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Correcting for background fields and multipole field errors in the localization of the magnetic axis in quadrupole magnets

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ABSTRACT

The fiducial marker localization with respect to the magnetic axis of the magnet elements is a crucial step in the qualification of the magnets for particle accelerators. Background fields, such as the Earth's magnetic field and fringe fields from electrical sources may degrade the accuracy of this axis localization. In this paper, we discuss stretched-wire measurements, in static and vibrating operation modes, for the correction of stray fields in the quadrupole axis localization to an accuracy of 0.3 μm. Moreover, we present an analytical model to correct the magnetic axis position error due to higher-order multipole field errors in the magnet. This correction is particularly important for the static stretched-wire measurement because the wire movement must be large enough to obtain a sufficient signal-to-noise ratio.

1. Introduction

The quadrupole magnets in particle accelerators must be aligned with very-high precision to focus the particle beam, while avoiding beta-beating [1] and beam-instabilities due to unwanted resonances. For the future Compact LInear Collider (CLIC) [2] an alignment precision in the micrometer range is required for the quadrupole magnets. The alignment of accelerator magnets must be accomplished with respect to their magnetic axes, defined as the loci of points within their bores where the magnetic flux density is zero. An effective tool for the localization of the magnetic axis consists of a conducting wire, pulled taut across the magnet bore and displaced at its end by precision stages, thus acting as a sensing element of the magnetic field [3–5].

Two wire-based methods for locating magnetic axes are presented in this paper. The stretched-wire [4] method consists of displacing the wire by moving its endpoints by means of two precision stages and integrating the measured voltage induced across the wire loop caused by the $\mathbf{v} \times \mathbf{B}$ term. The second method relies on the minimization of the vibration amplitude [6,7], excited by the Lorenz-force interaction between the magnetic field and an alternating current in the wire. The sensitivity of the method increases significantly at excitation frequencies close to the wire's mechanical resonance [8]. The alignment with sub-micrometer precision can be achieved using a phase-locked loop device in the wire-resonance condition [9,10].

The measurement results are affected by background magnetic fields such as the Earth's magnetic field and other stray fields from sources such as drive and tensioning motors, as well as remanent magnetization in steel structures. Uniform background fields can be compensated for as described in earlier work on the vibrating-wire method [11,12], for example, by using higher order vibration modes. This assumption of uniform background field does not hold in general, because of devices located along the wire, such as wire supports, vibration sensors, and tensioning motors [13]. These devices may, or may not, be moving with the wire stages and therefore their fringe fields are difficult to predict. The significant effect of the background field on stretched- and vibrating-wire methods was proven experimentally [13] by powering the magnet at different excitation currents. Other solutions, such as to flip the magnet about its transverse axis and changing the polarity of the magnet excitation current have been proposed. In the latter case, however, effects stemming from hysteresis effects in the magnetic field must also be taken into account.

The second significant source of uncertainty arises from the non-ideal magnetic field in the measured magnet. For example, the design of the CLIC final focus magnets aimed at maximum field strength at the expense of field quality. Multipole coefficients, obtained by Fourier analysis of the field on a reference radius [14] are used to express the field quality in accelerator magnets. For the stretched wire, an estimation of the error introduced in the axis location by higher-order

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multipole fields errors is given in reference [15]. A method for correcting the measurement of the field strength (gradient) when multipole field errors are known is presented in [14].

In this paper, we present a method to estimate and correct the effects of background fields and multipole field errors on the magnetic axis localization. The presented methods are not affected by magnet hysteresis and are suitable when the magnet cannot be rotated on the measurement bench.

In Section 2 the principle of the wire methods is briefly reviewed. In Section 3 the background field correction method is proposed. The effect of multipole field errors in locating the magnetic axis is discussed in Section 4. The setup used for the experimental validation and the results for the background field compensation and multipole field error correction are presented in Section 5.

2. Measurement principles of the wire methods

Compared to rotating-coil scanners [16] that must match the diameter and length of the tested magnet, the stretched-wire systems are more versatile for measuring magnets of different sizes and geometries, and are also suitable for magnet bores below 4 mm in diameter. Furthermore, the wire technique can resolve magnet pitch- and yaw-angle misalignment, which cannot be achieved by a single rotating-coil measurement. The effect of the wire sag can be easily estimated and corrected [6].

2.1. The stretched-wire method

The stretched-wire method is based on Faraday's law of induction. When a single conducting wire is displaced in a magnetic field, the integral of the induced voltage is proportional to the magnetic flux linked with the surface traced by the wire. Consider a right-handed reference frame with its origin located at one of the wire end points (stages). The x and y axes are in horizontal and vertical directions, and the z axis is along the magnet bore. Without lack of generality, this reference frame will be located at the initial wire position. Let the complex variable $\underline{z} = x + iy$ denote the wire position in the cross section and $\Phi(x, y)$ the flux linked with the surface traced by moving the wire from the origin to the position $\underline{z}$. Furthermore, let $\bar{g}$ denote the magnetic field gradient in an ideal quadrupole, averaged over the wire length. The magnetic flux linked with the traced surface is then given by

$$\Phi(x, y) = \bar{g}\, L\, \Re \left\{ \int_0^{\underline{z}} (\underline{z} - \underline{z}_c) \mathrm{d}\underline{z} \right\} = \frac{1}{2} \bar{g}\, L\, \Re \left\{ (\underline{z}^2 - 2\underline{z}\,\underline{z}_c) \right\}, \tag{1}$$

when the magnetic center is located at $\underline{z}_c = x_c + i y_c$. The integrated gradient can therefore be calculated from [4]

$$\bar{g}L = \frac{\Phi(x,0) + \Phi(-x,0)}{x^2} \qquad \bar{g}L = \frac{\Phi(0,y) + \Phi(0,-y)}{-y^2}. \tag{2}$$

Averaging between two measurements taken in opposite directions allows one to cancel the effect of an external dipole field. The coordinates (x_c, y_c) of the magnetic center are given by [4]

$$x_c = -\frac{x}{2} \frac{\Phi(x,0) - \Phi(-x,0)}{\Phi(x,0) + \Phi(-x,0)}, \qquad y_c = -\frac{y}{2} \frac{\Phi(0,y) - \Phi(0,-y)}{\Phi(0,y) + \Phi(0,-y)}. \tag{3}$$

The yaw and pitch angles of the magnetic axis with respect to the reference frame axis can be measured by moving the two wire ends in opposite directions, that is, a counter-directional movement of the wire stages, and determining the position where the second field integral takes its minimum value [17].

2.2. The vibrating-wire method

The vibrating-wire method is based on powering the wire with a sinusoidal current such that the Lorentz force excites the vibration of the wire. The measurement of the vibration amplitude and phase allows for the reconstruction of the distribution of the magnetic flux density along the wire. The current frequency is chosen to achieve resonance and thus to increase the measurement sensitivity [6]. At the resonant frequency, the vibration amplitude is approximated as a function of time t and longitudinal coordinate z by

$$u(z,t) \approx \frac{I_0}{\rho \beta \omega_m} \sin\left(\frac{m\pi}{L} z\right) \sin\left(\omega_m t - \frac{\pi}{2}\right) \frac{2}{L} \int_0^L B_n \sin\left(\frac{m\pi}{L} z\right) \mathrm{d}z, \tag{4}$$

where I_0 is the amplitude of the wire current, ρ the mass density per unit length, β the damping coefficient, ω_m the mth resonance frequency, L the length of the wire, and B_n the component of the magnetic flux density normal to the plane of wire vibration.

The wire frequency response can be described by the product of the vibration amplitude and driving current, averaged over one period T [6]:

$$G(\omega) = \frac{1}{T} \int_0^T u(z_0, t) I_0 \sin(\omega t) \mathrm{d}t, \tag{5}$$

where z_0 is the longitudinal position of the vibration sensor. At resonance of mth order, the above function is approximated by [18]

$$G(\omega) = a_m \frac{b_m - \omega}{4\omega(b_m - \omega)^2 + c_m^2 \omega}. \tag{6}$$

The above equation can be fitted to measurements of $G(\omega)$ at z_0 and at different frequencies in order to estimate the resonance frequency (parameter b_m), the damping factor (c_m), and the longitudinal field coefficients given by

$$C_m := \frac{2}{L} \int_0^L B_n \sin\left(\frac{m\pi}{L} z\right) \mathrm{d}z = \frac{\rho}{I_0^2} \frac{a_m}{\sin\left(\frac{m\pi}{L} z_0\right)}. \tag{7}$$

The magnetic center is located where C_m takes its minimum. In a quadrupole magnet, this position is found by measuring C_m at different transverse wire locations and applying a linear regression to deal with the low S/N ratio close to the axis. The magnet yaw and pitch angles can be determined in a similar way, but with the second resonance mode and counter-directional movement of the wire stages. The effect of a homogeneous background field can be compensated for by displacing the magnet along the wire to a position at $L/4$ rather than $L/2$, and by exciting the second and fourth modes. In this configuration the forcing terms of the background field on the wire cancel out. However, an inhomogeneous background field will couple with the second resonant mode. An alternative way is to change the polarity of the magnet either by tilting the magnet by 180° [19] about the x axis or by changing the polarity of the magnet excitation current and averaging between the measurements taken at opposite polarities. However, when inverting the magnet current polarity, an error due to magnet hysteresis may be introduced.

3. Background field correction

The above-mentioned problems can be circumvented by correcting for the background field by means of an analytical model, which was derived by studying the regularity conditions of the fields in accelerator magnets. The model allows one to compute the shift of the magnetic axis by varying the magnet strength at a non-negligible but stationary background field. This shift will lead to the measurement of what we denote as *apparent* magnetic axis (x_a, y_a). By fitting the measurement results to the model, the offset in the axis location can be determined. It is important to note that permanently magnetized regions inside the magnet, which are not affected by the magnet excitation current, will also be compensated for. Therefore this method cannot be used for hybrid magnets or magnets with rare-earth excitation.

3.1. Offset correction for the stretched-wire method

The model describing the relationship between the apparent axis (x_a, y_a) and the background-field corrected axis, denoted (x_b, y_b), is