PULSED TAUT-WIRE ALIGNMENT OF MULTIPLE PERMANENT MAGNET QUADRUPOLES*

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Abstract

A pulsed taut-wire system for aligning many collinear permanent magnet quadrupoles (PMQs) is described. Applications include aligning magnets in drift tube linac (DTL) tanks and linear transport lines. A short (<100-μs), rectangular current pulse accelerates the wire transversely at each PMQ by an amount proportional to the displacement of the wire from the magnetic center. The transverse waves propagate along the wire to a sensor where they are measured using a wide-band noninterceptive technique similar to that used for measuring beam position. Displacing the wire by known amounts using translation stages gives an accurate calibration of signal size versus misalignment. A technique for measuring the gradient-length product of a PMQ using the pulsed taut wire is also described.

Introduction

The technique of using a taut wire to align the quadrupoles in a DTL was developed at Lawrence Berkeley National Laboratory (LBL) around 1974. In the LBL technique all the magnets but one are turned off each time the wire is pulsed with current. The wire is deflected if it is not positioned at the magnetic center of the magnet under test. In this manner, the magnetic centers of all the magnets are measured, one at a time. The technique was further developed for finding the magnetic center of individual permanent magnet quadrupoles at Los Alamos.[1] Because these magnets could not be turned off the measurements had to be done on individual drift tube magnets before assembly of the DTL. Warren and Elliot [2] first applied the idea of using a short current pulse to give the wire an impulse, in the form of transverse momentum. The impulse varies along the length of the wire in proportion to the local magnetic field. This work was performed on magnetic dipoles used in wigglers. The transverse momentum splits into two equal amplitude waves that travel along the wire in opposite directions. Because the waves from each magnet are created by an impulse they are spaced along the wire and arrive at different times at a fixed sensor that measures wire position as a function of time. In this manner, multiple magnets can be measured with a single current pulse. We have extended the technique of using a short current pulse to align PMQs in DTL tanks. Techniques have been developed to obtain an absolute measurement of the position of each magnet with respect to the wire, and to subtract out wire sag when doing vertical alignment. In addition, we measure *in situ* the relative gradient-length product for all the magnets after they are assembled in the DTL tank.

Theory

If, at $t = 0$, a short current pulse (short being defined below) is applied to a wire displaced from the magnetic axis of a quadrupole by an amount ΔX_{mag} then the transverse impulse imparted to a length dz of wire is

$$\rho \, dz \, V_x = I \, \Delta t \, G(z) \, dz \, \Delta X_{mag} \qquad (1)$$

where I, Δt, $G(z)$ ρ, V_x, and ΔX_{mag} are the current, pulse length, quadrupole gradient, wire linear mass density, transverse velocity, and magnet displacement from the wire, respectively. The transverse impulse splits in half and propagates along the wire at a speed given by $c = \sqrt{(T/\rho)}$ where T is the wire tension. After the transverse wave passes a given point along the wire, the displacement of the wire from its initial position is given by the time integral

$$\begin{aligned} \Delta X_{wire} &= \int V_x \, dt \\ &= (I \; \Delta t \; \Delta X_{mag} / (2 \rho)) \int G(z) \, dt \\ &= (I \, \Delta t \; \Delta X_{mag} / (2 \rho c)) \int G(z) \, dz \\ &= (I \; \Delta t \; G L_e / (2 \rho c)) \; \Delta X_{mag} \quad , \qquad (2) \end{aligned}$$

where L_e is the effective length of the quadrupole and G is its average gradient.

The slope of the line that describes ΔX_{wire} versus ΔX_{mag} is proportional to GL_e the magnet gradient-length product, and a measurement of I, Δt, ρ, and c determines the gradient-length product absolutely.[3] We use translation stages to move the wire by known amounts relative to the magnet, thus varying ΔX_{mag}. For each position, the wire is pulsed with the same I and Δt and the wire deflection (ΔX_{wire}) is measured. Typical values for I, Δt, G-L_e, ρ and c are 20 A, 40 μs, 5 Tesla, 3.8×10^{-5} kg/m, and 130 m/s so that the proportionality constant relating ΔX_{wire} and ΔX_{mag} is of order unity; therefore, resolution for measuring magnet displacement is approximately equal to the resolution of the sensor and associated electronics for measuring wire position. Accurate measurements require satisfying the transverse impulse approximation, that is, that the wire moves a negligible amount transversely during the current pulse. Given two quadrupoles that are of opposite polarity but equally displaced from the wire, the measurement should, of course, indicate equal displacement. However, if the wire moves transversely before the current pulse is switched off, the focusing quad will move the wire into a weaker magnetic field and the defocusing quad into a stronger magnetic field, and the measurement will thus indicate that the defocusing magnet is a greater distance from the wire than the focusing magnet. Mathematically, the condition to be satisfied is

$$V_x \, \Delta t / \Delta X_{mag} = (I \, \Delta t^2 \, G)/\rho \quad << 1 \quad . \qquad (3)$$

An easy check on this condition is as follows: a reversal of the sign of the current effectively changes the polarity of

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each magnet yielding an equal but opposite deflection of the wire due to each magnet. A second condition on the pulse is that the distance the waves propagate along the wire during the current pulse be small compared to the distance between magnets, so that waves from different magnets are not superimposed. If Δz is the distance between magnets, this condition is satisfied if $\Delta z > c\,\Delta t$.

Wire Position Measurement

The wire position measurement technique is based on the development of electronics for precision, real-time position measurement of bunched particle beams.[4] A ferrite-loaded, 20 MHz $\lambda/4$ coaxial cavity is driven with ~ 1 W of RF power. The wire passes through the inner conductor along the axis of the cavity and is coupled to the longitudinal RF electric field at the open gap between the center conductor and the cavity end-wall. In this manner an RF current is induced on the copper wire. The RF field from the wire is detected by four B_θ loops that are used with signal processing electronics to measure the x and y position of the wire. Presently, wire position is measured with a 10 micron resolution and 35 kHz bandwidth. The bandwidth required is determined by the distance between magnets and longitudinal wave speed. For applications that require lower bandwidth, the signal-to-noise ratio improves and thus resolution improves. Sensitivity of the wire position measurement is determined by moving the sensor relative to the wire with translation stages. Our apparatus with a 4-mm aperture has a sensitivity of 1.4 mV/micron.

Experimental Results

Figures 1 and 2 are examples of raw data for vertical and horizontal deflections respectively from a DTL tank, before alignment, with 40 PMQ magnets arranged in a FODO lattice. The parabolic shape of the envelope of the vertical data in Fig. 1 is due to wire sag over the 2.3 meter-long tank. The average signal gets larger (smaller) in the middle of the tank if the wire is suspended below (above) the center of the magnets. The first step of analysis involves finding the peaks in the data as indicated by the circles in Figs. 1 and 2. For each magnet the deflection of the wire caused by that magnet is calculated from the difference between neighboring peaks. This procedure is repeated after translating the wire a known distance (ΔX_{mag}) and again measuring the wire deflection caused by each magnet. The difference of the wire deflection for the two cases is taken, inverted, and multiplied by the amount the wire was moved to yield a calibration in microns/volt for each magnet without any explicit measurement of the current, pulse length, wave speed, etc. In practice, the wire is moved between two positions on the opposite sides of the magnetic center, and thus signals of opposite polarity are obtained, as shown in Figs. 1 and 2. Therefore, by simply adding the absolute values of the deflections we obtain a number proportional to the G-L_e product as indicated by Eq. (2).

An example of this result for horizontal data is shown in Fig. 3. The top curve of Fig. 3 is inverted and multiplied by the distance the wire is moved to obtain the microns/volt calibration for each magnet. With a calibration file established an absolute measurement of the magnet alignment

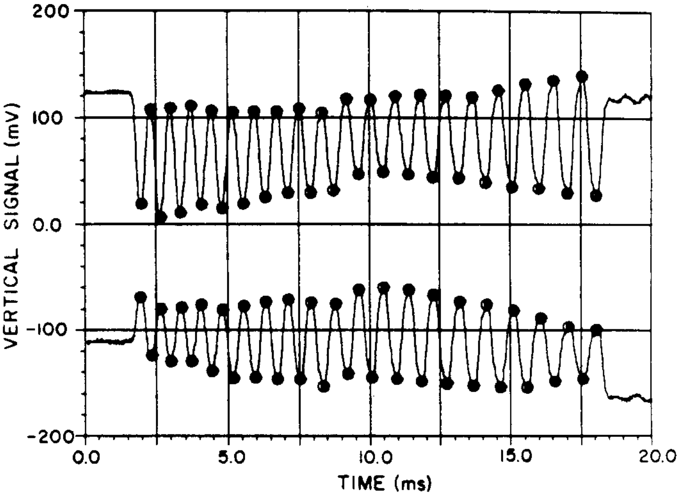


Fig. 1. Vertical position raw data for two different wire positions separated by 1.02 mm.

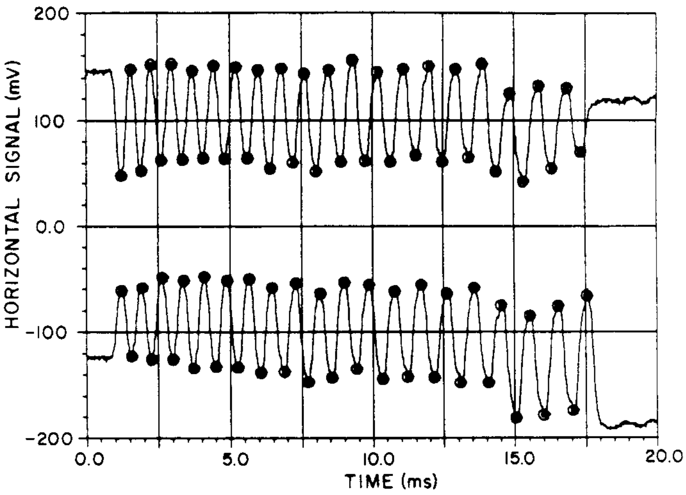


Fig. 2. Horizontal position raw data for two different wire positions separated by 1.14 mm.

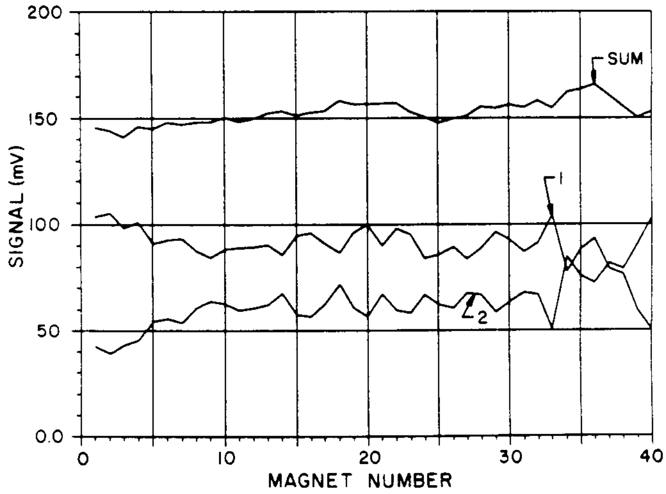
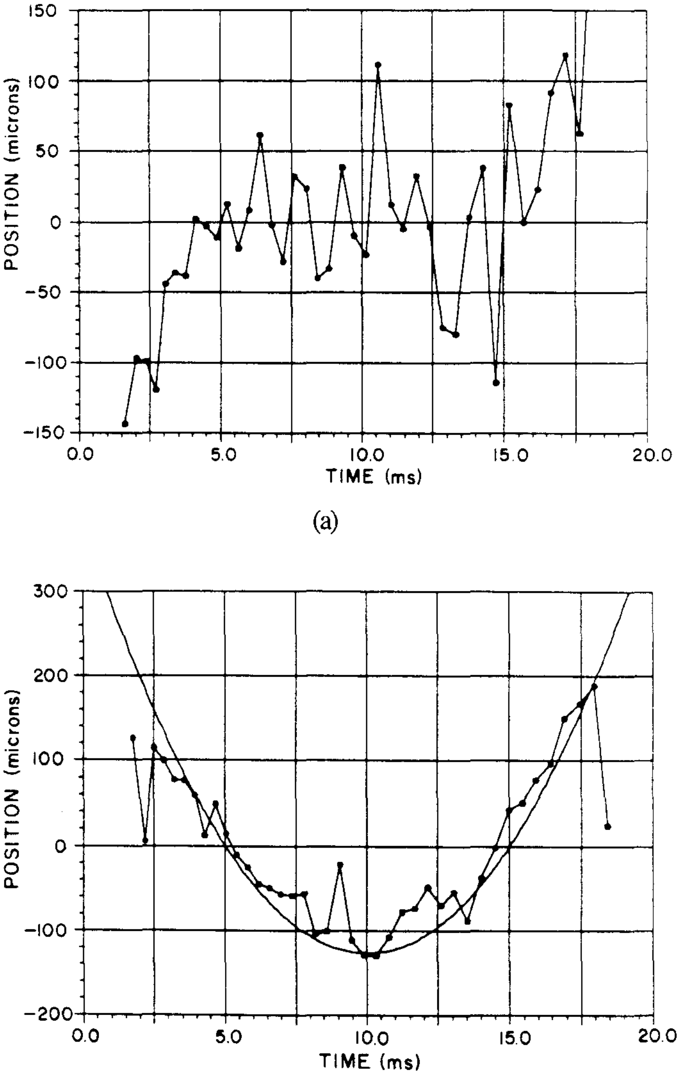


Fig. 3. Curves 1 and 2 are analyzed horizontal data for two different wire positions. SUM, the addition of curves 1 and 2 is proportional to the G-L product along the magnetic axis.

is obtained in the following manner. For data as shown in Figs. 1 and 2 the magnitude of the average deflection is calculated and then subtracted from the magnitude of the deflection due to each magnet. The magnitude of the average deflection is proportional to how far the wire is displaced from the magnets on average, whereas the difference from that average measures how far each magnet is displaced from the magnetic axis. Finally, this data is multiplied by the calibration factors to give a plot of the relative position of each magnet, in microns, with respect to the average displacement of the magnets from the wire.

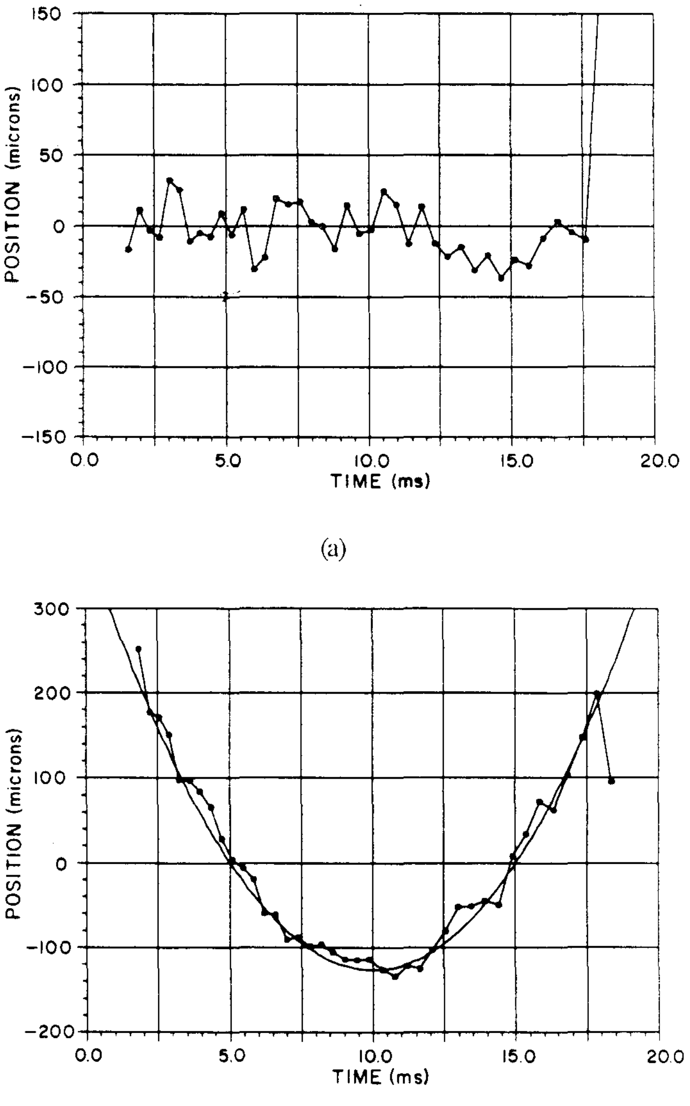
Examples of these measurements in both planes are shown in Fig. 4. With analysis that yields plots such as Fig. 4 the magnets can be precisely aligned. Fig. 5 is a plot of the calibrated displacement after fine adjustments to the magnet positions have been made from the case shown in Fig. 4. The adjustments are made to fit the vertical data to the parabola that describes the calculated sag of the taut wire, whereas the adjustments fit the horizontal data to a straight line with zero slope so that the magnetic axis is parallel with the wire.



(a)

(b)

Fig. 4. Horizontal (a) and vertical (b) alignment before adjusting magnet positions.



(a)

(b)

Fig. 5. Horizontal (a) and vertical (b) alignment after adjusting magnet positions.

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