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PULSED WIRE MEASUREMENTS OF A HIGH FIELD GRADIENT QUADRUPOLE WIGGLER*

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Abstract

Alignment of the quadrupoles in a quadrupole wiggler to sub micrometer precision is required for the collinear wakefield accelerator that is under consideration at Argonne National Laboratory for a compact Free-Electron Laser [1]. The pulsed wire measurement method is the only technique that we are aware of that allows for sub micrometer precision and the ability to distinguish between the various quadrupoles within the wiggler. A one period prototype wiggler was manufactured and subsequently measured using the pulsed wire technique. The goal of the measurements was to verify that the magnetic centers of each quadrupole could be located and aligned to each other within the required precision. The method and results are described.

INTRODUCTION

A compact structure-based collinear wakefield accelerator is under consideration at Argonne National Laboratory. It employs a Čerenkov radiation of a high charge drive bunch to create ~100 MV/m accelerating field for the following behind low charge witness bunch. A ~0.5 m long accelerator module consists of a ~2 mm ID corrugated waveguide embedded into a high magnetic gradient quadrupole wiggler as described in [2]. A corrugated waveguide is used as a retarded media that forces electrons to radiate and the quadrupole wiggler is used to enforce a stable motion of the drive bunch as proposed in [3] and [4].

Two quadrupoles representing one wiggler period were built and in this paper we focus on the magnetic measurements and on alignment of the quadrupoles. The requirement found in [5] with particle tracking is that the magnetic centers of the quadrupoles should be aligned with better than 1 μm precision in both x and y directions.

In what follows, we begin with a description of the measurement technique and the experimental setup, and proceed with presenting several representative measurements. Special attention is given to understanding of systematic errors.

MEASUREMENT TECHNIQUE

Measurement of the quadrupole centers and the integrated gradient were performed using the pulsed wire method [6]. This is the only method that we are aware of that allows us to measure mutliple individual quadrupoles in a wiggler-like configuration and achieve the desired sub-micron measurement resolution. Pulsed wire measurements are performed by placing a wire inside a magnetic field and tensioning the wire. This is followed by pulsing an electric current through the wire which is then displaced by the magnetic field. This displacement propagates down the wire as a traveling wave that passes by a laser-photodiode pair, the displacement of the wire is recorded by measuring the output of the photodiode. Here we write the output signal for the photodiode measuring the wire displacement in the y direction.

$$u_y(t) = \frac{I}{2T} \int_{c_0(t-\Delta t)}^{c_0 t} \int_0^z B_x(z) dz dz', \qquad (1)$$

where I and Δt is the magnitude and duration of the current pulse, c_0 is the velocity of the traveling wave due to tension, T, in the wire, $B_x(z)$ is a magnetic field to be measured and z is the distance along the quadrupole wiggler axis. The wire position $y(z)$ with respect to the magnetic center of the quadrupoles can then be obtained from $B_x(z) = G(z)y(z)$ where $G(z)$ is the magnetic field gradient whose variation along z is known. By changing y to x one obtains the same expression for the photodiode measuring the wire displacement as a function of time in x direction.

In Fig. 1 we show the expected signal calculated assuming that the wire has a small angle to the axis of the quadrupoles and that the first quadrupole is aligned to the wire and the second quadrupole has some offset. We also accounted for the change of the sign of the magnetic gradient from the first quadrupole to the second quadrupole.

The quadrupole magnetic integral can be quantified if all quantities in Eq. (1) are precisely known. An alternative is to use a reference magnet with a known field integral. It should be pointed out that these factors only need to be known to quantify a precise misalignment of the quadrupole. However, the measured voltage will be zero when the wire is in the center of the quadrupole. Thus, using the relative units should be sufficient for achieving a mutual alignment of the quadrupoles. The configuration of the pulsed wire measurement used for the measurement of a one period prototype of the high field gradient wiggler is shown in Fig. 2. It consisted of a 75 μm beryllium copper wire that was secured to fixtures at each end and tensioned using a manual linear stage. Horizontal and vertical positioning of the wire was controlled with linear stages from Thorlabs, model number NFL5DP20M. Each stage allowed for 5 mm manual travel and 20 μm piezo travel with a theoretical resolution of 20 nm. The 635 nm laser source, model MCLS1, was directed at a 40 μm slit, model S40R, and the intensity of the laser light was sensed by a photodiode, model SM05PD2A, which was connected to a photodiode amplifier, model PDA200C, that output a voltage proportional to the detected light. There are two laser-photodiode pairs, one to sense horizontal motion and one to sense vertical motion. Mounting the laser-photodiode pairs on a two axis stage,

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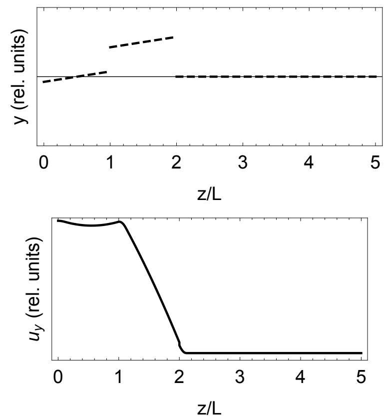

Figure 1: An example of the expected signal. The dashed line in the top plot shows the magnetic axis of the first and the second quadrupole. The bottom plot shows the photodiode signal. The current pulse width $\Delta t = 0.25L/c_0$, where L is the length of the quadrupole, was used in the calculation.

Thorlabs model Z812B, allowed the sensors to be positioned horizontally and vertically so that the wire blocked half of the 40 µm slit when at rest. The voltage output of the photodiode amplifier is recorded by a National Instruments VB-8034 8-bit oscilloscope. A Stanford Research Systems, DG535, pulse generator is used to trigger a transistor to control the pulse duration. Power for the current pulse is supplied by an analog output of the VB-8034. The voltage output from

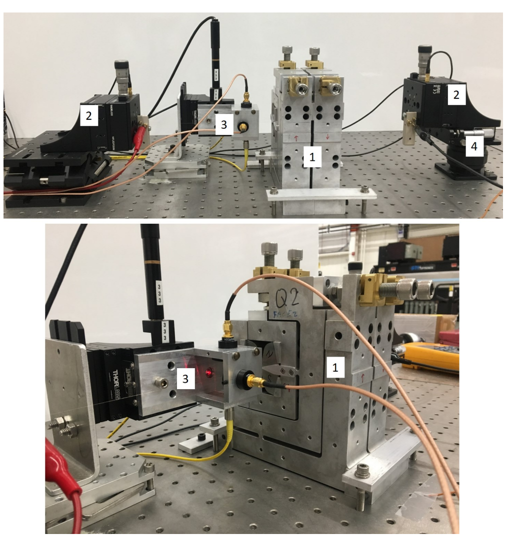

Figure 2: Pulsed wire measurement setup. 1: One period quadrupole wiggler prototype 2: Piezo stages 3: Laser-photodiode pairs 4: Linear stage for tensioning the wire.

the photodiode amplifier was scaled to either field integral units or distance from the quadrupole center. To scale the voltage without needing to know all of the parameters in Eq. (1), a Helmholtz style coil was fabricated to provide a known reference field. This magnet was first measured using a rotating coil measurement system at the APS. During each pulsed wire measurement setup, the reference magnet was measured. Measurement errors of the field integral or calculated position were then able to be quantified when determining the scale factor to be used when converting the measured voltage to integral values or distance. Errors in the position of the piezo drive were taken to be 80 nm, i.e, four times of the theoretical resolution of 20 nm provided by the manufacturer. There are also other systematic sources of errors such as repeatability of the pulsed wire system after disassembling and reassembling between measurement configurations, drift in the instruments used for measurements, and temperature fluctuations.

MEASUREMENT RESULTS

During alignment of an individual quadrupole to the wire, manual micrometer adjusters on the horizontal and vertical piezo stages were used to get the wire close to the center of the quadrupole. Following this, the position of the wire was moved in ~0.5 µm increments using the piezo stages to determine the sensitivity of the alignment method and the integrated gradient of the quadrupole. Displayed in Fig. 3 is the wire position with respect to the quadrupole magnetic center in x and y directions deduced from the magnetic measurement in a correspondence to the wire movement by the piezo stages. The linear fit to the data shows a remarkable one-to-one correspondence between the driven offset of the wire and the measured offset. Shown in Table 1 is the measured integrated gradient of one of the quadrupoles. Magnetic modeling of the quadrupole design predicted an integrated gradient of 30.25 T. Reported errors in the measured gradient or measured location of the wire were based on random measurement errors. For instance, when the integral of the calibration magnet was measured using a rotating coil, the measurement resulted in a value of 74 ± 3 µTm. The output of the photodiode amplifier when measuring the vertical field integral of the calibration magnet with the pulsed wire system was 0.179249 ± 0.002691 V. Combining these values we can get the scale factor and error when converting from voltage to an integral value as:

Table 1: Measured Integrated Gradient

	Integrated Gradient [T]	**Standard Deviation [T]**
Horizontal	31.28	1.22
Vertical	30.97	2.33

$$Scale = \frac{mag}{PD} \pm \frac{mag}{PD}\sqrt{\frac{(\Delta mag)^2}{mag} + \frac{(\Delta PD)^2}{PD}}, \quad (2)$$

where “mag” is the integral value of the calibration magnet and “PD” is the voltage output of the photodiode amplifier. Applying the measured values to Eq. (2) gives a scale factor of 412.83 µTm/V when measuring the vertical integral of

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the quadrupole. Furthermore, we used the predicted integrated gradient from the model to allow us to determine the position of the wire relative to the center of the quadrupole. The model predicted an integral value of 0.030 25 Tm at a 1000 μm offset. Therefore to convert the voltage to an offset value we multiply the scale factor by 1000 μm/0.030 25 Tm to get a scale factor of 13.647 ± 0.589 μm/V.

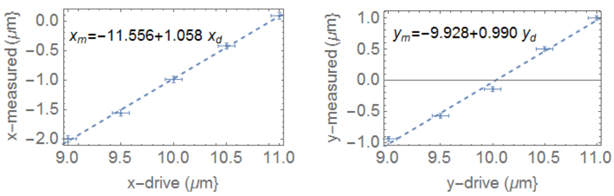

Figure 3: The wire scan measurements. Here "x-drive" and "y-drive" are the positions of the piezo stages and "x-measured" and "y-measured" are measured positions of the wire. The linear fit of the measured values as a function of the drive values are also shown. The horizontal error bar is determined by the error in the location of the piezo stages and the vertical error bars are determined from a spread in the measured data.

In the case of aligning two quadrupoles to the wire, the wire was first located in the center of one quadrupole using the manual adjusters on the piezo stages followed by using the piezos for final alignment. The second quadrupole was then aligned to the wire by using fine adjustment assemblies integrated into the quadrupole mechanical design. This process is illustrated in Fig. 4. The final result in x and y is given by the green curve in Fig. 4c and Fig. 4d. The double dip seen in both plots is believed to be mainly due to the angles between the quadrupole axis and the wire. Fig. 5 shows the deviations from the baseline alignment given by the green line in Fig. 4 measured around 8:30 am and 4:00 pm over three days.

CONCLUSION

It has been shown that the pulsed wire measurement technique can easily resolve sub-micrometer offsets of the individual strong focusing quadrupoles of the quadrupole wiggler. The alignment of one wiggler period with better than one micrometer mutual offset of the quadrupole magnetic centers has been demonstrated.

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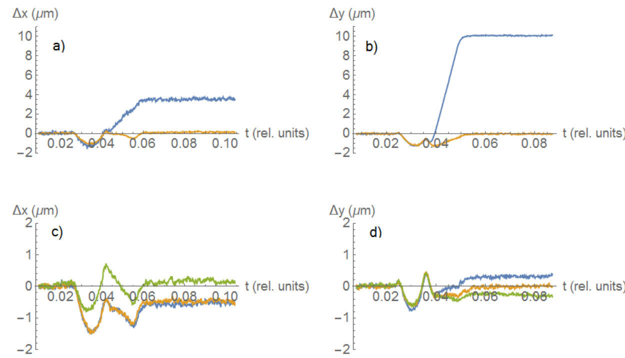

Figure 4: Illustration of the alignment of the second quadupole to the wire whose position was previously aligned to the magnetic center of the first quadrupole. Plots a) and b) show beginning and ending of the first iteration in the alignment in x and y. Plots c) and d) show three steps of the final tuning of the quadrupoles both in x and y. A small "cross-talk", i.e., non-orthogonality of the adjustment assemblies was observed.

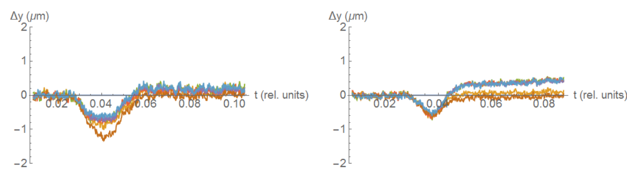

Figure 5: Long term stability of the two quadrupole system.

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