ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB126

PULSED WIRE MAGNETIC FIELD MEASUREMENT SYSTEM FOR SHORT-PERIOD LONG UNDULATORS

J. E. Baader*, S. Casalbuoni, European XFEL, Schenefeld, Germany

Abstract

The pulsed wire method is an attractive option to measure the magnetic field in insertion devices, mainly for those with restricted access (e.g., small gaps, in-vacuum/cryogenic environments, etc.). Besides first and second field integrals, experiments have proved the feasibility of reconstructing the magnetic field profile. Undulators with a small gap and short period are — and are planned to be — used at diffraction-limited storage rings and free-electron lasers. This contribution outlines the pulsed wire system's requirements to perform magnetic field reconstruction in such undulators. We examine the main expected limitations, particularly the dispersive, finite pulse-width, discretization error, and sag effects. Furthermore, we present the current status of developing the pulsed wire system at the European XFEL.

INTRODUCTION

The magnetic field characterization is an important step in the design of high-quality undulators for storage rings and free-electron laser applications. Local field measurements (i.e., point-by-point) are commonly performed by Hall probes. An alternative method named *pulsed wire* was introduced some decades ago [1]. Although several improvements have increased the performance of the pulsed wire method since then [2–7], the Hall probe-based systems are still required to characterize undulators adequately.

Measuring the magnetic field of devices with restricted access (e.g., small gaps, in-vacuum/cryogenic environments, etc.) can be particularly difficult with Hall probes. In this context, improvements of the pulsed wire method — mainly to reach higher absolute accuracy — are under investigation. For the SASE2 superconducting undulator (SCU) afterburner at the European XFEL [8], we plan to develop a pulsed wire system to measure the SCUs magnetic field in the final cryostat. This contribution shows the first steps taken towards developing such a system. Furthermore, we outline the main requirements to perform magnetic field reconstruction and examine some of the limitations of the technique, mainly the dispersive, finite pulse-width, discretization errors, and sag effects.

PULSED WIRE METHOD OVERVIEW

The pulsed wire method, first proposed by Warren in 1988 [1], consists of stretching a wire on the axis of the undulator and sending a current pulse through it. The Lorentz forces acting in the wire make an acoustic wave travel, in which optical detectors can measure the amplitude of the wire displacement over time. For a non-dispersive motion, the speed of the wave on the wire is $c_0 = \sqrt{T/m_L}$, where T is the wire tension in N and m_L is the wire linear density in kg/m. Figure 1 shows the schematic of the technique.

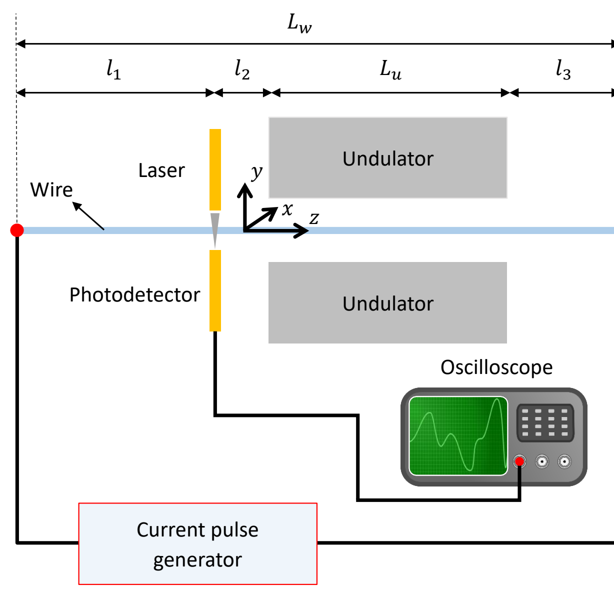

Figure 1: Two-dimensional scheme of the pulsed wire system and main lengths.

The wire displacement is proportional to the first or second field integral for squared current pulses, depending upon the pulse width δt. Let λ_u be the undulator period and L_u be the undulator length. If the pulse width is much smaller than the time the wave takes to travel one undulator period (i.e., if $\delta t \ll \lambda_u/c_0$), then the wire displacement follows the first field integral profile. To measure the second field integral, a pulse width should be longer than the time the wave takes to travel over the undulator length (i.e., $\delta t > L_u/c_0$). Some authors have explored the concept of applying a current shape of a positive followed by a negative short pulse [6, 9], which makes the wire displacement profile proportional to the magnetic field. The experimental and theoretical aspects of such an approach do not fall into the scope of this manuscript.

Compared to the Hall probe technique, the pulsed wire method has some advantages:

- It is suitable for restricted access devices, particularly for those with small gaps, since the wire diameter can be thinner than a Hall probe. Besides, it has the potential to map in-vacuum/cryogenic undulators;
- It is faster. The Hall probe technique requires sufficient settling time at each point for sensor reading to settle down;

* johann.baader@xfel.eu

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB126

- Both transversal magnetic field components x and y (see Fig. 1) can be measured simultaneously by setting two laser-photodetector pairs (parallel to the y-axis and x-axis, respectively). For Hall probes, it requires multi-axis sensors.

Even so, the technique also has some drawbacks. First, external vibrations and electronic noise disturb the wire displacement measurement, which results in a poor signal-to-noise ratio. Second, the wire must be long enough to avoid the reflections that come from the fixed ends and may reach the detection point while the main wave is passing. Particularly, the length l_1 showed in Fig. 1 should be at least half of the undulator length L_u, i.e., $l_1 < L_u/2$. A long wire gives rise to a third disadvantage: the catenary weight, also known as sag. For a maximum allowed sag S, the wire length should satisfy $L_w \leq \sqrt{8TS/(gm_L)}$, where g is the gravitational acceleration in m/s^2 [1].

Besides these issues, the finite flexural rigidity of the wire causes dispersion — when longer wavelengths travel faster through the wire than the shorter wavelengths. The dispersion will be particularly an issue for long undulators, since the longer wire will allow higher wavenumbers (i.e., short wavelengths) to reach the detector first and, therefore, disturb the main signal. According to Warren [1], dispersion can be neglected if

$$L_u \ll \frac{\lambda_u^3 T}{2\pi^2 E I_w}, \tag{1}$$

where E is the Young's modulus of the wire in N /m^2 and I_w is the second area moment of the wire[1] in m^4. Equation (1) reveals that not only longer undulators make the dispersion an issue. The shorter the undulator period, the more difficult it becomes to avoid the dispersive effects.

MAGNETIC FIELD RECONSTRUCTION PROGRAM

A program has been developed in Matlab to correct dispersion, finite pulse width, sag, and discretization errors [10]. Ref. [5] proposed numerical techniques to compensate the dispersion in the frequency domain, and a similar approach is used in our software.

Theoretically, the first field integral is proportional to the wire displacement for a pulse width going to zero. In experiments, nevertheless, this is impracticable. The pulse width must be finite, which will also introduce errors. Ref. [5] shows how to correct the finite pulse width effect, which is also considered in our program.

The wire displacement is sampled. We calculate the magnetic field samples $B[n]$ by either the first or the second forward finite divided difference of the field integral, depending upon whether the pulse width provides the first (I_1) or the second field integral (I_2). Mathematically, the samples of the magnetic field are obtained from the first field integral by

[1] For a circular cross-section wire with diameter d, $I_w = \pi d^4/64$.

$$B[n] = \frac{I_1[n+1] - I_1[n]}{\Delta z} \tag{2}$$

and by

$$B[n] = \frac{I_2[n+2] - 2I_2[n+1] + I_2[n]}{(\Delta z)^2} \tag{3}$$

if the second field integral is available. For both equations, Δz is the sampling space in m. This procedure introduces errors in the magnetic field. The program corrects the discretization effects on the frequency domain.

Sag is corrected numerically in the space domain, since the vertical component of the magnetic field is $B_y(y) = B_0 \cosh(2\pi y/\lambda_u)$, with B_0 being the on-axis field amplitude.

PROGRAM VALIDATION AND RESULTS

The model simulation aims to calculate the wire displacement for a defined magnetic field profile (input), taking into account dispersion, finite pulse width, discretization, and sag effects. After performing all the corrections, either Eq. (2) or Eq. (3) recovers the magnetic field (depending on the squared pulse width), which is then compared to the original magnetic field used as the input of the program. Table 1 shows the parameters we used to obtain the wire displacement for a short pulse.

Table 1: Parameters for Simulating the Wire Displacement and Magnetic Field Reconstruction

Parameters	Values
On-axis magnetic field amplitude, B_0	1 T
Undulator period, λ_u	10 mm
Undulator length, L_u	70 cm
Wire diameter, d	75 µm
Wire Young's modulus, E	124 GPa
Wire tension, T	2 N
Wire linear density, m_L	3.88×10^{-5} kg/m
Current pulse amplitude, I	5 A
Current pulse width (short), δt	3 µs
Sampling space, Δz	1×10^{-4} m

Replacing the parameters of Table 1 in Eq. (1) gives $L_u \ll 53$ cm. Since the undulator length in the simulation is 70 cm, one may expect the influence of dispersion in the results. Figure 2 displays the first field integral samples calculated from the magnetic field used as the input and the dispersive wire displacement. The dispersion impact is evident at the beginning (since higher wavenumbers travel faster) and at the end of the signal.

After correcting the dispersion and the finite pulse width, the magnetic field is reconstructed by applying Eq. (2). The difference between the original and reconstructed magnetic fields is shown in Fig. 3 as the dotted blue line, which has a root-mean-square deviation (RMSD) of 20 mT. We repeat the same steps, including the discretization error correction.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB126

For this case, the magnetic field error is presented as the solid orange line in Fig. 3, which has an RMSD of 5 µT. We also compared the magnetic field peaks obtained for each case. Figure 4 displays the results.

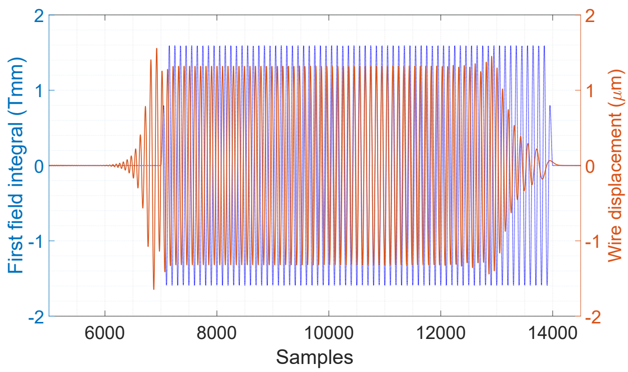

Figure 2: First field integral (dotted blue line) and the wire displacement (solid orange line).

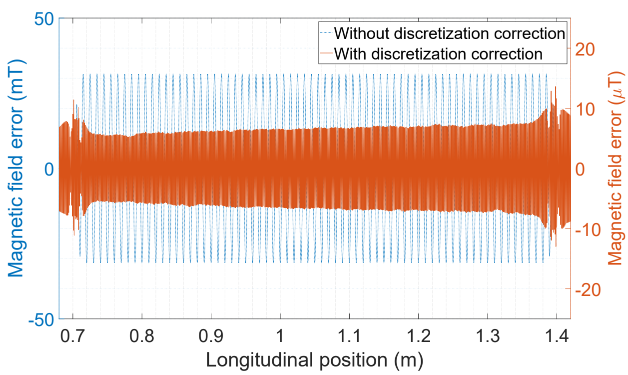

Figure 3: Magnetic field error comparison for the case where the discretization effect is corrected (solid orange line) and it is not corrected (dotted blue line).

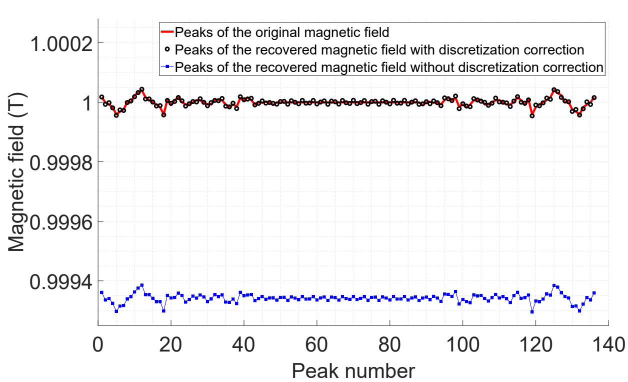

Figure 4: Comparison among the peaks of the original magnetic field (red line), recovered with (black circles) and without discretization correction (blue squares).

DEVELOPMENT STATUS AND PLANS AT THE EUROPEAN XFEL

At the European XFEL, most of the hardware required for the pulsed wire system has been purchased. For the motion detection, we will combine the laser THORLABS CPS532 and the photodetector THORLABS PDA100A2. The oscilloscope that measures the signal from the photodetector is the LECROY HDO6104A-MS (12-bit ADC, 10 GS/s). We plan to perform the initial tests with a 75 µm diameter Beryllium Copper wire, and other wire options are under consideration. The pulse generator will be built in-house. Capacitors will be charged up to 300 V by using the power supply FARNELL EA-PS 3032-20B. The nanosecond switching power Mosfet IRF840 releases the current onto the wire after being triggered by the function generator RS PRO RSDG2122X.

A short system will be first assembled. It will measure a prototype undulator, developed by LUX at Desy for laser-plasma driven light source applications [11]. This undulator has a length of approximately 30 cm, period of 1.6 mm, and the on-axis magnetic field amplitude is 0.6 T. Once the system is tested and commissioned for this short undulator, we will scale it to measure the U40 planar hybrid undulators at European XFEL [12].

Relevant research has been carried out to correct dispersion [5, 7]. However, for these studies, dispersion is not dominating [i.e., the condition shown in Eq. (1) is satisfied]. In the SASE2 SCU afterburner context [8], we foresee an upgrade of the system to test and commission it for in-vacuum and cryogenic environments. For such a system, dispersion will dominate; consider λ_u = 18 mm and the wire characteristics shown in Table 1. Replacing them in Eq. (1) gives $L_u \ll 3.07$ mm. Nevertheless, the undulator length to be measured will be approximately 4 m, longer than the required length to neglect dispersion.

SUMMARY AND OUTLOOK

The pulsed wire method is a promising solution to map the local magnetic field in small gap long devices. The technique has to be demonstrated to reconstruct the magnetic field for long undulators with a short period, particularly when the dispersion effect dominates. At the European XFEL, the hardware and software developments for a pulsed wire system are in progress. With this measuring system, we plan to test the tolerances needed for the FEL process of SCU lines, in particular for the SCU afterburner modules [8, 13].

ACKNOWLEDGEMENTS

The authors would like to thank Maximilian Trunk for providing several details of the pulsed wire system developed at Desy.

REFERENCES

[1] R. W. Warren, “Limitations on the use of the pulsed-wire field measuring technique”, *Nucl. Inst. Methods Phys. Res. A*, vol. 272, pp. 257-263, 1988. doi:10.1016/0168-9002(88)90233-1

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB126

[2] O. Shahal, B. V. Elkonin, and J. S. Sokolowski, "Dispersion interference in the pulsed-wire measurement method", *Nucl. Inst. Methods Phys. Res. A*, vol 296, pp. 588–591, 1990. doi:10.1109/fel.1989.716072

[3] D. W. Preston and R. W. Warren, "Wiggler field measurements and corrections using the pulsed wire technique", *Nucl. Inst. Methods Phys. Res. A*, vol. 318, pp. 794–797, 1992. doi:10.1016/0168-9002(92)91160-b

[4] M. Fabrice *et al.*, "Improvements of the pulsed-wire method to measure undulators", *IEEE Trans. on Applied Superconductivity*, vol. 10, pp. 1443–1446, 2000. doi:10.1109/77.828511

[5] D. Arbelaez *et al.*, "A dispersion and pulse width correction algorithm for the pulsed wire method", *Nucl. Inst. Methods Phys. Res. A*, Vol. 716, pp. 62-70, 2013. doi:10.1016/j.nima.2013.02.042

[6] M. Valléau *et al.*, "Measurements of SOLEIL Insertion Devices using Pulsed Wire Method", in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastian, Spain, Sep. 2011, paper THPC152, pp. 3242–3244.

[7] M. Kasa, "DSP methods for correcting dispersion and pulse width effects during pulsed wire measurements", *Measurement*, vol. 122, pp. 224–231, 2018. doi:10.1109/ultsym.2017.8092949

[8] S. Casalbuoni *et al.*, "Towards a superconducting undulator afterburner for the European XFEL", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, paper WEPAB132, this conference.

[9] P. N'gotta *et al.*, "First Results of a Pulse Wire Measurement System for ID Characterization at MAX IV", presented at the 21st International Magnetic Measurement Workshop (IMMW'21), Grenoble, France, Jun. 2019, unpublished.

[10] J. E. Baader and S. Casalbuoni, "Magnetic field reconstruction using the pulsed wire method: an accuracy analysis", unpublished.

[11] Laser PLasma Driven Light Sources, http://lux.cfel.de/.

[12] S. Abeghyan *et al.*, "First operation of the SASE1 undulator system of the European X-ray Free-Electron Laser", *J. Synchrotron Rad.*, vol. 26, pp. 302-310, 2019. doi:10.1107/s1600577518017125

[13] B. Marchetti *et al.*, "Study of the tolerances for superconducting undulators at the European XFEL", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May. 2021, paper THPAB035, this conference.