CBN 99-22

The Magnetic Center Finding using Vibrating Wire Technique.

A. Temnykh

Laboratory of Nuclear Studies
Cornell University, Ithaca NY 14853, USA

May 26, 1999

Abstract

The position of the magnetic center of the CESR Phase III super-conducting qudrupole magnet was determined using vibrating wire technique. The measurement was done at room temperature. The length of the magnet was $0.65\,m$ and the maximum gradient was $3.96 \cdot 10^{-2} T/m$. The magnetic center position was obtained with $\pm 9\mu m$ precision in vertical plane and with $\pm 17\mu m$ in horizontal. The techique allowed to detect less than $0.42Gcm$ of the magnetic field integral which appeared to be due to the misalignment between the quadrupole magnetic center and the thin stratched wire used as a probe.

The measurement setup, instruments and the method is described.

Introduction

Alignment of quadpupole magnets in respect to designed beam axis is very important issue for particle accelerators. The magnetic center of quadrupole magnets must be placed on axis to eliminate the unwanted trajectory distortions. To do it correctly one should know precisely the position of the magnetic center which may differ from mechanical.

There are a few methods generally being used to obtain magnetic center position. Here, the simplified version of vibrating wire technique discribed in [1] was used. This technique is based on the following phenomenon. The Lorenz forces between alternating current flowing through the taut wire and transversee magnetic field excite the mechanical wire vibration. If the frequency of driving

[1]Work supported by the National Science Foundation

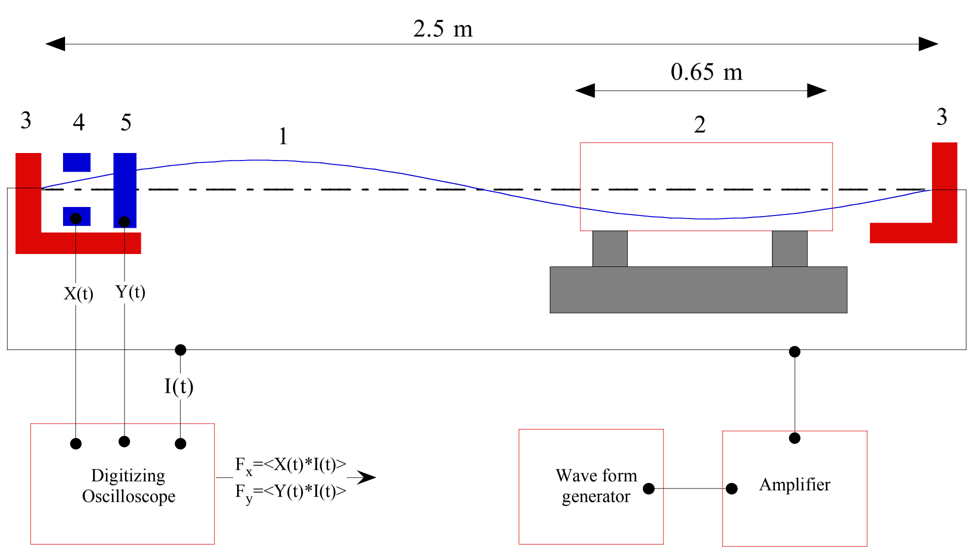

Figure 1: The measurement setup. 1 - stretched wire, 2 - superconductive magnet prototype, 3 - horizontal/vertical movable stages, 4 and 5 are horizontal and vertical wire motion sensors.

current is close to one of the wire resonance frequencies the effect will be especially strong. Amplitude and phase of the wire vibration will depend on sign and location of magnetic field along the wire. Measuring these characteristics for various frequencies of driving current one can reconstruct the magnetic field distribution along the wire.

The presented work was motivated by the needs of the CESR Phase III upgrade. This upgrade calls for super-conducting (SC) quadrupoles to provide final beam focus. SC quadrupoles will be placed into a cryostat with warm bore aligned in respect to the magnetic center of SC quadrupoles with precision better than $0.1mm$. All alignment must be done during assembly when quadrupoles are in warm state. It means that the measurement of the magnetic center position should be done at very small gradient, i.e., the measurement technique should provide a quite high sensitivity. The main goal of the presented work was to demonstrate that the vibrating wire method can be used for this type of alignment.

Instruments and method

The measurement setup is shown on figure 1.

The $100\mu m$ diameter copper-beryllium wire (1) with $2.5m$ of length was

Magnet length	$65cm$
Maxinum gradient	$48.5T/m$
Maximum current	$1225A$
Coil resistance at room temperature	$48\ \Omega$
Maximum current at room temperature	$1A$
Maximum gradient at room temperature	$3.96 \cdot 10^{-2}T/m$

Table 1: CESR Phase III super-conducting quad characteristics

stretched through the super-conductive quadrupole prototype (2). The wire ends were fixed on the stages (3) movable in horizontal and vertical planes with micro-screws. Two phototransistor-LED assemblies (4 and 5) placed on the left stage detected vertical and horizontal wire motion. Digital wave form generator with amplifier was used to drive AC current through the wire.

The magnet prototype characterictics are given in table 1. At room temperature the quadrupole coils have significant resistivity. Thus the current through the magnet was limited because of the magnet heating. However, it was found that one can keep 1A of current for very long time with just few degree temperature rise. This current was accepted as limit.

For the measurement, the wire vibration mode with the wire length equal to one wave length, see figure 1, was chosen to reduce the effect of background magnetic fields. It will be proved with formulas that if the background magnetic field is uniform on the wire length, this mode should not be excited at all. To maximize the effect of the quadrupole magnetic field, the testing magnet was placed at the maximum of the wire vibration amplitude as it is shown on scheme.

Oscilloscope TDS 430 with digital signal processor was used for signal analysis and processing.

The measured parameter F was the product of the horizontal wire position at the sensor location $X_w(t)$ and the driving current $I(t)$ averaged over time [1]. In the reference [1] it was shown that if the driving current frequency is close to the one of wire vibrating modes, parameter F may be described by the expression:

$$F = \frac{1}{T}\int_0^T X_w(t)I(t)dt \; = \; \frac{B_n I_0^2}{2\mu} sin(\frac{\pi n}{l} z_s) \frac{\omega - \omega_n}{4\omega(\omega-\omega_n)^2 + \omega\gamma^2} \qquad (1)$$

where ω and I_0 is the frequency and amplitude of driving current respectively, l_w is the wire length and z_s is the sensor position along the wire, μ is mass of wire per unit of length, ω_n is vibrating mode frequency, γ is damping rate. B_n is the coefficient of the Fourier sine transform of vertical magnetic field along the wire. For mode shown on figure 1, parameter n equals 2 and the expression

[1] Describtion for the vertical plane does not differ from horizontal

for B_n is:

$$B_2 = \frac{2}{l_w}\int_0^{l_w} B_y(z) sin(\frac{2\pi z}{l_w}) dz \qquad (2)$$

here z is coordinate along the wire, $B_y(z)$ is the vertical component of the magnetic field caused horizontal wire vibration. If the background field is a constant along the wire, accoding to formula 2 , coefficient B_2 will be zero and it will not affect measurement. In reality, the background magnetic field is not exactly constant along the wire. However, the choice of mode witn $n = 2$ significantly reduced the effect of background magnetic field . For the quadrupole magnet with gradient G and length l_m, ($l_m \ll l_w$), which placed at maximum of vibrating amplitude, as it shown on scheme, the coefficient B_2 will be:

$$B_2 \approx 2G\frac{l_m}{l_w}\delta x \qquad (3)$$

Here δx is the distance between the quadrupole magnetic center the wire position.

Composing equations 1 and 3 and assuming that the detuning $\delta\omega$ between driving current and mode frequencies, $\delta\omega = \omega - \omega_n$, is higher than damping rate, $|\delta\omega| \gg \gamma$ one can obtain:

$$F = \frac{I_0^2 l_m}{2\mu l_w} sin(\frac{2\pi z_s}{l_w}) \frac{2G}{4\omega\delta\omega}\delta x \qquad (4)$$

This expression indicates that parameter F has linear dependence on the distance between wire position and the quadrupole magnetic center δx and its sensitivity to δx is inverse proportional to detuning $\delta\omega$. To obtain the magnetic center position one should measure dependence of F on the wire position keeping driving current frequency as close as possible to mode frequency. The point where parameter F equals zero will be magnetic center location.

Measurements

The measured frequency of the $n = 2$ mode of wire vibration was close to $73.1\,Hz$. Probably due to small change of the wire temperature with time the frequency fluctuated at the level of $\pm 0.1\,Hz$. For small detuning $\delta\omega$ this fluctuation caused significant noise in the measured parameter F. To reduce the noise the frequency of driving current was settled $1.5\,Hz$ lower than the mode frequency. It was enough to reduce the noise in F while kept high sensitivity. The amplitude of current through the wire was $0.46\,A$.

In the process of measurement the wire was moved step by step through the center of magnet. In each point two measurements were done for $+1A$ and for $-1A$ of current through the magnet. The difference between these, δF, gave the effect of quadrupole magnetic field only, excluding the effect of background.

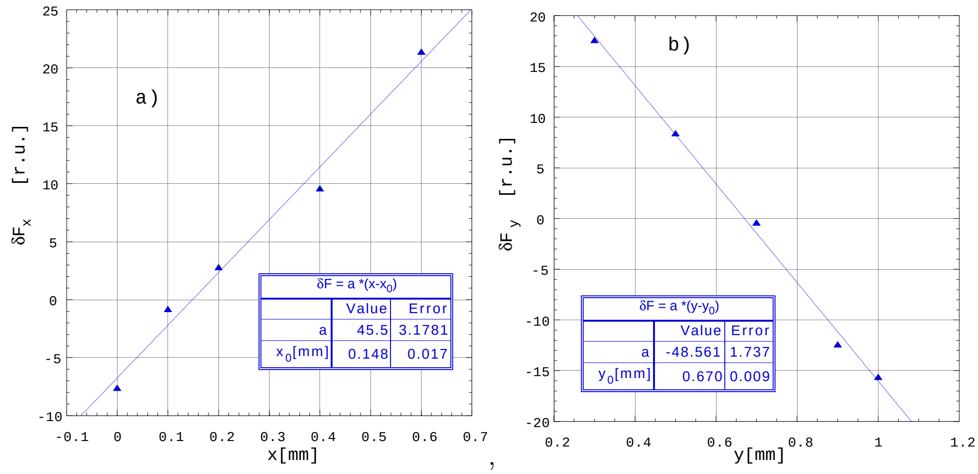

Figure 2: Parameters δF_x and δF_y versus wire position in horizontal, plot a), and in vertical plane, plot b). The points where $\delta F_{x,y} = 0$ give the horizontal and vertical position of magnetic center.

Horizontal position of magnetic center was found by moving wire in horizontal plane and detecting horizontal vibration. To obtain the vertical position of the magnetic center, wire was moved in vertical plane while detecting vertical wire vibration.

The data plotted on figures 2 shows the measured parameter $\delta F_{x,y}$ versus wire position in horizontal and in vertical plane. Indexes $_{x,y}$ refer to horizontal and vertical planes. According to formula 4 these data were fitted with linear dependence. The fitting indicated the magnetic center position at $0.148 \pm 0.017\, mm$ in the vertical plane and $0.670 \pm 0.009\, mm$ in horizontal. It should be mentioned that since the initial alignment of the wire relative to the mechanical magnet center was done with plastic ruler, the observed “zero” displacement of $0.148 mm$ in vertical and $0.670 mm$ in horizontal plane is very reasonable.

The precision, $\pm 0.017 mm$ in vertical plane and $\pm 0.009 mm$ in horizontal, is limited by random errors in measured parameters $F_{x,y}$. The reason for that, as it was mentioned before, is the vibrating mode frequency fluctuation caused by the small wire temperature change, probably, due to the surrounding air movement. However, one can see that this precision is much higher than required for the CESR Phase III assembly.

Let’s estimate the sensitivity of the vibration wire technique in this measurement. At the distance of $0.017 mm$ from the magnetic center of quadrupole with the gradient of $3.9 \cdot 10^{-2}\, T/m$ the magnetic field is $6.6 \cdot 10^{-7} T$. This is approximately $1\,\%$ of the background fields. The integral of this field over $0.65 cm$ of the quadrupole length is $4.3 \cdot 10^{-7}\, Tm$ ($0.43\, Gcm$).

It should be added that the amplitude of the driving current through the wire was $0.46\,A$, but it could be increased up to $1.5A$. For this current the sensitivity will 3 times higher.

Conclusion

The vibrating wire technique was used to obtain the position of magnetic center of the CESR Phase III super-conducting quadrupole prototype at room temperature. The position was found with the precision of $\pm 0.017\,mm$ in horizontal plane and $\pm 0.009\,mm$ in vertical. This satisfies all requirements for the CESR Phase III upgrade magnet alignment.

The applied technique allowed to detect $0.43\,Gcm$ of magnetic field error due to magnet misalignment.

Acknowledgment

I would like to thank Thomas Dilgen and John Cintorino for setting up the magnet and for help during data taking. I am also grateful to Jain Animesh and David Rice for great interest to this measurement and useful comments.

References

[1] A. Temnykh, Vibrating wire field-measuring technique, Nuc. Inst., A 399 (1997) 185-194

[2] J. Welch, G.F Dugan, E. Nordberg, D. Rice, The Superconducting Interaction Region Magnet System for the CESR Phase III Upgrade. Proc. 1997 Particle Accelerator Conference, vol. 3, pp. 3383-3385