

PULSED WIRE MAGNETIC FIELD MEASUREMENTS FOR AN IN-VACUUM UNDULATOR

C. W. Chen†, H. Chen, J. C. Huang, NSRRC, Hsinchu, Taiwan

National Synchrotron Radiation Research Center, Hsinchu Science Park, Hsinchu 30073, Taiwan

Abstract

An in-vacuum undulator is important for synchrotron radiation. An in-vacuum undulator with a permanent-magnet is used by the Taiwan Photon Source (TPS) in the National Synchrotron Radiation Research Center (NSRRC). Before installation in the storage ring, the magnetic field of the undulator is measured at the operational gaps. The magnetic-field for an in-vacuum undulator is measured using a Hall-probe and a stretched-wire measurement system. This study uses a pulsed wire magnetic field measurement system for an in-vacuum undulator. A reference magnet with a known magnetic field is used to determine the magnetic field profile for an in-vacuum undulator and it is demonstrated that the oil dampers crucial to eliminating dispersion waves for the pulsed wire measurement. The results are used to compare the magnetic field measurements that use a pulsed wire with those that use a Hall probe.

INTRODUCTION

A permanent-magnet in-vacuum undulator is used for the Taiwan Photon Source (TPS) in the National Synchrotron Radiation Research Center (NSRRC). The magnetic field for an in-vacuum undulator is measured in-situ using a Hall-probe [1]. However, an in-situ Hall-probe measurement is not easily installed and the measurement time is significant for a long undulator. In 1988, Warren first used a pulsed-wire to measure the integral field for a wiggler [2].

Several studies have used a pulsed-wire to measure the magnetic field for an undulator [3,4]. A pulsed wire measurement (PWM) quickly measures the 1st and 2nd integral fields and is easily in-stalled on any accelerator magnets or undulators. A previous study by the authors [5] developed a PWM system to measure the magnetic field for an in-vacuum undulator (period 22 mm, magnetic length 2 m). The results for an undulator that is measured using a PWM and those for a Hall-probe measurement show that the magnetic field and pole-length errors peak to peak are both less than 1 % and that the first and second integral fields are similar. The difference in the peak magnetic fields for the two measurement systems is less than 1 %.

This study uses a known magnetic field to map an undulator with an unknown magnetic field and it is demonstrated that the oil dampers eliminate wave dispersion and inhibit the propagation of reflected waves. The results using an in-vacuum undulator using PWM and Hall-probe to measure the magnetic field are compared.

PWM SYSTEM ON IN-VACUUM UNDULATOR

Many studies use a pulsed wire system for magnetic field measurement. This study uses a PWM system to measure the magnetic field for an in-vacuum undulator at the NSRRC, as shown in figure 1. Using the method of a previous study [5], a PWM system was established using a reference mag-net, which is a dipole magnet with a known magnetic field. A pulsed-wire system on an in-vacuum undulator contains a copper zirconium (CuZr) wire, pulse current circuits, two oil dampers, a wire-displacement detection system, a two-wire moving system and a 12bit oscilloscope. The in-vacuum undulator has a period of 22 mm and a magnetic length of 2 m.

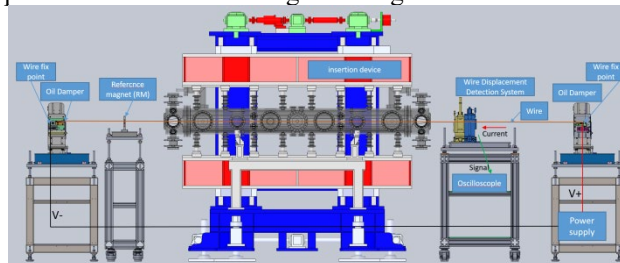


Figure 1: PWM system construction.

A 100 μ m diameter copper zirconium (CuZr) wire is used for this PWM system. CuZr wire has a high tensile strength and high conductivity. The wire material has a high tensile strength so the maximum sag on a long undulator is reduced. The reference magnet is located between the undulator and the oil damper holder. Any external vibration causes measurement errors so the wire-displacement detection system, the reference magnet and the wire-moving systems are installed on a honeycomb optical table. The wire passes through an oil damper at both sides near the wire-fixing points. On one side of the wire, a plastic holder is used to clamp the wire to a 2D motorized stage (OSMS26-200 & OSMS26-100, Opto-Sigma). The wire on the other side is fixed by a clamp to a tensiometer (LRK-100N, NTS Technology Co., LTD.).

The tensiometer controls the wire tension and is mounted on a motorized stage (TAMM100-50C, Opto-Sigma). On this side, the tensiometer system is mounted on a 2D motorized stage. A pulse circuit generates a current pulse with a width of 0~1s and a frequency of 1~1kHz. A power supply generates a voltage of 0~110V in the CuZr wire.

A wire-displacement detection system is located at one side of the undulator. A high-resolution and Laser-photodiode system with fast feedback is used to measure the displacement of the wire. A 12-bit resolution oscillo-

scope (MSO44, Tektronix, bandwidth 1.5 GHz, sampling rate 6.25 Gs/s) is used to collect data from the wire-displacement detection system. Labview™ and Matlab™ are used to acquire the measurement data and for analysis.

REFERENCE MAGNET

The reference magnet consists of a half-period in-vacuum undulator with a period of 22 mm. The gap for the reference magnet is fixed at 7mm, as shown in Figure 2a. A Hall probe (Type I3A, SENIS AG) bench is used to measure the magnetic field for the reference magnet. The Hall probe is calibrated using a nuclear magnetic resonance (NMR) probe. The calibration error for the magnetic field strength is less than 0.02 % and the calibration system is temperature-dependent [6].

Figure 2b shows the results for the Hall probe measurement at the gap center. The peak magnetic field for the reference magnet is 6584G. This reference magnet is used in the PWM system to map the magnetic fields for the undulator.

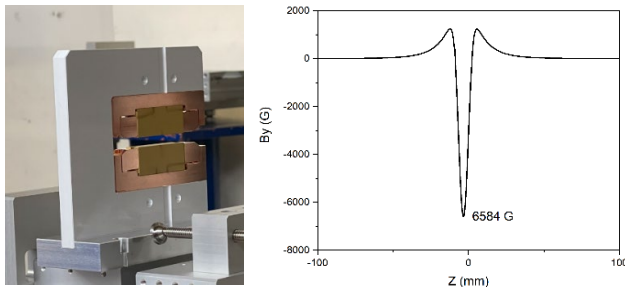


Figure 2 (a) Reference magnet and (b) results for Hall probe measurement at gap center.

CURRENT PULSE CIRCUITS

The current pulse circuit generates a short-width current pulse to measure the first magnetic-field integrals. Figures 3 & 4 show a schematic diagram of the current pulse generator and the circuit diagram. A digital pulse generator (DG535, Stanford Research) is used to trigger the MOSFET (IRF840). Before it is triggered, a voltage comparison circuit is used to set a threshold voltage to avoid false operation. When the MOSFET is triggered, the power supply (PAN110-5A, Kikusui) provides a voltage of 0~110V to the wire. The digital pulse generator is used to control the current pulse width and frequency.

In the voltage comparison circuit, the rise and fall times for the operational amplifiers such as $\mu A741$ are longer than switching time for the MOSFET and the shape of the current pulse is not correct, as shown in Figure 5a. Figure 5b shows the correct shape for the current pulse for an operational amplifier with shorter rise and fall times. The switching time for the MOSFET is $< 21\text{ns}$ and the respective rise and fall times for the $\mu A741$ and LT1226 are 300ns and 8ns. The signals in Figure 5 are the current pulse, the voltage of the gate (V_g), the voltage between the transistor drain and the source (V_{ds}) and the voltage between the transistor gate and the source (V_{gs}) from top to bottom.

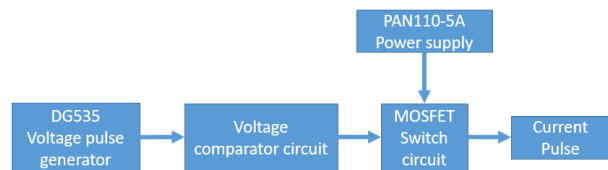


Figure 3: Schematic diagram of the current pulse generator.

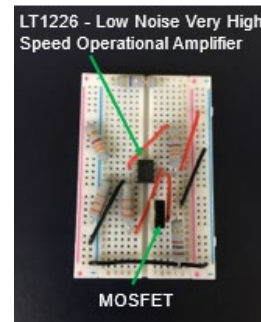


Figure 4: Circuit diagram for a current pulse generator.

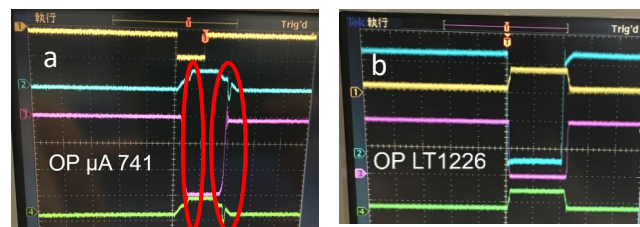


Figure 5: The shape of the current pulse using operational amplifiers: (a) $\mu A741$ and (b) LT1226.

OIL DAMPERS

Dispersion and reflected waves constitute noise in the PWM system. This wave directly causes errors in the magnetic field measurement. The proposed system uses an oil damper to eliminate dispersion waves and inhibit reflected waves. Figure 6 shows that the wire passes through an oil damper near the fixing points. The oil damper uses silicone oil. A syringe was used to inject oil into the plastic tube on the open side and a verification check ensured that the wire does not touch the plastic tube. Silicone oil of different viscosity was used and the appropriate viscosity for this PWM system was determined to be 1000cP. Highly viscous silicone oil does not eliminate dispersion waves and oil that is not sufficiently viscous does not remain in the plastic tube.

Figure 7 shows the experimental results demonstrating the effect of the oil damper. If no oil damper is used in the PWM system, there are visible dispersion and reflected waves. If the PWM system includes an oil damper at any side, the dispersion and reflected waves are present but they are attenuated. When oil dampers are installed at both sides, dispersion waves are eliminated but weak reflected waves are produced. A previous study [5] showed that increasing the distance between the wire fixed point and the location of the wire-displacement detection prevents an overlap of the main waves and the reflected waves if oil dampers are used.

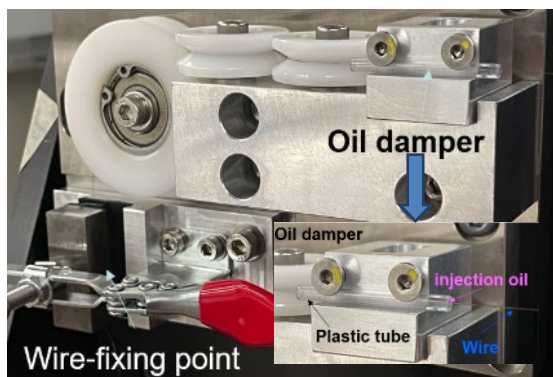


Figure 6: The oil damper.

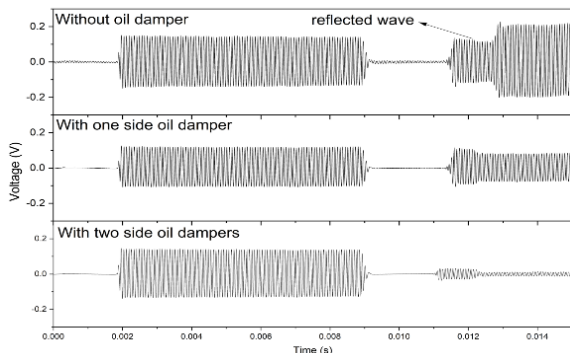


Figure 7: Experimental results demonstrating the effect of an oil damper.

WIRE-DISPLACEMENT DETECTION SYSTEM

A previous study [5] also used a detection system that includes a vertical and a horizontal optical-sensor pair. Each pair is composed of a diode laser that produces radiation with a wavelength of 633nm (LNC-13MMC, Schäfer+Kirchhoff, GmbH) and a fast-response photodiode (SM05PD3A, Thorlabs). The photodiode is installed on the opposite side of the laser and is mounted on a motorized stage. The photodiode diameter has an active area of 1.1 mm x 1.1 mm. The wire-displacement detection method focuses a laser beam on the wire. The photodiode detects the intensity of light that is not blocked by the wire. A motorized stage is used to scan the vertical and horizontal optical sensor pair and a linear range for the wire displacement is defined. The gradient has a value of around 0.25V/ μm and defines the transfer coefficient for voltage and wire displacement.

MEASUREMENT RESULTS

Using the principle of the Lorentz force and a general traveling wave, a short current pulse was used to determine the first integral field for the undulator. The wire displacement $U_{1st}(t)$ is calculated as [7]

$$U_{1st}(t) = \frac{I C_0 \delta t}{2T} \int_0^{C_0 t} B_y(z) dz \quad (1)$$

where I is the magnitude of the current, C_0 is the wave velocity, δt is the current pulse width, and T is the wire tension. In this case, the magnetic field for the undulator

is vertical and the wire displacement is only horizontal. The formula $\Delta t_{1st} \ll \lambda_u / C_0$ is used to determine the pulse width Δt_{1st} for the first integral measurements [8]. The λ_u is the period of the undulator. A short current pulse of width 10 μs was used for the first integral measurement. The wire tension was maintained at 6N during the measurement. The total length of the CuZr wire is 4 m and the resistance is 28ohm. An in-house power supply provides 50 V to the wire and generates 1.78 A. A previous study [5] showed that the repeatability of the PWM system for the first integral field measurement is <1%.

The magnetic field is calculated by differentiating the first integral field. Figures 8a & 8b show that a reference magnetic field is used to map an undulator with an unknown magnetic field. The red and black lines respectively represent the magnetic field performance for the reference magnet and the undulator, as measured using a Hall probe and the PWM system. The magnetic fields for the reference magnet that are measured using the two different methods are compared to determine the transfer coefficient for the magnetic field and the wire displacement. This transfer coefficient is used to map the magnetic field for the undulator. In the center of the undulator, the difference between the results for the two measurement methods is about $\pm 2\%$, as shown in Figure 8c.

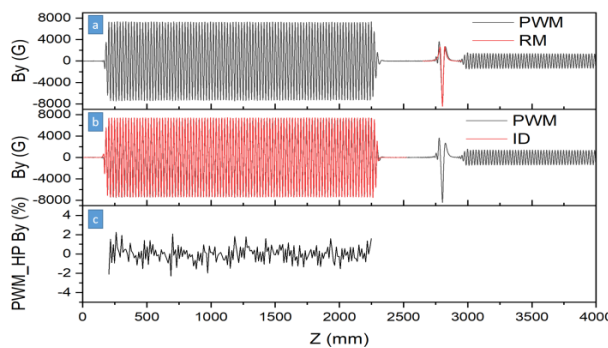


Figure 8 Comparison of magnetic field measurements using a pulsed wire and a Hall probe: (a,b) all magnetic fields and (c) difference between magnetic fields.

CONCLUSION

A PWM system is used to measure the magnetic field for an in-vacuum undulator. The experimental results show that the oil damper eliminates the dispersed wave and attenuates the reflected waves. In terms of the current pulse circuit, the rise and fall time for the voltage comparison circuit are crucial factors in obtaining a correctly shaped current pulse. The rise and fall times must match switching times for the MOSFET. A known magnetic field is then used to map an undulator with an unknown magnetic field. The measurements for undulator using the PWM and a Hall-probe are compared and the first integral field to be differentiated to determine the magnetic field for the undulator. A comparison of the results shows that the difference between the measurements for the two measurement methods is <2%. Future will use this method to measure the magnetic field for a cryogenic permanent magnet undulator (CPMU) with small gaps.

REFERENCE

- [1] C.-K. Yang, C.-H. Chang, J.-C. Huang, C.-S. Hwang, and T.-Y. Chung, "A Measurement System In Situ to Measure the Magnetic Field of an In-Vacuum Undulator", *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1–5, Jun. 2014. doi:10.1109/tasc.2013.2288321
- [2] R.W. Warren, Limitations on the use of the pulsed-wire field measuring technique, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 272, pp. 257 – 263, 1988.
- [3] M. Valléau, C. Benabderrahmane, M.-E. Couprie, O. Marcouillé, F. Marteau, and J. Vétéran, "Measurements of SOLEIL Insertion Devices using Pulsed Wire Method", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper THPC152, pp. 3242-3244.
- [4] J. E. Baader and S. Casalbuoni, "Pulsed Wire Magnetic Field Measurement System for Short-Period Long Undulators", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2903-2906. doi:10.18429/JACoW-IPAC2021-WEPAB126
- [5] C.W. Chen, H. Chen, J.C. Huang and C.S. Hwang, Pulsed-wire system for magnetic-field measurements on an in-vacuum undulator at NSRRC, *Phys. Open*, vol. 11, p. 100108, 2022.
- [6] C. W. Chen, Y. Y. Hsu, Y. L. Chu, H. Chen, C. K. Yang and J. C. Huang, "A Temperature-Dependent Calibration of Hall Probes for CPMU," in *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, pp. 1-5, Sept. 2022. doi:10.1109/TASC.2022.3172922
- [7] D. Arbelaez, T. Wilks, A. Madur, S. Prestemon, S. Marks, R. Schlueter, A dispersion and pulse width correction algorithm for the pulsed wire method, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 716, pp. 62 – 70, 2013. doi:10.1016/j.nima.2013.02.042
- [8] P. N'gotta , M. Ebbeni, A. Thiel, H. Tarawneh, "First Results of a Pulse Wire Measurement System for ID Characterization at MAX IV", presented at IMM21, Grenoble, France.