EFFECTS OF NON-AXISYMMETRIC SOLENOID FIELD ON BEAM QUALITY IN VELOCITY BUNCHING

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Abstract

Space-charge effect is not negligible during the early stage of beam acceleration in a photoinjector rf linac that is operated for generation of short electron pulses by velocity bunching. A solenoid with iron shield can be used to provide the required axis-symmetric magnetic field to balance the radial space-charge force of the beam. However, the iron shield cannot be perfectly symmetric because openings are reserved for feeding water pipes and electrical cables to the coils. In addition, alignment errors of the solenoid may also spoil the symmetry of the focusing field. In this study, simulation are carried out to investigate how does the non-axisymmetric solenoid field of different origins influence beam properties, such as beam size, transverse emittance during the rf bunch compression.

INTRODUCTION

A laser-driven photoinjector linac system has been built for the proposed NSRRC THz/VUV free electron laser facility [1]. It is a split-configuration that consists of a photo-cathode rf gun equipped with a short solenoid for emittance compensation and a 5.2-m, 2998 MHz S-band constant-gradient traveling-wave rf linac at downstream. To obtain maximal energy gain during acceleration, the electron beam is injected into the rf linac on the crest of the traveling radio frequency wave. In velocity bunching for short bunch generation however, the injection phase of electron beam has to be set near rf zero crossing [2]. Therefore, energy gain at the beginning of beam acceleration is small and the effects of space charge on transverse beam size and emittance are considered to be significant. To overcome this problem, a solenoid magnetic field is commonly employed to balance the radial space-charge force induced by the beam [3, 4]. The linac solenoid for the NSRRC photoinjector has been installed in the first two meters of the rf linac structure. It has two stacks of 9 coils with water channels for cooling. Iron plates are inserted between coils for field straightening. An iron shield is wrapped around the solenoid to prevent leakage of magnetic field (Fig. 1a). Precise alignment of the solenoid magnetic field to the beam axis is essential. The effects of the openings on solenoid iron shield for feeding of water pipes and electrical cables on field symmetry have to be investigated also. In this study, the effects of non-axisymmetric linac solenoid field on beam quality in the NSRRC S-band photoinjector system operating in short bunch mode by velocity bunching are investigated.

We have assumed the beam produced from the photo-cathode rf gun is a cylindrically uniform distribution in space. The beam quality at the entrance of the linac has been optimized by using the simulation code – General particle tracer (GPT) [5]. Based on the simulation results, the initial beam parameters are set at the linac entrance throughout our simulation study and are listed in Table 1.

Table 1: The Initial Electron Beam Quality at Linac Entrance

Energy [MeV]	*Energy Spread* [MeV]	*Beam Size* [mm]	*Bunch Length* [fs]	*Transverse Emittance* [mm-rad]
3.314	0.049	0.513	1.915	0.779

BEAM QUALITY CONTROL WITH LINAC SOLENOID

Beam quality at exit of the rf linac has been optimized for generation of ultrashort bunches after intensive simulations using GPT with an axis-symmetric solenoid field computed by POISSON [6]. It is found that the optimum field strength of the solenoid is at 500 gauss.

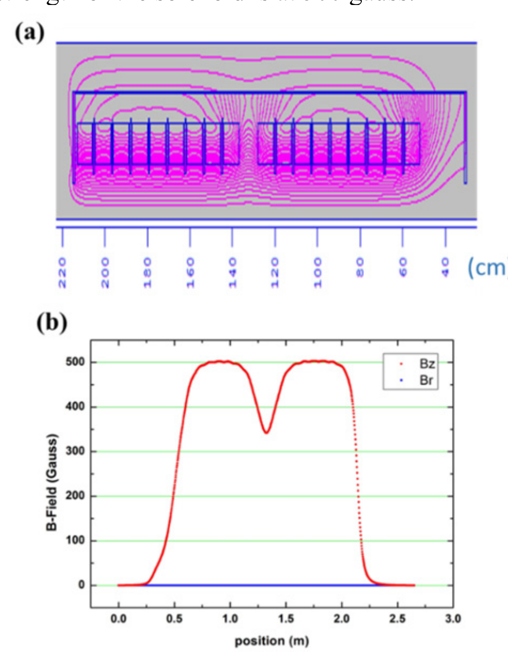

Figure 1: The model used in POISSON for calculation of the solenoid field and the calculated field line distribution (a). The magnetic field profiles along the solenoid (b).

We have compared the results of the case without the aid of linac solenoid field and the case with optimum solenoid field. Since the stay clear radius of linac structure is about 1.2-cm, RMS beam size has to be less than

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2-mm so that electrons do not lose much during acceleration. As shown in Fig. 2, without beam focusing by the solenoid field, the beam size evolves from 0.5-mm at the linac entrance (1.35-m) to about 4.2-mm at the exit. With solenoid field set at 500 gauss, the maximum beam size in the rf linac can be kept within 2.0-mm and without any particle loss.

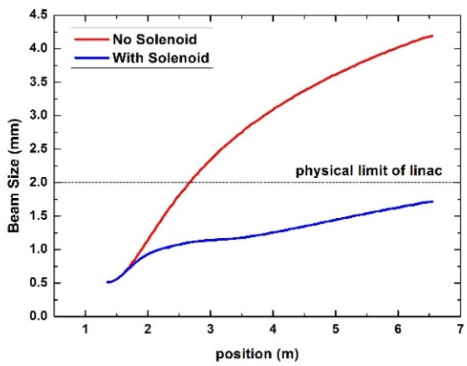

Figure 2: The evolution of beam sizes along the linac with (blue) and without (red) solenoid field for beam focusing.

ALIGNMENT ERRORS

First, we studied the effects of position offset which is comparable to the beam size. We considered the field axis of the solenoid magnet has a small offset, 0~3-mm, from the ideal beam axis in the horizontal direction. It is found that this offset does not have much influence on beam quality in velocity bunching except the transverse emittances. Table 2 summarized the beam properties at the exit of linac as calculated by GPT. Since the amplitude of beam emittance oscillation in the linac becomes larger as solenoid field position offset increases, the influence of position offset on transverse beam emittances is noticeable. The horizontal emittance is increased by about 21.9 % and vertical emittance is increased by 8.83 % due to the 3-mm solenoid field horizontal offset.

Table 2: Beam Quality at Linac Exit with Different Solenoid Field Offsets

Offset [mm]	0	1	2	3
Energy [MeV]	33.320	33.324	33.335	33.352
Energy Spread [MeV]	0.239	0.240	0.239	0.242
Hori. Beam Size [mm]	1.681	1.673	1.682	1.661
Verti. Beam Size [mm]	1.681	1.677	1.692	1.676
Bunch Length [fs]	63.886	64.618	64.885	67.755
Hori. Emit. [mm-rad]	2.431	2.473	2.654	2.964
Verti. Emit. [mm-rad]	2.423	2.423	2.499	2.637

Since the initial position of electron beam is not at the center of the solenoid field as we have assumed, individual electrons in this context will therefore have small transverse velocity components and rotates in the solenoid field about their guiding centres. The guiding centre of an electron is half of the distance of the solenoid field axis from the electron's initial position. Therefore, the final beam position at linac exit may change. As shown in the left plot of Fig. 3, the electron beam centroid oscillates as we have expected for gyro-motion of a charged particle beam at given energy. However, as the beam traverses across the linac after longitudinal position at ~2.5-m, the beam centroid moves toward the ideal beam axis as it slips gradually into favorable rf phases for gaining more energy from the accelerating field, the solenoid field is more difficult to bend the beam toward the beam axis and finally left the linac with a position offset. Beam centroid oscillates at twice the frequency of horizontal oscillation in the vertical direction. As the bunch slip into rf phases that gain energy from the accelerating field becomes more effective, the vertical displacement of beam center from the solenoid field axis is increasing after 2.5-m. As a result, the bunch leaving the linac with larger offset from the beam axis. In general, the larger the solenoid field offset, the larger the position deviations from the beam axis at linac exit as depicted in Fig. 3.

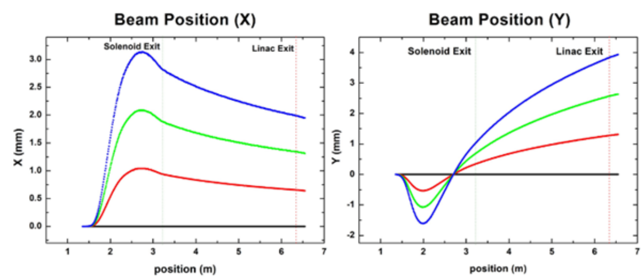

Figure 3: Evolution of the horizontal (left) and vertical (right) positions of beam center with different solenoid field offsets in the horizontal direction. (Black, red, green, and blue represent 0, 1, 2, 3 mm offset respectively.)

Another case to consider is the small tilt angle between solenoid field axis and the ideal beam axis. To study this, we assume the center position of the solenoid entrance is aligned correctly with the center of the beam axis but allows a 0~3mm position offset at the end of the solenoid in horizontal direction.

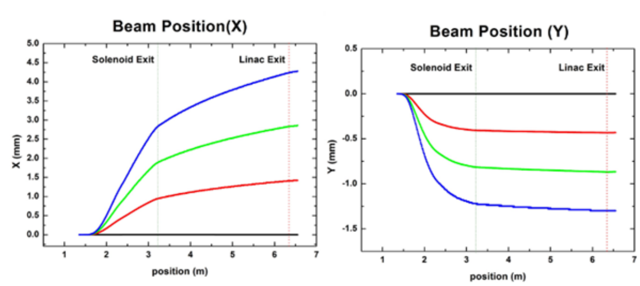

Figure 4: The positions of the beam center at linac exit in the horizontal (left) and vertical (right) directions for different values of tilt angle. (Black, red, green, and blue represent 0, 1, 2, 3 mm offset respectively.)

From the GPT calculation results, the tilt angle does not have much influence on beam properties. The transverse emittance in the 3-mm solenoid tail offset case is about 2% deviation from its original value. As shown the Fig. 4, the effect of tilt angle on final beam position is comparable to the case with solenoid position offsets.

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NON-AXISYMMETRIC MAGNETIC SHIELD

If the axis of a symmetric solenoid field is perfectly aligned with the ideal beam axis, there should be no transverse field components on the beam axis. However, it may happen that field distortions due to the openings for practical considerations spoil the symmetry of the focusing field.

(a)

(b)

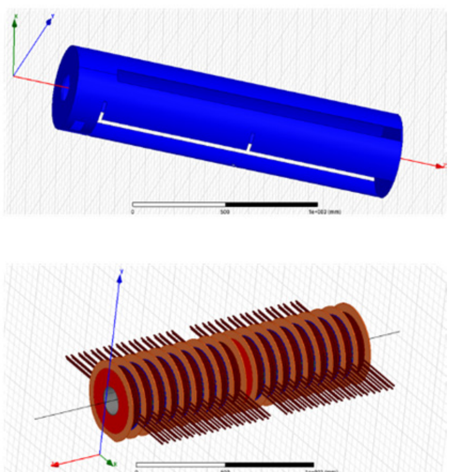

Figure 5: The model used in ANSYS Maxwell: (a) The solenoid iron shield, (b) the coil sets of the linac solenoid.

The 3D simulation software, ANSYS Maxwell [7] is used to evaluate the effects of non-axisymmetric iron shield on solenoid field in our case. Figure 5 is the model we used in ANSYS Maxwell. Figure 6 depicts the calculated longitudinal field component B_z along the axis. The profile looks similar to the longitudinal field profile calculated by POISSON. However, there is a discrepancy in the values field strength between the results calculated by the two software. Since the field minimum in transverse plane is shifted toward the direction with opening from the solenoid axis. It is believed that the discrepancy is due to distorted field pattern by the asymmetric iron shield geometry and a slight difference between the values of iron permeability we used in the two codes.

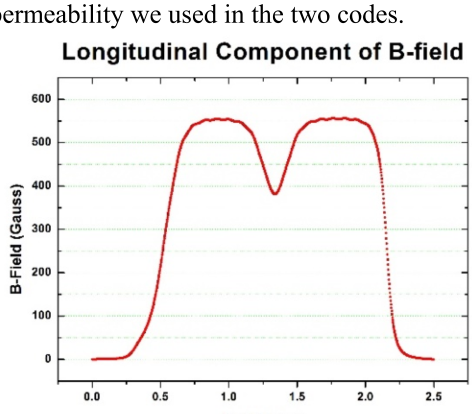

Figure 6: Longitudinal field component along the central axis of solenoid with shield.

Figure 7 is the calculated transverse fields of the solenoid with iron shield. It is found that there is some transverse field on the central axis of solenoid. In principle, these small transverse field components causes beam focusing off from the central axis. In our case, the maximum value of solenoid transverse field is limited to ~1.2 gauss in transverse plane. It is comparable to terrestrial magnetism and is considered not to have much perturbation on the beam trajectory. It is worth noting a smoother mesh is needed to remove the noisy data in Fig.7 but is limited by the computer resources.

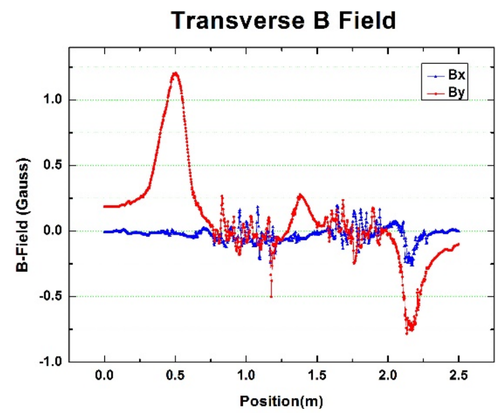

Figure 7: Transverse magnetic fields along the central axis of the solenoid with iron shield.

CONCLUSION

Since the NSRRC photoinjector linac will be operating near zero-cross phase for short bunch generation by velocity bunching, a solenoid is required for beam focusing during initial beam acceleration. As shown from our simulation results, alignment errors of solenoid magnetic field have effects on the beam trajectory in the linac and causing position offsets from the beam axis at linac exit. There is also a significant degradation of beam emittance due to alignment errors. Precise alignment of solenoid field to the beam axis has to be better than 100 µm. Asymmetry of the solenoid iron shield in our case does not introduce significant transverse magnetic fields that perturb the beam orbit as expected.

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