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STUDY FOR THE ALIGNMENT OF FOCUSING SOLENOID OF ARES RF GUN AND EFFECT OF MISALIGNMENT OF SOLENOID ON EMITTANCE OF SPACE CHARGE DOMINATED ELECTRON BEAM

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Abstract

SINBAD (Short and INnovative Bunches and Accelerators at DESY) facility will host multiple experiments relating to ultra-short high brightness beams and novel experiments with ultra-high gradient. ARES (Accelerator Research Experiment at SINBAD) Linac is an S-band photo injector to produce such electron bunches at around 100 MeV. The Linac will be commissioned in stages with the first stage corresponding to gun commissioning. In this paper, we present studies about the scheme adopted for the alignment of focusing solenoid for the ARES gun. The method is bench marked using ASTRA simulations. Moreover the effect of misalignment of the solenoid on the emittance of space charge dominated scheme and its compensation is also discussed.

INTRODUCTION

The goal of SINBAD (Short INnovative Bunches and Accelerators at DESY), a dedicated accelerator R&D facility at DESY, is to study ultra-fast physics and perform novel acceleration technique experiments [1-3]. The ARES (Accelerator Research Experiment at SINBAD) Linac [4] at SINBAD is a conventional S-band photo-injector providing ultra-short (FWHM, length <=1 fs-few fs) high brightness electron beam for injection into novel accelerators. ARES also will allow the manipulation of the beam by different bunch length compression techniques [5-7]. The 5 MeV RF gun of the ARES has been tuned and it is presently in the conditioning phase [8, 9], while the Linac will be commissioned in autumn 2019. In this paper we discuss the procedure developed for the alignment of solenoids of the ARES.

The schematic of the ARES and RF gun details are shown in Fig. 1. A focusing solenoid (named "Second Solenoid" in Fig. 1) located at 40.6 cm from the cathode is used for transverse focusing of electron bunches. The effect of misalignment of this solenoid on beam parameters, emittance and beam sizes have already been studied [10]. The solenoid named "First Solenoid" in Fig.1 and its bucking coil will be installed later on in 2019 to allow an improvement of the quality of the electrons. In the Linac part, 4 solenoids for each travelling wave structure, will allow to optimize the beam quality while compressing the beam via velocity bunching. The developed routine will be used to perform beam based alignment of all these solenoids of ARES.

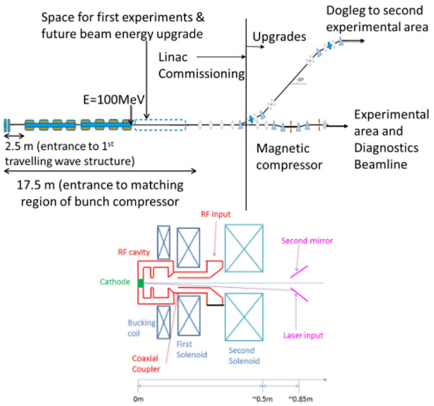

Figure 1: Layout of ARES Linac (on left) and zoom of the RF gun region (right).

BEAM BASED ALIGNMENT ROUTINE

Solenoid Description

The gun solenoid consists of two coils of equal length. Each coil can be adjusted to different polarities and hence allows for better control of the beam [10]. The two coils have field profiles that overlap with each other. The field profiles for the plus-plus and minus-plus polarity settings are shown in Fig. 2. Solenoid is housed on a manual micro mover system which has resolution of 100 µm in transverse direction and angular accuracy of approximately 0.5 mrad. Misalignment error can be in both transverse and angular planes.

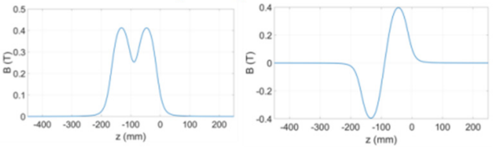

Figure 2: Field profiles for different polarity combinations of our solenoid.

For a coil with strength "K" and length "L", the Transfer Matrix for Positive and Negative polarity is given by Eqs (1) and (2) respectively [11]. Where K is strength and L is the effective magnetic length of the coil. Two screens are located downstream the solenoid for beam profile measurement.

$$M_{sol+} = \begin{bmatrix} \cos^2 KL & \frac{\sin KL \cos KL}{K} & \sin KL \cos KL & \frac{\sin^2 KL}{K} \\ -K \sin KL \cos KL & \cos^2 KL & -K \sin^2 KL & \sin KL \cos KL \\ -\sin KL \cos KL & -\frac{\sin^2 KL}{K} & \cos^2 KL & \frac{\sin KL \cos KL}{K} \\ K \sin^2 KL & -\sin KL \cos KL & -K \sin KL \cos KL & \cos^2 KL \end{bmatrix} \text{Eq (1)}$$

$$M_{sol-} = \begin{bmatrix} \cos^2 KL & \frac{\sin KL \cos KL}{K} & -\sin KL \cos KL & -\frac{\sin^2 KL}{K} \\ -K \sin KL \cos KL & \cos^2 KL & K \sin^2 KL & -\sin KL \cos KL \\ \sin KL \cos KL & \frac{\sin^2 KL}{K} & \cos^2 KL & \frac{\sin KL \cos KL}{K} \\ -K \sin^2 KL & \sin KL \cos KL & -K \sin KL \cos KL & \cos^2 KL \end{bmatrix} \text{Eq (2)}$$

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The total transfer matrix acting on the beam is combination of M_{sol+}, M_{sol-} and M_{drift}, depending on the choice of polarity settings. The two possible combinations for plus-plus and minus-plus polarity settings are given by Eq. (3) and (4) respectively.

$$PP = M_{drift} \cdot M_{sol+} \cdot M_{sol+} \tag{3}$$

$$PM = M_{drift} \cdot M_{sol-} \cdot M_{sol+} \tag{4}$$

Alignment Routine and Data Processing

The alignment model is based on the transfer matrices and assumes that there is no overlap of the magnetic field "B" of the solenoids with the electro-magnetic "E" field of the RF gun. If this is not the case, more complex numerical methods need to be adopted [12]. A Similar scheme has been adopted at BNL [13].

The final coordinates of the electron beam are determined from its initial position using the transfer matrix of the lattice.

$$\overline{F} = M \cdot (\overline{X} + \overline{\delta X})$$

Where $\overline{F}$ is final beam position vector, $\overline{X}$ is initial beam position vector, $\overline{\delta X}$ represents the offset in initial beam positions between the electron beam and the magnetic axis of the solenoid and M is the transfer matrix of the lattice.

In case of perfect alignment of the electron beam and the solenoid, the beam center and solenoid center coincide. We now assume that the reference system has origin at the center of the solenoid and that the beam has an offset with respect to this system. Under those conditions the initial position vector, $\overline{X}$ will become zero and the equation will be reduced to

$$\overline{F} = M \cdot \overline{\delta X}$$

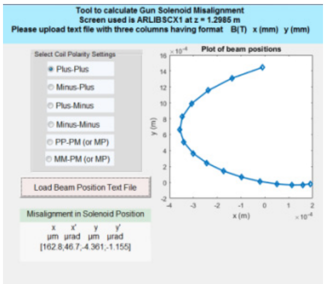
Or in matrix notation

$$\begin{bmatrix} x_f \\ x_f' \\ y_f \\ y_f' \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \cdot \begin{bmatrix} \delta x_i \\ \delta x_i' \\ \delta y_i \\ \delta y_i' \end{bmatrix} \tag{5}$$

In reality, in Beam Based Alignment (BBA) methods, we will need to adjust the position of the solenoid, by adjusting the 4 degrees of freedom of its mover on the reference trajectory on which the electron beam will be pre-aligned having set initially the solenoid off. Therefore a correction equal to $+\overline{\delta X}$ will have to be applied to the solenoid in order to align it with the reference beam trajectory. Inside vector $\overline{F}$, only x_f and y_f can be measured during alignment procedure which we read from the screen. Hence, only two out of 4 equations in Eq. (5) are usable. However, for a fixed solenoid position, for any value of solenoid-strength or polarity-setting, the final positions of the electron beam on a measurement screen downstream the solenoid will be different but the initial misalignment will be the same. Exploiting this fact gives us the freedom to construct a redundant system of equations according to our choice of solenoid strength and polarity settings. The new matrix is formed piling up the elements of the transfer matrix in Eq. (5) corresponding to a specific solenoid current.

$$\begin{bmatrix} x_{f1} \\ y_{f1} \\ x_{f2} \\ y_{f2} \\ \cdots \\ \cdots \\ x_{fN} \\ y_{fN} \end{bmatrix} = \begin{bmatrix} M_{11,1} & M_{12,1} & M_{13,1} & M_{14,1} \\ M_{31,1} & M_{32,1} & M_{33,1} & M_{34,1} \\ M_{11,2} & M_{12,2} & M_{13,2} & M_{14,2} \\ M_{31,2} & M_{32,2} & M_{33,2} & M_{34,2} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ M_{11,N} & M_{12,N} & M_{13,N} & M_{14,N} \\ M_{31,N} & M_{32,N} & M_{33,N} & M_{34,N} \end{bmatrix} \cdot \begin{bmatrix} \delta x_i \\ \delta x_i' \\ \delta y_i \\ \delta y_i' \end{bmatrix} \tag{6}$$

In Eq. (6) we use the third index of each matrix element to identify the specific current value. In order to analyze the measured data a MATLAB tool has been written. The routine provides a graphical user interface to select the polarity settings. The screen shot of the routine-panel is shown in Fig. 3. According to the measured misalignment; we will correct the solenoid position using the manual micro mover system. To check if the solenoid is aligned, we will need to choose one of the polarity settings (e.g. ++) and check that when we scan the current of the solenoid, the beam almost does not move on the screen anymore. If this is not the case, we need to repeat the procedure and do another iteration of the correction of the alignment.



Tool to calculate Gun Solenoid Misalignment
Screen used is ARLIBSCX1 at z = 1.2985 m
Please upload text file with three columns having format B(T) x (mm) y (mm)

Select Coil Polarity Settings
● Plus-Plus
○ Minus-Plus
○ Plus-Minus
○ Minus-Minus
○ PP-PM (or MP)
○ MM-PM (or MP)

Misalignment in Solenoid Position
x x' y y'
μm μrad μm μrad
[162.8;46.7;-4.361;-1.155]

Figure 3: Screen shot of MATLAB GUI.

TEST OF THE ROUTINE WITH ASTRA SIMULATIONS

In order to benchmark the routine using the ASTRA particle code [14], a measurement was simulated. We have introduced in the input lattice-file in ASTRA, a misalignment of the solenoid with respect to the beam trajectory. Positions of the beam at the measurement screen were recorded and used as input to test the routine for the data analysis. Before looking at the result of the benchmark, it is important to note the differences between the analytical model used by the MATLAB routine and the particle tracking algorithm used to simulate the beam dynamics in ASTRA. ASTRA directly applies the force generated by the magnetic field of the solenoid to each particle. The transverse magnetic field components are calculated from the derivatives of the on-axis field profile, which is provided in the input files for the simulation. The MATLAB routine uses instead the Linear Transfer Matrix formalism, the specific Transfer Matrix used in the MATLAB-tool is derived for a "flat-top" longitudinal magnetic field component B_z, that is significantly different from the field profile of our solenoid under study also shown in Fig. 2. This method anyway has the advantage of being extremely simple. The algorithm was rigorously tested with different cases of initial misalignment in ASTRA varying both the magnitude and

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the direction of the misalignment. Some examples of the test cases are shown in Table 1. The misalignments calculated by using the MATLAB tool differ from the input values used in the ASTRA simulations by approximately 18%. Considering the limitation of the micro-mover-system which is used to adjust the position of the solenoid, it can be safely inferred that the developed routine, using a simple model gives good result within the 100 µm accuracy limits of the micro-mover system and it is good enough for use at ARES.

Table 1: Examples of the Calculated Misalignment by the MATLAB Tool for Different Input Misalignments in the ASTRA Simulations

	Initial misalignment in ASTRA-simulations	**Scan using PP polarity**	**Scan using MP polarity**	**Scan using PP and PM polarities**
x (µm)	200	162.8	142.5	152.7
x' (µrad)	0	46.6	71.4	59.1
y (µm)	0	-4.36	-0.00	-2.2
y' (µrad)	0	-1.1	-0.00	-0.6
x (µm)	-200	-162.82	-142.57	-149.32
x' (µrad)	0	-46.69	-71.4	-63.18
y (µm)	0	4.36	0.06	1.49
y' (µrad)	0	1.15	0.03	0.40
x (µm)	-200	-304.05	-270.84	-287.45
x' (µrad)	-600	-688.34	-757.29	-722.81
y (µm)	300	521.52	438.77	480.14
y' (µrad)	1050	1227.34	1307.97	1267.65
x (µm)	200	304.05	270.84	287.45
x' (µrad)	600	688.34	757.29	722.81
y (µm)	-300	-521.52	-438.77	-480.15
y' (µrad)	-1050	-1227.34	-1307.97	-1267.65

EMITTANCE COMPENSATION

In a photo-injector, transversely defocusing space charge forces varies with the longitudinal position within the bunch and, combined with an external focusing field, can result in correlated emittance oscillations [15, 16].The misalignment of the solenoid can introduce an additional increase of the emittance of the beam due to the introduction of correlations and distortions of the transverse beam shape. In Fig. 4 we show the relative increase in emittances in x and y at the exit of the solenoid of the ARES photo-injector for different misalignments of the solenoid. In this figure, the misalignment is introduced only in horizontal transverse plane.

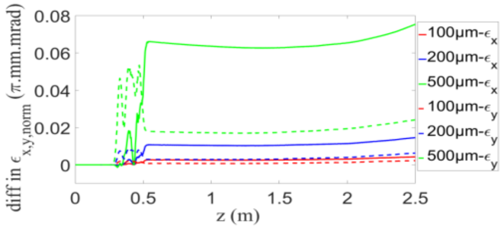

Figure 4: The difference in emittance x and y (emitmisaliged – emitaligned) for different values of solenoid misalignment in x-direction only. Solid line is for x-direction, and dashed is for y-transverse direction. Coils have opposite polarities in this case.

Major contributor of this increase is the space charge effect. Without space charge forces into action, negligibly small change in emittance after the solenoid is observed as shown in Fig. 5.

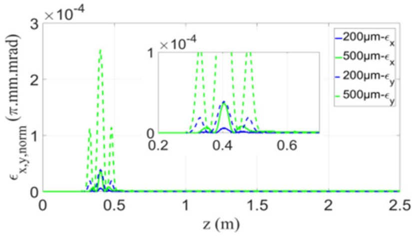

Figure 5: Evolution of emittance in the absence of space charge. The insight shows the zoom in scale for the emittance change in solenoidal field because particle experiences focusing and rotational forces.

Furthermore, the misalignment in solenoid introduces a kick; hence the phase space is shifted in the direction of misalignment (as shown in Fig. 6) and a longitudinal tilt of the bunch is introduced. The misalignment also introduces an asymmetry in the evolution of the x and y planes of the beam that will be difficult to compensate afterwards.

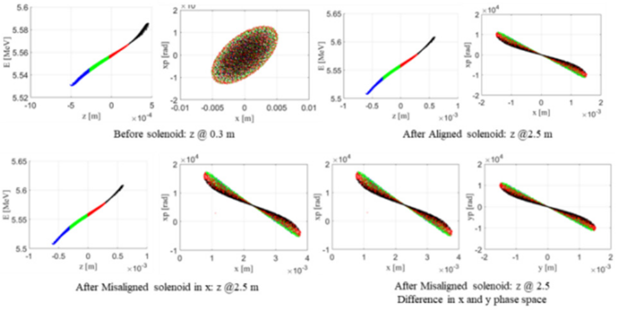

Figure 6: Evolution of transverse phase space for solenoid misalignment of 200 µm only in x direction: Bottom right figure clearly shows that phase space is shifted in the direction of misalignment.

With the above discussion, it was concluded that increase in emittance mainly occurs due to the effects of space charge. The slight increase in emittance can be partially compensated by further tuning the solenoid field. The kick in the trajectory could also in principle be compensated by a proper correction with steering magnets downstream the solenoid. However the correction of the misalignment of the solenoid by means of the micro-mover considerably simplifies the setting up of the machine working point and it is therefore envisaged.

CONCLUSION AND OUTLOOK

We have presented an algorithm for the alignment of solenoids of ARES Linac based on a simple model which uses Transfer Matrix of the Lattice. The routine has been developed in MATLAB and has been benchmarked with ASTRA. The routine gives results within the accuracy limits of the micro-mover system and is good enough for use at ARES. After initial verification of results during gun commissioning of ARES, the beam based alignment algorithm will be routinely used for the alignment for solenoids of ARES around travelling wave structures.

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