CBN 00-16

The use of Vibrating Wire Technique for precise positioning of CESR Phase III super-conducting quadrupoles in cryostats.

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December 19, 2000

Abstract

Vibrating wire technique has been used for precise positioning of CESR Phase III quadrupole magnets in cryostats at room temperature. The alignment was done at $8 \cdot 10^{-2} T/m$ of gradient of magnetic field at quadrupole magnets. The position of the magnetic center of the quadrupoles was measured with 0.03mm precision. The magnets were aligned with cryostat centerline with better than 0.2mm precision.

The measurement setup, instruments and the procedure are described.

Introduction

CESR Phase III upgrade calls for installation of four final focusing superconducting (SC) quadrupole magnets around interaction point (IP), see [3]. Two SC quadrupoles sharing common cryostat will be placed on each side of IP. The position of SC magnets will not be available for survey after they are placed inside of cryostats and cooled down. Thus the magnets should be precisely aligned with cryostats center at the moment of installation. Afterward, well defined references on cryostat's body can be used for precise positioning relative to global survey system.

The most direct way to align the magnet with cryostat is to measure it's magnetic center position and, using adjustment in the suspension mechanism, to

[1]Work supported by the National Science Foundation

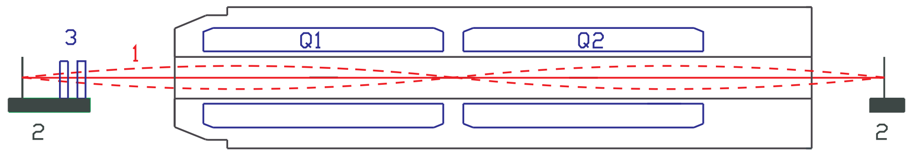

Figure 1: The measurement setup. 1 - probe (vibrating) wire, dashed line shows the mode of vibration used in measurement. Q1, Q2 - super-conductive quadrupoles inside of cryostat. 2 - stages movable in horizontal and vertical planes. 3 - horizontal and vertical wire position sensors.

align magnetic centers with cryostat center line. Because the adjustment mechanism is accessible only at room temperature, the magnet positioning should be done in warm state and then the magnetic center position should be verified again at low temperature. At room temperature the quadrupole coils have significant resistivity and the current through the magnet and the magnetic field gradient are very limited by magnet heating. It means that, the technique used for finding the quadrupole magnetic center must have high spatial resolution at very low magnetic field gradient. Suitable method, called "Vibrating wire technique" was developed in [1]. It is based on the following phenomenon. The Lorenz forces between alternating current flowing through the taut wire and transverse magnetic field excite a mechanical wire vibration. The vibration is especially strong if the driving current frequency is in resonance with one of the modes of wire vibration. The amplitude and the phase of vibration relative to the driving current depend on the magnetic field distribution along the wire. Measuring the phase and amplitude at various frequencies one can reconstruct the field distribution.

In [2] using a prototype magnet, it was demonstrated that the technique can be used for the required type of alignment. This paper reports details and results of the CESR Phase III SC quadrupoles alignment in cryostats at room temperature using the vibrating wire technique.

1 Setup description

The arrangement of the magnets and measurement setup is shown in Figure 1.

Two super-conductive quadrupoles, $Q1$ and $Q2$, were located inside a cylindrical cryostat as shown in Figure 1. Characteristics of Q1 and Q2 SC quadrupole magnets are given in Table 1. Because of significant resistivity of the magnet coils at room temperature, the current through the magnets during measurements was limited to 2A. At this current magnetic field gradient was $7.92 \cdot 10^{-2} T/m$.

The $100\mu m$ diameter, $3.02m$ length copper-beryllium wire (1), referred to

Magnet length	$65cm$
Maximum gradient	$48.5T/m$
Maximum current	$1225A$
Maximum current at room temperature	$2A$
Maximum gradient at room temperature	$7.92 \cdot 10^{-2}T/m$

Table 1: CESR Phase III super-conducting quad characteristics

here as either the probe or the vibrating wire, was stretched through the cryostat bore. The wire ends have been fixed on the stages (2) movable in horizontal and vertical planes with micro-screws driven by stepping motors. Two photo-transistor-LED assemblies (3) placed on the left stage detected vertical and horizontal wire vibration. A digital wave form generator was used to drive AC current through the wire. For a signal analysis as well as for control of digital wave form generator and stepping motors, a Macintosh Quadra 800 computer with application programs created in LabVIEW has been used.

Similar to the experiments described in [2], in order to reduce the effect of background magnetic field, the wire vibration mode with a wave length equal to the length of wire was chosen for the measurement, see Figure 1. The wire middle point, the node of the mode used in measurement, was right in the middle between $Q1$ and $Q2$. This arrangement provided equal sensitivity of the measurement for $Q1$ and $Q2$ misalignment.

2 Probe wire position determination

The first step was to establish the probe wire position in relation to the cryostat central line. On both ends of the cryostat there were four dowel pins placed at precisely defined positions, see Figure 2. The centers of the pins were located exactly in the vertical and horizontal mid-plane of the cryostat. The thin wires were stretched between the pins as is depicted in Figure 2 with vertical and horizontal offsets from mid-planes equal to the pin radius, $3.175\,mm$. These wires, here in called as a reference wires, were used to establish the probe wire position. Using movable stages the probe wire was shifted by small, $0.025\,mm$, steps toward the reference wires till they reached electrical contact. The special check was done to ensure that at this moment reference and probe wires were not bent. Taking into account the $0.1mm$ probe wire diameter, one can state that at this moment the center of the probe wire is $3.125\,mm$ off the cryostat's center. So, by moving the probe wire toward the cryostat center by $3.125\,mm$, the wire can be placed precisely on the cryostat center. Note that in the horizontal plane, the probe wire is aligned with cryostat center over all cryostat length while in vertical plane, because of sag, it is centered only at the location of the reference wires, i.e. at the cryostat ends.

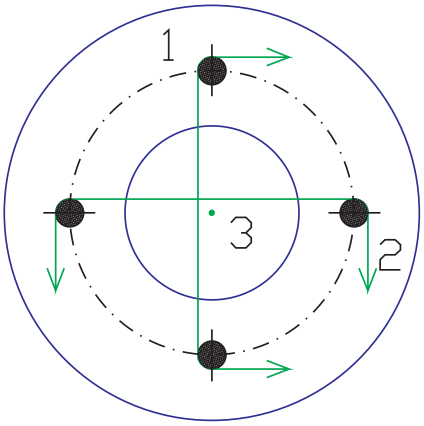

Figure 2: Schematical face view of cryostat end flange. 1 - dowel pins. 2 - horizontal and vertical reference wires. 3 - probe wire.

By repeating the described procedure a number of times and comparing final probe wire positions it was estimated that the possible error of probe wire position relative to cryostat center line was below $0.025mm$.

3 Vertical sag effect consideration

Some corrections have to be considered because of the vertical wire sag.

The formula for the vertical sag of the wire aligned with cryostat centerline will be:

$$y_{sag}(z) = -\frac{g}{8(l_w f_1)^2}(z - z_f)(z - z_r) \tag{1}$$

Here, y_{sag} is the vertical wire displacement relative to cryostat center line, z is the distance from wire end, g is gravity, l_w - wire length, f_1 - is the fundamental mode frequency of the wire vibration, z_f and z_r are longitudinal coordinates of the cryostat ends where the reference wires are located. Note that at the reference wire location the probe wire is on cryostat center, i.e., $y_{sag}(z = z_{f,r}) = 0$.

The measured parameter, $a_{2x,y}$, defined in the reference [1] is proportional to the second harmonic of the Fourier sine transform of magnetic field along wire. Index "2" indicates the second wire vibration mode, $_{x,y}$ are referring to the wire vibration in horizontal and in vertical plane. Note that vibration in vertical plane is excited by horizontal magnetic field and vice versa. For a quadrupole magnet aligned with the cryostat center, with gradient G, length l_m, and located at $z = z_m$, parameter a_{2y} will be:

Probe wire length	l_w	$302.2cm$
Front reference wire position	z_f	$53.3cm$
Rear reference wire position	z_r	$276.8cm$
Fundamental mode frequency	f_1	$32.7Hz$
$Q1$ and $Q2$ length	l_m	$65cm$
$Q1$ center position	z_m	$105.5cm$
$Q2$ center position	z_m	$196.7cm$
$Q1$ vertical sag correction	δy	$0.100mm$
$Q2$ vertical sag correction	δy	$0.136mm$

Table 2: Vertical sag correction.

$$a_{2y} \propto \int_0^{l_w} B_x(z,y) sin(\frac{2\pi z}{l_w}) dz = \int_{z_m-0.5l_m}^{z_m+0.5l_m} Gy(z) sin(\frac{2\pi z}{l_w}) dz \tag{2}$$

Here $y(z)$ is the vertical displacement of a probe wire relative to the cryostat center. If both ends of the probe wire are moved up by δy, $y(z)$ will be sum of sag and δy:

$$y(z) = y_{sag}(z) + \delta y \tag{3}$$

Substituting equation 3 in 2 and taking into account equation 1, one can find the distance at which the probe wire ends should be moved up to make a_{2y} equal zero:

$$\delta y = \frac{g}{8(l_w f_1)^2} \frac{\int_{z_m-0.5l_m}^{z_m+0.5l_m} (z-z_f)(z-z_r) sin(\frac{2\pi z}{l_w}) dz}{\int_{z_m-0.5l_m}^{z_m+0.5l_m} sin(\frac{2\pi z}{l_w}) dz} \tag{4}$$

This is the correction we have to apply to compensate the vertical sag effect. For a short magnet, $l_m << l_w/2$, equation 4 gives:

$$\delta y = \frac{g}{8(l_w f_1)^2} (z_m - z_f)(z_m - z_r) \tag{5}$$

Comparing this formula with equation 1 one can see that in this case the correction, δy, is the sag at the center of the magnet.

Table 2 shows some parameters of the setup and calculated sag correction. To compensate the sag when aligning the $Q1$ magnet, the wire ends should be moved up by $0.100mm$. For the $Q2$ alignment the ends should be moved up by $0.136mm$.

4 Measurement and magnet positioning

The alignment procedure for both cryostats, cryostat “1” and cryostat “2”, was identical and consisted of the following steps.

The first step was to establish the probe wire position as it is described in section 2.

Then by scanning the probe wire in vertical and horizontal planes and measuring parameters $a_{2x,y}$, the precise positions of the magnetic centers of the $Q1$ and $Q2$ magnets before adjustment were determined as illustrated on the two upper plots in Figure 3. On the plots vertical axes are measured $a_{2x,y}$, horizontal axes are position of probe wire in vertical and horizontal plane relative to cryostat centerline. Solid dots represent background measurement, i.e., with no current in $Q1$ and $Q2$. Triangles and squares are for 2A current in $Q1$ and in $Q2$ respectively. The magnetic center of quadrupoles is in location where $a_{2x,y}$ measured with the current in the magnets are equal to background. The data fitted with linear dependence gave the precise position of $Q1$ and $Q2$ magnetic center indicated in table 3 in the column “Position before tuning”. For the vertical position determination the calculated sag corrections were applied.

The next step was the magnet position adjustment. For that the probe wire was placed at cryostat center line in horizontal plane, in vertical plane it's ends were placed slightly higher to correct for the sag effect according to the above discussion. The frequency of the current through the probe wire was set close to the resonance of the second harmonic wire vibration. Comparing signals from the wire position detectors showing amplitude of the wire vibration, with and without current through the magnets, it was possible to estimate how far the magnetic centers of the quadrupoles was from the desired position. A few iterations of the measurements and adjustments of the magnet supporting system were needed to put the magnets in position such that the switching the current through the magnets off and on produced no effect on wire vibration. After that, the precise measurement of magnetic centers was repeated. Two lower plots of figure 3 and the column “Position after tuning” in the table 3 show the results of the final measurement.

It should be mentioned that the precise measurement of the magnetic center position by the probe wire scan took approximately 15minutes. The position estimation by comparing wire vibration amplitude for magnets turned on and off took just a few seconds.

Table 3 summarizes the results of the magnetic center position measurement before and after tuning for both of the cryostats. Before tuning, the average magnet displacement relative to the cryostat center was about $1\,mm$. After tuning, the measured displacement of three of four magnets is less than $0.1mm$. Vertical alignment of $Q2$ magnet in cryostat “2” was limited mechanically by its supporting system. This magnet has been positioned at $0.159mm$ below the cryostat center. The possible errors of the measured location of magnetic center is in the range of 0.01 and $0.03\,mm$.

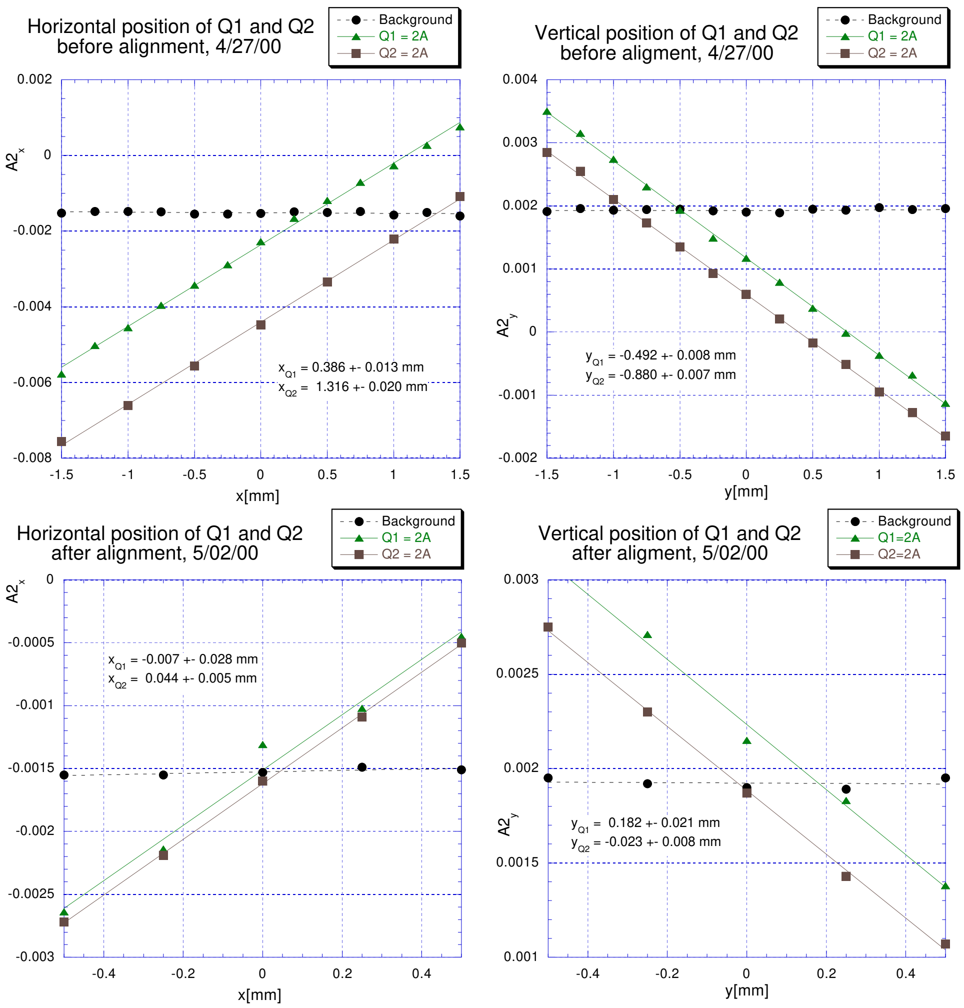

Figure 3: Cryostat “2”. $Q1$ and $Q2$ magnetic center position measurement before and after alignment. Vertical axis are the measured parameter $a_{2x,y}$. Horizontal axis on left plot is horizontal position of the probe wire relative cryostat center line. On the right plot horizontal axis is vertical position of the probe wire relative cryostat center at the reference wire location.

Cryostat Magnet	Position before tuning		Position after tuning	
	$x[mm]$	$y[mm]$	$x[mm]$	$y[mm]$
"1"				
Q1	0.286 ± 0.008	1.407 ± 0.028	0.013 ± 0.022	-0.001 ± 0.014
Q2	-0.816 ± 0.027	0.980 ± 0.034	0.065 ± 0.032	0.026 ± 0.027
"2"				
Q1	0.386 ± 0.013	-0.592 ± 0.008	-0.007 ± 0.028	0.082 ± 0.021
Q2	1.316 ± 0.020	-1.016 ± 0.007	0.044 ± 0.005	-0.159 ± 0.008

Table 3: Position of magnetic center of $Q1$ and $Q2$ quadrupoles in cryostat "1", and in cryostat "2" before and after alignment

Conclusion

The vibrating wire technique has been used for precise positioning of the CESR Phase III super-conducting quadrupole magnets inside of cryostats at room temperature. As a result, three of the four magnets have been aligned with the cryostat center with better than $0.1mm$ precision, the fourth magnet has been positioned at $0.159mm$ off the cryostat center because of limitation in the range of motion. The precision of the magnetic center position measurement was better then $0.03mm$.

The vibrating wire technique has been proved to be a very convenient and adequate tool for the precise alignment of the quadrupole magnets with low gradient.

Acknowledgment

I would like to thank David Rice and David Rubin for their attention to this work, Scott Chapman for help in the checking of the position of the probe wire. I am also very grateful to James Welch for his cooperation and for his help with the precise movement of the magnets.

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