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SUPERCONDUCTING SOLENOID FIELD MEASUREMENT AND OPTIMIZATION

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Abstract

The solenoid is a significant part of an electron injector to provide a proper focusing, and preserve the beam projected emittance. A superconducting solenoid is applied for the SRF photoinjector at HZDR. The solenoid itself can degrade electron beam quality due to magnetic field imperfections like multipole components. In order to determine the field aberrations in the solenoid, we measured the superconducting solenoid magnetic field in the cryomodule. A simple and effective method is used to analyze the multipole field components, which will be presented in this paper.

INTRODUCTION

As a significant part of an electron injector a solenoid provides proper focusing, and preseves the beam projected emittance. The normal-conducting injector system has a main focusing solenoid and bucking coil to zero the longitudinal magnetic field at the cathode position. The superconducting radio frequency (SRF) photoinjector system has one solenoid at the exit of the cavity. However, since 2005 [1], it was found that the aberrated field in the solenoid destroys the beam symmetry and enlarge beam emittance. Correctors consisting of normal quadrupole coils and skew quadrupole coils have been used in more and more electron injectors [2, 3].

To compensate the beam projected transverse emittance, a superconducting (SC) solenoid is in the cryomodule at the ELBE SRF Gun-II, located at about 0.097 m far from the exit of the gun cavity, as shown in Fig. 1. Detailed information on the SC solenoid design is given in [4].

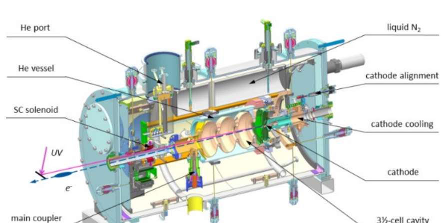

Figure 1: The current ELBE SRF Gun II and the SC solenoid in the cryomodule.

SOLENOID MAGNETIC FIELD EXPANSION

Considering there is no source of magnetic field in the solenoid, one can derive the transverse magnetic field as polynomial expansion depending on the longitudinal magnetic field derivatives with respect to z or Fourier series expansion (circular region) from Laplace's equation [5], such as in Eqs. (1) and (2):

$$B_r(r) = -\frac{r}{2}\frac{\partial B_z(0,z)}{\partial z} + \frac{r^2}{16}\frac{\partial^2 B_z(0,z)}{\partial z^2} + ... \quad (1)$$

$$B_r(r,\theta) = B_{r0} + B_{r0}\sum_{n=1}^{\infty} r^n[b_n cos(n\theta) - a_n sin(n\theta)] \quad (2)$$

In Eq. (1), $B_z(0,z)$ is the longitudinal on-axis magnetic field and the prime indicate derivatives with respect to z. In Eq. (2), a_n and b_n are the skew and normal $2(n+1)$-pole coefficients, respectively. They can be calculated using Fourier inverse formulas:

$$a_n = -\frac{1}{\pi B_{r0} r^n}\int_0^{2\pi} B_r(r,\theta)sin(n\theta)d\theta \quad (3)$$

$$b_n = \frac{1}{\pi B_{r0} r^n}\int_0^{2\pi} B_r(r,\theta)cos(n\theta)d\theta \quad (4)$$

B_{r0} could be set as the average of $B_r(r,\theta)$ over the circular boundary.

From Eq. (1), it is convenient to calculate the center of the solenoid field with fitting in cartesian coordinate system as Eq. (5)

$$B_r^2 \approx kr^2 = k[(x-x_0)^2 + (y-y_0)^2] \quad (5)$$

x_0 and y_0 are the transverse field center in horizontal and vertical directions respectively, k is the fitting linear coefficient.

The multipole components of the solenoid field can be calculated from Eqs. (2) to (4) using the measured points on the circular boundary. Considering different multipole component features with coordinate system, one can use this relationship to analyze multipole component in measurements. For instance, in solenoid field, the main transverse field, dipole field, normal quadrupole field, skew quadrupole field, shown as the following equations respectively:

$$\boldsymbol{B_t} = k_t x\boldsymbol{e}_x + k_t y\boldsymbol{e}_y \quad (6)$$

$$\boldsymbol{B_d} = k_{dx}\boldsymbol{e}_x + k_{dy}\boldsymbol{e}_y \quad (7)$$

$$\boldsymbol{B_n} = k_n y\boldsymbol{e}_x + k_n x\boldsymbol{e}_y \quad (8)$$

$$\boldsymbol{B_s} = k_s x\boldsymbol{e}_x - k_s y\boldsymbol{e}_y \quad (9)$$

here k_t is the main transverse field coefficient, k_{dx} and k_{dy} are the dipole component coefficient in horizontal and vertical direction, k_n and k_s are the normal and skew quadrupole

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component coefficients. $\boldsymbol{e}_x$ and $\boldsymbol{e}_y$ are the unit vectors in horizontal and vertical direction. Then the solenoid transverse fields in horizontal and vertical are:

$$B_x = (k_t + k_s)x + k_n y + k_{dx} \tag{10}$$

$$B_y = (k_t - k_s)x + k_n x + k_{dy} \tag{11}$$

The multipole component coefficients can be obtained by linear fitting using Eqs. (10) and (11).

SC SOLENOID MAGNETIC FIELD MEASUREMENT

The solenoid magnetic field measurement is conducted with the solenoid in the cryomodule cooled down to 4 K. The critical temperature of the coil´s NbTi wires is 9.2 K. A one-component Hall detector is used in the measurement pipe, as shown in Fig. 2. The longitudinal magnetic field is measured with 200 points along the cryomodule mechanical center axis, shown in Fig. 3. Each transverse field mapping will deliver one magnetic field component data with 11 × 11 points in one plane and 13 planes along the longitudinal direction are measured. Then the detector is rotated by 90° for mapping the other field component. From the transverse field measurements with two directions, the center of the solenoid field can be calculated by fitting Eq. (5), shown as Fig. 4. The detailed parameters are in Table 1 [1, 2].

Table 1: Basic Parameters of Solenoid

Parameters	Values
Field center in x direction	15.33 ± 0.02 mm
Field center in y direction	63.44 ± 0.02 mm
Effective length	40.33 ± 0.14 mm
Maximum field on axis	45.23 ± 0.12 mA

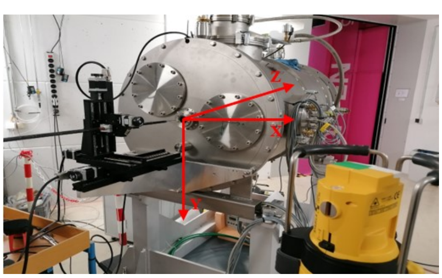


Figure 2: Cryomodule with SC solenoid and a 1D Hall magnetic field detector.

The solenoid field multipole components can be obtained by fitting Eqs. (10) and (11). Figure 5 shows that the fitting data is agree with the experiment data well, which means this method works. The dipole field and quadrupole filed coefficient in every plane is shown in Fig. 6.

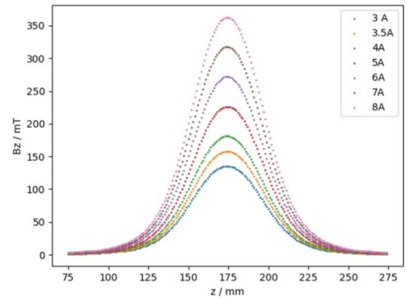
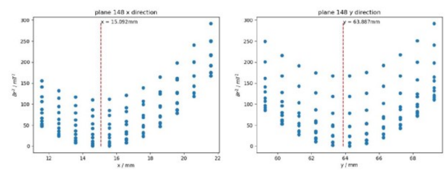
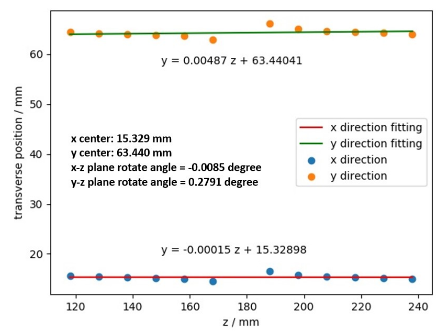


Figure 3: SC Solenoid longitudinal field on axis for different coil currents.

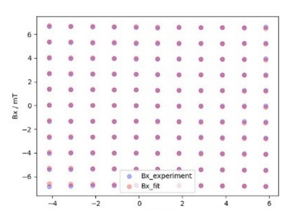


(a)

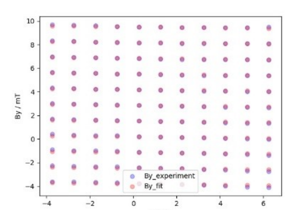


(b)

Figure 4: Solenoid transverse field center fitting. a) B_r^2 fitted with x and y as Eq. (5). b) The field centers in x and y directions of different planes at different positions.



(a)



(b)

Figure 5: Solenoid transverse field B_x (a) and B_y (b) fitted as Eqs. (10) and (11) (red dots) and experimental data (blue dots).

OPTIMIZATION AT SRF GUN BEAMLINE

To cancel the influence from the multipole components of the solenoid field, the correctors with a normal quadrupole coils and a skew quadrupole coils are used at the position 0.442 m far from the center of the SC solenoid (Fig. 7).

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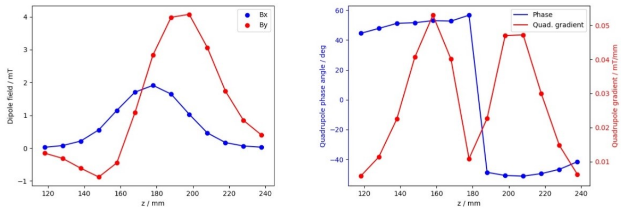

(a) (b)

Figure 6: Dipole field (a) and quadrupole gradient and phase (b) at different measurement planes for 4.0 A solenoid current.

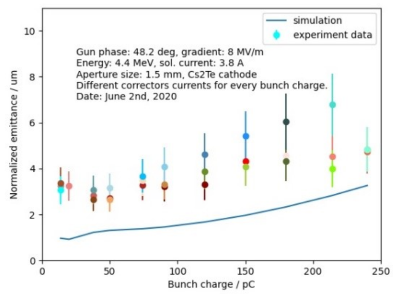

Figure 7: Normalized emittance vs. bunch charge. The spots with different colors are experiment data with different correctors current.

CONCLUSION

From the measurement results, although the magnetic transverse field multipole components are small comparing to the longitudinal filed, they will destroy the beam symmetry and enlarge beam projected emittance. The correctors can cancel this influence and optimize the beam projected emittance.

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