IN-VACUUM PULSED WIRE TECHNIQUE

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Abstract

The pulsed wire technique has been used in the past mainly for trajectory control in wigglers and undulators. Including dispersion and pulse width corrections improved significantly the quality of these measurements. Recent approaches use the measured pulse instead of the model of an idealized rectangular pulse and the impact of tiny, but relevant induced currents by the wire oscillation is understood. The in-vacuum pulsed wire system at European XFEL will be part of the SUNDAE2 (Superconducting UNDulator Experiment) horizontal test stand. In this contribution we report on the progress made and first measurements on a 5 m long permanent magnet undulator with 40 mm period. The aim is to be a true alternative for Hall-probe measurements.

MOTIVATION

European XFEL is planning to install up to six superconducting undulator (SCUs) modules downstream with respect to the permanent magnet undulators of the hard X-ray undulator line SASE2 [1]. To perform quality assurance on the SCU coils before installation in the tunnel, a horizontal test stand is being developed: SUNDAE2 [2]. As the vacuum chamber of the SCU will have a temperature of about 20 K, the measurements need to be done in vacuum. One of the techniques that will be used for measuring the field integrals and the magnetic field profile is the pulsed wire method. This is an attractive option to measure the magnetic field in insertion devices, mainly for those with restricted access as the above mentioned SCUs with a racetrack shape vacuum chamber of dimensions 5 mm × 10 mm and 5 m long.

PULSED WIRE SETUP AND METHOD

Figure 1 shows the configuration of the pulsed-wire system as it will later be used with the SCU modules. For preparation one of the PMUs with 40 mm period length as those installed in the European XFEL hard X-ray undulator lines is used and serves as reference. The vacuum chambers at the entrance and exit of the undulator are those of SUNDAE2 and house the measurement infrastructure. The measurement hardware includes an arbitrary waveform generator, a 4-quadrant amplifier, a 16(18)-bit oscilloscope, four stages including controls, two low noise lasers, and two photo diodes for x- and y-axis. In the pulsed-wire method, an electrically conductive wire is generally guided through the undulator magnetic field axis, which is where the electron beam will travel. The electric current causes the wire to be deflected by the Lorentz force generated by the undulators magnetic field. This deflection propagates along the wire as a wave and the transverse movement of the wire is measured using the shadow cast of a laser via a photo diode. The wire is stretched over a length of 11.18 m and has a resistance ranging from about 200 Ω for CuBe (D = 75µm) to 2500 Ω for titanium (D = 100µm). The latter requires a very high voltage to generate a sufficiently strong current in order to produce a detectable deflection, especially with very short pulses. The nonlinear relationship between the deflection and the photo voltage must be calibrated. This calibration process can be automated and performed either step-by-step or on the fly. The latter method is significantly faster and consequently reduces the likelihood of disruptions, which are more likely to occur over longer periods of time, e.g., due to external vibrations. Different current pulse lengths are used to directly measure the magnetic field profile, the first and second field integrals along the undulator magnetic field axis [3, 4]. In order to reconstruct those signals the current pulse is recorded as well as the photo diode voltage, which is proportional to the deflection of the wire.

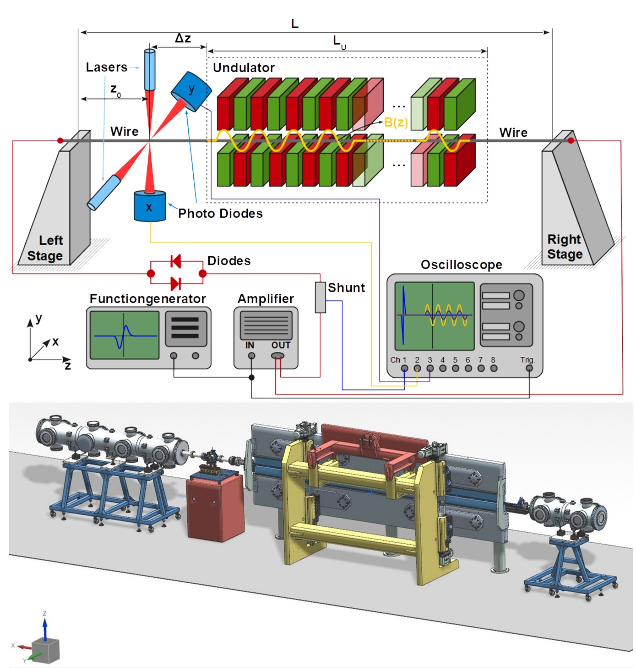

Figure 1: Top figure: Principle of the pulsed wire method. Bottom figure: Current pulsed wire setup with the U40 undulator and the vacuum chambers.

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PULSED WIRE TESTS

To this point, we have conducted numerous tests at ambient pressure, revealing several aspects that require further investigation.

Signal Decay

Initial tests showed a strong (exponential) signal decay similar to the upper Fig. 2 for the deflection. The deflection is calculated from the photovoltage using the calibration curve shown in Fig. 3. Inspired by a dissertation by Ebbeni from MAXLAB [5, 6], we were able to detect and suppress a feedback current induced by the movement of the wire in the undulators magnetic field using diodes. The magnetic field and the closed circuit of the pulsed wire act like an eddy current brake, which instantly dampens the movement of the wire. Blocking the feedback current allows removing the strong damping of the measured deflection of the wire along the undulator magnetic field axis that nevertheless still exhibits a very slight decay. If $I_p(t)$ is the applied current pulse then we find for the total current

$$I(t) = I_p(t) - \frac{1}{R}\int_{-\infty}^{\infty} \mathrm{d}z\, \partial_t u(t, z)\, B(z) \qquad (1)$$

where R is the total resistance of the wire plus the shunt resistor which is typical 10Ω. The test parameters for the CuBe wire were: $\rho \approx 8300\frac{\mathrm{kg}}{\mathrm{m}^3}$, $E \approx 125\,\mathrm{GPa}$, $D = 75\,\mu\mathrm{m}$, $T_0 = 1.96\,\mathrm{N}$ and $L = 11.18\,\mathrm{m}$. The residual current is shown in the right sub-figure of Fig. 4 for bipolar gaussian pulse (derivative of a gaussian).

The blocking can be achieved using (fast) diodes connected in an anti-parallel configuration or other fast switches such as MOSFETs. All of our tests to this point have been conducted using diodes, as these can be integrated into the circuit as passive components. Figure 2 illustrates the effects of the blocking diodes and the absence of air damping in a vacuum (bottom).

Arbitrary Current Pulses

Rectangular pulses, as they have typically been generated in the past by so-called "pulsers" (discharge of capacitors), contain high frequencies due to their steep edges. Therefore, other pulse shapes may offer better performance for reconstructing the magnetic field profile and its integrals. The use of arbitrary pulses requires a generalized method to reconstruct the magnetic fields. A general method was presented in [5] and [6]. Similar to methods using rectangular pulses, this method can handle short pulses with Gauss-, Lorentz- or sinc profiles. It also takes dispersion effects into account and considers in addition the current pulse shape. By using very short ($c_T\delta t = 2\,\mathrm{mm} < 40\,\mathrm{mm}$, $\delta t = 10\mu\mathrm{s}$, $c_T^2 = \frac{T}{A\rho}$) bipolar pulse, the wire deflection is proportional to the magnetic field. This holds also for the derivatives of the other mentioned pulse shapes.

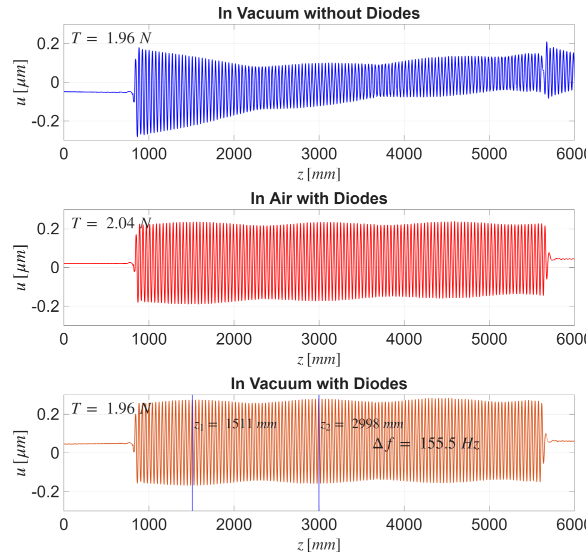

Figure 2: Wire oscillations without diodes in vacuum (top), in air with diodes (middle) and with diodes (bottom) in vacuum. Without diodes we find a strong decay with no clear ends of the undulator signal.

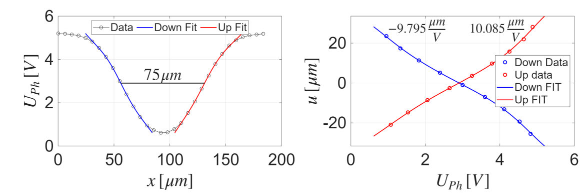

Figure 3: Calibration of the wire deflection u and the photo voltage U_{ph} interpolated by a smooth spline.

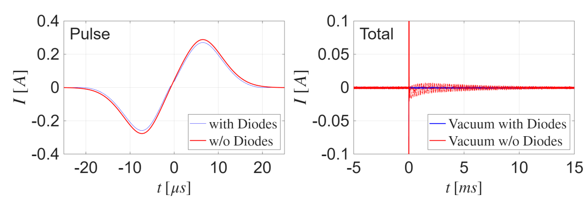

Figure 4: The detailed current pulse (left) and the total feedback current, amplified and corrected with a gain of 10 (right).

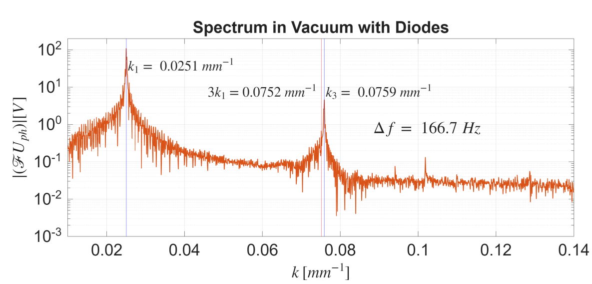

Figure 5: Spectrum of the vacuum measurement with diodes (bottom of Fig. (2)). The triple of the fundamental frequency $k_1 = 0.0251 mm^{-1}$ does not coincide perfectly with the third harmonic at $k_3 = 0.0759 mm^{-1}$. This generates a frequency shift $\Delta f = c_L(k_3 - 3k_1)$ of about 166.7 Hz.

Beat Oscillations

One further observation was the existence of beat oscillation for short and bipolar current excitations (see Fig. 2). The beat oscillations was around 150 Hz to 170 Hz for a tension of roughly 1.96 N. There is a clear shift of the higher modes peak position in the spectrum as shown in Fig. 5. This shift in the frequency might be explained by additional coupling between the transverse $u(t, z)$ and longitudinal $w(t, z)$ excitations. The longitudinal modes are excited by the transverse deflection due to the associated additional stretching of the wire. They travel at a much higher speed $c_L^2 = \frac{E}{\rho}$ and can already generate standing waves whilst the transverse wave package is initially propagating. Using the parameters of the CuBe wire from above, we can perform an first verification. Standing waves in a wire exhibit the nth frequency modes shown below for transverse and longitudinal excitations.

$$c_T = \sqrt{\frac{T}{A\rho}} \approx 231 \frac{m}{s}, \qquad c_L = \sqrt{\frac{E}{\rho}} \approx 3881 \frac{m}{s} \tag{2a}$$

$$f_T^{(n)} = \frac{n c_T}{2L} \approx n 10\,\text{Hz}, \qquad f_L^{(n)} = \frac{n c_L}{2L} \approx n 173\,\text{Hz}. \tag{2b}$$

In particular, the longitudinal fundamental mode at approximately 169 Hz agrees very well with observations.

FIELD INTEGRALS AND PHASE

First measurements in vacuum have been performed with a rectangular pulse allowing for a straightforward conversion to the first field integral according to [3]. Figure 6 shows the magnetic field and the first and second field integrals with a 10 μs rectangular pulse. The magnetic field and the second field integral are derived from the first field integral measurements. In Fig. 7 the corresponding phase error evaluation is shown. Whereas the trajectory agrees well the phase error is more sensitive to the beat oscillations. The same wire parameters as those specified above were used.

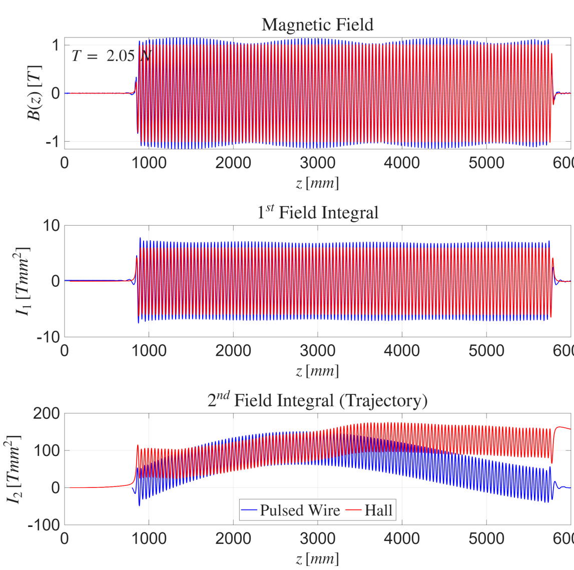

Figure 6: First field integral measurement I_1 (middle), the derived magnetic field B (top) and second field integral I_2 (bottom). The analysis does not correct for dispersion effects and pulse width effects.

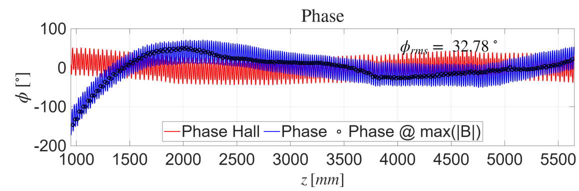

Figure 7: Phase error analysis calculated from the I_1. The rms phase error can be reduced from 34° below 10° by correcting long range orders only which might arise from the beat oscillation.

SUMMARY AND OUTLOOK

Recent measurements carried out in a vacuum confirm the assumption that the remaining loss is due to air resistance. After eliminating the feedback current, we still observe beat oscillations, which might be caused by the excitation of longitudinal oscillations. They also influence the field integral measurements and the phase error analysis. Nevertheless we could successfully reconstruct the trajectory of the undulator. The system is ready for use with SCU modules to measure the trajectory. To reconstruct the magnetic field, we still need to solve the problem of beat oscillations and extend the software to support arbitrary pulse shapes.

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