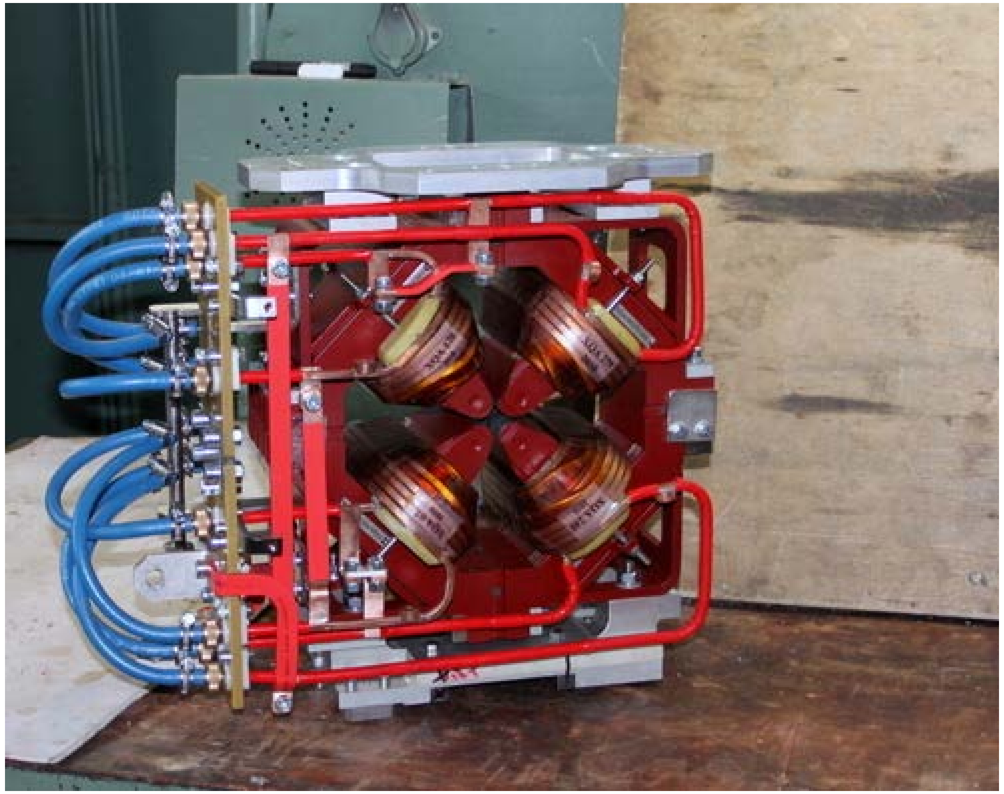
# The stability of the quadrupole magnet axis

The operation of the X-FEL requires a stability of the quadrupole magnet magnetic axis better than 5 μm for ±10% of a gradient range on at current of $I = 50\%\ I_{max}$, as well as a good quality of the magnetic field $\Delta B/B < 10^{-3}$

| | |
|---|---|
| Max gradient | 100 T/m |
| Aperture diameter | 16 mm |
| Length of the iron yoke | 0.1 m |
| Magnetic axis stability | < 5 μm |
| Field quality at R= 3 mm | $< 10^{-3}$ |



# Rotating coil setup

The rotating coil method.

Ceramic shaft of 15 mm diameter.

Main coil 20 turns, length  250 mm.

Two additional coils of 125 mm

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Rotating angle is done in fixed intervals.
Measured by an angle encoder with an accuracy of $2 \cdot 10^{-6}$.
For each rotation increment the voltage was measured.
The dependence of the voltage signal from the rotating angle will be transformed in a Fourier series.
Complete revolution - $360^0$

# The main error sources:

- Vibration of the shaft related to the bearings
- The angle measurement error
- Shaft sag (deflection)
- The noise from the power source

# Vibration of the shaft related to the bearings

Shaft vibration can be caused by the following problems:

- misalignment of the bearings,
- bending of the shaft,
- shifting of the center of rotation relative to the geometric axis and bearing,
- misalignment of the measuring shaft and the motor, torque imbalance,
- displacement of the center of mass of the shaft relative to the axis of rotation,
- etc.

# • The angle measurement error

We used a stepper motor VRDM LWC 397/50.

The accuracy of the stepper motor installation angle in our case is 6 minutes, which is relatively large and requires a measurement that is more accurate.

To measure the angle of rotation a goniometer LIRE 1170A is used.

The maximum possible error introduced to the total signal by this goniometer does not exceed $\pm 2 \cdot 10^{-4}$ in amplitude

# • The noise from the power source


Power supply type VCH-300.

Working current up to 300A

Voltages up to 12V.

The current stability is better than 0.01%.

Source is equipped with two contactless current sensors:

(one for stabilization and the other for independent measurements.)

# Bearing blocks

Each block contains two bearings.

The bearings are separated by a washer

The outer surface of the mandrel has

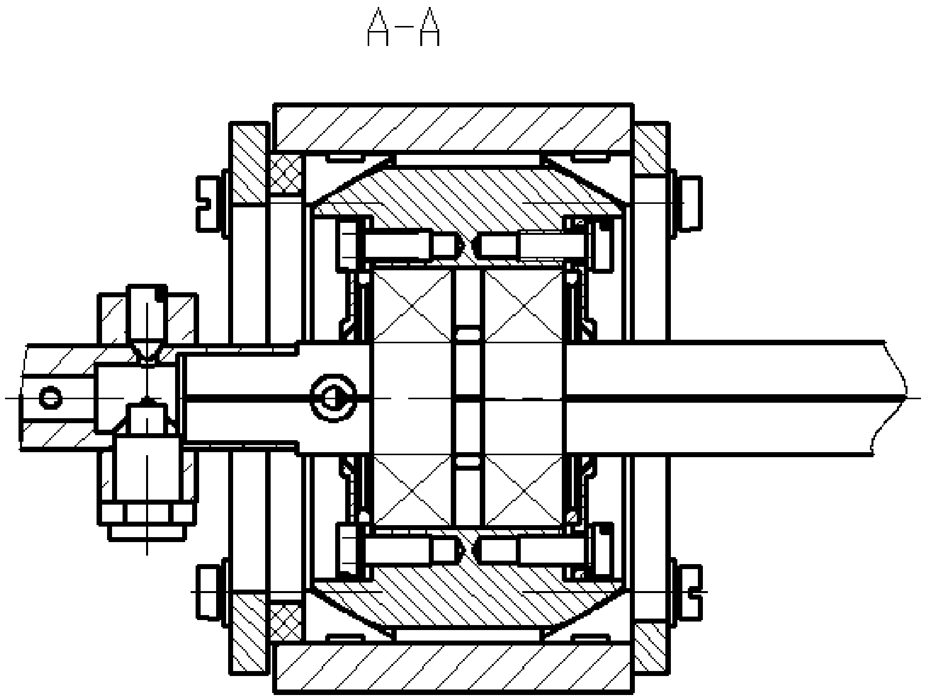
a  spherical shape.

The response surface of the case is conical.

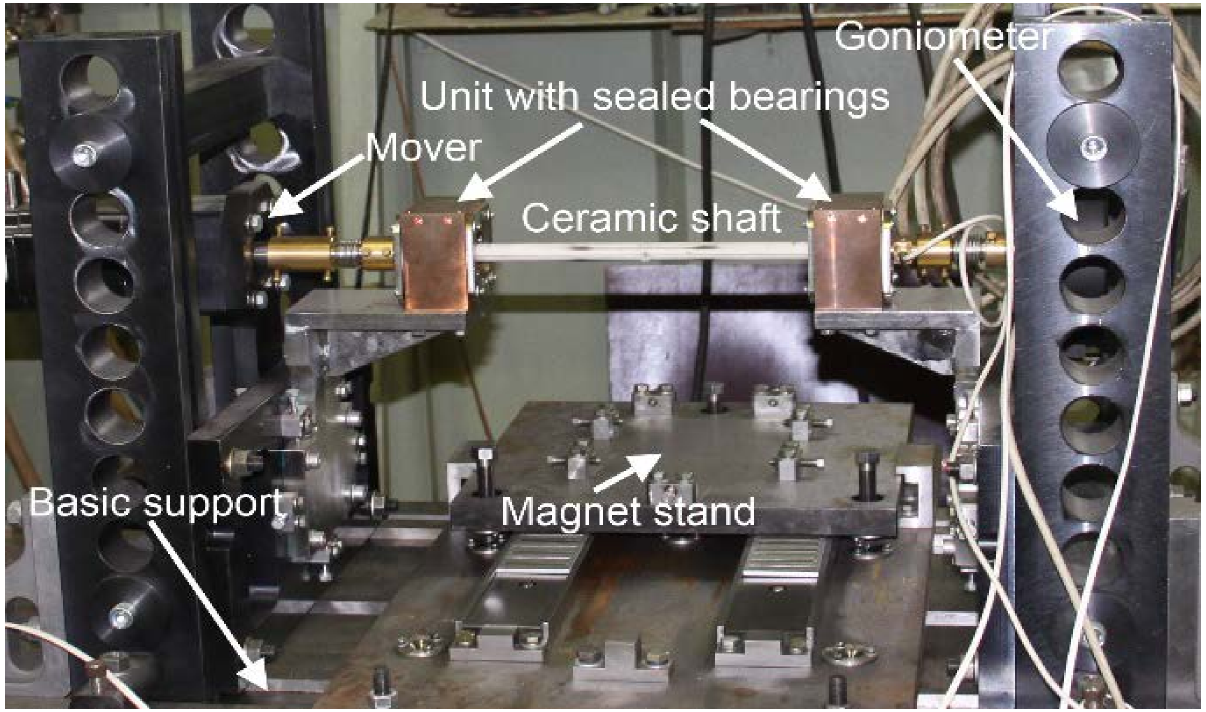
It align the shaft axis of rotation and

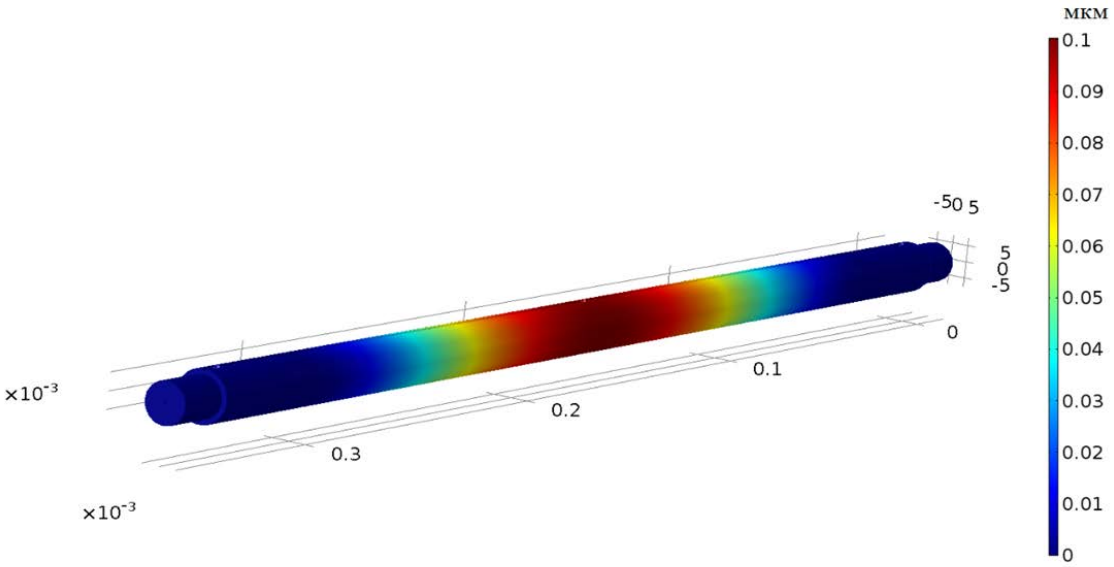
eliminate the appearance of misalignment

and vibration.



The shaft with bearing blocks
is mounted on a support.




Computation for the deflection

of the ceramic coils under the action of gravity

is of the order of 0.1 μm.

The formula for calculation of the quadrupole lens offset:

$$\Delta x = (A_1 \cdot A_2 + B_1 \cdot B_2)/\left(2 \cdot (A_2^2 + B_2^2)\right),$$

$$\Delta y = (A_1 \cdot B_2 - B_1 \cdot A_2)/\left(2 \cdot (A_2^2 + B_2^2)\right),$$

were $A_n$ and $B_n$ are skew and normal field harmonics

$$D_n = \sqrt{A_n^2 + B_n^2} \, .$$

If we have deviation $f(\theta, R)$, then $R = R_0 + f(\theta, R)$

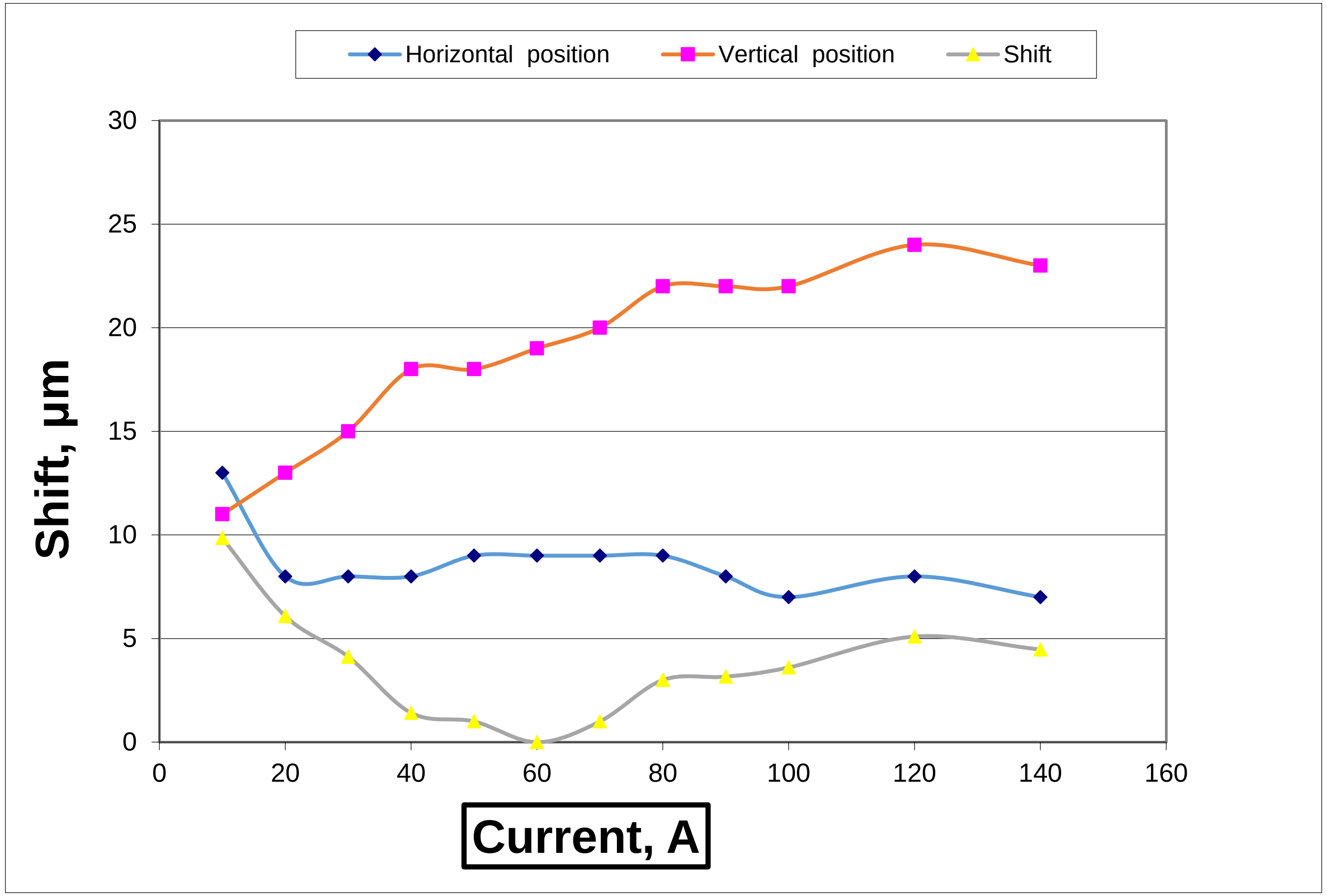
$$R = R_0 + \sum_{n=1}^{\infty} R_n \sin n(\theta + \varphi_r),$$

$$\Phi_\theta(\theta) = L \cdot \int_0^{R_0} \sum_{n=0}^{\infty} r^n \cdot D_n \sin(n\theta + \varphi_n)\, dr$$

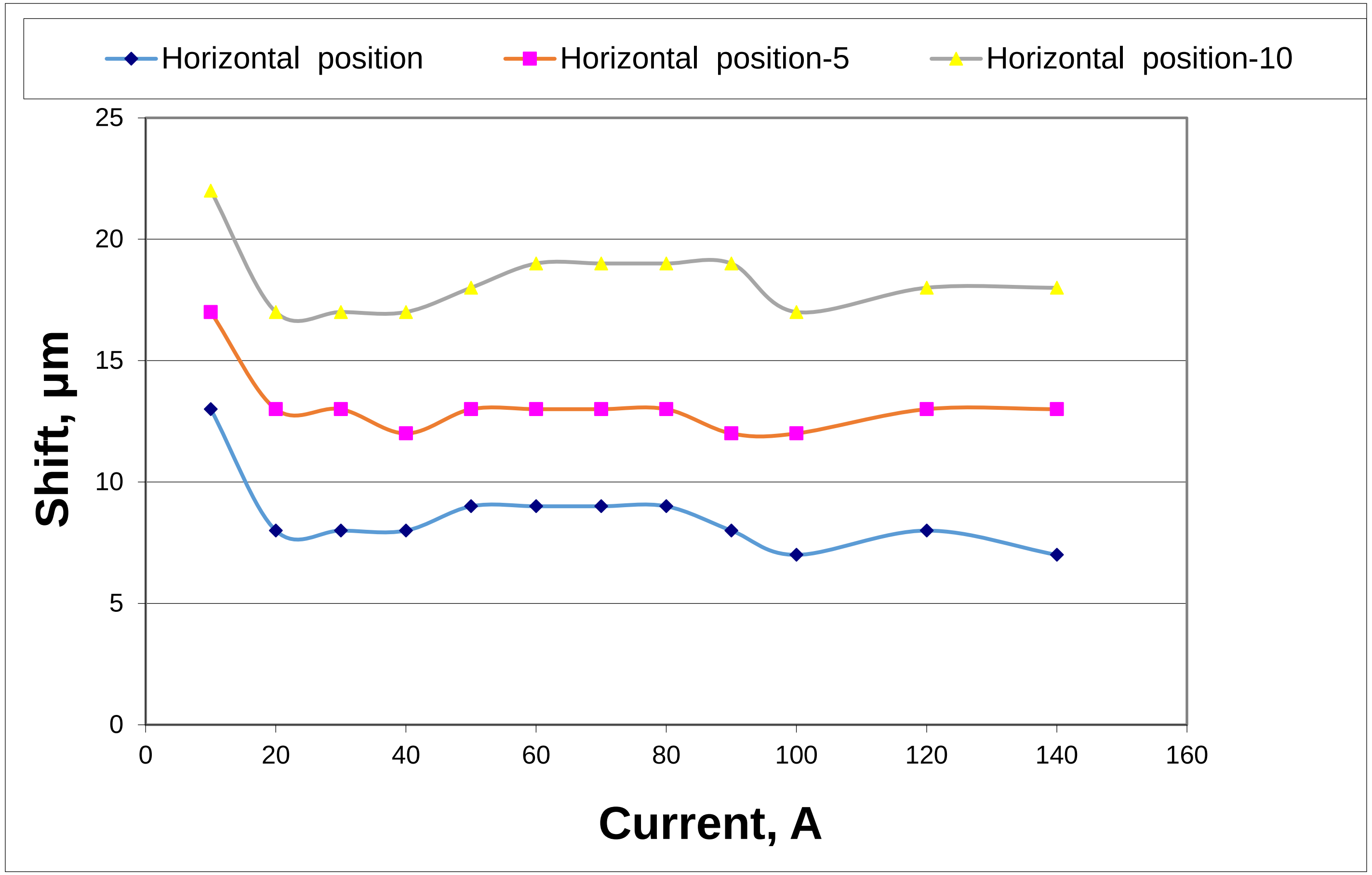
with $\varphi_r$ the phase shift, $\varphi_n$ the $n^{th}$ harmonics of the magnetic flux and L the length of the coil.

Error $\delta D = \Delta R/8$

# Axis position vs. current



# Quadruple horizontal shift



# Shift the position of the axis for 127 lenses