AN ULTRA-HIGH RESOLUTION PULSED-WIRE MAGNET MEASUREMENT SYSTEM

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Thesis Defense

Colorado State University

Overview

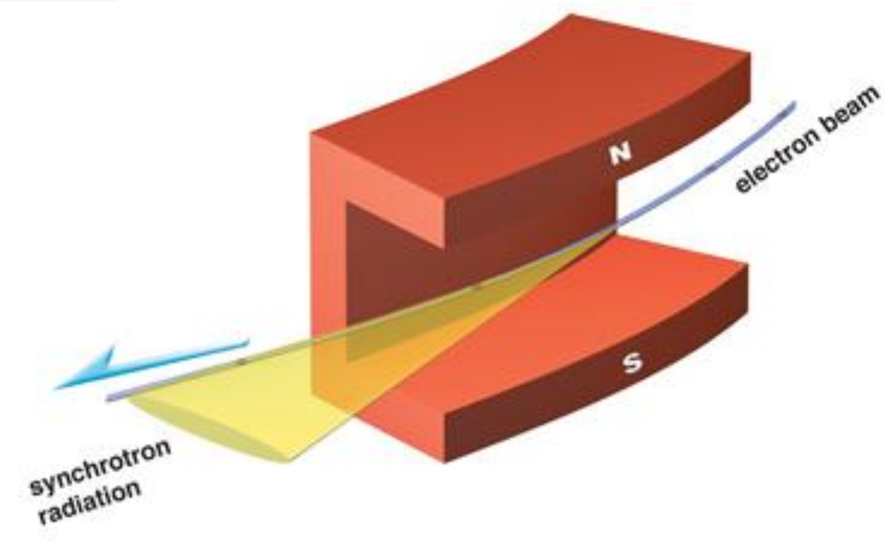
- Introduction and Background
- Pulsed-Wire Method Overview
- The CSU Undulator Specs
- Pulsed-Wire System Details
- Results

Introduction

- Synchrotron Radiation
- Undulator’s Function
- Characterization Techniques
- The CSU Undulator
- Description of Thesis

Synchrotron Radiation (SR)

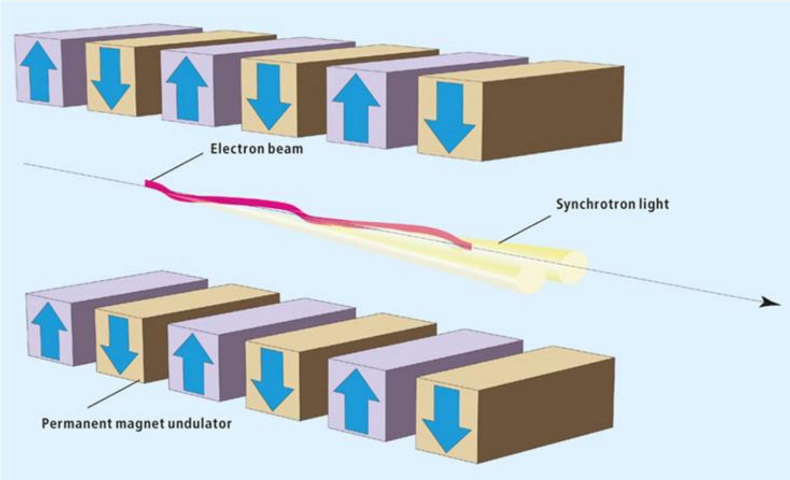
- **Occurs naturally in synchrotrons.**
  - Relativistic electrons undergo transverse acceleration due to a magnetic field.
  - Produces electromagnetic radiation, called SR.



http://www.nsrrc.org.tw/english/lightsource.aspx

Undulators

- **Description**
  - Series of alternating polarity dipole magnets.
  - Many bending magnets put together in a row.
  - Enhances SR light.
    - Coherent emission.
    - More monochromatic.

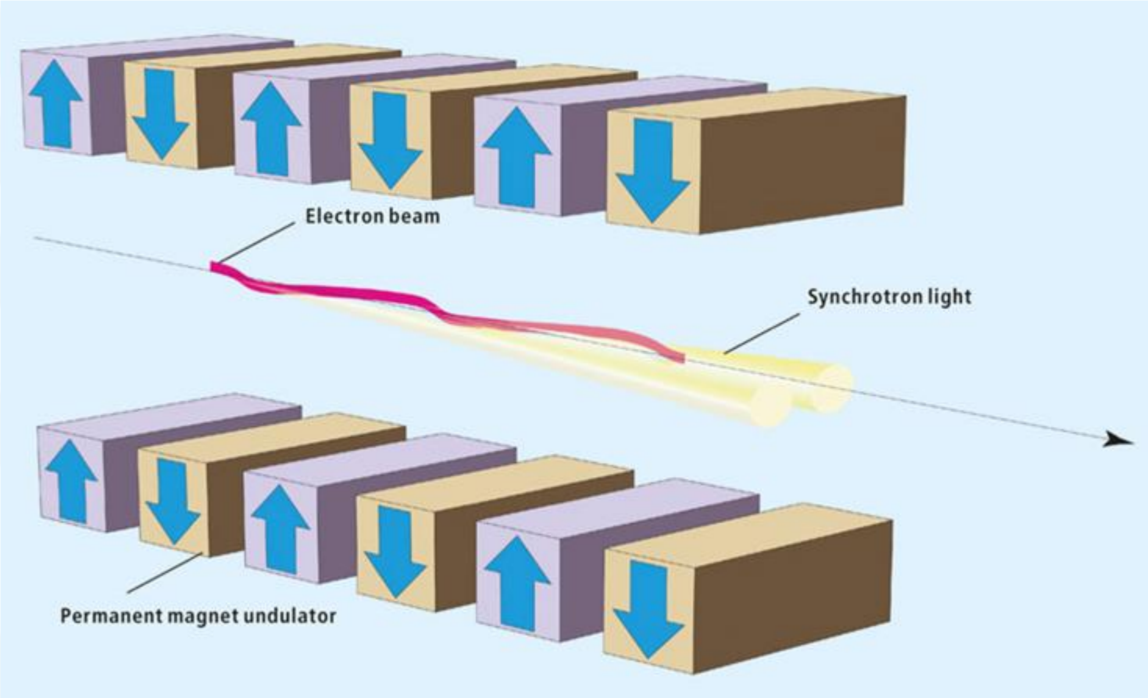


- **Types**
  - Electro-magnet
  - Pure Permanent Magnet
  - Hybrid (magnet/pole combo)
  - Super Conducting

Undulators

- **Lorentz Force**

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

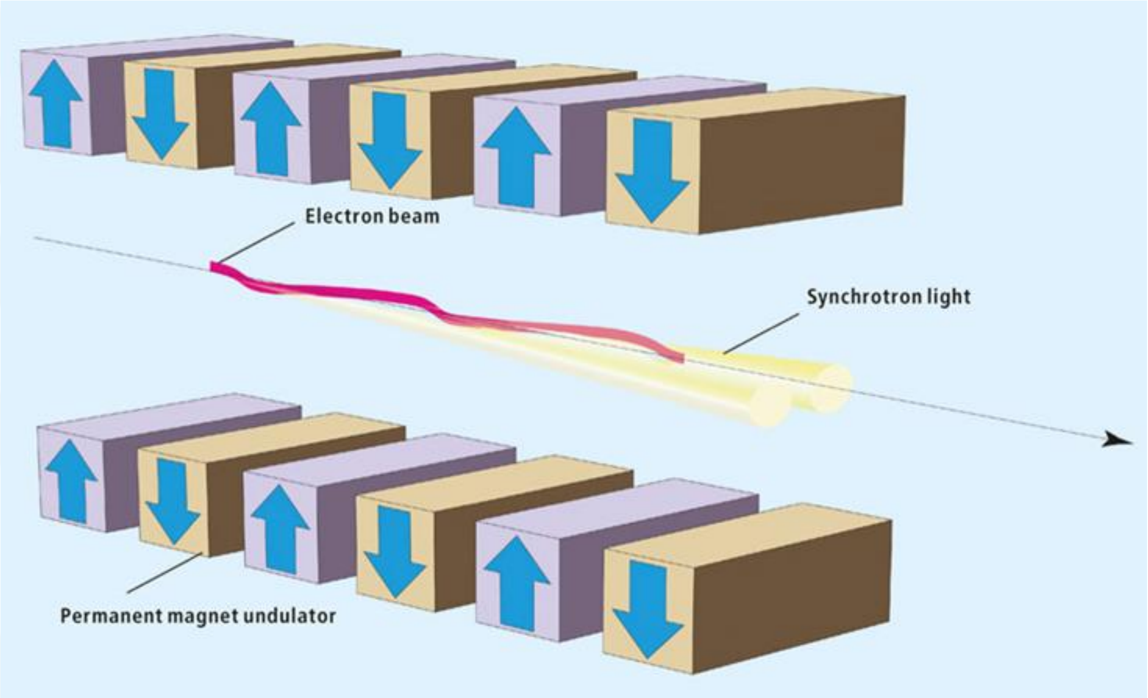


Chavanne, J., “The art of the undulator”, ESRF, January 2012, retrieved February 2015 from: http://www.esrf.eu/Accelerators/news/art-undulator

Undulators

- **Lorentz Force**

$$\vec{F} = \cancel{q\vec{E}} + \boxed{q\vec{v} \times \vec{B}}$$



Chavanne, J., “The art of the undulator”, ESRF, January 2012, retrieved February 2015 from: http://www.esrf.eu/Accelerators/news/art-undulator

Resonance Condition

- The average velocity of the ultra-relativistic electron is slower than the speed of light.
- The SR light out paces the electron by one optical period (λ_{rn}) for every undulator period (λ_u) of travel.
- The 'slippage' of the electrons relative to the light must equal, λ_{rn}.

$$\lambda_{rn} = \frac{\lambda_u}{2n\gamma^2}\left(1 + K^2/2\right) \qquad K = \frac{eB\lambda_u}{2\pi m_e c} \qquad \gamma = E/mc^2$$

Undulator Errors

- **Two types of errors.**
  - Trajectory and phase.
- **Reduces coherence and energy transfer between the electrons and light.**
- **Accurate undulator characterization is needed to be able to correct for any errors.**

Trajectory Error

- Occurs when an electron passes a dipole with improper field strength.
- The electron gets an incorrect total kick or angle change from the ideal sinusoidal trajectory.
- The direction of the electron and emitted light is then incorrect.
- Reducing overlap between the light and the electron bunch.

Phase Error

- **If a period in the undulator has a low field, the electron will have a higher average longitudinal velocity.**
  - The electron becomes out of phase.
- **The undulator resonance condition is not met if major phase errors are present.**
- **Errors reduce the coupling between the electrons and the EM wave.**

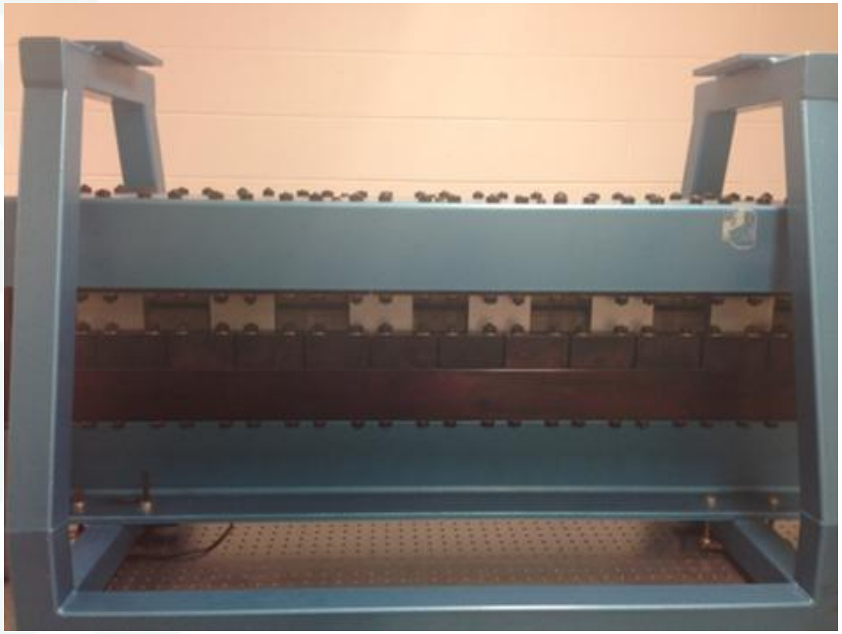
Undulator Characterization

- **Traditional Hall probe/Gauss meter**
  - Accurate
  - Time Consuming

- **Pulsed-Wire Method**
  - Ultra-fast
  - Can be used where field is inaccessible to a Hall probe

The CSU Undulator

- Hall probe measurements impossible due to support brackets holding gap steady.
- Pulsed-Wire (PW) measurements were previously done at the University of Twente.

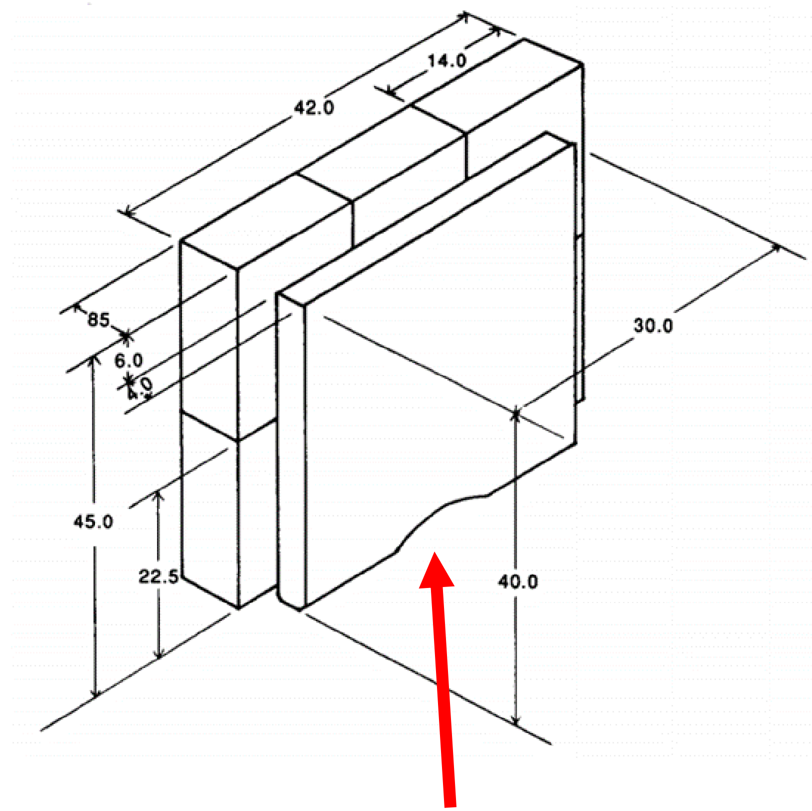


CSU Undulator Specs

Type	Hybrid: Sm_1Co_5 with Vanadium Permendur poles
Undulator Wavelength (Period) (λ_u)	25 mm
# of periods (N)	50
Gap size	8 mm
Field Strength	0.61 T

CSU Undulator Specs

Undulator Design Parameters [mm]		
Half Gap	h_s	4.0
Half thickness of pole	D_2	2.0
Half thickness of magnet	h_2	4.25
Height of pole	D_3	40.0
Height of magnet	h_3	45.0
Half width of pole	D_1	15.0
Half width of magnet	h_1	21.0



Verschuur, J.W.J., Warren, R.W., “Tuning and characterization of Twente wiggler”, Nucl. Instr. & Meth. A 375 (1996) 508-510

Description of Thesis

❖ Created a Pulsed-Wire Method

- Built the physical system.
- Found both the mechanical and magnetic centers of the undulator.
- Applied algorithms to measure dispersive components of the PW signal and remove them.
- Compared corrected PW data of a reference magnetic field to Hall probe measurements for absolute scaling.
- Determined the local magnetic field profile of the magnetic center of the undulator.

Pulsed-Wire Method

- Simple History
- Basic Understanding
- Output
- Limitations
- Correction

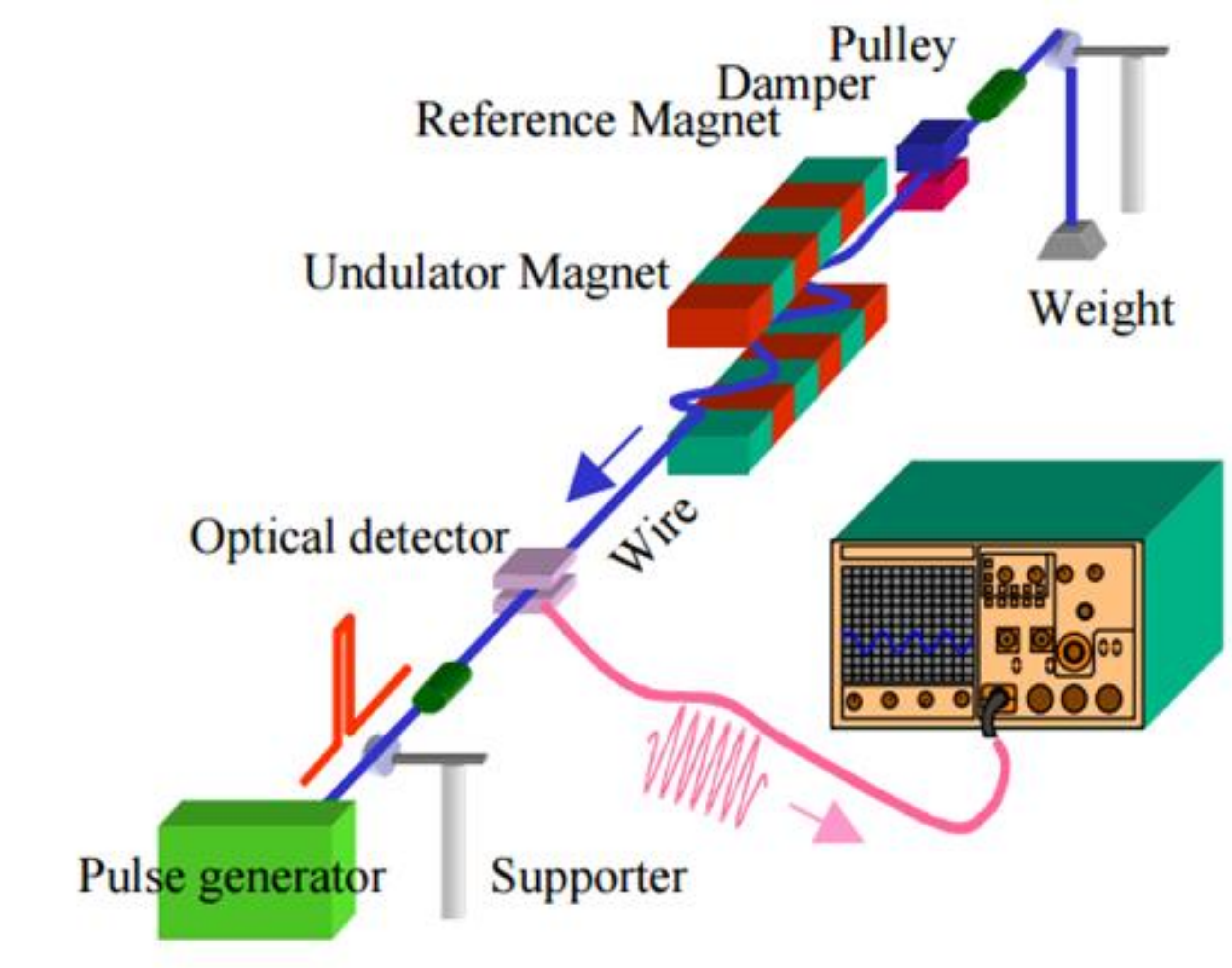
PW History

- 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 current pulse in a tensioned wire induces an acoustic wave (vibration) due to a magnetic field.**
  - Lorenz force causes the wire to move in a direction corresponding to the orientation of the magnetic field.
  - The wave travels in both directions along wire and can be measured.
- **Amplitude of wire vibrations are proportional to:**
  - Amount of current in the wire.
  - Strength of magnetic field being applied.
- **Using either short (μs) or long (ms) current pulses, the first or second field integrals can be deduced.**

Basic Understanding



Fan, T. C., Lin, F.Y. et al., “Pulsed wire magnetic field measurements on undulator U10P”, Proceedings of PAC2001, Chicago, USA, 2001, p. 2775-2777

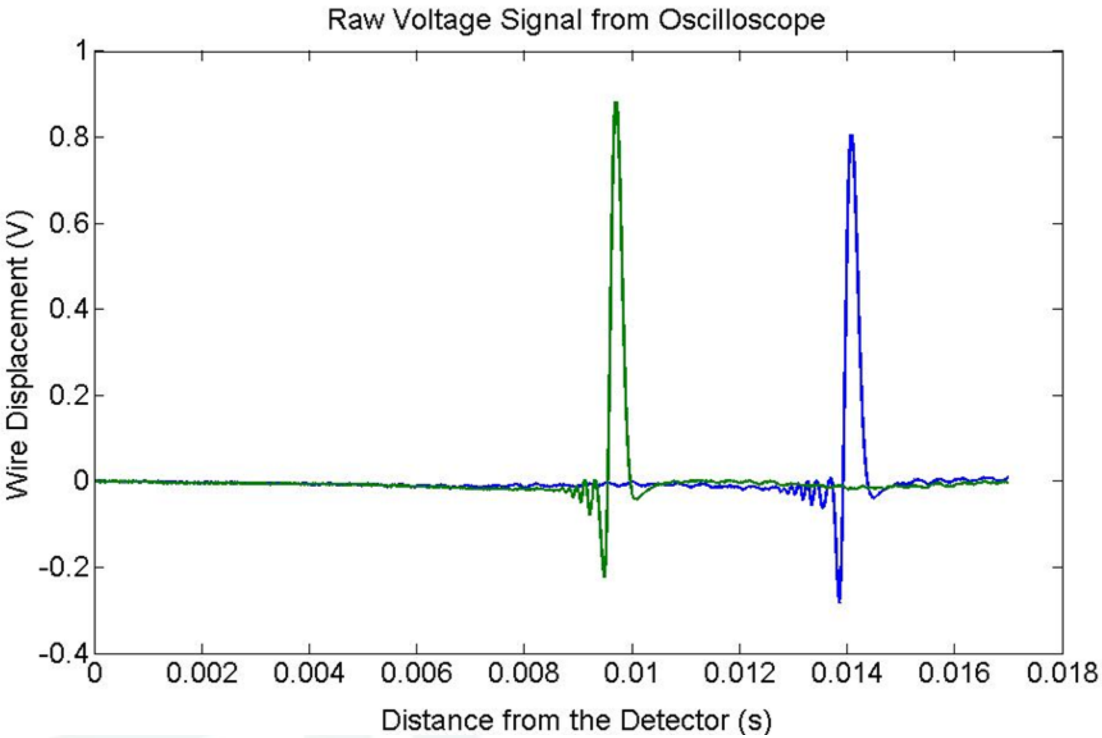
Output

- 1st and 2nd magnetic field integrals.
- Simulates both the transverse velocity and oscillation trajectory of a charged particle passing along the axis of the undulator.

$$u_{s0}(t) = \frac{Ic_0\delta t}{2T}\int_0^{c_0 t} B(\tilde{x})d\tilde{x} \longleftrightarrow v_x(z) = \frac{1}{\gamma m_e}\int_0^z qB_y(\tilde{z})d\tilde{z}$$

$$u_{s0}(t) = \frac{I}{2T}\int_0^{c_0 t}\int_0^{\hat{x}} B(\hat{x})d\hat{x}d\tilde{x} \longleftrightarrow x(z) = \frac{1}{\gamma m_e v_z}\iint_0^z qB_y(\tilde{z})d\tilde{z}d\hat{z}$$

Wave Speed Determination



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

$$c = \frac{\omega\Delta z}{\phi}$$

Dispersion Correction

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

$$c(\kappa) = c_0\sqrt{1 + \frac{EI_W}{T}\kappa^2}$$

$$c_0 = \sqrt{T / \mu}$$

- Need to find c_0 and EI_W experimentally.

Dispersion Correction Algorithm

- Start with the dispersive wire displacement:

$$u_s^{short}(t) = \frac{I\delta t}{2\mu}\int_{-\infty}^{+\infty}\frac{i}{\kappa c_0^2}\bar{B}(\kappa)e^{-i\omega t}d\omega$$

$$u_s^{long}(t) = -\frac{I}{2\mu}\int_{-\infty}^{+\infty}\frac{1}{(\kappa c(\kappa))^2\left(c+\kappa\frac{dc}{d\kappa}\right)}\bar{B}(\kappa)e^{-i\omega t}d\omega = \int_{-\infty}^{+\infty}H(\kappa)e^{-i\omega t}d\omega$$

- We can get a non-dispersive solution of $u(t)$ by using the equation:

$$u_{s0}(t) = \int_{-\infty}^{+\infty}\underline{F(\kappa)}H(\kappa)e^{-i\omega t}d\omega = \int_{-\infty}^{+\infty}H_0(\kappa)\,e^{-i\omega t}d\omega$$

Dispersion Correction Algorithm

- The function $F(\kappa)$ is a scaling function to solve for the non-dispersive solutions.

$$F^{short}(\kappa) = \frac{H_0(\kappa)}{H(\kappa)} = \left(\frac{c(\kappa)}{c_0}\right)\left(\frac{c(\kappa)+\kappa\frac{dc}{d\kappa}}{c_0}\right)\frac{i\omega(\kappa)\delta t}{e^{i\omega(\kappa)\delta t}-1}$$

$$F^{long}(\kappa) = \frac{H_0(\kappa)}{H(\kappa)} = \left(\frac{c(\kappa)}{c_0}\right)^2 \frac{c(\kappa)+\kappa\frac{dc}{d\kappa}}{c_0}$$

- We can then solve directly for $H_0(\kappa)$ and thus, $B(x)$.
  - 1st derivative for short, 2nd derivative for long.

Correction Algorithm Summary

- 1. Set evenly spaced ω_i over a large enough range to correctly capture $\bar{B}(\kappa(\omega))$.
- 2. For all ω_i numerically integrate

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

to obtain G(ω_i).

- 3. Calculate unevenly spaced κ values, $\kappa_i = \kappa(\omega_i)$, which are associated with H(κ_i) = G(ω_i).
- 4. Multiply H(κ_i) by F(κ_i) to obtain $H_0(\kappa_i)$.
- 5. For each time t_i numerically integrate

$$u_{s0}(t_i) = c_0\int_{-\infty}^{+\infty} H_0(\kappa)e^{-ic_0\kappa t_i}\, d\kappa$$

to determine the non-dispersive displacement solution $u_{s0}(t_i)$.

Pulsed-Wire System Details

- Setup
- Procedures
- Final Results
- System Difficulties
- Conclusions

Setup

- Physical Design
- Pulse Generation
- Wire Positioning
- Wire Tension
- Vibration Detection

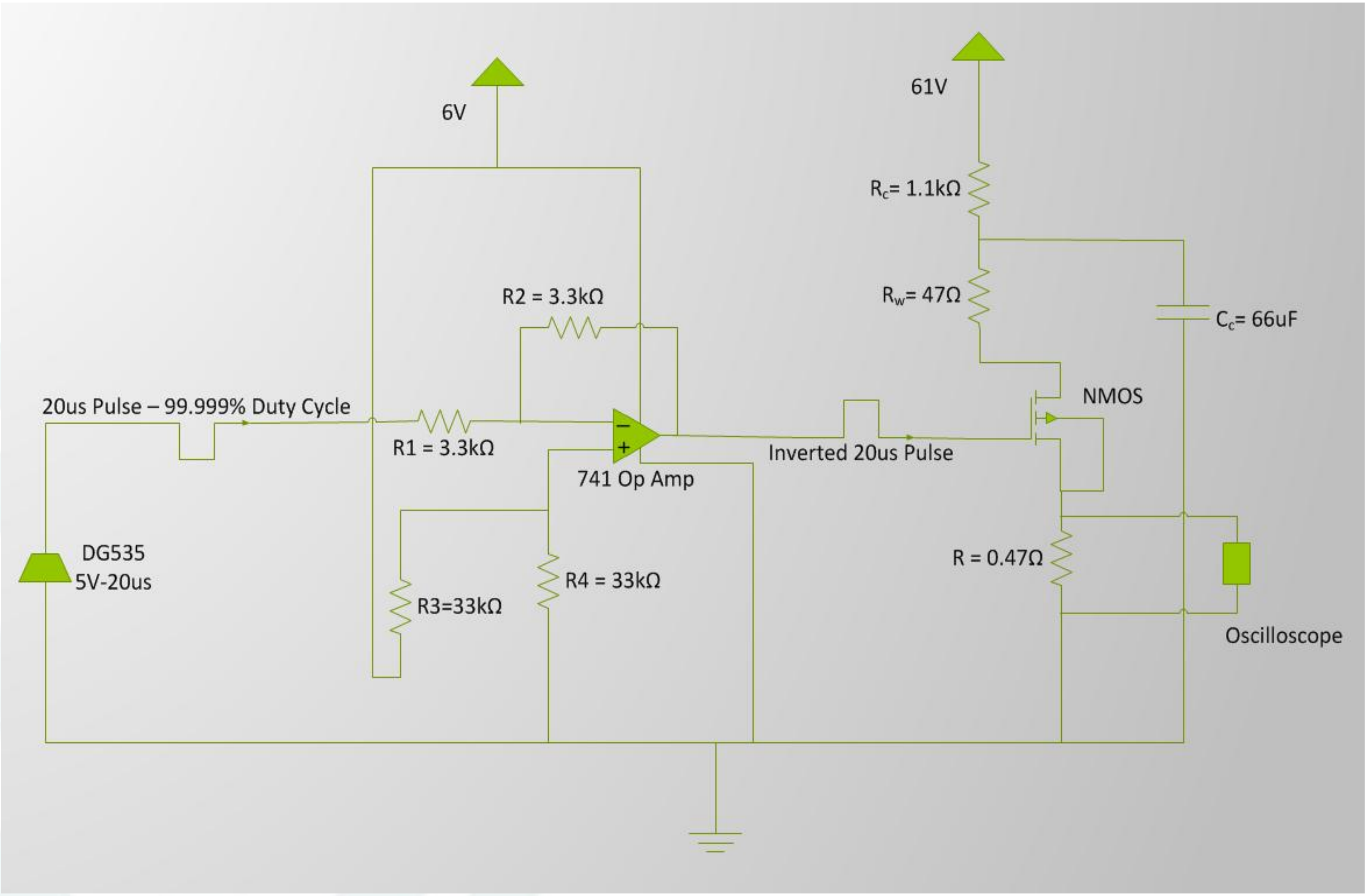
Setup: Design Specs

- **Must be built such that reflections of the acoustic wave from the end wire mounts are not measured.**
- **The disturbance (vibration) travels in both directions at the same velocity, so the wire must be at least twice as long as the undulator.**
- **Total length = 3 m.**
  - Addition of reference magnet increased length.

Setup: Pulse Generation

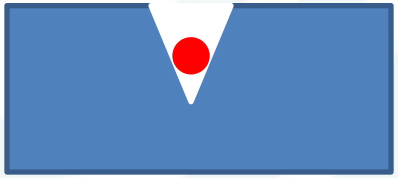
- **The width of the pulses must be set to accurately extrapolate the first and second field integrals.**
- **1st integral = short pulse.**
  - 20 µs
- **2nd integral = long pulse.**
  - 12 ms

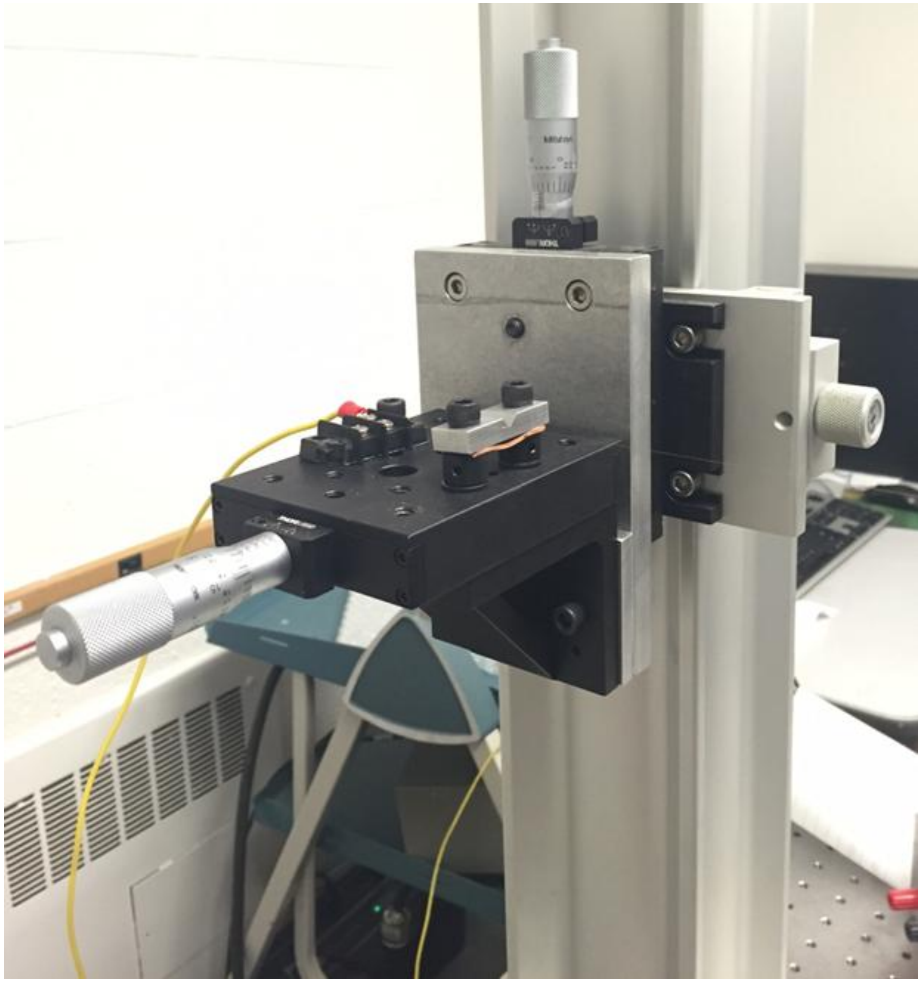
Pulse Circuit Diagram



Setup: Wire Positioning

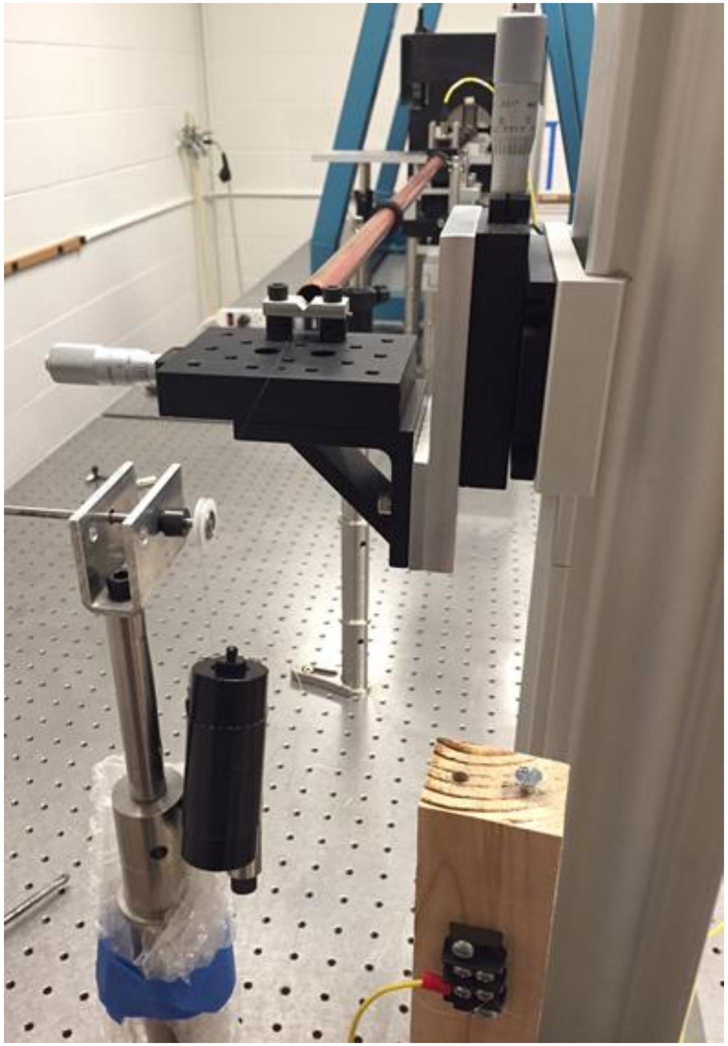
- 2-Axis Translation Stage with 25 µm resolution.
- "V-Blocks" to hold wire steady during alignment and experiments.





Setup: Wire Tension

- **Weight**
  - Used 2.3 N and 0.85 N.
- **Higher tension reduces dispersive effects, increases wave speed, and decreases wire displacement.**



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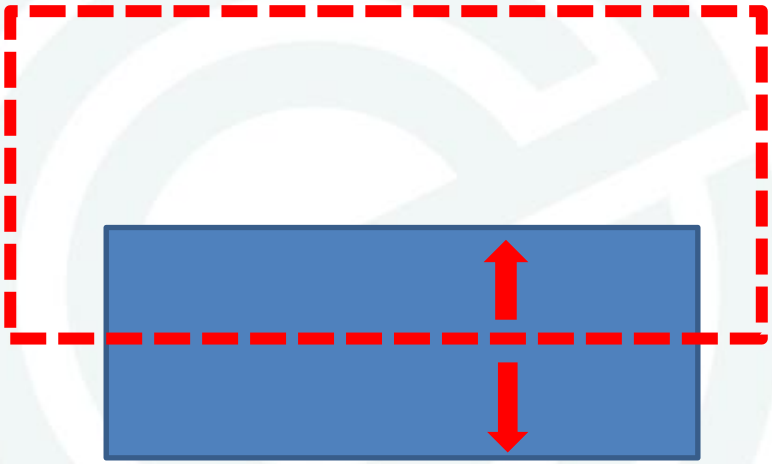
Setup: Wire Vibration Detection

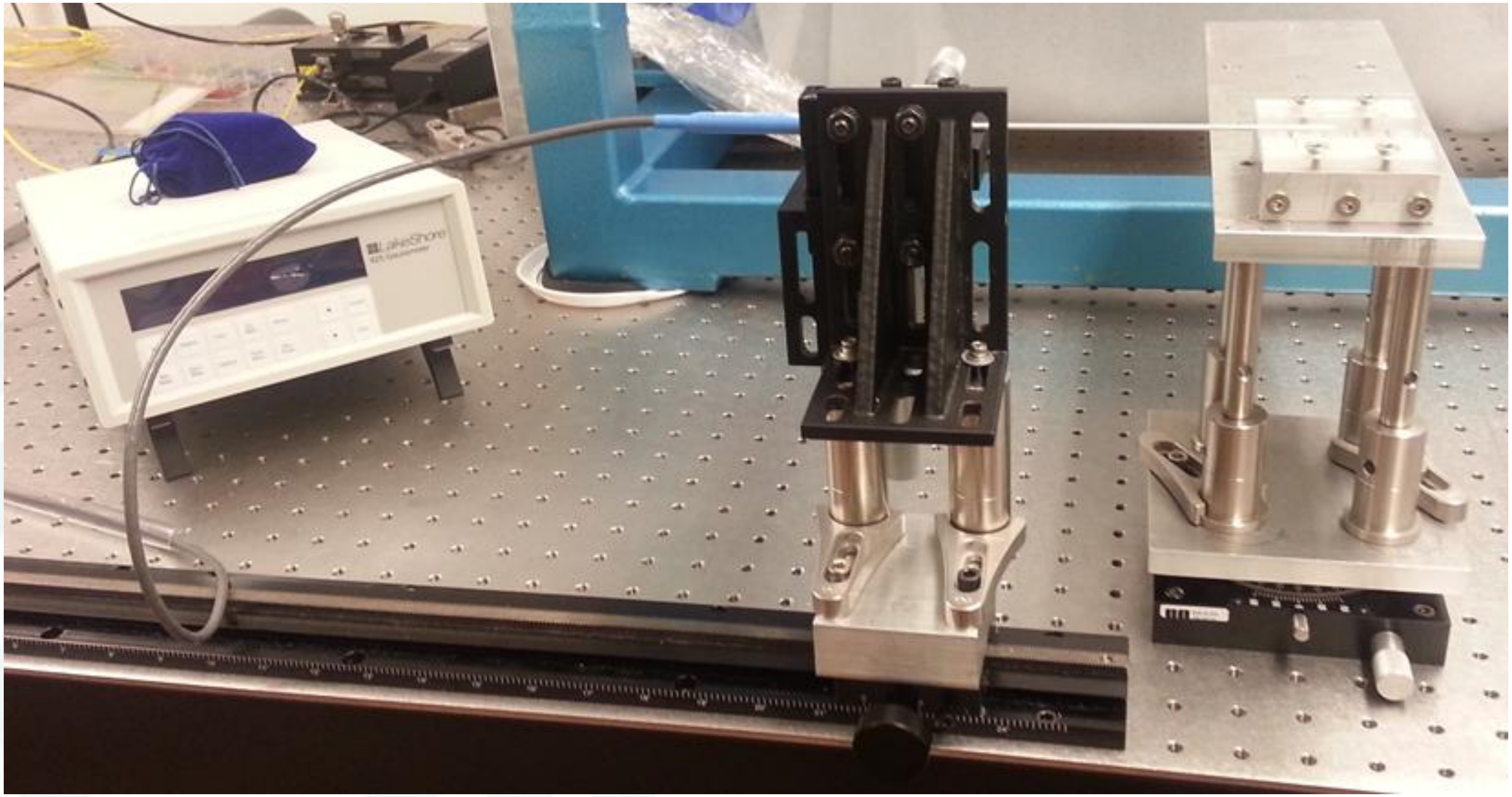
- 635 nm fiber laser
- 40 µm Slit
- Amplified Si photo-detector



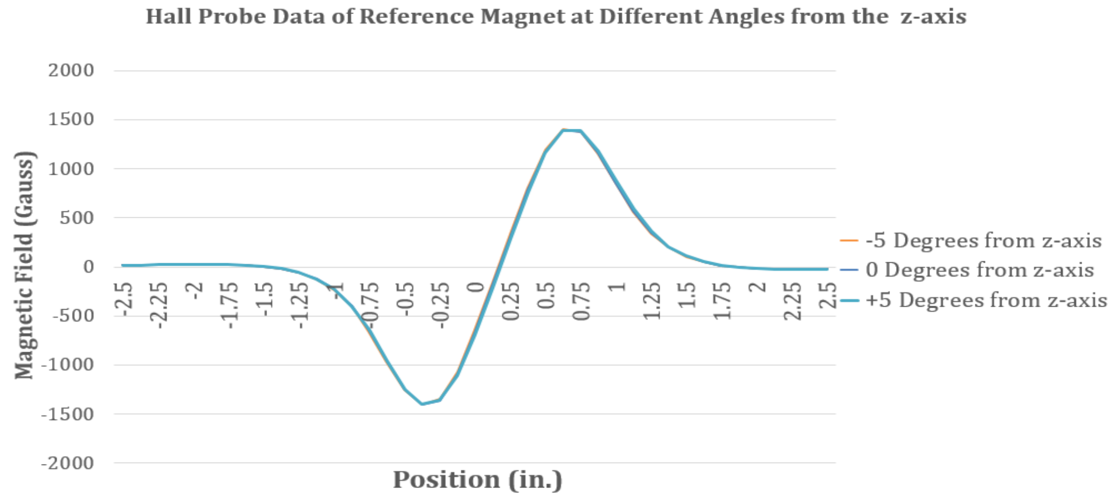
Procedure

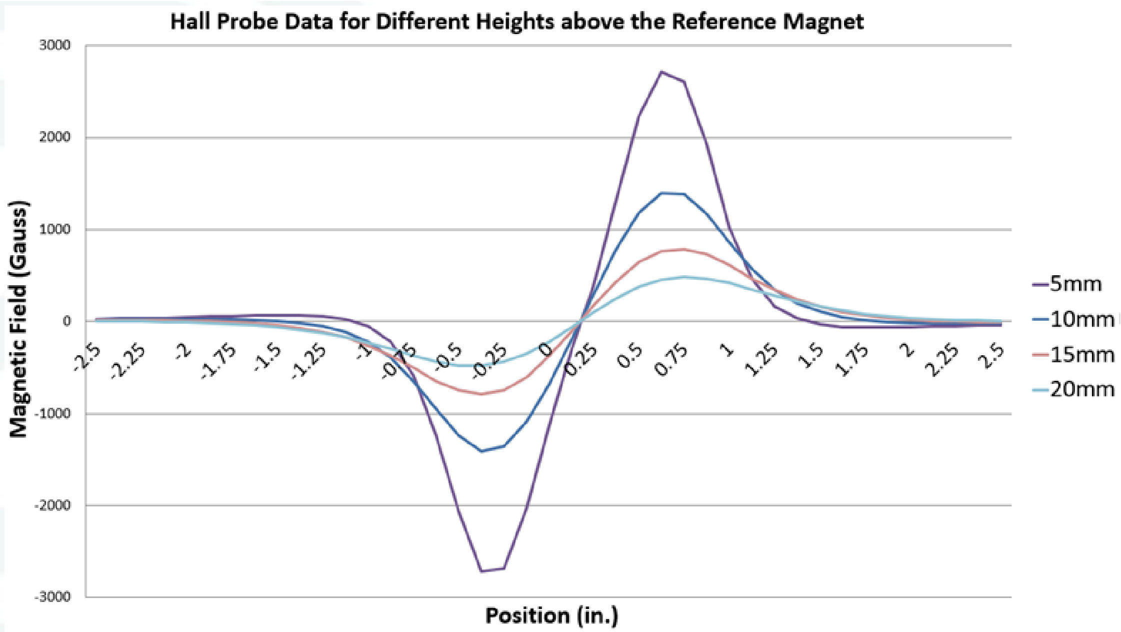
- **Reference Magnet Base Measurement**
  - Hall probe and Gauss meter
- **Measurement and Data Acquisition**
- **Undulator Center Determination**
  - Mechanical
  - Magnetic

Hall Probe Data-Reference Magnet



Hall Probe Data-Reference Magnet





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Measurements and Data Acquisition

- **Current pulse is introduced in the wire.**
  - Oscilloscope starts measuring when the pulse turns “on.”
- **Oscilloscope sees the wire vibration (displacement) as a voltage change.**
  - Change proportional to the field and current amplitude.
- **Data is transferred to a computer and processed through Matlab.**

Procedures: Undulator Gap Center

- **The PW needs to accurately simulate the electron beam.**
  - Measurements must be done at the magnetic center of the undulator.
- **Found the mechanical center and made fiducial marks to easily and accurately reposition the wire in the future.**
- **Determined the magnetic center of the undulator and documented its position from the mechanical center.**

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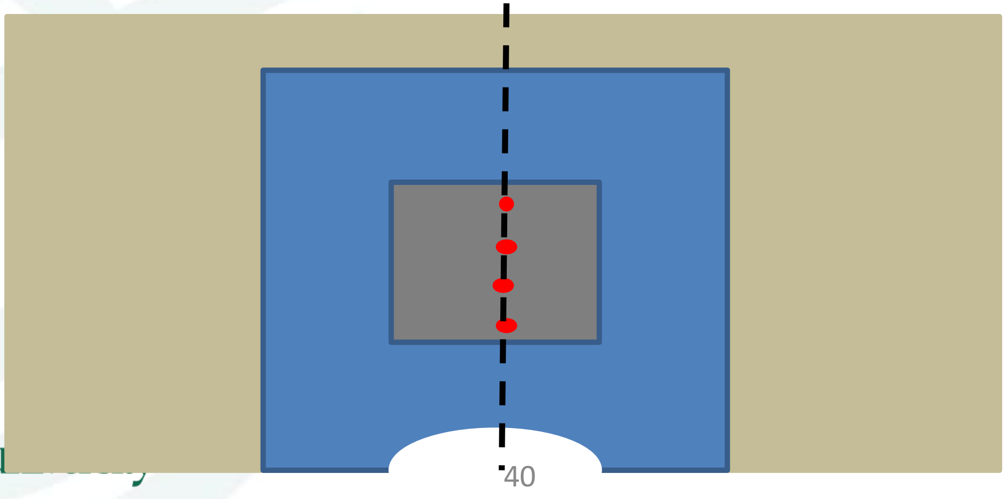
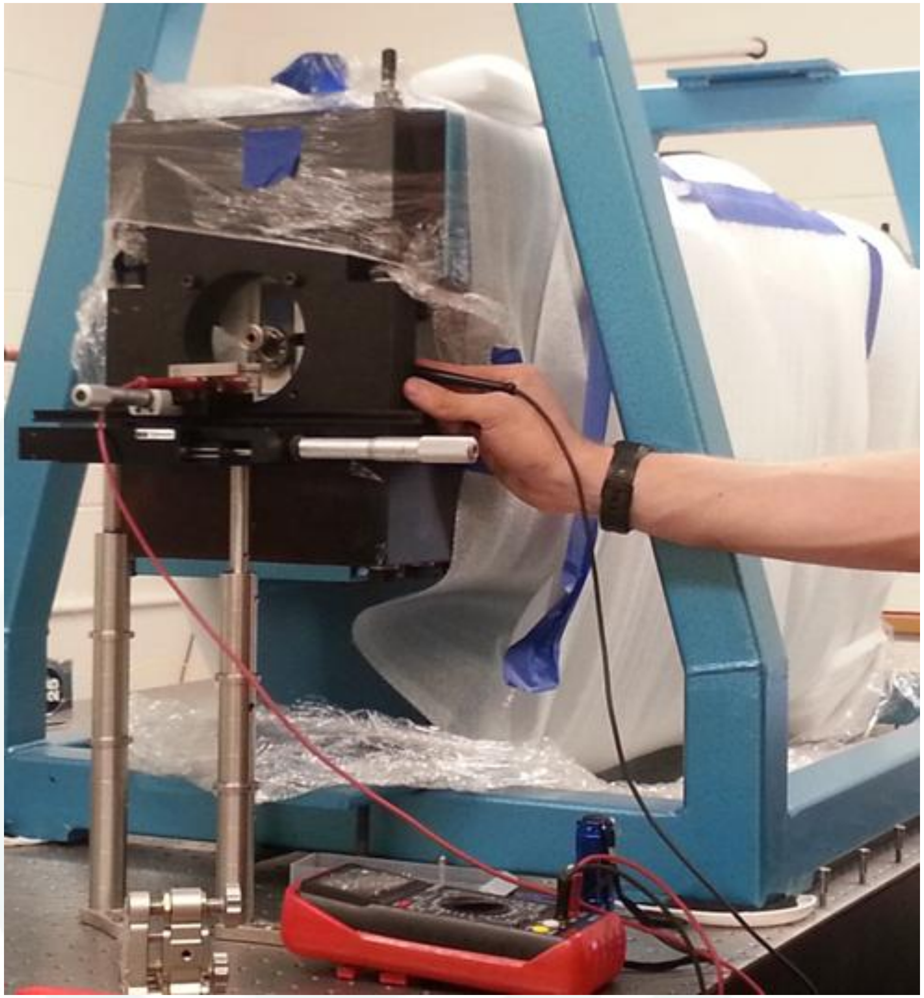
Mechanical Center

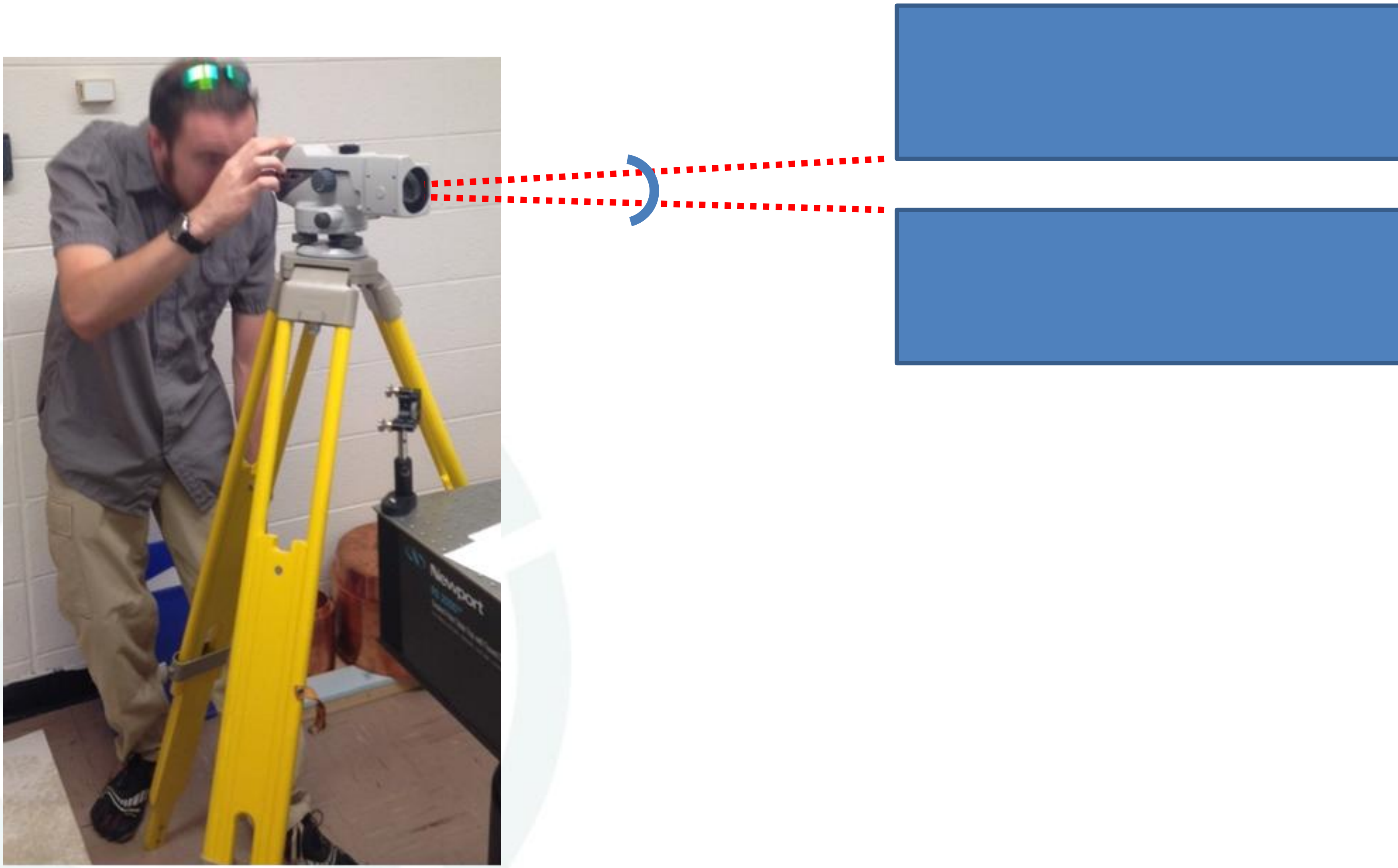
- Used mounted multi-meter probes to find horizontal center.
- Surveying scope was used to find vertical center.
- Fiducial marks were placed in different locations on the undulator.



Mechanical Center

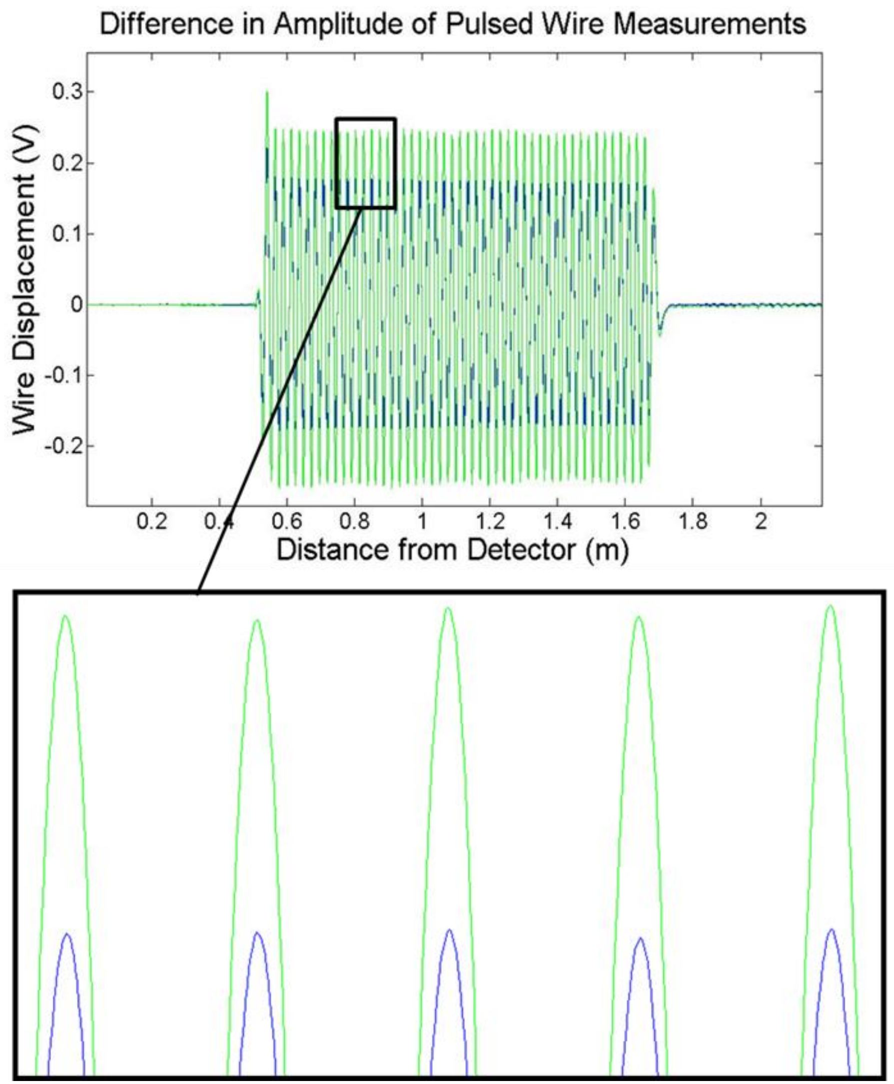


Mechanical Center



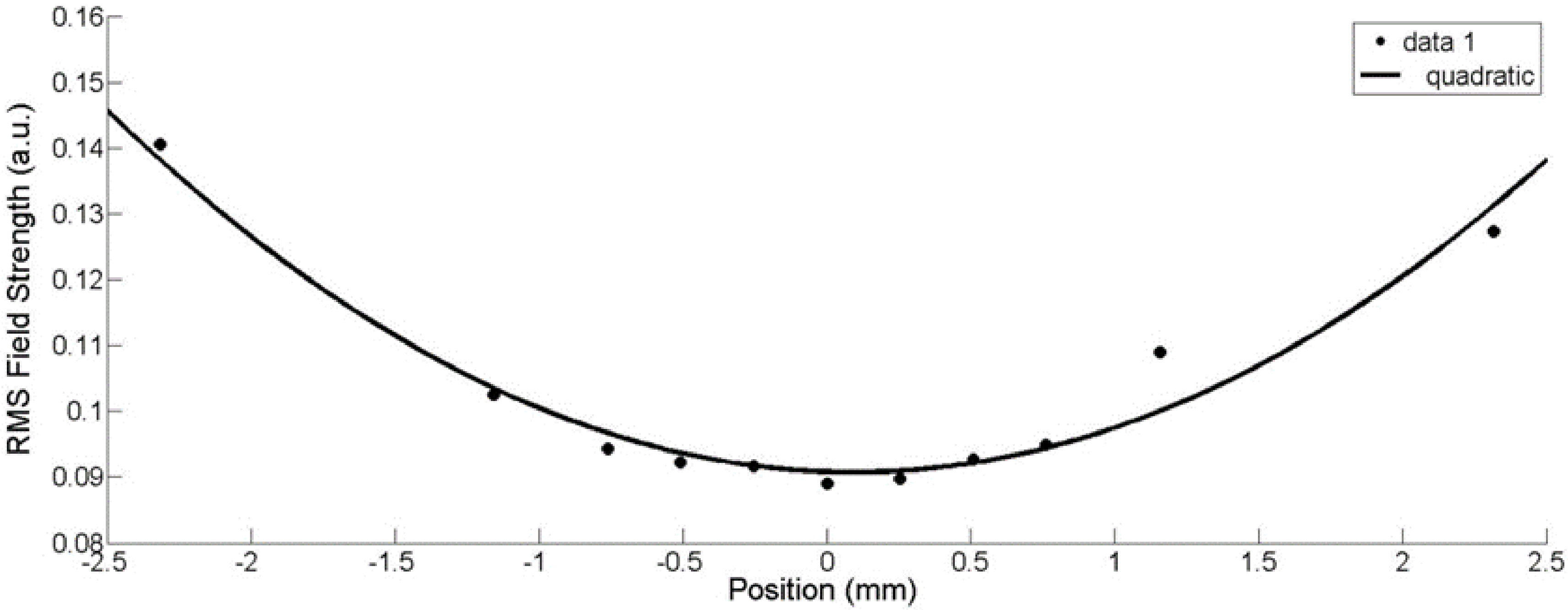
Magnetic Center

- **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.**



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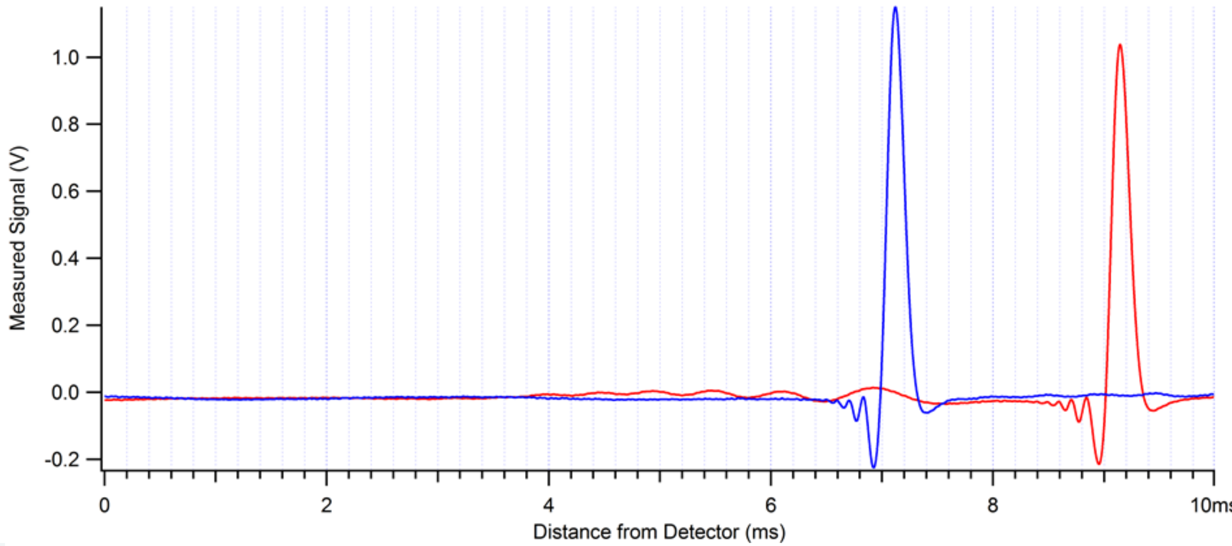
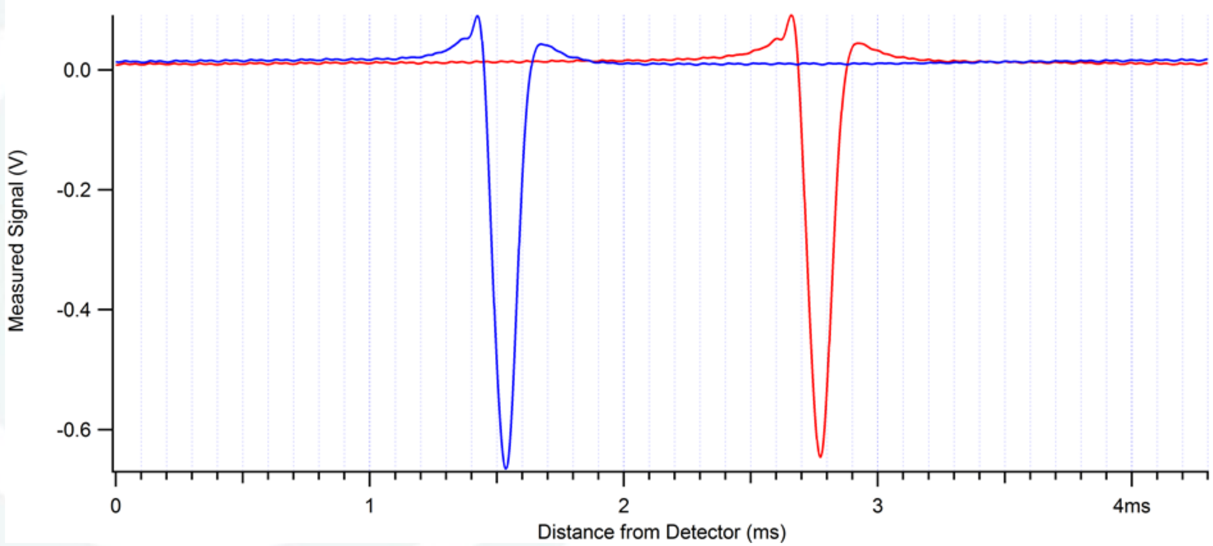
Final Results

- Found dispersive wave speed.
- Corrected for dispersion in reference magnet signal.
- Comparison to Hall probe data to find absolute scaling needed for accurate magnetic field profile.
- Corrected 1st and 2nd field integral PW measurements for undulator.
- Found the magnetic field profile of the undulator.

Reference Magnet Measurements



$$\Delta z = 30cm$$



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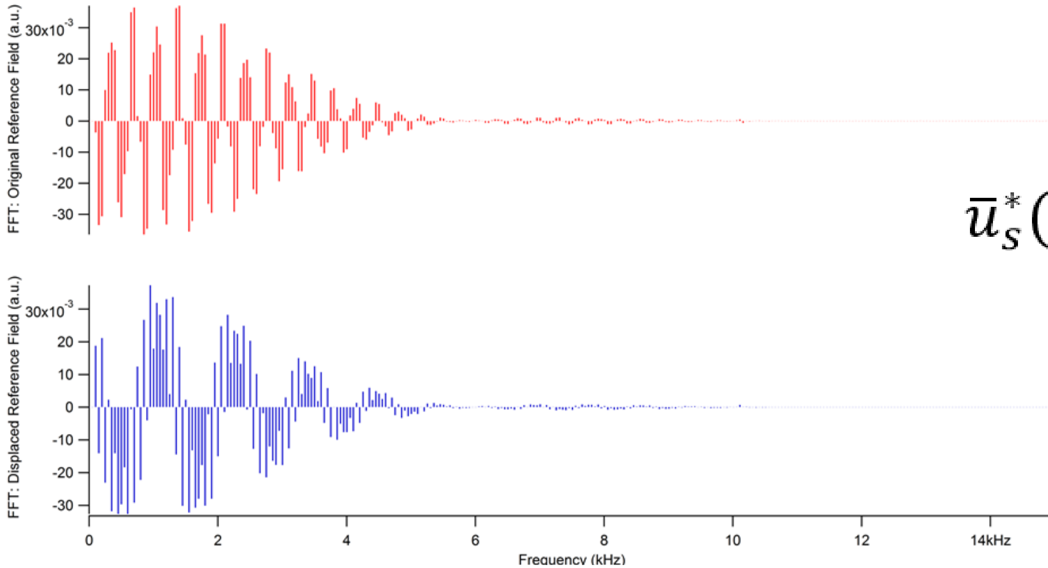
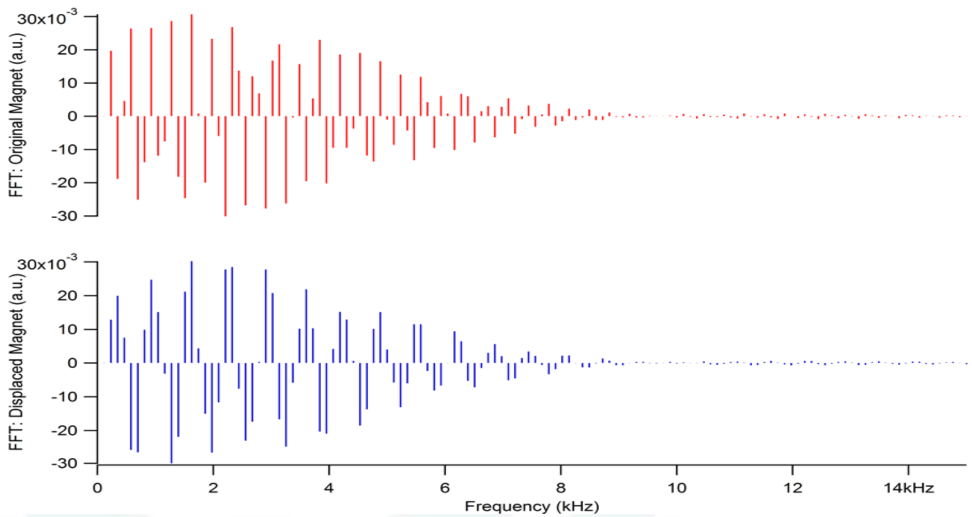
FFTs of Reference Magnet Signals



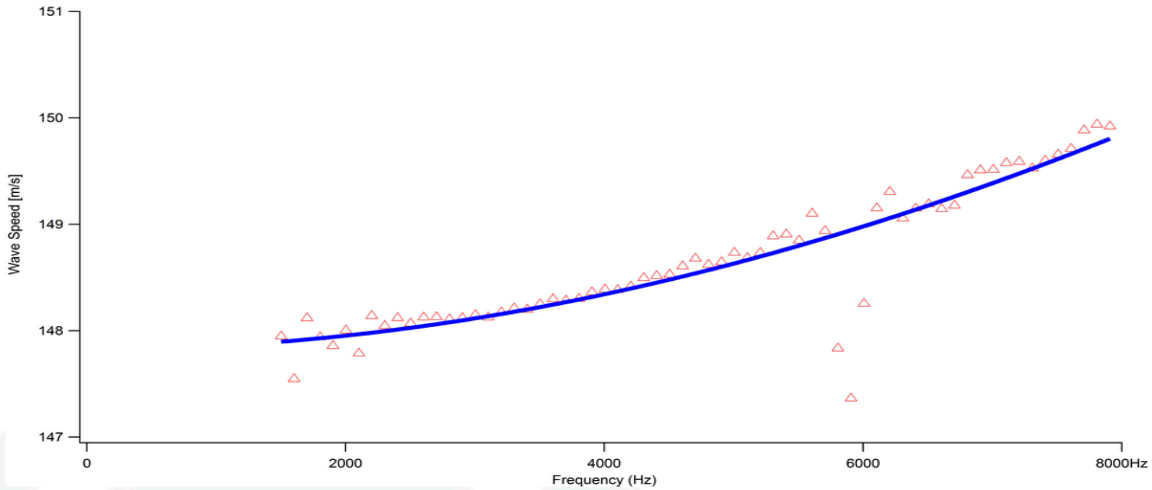


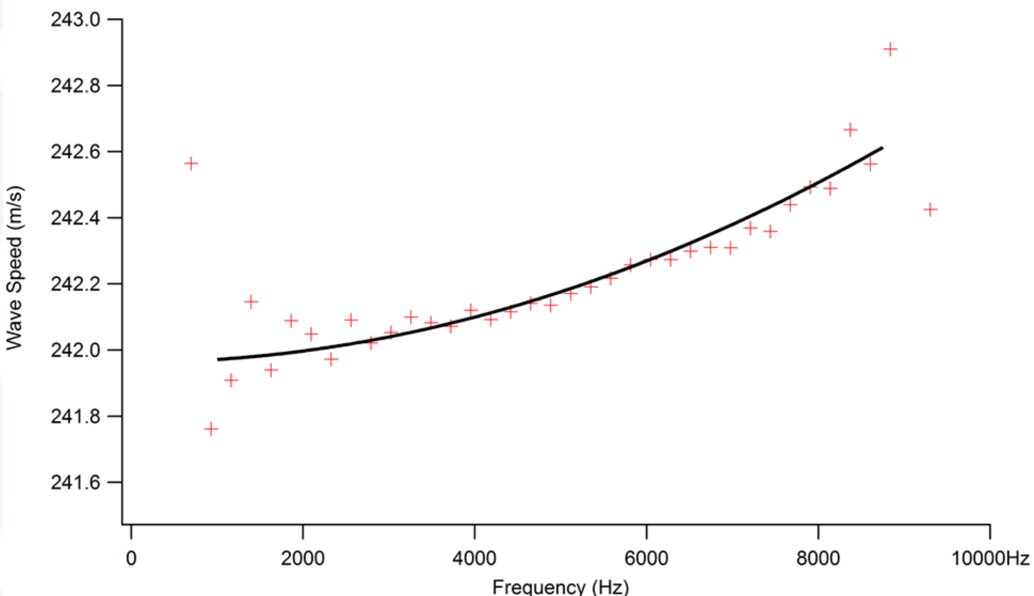
$$\bar{u}_s^*(\omega)\bar{u}_{s\Delta z}(\omega) = |G(\omega)|^2 e^{i\kappa\Delta z}$$

$$c = \frac{\omega\Delta z}{\phi}$$

$$\Delta z = 30cm$$

Dispersive Wave Speed





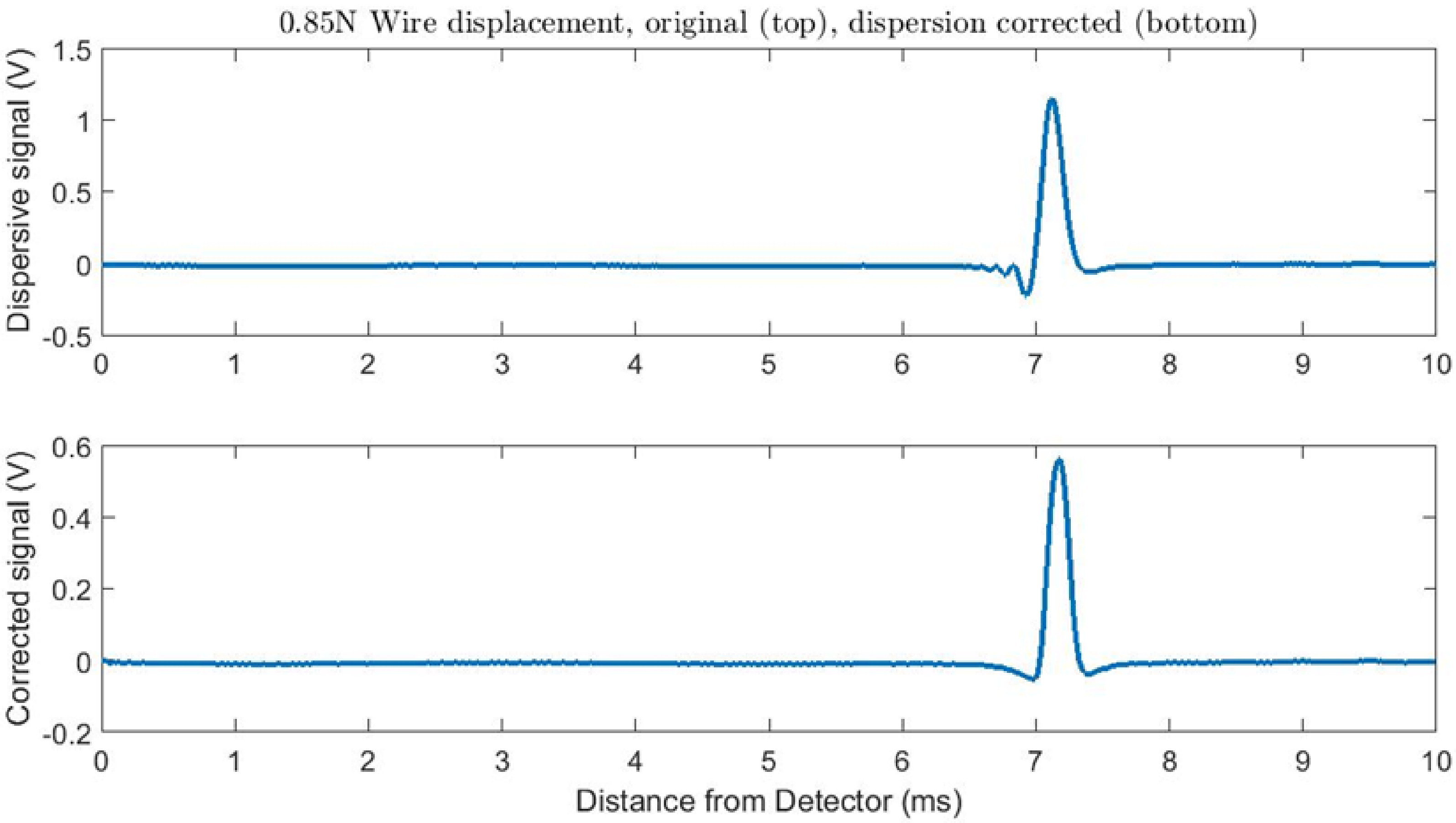
$$c = \frac{\omega \Delta z}{\phi}$$

Wave Speed Parameters

$$c(\kappa) = c_0\sqrt{1 + \frac{EI_W}{T}\kappa^2}. \qquad \kappa = \frac{\omega}{c}$$

Table 3: Wave Speed Parameters		
Tension (N)	0.85	2.3
C0 (m/s)	148	242
EI_W (Nm^2)	$2.13*10^{-7}$	$2.38*10^{-7}$

Dispersion Corrected: Short Pulse (1st Integral)



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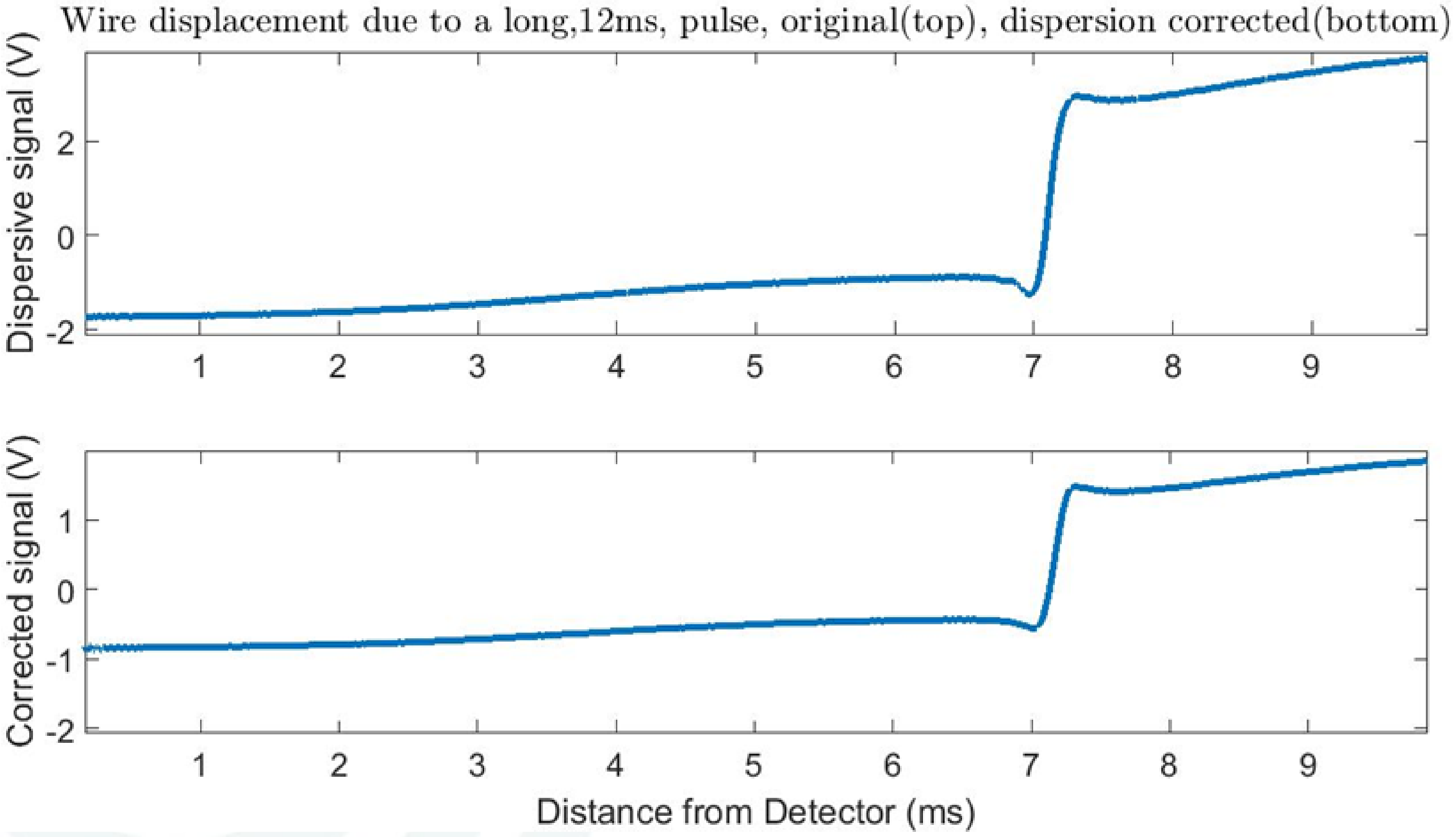
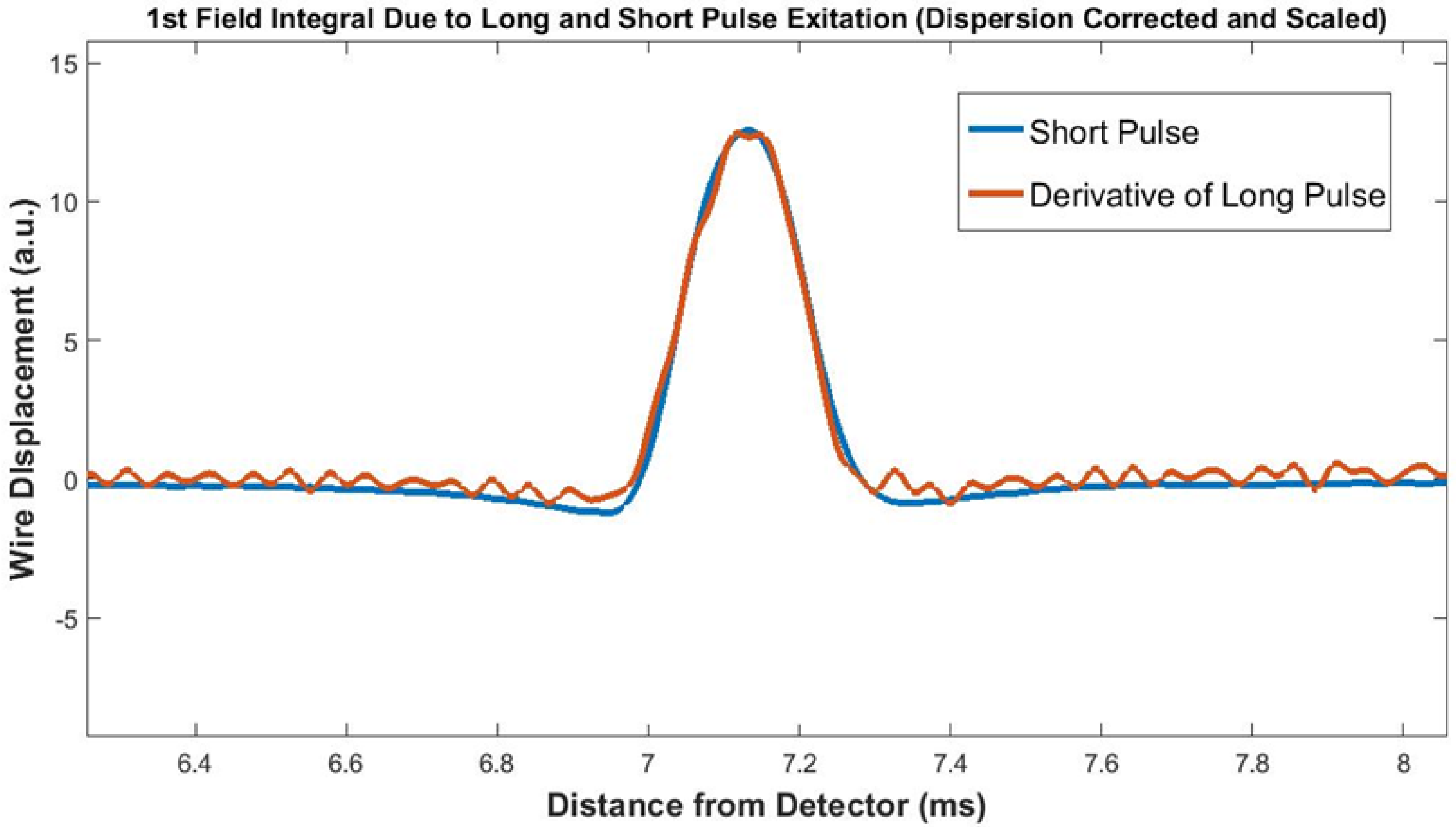
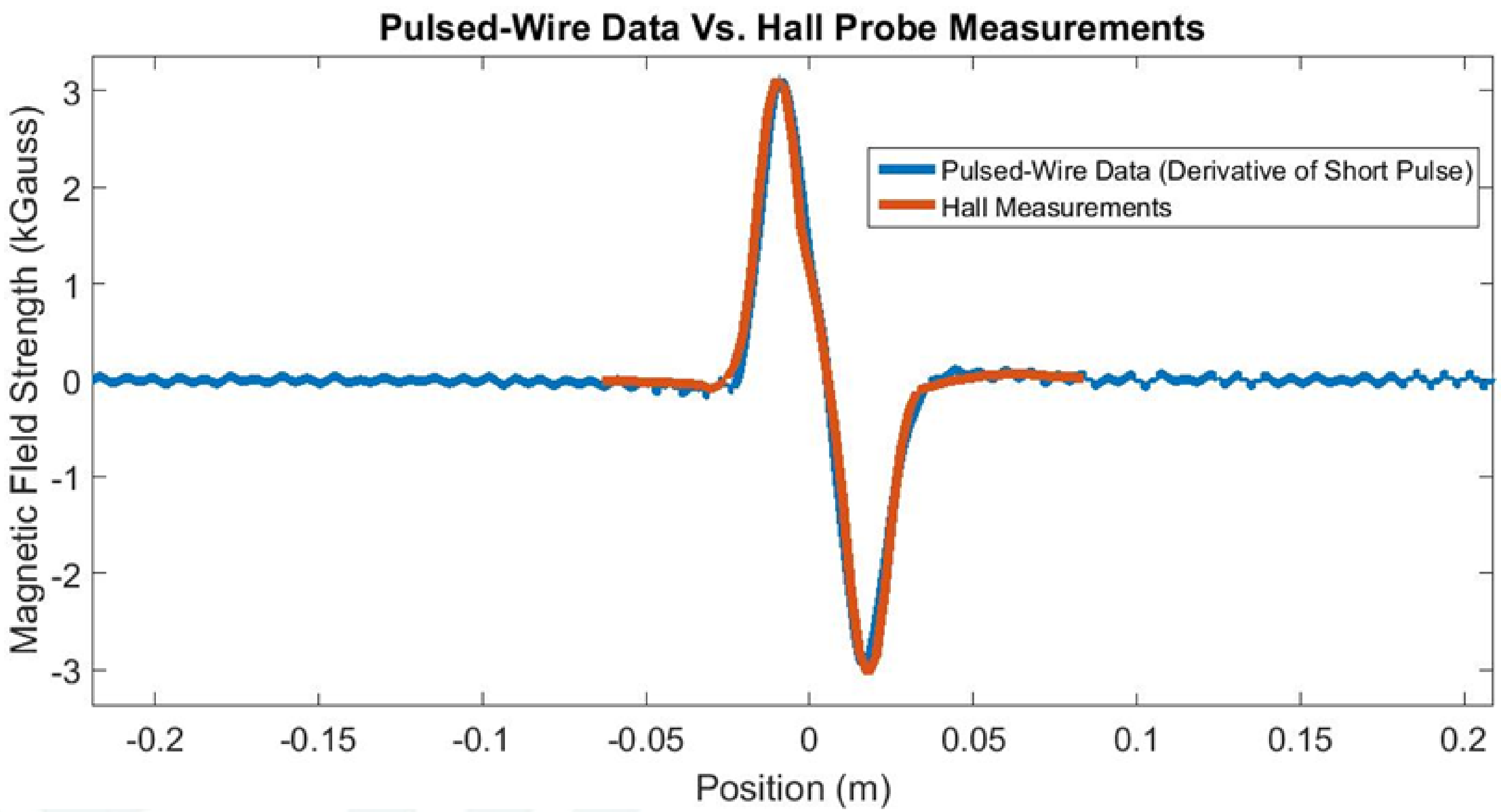
Dispersion Corrected: Long Pulse (2nd Integral)



1st Integral Compared to Derivative of 2nd Integral



Pulsed-Wire Measurements Compared to Hall Probe

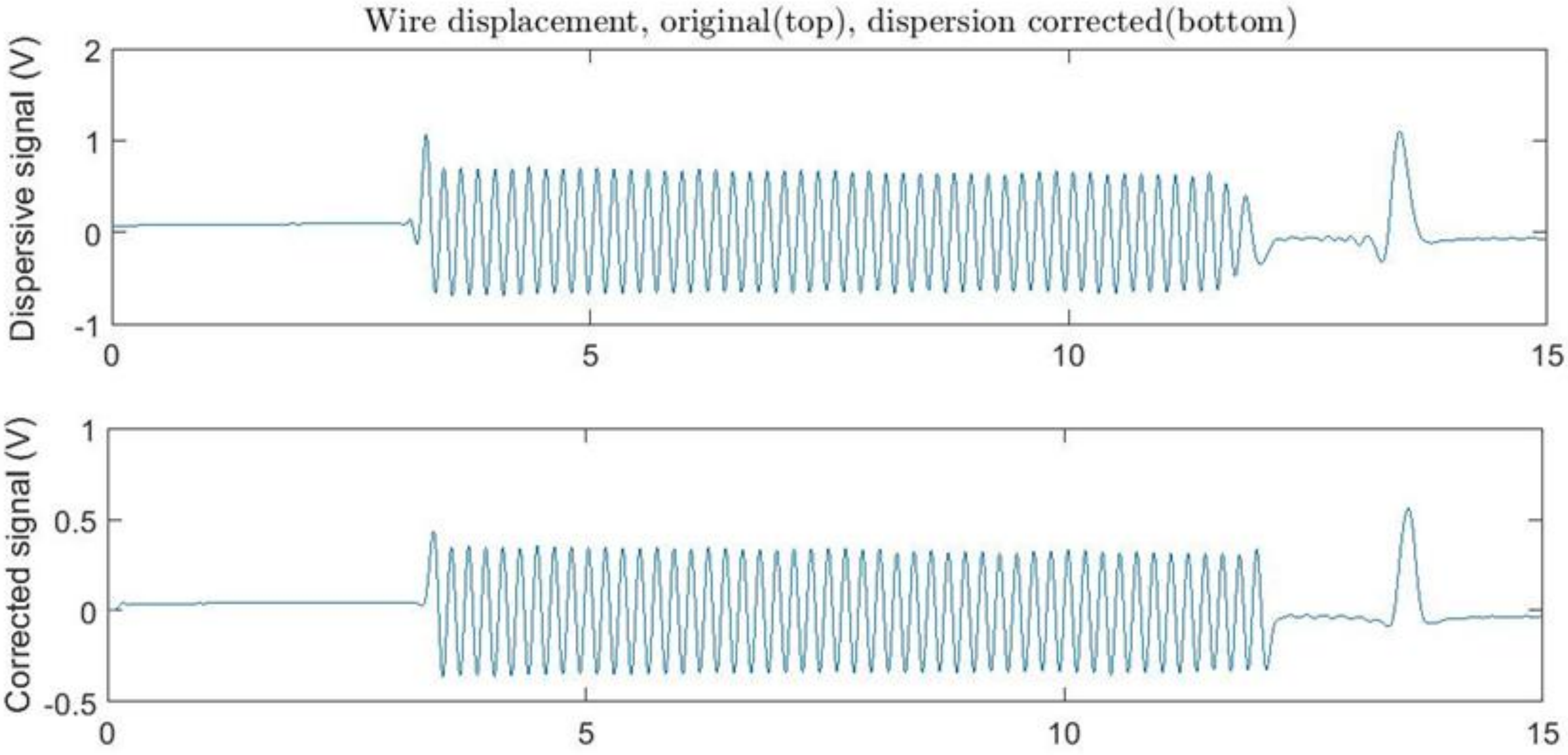


$$u_{s0}(t) = \frac{Ic_0 \delta t}{2T} \int_0^{c_0 t} B(\tilde{x}) d\tilde{x}$$

$$\frac{Ic_0 \delta t}{2T} = 6.5 * 10^{-4}$$

Absolute Scaling factor = **$5*10^{-4}$**

1st Integral of the Undulator and Dipole



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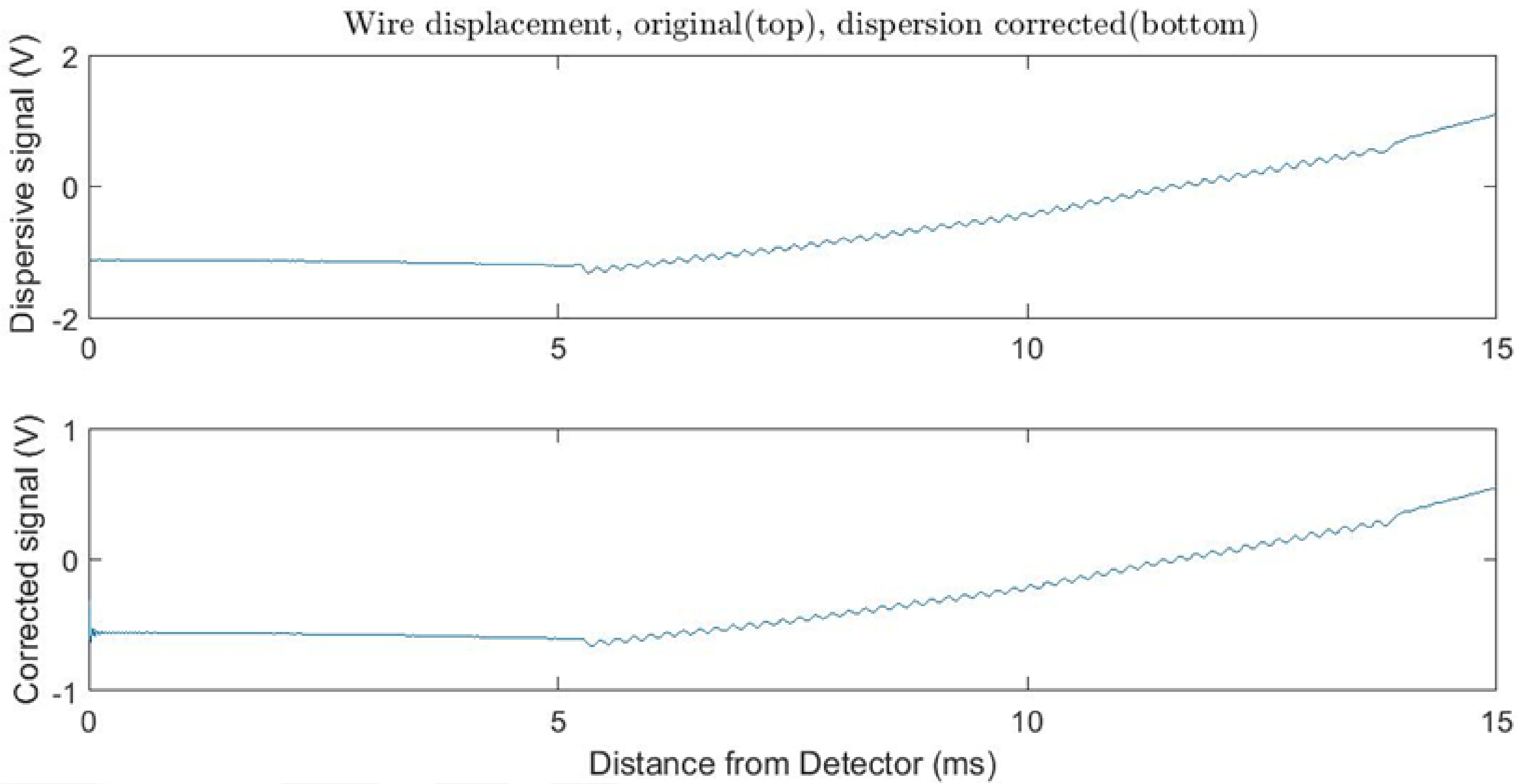
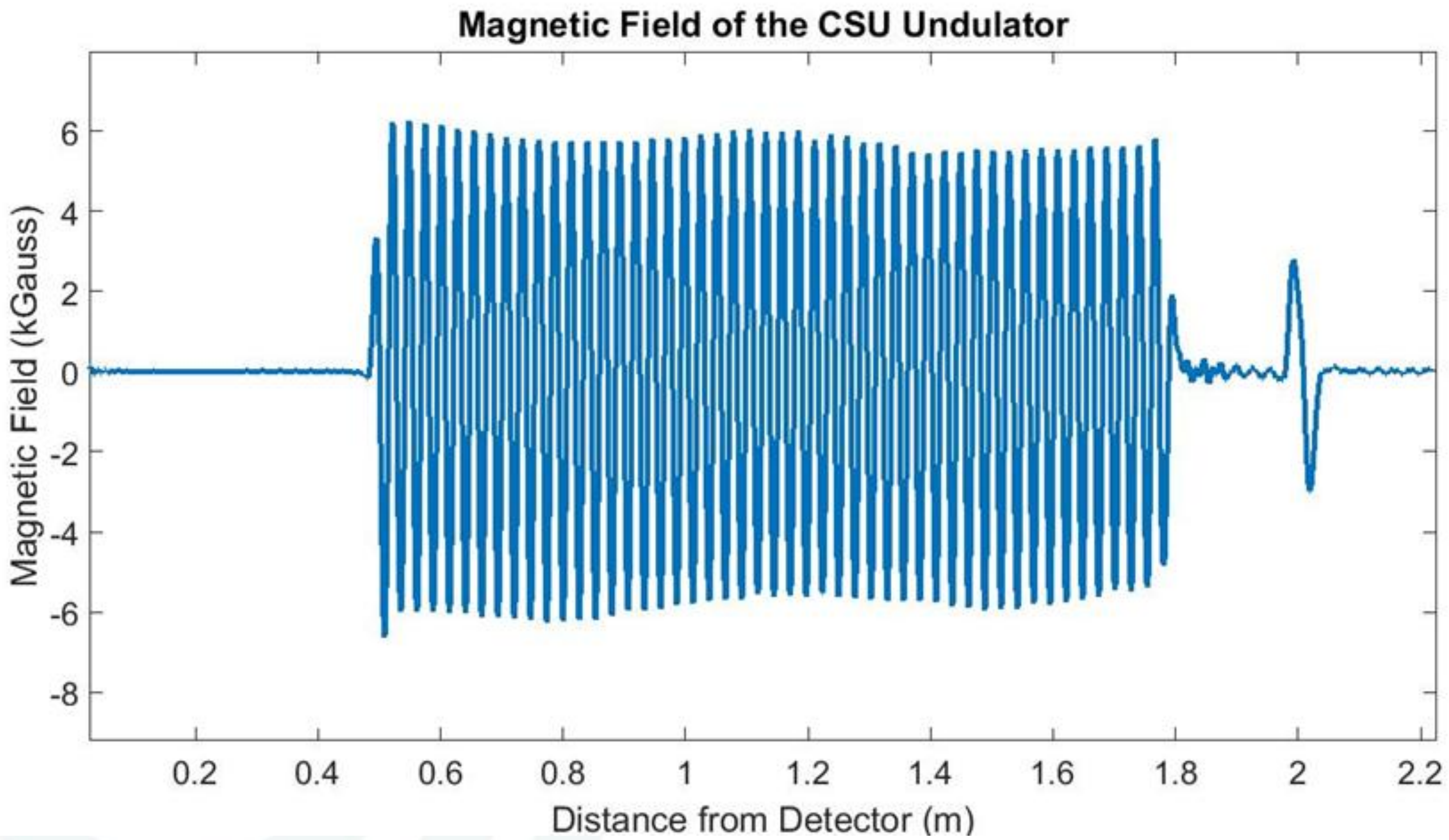
2nd Integral of the Undulator



Local Magnetic Field of CSU's Undulator Magnet



System Difficulties

- **Large amount of noise was prominent.**
  - Air
  - Poor table isolation from ground
  - Electrical
- **Limitations**
  - Oscilloscope resolution

Conclusions

- The results given are reproducible.
- The method can be used for many different types of magnets in the future for ultra-fast field profiling.
- Practical Applications: PW kit for KYMA

Future Work

- **Find specific locations of field errors.**
- **Perform corrections on dipoles with errors.**
  - Place ferromagnetic material (shims) at specific locations to correct errors.
    - Already documented where current shims are located.
- **Shorter reference magnetic field.**
  - Higher frequency components results in better calculations of the dispersive wave speed.

Thank you!

Experiment still setup for anyone interested to see!