AN ULTRA-HIGH RESOLUTION PULSED-WIRE MAGNET MEASUREMENT SYSTEM*

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Abstract

Traditional magnet measurements systems for undulator magnets have relied on the use of calibrated Hall probes placed on a rigid mechanical arm and passed down the length of the undulator. This works for the most common undulators that have ready access along an entire side of the magnet; however, new magnet designs such a superconducting undulator magnets are not constructed with such convenient access for a Hall probe, and another method is warranted. In this manuscript we explore the used of a dispersion and pulse length corrected pulsed-wire measurement system to measure our undulator magnet. The background and method are described and our results given.

INTRODUCTION

Modern accelerators including accelerator-based light sources rely on the detailed, accurate, and precise measurement of their magnetic devices. Of particular interest in light sources is the measurement of the undulator magnet. The quality of the light being generated from these devices is strongly dependent on the accuracy of the magnetic field profile, and this pushes one to ensure that the fields are accurately measured.

Until recently, the actual design of undulators has followed a historical trend largely driven by the design of the standard 3rd–generation synchrotron light source. In such machines the beam is guided horizontally around the machine circumference by large dipole magnets with their primary magnetic field oriented in the vertical direction.. In these 3rd–generation machines the vast majority of the undulators are powered with permanent magnet material and this material is susceptible to radiation damage making it a design criteria to ensure that the undulators are not hit by radiation, be it synchrotron radiation or electron beam losses ([1] and references contained therein). The obvious way to do this is to arrange the out of the plane of the machine and the synchrotron radiation. These criteria have led to a standard undulator design very similar to what is shown in Figure 1 where there is an opening along the entire length of one side of the undulator magnet array. Such a structure not only lends itself well to fitting in standard storage rings, but also to magnetic measurement as a measurement probe can easily be inserted and positioned accurately along the entire length of the structure. But as the light source community has matured and the machines have reached new levels of performance, undulator designs, too, have progressed. The measurement methods have had to adapt to new configurations. These boutiuqe undulators can have very small gaps, exotic geometries, no side gaps and/or can be in vacuum. It is with this in mind that we decided to adapt one of these newer measurement methods to our own undulator.

Figure 1: A common undulator configuration where there is an opening along the entire length of one side.

We have at Colorado State University (CSU) [2] an undulator magnet. The primary undulator parameters are listed in Table 1. This undulator was constructed, measured, and tuned a number of years ago and used for an FEL program at the University of Twente in the Netherland [3,4]. Since that time it has been shipped across the Atlantic and has been in storage. It is a fixed-gap undulator, and to simplify the construction the gap has been set with gauge blocks along both sides of the gap (Figure 2) thus precluding measurement in a standard undulator magnet measurement configuration.

Table 1: Primary Undulator Parameters

Parameter	Value
K	1
Period	2.5 cm
Gap	8 mm
Material	Sm_2CO_5
Periods	50
Length	1.25 m

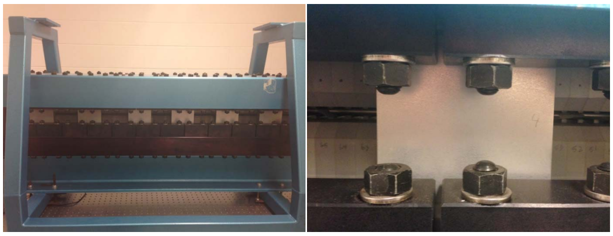

Figure 2: Left, the CSU undulator. Right, close-up of the gauge blocks fixing the magnet gap.

Warren developed a pulsed wire magnet measurement system [5]. In this method a thin wire is stretched though the length of the undulator magnet. An electric current is then pulsed through the wire. The resulting Lorentz force generates an impulse that in turn generates a transverse travelling wave along the wire, the amplitude and time structure of which is representative of the magnetic field along the length of the undulator. This motion can then be measured giving a representation of the undulator field.

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Dispersion in the wire causes the resulting detected waveform to be distorted compared to the actual field shape, and correction for the dispersion was necessary. Recently a group (LBNL) developed a system complete with dispersion and pulse length correction [6]. It is this methodology that we have adopted.

The LBNL system proved to be quite accurate; however, the length of the undulator measured was quite short compared to our undulator (20 cm vs. 1.25 m). The sensitivity to external influences such as ambient vibrations and air currents was of interest as was the validity of using only the dispersion correction without any possible correction for amplitude variation that might occur over a longer length of wire.

Our magnet utilized parabolic pole tip focusing. This also makes the undulator positioning more critical in the more difficult to align horizontal plane. The pulsed wire system will be used to help fiducialize the device to the required ± 500 micron in both planes. In addition our tolerance to the average rms phase error is not severe with nearly 10 degrees being acceptable. More critical is to ensure that the first and second field integrals are under control.

METHODOLOGY DETAILS

The essence of the LBNL paper [6] was to measure the dispersion in a wire and then fit it to the theoretical form of the dispersion given by the Euler-Bernoulli theory. The assumed wave velocity dispersion equation is given by

$$c(\kappa) = c_o\sqrt{1+\frac{EI_w}{T}\kappa^2} \tag{1}$$

where $c_o = \sqrt{T/\mu}$, T is the tension of the wire, μ is the wire mass per unit length, E is the Young's modulus of the wire, I_w is the wire moment of inertia, and κ is the wavenumber. A reference magnet can be measured and the signal recorded for two different positions along the wire spaced by Δx. The wave velocity as deduced from the two signals are related to one another through the equation

$$c = \frac{\omega\Delta x}{\phi} \tag{2}$$

where $\phi = \kappa\Delta x$. A fit to the theoretical value can then be used to reconstruct the actual waveform by removing the dispersion.

There are two cases to consider, the first of a short current pulse and the second of a long current pulse. In the first case the resulting waveform measured is proportional to the first integral of the magnetic field, while the signal measured from the long pulse is proportional to the second field integral. The LBNL recipe to remove the dispersion from the measured data follows these steps.

1. Make a measurement of the wire displacement as a function of time, $u_s(t)$, over a sufficiently broad frequency range.
2. Numerically integrate the following function for discrete equally spaced values of ω_i.

$$H(\kappa(\omega_i)) = G(\omega_i) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} u_s(\tau)e^{j\omega_i\tau}\,d\tau \tag{3}$$

3. Using the dispersion relationship calculate unequally spaced values of $\kappa_i = \kappa(\omega_i)$ associated with $H(\kappa_i) = G(\omega_i)$.
4. Multiply $H(\kappa_i)$ by $F(\kappa_i)$, where for the short pulse case

$$F^{short}(\kappa) = \frac{H_o(\kappa)}{H(\kappa)} = \left(\frac{c(\kappa)}{c_o}\right)\left(\frac{c(\kappa)+\kappa\, {dc}/{d\kappa}}{c_o}\right)\frac{j\omega(\kappa)\delta t}{e^{j\omega(\kappa)\delta t}-1} \tag{4}$$

   to obtain $H_o(\kappa)$.
5. For each time t_i numerically integrate

$$u_{s0}(t_i) = c_o\int_{-\infty}^{\infty} H_o(\kappa)e^{-jc_o\kappa t_i}\,d\kappa \tag{5}$$

   to determine the non-dispersive displacement solution $u_{s0}(t_i)$ for the short pulse case.

EXPERIMENTAL SETUP

The experimental setup is shown in Figure 3, and the basic equipment used in the initial tests were very similar to those used by the LBNL group. In the first adaption of the device to practice we used a digitizing oscilloscope with Ethernet connection to capture and read out the data. For better resolution and flexibility, a subsequent version of the system used a 14-bit, 100 MHz National Instruments (NI) digitizer system.

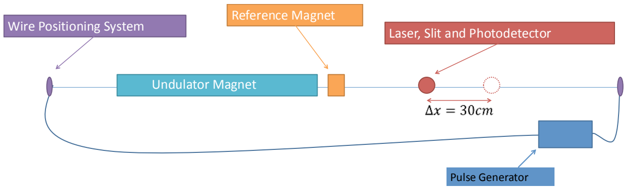

Figure 3: Basic experimental setup.

A home built 1-A, 50 V-pulser utilized a transistor operated in avalanche mode was used for the pulser. A subsequent model was constructed with a high performance, programmable pulse generator supplied by AvTech.

The system measurement sensitivity was approximately 20 mV/μm making even the slightest motions visible. Our wire was stretched out over 3 m in length making it very susceptible to vibrations and air currents. To minimize this the entire system was mounted on an optical table fitted with pneumatically damped supports. Air currents were minimized in the room to the extent possible and a tube was fitted where possible over the length of the exposed wire.

Our system did not exhibit any issues with wire sag, nor with pulse amplitude variation along the length of the wire. In addition there did not appear to be any evidence of the wire vibration coupling between the horizontal and vertical directions. Inhomogeneities in the wire, however, did cause spurious signals from reflections.

EXPERIMENTAL RESULTS

Measurements of the dispersion in the wire were made via the method outlined above. The results are shown in

Figure 4. The low frequency artifact seen in the red plot was due to noise in the room, but does not influence the results as it is outside of the frequency range of interest. Figure 5 shows the resultant calculated velocity as a function of frequency along with a fit to the data based on Equation 1. This velocity information as a function of frequency was then used to remove the dispersion and generate the non-dispersed signal shown in Figure 6.

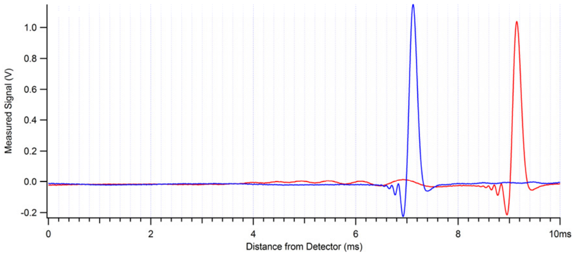

Figure 4: Reference Magnet measurements taken 30 cm from each other used to calculate the dispersive wave speed in the wire.

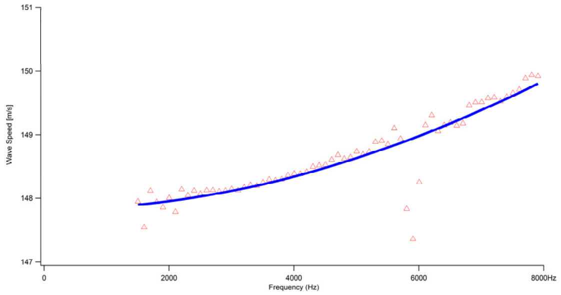

Figure 5: Wave speed determination from two measurements, 30cm apart.

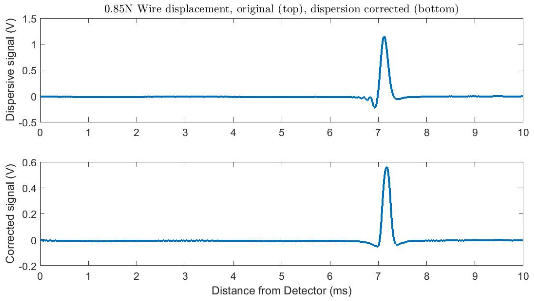

Figure 6: Uncorrected vs. corrected signal of the reference magnet for a short, 20 μs pulse.

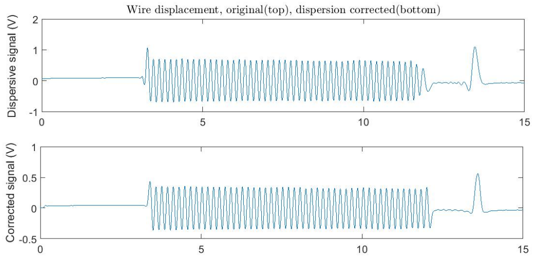

Figure 7: Uncorrected first integral (short pulse) top, and corrected (bottom).

Figure 7 top shows a raw measurement of the undulator using the short pulse. The result is the average of 50 measurements. One can clearly see the effects of dispersion in the plot, particularly near the beginning and end of the signal. The little bump at the end is the reference magnet. Its signal is used to provide an absolute calibration of the undulator measurement. Figure 7 bottom also shows the corrected measurement.

We have identified key areas for improvement. A location with lower ground vibrations is ideal as is a location with less airflow. With regards to airflow, a better system to shield the wire should be developed.

SUMMARY

A pulsed-wire magnet measurement system was constructed to characterize our undulator. The measurements were corrected for pulse length and dispersion and the results were adequate for the needs of our undulator system. The pulsed-wire system, particularly with the dispersion corrections, shows tremendous promise as a complimentary tool to measure some of the more unique undulators that are being designed and constructed today. Such a system, if constructed and operated correctly, might have the potential to measure undulators at precision levels comparable to those made today with Hall probe systems. If so, it might provide undulator designers and mechanical engineers with some needed flexibility in the design as they would not need to concern themselves with how one might measure the fields with a Hall probe system.

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