Experience with the use of a pulse width and dispersion corrected pulsed-wire technique to characterize an undulator magnet

Stephen Milton, Alex D’Audney, Sandra Biedron
Colorado State University
Background
The CSU Accelerator Laboratory Concept

• Create a “Best-in-Class” research facility/training center for accelerator beam science, engineering, and technology
  • Capitalize on the following desires/trends
    • Small
    • Efficient
    • Cost effective
  • Train the next generation of accelerator scientists, engineers, and technologists
  • Perform world-class research in beam physics
  • An operational accelerator research and training facility will attract world-class employees, collaborators, and users to CSU.
The Advanced Beam Laboratory
CSU Accelerator Laboratory

Donated by the Univ. of Twente

Donated by the Boeing Corp.
# ABL Basic Layout and Initial Capabilities

## Laser Lab 1

**100-150 Terawatt Ti:Sapphire laser system.**
- Wavelength: 0.8 micrometers
- Energy before compression: 13 Joules
- Repetition rate: up to 5 Hz
- Plans to scale to 0.5 Petawatt

## Laser Lab 2

**1 J, 5 picosecond, 100 Hz repetition rate diode-pumped laser (100 W average power)**
- Wavelength: 1.03 micrometers
- Highest repetition rate diode-pumped chirped-pulse-amplification laser in the world
- Can be scaled in repetition rate and pulse energy, future parameters depend on funding

## Accelerator Lab

**6 MeV Photocathode Driven Electron Linac**
- L- Band (1.3 GHz)
- Two Klystrons Available (One needed for PC Gun)
- 15 us pulse durations at 10 Hz
- Up to 81.25 MHz pulse rates available
### Major System Parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Linac</strong></td>
<td>Frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td></td>
<td>Repetition Rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td></td>
<td>Micropulse Rep. Rate</td>
<td>81.25 MHz (max.)</td>
</tr>
<tr>
<td><strong>Klystron</strong></td>
<td>Type</td>
<td>TH 2022C (Thales)</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>20 MW</td>
</tr>
<tr>
<td><strong>Modulator</strong></td>
<td>Type</td>
<td>PFN</td>
</tr>
<tr>
<td></td>
<td>Pulse Duration</td>
<td>15 µsec</td>
</tr>
<tr>
<td><strong>Undulator</strong></td>
<td>Type</td>
<td>Hybrid: NdFeB</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>1 (at 8 mm gap)</td>
</tr>
<tr>
<td></td>
<td>Period</td>
<td>25 mm</td>
</tr>
<tr>
<td></td>
<td>Periods</td>
<td>50</td>
</tr>
</tbody>
</table>
Past Performance of Linac System

- As Achieved at the University of Twente

<table>
<thead>
<tr>
<th></th>
<th>CEA</th>
<th>Boeing</th>
<th>AFEL</th>
<th>CERN</th>
<th>TEUFEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>1.4</td>
<td>5</td>
<td>13</td>
<td>4.1</td>
<td>6</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>1.9</td>
<td>0.8</td>
<td>0.3</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Emittance (π mm mrad)</td>
<td>25</td>
<td>9</td>
<td>2.1</td>
<td>52</td>
<td>1.22</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>19</td>
<td>91</td>
<td>95</td>
<td>760</td>
<td>40</td>
</tr>
<tr>
<td>Brightness (A/π² mm² mrad²)</td>
<td>0.06</td>
<td>2.2</td>
<td>43</td>
<td>0.6</td>
<td>53.7</td>
</tr>
</tbody>
</table>

A High Brightness Electron Beam for Free Electron Lasers
Van Oerle, Bartholomeus Mathias

Ph.D. Thesis Univ. of Twente
1st Experiment: THz Free-Electron Laser

- Tunable between 200-800 microns
- About 1 MW peak power from 900 MW available peak beam power (6 MeV, 150 A peak current)
- Average: a few mW (81.25 MHz rep rate, 15 microsecond macropulse, 25-ps micropulse)

Courtesy Univ. of Twente
Cartoon of Original Set up

\[ \lambda_s = \frac{\lambda_w}{2\gamma^2} \left( 1 + K^2 \right) \]

RF-linac

\( E = 3.1 - 6.5 \text{ MeV} \)
\( \delta E < 0.4 \% \)
\( I < 400 \text{ A} \)
\( \varepsilon < 10 \pi \text{ mm mrad} \)

wiggler

\( \lambda = 25 \text{ mm} \)
\( B = 0.7 \text{ T} \)
\( N = 50 \)

'waveguide' structure
hole coupling

\( L = 1835 - 1842 \text{ mm} \)

spectrometer

FEI-light

electrons

OTR-screen

gated camera

Courtesy Univ. of Twente
The Problem
The Problem, or at least one of them.
The Problem, or at least one of them.
Undulator Characterization: Most Common

- Traditional Hall probe
Undulator Characterization: Most Common

❖ Traditional Hall probe: Works best with clear access
## CSU Undulator Specs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>1 (0.61 T)</td>
</tr>
<tr>
<td>Period</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Gap</td>
<td>8 mm</td>
</tr>
<tr>
<td>Material</td>
<td>Sm$_2$CO$_5$</td>
</tr>
<tr>
<td>Periods</td>
<td>50</td>
</tr>
<tr>
<td>Length</td>
<td>1.25 m</td>
</tr>
</tbody>
</table>
# CSU Undulator Specs

<table>
<thead>
<tr>
<th>Undulator Design Parameters [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Gap</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Half thickness of pole</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Half thickness of magnet</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Height of pole</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Height of magnet</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Half width of pole</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Half width of magnet</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Gap</td>
<td>4.0</td>
</tr>
<tr>
<td>Half thickness of pole</td>
<td>(D_2) 2.0</td>
</tr>
<tr>
<td>Half thickness of magnet</td>
<td>(h_2) 4.25</td>
</tr>
<tr>
<td>Height of pole</td>
<td>(D_3) 40.0</td>
</tr>
<tr>
<td>Height of magnet</td>
<td>(h_3) 45.0</td>
</tr>
<tr>
<td>Half width of pole</td>
<td>(D_1) 15.0</td>
</tr>
<tr>
<td>Half width of magnet</td>
<td>(h_1) 21.0</td>
</tr>
</tbody>
</table>

Additional Background

❖ Students

- Good project for them
  - Measure an undulator
  - Read and understand a paper
  - Build a pulsed current source
  - Buy and assemble the equipment
  - Set up the measurement
  - Make the measurements
  - Write up reports
    - Conference papers
    - Senior design project papers
    - 1 Masters Thesis
Students Involved

❖ Alex D’Audney
  ❖ Senior design and Masters Thesis
❖ Sky Medicine Bear
  ❖ Senior design (Pulsed current source)
❖ Sean Stellenwerff (Univ. of Twente)
  ❖ System construction and software
❖ Joshua Smith
  ❖ Summer intern (Mechanical/survey)
❖ Jonathan Hoffman
  ❖ Summer intern (Mechanical/survey)
PW History

❖ Concept first developed by R. W. Warren at LANL in 1988.
❖ Has been used in a variety of specialized cases in the characterization of magnetic fields.
❖ The method’s accuracy was previously limited due to dispersive effects in the wire and the finite pulse width.
❖ Newly developed mathematical algorithms can correct for these limitations.
Basic Understanding

A dispersion and pulse width correction algorithm for the pulsed wire method

D. Arbelaez a,*, T. Wilks a, b, A. Madur a, S. Prestemon a, S. Marks a, R. Schlueter a

a Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
b University of California, Berkeley, CA 94720, USA
LBNL Results

Uncorrected

Corrected
1\textsuperscript{st} and 2\textsuperscript{nd} magnetic field integrals.

Simulates both the transverse velocity and oscillation trajectory of a charged particle passing along the axis of the undulator.

\[
u_{s0}(t) = \frac{Ic_0\delta t}{2T} \int_0^{c_0 t} B(\tilde{x}) d\tilde{x} \iff v_x(z) = \frac{1}{\gamma m_s} \int_0^z qB_y(\tilde{z}) d\tilde{z}
\]

\[
u_{s0}(t) = \frac{I}{2T} \int_0^{c_0 t} \int_0^{\tilde{x}} B(\tilde{x}) d\tilde{x} d\tilde{x} \iff x(z) = \frac{1}{\gamma m_s v_z} \int_0^z qB_y(\tilde{z}) d\tilde{z} d\tilde{z}
\]
Dispersion Correction

❖ From the Euler-Bernoulli equation for the bending of thin rods:

\[ c(\kappa) = c_0 \sqrt{1 + \frac{EIw}{T} \kappa^2} \]

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

❖ Need to find \( c_0 \) and \( EIw \) experimentally.
Dispersion

A reference magnet can then be measured and the signal recorded for two different positions along the wire spaced by $\Delta x$. It can then be shown that for a given frequency the wave velocity as deduced from the two signals are related to one another through the equation

$$c = \frac{\omega \Delta x}{\phi} \quad \text{where} \quad \phi = \kappa x$$

This relationship then gives the wave speed as a function of frequency $\omega$, and a fit to the theoretical value can then be used to reconstruct the actual waveform by removing the dispersion.
Wave Speed Determination

\[ \bar{u}_s^* (\omega) \bar{u}_s \Delta z (\omega) = |G(\omega)|^2 e^{i \kappa \Delta z} \]

\[ c = \frac{\omega \Delta z}{\phi} \]
\[ \bar{u}_s^*(\omega) \bar{u}_{s\Delta z}(\omega) = |G(\omega)|^2 e^{i\kappa \Delta z} \]

\[ c = \frac{\omega \Delta z}{\phi} \]

\[ \Delta z = 30 \text{cm} \]
Dispersive Wave Speed

\[ c = \frac{\omega \Delta z}{\phi} \]
Correction Algorithm Summary

1. Make a measurement of the wire displacement as a function of time, $u_s(t)$, over a sufficiently broad frequency range to capture all features of the magnetic field.

2. Numerically integrate the following function for discrete equally spaced values of $\omega_i$.

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

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

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

to obtain $H_o(\kappa)$.

5. For each time $t_i$ numerically integrate

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

to determine the non-dispersive displacement solution $u_{s0}(t_i)$ for the short pulse case. A similar process is used for the long pulse case.
Setup: Wire Positioning

- 2-Axis Translation Stage with 25µm resolution.
- “V-Blocks” to hold wire steady during alignment and experiments.
Setup: Wire Tension

❖ **Weight**
  - Used 2.3N and 0.85N.

❖ **Higher tension reduces dispersive effects, increases wave speed, and decreases wire displacement.**
Isolation required
Detector region
Setup: Wire Vibration Detection

- 635nm fiber laser
- 40µm Slit
- Amplified Si photo-detector
Magnetic Center

- Curved poles for parabolic pole focusing assisted in determining the magnetic center.
  - Field strength increases the further you get from the magnetic center.
Magnetic Center

- RMS values of the field strength within the undulator at various locations within the gap.
Dispersion Corrected: Short Pulse (1st Integral)
Dispersion Corrected: Long Pulse (2\textsuperscript{nd} Integral)

Wire displacement due to a long, 12ms, pulse, original (top), dispersion corrected (bottom)
1st Integral of the Undulator and Ref. Magnet
2\textsuperscript{nd} Integral of the Undulator

Wire displacement, original (top), dispersion corrected (bottom)

Dispersive signal (V)

Corrected signal (V)

Distance from Detector (ms)
System Difficulties

❖ Large amount of noise was prominent.
   ▪ Air
   ▪ Poor table isolation from ground
   ▪ Electrical

❖ Limitations
   ▪ Oscilloscope resolution
Improvements

- Better pulser
  - Originally used a home made current pulse
    - Noisy
  - Bought an AvTech Pulser
    - Very nice but expensive (~$11k)
    - Computer interface to NI available
      - Works well
- Better digitizer
  - Originally used an available scope
    - Limited dynamic range
    - Limited memory
  - Bought a 16-bit NI digitizer
    - Very nice

- Better environmental isolation
  - The area we were in was VERY noisy and “windy”
- Better reference magnet
  - We were limited to what we had and so ours had a non-zero 2nd integral
  - Would like it as short as possible
    - Higher frequency content
Additional steps

- Technology transferred to industry
  - KYMA S.r.L.
- Special thanks to Giuseppi Fiorito and Raffaella Geometranta
- Find another student to tune the device
Thank you