First Results of a Pulse Wire Measurement System for ID Characterization at MAX IV

P. N’gotta, M. Ebbeni, A. Thiel, H. Tarawneh

IMMW21 Grenoble, France

June 2019
Outline

- Status of MAX-IV ID project
- Presentation of the PWM method
- Numerical simulations
- PWM bench implementation
- Measurements results
- Conclusion
SXL FEL Undulator development

- Due to limited accessibility a functioning **pulsed wire system is needed**.
- Horizontal slit can be incorporated if necessary for Hall-probe access.

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>SmCo ($B_r$=1.1 T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period Length</td>
<td>40 mm</td>
</tr>
<tr>
<td>Photon energy range</td>
<td>0.25 – 1 keV</td>
</tr>
<tr>
<td>Magnetic gap range</td>
<td>8.0 – 17.3 mm</td>
</tr>
<tr>
<td>Effective K range</td>
<td>3.9 – 1.51</td>
</tr>
<tr>
<td>Max. gap / min. eff. K</td>
<td>28 mm / 0.55</td>
</tr>
<tr>
<td>Undulator magnetic length</td>
<td>3 m</td>
</tr>
</tbody>
</table>
Presentation of the PWM method

Pulsed wire system layout

- Local field measurement (Similar to Hall probe)
- First and second Field integral measurements
- Magnet alignment (magnetic center)
- Fast measurement (<50 ms !)

- Signal distortion (dispersion, resonance, perturbations, ...)
- Low signal to noise ratio
- Wave damping
- Wire Sag

Courtesy T.C. Fan
Presentation of the PWM method

Analytical modelisation

Time domain

- Input signal (current pulse)
- System kernel (impulse response)
- Output signal

\[ y(t) = x(t) * h(t) = \int_{0}^{t} x(\tau) \cdot h(t-\tau) d\tau \]  
(Convolusion product)

Frequency domain

- Fourier transform

\[ y(\omega) = h(\omega) \cdot x(\omega) \]  
(Product)

Pulse wire system
Impulse response
Fourier transform

\[ h(\omega) = \frac{-1}{2\mu} \left( \frac{1}{i \cdot \omega} \cdot \frac{1}{c_0} \cdot \bar{B}(k) \right) \]

Wire mass density
Integrator Fourier transform
Magnetic field Fourier transform

Wave number  
\[ k = \frac{2\pi}{\lambda} \]

Wave length [m]

Wave speed [m/s]
Wire tension [N]

\[ c_0 = \sqrt{\frac{T}{\mu}} \]

\[ \omega = k \cdot c_0 \text{ [rad/s]} \]
Presentation of the PWM method

Analytical modelisation

Dispersion Origin and effects

- Different speed of each frequency component of the wave signal
  \[ c_0 \Rightarrow c(k) \]
  \[ \omega = k \cdot c(k) \]

\[
h(\omega) = \frac{-1}{2\mu} \left( \frac{1}{i \cdot k \cdot c(k)} \cdot \frac{1}{c(k) + \frac{dc(k)}{dk}} \cdot \bar{B}(\omega) \right)
\]

- Corrupted integrator
- Non constant wave speed

Simulation of dispersive wave

Correction strategy

\[ x(\omega) \rightarrow h_0(\omega) \cdot \delta(\omega) \rightarrow y(\delta(\omega)) \rightarrow \delta(\omega)^{-1} \rightarrow y_0(\omega) \]

Orginal kernel
Dispersion
Dispersive output signal
Correction function
Corrected signal

\[ \delta(\omega)^{-1} = \left( \frac{c(k)}{c_0} \right) \left( \frac{c(k) + k \cdot \frac{dc(k)}{dk}}{c_0} \right) \frac{i \cdot k \cdot c(k) \Delta t}{e^{i \cdot k \cdot c(k) \Delta t} - 1} \]

Measurement of wave speed function \( c(k) \)

D. Arbelaez et al.
Numerical simulations

Simulations goals

- Signal dispersion
- Test of the wave speed identification
- Test the efficiency of the correction method
- Test the sensitivity of the correction result

Simulations Parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>variable</th>
<th>value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator period</td>
<td>( \lambda_u )</td>
<td>20</td>
<td>mm</td>
</tr>
<tr>
<td>Undulator Length</td>
<td>( L_u )</td>
<td>2</td>
<td>m</td>
</tr>
<tr>
<td>Wire tension</td>
<td>( \tau )</td>
<td>5</td>
<td>N</td>
</tr>
<tr>
<td>Wire flexural rigidity</td>
<td>( E_{ij} )</td>
<td>6.4 \times 10^{-7}</td>
<td>Nm^2</td>
</tr>
<tr>
<td>Wire mass per unit length</td>
<td>( \mu )</td>
<td>6.9 \times 10^{-3}</td>
<td>kg/m</td>
</tr>
<tr>
<td>Current pulse amplitude</td>
<td>( I_{\text{pulse}} )</td>
<td>2</td>
<td>A</td>
</tr>
</tbody>
</table>

- Copper-Nickel-Silicon wire
- 100 \( \mu \)m diameter
- \( C_0 = 269 \) m/s

Wire displacement expression

\[
\begin{align*}
V_s(t) &= \frac{I_{\text{pulse}}}{2\mu} \int_{-\infty}^{\infty} \frac{e^{i\omega t} - 1}{\omega^2} B(k) e^{-i\omega t} dk \quad \text{(short and long current pulse)} \\
V_s(t)' &= \frac{I_{\text{pulse}}}{2\mu} \int_{-\infty}^{\infty} \left( e^{i\omega t} - 1 \right) \left( 1 - e^{i\omega t} \right) B(k) e^{-i\omega t} dk \quad \text{(positive-negative current pulse)}
\end{align*}
\]

Discrete version for simulation

\[
V_{sD}(t) = 2\text{Re} \left( \frac{I_{\text{pulse}}}{2\mu} \sum_{k=1}^{N_{\text{s}}/2-1} \left( e^{i\cdot k_1 \cdot c(k) \cdot \Delta s} - 1 \right) \frac{B(k) e^{-i\cdot k_1 \cdot c(k) \cdot \Delta s}}{(k \cdot k_1 \cdot c(k))^2} \right)
\]

- first order
- Wave number
- Sampling step \([\text{mm}]\)
- Sample number

Undulator model magnetic field

\[
c(k) = c_0 \sqrt{1 + \frac{E_{ij}}{T} k^2}
\]

(generation of a discrete Table of wave speed function)
Numerical simulations

**Undulator magnetic field (model)**

- First Field integral
- Second Field integral

**Pulsed wire measurement (Simulation)**

- Wire displacement [nm]
- Field integral [T·m]

\[
\Delta t \ll \frac{\lambda_u}{c_0} \quad \Delta t \geq \frac{L_u}{c_0} \quad \Delta t \geq \frac{L_u}{c_0}
\]
Numerical simulations

Dispersion correction
- Wave speed measurement \( c(k) \)
- Identification of the parameter \( E_{iW} \)

Wave speed measurement
- Measurement at two location
- Use of undulator field or thin dipole magnet

Thin dipole 10mm length

\[
c(\omega) = \frac{\omega \Delta x}{\text{Arg}(\hat{V}_{sd}^*(\omega) \cdot \hat{V}_{sd}(\omega))} \rightarrow E_{iW}
\]

Wave speed measurement with thin dipole 10mm length

\[\Delta x_{\text{shift}} < \lambda_u\]

Wave speed measurement with undulator
Numerical simulations

Dispersion correction

\[
V_{sD_0}(t) = 2\Re e \left( \sum_{\omega=1}^{\omega=(N_{\text{sample}}/2)-1} \overline{V}_{sD}(\omega) \cdot \overline{F}_C(k(\omega \cdot \omega_f)) e^{-i \cdot c_0 \cdot k(\omega \cdot \omega_f) \cdot t} \right)
\]

Corrected signal

Dispersed signal FFT

Correction function

\[
\overline{F}_{C_B}(k) = \frac{\Delta t^2}{c_0} \frac{\left(k \cdot c(k)\right)^2 c_0}{\left(e^{i \cdot k \cdot c(k) \Delta t} - 1\right) \left(1 - e^{i \cdot k \cdot c(k) \Delta t}\right)}
\]

Field correction function

\[
k(\omega) = \sqrt{-\frac{T}{Ei_w} + \frac{\sqrt{T} \cdot c_0^2 T + 4 Ei_w \omega^2}{c_0 Ei_w} / \sqrt{2}}
\]

Frequency to wave number transfert function
Numerical simulations

**PWM signal correction simulation**

Error: Original field - corrected signal

Field

$S/N = 5.10^3$

Field integral

$S/N = 3.5.10^3$

**Dispersion correction**

Second Field integral

**Sensitivity to Eiw error**

Error RMS normalized

Eiw fit error [%]
PWM bench implementation

PWM Bench architecture

Overview of the pulsed wire test setup

Test EPU

Stretch / pulsed wire towers

Flip coil bench

Kugler Hall probe bench
First measurements results

### Hall probe measurements

- Kugler flat stone Hall probe measurement system is used as a reference for the wire system, i.e. local field value and phase error.
- 68mm period undulator
- 2m Length
- 20mm Gap

### PWM calibration and parameters

- **Photodiode Calibration curve**
- Noise RMS: 3 mV

- First measurement at different wire tension
- Copper-beryllium wire (CuBe) available
- Current pulse 4A, 100 μs
- Wire Diameter 125 μm
- Wire length 5.5 m
- C0=279 m/s
- Low Elw parameter (wire inertia x young modulus)
- Low Dispersive effects
First measurements results

Forseen of the PWM measurement with Hall probe data

- Copper-beryllium wire (CuBe)
- Current pulse 4A, 100 μs
- Wire Diameter 125 μm
First measurements results

PWM measurements

- Effect of wire tension

- Measurements analysis
  - Signal shape modulation (wire resonance mode?)
  - Signal Damping
  - Ghost Tail signal
  - Noise @ 0.5μm (measurements without Lock-in amplifier)
  - Good repeatability of the measurements

- Wave speed measurement with undulator field
  - Fit around the undulator order

\[ \Delta X_{shift} = 6mm \]
First measurements results

PWM measurements  $T=8N$

Hall probe measurements

<table>
<thead>
<tr>
<th>Graph</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM meas</td>
<td>PWM meas corrected</td>
</tr>
<tr>
<td>B [T]</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>Field integral [Tm]</td>
<td>$x10^3$</td>
</tr>
<tr>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2nd field integral [Tm]</td>
<td>$x10^6$</td>
</tr>
<tr>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>0</td>
<td>-200</td>
</tr>
</tbody>
</table>

P. N’gotta
Conclusion

- PWM system is operational
- First results encouraging
- Good agreement between simulation and measurements
- Dispersion correction code effective
- Improvement of the PWM model (remove the wire resonance mode)
- Reduction of the signal noise with the Lock-in amplifier
Thank for your attention

References

- M. Valleau, Measurements of SOLEIL Insertion Devices using the pulsed wire method, IMMW18, New york, 2013
- M. Kasa, methods for correcting dispersion and pulse width effects during pulsed wire measurements, Nuclear Instruments and Methods in measurement, 122, (224-231), 2018
- H. tarawneh et al., Compact APPLE X for Future SXL FEL and 3 GeV Ring at MAX IV Laboratory, IPAC2019, Melbourne, 2019