\sigma_x^2 + x_0^2} \quad (5)$$

$$\varepsilon_{y,n} = \left|\frac{\partial^2 p_r}{\partial r \partial z}\right| \sigma_z \sigma_y \sqrt{\sigma_y^2 + y_0^2} \quad (6)$$

## SOLENOID AND QUADRUPOLE MISSALIGMENT EFFECT ON OFF AXIS BEAM

The particle coordinates linear transformation on solenoid magnets are related to their initial values $(x_1, x_1', y_1, y_1')$ and the deflection coordinates $(\Delta_x, \theta_x, \Delta_y, \theta_y)$ of solenoid magnets and can be described by transfer matrices:

$$\begin{bmatrix} x_2 \\ x_2' \\ y_2 \\ y_2' \end{bmatrix} = M_{sol} \begin{bmatrix} x_1 \\ x_1' \\ y_1 \\ y_1' \end{bmatrix} + \Delta_x \begin{bmatrix} 1-C^2 \\ KSC \\ SC \\ -KS^2 \end{bmatrix} + \Delta_y \begin{bmatrix} -SC \\ KS^2 \\ 1-C^2 \\ -KSC \end{bmatrix} +$$

$$\theta_x \begin{bmatrix} \frac{(1+C^2)L}{2} - \frac{SC}{K} \\ 1 - C^2 - \frac{KSCL}{2} \\ \frac{S^2}{K} - \frac{SCL}{2} \\ SC + \frac{KS^2 L}{2} \end{bmatrix} + \theta_y \begin{bmatrix} \frac{SCL}{2} - \frac{S^2}{K} \\ -SC + \frac{KS^2}{2} \\ \frac{(1+C^2)L}{2} - \frac{SC}{K} \\ 1 - C^2 - \frac{KSCL}{2} \end{bmatrix} \quad (7)$$

Here,` $K = \frac{qB_0}{2P_0}$, $C = \cos(KL)$, $S = \sin(KL)$, and $KL$ is the rotation angle around the $z$-axis [6]. From the matrix expression (7), it is possible to separately and simultaneously observe the influence of the angular and spatial deviations of the solenoid magnets on the beam dynamic.

Angular and spatial deviations of the quadrupole magnets also lead to changes in the characteristics of the beam. The kick received by the beam passing through the quadrupole magnet deviated from the center is directly proportional to the strength of the quadrupole magnet and the magnitude of the deviation

$$\Delta x' = -\frac{G_N}{B_\rho} dx, \ \Delta y' = -\frac{G_N}{B_\rho} dy \quad (8)$$

Then, the change in the position of the beam at the some observation point can be determined from expression (8) and the first-order transformation matrix

$$\Delta x = -R_{12} \frac{\Delta G_N}{B\rho} dx = -R_{12} \frac{B' l_Q}{B\rho} dx \quad (9)$$

where $R_{12}$ is the transformation matrix from the quadrupole to the observation point, and $l_Q$ is the effective length of the quadrupole [7]. A similar expression can be obtained for the vertical plane as well. Thus, by determining the deviation $dx$ using the mentioned method, it is possible to move the quadrupole by the same amount, as a result of which the beam will pass through the center of the magnet.

## STUDY OF AREAL GUN RF RADIAL FIELD EFFECT ON OFF AXIS BEAM

The deviation of the beam from the axis of the RF accelerating field can be caused by the deviation of the laser beam at the cathode. In this case, the influence of the transverse fields of the RF leads to an increase in the beam emittance.

The AREAL RF gun based on S-band ($3\ GHz$) 1.5-cell (total length $10.5\ cm$) standing wave cavity and powered by $7\ MW$ power klystron (pulse duration of $4\ \mu s$). The maximum cavity voltage is about $5\ MV$, corresponding to a peak accelerating gradient of $117\ MV/m$ [8].

Figure 1 presents a comparison of ASTRA simulation and theoretical results for emittance at the exit of the 1.5-cell AREAL RF gun in a scenario where the beam deviation from the axis of RF field is $-7mm$ to $7mm$ ((a) $y_0 = 0$, and (b) $y_0 = 5mm$).

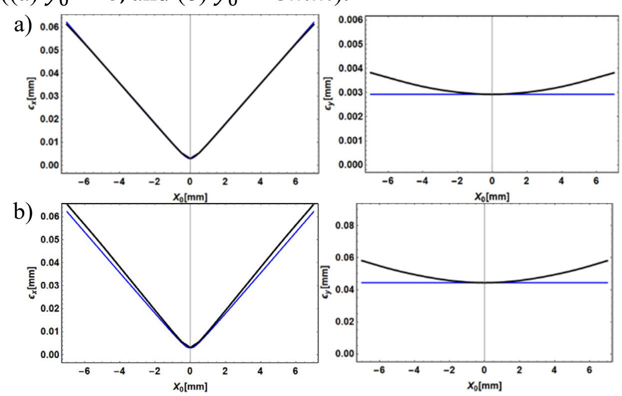


Figure 1: The emittance growth of off-axis beam.

The beam energy is $3.6\ MeV$, corresponding to a $71 MV/m$ accelerating gradient, and the charge is $250\ pC$, which corresponds to the nominal operation regime of the AREAL accelerator. The initial transverse rms sizes of beam at the cathode are $\sigma = 0.33mm$ for both the vertical and horizontal planes, based on the laser spot size. The unitless coefficient for RF characterization is $\alpha = 6.9$, for abovementioned parameters. During the ASTRA simulation, the space charge effect is neglected to show only the RF field effects on beam emittance. The discrepancy of simulation and theoretical results for vertical $\varepsilon_y$ emittance occurs because, in theory, the correlation between the x and y axis is neglected, but in the simulation, the correlation exists. From the analysis, it is obvious that the effect of the RF field on emittance is around $0.03\ mm\ mrad$, which is approximately 3% of the designed emittance. The same analysis for vertical misalignment was conducted, and the results were similar to those in the horizontal cases.

At the AREAL linear accelerator, the image of the beam can be obtained at the YAG station, which is located at a distance of $1.485\ m$ from the cathode. The experiment was done for the beam energy of $3.6\ MeV$. The effect of the transverse fields of the RF was observed by the changes in the position of the beam center at the YAG station when the center of the laser beam deviated. The center of the laser

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was moved from $-2\,mm$ to $2\,mm$ in $1\,mm$ steps, corresponding to the laser mirror acceptance range. It's worth noting that the deviation of the beam center is caused not only by the deviation of the laser spot and the radial fields of the RF fields but also by the deviation of the solenoid magnet from beam axis. Figure 2 shows a comparison of ASTRA modeling and experimental results.

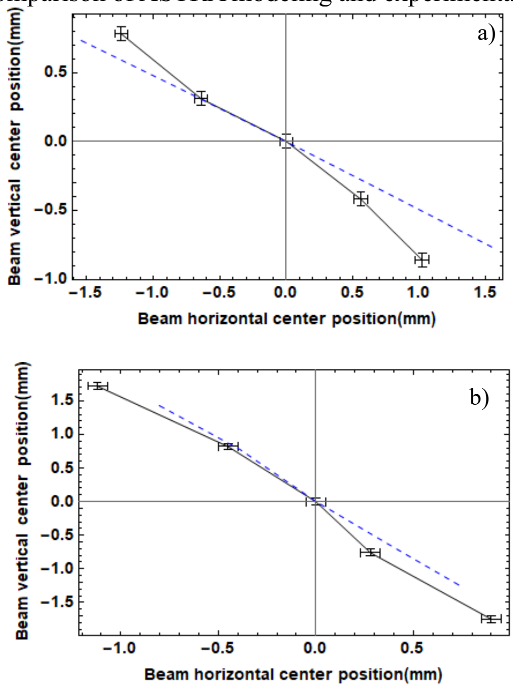


Figure 2: Beam center position on YAG screen in a case of laser spot deviation on a) horizontal and b) vertical directions. Experiment-solid line, simulation-dashed line.

The experimental and the simulations results are in good agreement, and its shown that 1mm deviation of laser spot in horizontal direction results around $0.55\,mm$ horizontal and around $0.33\,mm$ vertical deviation of the beam center on YAG screen (Fig. 2a). The $1\,mm$ deviation of laser spot in vertical direction results around $0.5\,mm$ horizontal and around $0.8\,mm$ vertical deviation of the beam center on YAG screen (Fig. 2b). Because of cylindrical symmetry of RF gun and as it can also be seen from ASTRA simulations the beam center position deviation because of off axis beam should be symmetric. The discrepancy can occur because of solenoid magnet deviation. The study can be used for centering the beam with RF field to minimize the RF radial fields effects on the beam.

## SOLENOID MISSALIGMENT EFFECT STUDY FOR BEAM BASSED ALIGMENT

The deviation of the magnetic system causes a displacement of the center of the beam and the rms dimensions with respect to the axis one.

In Fig. 3 presented the ASTRA simulations results of solenoid magnet linear misalignment effect on AREAL $3.6\,MeV$ beam center position. The solenoid magnet is offset $0-5mm$ horizontally and vertically with respect to the beam axis. It is shown that solenoid magnets $1\,mm$ misalignment results to around of $2\,mm$ beam center misalignment on YAG screen.

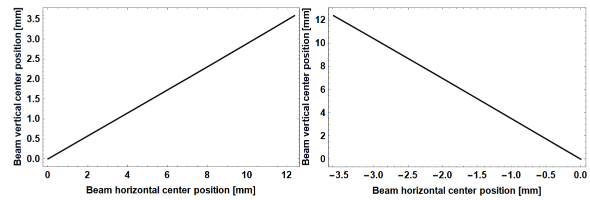


Figure 3: The beam center position misalignment by solenoid magnets deviation.

To perform beam-based alignment, the deflection of the beam center as a function of the solenoid magnet field was also investigated. In the case when the beam and the solenoid magnet are co-axis, the position of the center of the beam should not depend on the magnetic field. Beam-based tuning involves adjusting the position of the solenoid magnet while keeping the position of the beam center unchanged by changing the magnetic field value [9].

The center position displacement of beam related with the solenoid magnetic fields in YAG for various misalignments of solenoid magnet is presented in Fig. 4.

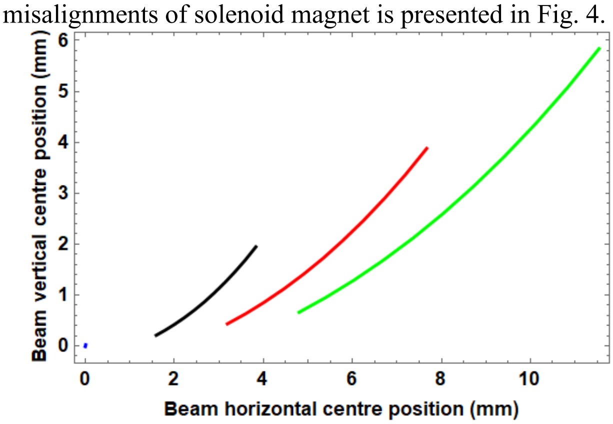


Figure 4: The beam center position displacements for various magnetic field of solenoid in a case of solenoid misalignment of 0-3mm.Blue-0mm, Black-1mm, Red-2mm, Green-3mm.

## CONCLUSION

In this paper the RF radial field effect on AREAL accelerator was studied as a first step for beam-based alignment. It is shown that for AREAL accelerator the RF radial fields effect on the beam emittance is around of 3%. The solenoid magnet misalignment effect on the beam was investigated by ASTRA simulations.

The obtained results will be used for AREAL accelerator systems alignment, which is crucial for AREAL upgrade program. The results also can be used for automatization tool of beam-based alignment in AREAL accelerator.

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