Superconducting solenoid fields measurement and optimization

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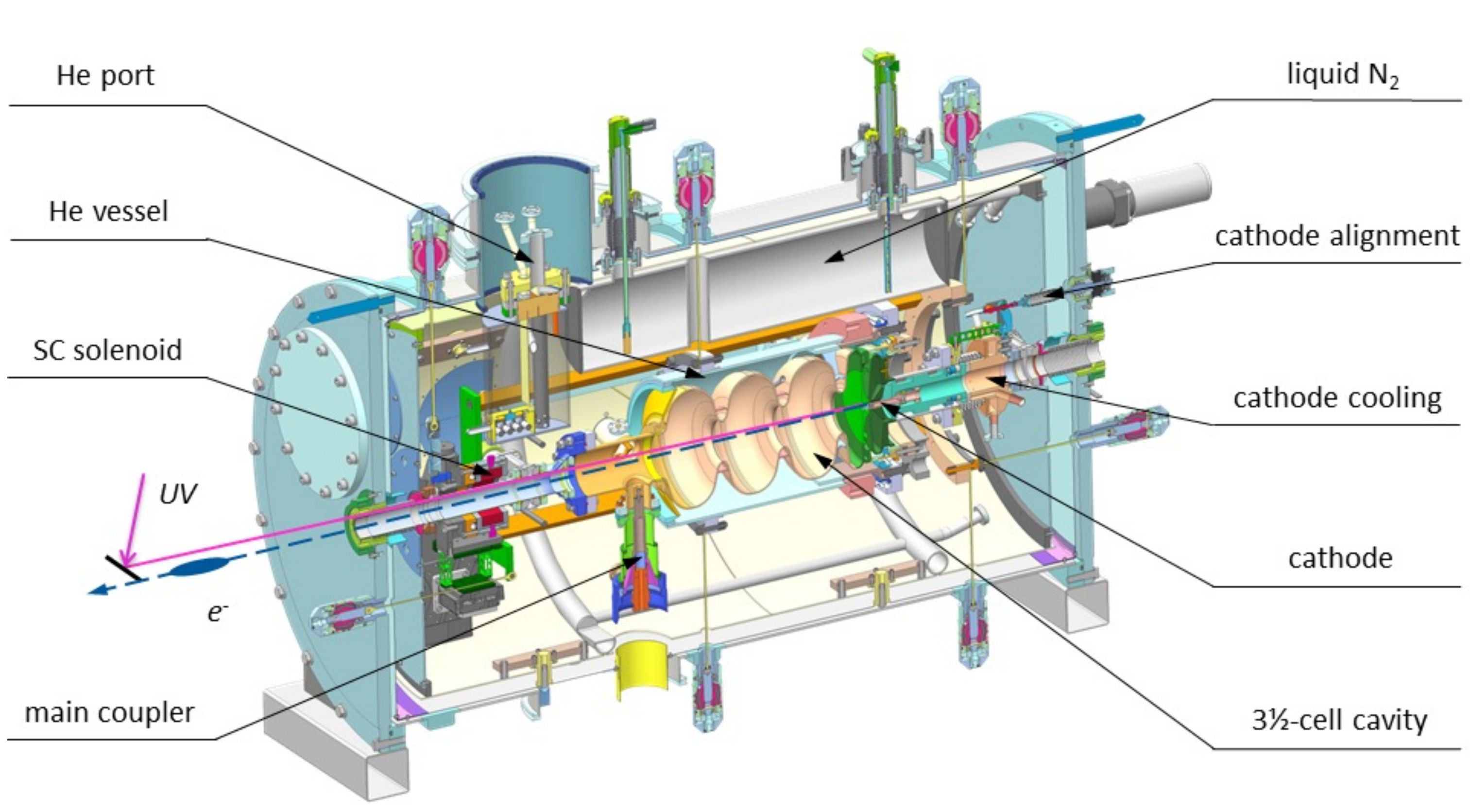
S. Ma, A. Aronld, M. Petr, Z. Paul, R. Anton, J. Schaber, J. Teichert, R. Xiang, Institute of Radiation Physics, HZDR, 01328 Dresden, Germany.
H. Qian, Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany

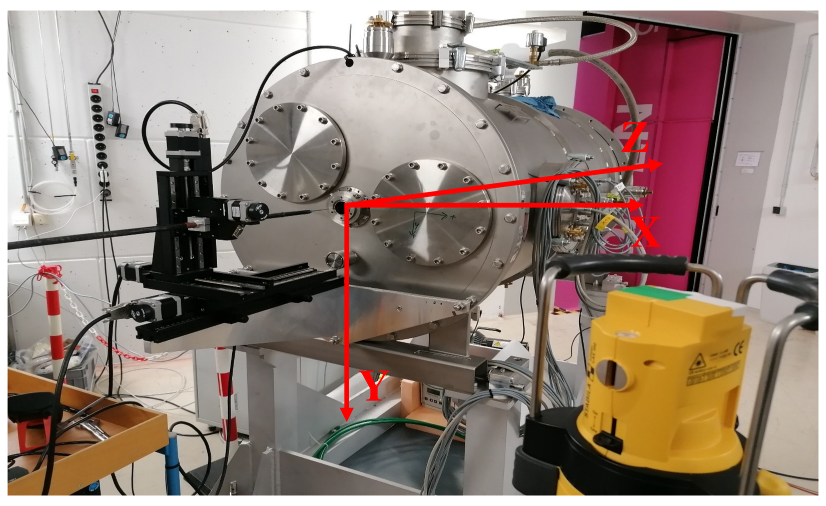
Introduction

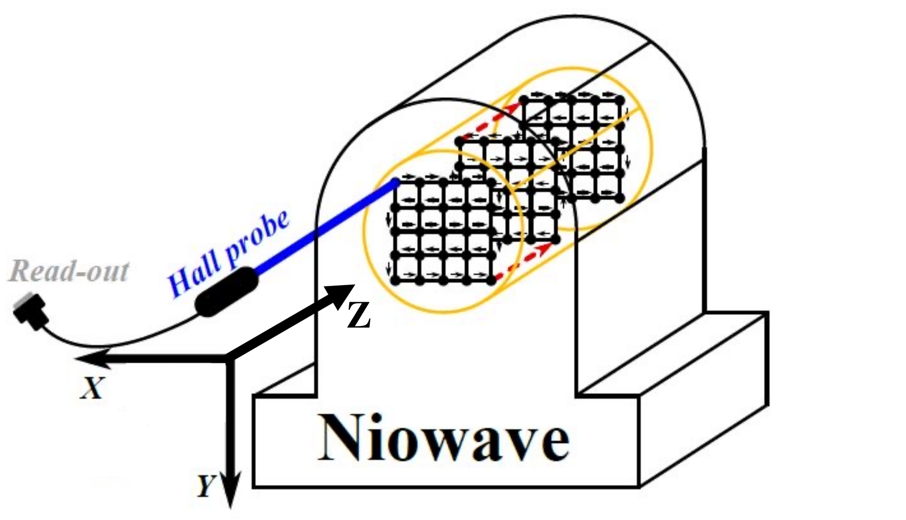
In order to reduce the projected transverse beam emittance, a solenoid is usually used at normal conducting as well as superconducting radio frequency (SRF) photoinjectors. At the ELBE SRF Gun-II, a superconducting solenoid is located inside the gun´s cryomodule about 0.1 m far from the end of the gun cavity. The aberration of the solenoid field, such as quadrupole component, will influence the beam symmetry and enlarge the projected transverse emittance. To analyze the multipole components of the solenoid field, a simple method is used and works well. The influence of the quadrupole field to emittance is studied and the correctors have been used to cancel this multipole field.



Solenoid magnetic field analysis

Experiment setup and magnetic field center





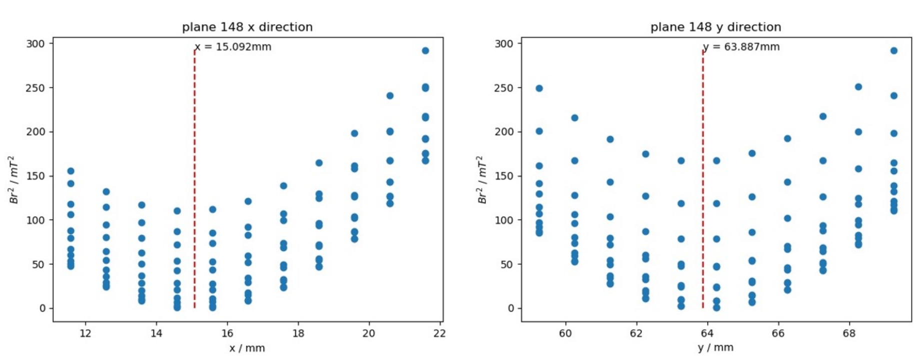
$$B_r \approx \left(-\frac{r}{2}\right)\left[\frac{\partial B_z}{\partial z}\right] + \left(\frac{r^3}{16}\right)\left[\frac{\partial^3 B_r}{\partial z^3}\right] + \cdots$$

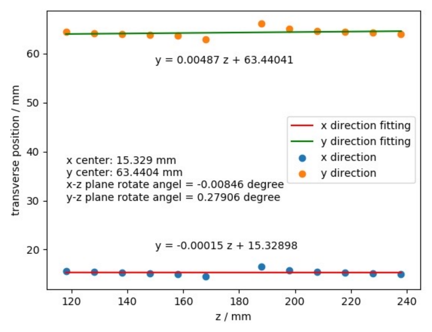
$$B_r^2 \approx kr^2 = k_r[(x-x_0^z)^2 + (y-y_0^z)^2]$$

$$B_{z,r} \approx B_{z,0} - \left(\frac{r}{4}\right)^2\left[\frac{\partial^2 B_{z,0}}{\partial z^2}\right] + \cdots$$

$$B_{z,r} \approx B_{z,0} - k_z[(x-x_0^z)^2 + (y-y_0^z)^2]$$

X center: 15.329 mm, $\Delta x = 1.251\ mm$
Y center: 63.404 mm, $\Delta y = 0.846\ mm$
x-z plane rotate angle: -0.00846 deg
y-z plane rotate angle: 0.279 deg

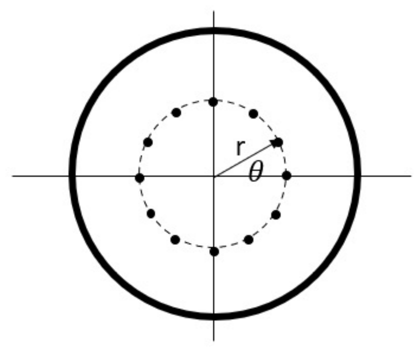




Solenoid multipole field analysis

Method one

Analyze the solenoid field from Laplace's equation using Fourier series.



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

a_n and b_n are the skew and normal 2(n+1)-pole coefficients, respectively.

$$a_n = -\frac{2}{M|B|r^n}\sum_{m=0}^{M-1}|B_m|\sin\left(\frac{2\pi nm}{M}\right)$$

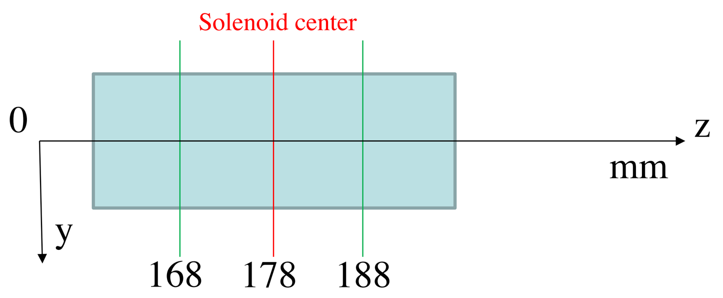
$$b_n = \frac{2}{M|B|r^n}\sum_{m=0}^{M-1}|B_m|\cos\left(\frac{2\pi nm}{M}\right)$$

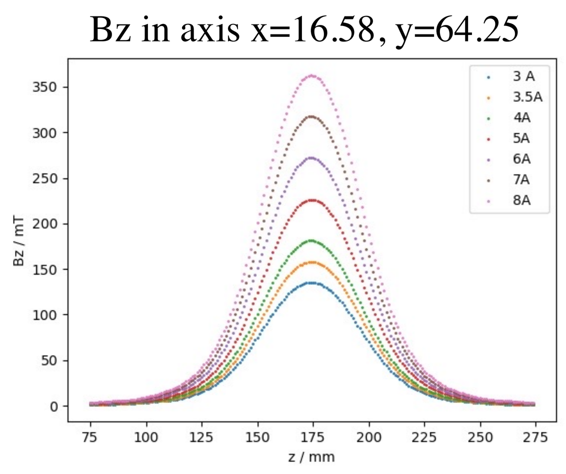
Method two

Linear fitting using the feature of the field depending on the cartesian coordinate system.

Transverse field	$\vec{B_t} = k_t x\vec{e_x} + k_t y\vec{e_y}$
Dipole component	$\vec{B_b} = k_{bx}\vec{e_x} + k_{by}\vec{e_x}$
Normal quadrupole component	$\vec{B_n} = k_n y\vec{e_x} + k_n x\vec{e_y}$
Skew quadrupole component	$\vec{B_s} = k_s x\vec{e_x} - k_s y\vec{e_y}$
Horizontal magnetic field	$B_x = (k_t + k_s)x + k_n y + k_{bx}$
Vertical magnetic field	$B_y = (k_t - k_s)y + k_n x + k_{by}$

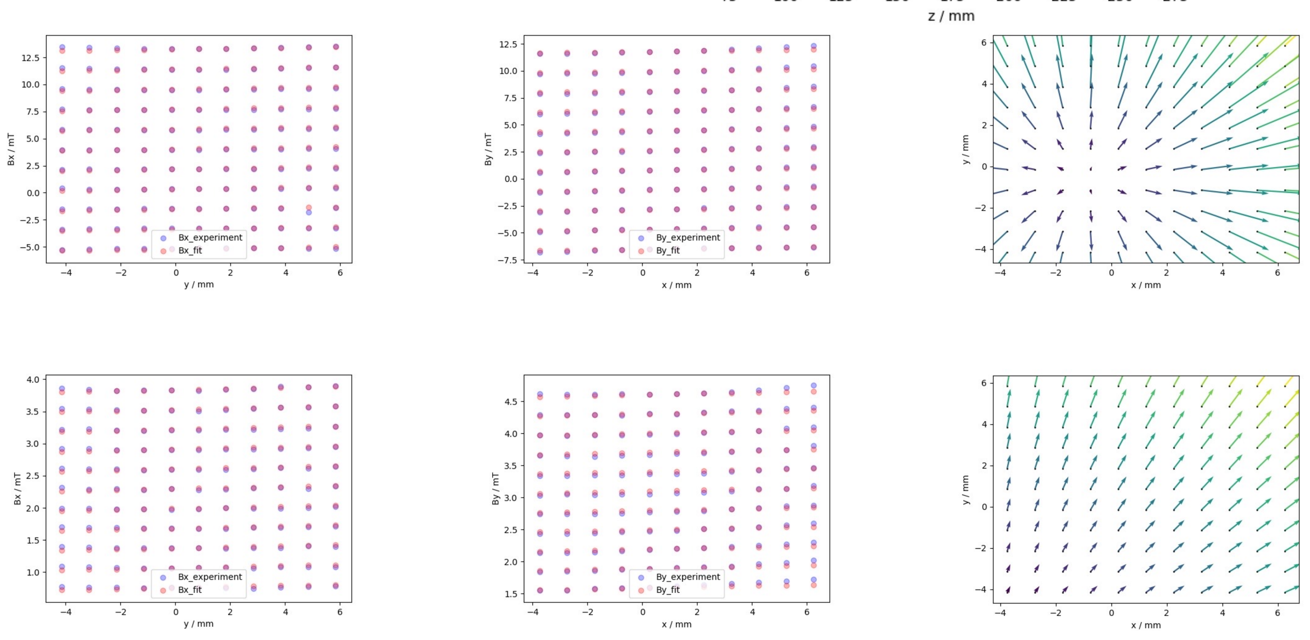
Measurement results

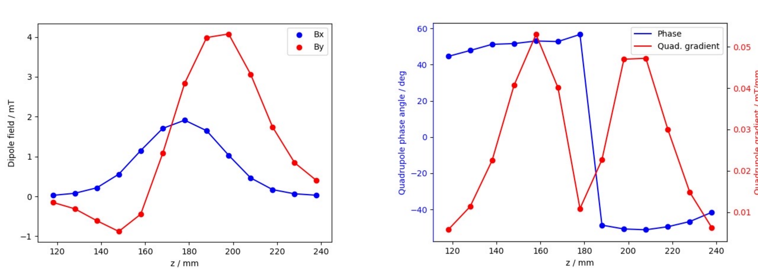




z = 168 mm

z = 178 mm

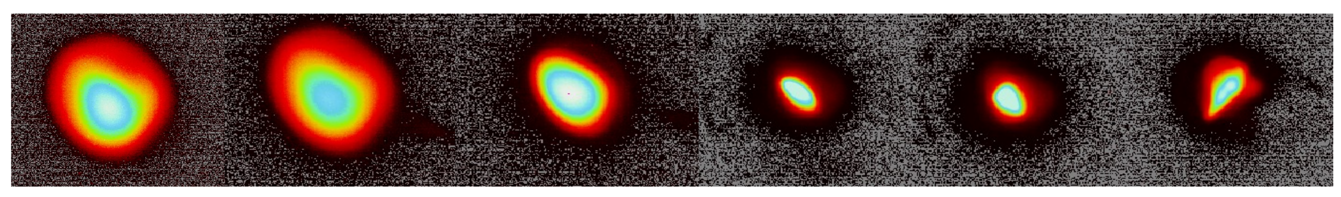




Field center in x direction	15.329 ± 0.0227 mm
Field center in y direction	63.4404 ± 0.0197 mm
Effective length	40.33 ± 0.143 mm
Longitudinal field	45.2267 ± 0.117428 mT/A

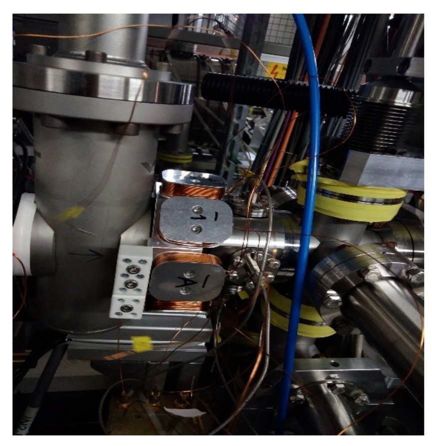
From the measurement results, the mechanical alignment is well. The second method can analyze the solenoid multipole fields easily and fast. The influence of the magnetic field center is negligible compared with the first method. The quadrupole component is inverse symmetric with the center of field.

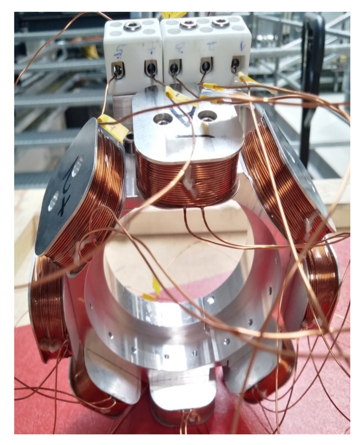
Influence to beam profile, projected emittance and correction



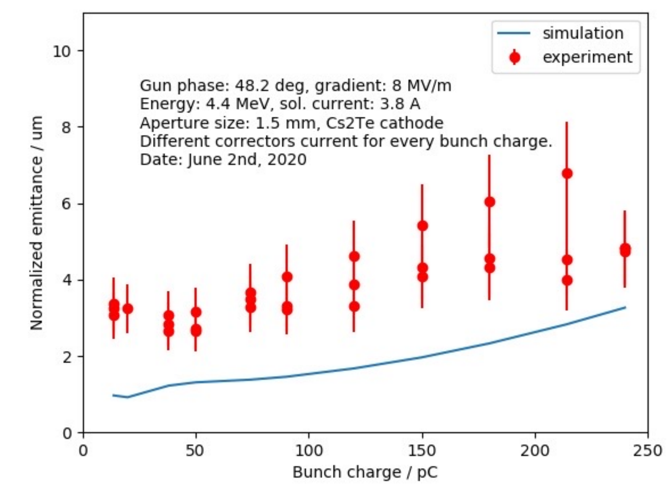
3.0 A 3.3 A 3.6 A 3.9 A 4.0 A 4.2 A

The way to correct the problem is to use a reverse coupled field: a rotated quadrupole field + normal quadrupole field.





Parameters:
- Combination of a normal and a skew quads
- Aluminum frame
- 0.56 mm copper cable
- 140 windings per coil
- Non-magnetic screws
- Q_grad = 0.0117 T/m @ 1A
- Position 0.437 m to solenoid center



Conclusions

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.

Acknowledgement

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Contact: Shuai Ma, Institute of Radiation Physics, Radiation Source ELBE. Email: s.ma@hzdr.de